

Meteorological features behind spring runoff formation in the Nemunas River

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This paper is concerned with atmospheric circulation as the central factor influencing snow melting conditions and consequently the spring runoff characteristics of the Nemunas River. The analysis includes snow water equivalent (SWE) accumulated before the start of snowmelt runoff and its relationship with maximal water discharge and flood volume. The results show that the relationship has a dipolar character. The cohesion between SWE and the maximal runoff was divided into two different groups: A and B. The increasing maximal values of SWE correspond to the rapidly increasing maximal water discharge during the runoff seasons in group A and slowly increasing discharge in group B. Intensive snow melting following significant warm advection in the lower troposphere or, conversely, dominant radiative snow melting despite the high values of snow water equivalent, cause the high magnitude spring floods of the Nemunas River. The importance of atmospheric circulation increases during the beginning of the spring runoff in particular.

Introduction

About 50% of the annual runoff falls in the spring flood period in many of the plain regions of northern and eastern Europe. The spring flood also accounts for about 40% of annual runoff in Lithuania.

Therefore, hydrologists and forecasters focus on studies of snow water equivalent (SWE) and snow melting conditions (Carroll 1996, Luce *et al.* 1998, Carroll *et al.* 1999, Skaugen 1999). The snow water equivalent is one of the central factors affecting water balance fluctuations in Lithuania. In addition, micrometeorological

factors make a considerable contribution to the snow melting process and resultant runoff. (Koh and Jordan 1995, Pomeroy *et al.* 1998, Bengtsson *et al.* 2000).

The present study deals with the main formation features of the snowmelt runoff of the Nemunas River. Hydrologists coming from several countries attempt to link the rates of spring flood formation and flood characteristics with the thermal conditions during this period. Many studies of the snow melting process and its impact on the magnitude of spring runoff were made between the 1950s and 1960s in the former Soviet Union (Makarova 1956, Komarov 1959,

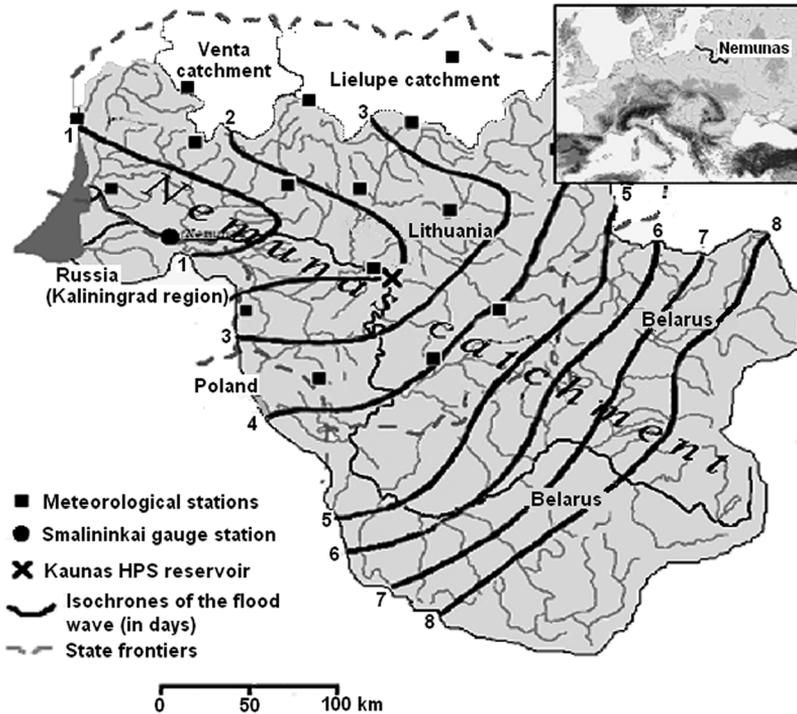


Fig. 1. Map of the Nemunas River catchment area with isochrones of flood wave propagation. The neighbouring river basins within the Lithuanian territory are shown in different shades. Meteorological stations (from which data was used in the study) are indicated as black squares.

Kuzmin 1951, 1960, 1961).

A broad spectrum of studies of snow-melting process was summarized by Male and Gray (1981). The degree-day is one of the elements used in several studies to describe snow melting conditions (Kuchment and Gelfan 1996, Semadeni-Davies 1997). Other scientists relate the magnitude of the spring flood with precipitation amount and its characteristic during the snow melting period (Sui and Koehler 2001). A scientific report produced by the U.S. Army Corps of Engineers (1998) presents generalized snowmelt equations (for open and forested areas). The latter underlines the atmospheric circulation processes as a very important agent influencing different snow melting conditions and snowmelt runoff character.

Characteristics of catchments

The Nemunas is the largest Lithuanian river, draining about 5.3% of the Baltic Sea basin area. The Nemunas River catchment is situated in Lithuania (47.5% of the total Nemunas catchment area) Belarus and Russia (Fig. 1). The

river length is 937 km and the total catchment area ~98 000 km². Nemunas is a large river typical for a temperate climatic zone. High spring floods are frequent in the lower reaches of the river. Until 1960, the mean water level amplitude during flood period was about 10 m in the middle stream and 2–3 m in the lower reaches. After 1960, a Hydropower station with a dam was constructed on the Nemunas River, close to the town of Kaunas (the resultant water reservoir occupied a 63.5 km² area upstream) and floods were suppressed in this region.

Observations show that severe floods with a large inundation of water occur there once every 10–20 years. At present, the floods are dangerous only in the lower reaches and delta region. About 200 km² of territory in the northern part of the Nemunas River delta experiences yearly spring runoff flooding (this rarely occurs in winter). In the spring of 1958, an extreme flood took place in the lower reaches of the Nemunas and about 600 km² of the territory was underwater (400 km² in Lithuania and 200 km² in the Russian Kaliningrad Region). Most of the inundated areas are farmland with only a few settlements.

Most rivers are characterized by slow flow

velocity in their streams and by the slow flood wave propagation. Mean flow velocity in the river cross sections ranges from 0.4 to 0.7 m s⁻¹ and it only exceeds 0.7 m s⁻¹ during the spring flood period. This feature is characteristic not only of the Nemunas River but also of most of its tributaries. For the flood wave to travel from the distant catchment sites (sources) to the lower reaches takes longer than eight days. Flood wave isochrones (Fig. 1) represent points of average flood propagation rates every spring (Gailiusis *et al.* 2001). All the territory involved in the catchment area lies within a comparatively flat relief area. The source altitude is 176.0 m and the mouth is 0 m above sea level. They have very similar climatic conditions.

There are two spring runoff types in the Nemunas River: (1) winter and spring snowmelt and (2) rainfall-induced. Extreme floods depend only on the first type. The absolute maximum water discharge ever registered in the Nemunas lower reaches was 6820 m³ s⁻¹ whereas maximal value of the warm season is almost three times smaller. The mean maximum spring runoff discharge is 2270 m³ s⁻¹ and this is almost 3.5 times as great as what occurs during summer–autumn season. The spring flood accounts for 40% of the annual runoff volume. The mean spring flood start-date lies around the middle of March. Spring floods usually continue for about 60 days. However, flood onset dates as well as flood timescale may deviate considerably from the mean values in different years. Melting snow forms the major part of the spring flood volume (50%–90%). The flood discharges of the Nemunas River in the Smalininkai gauge station fluctuate from 807 to 6820 m³ s⁻¹.

Material and methods

The Smalininkai gauge station (operational from 1812) was used in the analysis because it is the closest point to the lower reaches having the longest discharge data set on the Nemunas River (112 km from the mouth, and 81 200 km² catchment area up to this cross section). The analyzed period covers 30 years (1960–1999), and the flood runoff characteristics were calculated for this period. The launch of the Kaunas

Hydropower station in 1960 upstream of the analysis station was a weighty argument for the period selection. Stored water in the snow cover — snow water equivalent (SWE) — was chosen as the main parameter describing snow cover before snowmelt runoff onset. It is clear that other indices such as the precipitation rate during the snow melting period and particular watershed conditions make a very substantial contribution to the character of the spring runoff volume and the hydrographic shape as well. Nevertheless, atmospheric circulation is one of the foremost snow melting factors and the subsequent spring runoff characteristic was the main purpose of the present research.

The maximal SWE average for the period 1961–1999 over the whole catchment area is around 50 mm. The highest values are found in the southeastern corner of the Nemunas catchment area (the territory of Belarus) (about 70–80 mm), and the lowest in southwestern Lithuania (20 mm). The mean date of the disappearance of permanent snow cover fall in the middle of March.

The mean date ranges within 10–15 days between the remote points of catchment. This period is close to the wave propagation time from the sources to the delta region (eight days). In cases where the intensive snow melting starts earlier in the sources (which happens rarely), a huge amount of melt water could flow into the delta region. Thereby in a short time (approx. 20–30 days), a well-defined flood wave could be formed. Unfortunately, the calculations cover only the Lithuanian part of the catchment because of an inability to get all the necessary data from Belarus. Snow melting due to similar climatic conditions usually starts almost simultaneously in different sub-basins of that catchment area and inflow data at the Lithuanian–Belarusian border seems to be quite representative for the whole basin.

We chose the following parameters to describe the main flood characteristics:

- snow water equivalent (SWE, mm) determined for the dates before flood onset;
- maximal water discharge (Q_{\max} , m³ s⁻¹) during the flood period;
- total flood volume (TFV, km³);

- flood volume after removing base flow (FVB, km³). This parameter estimation is based on consecutive 30-day periods when daily discharges were maximal.

As the main spring flood magnitude indicator we select the maximal water discharge (Q_{\max} , m³ s⁻¹). From a practical point of view this indicator seems to be more important than the spring total flood volume because of the opportunity for inundation assessment. Consequently, this allows a relatively precise determination of the flood area. Indices like maximal discharge and spring flood volume in the Nemunas River also seem to be coherent and thereby all determined atmospheric circulation regimes correlate both with Q_{\max} and with FVB.

Another important point is the use of the snow water equivalent as well as the snow melting conditions as main predictors for the forecast of spring runoff magnitude. Without any doubt, there are many other useful indices able to describe spring runoff magnitude such as frozen ground depth, water level before the onset of spring runoff (the latter is tightly related to soil water), ice hummocks, etc.

The frozen ground damps the infiltration of the surface water at the start of the spring runoff period in the Nemunas catchment area and it is a common feature of every flood season. On the other hand the correlation between the mean frozen depth across the basin and the discharge maximum in Smalininkai is rather small ($r = 0.31$, and it is under 99% significance level) to state the close coherence between those two parameters.

All of the analysed periods were limited by 30 consecutive days describing the evident ascending and descending hydrograph slopes and including the highest discharge values. This was done to enable the standardization of the snow melt runoff period and to avoid the loss of important data. As a rule, extreme floods (such as the one that occurred in March–April 1979) are forced by ice hummocks, and the prediction of their spatial and temporal formation as well as their intensity is very complicated. Eliminating the extreme spring flood of 1979 from the analysis showed that the relation between frozen ground depth and maximal discharge

becomes unessential ($r = 0.07$). Consequently, the authors persist with the assumption that the snow water equivalent accumulated before the flood beginning and the snow melting conditions are the most reliable predictors for the spring runoff magnitude. Daily discharge data and flood volume values were provided from the Smalininkai gauge station. SWE data were taken from 20 almost equally spaced measurement points located in the central part of the catchment area; they represent the last five-day period before the onset of snowmelt runoff. The above listed parameters are very important in flood wave formation. Also of importance are the sea level pressure, 500 hPa geopotential height and 850 hPa level temperature daily data extracted from the NCEP/NCAR Reanalysis archive: absolute values and anomalies (Kalnay *et al.* 1996). Daily anomalies were calculated from the 1968–1996 period climatology. The latter data were used in the classification analysis of daily weather patterns (*see below*) for different snowmelt runoff hydrograph types. Usually the spring runoff hydrograph has one peak (sloping up before it and down after it) but in some years, the hydrograph has more peaks with intermediate periods between them. Cold outbreaks of different length, which are frequent in early spring, cause pauses in the upwards slope. On the other hand, wet periods with intensive cyclone activity and quasi-stationary fronts usually followed multistage sloping down of hydrograph.

The North Atlantic Oscillation (NAO) index was also used in the study, because the NAO index reflects large scale zonal circulation intensity over the NE Atlantic and western Europe, whereas this is not always related to the westerly flow over the Baltic region. The NAO index raw data is available from the Department of Meteorology of the University of Reading website.

The classification scheme includes the 500 hPa height anomaly (HA500) fields and sea level pressure (SLP) fields over the European region. Atmospheric processes prevailed during the snowmelting period and the main snowmelt runoff period was classified separately. A five-day running mean was used as a smoothing filter for the daily HA500. Later, a time series was formed of the consecutive averaged atmospheric fields and the dominant patterns (covering more

than one third of the period) were derived in the classification scheme. This procedure was repeated for SLP data separately. Therefore the dominant patterns of HA500 and SLP are distinct and are not related to each other. The HA500 field classification scheme includes the determination of positive and negative anomaly centers, anomaly magnitude and main flow position in relation to the Lithuanian territory. Contrary, SLP fields were divided into cyclonic, anticyclonic and divergent (non-gradient) flow patterns. In addition, the position of synoptic objects (cyclone, anticyclone, trough, ridge, etc.) with regard to the Lithuanian territory was determined in this scheme.

The spring floods of each year were divided into three different time segments. The first represents the period between the beginning of snowmelt and the onset of flooding. The second period lies within the maximal flood wave period. The third period represents the remaining flood period from the highest point to the end of hydrograph slope. This procedure was necessary to assign weather patterns to different spring runoff stages.

Additionally, the NASA GISS “Atlas of Extratropical Storm Tracks” was used to define the origin of surface cyclones and related air masses. This electronic database covers the 1961–1998 period (Chandler and Jonas 2002). The SLP fields used in this atlas are derived from the 12-hourly (0Z and 12Z) 500 hPa and 1000 hPa geopotential heights generated by the NCEP Reanalysis project (Kalnay *et al.* 1996) and they are a data assimilation product, based on both observations and computer modeling techniques.

Results

The connection between SWE in the pre-flooding period and maximum water discharge (Q_{\max}) was analyzed in this study. The results show the dipolar character of the relation. The increasing SWE maximal values correspond with the rapidly increasing Q_{\max} (A type years) and slowly increasing Q_{\max} (B type years) (Fig. 2). Consequently, the relation was separated into two groups of scattered points and every group is represented by a linear regression curve with a

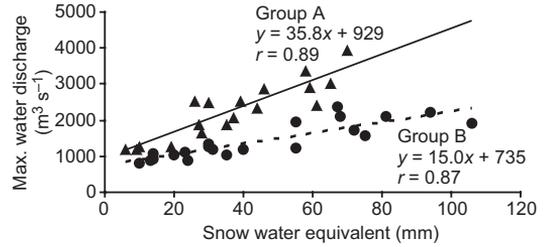


Fig. 2. The relationship between the snow water equivalent (SWE) calculated before spring runoff onset and the maximum water discharge (Q_{\max} , $\text{m}^3 \text{s}^{-1}$) in the Nemunas River from 1960–1999.

corresponding equation. Despite differences in hydrograph of those groups they seem almost identical comparing the dates of the highest flood peaks: the mean date in group A is 27 March and in group B 24 March. Furthermore, these groups were analyzed separately extracting the dominant weather patterns that influence different types of flood and its (the flood’s) characteristics.

The mean SLP anomaly over the Baltic region is predominantly negative in A years, particularly in the first and second flood time segments, and such a SLP anomaly has an opposite sign in B years. The third segment when averaged SLP anomalies change their sign to opposite makes an exception (Fig. 3a). The analysis also showed that two thirds of the spring runoff seasons are distinguished by negative (positive) SLP anomaly in A (B) years in the first flood time segment. In the second segment of spring runoff timescale, this relation is rather weak (Fig. 3b).

Classification of HA500 fields show that early snow melting runoffs starting in February and very rarely in January are distinguished by an enhanced zonal flow over Europe and high positive values of (NAO) index. Most floods of this type tend to have lower values of FVB and Q_{\max} than “normal” floods.

Negative HA500 anomalies prevail over western Europe and the northeastern Atlantic and positive HA500 anomalies prevail over eastern Europe in the spring runoff seasons belonging to group A. This atmospheric pattern (first) accounts for 27.6% of the total snow melting period and produces enhanced southerly flow over the Baltic region (Fig. 4a). The second pattern looks like a meridionally stretched dipolar system: high above northern Europe and low over

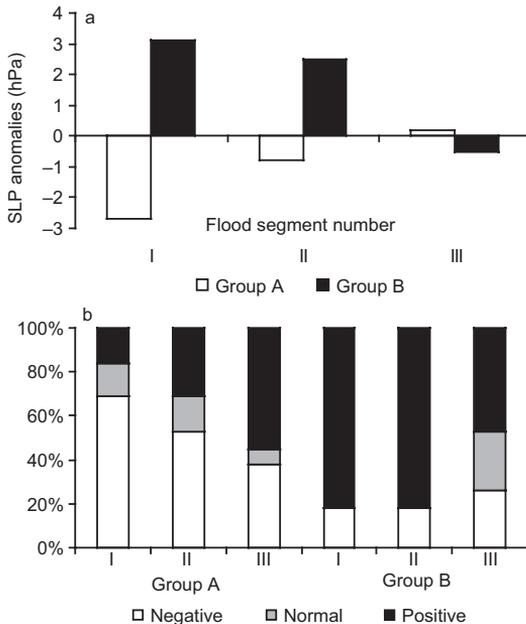


Fig. 3. Averaged sea level pressure anomalies (hPa) and (a) the percentage of years with different pressure anomaly (negative, normal and positive), (b) during different spring flood time segments and in different flood type seasons (A and B) over the southern Baltic region (53°–57°N, 17°–28°E).

the Mediterranean and Balkans and this accounts for 22.6% of the variation in pressure fields during the spring runoff season. That pattern is the blocking pattern over Europe and induces easterly and southeasterly low-level winds over the Baltic and central Europe (Fig. 4b). The third pattern (17.1%) shows a significant negative geopotential height anomaly over central Europe and the North Sea and also induces southerly winds (weaker), as in pattern one. The fourth pattern substantially differs from the previous patterns. It is in very good correlation with the NAO index and shows an intensive zonal flow over the whole of Europe (15.4%). Other large-scale weather patterns together account for less than 20% of data variance and show no significant temperature advection over Lithuania.

SLP fields related to the snow melting period in this group were split into two almost equal parts: cyclonic circulation makes 46% and anticyclonic 48.1% of time. The eastern periphery of the surface cyclone and western (southwestern) periphery of the quasi-stationary anticyclone induce southeasterly surface winds and consider-

able warm advection (> 2 K/12 hours at 850 hPa level) These SLP patterns occur 41.8% of time.

During the main spring runoff time the atmosphere circulation patterns differ significantly from the dominant patterns of the snow melting period. A blocking pattern (24.6%) and the first type of weather pattern (20.4%) become dominant during such spring run-off periods. Enhanced zonal and sub-zonal circulations account for 19.6% of the total time and the negative HA500 anomaly centre accounts for 15.7% of the total time.

Cyclonic SLP fields prevail (59.2%) in A group floods. The dominant SLP patterns are: eastern periphery of surface cyclone (large-scale trough) and the divergent flow in the low-pressure system — together they account for 45% of the time.

The picture is quite different in group B during the spring runoff periods. The positive values of the HA500 field are located over western Europe during the intense snow melting period (35.5%). Positive anomalies over Baltic and the first circulation type account for 45.4% of the period's length (Fig. 4c). The anticyclonic SLP fields are dominant (77.2%) with the prevailing (58.2%) western part of surface anticyclone. Cyclonic fields become prevalent during the group B seasons. During the main spring runoff time, the positive HA500 becomes dominant over the Baltic region (more than 50%) as anticyclones prevail (79.1%) in the SLP field. The first five highest Q_{\max} events in group A are related to the few active cyclones crossing (with their centres) the grid box 52°N–58°N, 15°E–33°E, or to quasi stationary meridionally extended fronts over the eastern Baltic. Such synoptic objects have a percussive effect on precipitation and consequently on the discharge of water. Besides such an anomalous circulation (usually the trajectory of cyclones lies within a narrow belt extending from central Scandinavia–Finland to northwestern Russia) has a triggering effect, intensifying snow melting in the whole catchment area. Contrarily there were no active cyclones in the group B seasons with the highest SWE values.

In order to study the spring melt effect by itself (without the influence of watershed conditions), runoff discharges Q_{\max} were derived from

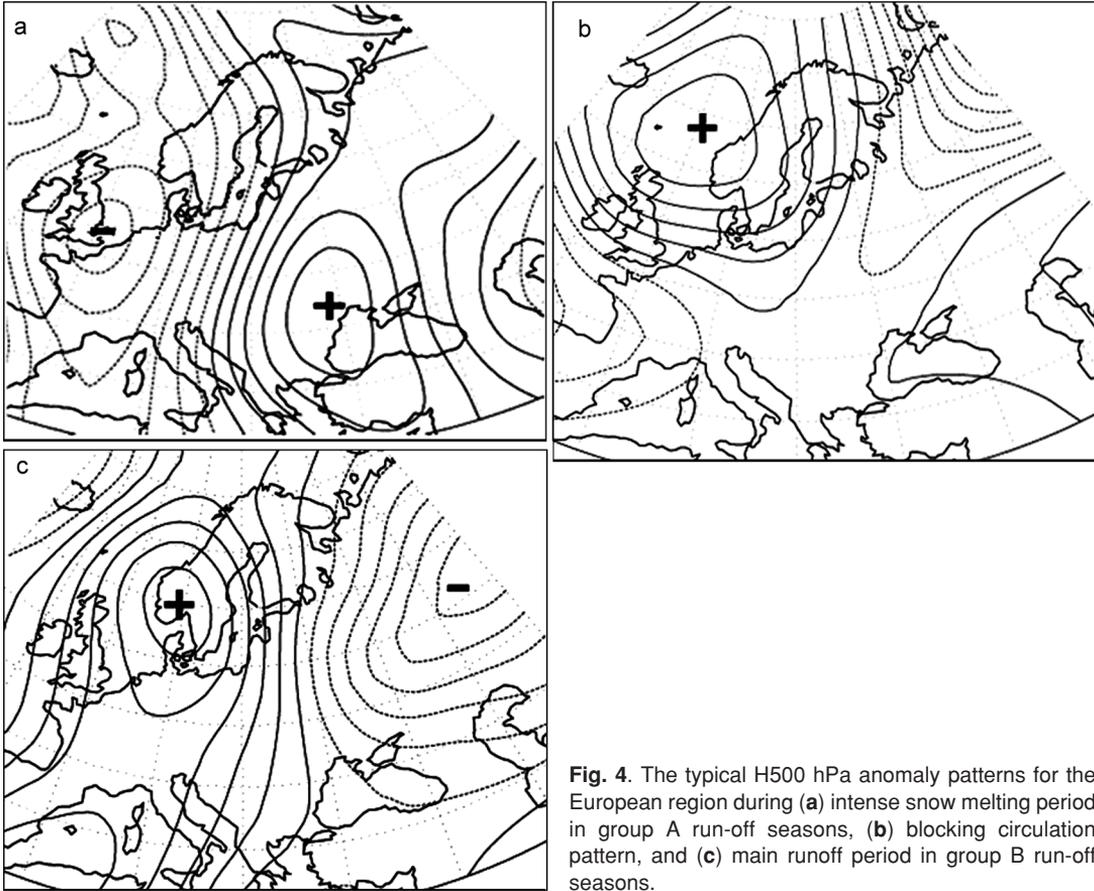


Fig. 4. The typical H500 hPa anomaly patterns for the European region during (a) intense snow melting period in group A run-off seasons, (b) blocking circulation pattern, and (c) main runoff period in group B run-off seasons.

the years with similar snow water equivalent (normalized value z varies from 0.2 to 0.8) values and total runoff volumes (z varies from 0 to 1). The selected years were divided into two groups with respectively high and low discharge values. The mean ratio between the second and first group discharges is 1.5.

By limiting all snow melting time length to 30-day periods, the main atmosphere pattern differences were found by subtracting the average atmospheric fields of the first group from the second one. The predominant cyclonic circulation covers northern Europe and the negative sea level pressure difference area occupies almost all of Europe (dark shading) except the British Isles and the northeastern Atlantic (Fig. 5a). On the other hand, the higher thickness (between 500 and 1000 hPa levels) values are located over northeastern Europe (first maximum) and along the coastline of western Europe. This indicates the warm air mass conveyor in the southern

periphery of the northeast Atlantic storm track (Fig. 5b). Such spatial differences show that favorable conditions for an uninterrupted flood character prevail in the group A spring runoff seasons. By contrast, atmosphere circulation was more favorable for nighttime frost and daytime evaporation in the group B seasons because of weakened atmospheric circulation in the middle troposphere and a corresponding increase in the frequency of surface high pressure patterns.

Conclusions

The meteorological conditions of snow water melting are very important flood forming factors in the Nemunas catchment area. Their influence is quite different during the intense snow melting period and the main flood wave period, when the maximal water discharge values are observed.

Mean sea-level pressure is lower (higher)

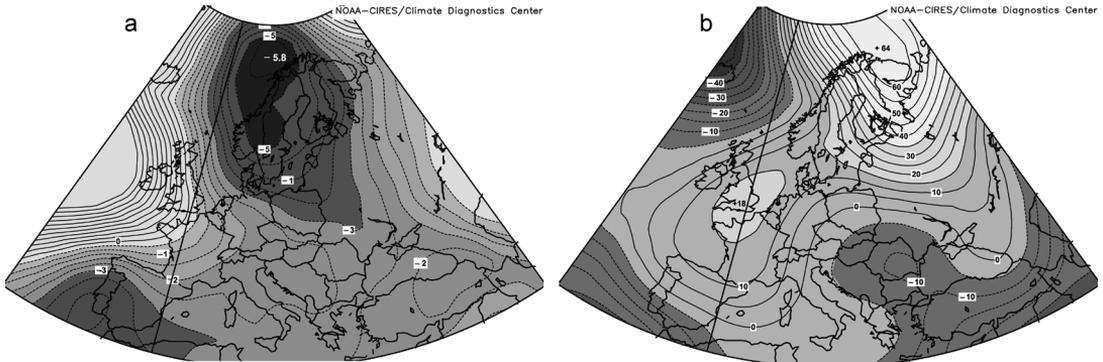


Fig. 5. The difference in the averaged atmospheric fields between groups A and B of the years with similar SWE: (a) sea level pressure (hPa), and (b) 500–1000 hPa thickness (m). Isolines are every 0.5 hPa and 5 m respectively. Letters L and H denote the centres of highest negative and highest positive differences respectively. See explanations in the text.

than normal in the seasons with the adequate (inadequate) runoff responses to the high SWE values or respectively in the group A (B) snow melting periods. Southerly flow accompanied by warm advection is the typical large-scale atmosphere circulation feature during the snow melting period in the years with group A spring runoff types over the Baltic region. An anti-cyclonic circulation is the dominant SLP field during the main spring runoff seasons belonging to group B. In these seasons, blocking ridges have damped cyclonic circulation over Europe and favoured dry air invasions from the east. The snow melting process is delayed and despite high precedent SWE values, the maximum spring runoff discharge is lower than normal.

Cyclonic activity is another important flood formation feature. Cyclone centers passing the eastern Baltic or quasi-stationary meridional fronts with sharp temperature gradients produce continuous heavy rains and have a hasty impact on flood development rates. Early floods (starting in winter) purely depend on temperature advection and are characterized by enhanced zonal flow in the middle troposphere over central and northern Europe.

The classification of atmospheric processes for the spring runoff period seems to be accurate only in the first (one or two) flood time segments. The rest of the flood period experiences rather inertial forcing including earlier atmospheric conditions, soil moisture and runoff character in the upper reaches.

Despite all the above listed factors, the most hazardous floods in the lower reaches of the Nemunas are usually the compound result of high values of SWE in late winter, continuous rains during snow melting, deep soil frost, ice hummocks in river meanders and the Curonian lagoon water level which rises following strong westerly winds.

According to the recent global circulation model results for the Lithuanian territory (including scenarios for doubling carbon dioxide), the precipitation rate will significantly increase in the cold season and the mean winter temperatures will also be warmer than now. This is a significant factor in the prediction of shifted spring runoff peaks to the earlier dates (on average from April to March) and to the lower values of the flood magnitude in the Nemunas river lower reaches.

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