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Ice regime dynamics in the Nemunas River, Lithuania

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ABSTRACT: Ice cover persistence in the lower reaches of the Nemunas River has decreased during the last 150 yr. The variation in the river freeze- and break-up dates is related to climatic variables. The significance of the negative break-up trend exceeds that of the positive freeze-up trend. Low-frequency large-scale atmospheric circulation patterns such as the North Atlantic Oscillation and Arctic Oscillation (NAO/AO) appear to have more influence on the break-up date than on the freeze-up date. Different classification methods applied to the atmospheric patterns prevailing in the early freeze-up events reveal similar results; however, differences arising between classifications are attributable to non-persistent and high frequency patterns.

KEY WORDS: River ice cover · Freeze up · Break up · Atmospheric forcing

1. INTRODUCTION

River ice is present during a part of the year on many rivers of cold, and even temperate, regions of the globe. The river ice has significant hydrologic effects, including extreme flood events caused by ice jams, interference with transportation and energy production, low winter flows and associated ecological and water quality consequences (Prowse & Beltaos 2002).

Recent record shows a trend of later freeze up and earlier break up of ice on rivers and lakes, in agreement with other global warming indicators, e.g. a rise in air temperatures over moderate latitudes of the Northern Hemisphere and particularly over interior continental areas. Freeze- and break-up dates change by approximately 4 to 7 d for every °C change in air temperature (WMO 1997), and so can be used as an indicator of climate change. In addition to ecological effects on freshwater systems, changes in lake and river ice cover could have additional effects, such as the economic effect on 'ice road' transportation.

Comprehensive river ice studies date back to the beginning of the 20th century. Research into river heat balance and its components was lead by Devik (1931). Krickij et al. (1947) specified and simplified the heat balance calculations experimentally. Gotlib et al. (1983) investigated the dependence of riverine ice regimes on upstream hydrotechnical facilities. These authors also developed quantitative assessment methods for river freeze-up forecast. Temporal variation in river ice break-up dates, and the predictability of these dates, was analysed by Bulatov (1972), Buzin & Lazarevskaja (1980), Donchenko (1987) and Shiklomanov (1989). Donchenko (1987) divided break-up processes into 3 types: (1) processes forced by solar radiation together with air and water temperatures; (2) processes dominated by ice melt together with water stream impact; and (3) processes associated with increased pressure on ice cover forced by rising water levels and accelerating stream flows. According to Shiklomanov (1989), it is likely that upstream hydrotechnical facilities such as hydropower plants increase the ice cover break-up rate substantially.

Ice regime characteristics of the inland waters in the former Soviet Union are comprehensively depicted by Vazhnov (1976), Michailov & Dobrovolsky (1991) and, more globally, by Ashton (1986).

Little research has been done on the relationships between riverine ice regimes and atmospheric circulation patterns. Beilinson (1989) has identified large-scale atmospheric circulation patterns preceding anomalous freeze- and break-up dates in Kazakhstan water bodies, and Jasek (1999) argued that the 1998 anomalous early break up and flood on the Yukon river

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was forced primarily by El Niño and its mid-latitude teleconnections.

Kilkus (1989, 1992, 1998) and Rainys (1975) examined the ice regime of rivers and lakes in Lithuania. Kilkus & Valiuskevicius (2001) were the first to analyse long-term (1811–1995) ice cover parameters and their trends in various national inland water bodies, while Bukantis & Kilkus (2004) were the first to relate the North Atlantic Oscillation (NAO) to the hydrological regime of various water bodies in Lithuania.

Anthropogenic influences on the Nemunas River ice regime are examined in only a small number of papers. Rainys (1975) asserted that changes in the river ice cover formation were observed 20–30 km downstream of the Kaunas Hydropower Plant (HPP). Using a variety of statistical techniques, Stonevicius (2004) found that the main turning point in the ice regimes of the Nemunas and Neris rivers occurred in 1972 (Kaunas HPP was built in 1960), and that this turning point was probably caused by climate change. Of all ice cover break-up events during 1950–2000 in the Nemunas River lower reaches, 91.7% were forced by a rapid rise in water level (34 spring runoff events and 10 wintertime events).

The most recent results for Canada show an interesting regional difference, with rivers over the western regions generally showing trends toward earlier break up, and rivers over the eastern regions showing later break up (Zhang et al. 2001).

Many factors influence river and lake ice break up, i.e. air temperature, ice thickness, snow cover, wind, water temperature and depth of water below the ice. In fact, river ice is affected by several meteorological variables that define the surface energy balance. Air temperature is the most important variable affecting lake ice, strongly influencing freeze up, growth, duration, and break up (Barry & Maslanik 1993). For rivers, air temperature dominates ice formation and growth, while rainfall and snowmelt control basin runoff, flow, and ice break up.

In many temperate regions, water temperatures in rivers respond rapidly to changing air temperatures, causing frequent cycles of ice and water storage in the channel and its subsequent release as unsteady flow. More stable river ice conditions develop in colder regions, typically causing a large seasonal shift in flow, with water stored during freeze up making an important contribution to the flood at break up (Smith 2000). Of particular concern are large flow changes due to hydropower production that degrade habitats and can even initiate significant erosion (Liebscher, 1993).

Magnuson et al. (2000) revealed significant trends towards earlier break up and later formation of lake ice, providing further evidence for systematic global warming over the past 150 yr (1846–1995). The annual duration of ice cover in many sites of the Northern Hemisphere has decreased over the past century. The average rate of change over the 150 yr period was nearly 9 d later for freeze-up dates and almost 10 d earlier for break-up dates, according to Magnuson et al. (2000). The importance of long-range freeze- and break-up observation records is that they are visual, making them difficult to refute in any general way. In the 19th century, the selection of ice cover observation sites was not always representative of station distribution. Moreover, the skill of observers is unknown, and the Smalininkai station used in the present study is not an exception in this regard.

The main goal of this study was to reveal the large-scale circulation impact on the river ice regime, and to distinguish the most typical weather regimes responsible for river freeze- and break-up processes using objective classification methods.

Data and methods are presented in Section 2. The study area (see also Fig. 1) and river hydrological regime are described in Section 3. Trends of long-term ice phenomena and the influence of large-scale circulation on the ice regime of the river are examined in Section 4. Typical weather regimes forcing or dominating during river freeze up are examined in Section 5, and conclusions are presented in Section 6.

2. DATA AND METHODS

Nemunas River ice phenomena (lower reaches) and water level and/or discharge data were taken from the Smalininkai gauge station archive for the period 1812–2000. Ice phenomena and water-level observations were both always taken from the same site; ice-phenomenon observations were made visually. The definition of freeze- and break-up processes remained unchanged over the complete period. The freeze up was registered when the entire river surface observable from the Smalininkai station was covered by motionless ice. The break-up event was recorded when at least the majority of the river (usually two thirds of the observable river surface) started to move.

River ice observations were made as part of a water-level observation programme based at Smalininkai. Since 1811, water-level observations have been performed twice daily; one in the early morning and one in the afternoon or evening. River ice observations were limited to ice break-up (ice drift) date and ice cover persistence until 1945. After this date, observations of the ice thickness, break-up type and the state of ice cover were also recorded. Station equipment and the location of gauges varied up until 1827. Water level data were considered precise after 1827. River ice observations were consistent over the entire period, because they were always made over the same section of river. River discharge was first measured at Smalininkai in 1875. However, regular and consistent discharge measurements only date from 1896.

The air temperature at 2 m level was taken from the Kaunas meteorological station, using an uninterrupted time series from 1900 onwards. Gridded daily atmospheric data — geopotential height at 700 mb level — were taken from NCEP/NCAR reanalysis, going back to 1948. In addition, the following atmosphere circulation indices were used: (1) the monthly NAO index, starting from 1826 (Jones et al 1997) and taken from the Climatic Research Unit of the University of East Anglia website (available at: www.cru.uea.ac.uk/cru/data/nao.htm; (2) the daily NAO index, starting from 1950 (Barnston & Livezey 1987) taken from the USA National Weather Service (NWS) Climate Prediction Center archive; (3) the monthly Arctic Oscillation (AO) index starting from 1950 (Thompson & Wallace 2000; available at: www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml); and P. Hess & H. Brezowsky (H/B) large-scale daily weather pattern data since 1882 ('Grosswetterlagen'; available at: http://www.wetterzentrale.de/cgi-bin/wetterchronik/home.pl?read=743&jump1=region&jump2=1) (Gerstengarbe et al 1999).

The leading atmospheric circulation patterns preceding river ice formation (last 3 d before freeze up) were extracted using both principal component analysis (PCA) (Lins 1997, Jolliffe 2002) and cluster analysis (CA) (Hartigan 1975, Davis & Walker 1992) and compared with the daily H/B classification patterns which were aggregated to larger groups according to the geopotential height field similarity for the Baltic region.

At the first stage in CA analysis, the hierarchical clustering (complete linkage; Euclidean distance) was applied to 700 mb height-anomaly daily data that revealed 3 large clusters. After applying a K-mean technique, 3 cluster centres were determined.

Using a PCA technique, the first 4 principal components (PCs) were extracted from the daily geopotential height anomaly data. Rotated PCA only fractionally improved the explained variance. Therefore, unrotated PCs were used in further analysis.

For this study, 5 new large-scale circulation group-patterns were formed from the catalogue of large-scale weather patterns prepared by H/B (Tables 1 & 2). Group 1 includes the HFZ, HFA, HNFZ and HNFA pat-

Table 1. Hess/Brezowsky circulation-pattern ('Großwetterlagen') terms and their abbreviations and definitions in English

Original term	Abbreviation	English description
Hoch Fennoskandien zyklonal	HFZ	Upper high over Scandinavia; central Europe under cyclonic circulation
Hoch Fennoskandien antizyklonal	HFA	Upper high over Scandinavia; central Europe under anticyclonic circulation
Hoch Nordmeer–Fennoskandien zyklonal	HNFZ	Upper high over Fennoscandia and the North Sea; central Europe under cyclonic circulation
Hoch Nordmeer–Fennoskandien antizyklonal	HNFA	Upper high over Fennoscandia and the North Sea; central Europe under anticyclonic circulation
Winkelförmige Westlage	WW	Westerly flow makes a cyclonic hook over central Europe
Südliche Westlage	WS	Westerly flow occupies southernmost position over Europe
Südostlage zyklonal	SEZ	Upper ridge from the extended southeast; central Europe under cyclonic circulation
Südostlage antizyklonal	SEA	Upper ridge from the extended southeast; central Europe under anticyclonic circulation
Südlage zyklonal	SZ	Upper southerly flow over central Europe with surface cyclonic circulation
Südlage antizyklonal	SA	Upper southerly flow over central Europe with surface anticyclonic circulation
Hoch Mitteleuropa	HM	Anticyclonic circulation over central Europe
Hochdruckbrücke (Rücken) Mitteleuropa	BM	Upper cut-off low over southeastern Europe, surface high pressure system over central Europe
Hoch Nordmeer–Island, antizyklonal	HNA	Upper high over North Sea and Iceland, central Europe under anticyclonic circulation
Nordwestlage zyklonal	NWZ	Upper northwesterly flow over central Europe with surface cyclonic circulation
Nordwestlage antizyklonal	NWA	Upper northwesterly flow over central Europe with surface anticyclonic circulation
Nordlage zyklonal	NZ	Upper northerly flow with cyclonic curvature over central Europe

Table 2. Hess/Brezowsky aggregated circulation patterns (Grosswetterlagen) used in this study. See Table 1 for Hess/Brezowsky abbreviations

No.	Pattern groups	Hess/Brezowsky abbreviations			
1	FScanAn	HFZ	HFA	HNFZ	HNFA
2	SouthZonal	WW	WS		
3	EastAn	SEZ	SEA	SA	SZ
4	AnCentral	HM	BM		
5	NWest	HNA	NWA	NWZ	NZ

terns that initiate an upper easterly flow over the southern Baltic. Group 2 patterns (WW and WS) exhibit an upper trough over the southern Baltic with the contours of cyclonic curvature. Group 3 patterns (SEZ, SEA, SZ and SA) exhibit a warm-core anticyclone southward from the Baltic Sea and near-surface anticyclonic circulation. Only 2 patterns belong to Group 4 (HM, BM), which exhibits an upper trough over the Baltic and stable anticyclonic conditions near the surface. Group 5 integrates 4 patterns (HNA, NWZ, NWA and NZ) responsible for northerly or northwesterly flow over the southeastern Baltic (Table 2).

Group 1 was termed FscanAn because of the prominent upper high pressure field over Scandinavia, the Norwegian Sea and/or Northern Russia. Group 2 was termed SouthZonal because it shows a southward shift of the zonal westerly flow. Group 3 was termed EastAn because of the upper and lower anticyclonic circulation extending to Russia. Group 4 was termed AnCentral because of the presence of a surface anticyclone under a large-scale trough over central Europe. Group 5 was termed Nwest because of the north-northwesterly flow over the Baltic region (Table 2). Other patterns not included in Tables 1 & 2 were not very common for the analysed freeze-up events. The PCA technique was also applied to cold season hydrographs (1950 to the present) constructed from 10 d water-level averages. This allowed the main prevailing seasonal (November–April) hydrograph types to be extracted.

3. BASIN HYDROLOGICAL REGIME

The Nemunas is the longest Lithuanian river (937 km), and has a total catchment area of ~98 000 km^2. Nearly 47.5% of the catchment lies within Lithuanian territory. The last 100 km length of the river serves as the international border between the EU and Russia, while the upper reaches of the river are in Belarus (Fig. 1).

Flow direction is predominantly westward in the lower reaches of the Nemunas River. The river slope in this section is only 10.5 cm km^{-1}. There are many islands and bars which significantly impede navigation. Intensive sedimentation takes place a short distance (~12 to 15 km) downstream from Smalininkai and this section of the river has been dredged continuously since the 19th century.

As with the majority of rivers in Lithuania (except for a small number in the west of the country) the spring flood accounts for >40% of the annual runoff. The mean spring flood start-date is in the middle of March. Nemunas River is ice-covered during much of the winter season. River ice processes can be classified as either freeze up or break up. The characteristics of these processes depend upon weather and flow conditions as well as the operating regime of hydrotechnical facilities upstream. The Nemunas River has many tributaries of different lengths fed by a variety of hydrological sources.

The Smalininkai gauge station is located in the lower reaches of the river, about 108 km upstream from the mouth. The ice regime in this river sector has remained unaffected by dredging works and continuous navigation use over the entire period. Dredging in the lower reaches of the river was normally carried out during the warm half of the year, after the high water period. Kaunas HPP was built in 1960 ~116 km upstream from Smalininkai gauge station. Earlier studies have shown that the influence of Kaunas HPP on the river hydrological regime is detectable as far as 100 km downstream from the HPP and 50 km downstream for ice cover phenomena (Jablonskis et al. 1993, Vaitiekuniene & Vinceviciene 2001, Zdankus & Sabas 2006). The mean annual water storage in the Kaunas reservoir is 4.6×10^8 m^3 (Kilkus 1998).

Air temperature and hydrological regime are the 2 most important factors affecting water heat loss and ice formation during the freeze-up period. These are the primary processes by which the river water temperature drops at the beginning of the cold season. Spring

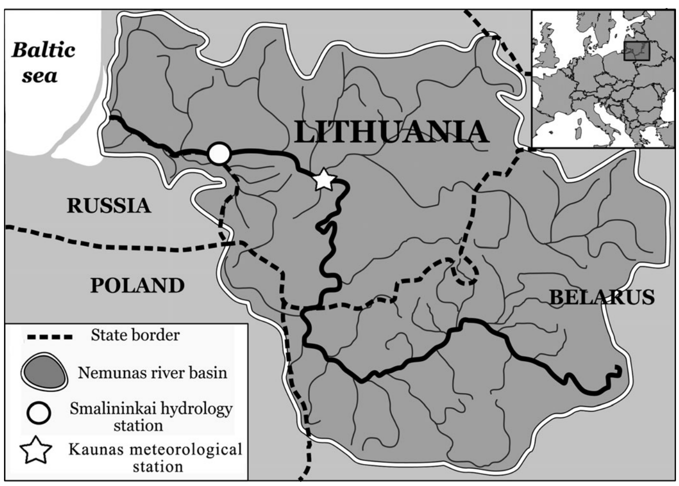


Fig. 1. Nemunas River catchment and locations of the Smalininkai and Kaunas stations

snowmelt and rainfall (with subsequent runoff) are the major factors affecting the ice break-up process in the Nemunas River. High rates of snowmelt and (liquid) precipitation, and consequently a rapid increase in river streamflow, causes the early break up. During the 1950–2000 period, 91.7% of all break-up events in the Nemunas River lower reaches were forced by a steep water-level rise (Stonevicius 2004).

The PCA analysis of the Nemunas River hydrographs for the winter and following spring runoff seasons (1 December to 30 April) reveal 3 main patterns that explain 41.0, 16.6 and 11.2% of variance, respectively (Fig. 2). Pattern 1 has one significant peak in the spring runoff period (centred at 10 April), and represents a continental-type winter with prevailing negative temperatures, increased frequency of cold spells and decreased frequency of thaws. During winter and early spring, water-level fluctuations are negligible, with only a slight increase at the beginning of the season, indicating the effect of ice-damming on the water levels. Pattern 2 is typical for a cold winter, with a shallow snow depth following a long and wet autumn season. It has 1 peak at the end of the season and gradual water level decrease until the end of March. This is evidence of the gradual (downward) freezing of groundwater horizons. Pattern 3 exhibits a high water regime during winter (mild winter regime) with several peaks in spring.

Pattern 1 (its positive mode) was dominant in the early 1950s, during all of the 1960s and during other cold winter periods such as 1978/9, 1984/5, 1986/7 and 1995/6. The negative mode falls to extremely warm winters—e.g. 1973/4 and 1989/90. Pattern 2 is not very frequent in its positive mode and marks some extreme cold winters—1955/6, 1962/3, 1969/70, 1995/6 and others. The negative mode (rising water levels in winter and a significant decrease in water levels in April) dominated in the 1980s and 1990s. Pattern 3 was not a dominant pattern during the analysed 50 yr period,

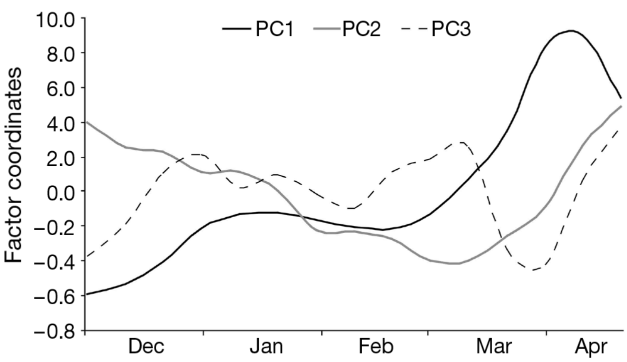


Fig. 2. Factor coordinates of Nemunas River cold season (November to April) water levels (10 d averages), 1950–2000. See Section 3 for further details

except in some individual mild winters and the last 4 yr of the period. The negative mode is more pronounced in the early part of the analysed period.

4. LONG-TERM TRENDS

Ice cover formation in the Nemunas River lower reaches is possible from November to April. The earliest observed freeze-up date was recorded on 8 November 1920, and the latest date on 11 March 1949 (for the latter the ice cover only lasted 4 d). For the whole dataset, mean and median freeze-up dates almost coincide (18 and 17 December, respectively), while the standard deviation is large: 21.7 d. The frequency distribution of freeze-up dates is asymmetric and positively skewed.

The most favorable period for the river freeze up is the last third of December (18.7% of the seasons), and almost 79% of all cases were observed in the period from the end of November to the first days of January. There were 2 seasons—1975 and 1998—when ice cover did not form at all. During the last 50 yr, freeze-up events have decreased significantly in number in November and increased significantly in January. Fluctuations in break-up dates and ice cover period show slightly negative trends, statistically significant at the 0.01 confidence level (CL), while freeze-up dates exhibit positive a trend significant only at the 0.05 CL. The ice cover regime has changed since the 1950s (Fig. 3). A LOWESS fitting technique applied to ice-cover regime data since the 1810s shows the positive trend in freeze-up dates after the 2nd decade of the 20th century and the negative trend in break-up dates since the middle of the 19th century. Especially notable is the sharp slope of the descending LOWESS curve (break-up dates) which started in the middle of 1970s (Fig. 4).

Break-up dates come principally between the middle of March and the beginning of April. The median break-up date is 16 March; however the probability density function is asymmetric and negatively skewed. Break-up dates between 1 and 10 April were observed in almost 30% of all analysed seasons. About 90% of the dates are within the period 20 February to 20 April. The earliest break-up dates (in 1925, 1989 and 1990) were related to winter flash floods, while one of the latest dates (in April 1939) was related to a harsh winter and cold early spring (Fig. 3). The actual latest date was recorded in the first half of 19th century but we have no air temperature regime data for this period.

Two-thirds of the earliest break-up dates (starting from the end of December) are concentrated in the last 13 yr of the analysed period (1988–2000). Late ice break ups (last days of March and first half of April)

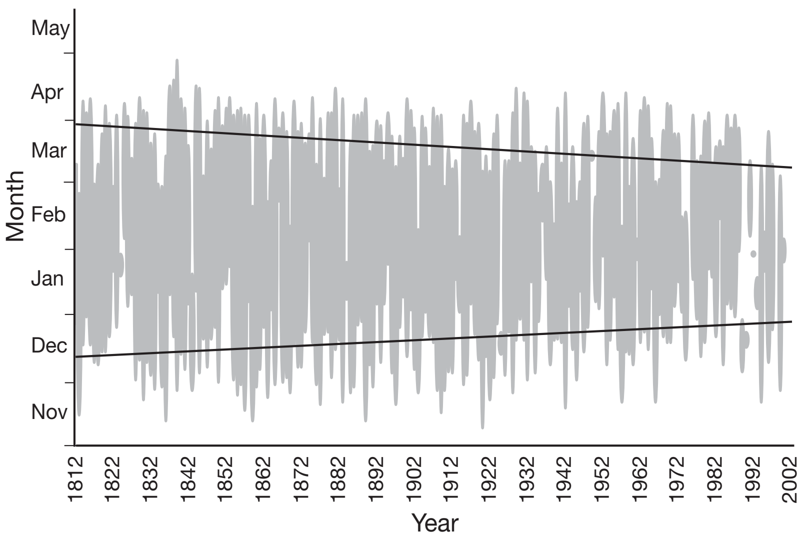


Fig. 3. Ice cover during 1812–2000. Grey vertical bars: period of ice cover; black lines: linear trends of freeze-up (lower) and break-up (upper) dates

make up almost 50% of seasons during the entire analysed period (1812–2000), while only 2 such events have been recorded in the 1988–2000 period (Fig. 4).

Persistence of ice cover on the Nemunas River has comparatively high interannual variability. The mean value of ice duration is 84 d while 70% of its probability lies within 70 and 120 d. Seasons with river ice cover duration >120 d account for only 10.2%, while those <70 d account for 19.8%. As with break-up dates, the frequency distribution of ice cover duration is asymmetric and negatively skewed with a very sharp slope after 120 d. Two seasons (1975 and 1998) were included in the analysis with a value of zero, because of the absence of ice cover in these seasons. The longest ice cover season recorded is of 143 d, in 1889. The analysis of ice-cover persistence differs from that of freeze- and break-up events analysis. Drastic changes in large-scale weather patterns during the cold season cause wide fluctuations in ice cover, and ice can form and disappear twice or more times per season. One stable ice cover period prevails during the cold season in the Nemunas River lower reaches, and accounts for 75% of seasons; 22.5% of seasons had 2 ice-cover periods; the remainder (2.5% of seasons) were very changeable seasons (freezing and breaking up 3, 4 and more times) in 1948, 1957, 1959 and 1999. The second peak of the frequency of such cold seasons was observed 1880–1919, despite the fact that freeze-up dates in this period were earlier than normal. Conversely, very stable ice cover regimes were documented in the 1810s, 1850s, 1870s, 1930s and 1960s. Such results agree with the findings of Jones et al. (2001).

The 10 d means of daily atmospheric circulation indices such as NAO and AO show positive correlations with freeze-up dates from the middle of November to the beginning of January, and a positive NAO/AO phase with enhanced zonal circulation may have inertial forcing for river ice formation. Statistical significance however exceeds the 95% CL only in the middle of November for AO and the end of December for NAO. A sharp change in correlation coefficients occurs at the beginning of November (Fig. 5). So the AO index in the second half of October was only partly related to the ongoing river ice season: a positive (negative) AO phase in this period indicates earlier (later) than normal freeze-up dates (NAO does not exceed the 95% CL). The same indices represent the ice break-up dates more effectively than freeze-up dates: statistically significant negative correlations from the beginning of January until the end of March indicate earlier (later) than normal break-up

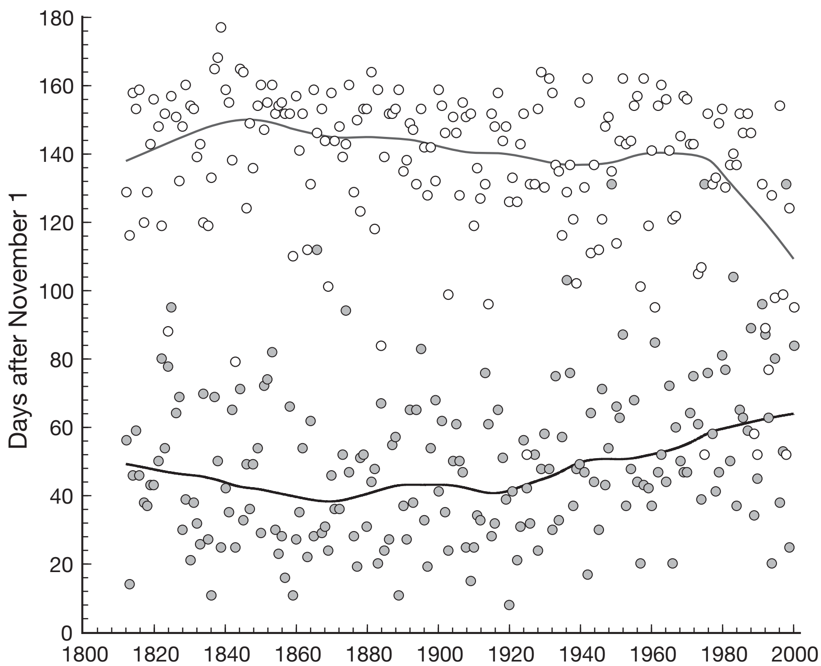


Fig. 4. Scatter plots of freeze-up (◉) and break-up (○) dates in the Nemunas River lower reaches and their LOWESS fitting (black and grey curves, respectively). Dates expressed as number of days after November 1

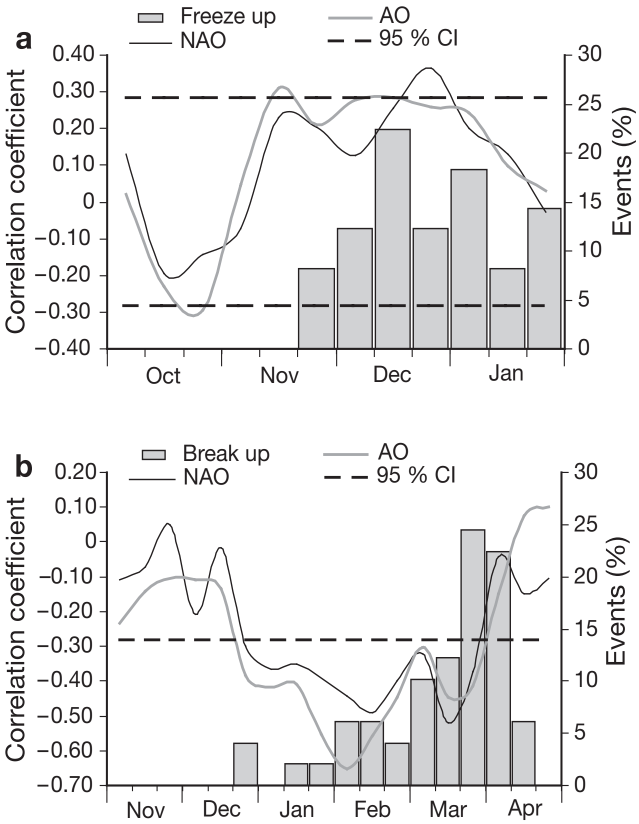


Fig. 5. Frequency (bars) of (a) freeze-up and (b) break-up events (%). Correlations (curves) between Arctic Oscillation (AO) and North Atlantic Oscillation (NAO) indices and river (a) freeze-up and (b) break-up dates, respectively. Dashed lines: (a) upper and lower, and (b) lower 95% CL

dates under positive (negative) AO/NAO phase (Fig. 5). Most probably, this coherence implies that most cold seasons are not dominated by one particular regime, and greater persistence of any of the NAO/AO phases exists in the second half of the winter rather than in the first half. Moreover, that persistence has a predictive potential for the river ice break up and the spring runoff early warning in the delta region.

On a monthly timescale, January to February AO/NAO and NAO Jones et al. (1991) indices are positively correlated with surface temperature in the Baltic region with lags of 0 to 3 mo (not shown), while in the first half of the cold season only the AO index has negative statistically significant correlations with 3 mo lagged January surface temperature (Fig. 6). That yields up the existing AO (and probably NAO) temporal evolution—e.g. a quasi-persistent transition phase between positive and negative indices during late autumn and early winter. Although the NAO is the dominant pattern of the regional atmospheric circulation variability, it explains only a fraction of the total variance, and a dominating NAO or AO phase cannot solely characterise most analysed seasons.

5. TYPICAL WEATHER REGIMES DURING RIVER FREEZE-UP PERIODS

The dependence of the river ice freeze-up process on atmospheric forcing over the East European Plain has been thoroughly documented by Shuliakovsky (1960).

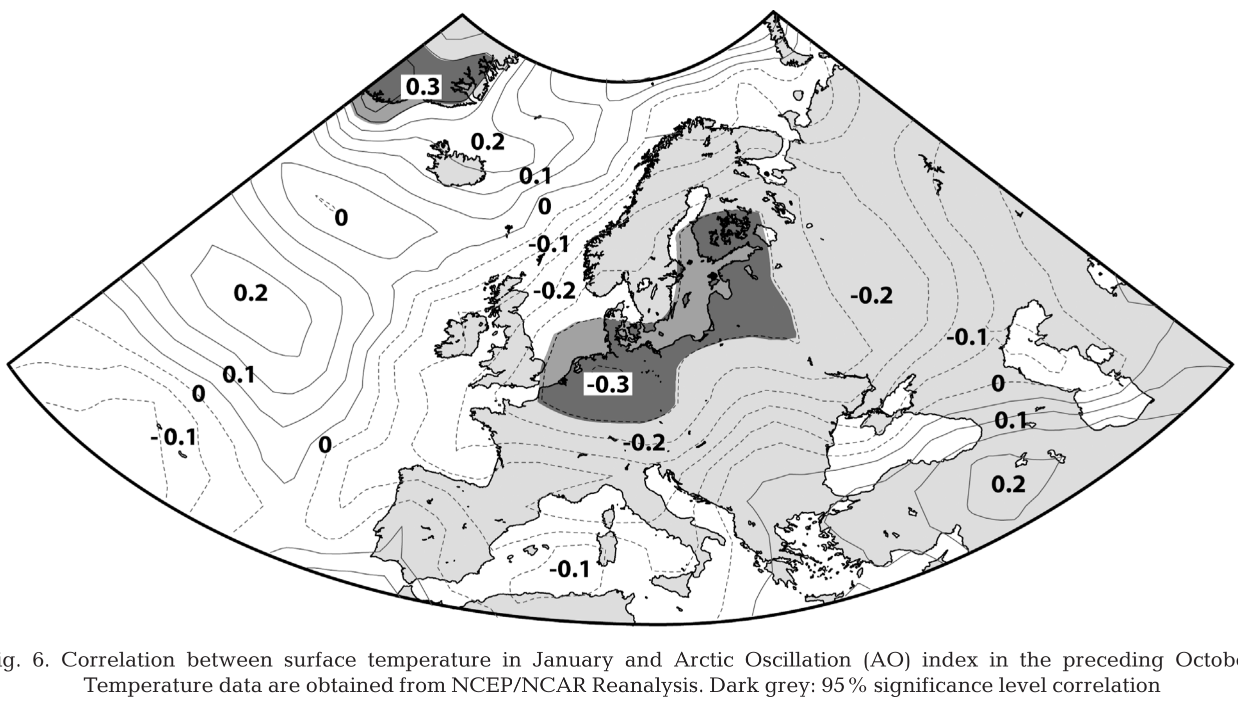


Fig. 6. Correlation between surface temperature in January and Arctic Oscillation (AO) index in the preceding October. Temperature data are obtained from NCEP/NCAR Reanalysis. Dark grey: 95% significance level correlation

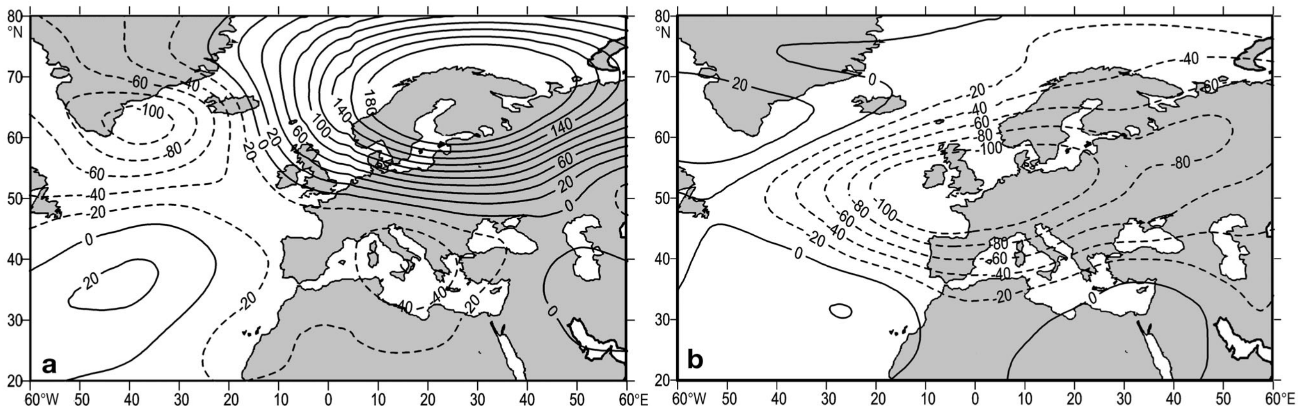
The technique proposed by Shuliakovsky (1960) included calculations of water temperatures during periods of permanent air temperature decreases which used additional data such as heat and groundwater fluxes. The normal practice is to calculate freezing degree-days up to ice cover formation. For example, the freezing degree-days according to the Kaunas meteorological station records correlate with freeze-up dates at the Smalininkai gauge station (r = 0.54). The main shortcoming of this approach is that the later the freeze up, the larger the freezing degree-days. So, in the present study, freezing degree-days were calculated for a fixed period, e. g. 30 d.

We applied 3 different classification methods applied to the atmospheric circulation patterns influencing intensive cooling/freeze-up processes. All freeze-up events recorded later than 1 January were excluded from the analysis because the water temperature is close to 0 °C in midwinter, and thus little further cooling is required for river freeze up. In addition, earlier studies (Stonevicius 2004) revealed that the break-up process in the Nemunas River has no bearing on weather patterns that are likely to force it, and classification methods used in the present study did not apply to atmospheric circulation patterns prevailing during the river break-up period.

Clusters derived from the 700 mb anomaly represent 3 main low-frequency atmospheric modes (LFMs) responsible for intensive cooling in the Baltic region. The first 2 LFM clusters each represent 37% of the anomaly data variance and the third LFM cluster represents 26%. The first LFM cluster represents the typical Scandinavian anticyclogenesis (Fig. 7a). Intensive radiative cooling and cold advection following easterly and southeasterly winds prevail over the eastern Baltic region (Fig. 7a). The second LFM cluster indicates the southward shift of the upper frontal zone (UFZ) to the Mediterranean and southern Russia (Fig. 7b). Surface cyclones moving beneath the UFZ induce cold advection to the Lithuanian territory in its rear side and the northern periphery (Fig. 7b). The third LFM cluster is typical of the NAO/AO negative phase and of blocking over North Atlantic (Fig. 7c). Easterly flow spans almost all of the European–North Atlantic sector and the pattern is very favorable for land surface cooling (Fig. 7c).

The first 4 derived PCs represent 72.7% of the variance of all geopotential data (used in this study). The first 3 PCs appear to be similar to the 3 LFMs while the fourth is not.

The first principal component (PC1) (30.0%) is very similar to the first LFM cluster and represents the upper Fennoscandian anticyclone favorable not only for cold advection but also for clear sky cooling (Fig. 8a). The only difference is found in the Mediterranean region where the first LFM cluster represents the winter cyclo-



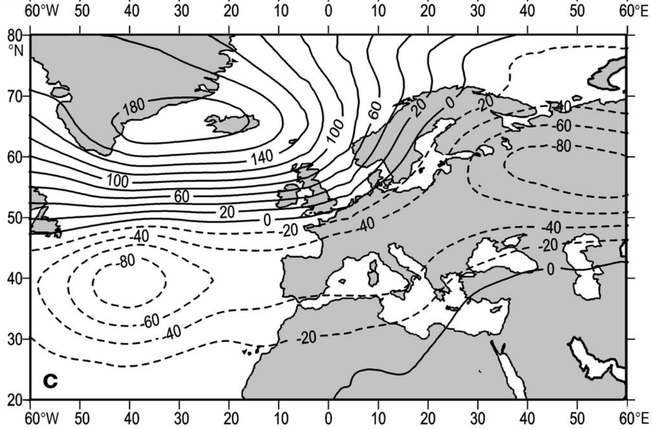


Fig. 7. (a–c) Three clusters (LFM) of the 700 mb height anomaly explaining, respectively, 37, 37 and 26 % of the anomaly field variance applied to the atmospheric circulation patterns responsible for the earliest freeze-up events. Contours—solid: positive, dashed: negative; interval: 20 m. See Section 5 for further details

genesis region better than the PC1. PC2 (18.3%) in its negative phase is related to the second LFM cluster, while the positive phase represents the upper trough over central Europe where the jet exit region is seen in its northern part (Fig. 8b). Such a large-scale pattern slows down Atlantic cyclones and fronts and deflects them to southeast. So there are 2 freeze-up process-enhancing factors: (1) cold advection behind southward moving surface cyclones and (2) surface anticyclogenesis under the right side of the jet stream exit region (Holton 1992). PC3 (14.9%) is, like the third LFM cluster, typical of the negative NAO phase, and represents blocking over the Northeastern Atlantic with a large-scale cold trough downstream and an intensive cyclogenesis region to the southeast of Newfoundland (Fig. 8c). The only difference between the third LFM and PC3 patterns is that the positive correlation center shifts to the southeast in PC3. This pattern is favorable for cold air accumulation over Eastern Europe and tracking polar anticyclones southward over the Baltic region. PC4 (9.5%) in its positive phase does not exhibit a very persistent weather pattern, with a blocking ridge over the Baltic and local cyclogenesis region over the western Mediterranean (Fig. 8d). This pattern favors radiative cooling under the clear sky conditions in Lithuania. The negative phase represents a local storm track, oriented from northwest to southeast, and thus enhancing easterly–southeasterly flow over the eastern Baltic.

The earliest freeze-up periods were analysed for 1951–1998 and 1882–1998 using the aggregated H/B atmospheric circulation patterns (see Table 2).

The NWest pattern appears to be similar to atmospheric circulation prevalent in the negative NAO phase—i.e. FScanAn—with the PC1 (Fig. 8a) or the first LFM cluster (Fig. 7b). SouthZonal could be compared to the second LFM cluster and/or East Atlantic pattern, which is the second prominent atmospheric circulation mode of low-frequency variability over the North Atlantic (Barnston & Livezey 1987). The frequency of this pattern has increased, particularly during the last 2 decades (not shown). EastAn is consistent with the PC3 pattern (Fig. 8c), and is not related to cold advection in Lithuania. However, it does favor clear sky conditions. The AnCentral pattern experienced the most substantial changes in occurrence. It was one of the leading patterns in the first half of the 20th century, but became negligible during the last half (1951–1998). The AnCentral weather regime is very favorable for radiative cooling in the Baltic region during winter. The frequency of other aggregated patterns increased in the second half of the

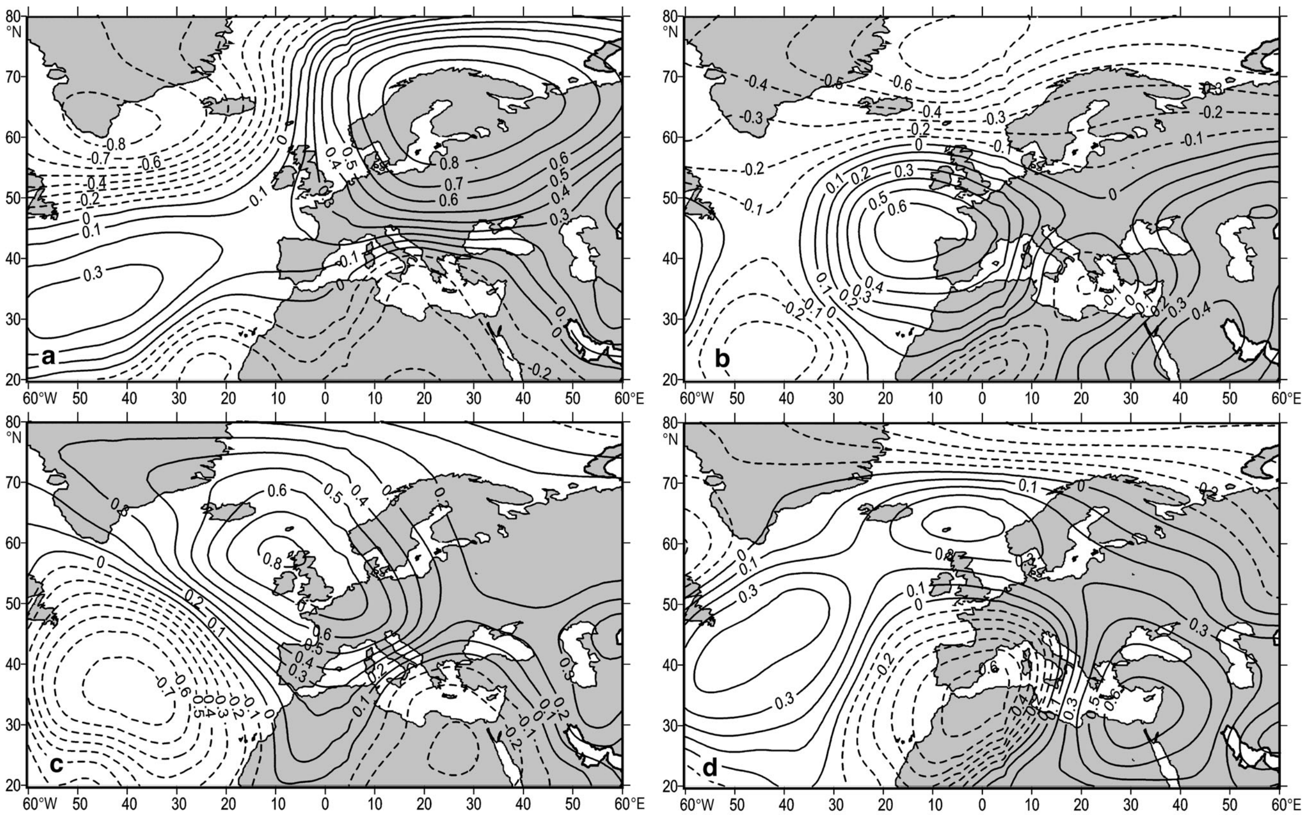


Fig. 8. (a–d) Correlations of principal components PC1–PC4, respectively, with the 700 mb height anomaly fields prevailing during the earliest river freeze-up events. Contours—solid: positive, dashed: negative; interval: 0.1

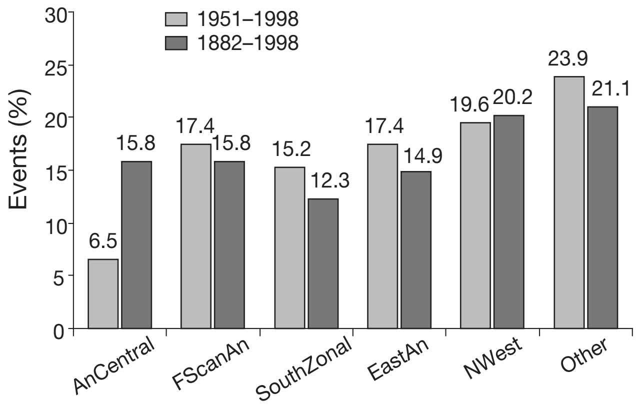


Fig. 9. Frequency of early freeze-up episodes that occured for each Hess/Brezowsky aggregated large-scale circulation type for the periods 1951–1998 and 1882–1998. See Tables 1 & 2 for circulation types and abbreviations

20th century (Fig. 9). The NWest pattern accounted for one-fifth of the variance of daily H/B patterns and did not show any substantial changes in its frequency during the whole analysed period. However, the intensive radiative cooling and/or cold advection in Lithuania are not typical features of this pattern. The frequency of the rest of the analysed patterns, FScanAn, EastAn and SouthZonal, has increased during the later half of the 20th century.

6. DISCUSSION AND CONCLUSIONS

Despite artificial regulation of the intensively-used Nemunas River channels during the 20th century, the river ice regime seems to follow regional climate change. Tendencies for the river ice cover period to decrease over the second half of the last century match other climate change indicators, such as duration of snow cover or sea-ice extent at regional and hemispheric scales (IPCC 2001).

The dynamics in the Nemunas River freeze- and break-up dates yields statistically significant trends since the first half of 19th century, while smoothed data (LOWESS) show an increasing slope of trends for freeze-up dates since the 1910s (positive) and a downward trend since the 1980s. However, there are substantial interannual and intraseasonal changes in ice cover duration. The NAO is a well-known large-scale atmospheric phenomenon, and its impact on European winter thermal anomalies is widely documented in scientific literature (Hurrell et al. 2003, Kistler et al. 2001). However, the present study shows a weak correlation between river freeze-up dates and monthly and weekly NAO/AO indices, while break-up dates are more closely associated with these atmospheric circulation modes. Only early freeze-ups (dates depending on the lower tercile of probability density function) are predetermined by the weakened and even negative NAO-like circulation patterns.

Different classification methods applied to atmospheric data representing the earliest freeze-up events benefit from using several large-scale atmospheric circulation types (patterns) favorable for cold outbreaks or intensive radiative cooling in the Baltic region. Scandinavian anticyclogenesis always precedes continental polar and/or arctic air-mass advection with prevalent easterly northeasterly winds, and is related to clear sky conditions during winter. The negative NAO phase does not obviously guarantee sudden river ice formation because the prevalent meridional flow pattern differs in sign over the western and eastern parts of Europe. However the long duration of such phases ultimately reduces Atlantic air-mass penetration further to the east. Persistent anticyclones over central Russia induce a south-southeasterly flow over central Europe and bring fair-weather conditions over the eastern Baltic region. In the late autumn, when the Russian steppes are not yet snow-covered, the continental air does not have a significant cooling effect, but in December such an air mass only differs marginally from the continental polar mass located further east or northeast. Finally, all other weather patterns more or less represent higher than normal surface pressure fields under an upper large-scale trough. On the other hand, the late freeze-up process does not depend on particular weather regimes because of the prevalent (close to zero) low water temperatures.

Clustering algorithms are able to identify patterns which correspond to peaks in the probability density function of the set of analysed weather regimes, while the PCs, each constrained to be spatially and temporally orthogonal to each other, are then scaled according to the amount of total data variance they explain (Cassou et al. 2004). The preferred atmospheric circulation states—using PCA—come in pairs, in which anomalies of opposite polarity have the same spatial structure. Moreover, the subjective classification, such as the H/B aggregated weather patterns is substantial only for the particular region of its origin, e.g. central Europe. Extracted main weather regimes prevailing during early freeze-ups seem to be similar despite differences in the applied technique. This is particularly true for the patterns explaining the largest part of data variance. Conversely, weather regimes representing less than a quarter of the data variance do not seem to be persistent large-scale patterns.

The second half of the winter period tends to be uniform in atmosphere circulation, and thus monthly circulation indices show better cohesion with ice cover break-up dates than with freeze-up dates. As a rule, the harsher the winter, the more substantial the break-up event. Later break ups (after such winters) are associated with radiative forcing which is able to exceed the atmospheric circulation contribution. Therefore, the retrieval of pure weather patterns responsible for the break up seems to be a complex task. There are enough large river basins that have many sub-basins with different hydrological regimes and spring runoff times. It is likely that the runoff propagating downstream from the upper reaches has the largest impact on the ice cover break-up dates for the lower reaches of the Nemunas River.

The present study does not address how changes in the river ice regime could influence spring runoff behavior, which would require further research. However, rare intrusions of the sudden, and exceptionally harsh, cold air masses not only disturbs the river regime, but are also a sign of the increasing number of climate extremes in the last decades.

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