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Snow water equivalent variability and forecast in Lithuania

Egidijus Rimkus and Gintautas Stankunavichius

Department of Hydrology and Climatology, Vilnius University, Ciurlionio 21/27, LT-2009 Vilnius, Lithuania

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Atmosphere circulation is the most important modulator of snow cover parameters. This study deals with the relation between the dominant Northern Hemisphere circulation mode, called the Arctic Oscillation (AO), and the spatial distribution of the snow water equivalent (SWE) within the territory of Lithuania. The results indicate an inverse relation between the extreme AO phase and the SWE. However, the largest spatial differences are seen in the positive AO phase. The absolute altitude and slopes expositions play a more significant role in that case. During the extreme negative AO phase, a decreasing temperature as a function of distance from the seacoast from west to east becomes more significant to the accumulation of snow cover. The study also includes a climatic forecast for changes in the snow water equivalent based on the outputs of five climate models. Under an increasing winter air temperature and rain fraction in winter precipitation, the SWE will decrease distinctly causing a change in river feeding regime.

Introduction

The permanent snow cover formation in Lithuania depends on the air temperature in December, and its mean dates extend from the second part of December (the eastern and the northeastern part of Lithuania) to the first days of January (the seacoast and the southwestern part). The snow cover thickness depends mostly on the monthly mean air temperature and precipitation during the snow cover accumulation period (January–February). Usually the highest values of the snow water equivalent (SWE) are recorded in the second part of February. Exceptions to this can be mild, changeable winters with frequent thaws, when the SWE depends mostly on liquid precipitation events with a negative or close-to-zero air temperature.

The sequence of changes in atmosphere circulation patterns during the snow accumulation period plays an important role in the variation of snow cover parameters and, later in spring, in a flood character. It is difficult to make a connection between the development of the snow cover and weather patterns because of their different classifications for the Baltic region. On the other hand, there are well-known circulation indices suitable for the description of the large (planetary) scale atmospheric circulation over the whole Northern Hemisphere and European-Atlantic sector. The most informative of these are the North Atlantic Oscillation (NAO) and

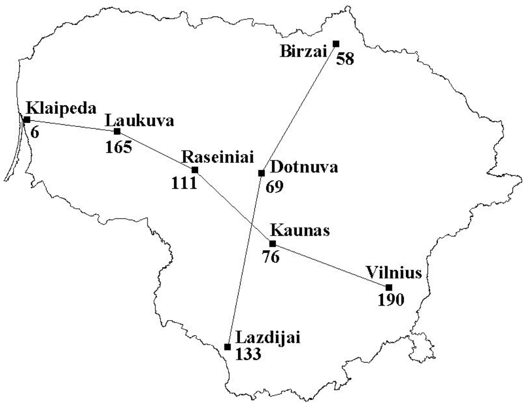

Fig. 1. A scheme of the reference meteorological stations in Lithuania. The two lines represent the long and short axis of the territory. The numbers on the map indicate the absolute altitude of each meteorological station. See explanations in the text.

the Arctic Oscillation (AO). In this paper, a preference was given to the AO index for the following reasons: (1) the NAO index is suited best for the western Europe because of its small distance to the reference points compared with the rest of Europe, (2) the spatial structure of the NAO pattern changes from November to March, even though these changes are not very distinct, and (3) the lower-tropospheric (850–1000 hPa) temperature over the south eastern Baltic correlate with the AO index best of all. The Arctic Oscillation (AO) is the leading mode of the high-latitude variability in the Northern Hemisphere, as characterized by the first empirical orthogonal function of the mean sea-level pressure with associated regression patterns of the temperature, zonal wind, and geopotential height from the surface to the stratosphere. The strong zonal symmetry of pressure fields led Thompson and Wallace (2000) to call it the northern "annular mode". The terms "Arctic Oscillation", "northern annular mode" and "leading mode of the Northern Hemisphere" are used in literature to describe the same phenomenon. The AO in the troposphere is coupled strongly with the strength of the stratospheric polar vortex, and stratospheric circulation anomalies are seen to propagate downward to the Earth's surface where they are reflected as changes in the magnitude and sign of the AO (Baldwin and Dunkerton 1999). Intra-seasonal changes in the stratospheric circulation have been observed to precede both high-latitude and low-latitude Atlantic climate anomalies and significant weather events. The first empirical orthogonal function is identified as the AO, while the second one apparently includes the variability that is partly identified with the more localized NAO, and the third one is dominated by the variability of the Aleutian low (Boer *et al.* 1999).

Material and methods

In this study the gridded monthly values of the geopotential height at the 500-hPa level and the sea-level pressure from 1958 to 1998 over the North Atlantic–European domain were taken from National Centers of Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Kalnay *et al.* 1996). These data were used to determine the dominant lower-troposphere flow patterns over the Baltic region. The monthly AO time series were obtained from Baldwin and Dunkerton (1999) for the January–February season. Extreme circulation phases were picked out using the seasonal AO index: equal to or greater than one (positive) and equal to or less than minus one (negative), because of the standardized AO index. The SWE data were obtained from 18 Lithuanian meteorological stations representing the snow cover variation over the territory (for the 1958–1998 period). Some of the stations (8 out of 18) were selected and analyzed separately, since they form a long axis in the WNW–ESE direction and a short axis in the SSW–NNE direction (Fig. 1). These two axes are expected to reveal the differences in the snow cover on the leeward and windward slopes in complicated orographic regions. The relative distributions of the snow water equivalent along the long and short axis of the Lithuanian territory during the extreme positive and negative AO phases were determined.

Outputs of Global Climate Models experiments from five modeling centers (HadCM2 (United Kingdom); ECHAM4 (Germany); CGCM 1 (Canada); GFDL-R15 (USA); CSIRO-Mk2 (Australia) were used in this study and

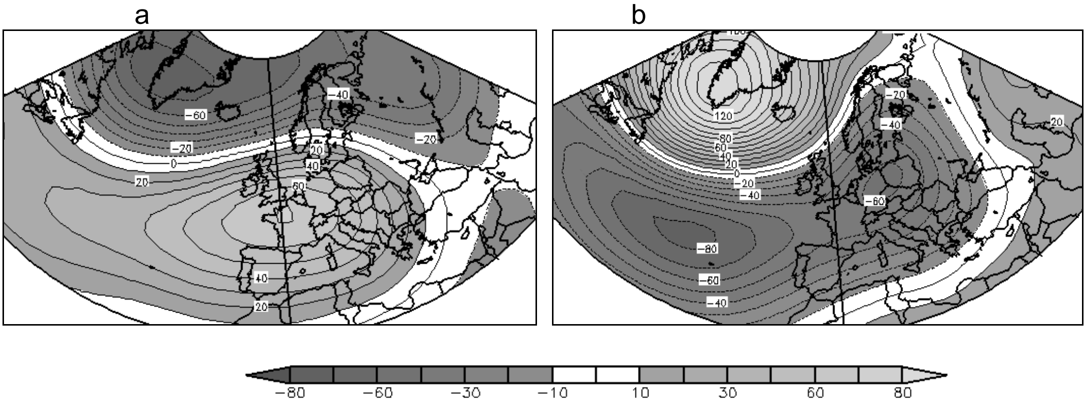

Fig. 2. Composites of the H500 geopotential height (in m) for the snow accumulation period (January–February) in years with an extreme high (**a**) and low (**b**) AO index. The dark (light) shading indicates negative (positive) geopotential height anomalies extracted from the climatology based on the monthly mean values during the period 1979–1995. The image is provided by the NOAA-CIRES Climate Diagnostics Center, Boulder Colorado from their Web site at http://www.cdc.noaa.gov/.

obtained from the IPCC data distribution center. According to contemporary climate model predictions, it is possible to directly forecast a few meteorological parameters, including the air temperature, precipitation, etc. Regression relations between these parameters snow depth and SWE have been used to forecast the changes in snow cover parameters. The inhomogeneous composition of precipitation (especially in the seacoast region) and the differences in the number of days with thaws at different years cause a rather weak correlation between the amount of precipitation during the accumulation period and the maximum snow water equivalent. The relationship between a complex parameter $p^2 \times t$ (p is the precipitation amount (mm) and t is the mean air temperature (°C) during the accumulation period) and the maximum SWE is stronger than that in the above mentioned case, and has been approximated by an exponential type of regression. The changes in the maximum snow water equivalent are inconsiderable when the mean air temperature is close to 0 °C during the accumulation period. The probability for a permanent snow cover formation is likely to decrease in this case. Due to this condition the maximum value of the SWE could frequently be achieved within one synoptic process. Such processes are usually separated by thaw periods during which the snow cover may disappear.

Results

During the positive AO phase a westerly flow predominates over the whole European-Atlantic sector, the exceptions being the Mediterranean and the Middle East. The negative AO exhibits an easterly flow at least in the mid-Atlantic and positive pressure (height) anomalies over the northwestern part of this sector. Furthermore, the most negative pressure height anomalies over the Central Europe are in phase with a southward shift of a storm track — surface cyclones reach the southeastern Baltic in a mature stage and their centers (the northern parts) produce abundant snowfall or snowy rain (Fig. 2). The differences in the maximum SWE in Lithuania became particularly evident in the extreme AO phases. The mean territorial values of this parameter reached 58 mm during the negative AO phase ($I_{AO} \leq -1$) and decreased to 24 mm during the positive AO phase ($I_{AO} \geq 1$). The correlation between the snow water equivalent and the AO index for the whole study period (1958–1998) was negative and statistically significant ($r = -0.51$). Not always is the AO is a sufficient indicator. For example, in January–February 1966 an extreme negative (–2.1) AO index was influenced by an extreme negative sea-level pressure anomaly (–20 hPa) over the middle North Atlantic (50–55°N, 30–50°W).

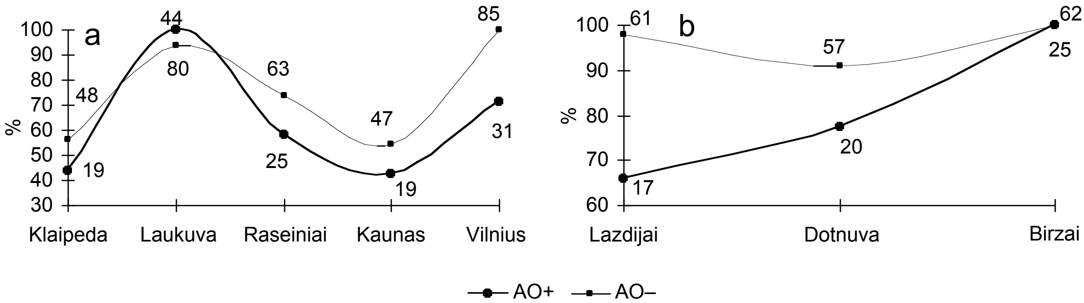

Fig. 3. The relative distribution of the snow water equivalent (in percent) along the long (**a**) and short (**b**) exis of the Lithuanian territory during an extreme positive (solid line) and negative (thin line) AO phase. The numbers on curves indicate the absolute values (in mm) of the snow water equivalent.

A strong easterly flow was dominant only in the western part of the Atlantic midlatitudes, and only slight flow anomalies were observed in the northern Europe. This period was characterized by a small snow water equivalent due to a low cyclone activity in the Baltic region.

The snow water equivalent data have been represented as a percent of the highest value in each territory, for seasons with both a high and low AO index. The snow water content increased along the long axis and reached its maximum in the eastern side of Lithuania during the negative AO phase, and peaked in the Zemaiciai Upland region (Laukuva) during the positive phase (Fig. 3). The smallest values were found at the lowlands in the coastal area (Klaipeda) and in the middle Lithuania (Kaunas). The stations on the short axis showed a gradual increase of the water content in the snow mass when going from the south (Lazdijai) to the north (Birzai). The SWE was slightly less in the middle Lithuania than in its southern part during the negative phase. The absolute values of the SWE showed that in the positive AO phase when positive temperature anomalies prevailed over the whole territory, the maximum values remained on the windward slopes of Zemaiciai Upland (Laukuva) but not in the eastern Lithuania (Vilnius). Such a spatial distribution of the SWE is mostly influenced by an increased precipitation amount on the western slopes of Zemaiciai Upland (orography forced precipitation under the intense westerly flow). The mean air temperature, decreasing from west to east of Lithuania, seems to be play a secondary role.

Observations suggest that the AO, as well as the spatially more confined North Atlantic Oscillation (NAO), have exhibited a positive trend since the early 1980s (Hurrell 1995, Thompson and Wallace 1998, Wallace 2000). Significant future changes in the maximal SWE and the feeding of rivers are possible if these tendencies will continue. The character of the change in the predicted air temperature and precipitation in the 21st century in Lithuania is similar to most GCM experiment outputs despite differences in the absolute values of these outputs. The simulations show that the air temperature and precipitation will increase particularly rapidly in cold seasons. The tendencies of the current climate change in Lithuania will remain the same in the future: the difference in the precipitation amount and air temperature between the cold and warm seasons will be smaller. This means that climate in Lithuania becomes less continental in character. On the other hand, the air temperature during the accumulation period will increase by 0.3 °C/decade at the beginning of the 21st century, by 0.6 °C/decade in the middle of it, and by 0.4 °C/decade at the end of the century. The precipitation amount will rise by two millimeters per accumulation period in every decade of the 21st century. As a result of the air temperature increase during the accumulation period, the maximum snow depth will decrease significantly within the territory of Lithuania. The SWE will also decrease because there will be no changes in the snow cover density: the higher temperature of solid precipitation and more frequent mixed precipitation cases will be compensated by shorter accumulation periods.

A forecast of the SWE is based on the predictions presented above. Two scenarios were analyzed: (1) the mean temperature of the accumulation period will rise by 1.5 °C and precipitation by 8 mm (as expected around the year 2040), (2) the mean temperature will rise by 3 °C and precipitation by 14 mm (as expected around the year 2065). The calculated territorial average of the maximum SWE in Lithuania was 40 mm for the time frame 1961–1990. The highest value of the SWE was determined for Zemaiciai Upland (60 mm), and the lowest one for the southwestern part of Lithuania (21 mm) (Fig. 4). The spatial distribution of the SWE will remain in its earlier state if the changes in the air temperature and precipitation during the accumulation period will remain the same, as predicted by models, but the range of dispersion will decrease (from 39 mm in the period 1961–1990 to 26 mm in the year 2065). The average maximum SWE will decrease to 34 mm and 28 mm according to the two scenarios described above. Such changes will also predetermine the character of feeding of Lithuania rivers. While the snow water portion in the annual runoff of Lithuania rivers made up 31% during the period 1961–1990, in the future it is likely to decrease to 26% (2040) and 21% (2065). The character of annual hydrograph of rivers, influenced by snow nutrition, will change most of all parameters.

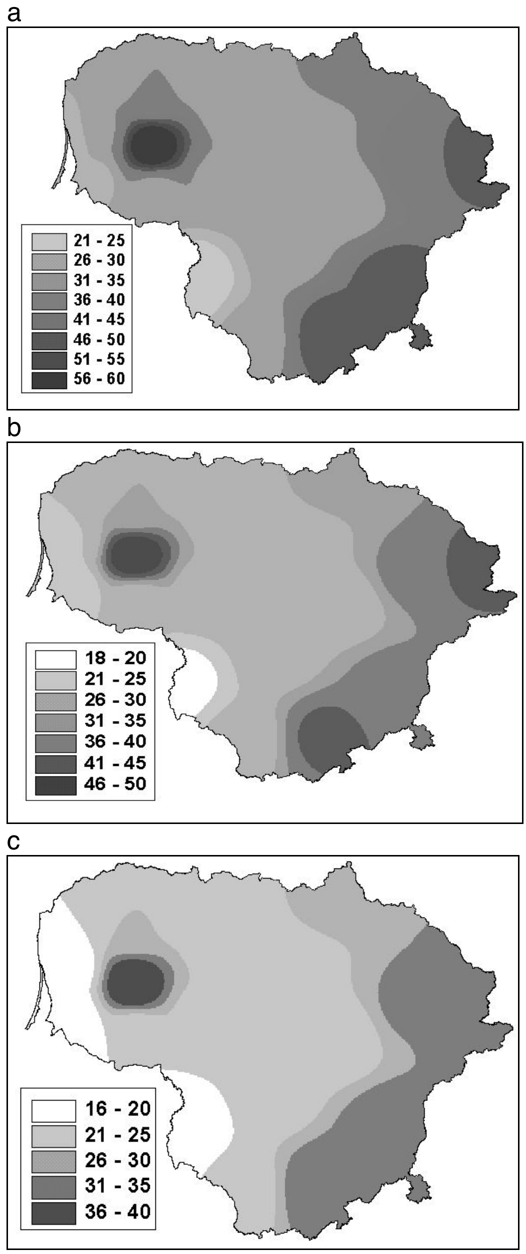

Fig. 4. Average maximum of the SWE (mm) during 1961–1990 (**a**), and the predicted SWE under the first (**b**) and second (**c**) scenarios of a regional climate change. See explanations in the text.

Discussion

This study showed a close connection between the dominant hemispheric circulation mode and the snow water equivalent in Lithuania. The Arctic Oscillation is a sufficient indicator to describe the regional features of a large-scale atmospheric circulation in Europe, even though a more complex approach should be applied when analyzing the precipitation fields or, even more, the snow cover parameters. Further research should be put on the sub-scale analysis of weather patterns that generate precipitation (e.g. frontal parameters or the synoptic climatology of cyclones), which would be able to reveal intra-monthly fluctuations in the snow cover accumulation. Regional climate change scenarios developed recently allow the prediction of changes in the snow water equivalent more precisely in certain domains.

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