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ORIGINAL RESEARCH ARTICLE

Influence of climate change on the ice conditions of the Curonian Lagoon

Darius Jakimavičius*, **Diana Šarauskienė**, **Jūratė Kriaučiūnienė**

Laboratory of Hydrology, Lithuanian Energy Institute, Kaunas, Lithuania

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Summary The Curonian Lagoon is a shallow freshwater lagoon of significant environmental value in the south-eastern part of the Baltic Sea. The objective of the study was to evaluate changes of ice indices (duration, thickness and breakup dates) of this lagoon and to assess their possible tendencies in the 21st century. A methodology was developed combining the assessment of past changes (1960—2017) of ice indices and their projections in the near (2021—2040) and far (2081—2100) future periods using a hydrometeorological database, statistical methods and regression analysis as well as regional climate models and RCP scenarios. Climate change has a considerable impact on ice conditions in the Curonian Lagoon. During the historical period of 1960—2017, the Curonian Lagoon was covered with ice for 72 days a year, ice thickness reached 23 cm, whereas ice breakup was observed in the middle of March on average. According to the different scenarios, in the near and far future periods, ice duration will last 35—45 and 3—34 days, respectively. Ice thickness is projected to be 13—15 cm in the near future, whereas, at the end of the century, it is expected to decline to 0—13 cm. In the past, the lagoon ice cover remained until the middle of the third decade of February. At the end of the 21st century, RCP8.5 scenario projects the most drastic shifts: the permanent ice cover might be absent, whereas short-term ice cover is expected to melt already in the beginning of January.

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* Corresponding author at: Laboratory of Hydrology, Lithuanian Energy Institute, Breslaujos st. 3, LT444003 Kaunas, Lithuania. Tel.: +370 8 37 401901.

E-mail address: darius.jakimavicius@lei.lt (D. Jakimavičius).

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1. Introduction

Sea-ice is considered as one of the most sensitive and obvious indicators of climate change. In nature, the formation and melting of sea-ice are conventional processes, but in recent years, acceleration of their changes is intimidating. It was estimated that the Arctic sea-ice area shrank by $\sim 2 \times 10^6$ km^2 or by 17.5% over the last 40 years (Olonscheck et al., 2019). As sea-ice areas diminish, the albedo of the Earth's surface decreases, therefore less and less sunlight is reflected and more and more of it is absorbed. As a result, the air temperature rises even faster resulting in an even more rapid increase of sea-ice melting (Stroeve et al., 2012).

Ice regime changes are not only accelerating climate change but can lead to various ecological crises, as the ice cover (and the snow layer on it) limits the penetration of light into deeper layers of water bodies as well as the gas exchange between water and atmosphere. The shortening of the ice cover period has a significant impact on the biogeochemical processes and functioning of the aquatic ecosystem (Beall et al., 2016; Lindenschmidt et al., 2018; Woodward et al., 2010). It has been found that the shorter ice duration leads to losses of time required for settling and consolidation of suspended particles into sediments, thereby reducing the extent of re-suspension following ice thaw and thus increasing the concentration of nutrients (Kleeberg et al., 2013).

Global-scale changes are particularly well reflected in the ice regime of water bodies in northern latitudes. It was estimated that 14,800 lakes currently experience intermittent winter ice cover around the Northern Hemisphere and this number will increase by a dozen times at rising air temperatures (Sharma et al., 2019). Significant impacts of future climatic changes on lake ice phenology were identified for northern temperate lakes in the Laurentian Great Lakes region of North America (Hewitt et al., 2018). Alarming shifts in ice extent and timing based on past trends are projected for the Bering and Chukchi Seas (Douglas, 2010). A study of ice seasons in the Baltic Sea during the 20th century also revealed a vulnerability of the ice formation process to the observed climate changes (Jevrejeva et al., 2004). The projections reveal that the Baltic Sea ice will significantly decrease during this century as well (Jylhä et al., 2008; Luomaranta et al., 2014). The Climatological Ice Atlas (Sztobryn and Przygrodzki, 2012) provides detailed information about the western and southern parts of the Baltic Sea in 1961—2010. It shows trends in reducing ice duration and earlier ice breakup dates in the Baltic Sea lagoons and bays. Ice conditions in the largest coastal lagoon of the Baltic Sea — the Curonian Lagoon — are also of great interest and attract attention from research teams (Baukšys, 1978; Rukšėnienė et al., 2015). Baukšys (1978) analysed ice regime data of the Curonian Lagoon in 1948—1972 and estimated that this lagoon froze up at the beginning of December, while ice breakup occurred at the beginning of April. Ice duration continued for 110 days on average, ranging from 12 to 169 days. Rukšėnienė et al. (2015) identified a relation between ice phenomena and air temperature, SST and salinity in the Curonian Lagoon using ice data of 1993—2013. However, no publications can be found that discuss future changes of ice indices of this unique brackish lagoon while using regional climate models and RCP scenarios recommended by the IPCC's Fifth Assessment Report (AR5) for their projections.

The objective of this paper is to evaluate the changes of ice indices of the Curonian Lagoon and to assess their possible tendencies in the 21st century using a hydrometeorological database, regional climate models, RCP scenarios and statistical analysis methods.

2. Material and methods

2.1. Study area

The Curonian Lagoon is a shallow freshwater lagoon in the south-eastern part of the Baltic Sea (Fig. 1). The Nemunas River supplies about 90% of its inflows. The Curonian Lagoon has a significant international environmental value. The Nemunas delta is a regional park and is included in the list of Ramsar Convention sites. The lagoon itself is considered as a very valuable and important bird area preserved by the Bonn Convention. Since 1929, in the Ventė Cape ornithology station based in the headland of the Nemunas delta, about 60—80 thousand birds are ringed each year. The Curonian Lagoon is also well-known for the richness and abundance of its fish species. The Curonian Spit National Park is included in the UNESCO World Heritage List.

The surface area of the lagoon is 1584 km^2 in total. 381.6 km^2 of its northern part belong to Lithuania. The volume of the Curonian Lagoon is 6.2 km^3, the mean depth is 3.8 m, while the maximum depth is 5.8 m (Gailiušis et al., 2001). A 98 km long Curonian Spit separates the lagoon from the Baltic Sea coast. Water exchange with the sea is possible only through the Klaipėda Strait, where the port of Klaipėda is located. Due to the geographic location and local climate conditions, the Curonian Lagoon is ice-covered for an average of 72 days. However, due to intensive shipping, even in severe winters, ice cover in the territory of the Klaipėda port is being broken by vessels entering or leaving the port. The rest of the lagoon usually remains covered with ice, the thickness of which varies between 10 and 70 cm (Baukšys, 1978).

2.2. Methodology and data

A methodology was developed combining the assessment of past changes (1960—2017) of ice indices (ice duration, thickness and breakup date) and their projections in the near (2021—2040) and far (2081—2100) future. Changes in the past were evaluated using statistical analysis methods, whereas projections were carried out according to the created methodology covering two main steps (Fig. 2).

The first step was an assessment of the statistical relationship between the ice indices (ice duration, thickness and breakup date) in the Curonian Lagoon and different hydrometeorological parameters such as air and water temperatures, wind speed and atmospheric circulation indices (NAO, AO, SCAND) (Fig. 2). Data of the reference period of 1986—2005 (recommended by IPCC, 2013). Meteorological

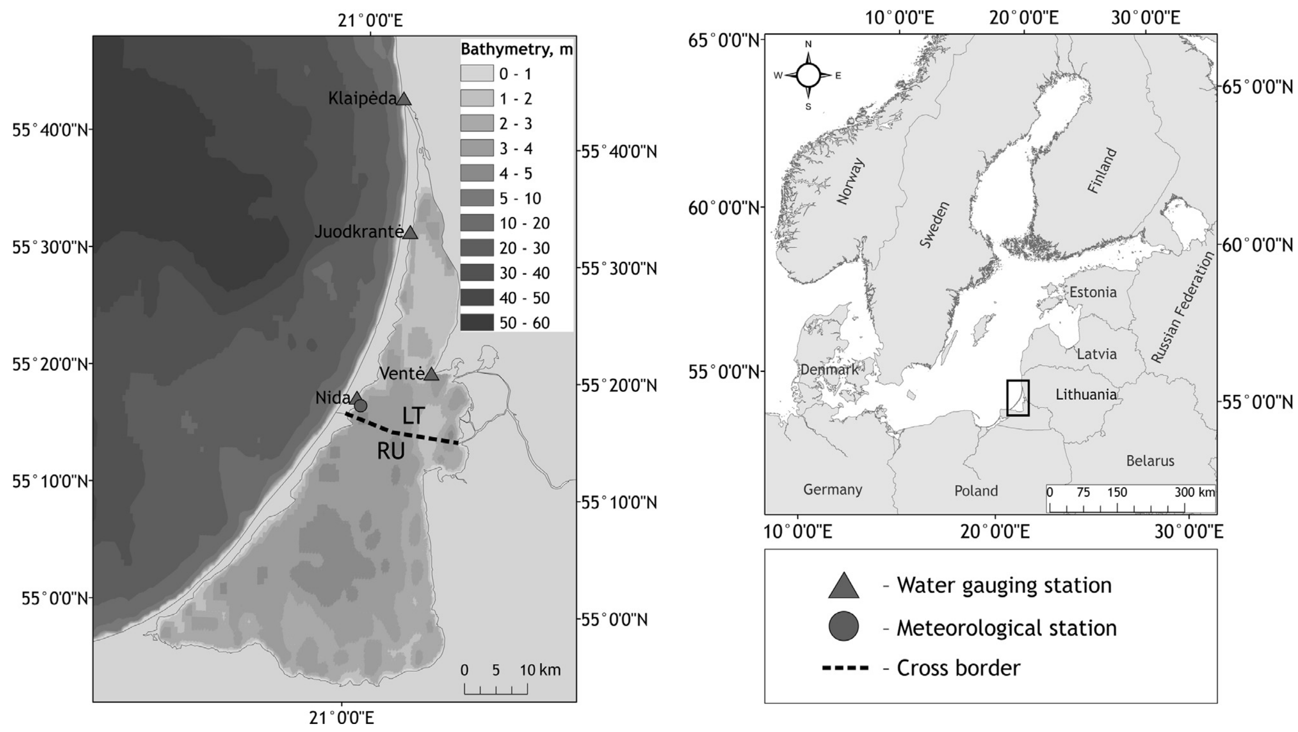

Figure 1 Location of the Curonian Lagoon and monitoring stations (MSs).

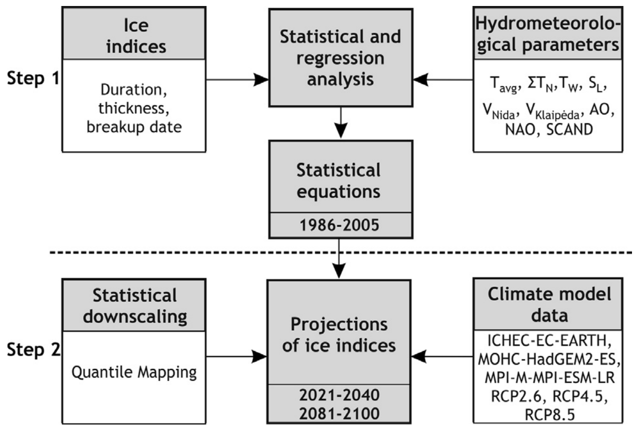

Figure 2 Methodological scheme for projection of ice indices. T_{avg} — mean air temperature in December—February at Nida MS, T_W — water temperature of the winter season in the Curonian Lagoon, ΣT_N — sum of negative air temperatures at Nida MS, V_{Nida} and $V_{Klaipėda}$ — wind speed at Nida and Klaipėda, S_L — salinity of the Curonian Lagoon in winter season, NAO, AO and SCAND — atmospheric circulation indices.

parameters having the most significant impact on ice formation were identified. Statistical relationships (equations) were created between the identified meteorological parameters and the selected ice indices. These equations were intended to be used for projections.

In the second step, in order to make projections of ice indices, future changes of meteorological parameters according to three regional climate models and three scenarios called representative concentration pathways (RCPs) were determined (Fig. 2). RCPs were used to create projections based on various factors, including demographic data, economic activity, lifestyle, energy use, technology and climate policy. They describe four different pathways of greenhouse gas concentration (GHG) emissions and atmospheric concentrations, air pollutant emissions and land use in the 21st century (IPCC, 2013). In this study, the three most common RCPs were applied: RCP2.6, RCP4.5 and RCP8.5. RCP2.6 is representative of scenarios that lead to very low GHG levels: the projected peak in radiative forcing is at about 3 W/m^2 by mid-century and declines to 2.6 W/m^2 by 2100 (van Vuuren et al., 2011). RCP4.5 is considered as a stabilisation scenario in which the total radiative forcing (4.5 W/m^2) is stabilised shortly after 2100, without overshooting the long-run radiative forcing target level (Thomson et al., 2011). RCP8.5 is characterised by rising GHG emissions over time, representative of scenarios that lead to high GHG concentration levels (Riahi et al., 2011). A grid cell of the selected regional models (ICHEC-EC-EARTH (thereafter EARTH, the Norwegian Earth System Model), MOHC-HadGEM2-ES (thereafter HAD, Hadley Centre Global Environmental Model, UK) and MPI-M-MPI-ESM-LR (thereafter MPI, the Max Planck Institute for Meteorology)) is 11 × 11 km (https://www.euro-cordex.net). We used one of the model output statistics methods (MOS) for recalculation of the values from the regional climate model (RCM) cell to the location of the meteorological station. The selected method of Quantile mapping (QM) is suitable not only for statistical downscaling of air temperature but for the data of other meteorological parameters as well (Gudmundsson et al., 2012; Sunyer et al., 2015). The main equation of this method is the following:

$$P_0 = h(P_s) = F_0^{-1}(F_s(P_s)), \tag{1}$$

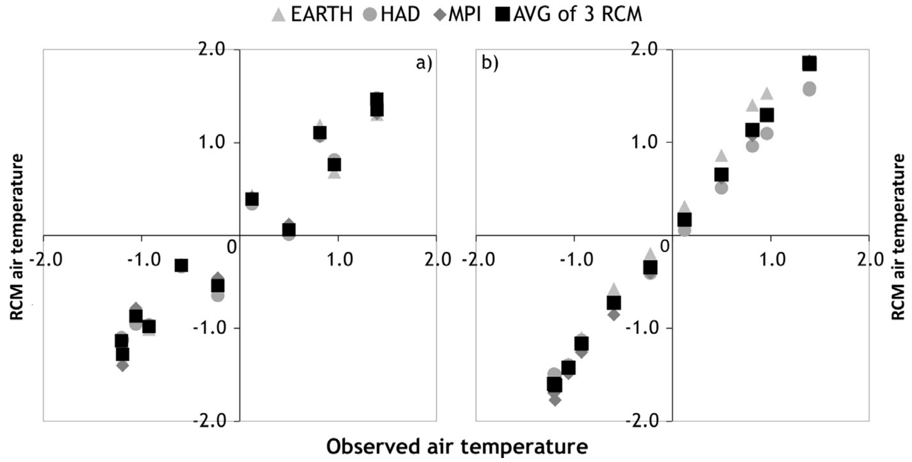

Figure 3 A normal Q—Q plot projections of Nida MS air temperature data in the reference period according to regional climate models without (a) and using (b) Quantile mapping method.

where P_0 — observed meteorological parameter, P_s — meteorological parameter of climate model, F_s — cumulative distribution function (CDF) of P_s, F_0^{-1} — inverse CDF of P_0.

All calculated results are assessed with respect to the reference period (1986—2005).

A specific example of the application of the QM method for air temperature data at Nida MS is provided in Fig. 3. A normal Q—Q plot was prepared comparing average monthly air temperature standard data (y-axis) of regional climate models (RCMs) to a standard observed air temperature data (x-axis) in the reference period (1986—2005). Considerable differences between the observed data and its projections according to RCMs were identified (Fig. 3a). For a more accurate estimate of future changes in air temperature patterns, the reference temperature data should correspond to the climate model projections for the reference period as much as possible. Recalculated air temperature data of the reference period according to the RCMs and using the QM method was almost identical to the observed temperature data at Nida MS (Fig. 3b). Thus it can be concluded that the selected regional climate models and downscaling technique are suitable for air temperature projections and can be used to project ice indices as well.

According to the created statistical equations between ice cover indices and hydrometeorological parameters, projections of ice cover duration, thickness and breakup dates were made using three regional climate scenarios under three RCP scenarios for the near (2021—2040) and far future (2081—2100) periods. The results of the projections were compared with ice indices calculated using the same climate models for the reference period (1986—2005).

Ice data (days with ice (duration), thickness and breakup dates) of 1960—2017 from Klaipėda, Juodkrantė (closed in 2012), Nida, Ventė and Uostadvaris (opened in 2013) water gauging stations (WGS) (Fig. 1) were used for ice regime analysis in the past.

Equations for projections of ice cover indices were created according to air temperature at Nida meteorological station (MS), wind speed at Klaipėda and Nida MS, lagoon water temperature near Nida, water salinity near Juodkrantė and atmospheric circulation indices (NAO, AO, SCAND). Air temperature data of regional climate models EARTH, HAD and MPI according to RCP2.6, RCP4.5 and RCP8.5 scenarios were obtained from the EURO-CORDEX database (https://www.euro-cordex.net). Atmospheric circulation indices were derived from the NOAA database (www.cpc.ncep.noaa.gov).

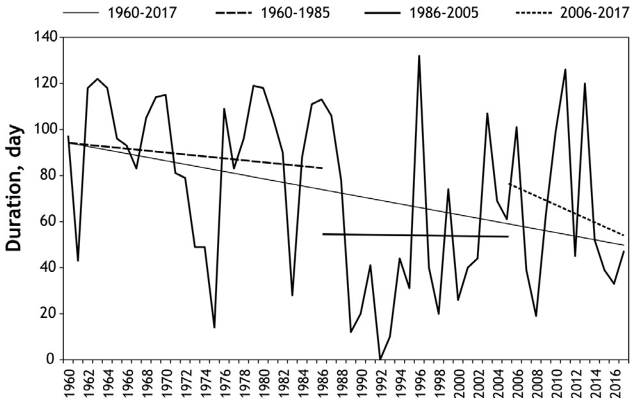

Figure 4 Duration of the Curonian Lagoon ice cover in 1960—2017.

3. Results

3.1. Ice conditions in the historical period

The analysis of mean annual ice indices (duration, thickness and breakup dates) according to data of Klaipėda, Juodkrantė, Nida and Ventė WGS identified change patterns and trends of these indices in the historical period of 1960—2017 (Fig. 4—6).

The Curonian Lagoon is covered with ice for 72 days a year, on average. The duration of ice cover in different years varied from 10 (1993) to 132 days (1996). The relations between the mentioned ice data and the mean winter temperature (T_{winter}) of Nida MS were determined. Permanent ice cover may not form at all if T_{winter} is above 2.4°C (as in

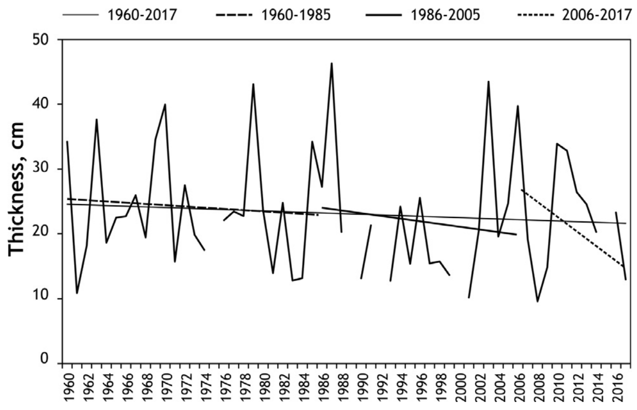

Figure 5 The mean thickness of the Curonian Lagoon ice in 1960—2017.

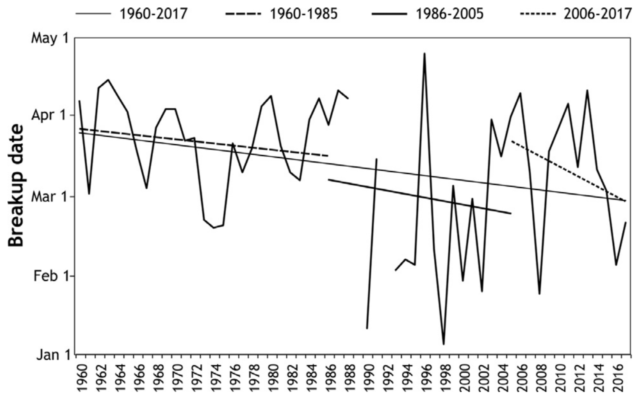

Figure 6 Ice breakup dates in the Curonian Lagoon in 1960—2017.

1992). The permanent ice cover lasts up to 20 days when 1°C $<T_{winter} < 2.4$°C, 20—60 days — when -1.3°C $<T_{winter} < 1$°C, 60—100 days — when -3.6°C $<T_{winter} < -1.3$°C and the lagoon ice cover remains for 100—140 days if T_{winter} decreases down to -3.6°C.

Figure 4 reveals a steady decline in ice duration in the historical period. In 1960—2017, permanent ice of the Curonian Lagoon decreased by 0.8 day/yr. However, the decrease rate was different in separate periods: in 1986—2005 (during the reference period used for projections) it changed only slightly, while in 1960—1985 (before the reference period) it declined to 0.4 day/yr. In 2006—2017 (after the reference period) it fell to 1.9 days/yr.

Ice thickness is another critical index which was analysed over the historical period. Strong variation of the annual ice thickness of the Curonian Lagoon is presented in Figure 5. In certain years with cold winters, the mean thickness of ice cover exceeded 40 cm (in 1979, 1987 and 2003). However, in the case of warm winters, the constant ice cover did not form or was too thin to allow safe measurements (1975, 1989, 1992, 2000, and 2015). The detected trends revealed an unsubstantial but steady decline of the analysed index. Over the entire period of 1960—2017, ice thickness decreased by 3 cm. Until 1986, the average thickness of ice decreased by 0.1 cm/yr. It decreased by 0.2 cm/yr during the reference period and by 1.0 cm/yr since 2006.

The last analysed ice index of the Curonian Lagoon was the ice breakup date (Fig. 6). During the entire observation period, the earliest date of the ice breakup was in the first decade of January, while the latest date was in the last decade of April. A significant negative trend in ice breakup dates was identified (Fig. 6). At the beginning of the observation period, on average, the Curonian Lagoon ice broke up in the third decade of March, while at the end of this period it broke up in the third decade of February. Therefore, the records reveal that ice breakup has advanced by one month (every second year it is reduced by one day). Over the observation period, ice broke up earlier in a different speed: until 1986, this process started earlier by 0.2 day/yr, during the reference period — by 0.6 day/yr and since 2006 — by 1.9 days/yr.

The data showcased in Figures 4—6 revealed that in the period of 2006—2017, considerable tendencies of decreasing ice duration and thickness as well as the earlier beginning of ice breakup process in the Curonian Lagoon were being observed.

3.2. Evaluation of hydrometeorological parameters with the greatest impact on ice formation

Local hydrometeorological conditions (air and water temperatures and wind speed) and atmospheric circulation indices (NAO, AO, SCAND) determine ice indices (its duration, thickness and breakup date). Hydrometeorological parameters having the greatest impact on ice formation in the Curonian Lagoon were identified applying correlation analysis. The estimated correlation coefficients are provided in Table 1.

Mean air temperature in December—February at Nida MS (T_{avg}), sum of negative air temperatures at Nida MS (ΣT_N) and water temperature of the winter season in the Curonian Lagoon (T_W) were identified as best correlating with ice indices. A very weak correlation existed between ice indices and atmospheric circulation indices. The rest of the studied parameters (wind speed (V_{Nida}, $V_{Klaipėda}$) and salinity (S_L) in winter season) did not show a significant relationship.

Therefore, T_{avg}, ΣT_N and T_W were used for further analysis. Equations describing the dependence of ice indices on the selected hydrometeorological parameters were developed using polynomial regression analysis (Eqs. 2—4):

$$D = -0.0003\Sigma T_N^2 + 0.3701\Sigma T_N - 5.0079, \tag{2}$$

$$T = -0.00001\Sigma T_N^2 + 0.0479\Sigma T_N + 9.9040, \tag{3}$$

$$B = -0.0003\Sigma T_N^2 + 0.3797\Sigma T_N + 9.0662, \tag{4}$$

where D — ice duration, days, T — average thickness of ice cover, cm, B — date of complete ice breakup, days, ΣT_N — the sum of negative air temperatures at Nida from December to April, °C.

Correlation coefficients between the observed ice indices and those calculated according to equations varied from 0.89 to 0.94. This indicates that the created equations are suitable to project future changes of ice indices. These developed equations were based on statistical relations between the sum of negative air temperatures and ice indices

Table 1 Linear correlation coefficients between ice indices and hydrometeorological parameters.

Ice indices	Hydrometeorological parameters								
	T_{avg}	T_W	ΣT_N	V_{Nida}	$V_{Klaipėda}$	S_L	NAO	AO	SCAND
Duration	−0.93	−0.71	−0.91	0.09	−0.10	−0.20	−0.24	−0.48	0.28
Thickness	−0.83	−0.46	−0.90	0.20	0.04	0.12	−0.02	−0.24	−0.07
Breakup date	−0.93	−0.55	−0.91	0.13	−0.11	−0.22	−0.25	−0.49	0.25

where T_{avg} — mean air temperature in December—February at Nida MS, T_W — water temperature of the winter season in the Curonian Lagoon, ΣT_N — sum of negative air temperatures at Nida MS, V_{Nida} and $V_{Klaipėda}$ — wind speed at Nida and Klaipėda, S_L — salinity of the Curonian Lagoon in winter season, NAO, AO and SCAND — atmospheric circulation indices.

of the period of 1986—2005. They can be applied only if $\Sigma T_N \leq -60°C$. Otherwise, if $\Sigma T_N > -60°C$, it is assumed that a permanent ice cover is absent.

3.3. Ice conditions in the near and far future

Projections of ice indices in the Curonian Lagoon for the near (2021—2040) and far future (2081—2100) periods were assessed as the mean of three regional climate models (RCMs) according to a different RCP. The results were compared with the values of ice indices calculated using the same RCMs for the historical period (1986—2005). The findings revealed that in both future periods the ice regime in the lagoon is going to change significantly. In the near future, these changes will be negligible, whereas. at the end of the century (especially according to RCP8.5), ice phenology and thickness are expected to change substantially (Fig. 7).

According to the data of RCMs, ice duration on the Curonian Lagoon during the winter season is on average 55 days in the reference period. This number can vary from 17 to 87 days in different years depending on climate conditions (i.e. air temperature). The analysis of future projections shows that the dispersal of values of ice indices in the range of 25—75% quartiles decreases when climate scenarios get extreme (Fig. 7a), but the gap between the extreme values and the mean increases. According to the scenarios, ice duration will last from 35 to 45 days on average in the near future, while only lasting for 3—34 days in the far future (Fig. 7a).

According to the data of RCMs, the mean ice thickness of the lagoon varied from 9 to 27 cm (19 cm on average) in the reference period (Fig. 7b). No drastic trends in ice thinning were identified for the near future period: ice thickness is projected to be 13—15 cm depending on the used scenario (Fig. 7b). However, in case of the most extreme RCP8.5 scenario, in the far future ice cover will form only once every five years and its thickness will reach 4—11 cm. At the end of the century, ice thickness is expected to be 13 cm and 9 cm according to RCP2.6 and RCP4.5 scenarios respectively. This index is projected to decline by 32% and 53% according to RCP2.6 and RCP4.5 scenarios respectively relative to the reference period.

The index of ice phenology in the Curonian Lagoon was its breakup date. During the reference period, the lagoon ice cover remained until the middle of the third decade of February. However, the statistical relationship between ice breakup dates and the sum of negative air temperatures as well as the regional climatic data revealed that this date advanced both in the near and far future (Fig. 7c). During the first period, in case of RCP2.6 scenario, the breakup will be observed in the middle of the second decade of February, while according to the most pessimistic scenario it will occur at the end of the first decade of this month (i.e. by 8 days later). In the far future period, the breakup will advance even more: it might begin in the first days of February (according to RCP2.6) or even at the end of the third decade of January (according to RCP4.5). RCP8.5 scenario projects

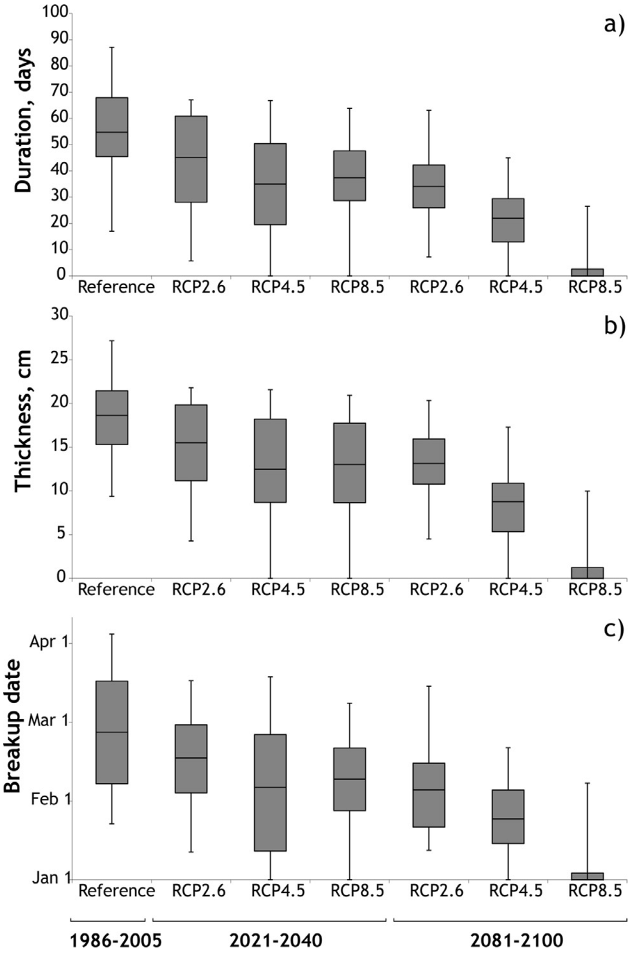

Figure 7 Ice indices in the near (2021—2040) and far future (2081—2100) relative to the reference period: a) duration, b) thickness, c) breakup date.

the most drastic shifts: at the end of the 21st century, the long-term ice cover might be absent, whereas short-term ice cover is expected to melt at the beginning of January.

4. Discussion

The present study was intended to assess the impact of climate change on ice conditions of the Baltic Sea's Curonian Lagoon. Many authors confirm that climatic factors (such as air temperature, wind speed, etc.) have the greatest influence on the sea-ice regime (Baukšys, 1978; Kļaviņš et al., 2016; Stroeve et al., 2012; Sztobryn et al., 2012). As it was expected, the results showed an obvious influence of rising air temperatures on the lagoon ice regime both in the past and future, i.e. ice duration and thickness will continue to decrease, while ice breakup is expected to begin earlier.

Other studies and observation data show that lagoons of the Baltic Sea have different ice regimes, although they are located in similar geographical and climate conditions. According to the Climatological Ice Atlas (Sztobryn and Przygrodzki, 2012), in 1961—2010, in the southern part of the Baltic Sea, the average number of days with ice in the Vistula Lagoon was 83 days, while in the western and eastern parts of the Szczecin Lagoon it was 60 and 61 respectively. A recent study by Chubarenko et al. (2019) generalised the data of the Vistula Lagoon from 1946 and confirmed a decreasing trend of the number of days with ice coverage. According to Dailidienė et al. (2012), the duration of the ice season in the Baltic Sea itself (at Nida) decreased by 50% during the period of 1961—2005 due to continuously warming winters and today the duration of ice season is approximately one month. Further north, in the Gulf of Riga, which has a direct connection with the Baltic Sea, the estimated average number of days with ice cover for the period of 1949—2013 was 64 (at Salacgriva) (Kļaviņš et al., 2016). The authors of the current study estimated that according to the data of 1960—2017, the Curonian Lagoon is covered with ice for 72 days per year on average; this number varies from 10 to 132 days and is in line with the mentioned findings.

The estimated rate of decrease of ice duration in the Curonian Lagoon was 2.0 days/10 years over the observation period (1960—2017) and was similar to the ones estimated in the Szczecin Lagoon (in 1889—1995) (Kozuchowski and Girjatowicz, 1997), the Gulf of Riga (in 1949—2013) (Kļaviņš et al., 2016) and the Vistula Lagoon (in 1961—2010) (Sztobryn and Przygrodzki, 2012): 2.6, 2.7 and 3.2 days/10 years respectively.

Due to climate change, ice cover breakup dates in the Baltic Sea and its lagoons are getting earlier as well. It was estimated that in the Gulf of Riga ice disappears earlier by 5.2 days/10 years (1949—2012) (Kļaviņš et al., 2016), while in the lagoons of Vistula and Szczecin ice melts earlier by 3.7 and 3.6 days/10 years (1961—2010) respectively (Sztobryn and Przygrodzki, 2012). According to the current study, ice on the Curonian Lagoon breaks up 4.4 days earlier every 10 years.

According to Jevrejeva et al. (2004), 100 year-long time series of ice data from the coastal observation stations in the Baltic Sea provide evidence of a general trend toward easier ice conditions; the largest change is in the length of the ice season, which is decreasing by 14—44 days per century. The trends of a reduction of about 8—20 days per century to the earliest ice breakup detected in this study are in agreement with a warming trend in the winter air temperature over Europe. Other studies by Tarand and Nordli (2001) and Jaagus (2006) in Finland, by Jevrejeva (2001) in Latvia and by Sztobryn (1994) in Poland are also in accord with the current study, indicating negative trends in the ice cover duration and thickness in the Baltic Sea coastal waters.

Ice regime changes are recorded not only in the Baltic Sea and its lagoons but also in other lagoons and lakes of the world. A similar pattern of results was obtained by Shirasawa et al. (1994) in the Saroma Lagoon (Hokkaidō, Japan), where the estimated average duration of ice cover of 110 days in 1963—1978 declined to 72 days in 1979—1992. In Canada, in the period of 1951—2000, trends toward earlier ice breakup dates were detected for many lakes during the latter part of the 20th century (Brown and Duguay, 2010; Duguay et al., 2006; Latifovic and Pouliot, 2007). Long-term records of winter ice duration, formation, and breakup dates (1869—1996) and maximum thickness (1950—1995) on the World's deepest Lake Baikal revealed highly significant trends of decreasing ice duration and thickness over the period, associated with later ice formation and earlier breakup dates, and these trends are broadly in line with those of winter air temperatures in the region (Todd and Mackay, 2003).

Ice regime changes are related to the water body thermal regime, which in turn has a major role in the water ecosystem and its biochemical processes. Due to climate change, expected changes in ice conditions are going to have considerable consequences for aquatic systems, which is the reason why the projection of these negative effects is of great importance. Therefore, investigation of the ice regime of large water bodies should also encompass projections of its changes using climate models based on different future scenarios. However, while reviewing the available literature, no such scientific studies were found about the projection of ice indices in the Curonian Lagoon or other lagoons of the Baltic Sea. Projections based on simulations produced with seven regional climate models under two greenhouse gas emissions scenarios (A2 and B2) for the period of 2071—2100 made by Jylhä et al. (2008) showed a drastic decrease of ice in the Baltic Sea. A similar investigation which used climate models and emission scenarios recommended by the IPCC's Fourth Assessment Report (AR4) (2007) was carried out for Lake Ontario (Canada) (Minns et al., 2014). It was found that in the middle of the 21st century, lake ice will break up 7—8 days earlier relative to the reference period. The duration of the ice cover on Lake Ontario will reduce from 14 (according to the mildest scenario) to 17 days (according to the most drastic scenario), while the maximum ice cover thickness will decrease from 7.5 to 9.0% compared to the reference period (Minns et al., 2014). Luomaranta et al. (2014) estimated future changes in the Baltic Sea ice indices under the RCP4.5 and RCP8.5 scenarios based on temperature responses produced by 28 CMIP5 GCMs. According to both studied RCP scenarios, the annual maximum ice extent was found to decrease markedly. As expected, the decline in mean maximum sea ice thickness in coastal areas is faster in the RCP8.5 scenario than in the RCP4.5 scenario. According to RCP8.5, in a conventional winter of the 2080s, sea ice would only occur in the Bay of Bothnia, with a maximum ice thickness of 30—40 cm, and in the north-eastern parts of the Gulf of Finland, with an ice thickness of 0—10 cm. Consistent with the available literature, the current research identified similar tendencies of ice regime changes due to climate change in the future. Projections showed that in the near future, ice duration will reduce to 35—45 days in the Curonian Lagoon, while in the far future, it will last only for 3—34 days. Significant shifts in ice thickness were identified only in the second future period, when changes projected under the RCP8.5 scenario may even lead to ice loss. Ice breakup will advance almost by a month according to the extreme scenario relative to the reference period.

Tendencies of changes of ice indices are similar in the Curonian Lagoon and the mentioned water bodies around the World. The intensity of changes of ice indices depends on morphometric characteristics of water bodies (such as volume, surface area, and depth) as well as local geographical—climatic conditions.

5. Conclusions

Climate change has a considerable impact on ice conditions of the investigated Curonian Lagoon as it was well demonstrated using both historical data and the future projections. During the historical period of 1960—2017, the Curonian Lagoon was covered with ice on average for 72 days a year, permanent ice cover decreased by 0.8 day/yr, ice thickness declined by 3 cm, whereas ice breakup has advanced by one month.

According to different scenarios, in the near future (2021—2040), ice duration will last 35—45 days, while in the far future (2081—2100), it will remain only for 3—34 days. In the reference period of 1986—2005, ice duration was 55 days on average.

In the near future, ice thickness is projected to be 13—15 cm, whereas at the end of the century, it is expected to decline to 13 (under RCP2.6) or even 9 (under RCP4.5) cm. While during the reference period, the mean ice thickness of the lagoon was 21 cm.

The lagoon ice cover remained until the middle of the third decade of February; this date will advance both in the near and far future. RCP8.5 scenario projects the most drastic shifts: at the end of the 21st century, the long-term ice cover might be absent, whereas short-term ice cover is expected to melt at the beginning of January.

Similar trends of changes of ice indices are expected to occur in other unexplored water bodies since the identified changes are closely in line with the described studies. Future research should further develop and confirm these initial findings by using numerical ice sheet models and the newest climate scenarios data.

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