Long-term changes in hydrological regime of the lakes in Latvia

Elga Apsīte, Didzis Elferts, Andrejs Zubaničs and Inese Latkovska

ABSTRACT

Changes in the hydrological regime of the lakes of Latvia depend on natural and anthropogenic causes. This publication summarises the results of the research on the long-term changes in the water level, thermal and ice regimes in the seven largest lakes of Latvia: Liepājas, Usma, Ķīšezers, Burtnieks, Rāzna, Sventes and Lielais Ludzas, and their regional specifics from 1926 to 2002. For most of the studied lakes, the water level has been regulated, except for the lakes Liepājas, Burtnieks and Ķīšezers. Global climate warming has caused considerable changes in the hydrological regime of the lakes during the last decades and the surface water temperature has increased. At the same time, the number of days with ice cover and the thickness of ice have decreased. A positive trend in the freezing date and a statistically significant negative trend for the ice break-up date was found for all lakes. The lakes Liepājas and Usma are located in the western part and Lake Kīšezers in the central part, therefore their hydrological regime, in particular, the thermal and ice regime, differs from the lakes Burtnieks, Rāznas, Sventes and Lielais Ludzas which are located in the northern and south-eastern part of Latvia.

Key words | ice, lake, long-term changes, water level, water temperature

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INTRODUCTION

It is a well-known fact that at the end of the 20th and start of the 21st century, new and more pronounced global climate warming was observed (IPCC 2007) which determined changes in the hydrological cycle and processes (Bolle *et al.* 2008), including changes in the hydrological regime of lakes. This encouraged the development of many studies of climate impacts on the hydrology and environment of the European and North American lakes. The surface water temperature increase of lakes during the 1990s was identified (e.g., Korhonen 2002; Arvola *et al.* 2010). Extension of the duration of the ice-free period, an increasing trend in ice freezing dates and a decreasing trend in ice break-up dates were reported (e.g., Magnuson *et al.* 2000; Weyhenmeyer *et al.* 2004, 2005; Korhonen 2006; Livingstone *et al.* 2010b). Regional and supra-regional coherence in limnological variables such as duration of the ice cover and water temperature was found by Livingstone *et al.* (2010a). The simulation results of ice growth and decay of Finnish lakes at the end of the 21st century by Leppäranta (2010) predict a much shorter ice season and thinner ice depending on the emission scenario. Lakes Erken in Sweden, Esthwaite Water in the UK and Mondsee in Austria were predicted to become warmer, to stratify early and to have longer and more intense periods of thermal stratification for the period 2071–2100 in a study by Jones *et al.* (2010).

Lakes present a very common landscape element in Latvia and in the Baltic Range which extends to some highland areas featuring lakes in Lithuania, Poland and northern Germany. In Latvia, there are 2,256 lakes with a water surface area above 1 ha and their total water surface area equals approximately 1,000 km^2. The majority of the lakes are small. The water surface area of just 16 lakes exceeds 10 km^2 (Tidriķis 1995). The average coverage of lakes in Latvia is 1.5%. It is approximately similar to the situation in Lithuania, but considerably less than in Estonia (5%), Sweden (8.5%) or Finland (9%). Most of the lakes are of

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glacial origin. In the 20th century, the number of lakes decreased because they had become overgrown, water was drained or lakes merged.

Earlier studies of Latvian lakes were connected with morphometric elements for some lakes in the 1930s, e.g., by Stakle (1935), Slaucītājs (1935, 1938) and later by Kotov *et al.* (1958). Broader research of the thermal and ice regime of rivers and lakes and their regional differences was conducted by Glazacheva (1964, 1965). The rivers and lakes of the western part of Latvia have a shorter ice season, thinner ice and warmer water during the year compared with the eastern part. A report by Glazacheva (2004) is among the last short summary publications about the long-term changes of water level due to natural and anthropogenical impacts for some Latvian lakes from 1926 to 1990. It should be noted that recently no broader researches on those topics have been carried out. Besides, as from the year 2003, regular monitoring of the Latvian lakes has no longer been performed.

Therefore, the objective of this study was to analyse the long-term changes of the hydrological regime, i.e., the water level and the surface water temperature, ice regime parameters and the regional differences of the seven largest Latvian lakes caused by natural and anthropogenic impact.

MATERIALS AND METHODS

Study lakes

The seven largest Latvian lakes with long data observation series and different geographical locations (Figure 1) were selected for the study. The major data describing the lakes' morphometry are presented in Table 1.

Lakes Liepājas and Usmas are located in the western part of Latvia and Lake Ķīšezers is located in the central part. All lakes are a remainder of the Baltic Ice Lake or a relict. Water surface area varies from 17 to 37 km^2. Lakes are shallow with a depth of up to 2 m, except for Lake Usma. Lake Usma is the second largest lake in Latvia from the point of view of water volume (190 mill. m^3), and the water exchange takes place on average once in 2 years.

The fourth largest lake, Burtnieks, is located at 39.5 m above sea level (a.s.l.) in the northern part of Latvia in the Tālava lowland. The lake is of glacial origin and belongs to the group of shallow lakes. The water exchange takes place on average six or seven times per year.

The lakes Rāznas, Lielais Ludzas (hereinafter Ludzas) and Sventes are located in the south-eastern part of Latvia in the Latgale and Augšzeme highlands. The lakes are of glacial origin. They are characterised by higher average and maximum water depth values. Lake Rāznas is the second largest lake in Latvia from the point of view of the water surface area which amounts to 57.6 km^2 and the largest lake in Latvia from the point of view of the volume of water, i.e., 405 mill. m^3.

Data and methods

The changes in the hydrological regime (water level, surface water temperature and ice parameters) of the Latvian lakes were investigated by using the records of the Latvian Environment, Geology and Meteorology Centre and the publication of the Marine Board by Stakle & Kanaviņš (1941). The hydrological data series used are presented in Table 2. For the purpose of analysis of the water level (in centimetres above the zero post mark) and surface water temperature (in Celsius degrees from March to December), monthly mean data were used. In the analysis of the ice regime, the data on the ice thickness and duration, freezing and break-up dates were used. The date of freezing was assumed to be the first day of ice occurrence. The date of disintegration of the ice cover during a period with regular ice cover was assumed to be the date of ice break-up. The number of days with ice cover was calculated as the actual number of days on which ice occurred. For assessment of the climate changes in the Latvian lakes, the severity index was calculated by Sztobryn *et al.* (2009). The index was used for the seasonal number of days with ice and the probability of ice occurrence. In the study of the lakes' ice regime, the daily air temperature data from 1945 to 2002 of the closest meteorological station (Liepāja, Stende, University of Latvia, Rūjiena, Rēzekne and Daugavpils) were used (Figure 1). The absolute value of the sums of negative air temperatures was calculated for each meteorological station for the time period from November 1 of the preceding year to April 30 of the current year.

The data statistical analysis was performed by using the software R 2.15.1. (R Development Core Team 2012). Pearson correlation analysis was used for testing the

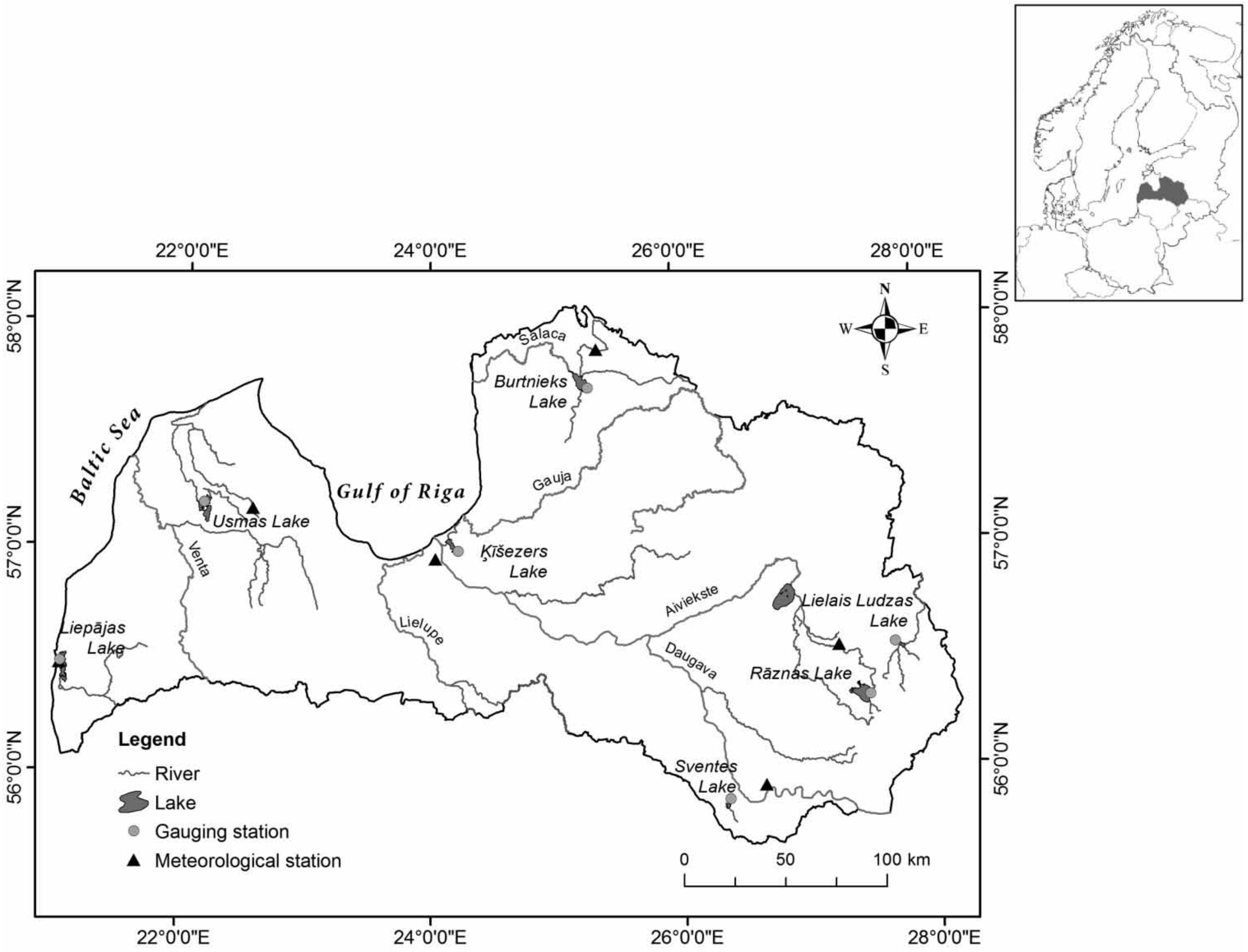

Figure 1 | Location of studied lakes, gauging and meteorological stations.

Table 1 | Morphometric parameters and location of studied lakes

Lake	Watershed, km^2	Surface area, km^2	Volume, mill. m^3	Maximum depth, m	Average depth, m	Location a.s.l., m
Liepājas	2515	37.15	37	2.8	<2	0.2
Usmas	396	37.2	190	27	5.4	20.6
Ķīšezers	1900	17.3	42	4.2	2.4	0.1
Burtnieks	2215	40.1	88	3.3	2.4	39.5
Rāznas	221	57.6	405	17	7.1	163.8
Ludzas	473.5	8.46	30.9	6.5	3.5	132.8
Sventes	18	7.35	57.3	38	7.8	137

relationship between the absolute value of the negative temperature sums and ice parameters (freezing date, break-up date, number of days with ice cover and maximum ice thickness). Empirical cumulative distributions of freezing and break-up dates for each lake were calculated and compared by applying the Kolmogorov–Smirnov test

Table 2 | Hydrological data series used in the study

Lake	Water level, cm	Surface water temperature, °C	Date of freezing and ice break-up; number of days with ice cover; the maximum ice thickness, cm
Liepājas	1933–2002	1946–2002	1945–2002
Usmas	1926–2002	1946–2002	1945–2002
Ķīšezers	1930–2002	1946–2002	1945–2002
Burtnieks	1947–2002	1946–2002	1946–2002
Rāznas	1948–2002	1948–2002	1948–2002
Ludzas	1959–2002	1951–2002	1965–2002
Sventes	1964–2002	1948–2002	1948–2002

(Sokal & Rohlf 1995). The multivariate Mann–Kendall test (Lettenmaier 1988; Loftis *et al*. 1991) was used for identifying the trend shift in the annual and monthly data analysis. The test was applied separately to each variable at each site, at a significance level of $p < 0.05$. The trend was considered statistically significant at the 5% level, if the test statistic was above 1.96 or below –1.96.

RESULTS

Changes in water level

In our study natural fluctuations in the annual mean water level, where the periods of low water alternate with high water periods, can be seen for the lakes Burtnieks, Ķīšezers and partly Usmas (Figure 2). A pronounced low water period can be seen at these lakes in the 1930s to 1940s and 1960s, and starting from the 1970s, it changed to a pronounced high water period that lasted until the 1990s. From 1929 to 1930, the Salaca river channel was deepened at the outlet of Lake Burtnieks, thereby lowering the water level of the lake by 1 m. As regards the study period 1947 to 2002, there are no data about water level adjustment works performed manually at Lake Burtnieks. Therefore, these could be considered natural processes that have taken place mainly under the impact of climate change and due to the lake itself trying naturally to restore the water level to the initial level. This is confirmed by comparison of the long-term changes of lake water level with the changes in discharge of the Salaca river from 1951 to 2002 (Figure 3). Two periods can be distinguished in the water regime of Lake Burtnieks and the Salaca river: low water from 1947 to 1977 and high water from 1978 to 2002. The situation is more complicated at Lake Ķīšezers. Changes in the water level depend not only upon climate conditions and the amount of water inflowing from the drainage basin but also upon the influx and deflux at Riga Sea Gulf and the River Daugava water flow regime. Long-term changes in the water level of Lake Usmas were also impacted by direct human activity. In 1969, the water level in the lake was raised on average by 0.2 m. The most differing long-term changes in water level can be seen in Lake

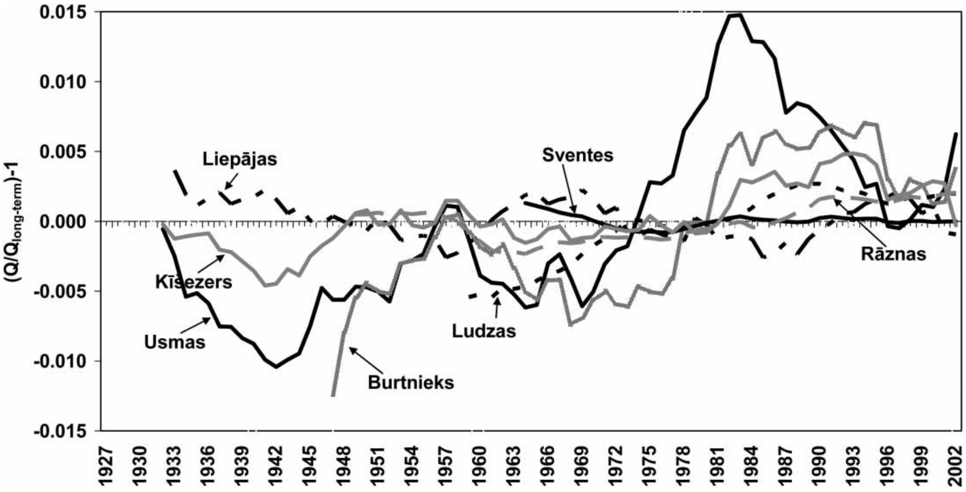

Figure 2 | Integral curve of the annual mean water level in the studied lakes during the period 1927–2002. The curves are smoothed with a 6-year moving average.

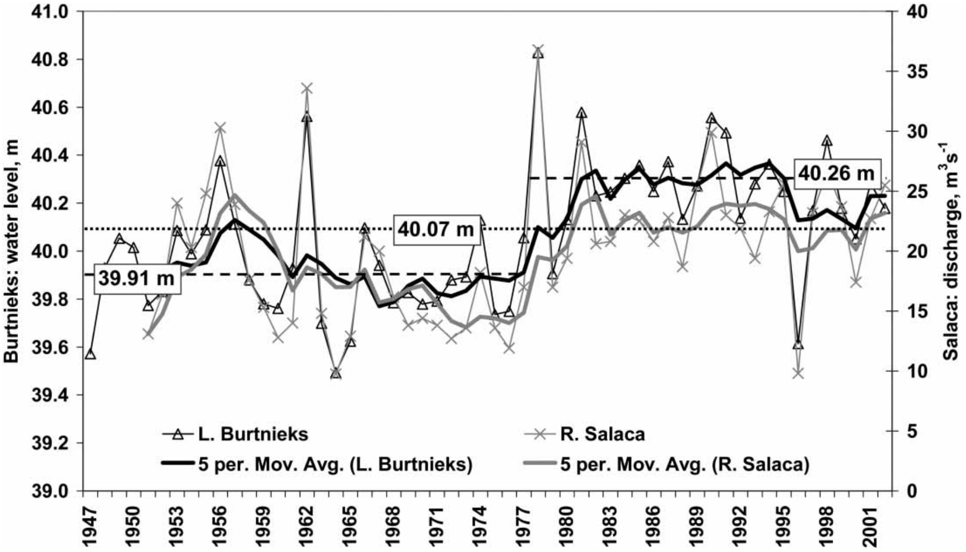

Figure 3 | Changes in the annual mean water level and changes in the annual mean discharge of the Salaca river from 1947 to 2002. The numbers represent the long-term mean water level of the period. The dotted line is the long-term mean value of water level during the period 1947–2002; the interrupted lines are the long-term mean value of water level during the periods 1947–1977 and 1978–2002, respectively.

Liepājas. The changes in the water level regime of this lake are essentially determined by the water influx and deflux of the Baltic Sea via the Port Channel (constructed in 1697–1703) and the inflowing water from the drainage basin.

The long-term changes in annual mean water level are more smoothed for the lakes that are located in the south-eastern part of Latvia – Rāznas, Ludzas and Sventes (Figure 2). This should be related to both natural processes and human activity. Lake Sventes was regulated in 1964 when the water level of the lake was lowered by 0.5 m. Lake Ludzas was regulated several times, i.e., the Felicianova small-scale hydropower station was constructed in the 1920s. Its operations were suspended in the 1970s and resumed again in the 21st century. Of all the lakes considered, Lake Rāznas has been most regulated (Figure 4). During the period 1951 to 1955, the Spruktu hydropower station was built on the outlet of the River Rēzekne and was in operation until 1977. Thereby the water level of the lake was lowered by 0.3 m on average. After the closure of the Spruktu hydropower station, the natural water level was restored in the lake from 1985 to 1992 (on average up to 163.32 m a.s.l.), when an eel catching device was constructed and the water level of the lake was raised by 0.29 m. During the period from 1993 to 2002, the Spruktu hydropower station and the Kaunata gates were reconstructed. The gates continue to maintain the water level of the lake at the artificial level that was raised by another 5 cm following their reconstruction.

Changes in surface water temperature

The results of the analysis of the surface water temperature show that the long-term annual mean temperature was highest for the lakes Liepājas, Usma and Ķīšezers where it was 10.1 to 10.4 °C (Table 3). The long-term annual mean water temperature is generally lower for the lakes that are located in the northern and south-eastern part, except for lakes Sventes and Ludzas. In the Latvian lakes the surface water temperature is highest in July and August and it is lowest during the period of the formation of ice cover.

The long-term annual mean surface water temperature had a statistically significant positive trend from 1946 to 2002, except for Lake Liepājas (Figure 5). During the last 15 years, the annual mean water temperature increased by 0.4–0.8 °C in comparison to the preceding period. The analysis of the monthly mean surface water temperature demonstrated that a statistically positive significant trend could be seen during the spring months of March, April and May for all the lakes, except for Lake Burtnieks. Significant positive long-term changes in water temperature were

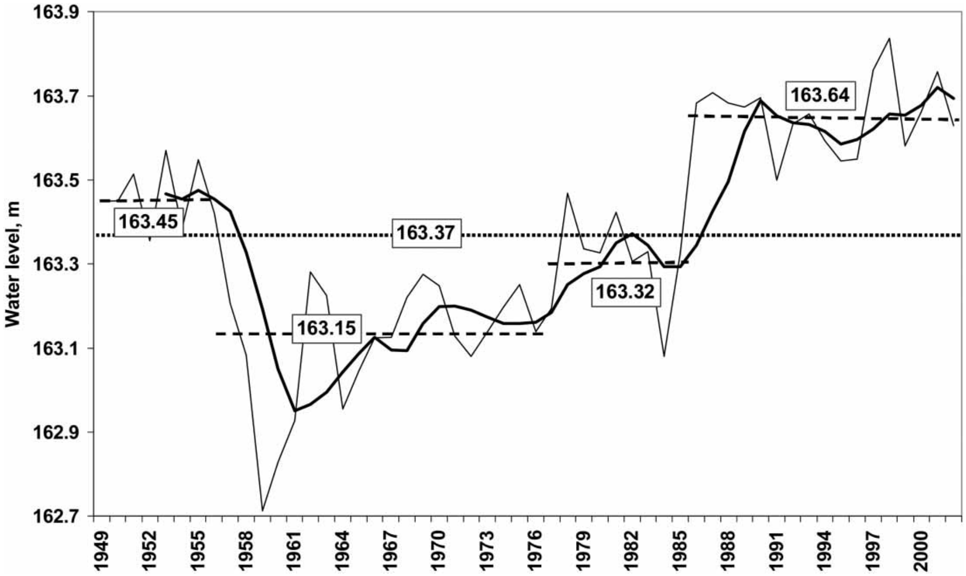

Figure 4 | Changes in the annual mean water level of Rāznas lake from 1927 to 2002. The numbers represent the long-term mean water level of the period. The dotted line is the long-term mean value of water level during the period 1949–2002; the interrupted lines are the long-term mean value of water level during the periods 1949–1955, 1956–1977, 1978–1984 and 1985–2002, respectively.

Table 3 | Monthly and annual mean surface water temperatures

	Month										
	M	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**Annual mean**
Liepājas	1.5	5.3	13.9	17.6	18.9	17.8	13.3	8.3	3.6	1.3	10.1
Usmas	1.0	4.9	12.3	17.6	19.6	19.1	14.9	9.1	3.5	0.7	10.3
Ķīšezers	0.9	5.5	13.9	18.5	20.1	19.2	14.2	8.2	2.9	0.6	10.4
Burtnieks	0.2	3.7	12.7	17.7	19.2	18.0	12.9	6.7	1.9	0.3	9.3
Rāzna	0.2	2.6	10.8	17.0	19.1	18.2	13.4	7.4	2.4	0.3	9.1
Sventes	0.3	3.1	11.3	17.7	20.0	19.6	15.3	9.8	4.2	0.8	10.2
Ludzas	0.4	4.5	13.1	18.3	20.0	18.8	13.5	7.4	2.0	0.3	9.8

also found in July (Liepājas, Rāznas), in August (Ķīšezers, Rāznas, Sventes, Ludzas), in November (Ķīšezers) and in December (Rāznas).

Changes in the ice regime

Ice freezing and break-up dates

Generally, the formation of ice cover starts in the second half of November in the highlands in the northern and south-eastern parts of Latvia, and in the first half of December in the western and central parts. Ice cover breaks up during the period from the second half of March to mid-April. As can be seen from the example of the lakes Usmas and Rāznas in Figure 6, at the turn of the centuries, i.e., between the 20th and 21st centuries, the formation of ice cover started in early December and ice cover break-up took place as early as mid-March or at the end of March. Similar trends of long-term changes apply to the calculated freezing date and break-up date in days per decade (Table 4). A sharper decrease in days could be seen for the break-up date and in the lakes of western Latvia, i.e., the ice breaks 6–7 days earlier per decade.

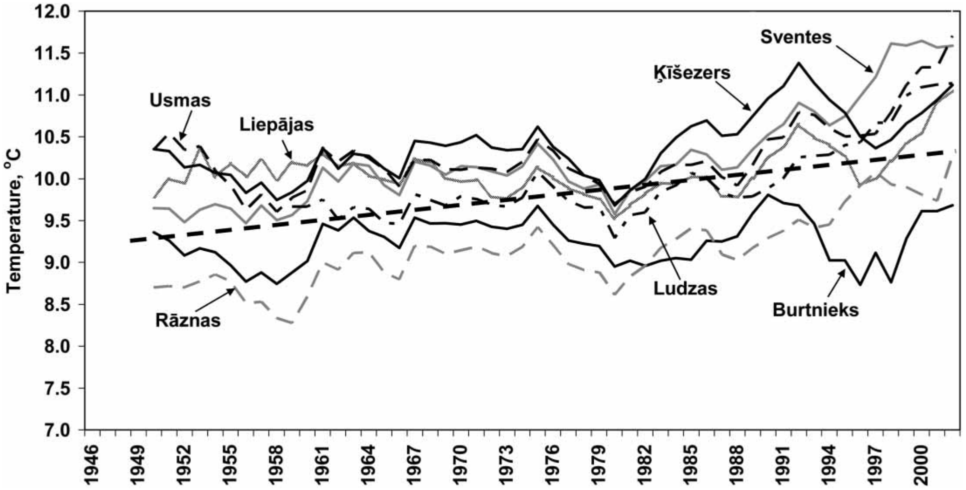

Figure 5 | Long-term changes in annual mean surface water temperature (March–December) from 1946 to 2002. Water temperature curves are smoothed with a 5-year moving average.

Therefore, during the study period the ice freezing date occurred increasingly later, i.e., there is a positive trend, but it is not statistically significant. The ice break-up date has been occurring increasingly earlier, i.e., there is a statistically significant negative trend, except for Lake Ķīšezers.

Cumulative distribution curves of dates demonstrate substantial regional differences. As can be seen in Figure 7, during the whole study period, ice break-up dates in the lakes of the south-eastern part (Rāznas, Ludzas, Sventes) are usually much later than in the western and central parts of Latvia (Liepājas, Usmas and Ķīšezers). This distribution of break-up dates varies statistically significantly between different parts of Latvia. The situation is different as regards the cumulative distribution curves of the ice freezing dates (Figure 8). Although the distribution of the dates looks different, only two statistically significant groups are formed – lakes Burtnieks and Ludzas in one group, and all the other lakes in the second group.

Number of days with ice cover and severity index

Table 5 summarises data about the duration of ice cover during the period 1945/46–2001/02 that varies among the studied lakes. The shortest duration of ice cover applies to the lakes Liepājas, Usma and Ķīšezers and it is 85–105 days. The longest duration of ice cover applies to the lakes that are located in the northern and south-eastern part of Latvia where it is 120–138 days.

Observations indicate that until the end of the 1980s ice cover was maintained in the lakes on average for 3.5–5 months or 6 months during severe winters. During the last 15 winter seasons (1988/89–2001/02), in comparison to the preceding study period (1945/46–1987/88), the number of days with ice cover has decreased on average by 14–33 days (Figure 9). The highest decrease in the number of the days with ice cover applies to the lakes of the western part of Latvia and Lake Ķīšezers where it amounts to 20–33 days. The decrease has been less in the lakes of the northern and eastern parts where it amounts to 10–16 days. The above regional differences also demonstrate the changes in the calculated number of days with ice cover per decade (Table 4). The duration of ice cover has decreased and it is a statistically significant trend in Lake Liepājas (by 6.2 days per decade), in Lake Usma (by 7.1 days per decade) and in Lake Sventes (by 3.7 days per decade). The changes identified above generally agree with the results of the Mann–Kendall test. It shows that statistically significant long-term changes, i.e., a decreasing trend, were identified for the lakes Liepājas, Usmas, Rāznas, Sventes and Ludzas.

In order to assess the climate changes in the winter season and regional differences, the severity index was calculated. Figure 10 shows that the severity index varies among regions: it is higher for the lakes located in the northern and south-eastern of Latvia, i.e.,

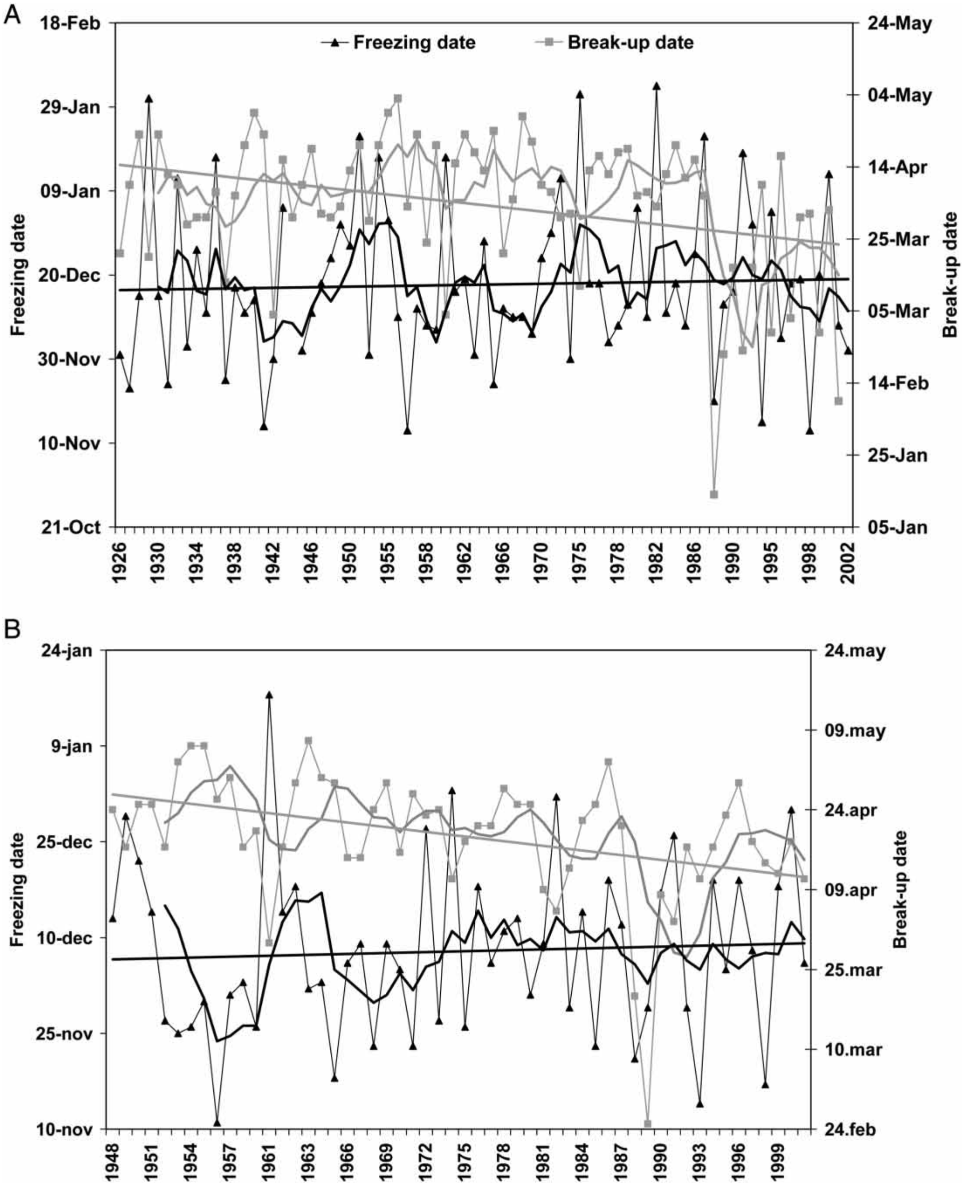

Figure 6 | Long-term changes in the freezing date and the ice break-up date for the lakes Usmas (A) and Rāznas (B).

Burtnieks, Rāzna, Sventes and Ludzas, and it is lower for Usma and Liepājas located in the western part, and also for Lake Ķīšezers. Based upon the calculated severity index, the most severe and warmest winter seasons correspond to the seasons with the longest and shortest duration of ice cover. The most severe winters could be observed from 1954/55 to 1958/59, and in the years 1965/66, 1968/69 and 1995/96. The warmest winters were in the years 1960/61, 1974/75, 1988/89 and 2001/01.

Maximum ice thickness

The long-term changes in the lake ice thickness can be described as alternations of the periods with thicker and thinner ice cover (Figure 11). Ice thickness was

Table 4 | Changes in the occurrence of ice at lakes in days per decade

Lake	Freezing date	Break-up date	Ice duration
Liepājas	0.13	−5.8	-6.2^{a}
Usmas	0.59	−7.1	-7.1^{a}
Ķīšezers	−0.59	−2.5	−3.2
Burtnieks	−1.78	−4.1	−2.7
Rāznas	−0.27	−1.8	−1.4
Ludzas	−0.14	−3.8	−3.3
Sventes	−0.37	−4.2	-3.7^{a}

[a]Statistically significant at $p < 0.05$.

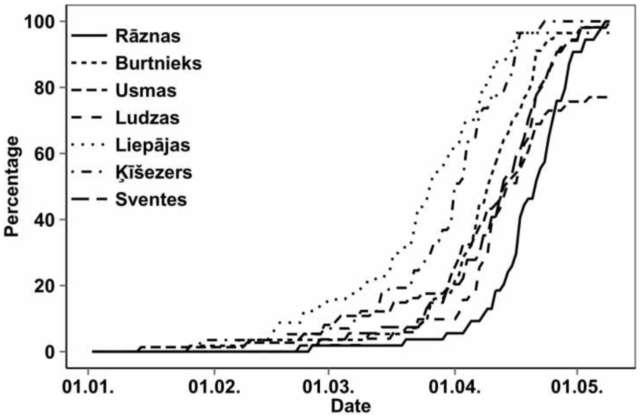

Figure 7 | Cumulative percentage of years for each lake with no ice cover (break-up) on a particular date.

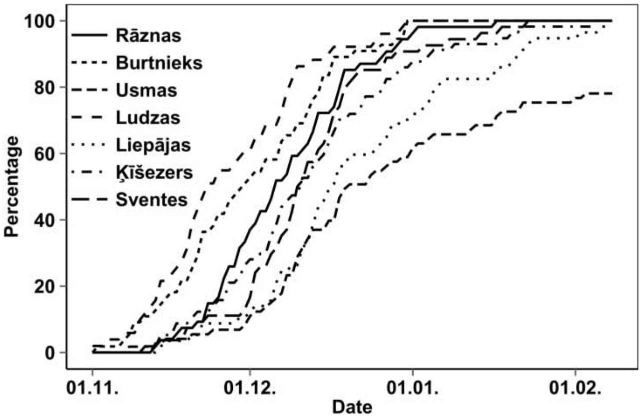

Figure 8 | Cumulative percentage of years for each lake with ice cover (freezing) on a particular date.

pronouncedly higher during the period 1945–1987 and lower during the period 1988–2002. The Mann–Kendall test shows that a statistically negative trend was identified for the annual maximum ice thickness for all the studied lakes, except for Lake Liepājas.

In the Latvian lakes, the maximum ice thickness increases in the direction from west to east, and accordingly is 36–39 cm and 50–57 cm (Table 5 and Figure 12). The highest mean and maximum ice thickness can be observed in March, but it can occur also in February and April.

Relationship between ice conditions and air temperatures

The dates of both ice freezing and ice break-up and the annual maximum ice thickness of a given year can be estimated quite well on the basis of the air temperature. The absolute value of the negative air temperature sum shows a negative correlation with the freezing date (Table 6), but in the case of lakes Burtnieks, Sventes and Ludzas, it is not statistically significant. The break-up date, the number of days with ice cover and the annual maximum ice thickness show a very strong positive correlation with the absolute negative air temperate sum which is statistically significant at $p < 0.05$ for all studied lakes.

DISCUSSION

There is a number of early studies concerning long-term changes in the hydrological regime, i.e., water level, surface water temperature and ice parameters, of lakes in Europe

Table 5 | Average number of days with ice cover and average maximum ice thickness of the period 1945/46–2001/02

Lake	Number of days with ice cover	Maximum ice thickness (cm)
Liepājas	85	36
Usmas	104	39
Ķīšezers	105	37
Burtnieks	128	50
Rāznas	133	57
Sventes	120	50
Ludzas	138	52

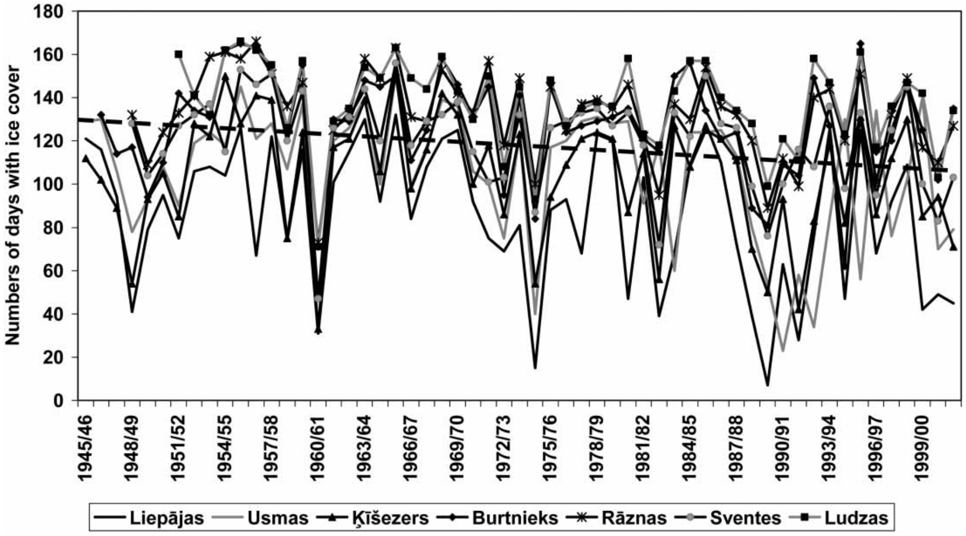

Figure 9 | Long-term changes in the number of days with ice cover during the period 1945/46–2001/02.

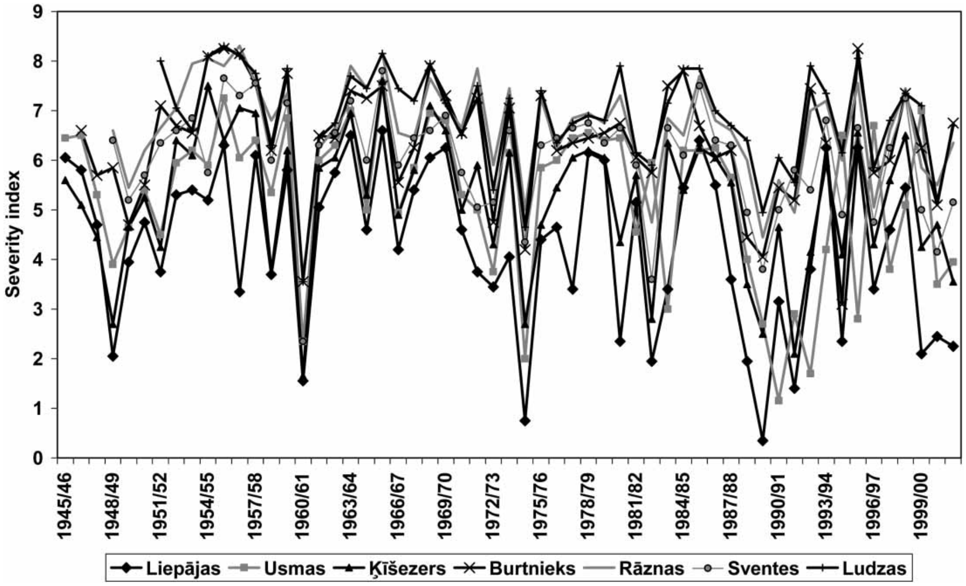

Figure 10 | Changes in the severity index of the lakes during the period 1945/46–2001/02.

and North America. The results of these studies display quite similar patterns to those observed in this study.

Lakes are a natural indicator reflecting the humidity conditions of the territory and their variability. The dynamics of the condition of lakes over time are best described by the regime of the water level and its changes. The long-term changes of annual mean water level in Latvia have been dependent on anthropogenic and natural causes as was concluded in an early study by Glazacheva (2004) for the lakes Burtnieks, Sventes, Usmas and Liepājas for the period 1926 to 1990. The history of the modification of the water level of Latvian lakes under the impact of human activities started as early as the 18th to 19th century. It had the broadest and most essential scope in the 20th century which is the period that relates to hydromelioration, hydro energy, fisheries and other

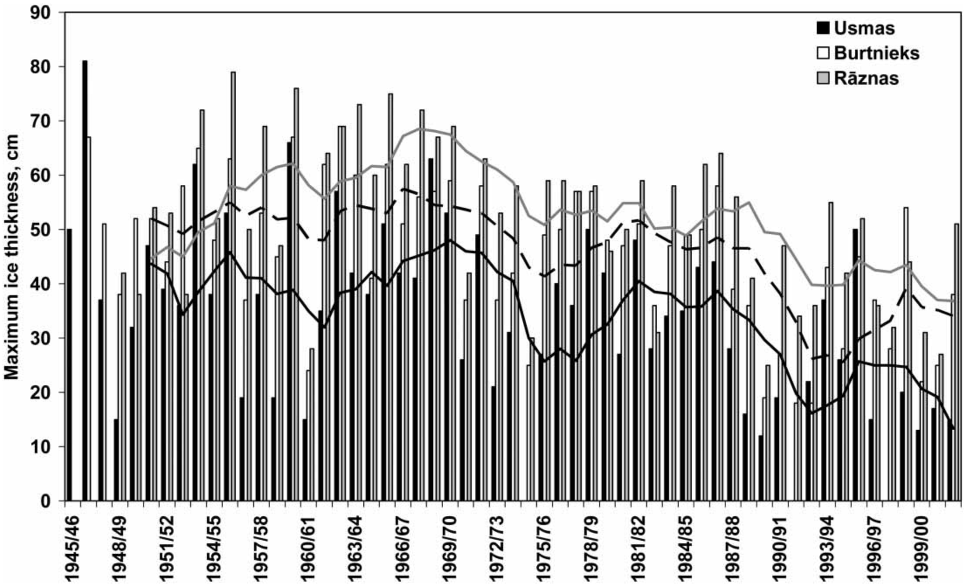

Figure 11 | Long-term changes in the annual maximum ice thickness during the period 1945/46–2001/02. The curves are smoothed with a 6-year moving average.

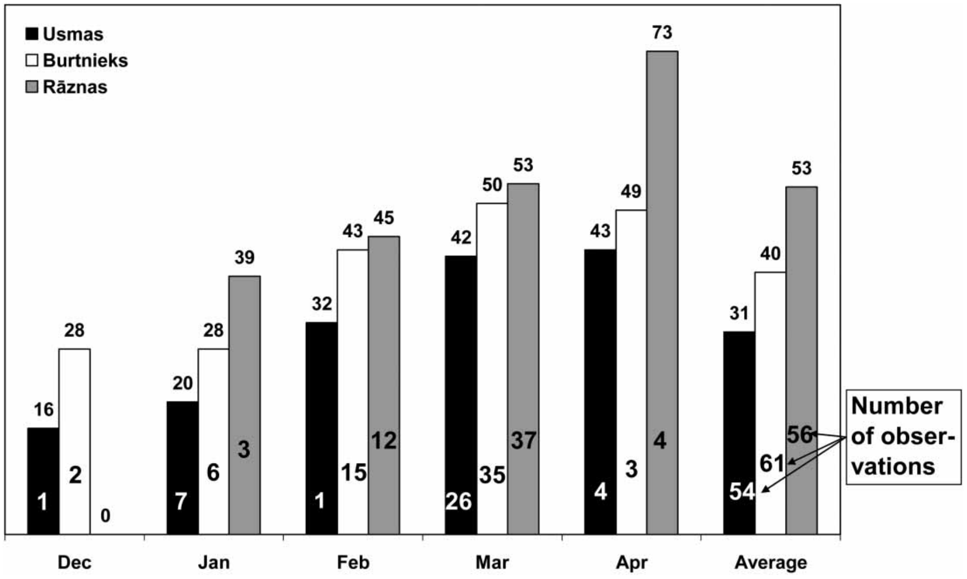

Figure 12 | Long-term changes in the monthly maximum ice thickness.

works controlling the water level of lakes. The natural fluctuations of the water level are caused by different macro processes, like the atmospheric circulation, changes in the solar radiation which determine the thermal and ice regime of the lakes, as well as the amount of precipitation (Glazacheva 2004).

As regards European lakes, the study by Arvola *et al.* (2010) has reached the conclusion that there is now convincing evidence of the long-term increase in their surface water temperatures, which appears to have accelerated during the 1990s. These comparisons complement the results of more detailed regional studies, e.g., by Livingstone &

Table 6 | Correlation between the negative air temperatures sum (absolute value) and ice regime parameters

Lake/ parameter	Freezing date	Ice break-up date	Number of days with ice cover	Maximum annual ice thickness
Liepājas	– 0.40[a]	0.65[a]	0.79[a]	0.91[a]
Usmas	– 0.33[a]	0.73[a]	0.57[a]	0.84[a]
Ķīšezers	– 0.33[a]	0.59[a]	0.63[a]	0.74[a]
Burtnieks	– 0.18	0.61[a]	0.57[a]	0.84[a]
Rāznas	– 0.28[a]	0.57[a]	0.58[a]	0.73[a]
Sventes	– 0.27	0.70[a]	0.65[a]	0.83[a]
Ludzas	– 0.21	0.73[a]	0.63[a]	0.79[a]

[a]Statistically significant at $p < 0.05$.

Dokulil (2001), Livingstone (2003) in central Europe, George et al. (2007) in the UK and Ireland. At the same time, in northern Europe statistically significant trends were found only in a few lakes (Korhonen 2002), which, in fact, is in good agreement with the previous observations from North America (Arvola et al. 2010). However, our study results regarding annual and monthly mean surface water temperature increase in a particular study period agree very well with the study results by Lizuma et al. (2007) regarding the air temperature in Latvia from 1950 to 2003. They have found that the annual mean air temperature has increased by 1.4 °C during the last 50 years. The highest increase in the mean air temperature was recorded in spring (March, April and May) and in late autumn and early winter (November and December).

The records of a lake's ice season, i.e., the break-up date, the number of days with ice cover and maximum annual ice thickness, are good indicators for assessing the inter-annual and seasonal climate variability, especially in relation to long-term climate change (Magnuson et al. 2000; Beltaos & Burrell 2003). The results of our study on the long-term changes in the ice regime parameters of the Latvian lakes are similar to those regarding the northern hemisphere by Magnuson et al. (2000) and regionally the northern countries, e.g., by Korhonen (2006) and Weyhenmeyer et al. (2004). Magnuson et al. (2000) have concluded that the freezing date has been occurring progressively later (at the mean rate of 5.7 days per 100 years) and the ice break-up has been progressively early (at the mean rate of 6.3 per 100 years), implying an overall decrease of the duration of ice cover (at the mean rate of 12 days per 100 years) in various regions of the northern hemisphere since at least the middle of the 19th century. The results of the study by Korhonen (2006) in Finland clearly showed that there was a statistically significant change towards earlier ice break-up from the late 19th century to the present time. There is also a significant increasing trend towards a later ice freezing date and a shorter duration of the ice cover. Series of the maximum ice thickness showed both decreasing trends in the southern part of the country and increasing trends in the central and northern regions. These trends were statistically significant for approximately 50% of the observation sites. At the same time, Weyhenmeyer et al. (2004) found that the date of the ice break-up responds much more strongly to the inter-annual variations in the air temperature in southern Sweden, where winters are relatively mild and duration of ice cover usually varies between 0 and 125 days, compared to northern Sweden where winters are more severe and ice cover usually lasts for 200 to 250 days.

Climate warming at the turn of the centuries, i.e., between the 20th and 21st centuries, is likely to be the most important factor responsible for the recent shifts in lake ice regime parameters, although regional differences may reflect the differing importance of impact by large-scale climate drivers, such as ENSO and NAO/AO (Livingstone et al. 2010a). Williams & Stefan (2006) and Korhonen (2006) have pointed out that the air temperature is the dominant variable driving in ice phenology. Statistically, the air temperature can often explain 60–70% of the variance in the date of ice break-up on lakes (Livingstone 1997). The results of this study show that also the absolute negative air temperature sum has a strong correlation with the duration of ice cover and the annual maximum ice thickness and provides an explanation of the variance on average by 60–80% and 70–90%, respectively.

Thermal and ice regimes of lakes is determined by the location of lakes and climatic conditions as well as the size and depth, and inflow of underground and surface waters such as streams and rivers (Glazacheva 1965). Our study results show that these long-term changes in annual and monthly mean surface water temperature and ice regime parameters are substantially determined by geographical location and the meridional zonality of the climate. The western lakes, including Ķīšezers, are subject to a stronger considerable impact of the meteorological processes occurring over the North Atlantic and the Baltic Sea than lakes in other parts of Latvia, particularly in comparison to the eastern part (Glazacheva 1964, 1965). In the western part, there are milder winters and autumns and cooler springs and summers. This tendency changes in the direction from west to east. Therefore, the lakes Liepājas, Usmas and Ķīšezers have a comparatively shorter ice cover period, the water warms up faster in spring and cools down later in autumn, and annual mean surface water temperature is higher. In this case, the results of our study comply with the results of the studies by Glazacheva (1964, 1965) regarding the regional differences of thermal and ice regimes of the Latvian lakes during the period from the mid-1940s to the 1960s. Unfortunately, the scope of these studies does not cover the long-term changes of surface water temperature and ice regime parameters.

CONCLUSIONS

The long-term time series of the water level from 1926 to 2002, the surface water temperature and ice parameters (date of freezing and break-up, numbers of days with ice cover and annual maximum ice thickness) of seven Latvian lakes from 1945 to 2002 were examined by statistical methods.

Most of the studied lakes are regulated by human activity and this can be seen in the long-term changes of the water level – the level fluctuations are much more smoothed out. Global climate warming at the turn of the century has caused considerable long-term changes in the hydrological regime of the lakes during the last decades. The surface water temperature has increased significantly and the number of days with ice cover and the maximum ice thickness has decreased significantly in most studied cases. An increasing trend in the freezing date and a statistically significant decreasing trend for the ice break-up date were found for all lakes.

This study also indicated regional differences in the hydrological regime of the lakes. The lakes Liepājas, Usma and Ķīšezers are located in the western and central parts where there is a greater impact by meteorological processes occurring over the North Atlantic and the Baltic Sea on the hydrological regime than in other parts of Latvia. Therefore, its hydrological regime, in particular, the thermal and ice regimes, are different from that of the lakes Burtnieks, Rāznas, Sventes and Ludzas which are located in the northern and south-eastern parts of Latvia. The results of the study prove that the lakes Liepājas, Usma and Ķīšezerrs have comparatively higher surface water temperature during the ice-free period and ice forms later, breaks-up earlier and remains for a shorter time period, and ice cover is thinner.

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