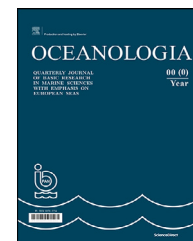




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ORIGINAL RESEARCH ARTICLE

Study of ice cover impact on hydrodynamic processes in the Curonian Lagoon through numerical modeling

Rasa Idzelytė^{a,*}, Jovita Mėžinė^a, Petras Zemlys^a, Georg Umgiesser^{b,a}

^a Marine Research Institute, Klaipėda University, Klaipėda, Lithuania

^b CNR – National Research Council of Italy, ISMAR – Institute of Marine Sciences, Venice, Italy

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Summary In this study, we present an analysis of the hydrodynamic processes under ice cover in the largest lagoon in Europe – the Curonian Lagoon. By applying a finite element numerical modelling system (SHYFEM) and remote sensing ice cover data, the residual circulation, water fluxes through specific areas of the lagoon, saltwater intrusions, and water residence time (WRT) were investigated. The results, taken over an 11 year period, show that ice cover affects the circulation patterns in the lagoon by forming and shifting different gyre systems. Different circulation patterns are observed throughout all the meteorological seasons of the year. Since ice decreases circulation, water fluxes also decrease, especially in a cross-section in the middle of the lagoon, where the ice-cover suppressed wind-stress has a higher impact on the water movement rather than it has in the north. The presence of ice cover also decreases the salinity of the water in the northern part of the lagoon. In general, the salinity in the water column averaged over different periods is vertically uniform, however, a slight increase of salt concentration can be observed at the bottom layers in the Klaipėda Strait, where the difference of > 1 PSU between bottom and top layers shows up on average 130 hours per year. The ice cover also decreases the saltwater intrusions into the lagoon by nearly 14 days per year. The increase of WRT is most prominent after long ice cover periods, away from the river inlets, especially

* Corresponding author at: Marine Research Institute, Klaipėda University, Universiteto ave. 17, 92294, Klaipėda, Lithuania.

E-mail address: rasa.idzelyte@apc.ku.lt (R. Idzelytė).

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in the southern part of the lagoon, where without the help of the wind action, water takes a longer time to renew than in the northern part.

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1. Introduction

Changing ice cover conditions have a strong impact on the hydrodynamics, exchange processes, and overall ecosystem of the water body, including the fisheries and tourism sector. Ice cover formation is controlled by variations in heat exchange and mixing, as well as the heat storage capacity of the water body (Bengtsson, 2012). The initial ice formation can be rather complex with many freezing and break-up events depending on the strength of the heat loss and wind stress at the water surface.

Ice cover affects a water body in several ways. It suppresses the direct wind stress to the water surface and significantly alters the circulation and mixing (Wang et al., 2010). The movement of the water is highly regulated by thermal processes and by the vertical motion of the ice cover (Bengtsson, 2012). Convective mixing is induced when there is enough light penetrating through the ice and by heat exchange with the sediments. The latter is a very slow process capable to last throughout the whole winter (Bengtsson, 1996). Inflowing water from the rivers induce circulation near the inlets, thus it may only have a local effect on the overall circulation (Cushman-Roisin, 2019).

Freshwater bodies connected to the sea by a strait, such as the Curonian Lagoon, are prone to saltwater intrusions (Müller et al., 2018; Zemlys et al., 2013, and references therein). Although it is a natural process, it can likewise be induced by human activity, e.g., dredging in the strait area (Yuan and Zhu, 2015). This process not only alters the ecosystem of the freshwater environment (Cañedo-Argüelles et al., 2019), but also affects the freezing and melting of the ice (Idzelytė et al., 2019). It can be an increasingly more serious issue due to the climate change with increasing air and water temperatures (Jakimavičius et al., 2018; Wolanski et al., 2019), rising sea level (Carrasco et al., 2016), and the escalating number of extreme weather events (Janković and Schultz, 2017; Ummenhofer and Meehl, 2017).

Lagoons are influenced not only by salty marine water but also by freshwater input from the rivers. The average time a water parcel stays in a domain before leaving it is called water residence time (Ambrosetti et al., 2003). Ice highly affects the ability of the water to be renewed by fresh water from the river inlets, thus its residence time tends to increase, affecting the water chemical composition (Vincent, 2009), and thus affecting the time and intensity of algal blooms in early spring (Nguyen et al., 2017; Twiss et al., 2014).

Ice cover not only alters the physical properties of the water body, but it also has ecological repercussions. The magnitude of solar radiation entering the water body is highly diminished by ice and snow cover on top of it. This

way, lowered temperature affects all the chemical and biological processes (Hampton et al., 2017; Wotton, 1995). In general, light provides radiation for primary production and in particularly productive water bodies, the limited light penetration causes dissolved oxygen depletion due to increased respiration of aquatic organisms and microbial decomposition (Vincent, 2009). The addition of the oxygenated water and transfer of oxygen from the atmosphere replenish its levels in the water column. Water motion is primarily responsible for reaeration. When the ice cover blocks the wind stress, there is no motion on the surface, thus oxygenated water can only come from the water inflow areas.

As the climate is changing, leading to increased temperatures, the ice cover season duration is shortening in the Curonian Lagoon (Dailidiene, 2007; Idzelytė et al., 2019). This may lead to the increased coastal erosion, because ice on the coast is a natural breakwater, protecting the shore from winter storms, and preventing the deflation of the sand (Jarmalavičius, 2007). On the other hand, when the ice breaks up and starts drifting, ice heap has a great impact on abrasion of the shoreline, which depends on the mass of the ice, direction and speed of the wind, and water currents. The ice drift affects water level fluctuations in the lagoon by damming the rivers, thus significantly increasing flooded land areas and partially or sometimes even completely changing the riverbed. In the north of the Curonian Lagoon floe clutters cause an increase of the overall water level, reducing the outflow to the sea. Moreover, the lagoon would have much higher suspended sediment concentrations in the water column if the ice cover would not be present during the winter season (Mėžinė et al., 2019).

The circulation patterns, saline water intrusions, and water residence time (WRT) in the Curonian Lagoon have been of high study interest. Ferrarin et al. (2008) showed that the main forcing affecting the circulation patterns in the northern part of the lagoon is the Nemunas River discharge and in the southern part, it is largely driven by wind forcing. The study by Zemlys et al. (2013) revealed that saline water intrusions from the Baltic Sea through the Klaipėda Strait into the lagoon are gradually decreasing and become negligible at a 20 km distance to the south of Kiaulės Nugara Island. Additionally, the results showed that the model performance during the winter season was worse, presumably because ice cover was not included in that model set up. This was improved by Umgiesser et al. (2016), producing better results by using the interpolated data of ice observations from four ground stations. Their study of water renewal time demonstrated that, overall, it is changing only slightly, although a notable increase in WRT is observed during long winters. The above-mentioned study used in situ ice observations from a limited number of

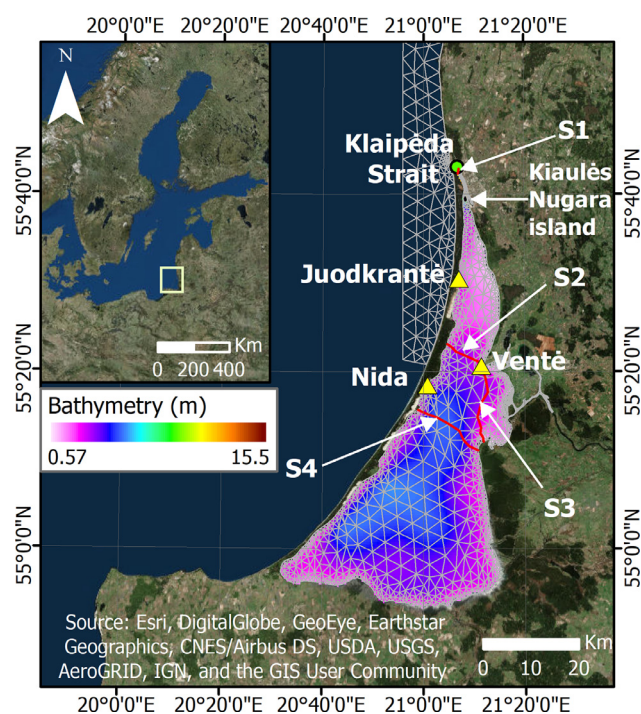


Figure 1 Location of the Curonian Lagoon with respect to the Baltic Sea. The irregular triangular network represents the computational grid, colors throughout the domain indicate the bathymetry of the lagoon, yellow triangles denote ice cover observation stations, the green circle shows a point in Klaipėda Strait for the salinity analysis, and red lines indicate cross-sections for the computation of the fluxes in the Klaipėda Strait (S1), North of Nemunas (S2), Nemunas Delta (S3), and at Lithuanian-Russian border (S4).

stations in the northern part of the lagoon, which were shown by Idzelytė et al. (2019) to not truly represent the real ice cover dynamics in the Curonian Lagoon. Furthermore, only 4 years of ice cover data were available.

With a complete set of ice data for 11 winters, it is now possible to carry out a much more complete study of the ice impact on the hydrodynamic process occurring in the Curonian Lagoon. Therefore, the aim of this paper is to analyze the ice cover effect on the circulation, water exchange capabilities, saltwater intrusions, and water residence time for the period of 2004–2015 using remote sensing ice cover data in the numerical model SHYFEM, simulating the hydrodynamics of the Curonian Lagoon.

2. Material and methods

2.1. Study site

The Curonian Lagoon is located in the southeastern corner of the Baltic Sea (between 54.9°N and 55.9°N) separated from it by a sandy spit, called Curonian Spit and connected to it by the narrow Klaipėda Strait (Figure 1). By occupying an area of around 1584 km² (volume 6.3 km³) (Žaromskis, 1996), it is the largest coastal lagoon in Europe with the northern part belonging to Lithuania, and the larger south-

ern part – to Russia. The Curonian Lagoon is a shallow water body having a mean depth of roughly 3.8 m, the maximum natural depth of 5.8 m in the southern part of the lagoon (Gasiūnaitė et al., 2008) and dredged areas in the Klaipėda Strait up to 15.5 m deep. The southern part is characterized by being freshwater, which is due to the river discharge into the lagoon of approximately 21.8 km³ yr⁻¹, mainly supplied by the Nemunas River (Dailidienė and Davulienė, 2008; Jakimavičius, 2012). River water is the main water renewal source, especially in the northern part of the lagoon (Umgiesser et al., 2016); however, this area is characterized by a higher salinity due to the Baltic Sea water intrusions, which are determined by the water level difference of the Baltic Sea and the Curonian Lagoon. Saline water inflows along the western shoreline where the influence of Nemunas discharge is weaker (Zemlys et al., 2013). The variability of circulation patterns depends mainly on seasonal changes in hydrographic forcing and on the dominant wind regimes (Umgiesser et al., 2016). The latter are responsible also for the internal mixing and redistribution of the water masses.

Every year the Curonian Lagoon is covered by ice, however, the duration of the ice cover season is displaying a tendency to decrease with the lagoon becoming ice-free sooner. The variability of the ice cover extent throughout the season highly depends on the air temperature. If it is very low for a longer period, then a thick ice cover is able to form, which is capable to withstand positive air temperature events. However, if the negative air temperature is not very low or unstable throughout the ice season, a lot of break-up and refreezing can occur. Historical ice observation data (Baušys, 1978) show that a 10–70 cm ice thickness used to form in the lagoon, but it is steadily decreasing and is projected to be 13–15 cm or thinner by the end of the century due to the climate change (Jakimavičius et al., 2019). There is a significant trend in the final melt onset dates, denoting that ice is starting to melt sooner. Firstly, ice starts breaking in the northern part of the lagoon due to the turbid nature of this area – inflowing saline Baltic Sea water and outflow from the Nemunas River. The southern more limnic part of the lagoon is covered by ice longer than in other areas and melting there is affected more by higher temperatures and wind. Typically, ice cover starts to retreat from the western shoreline to the eastern part of the lagoon due to the prevailing westerly winds during wintertime (Idzelytė et al., 2019).

2.2. Data

For the ice cover data, we used Synthetic Aperture Radar (SAR) images received from three remote sensing missions: Envisat ASAR, RADARSAT-2, and Sentinel-1A and 1B, as well as data from spectroradiometer MODIS. Overall, 11 winter periods from 2004 to 2015 were analyzed and a total of 511 images were processed, with a frequency of 2–5 images per week. The ice polygons were manually digitized from satellite images using ArcGIS software (more about data processing techniques and results see Idzelytė et al., 2019), converted to points in the numerical model grid, and interpolated to fill in the gaps between the dates of received satellite images. The satellite data were validated with ground observations taken once per day in three coastal stations in Juodkrantė, Nida, and Ventė. Ice observation data

was provided by the Marine Research Department of the Environment Protection Agency of Lithuania. Both datasets (satellite images and ground observations) agree quite well, giving a correlation coefficient of 0.92. Some inconsistencies arise in defining the freeze onset in the lagoon, due to the temporal resolution of satellite images being not high enough to capture the fast ice formation. Nonetheless, during the melting period when ice is drifting and break-up occurs far away from the coastal stations, it is firstly detected in satellite images, likewise, the last observation of ice in the lagoon. Therefore, in most cases, satellite data are superior with respect to in situ observations for defining the key stages of ice cover formation and decay.

There are five open boundaries defined in the study domain – one for the Baltic Sea, and other four for the discharging rivers: Nemunas, Miniija, Matrosovka, and Deima. Salinity, temperature and water level data at the open sea boundary for the period of 2004–2006 were obtained from the forecasts of operational hydrodynamic model MIKE21 provided by the Danish Hydraulic Institute, for the period of 2007–2009 and 2014–2016 from forecasts of the operational hydrodynamic model HIROMB (High Resolution Operational Model for the Baltic Sea) provided by the Swedish Meteorological and Hydrological Institute, and for the period of 2010–2013 from the forecasts of MOM (Modular Ocean Model) provided by Leibniz Institute for Baltic Sea Research in Warnemünde, Germany. Lithuanian Hydrometeorological Service (LHS) under the Ministry of Environment provided the daily river discharge data.

Meteorological forcings for the period of 2009–2010 were obtained from the forecasts of operational numerical weather prediction model HIRLAM (High Resolution Limited Area Model) provided by LHS, and for the rest of the years data obtained from ECMWF (European Centre for Medium-Range Weather Forecasts) were used.

2.3. Hydrodynamic model

The open source hydrodynamic finite element model for shallow water bodies SHYFEM was used to simulate ice cover effect on circulation, saltwater intrusions from the Baltic Sea, water residence time in the lagoon, and mass fluxes through sections shown in [Figure 1](#). The model was developed at ISMAR-CNR (Institute of Marine Sciences – National Research Council, <http://www.ismar.cnr.it/shyfem>) and has been already successfully applied for studying hydrodynamic processes of numerous lagoons in Europe ([De Pascalis et al., 2011](#); [Ferrarin et al., 2010a, 2010b, 2013](#); [Molinari et al., 2014](#)), as well as the Curonian lagoon for which the calibration and validation of the model was done ([Ertürk et al., 2015](#); [Ferrarin et al., 2008](#); [Zemlys et al., 2008, 2013](#)). The results obtained by [Umgiesser et al. \(2016\)](#) showed that the model with a simple ice module gave much better results compared to the reference (ice-free) simulation.

SHYFEM consists of several modules: hydrodynamic, transport and diffusion, sediment transport, wave, and an ecological module. It is based on an unstructured grid, which makes it suitable for application to lagoons, coastal seas, estuaries, and lakes with complicated geometry and bathymetry. This model is able to provide 2D as well as 3D simulations; for this study we used a 3D set-up. The

equations are integrated in time using a semi-implicit discretization scheme and spatial discretization is achieved using a partially modified finite element method. For salinity and temperature computations, a transport diffusion model is used that takes into account the heat fluxes from the atmosphere and input from rivers. The water residence time computation is done by transforming the near exponential decay of a conservative tracer with a logarithm application to a straight line that then can be used for estimating the WRT through linear regression ([Cucco and Umgiesser, 2006](#)).

The ice cover data in the model is represented by a number with values between 0 and 1, where marginal value 0 denotes the absence of ice and value 1 denotes water surface completely covered by ice. The presence of ice was accounted for in the model by weighting the wind drag coefficient by the fractional ice value. This is done to scale the momentum input through the surface by the area free of ice. For the areas having ice concentration equivalent to 1, the momentum transfer to the sea is completely suppressed. This study does not consider ice-ocean stress ([Umgiesser et al., 2016](#)). More explanation about the model and its equations can be found in [Bellafiore and Umgiesser \(2010\)](#), [Ferrarin et al. \(2017\)](#), [Maicu et al. \(2018\)](#), and [Umgiesser et al. \(2004\)](#).

2.4. Modelling set up and scenarios

The computational grid of the study area consists of 1309 nodes and 2027 triangular elements ([Figure 1](#)). The resolution is much finer in the Klaipėda Strait. For the vertical discretization, 10 sigma layers have been used. A part of the Baltic Sea in front of the lagoon is also included into the numerical grid, preventing the disturbances for computations of the exchanges through the Klaipėda Strait area. The Baltic Sea and Klaipėda Strait were considered ice-free for all simulations since naturally there is no landlocked ice due to intensive shipping, higher depths, and inflowing warmer water from the Baltic Sea.

Three types of simulations have been carried out: 1) ice cover artificially switched off in the model (hereafter no-ice); 2) with ice cover data obtained from the satellite observations (hereafter real ice); 3) an additional set of simulation run where the lagoon is completely covered by ice during the ice cover season, including the Klaipėda Strait area (hereafter idealized ice). The comparison of the ice and idealized ice season simulations allows a better understanding of the role of ice cover in the hydrodynamic processes in the Curonian Lagoon.

The simulation period was from 2004-01-01 to 2015-12-31. Only 11 years were analyzed as the simulation of the year 2004 was used for the model spin-up. For the analysis of ice cover impact on the velocity and direction of the water currents, water fluxes, salinity, and water residence time, the simulation results were averaged over the meteorological seasons of the year: winter (December, January, February), spring (March, April, May), summer (June, July, August), and autumn (September, October, November), as well as over the ice cover seasons, each of them having different durations (different beginning and ending dates of the ice season).

The average differences of simulation results obtained with ice switched on and switched off in the model (real

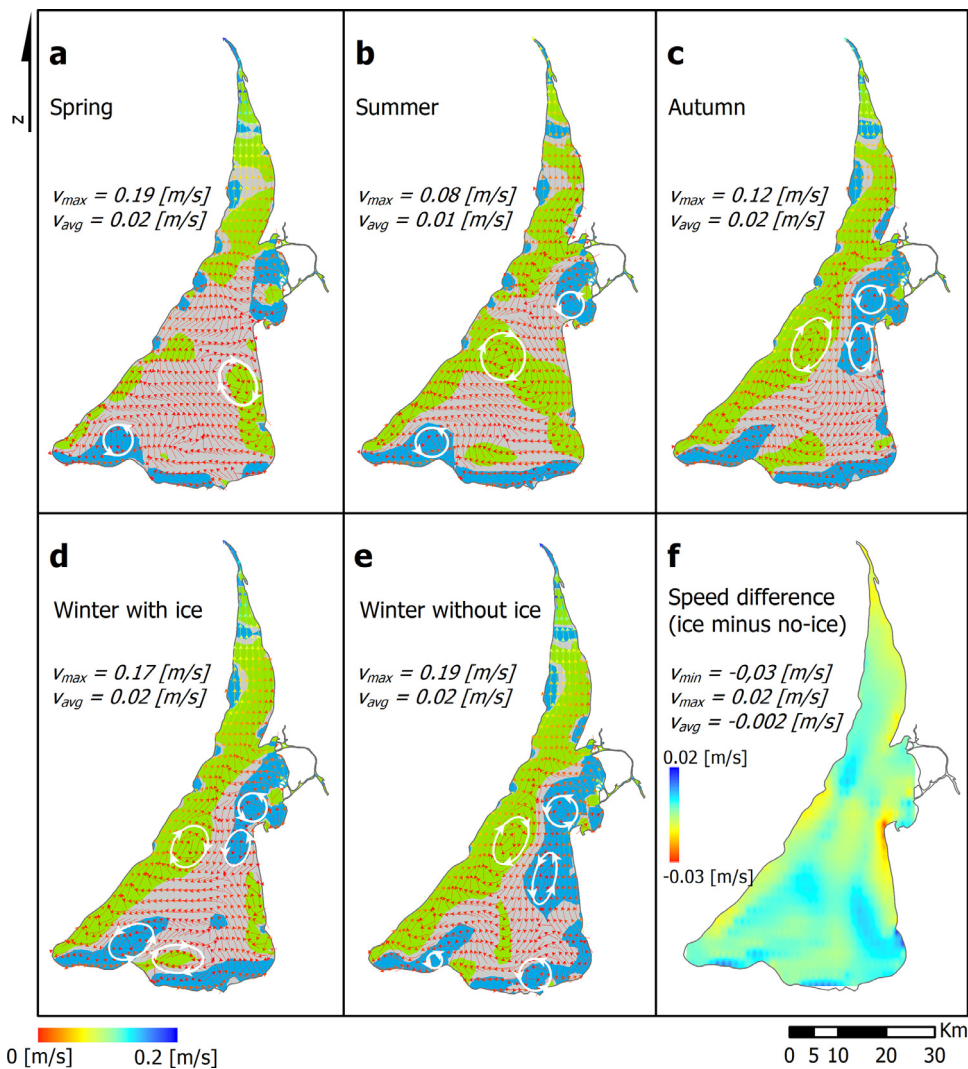


Figure 2 Water circulation (vectors are colored by the current speed in m/s) averaged over the whole simulation period of simulations with ice data in: (a) spring, (b) summer, (c) autumn, and winter seasons (d), without ice in winter (e), and the current speed difference of these winter computations (ice minus no-ice, f). White circles with arrows show gyre systems and their direction, colors in the map show positive (blue), negative (green), and irrotational (gray) vorticity, and numbers indicate the maximum (V_{max}) and average (V_{avg}) velocity of the residual currents.

ice minus no-ice and idealized ice minus no-ice) were calculated to analyze the impact of the ice cover to the above-mentioned hydrodynamic properties of the lagoon. This was done for the averaged ice cover seasons. The salinity time series difference between the bottom and top layers of the water column in Klaipėda Strait (green circle in Figure 1) were analyzed to identify the number of hours per year of salt concentration exceeding the threshold of 1 and 3 PSU. The vertically averaged salinity time series in Juodkrantė were analyzed to count the number of days when the salt concentration exceeds the 2 PSU threshold.

Simulation results of 2004–2015 period were also used for computing the water residence time (WRT) switching its calculation on in the model for the different periods: 1) for the ice-free part of the year and the ice cover season (WRT_{ice}^{real} for the real ice cover and WRT_{ice}^{ideal} for the idealized ice cover season); 2) for every meteorological season of the year defined above (WRT_{season}). All calculations were

done twice – considering ice cover data and without it. The water residence time for the winter season (WRT_{winter}) was compared with WRT_{ice}^{real} and the results from Umgiesser et al. (2016). Since the northern and southern part of the Curonian Lagoon has different hydrodynamic properties, WRT was computed separately for both of these areas, as well as for the total lagoon area.

3. Results

3.1. Circulation

The behavior of water motion can be inferred through the analysis of the residual currents, which are currents averaged over a longer period, in our study, averaged over every meteorological season of the year (Figure 2). Residual currents indicate the mean flow of the water, even if much

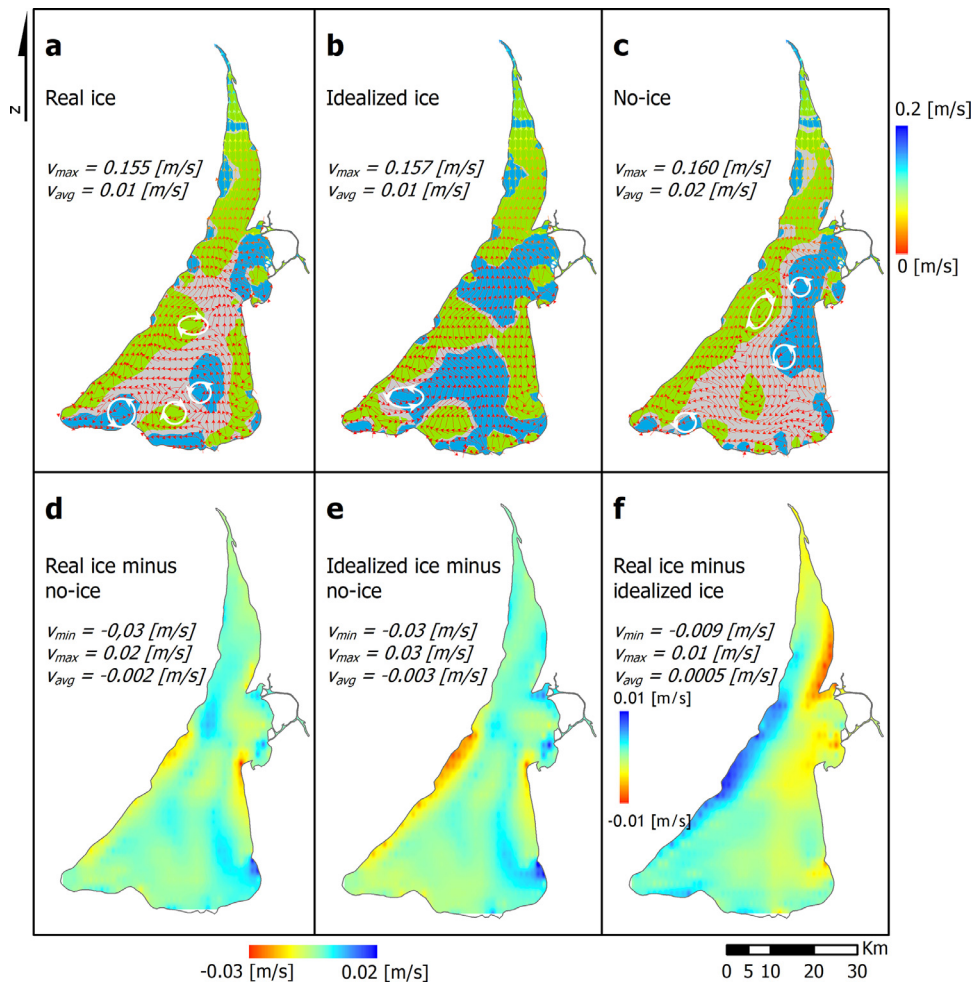


Figure 3 Water circulation (vectors are colored by the current speed in m/s) averaged over ice cover season in simulation with (a) real ice cover, (b) idealized ice cover, and (c) no-ice season set-up, as well as the current speed difference in m/s between simulations: (d) real ice cover minus no-ice, (e) idealized ice cover minus no-ice, and (f) real minus idealized ice cover. White circles with arrows in a, b, and c show gyre systems and their direction, colors in these maps show positive (blue), negative (green) and irrotational (gray) vorticity, and numbers indicate the minimum (v_{min}), maximum (v_{max}), and average (v_{avg}) velocity of the residual currents.

higher and lower instantaneous values can be detected. In the Curonian Lagoon, we can observe a strong flow from the Nemunas River northward to the Klaipėda Strait, having the highest speed throughout the year. During spring season (Figure 2a) in the southern part of the lagoon a two gyre circulation system is observed, one – anticlockwise in the southwestern corner of the lagoon, and the second – clockwise along the eastern shoreline. In summer, the latter one shifts towards the middle part of the lagoon and a third anticlockwise gyre system forms in the Nemunas Delta area (Figure 2b). In summer the current speed is much slower than in spring, with a slightly more pronounced flow along the western shoreline. In autumn (Figure 2c), the current speed slightly increases and the gyre in the southwestern part of the lagoon is not as apparent as during the previous seasons. In addition to this, another anticlockwise gyre system is observed to form in the middle of the lagoon, near the eastern shore. During the winter season under the ice cover (Figure 2d) the same gyre systems remain in the central part of the lagoon and in Nemunas Delta, however, the

anticlockwise gyre in the southwestern part of the lagoon becomes more apparent and another clockwise system can be observed to form next to it. The water flow along the western part of the lagoon slightly decreases during winter and it becomes more chaotic near the eastern shoreline, where ice cover stays the longest.

The difference of the simulation results of winter circulation with and without the ice cover (Figure 2f) was computed to investigate how ice cover affects the velocity of the residual currents during the winter season. The results show that circulation under the ice cover becomes weaker by up to 0.03 m/s. Water during the winter season flows slower along the perimeter of the lagoon, especially near the eastern shoreline. As mentioned above, in the simulation with ice cover one can observe a more chaotic water movement along the southeastern shoreline (Figure 2d), compared to simulation results when the ice cover was omitted (Figure 2e). Additionally, there is a difference in gyre systems in the southern part of the lagoon, being more pronounced under ice cover.

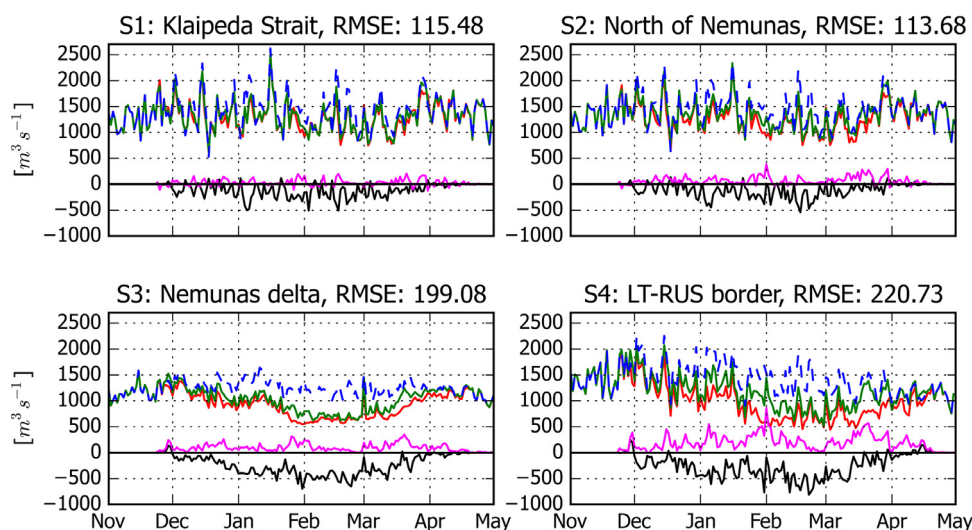


Figure 4 Average water fluxes through cross-sections at Klaipėda Strait (S1), north of Nemunas (S2), Nemunas delta (S3), and Lithuanian-Russian border (S4). The location of each cross-section is shown in Figure 1. Green solid lines indicate water fluxes of simulation with real ice, blue dashed lines – simulation without ice, the black solid line denotes the difference of these simulations (real ice minus no-ice), the red solid line shows the results of simulation with idealized ice, and the magenta solid line indicates the real ice and idealized ice simulation difference (real ice minus idealized ice). Negative values denote higher southward fluxes in the simulation without ice.

Concerning the average residual currents during the real ice cover season (Figure 3a), two gyre systems in the southern part of the lagoon, which are similar to the results averaged over the winter season, can be found (Figure 2d). However, there is a third gyre next to it and only one gyre in the middle of the lagoon during the real ice cover season. For the idealized ice cover (Figure 3b), when the lagoon is completely covered by ice throughout the whole ice season duration, only one gyre forms in the southwestern part of the lagoon. The distribution of the gyre systems in the simulation without ice (averaged over the ice season duration, Figure 3c) is similar to the results averaged over the winter season (Figure 2e), with only one gyre missing near the southern shoreline. The difference of current speed in simulations with real ice and without it (Figure 3d) is similar to the one averaged over the winter season (Figure 2f). The difference of idealized ice cover and no-ice seasons is more pronounced near the western shoreline (Figure 3e). In the idealized case, when the lagoon is completely covered by ice water flows slower along the western shoreline and it is slightly stronger along the eastern shoreline in the northern part of the lagoon, compared to the flow during the real ice cover season (Figure 3f).

By looking at the residual currents of each ice cover season separately (not shown here), it can be seen that in the southern part of the lagoon, the current speed noticeably decreases. This is due to this area being sheltered from the wind by ice cover for a longer period compared to the northern part. When the ice cover is more variable, meaning that it decomposes and refreezes several times throughout the season, it leads to slightly higher current speeds. During each ice-cover season, in the Klaipėda Strait area and approximately 5 km southward from Kiaulės Nugara island, the current speed is always higher compared to the rest of the lagoon. However, if this area is fully covered by ice for a longer period, then the current speed slightly decreases.

3.2. Fluxes

For the computation of the fluxes, four cross-sections were set – in Klaipėda Strait, north of Nemunas River, Nemunas delta, and along Lithuanian-Russian border (red lines in Figure 1). Although the water fluxes through each of the specified sections are rather the same (fluctuating around 1000–1500 $\text{m}^3 \text{s}^{-1}$), one can clearly see the difference between simulations with ice and without it. The results show that the ice cover has a higher impact on the water fluxes in the Nemunas delta area (S3 in Figure 4) and through the borderline of the two countries (S4). The difference between simulation results with and without ice is nearly twice as high in these sections than it is in Klaipėda Strait and north of Nemunas sections. The difference is only observed during the ice cover season.

The comparison of idealized ice (fully ice covered lagoon during the ice cover season) and real ice season (ice cover from remote sensing data) simulation results shows that the prolonged full ice cover (idealized ice) has the greatest impact only in middle of the lagoon (at the cross-section along the Lithuanian-Russian border). The changes of the fluxes in the rest of the sections are much smaller.

3.3. Saltwater intrusions

Throughout the meteorological seasons of the year (Figure 5), higher salinity concentration is always observed in the northern part of the lagoon. It is especially prominent in autumn (Figure 5c), while the lowest concentration is observed in spring (D_{max} in Figure 5a). For the spatial average of the salinity over the whole lagoon area, one can see that during winter it is lower under the ice than it would be if the ice cover would not be present (D_{avg} in Figure 5d and e, respectively). The difference between

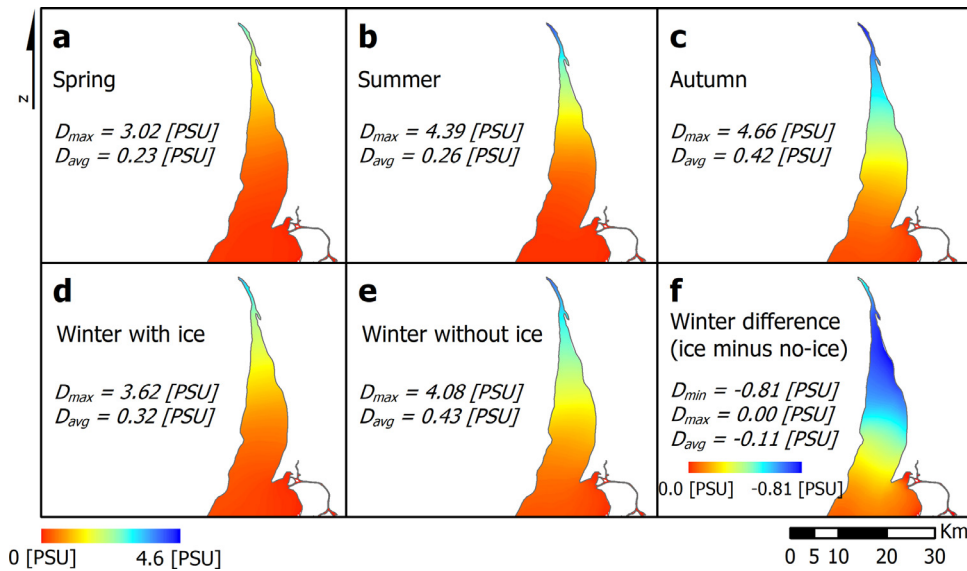


Figure 5 Distribution of salinity in the northern part of the Curonian Lagoon averaged over the whole simulation period of computations with ice data in (a) spring, (b) summer, (c) autumn, and (d) winter seasons, (e) without ice in winter, and the salinity difference of the winter simulations (ice minus no-ice, f). The numbers indicate the maximum (D_{max}) and average (D_{avg}) value of the salinity over the total lagoon area.

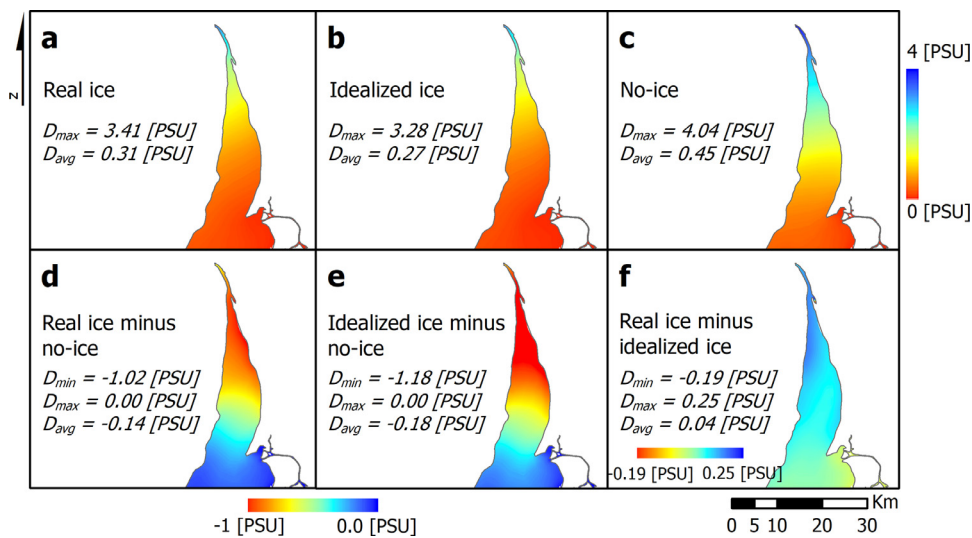


Figure 6 Salinity averaged over ice cover season in simulation with (a) real ice cover, (b) idealized ice cover, and (c) no-ice season set-up, as well as the difference between the simulations: (d) real ice cover minus no-ice, (e) idealized ice cover minus no-ice, and (f) real minus idealized ice cover. The numbers indicate the minimum (D_{min}), maximum (D_{max}), and average (D_{avg}) of salinity over the total lagoon area.

simulations considering ice and no-ice (ice minus no-ice) is negligible in the southern part of the lagoon, but in the north the salinity can be lower by up to 0.81 PSU under the ice cover (Figure 5f) than it would have been if the ice had not been present during the winter season.

The duration of the ice covering the northern part of the lagoon does not have a high impact on salinity when comparing the real and idealized ice seasons (Figure 6a, b, and f). The spatially averaged salinity of the differences between simulations with real ice cover and without it (real ice minus

no-ice, Figure 6d) shows that during the real ice cover season salinity can decrease by up to 1.02 PSU, which is higher than the value averaged over the winter season (Figure 5f). During the idealized ice-cover season (Figure 6e), when the lagoon is completely shut off from the atmosphere by ice, salinity under the ice can decrease by up to 1.18 PSU, compared to a situation where ice cover is not present. It is the highest difference compared with values averaged over winter and real and idealized ice cover season, indicating that the presence of the ice and the duration of its full cover

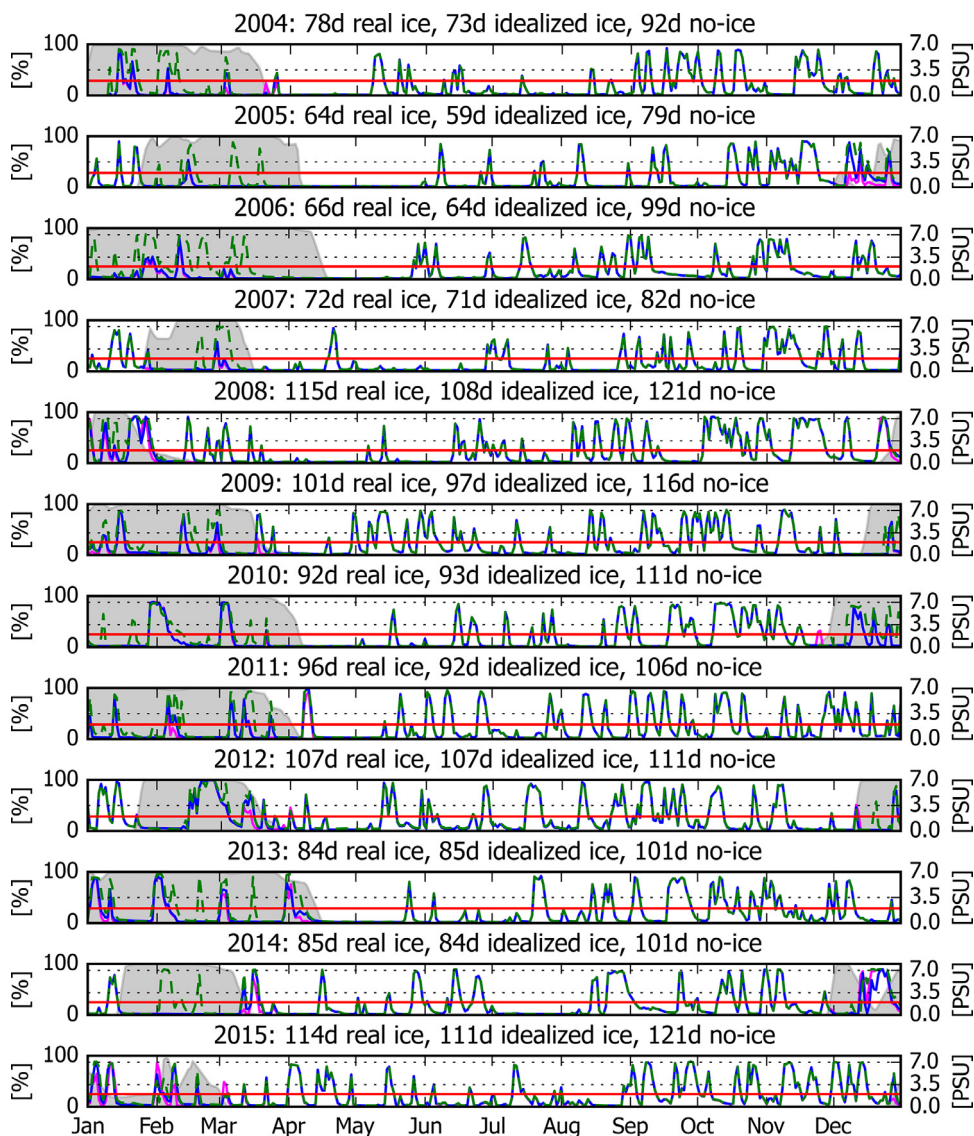


Figure 7 Vertically averaged salinity time series in Juodkrantė. Graph title indicates the year of plotted values, as well as the number of days when the salinity exceeds the threshold of 2 PSU (red solid line) when computations are done using real (real ice, blue solid line) and idealized (idealized ice, magenta solid line) ice cover data, as well as without ice (no-ice, dashed green line). Grey areas show the percentage of ice covering the lagoon, the duration of every ice cover season can be seen in Figure 8.

decreases the intensity of saline water intrusions from the Baltic Sea through the Klaipėda Strait further into the Curonian Lagoon.

The difference of salinity between the bottom and top layers of the water column in the Klaipėda Strait area (green point in Figure 1) shows a high variability throughout the years. In Table 1, the number of hours when this difference exceeds 1 PSU and 3 PSU are shown. The average number of hours is seen to be much higher when the salinity difference exceeds 1 PSU threshold in simulation with ice cover.

In Juodkrantė salinity surpasses the 2 PSU threshold nearly 90 days on average per year when the ice cover is switched-on in the model (Figure 7), this is 13.9 days less on average than in the model results of the simulation without the ice, and the difference between idealized ice cover season and no-ice simulation results is 16.3 days, clearly denoting that the highest impact is observed when the lagoon

is fully covered by ice. In Klaipėda Strait salinity is exceeding the 2 PSU threshold on average for 237 days per year, when real ice cover data is used in the model, which is 10.5 days less than the records of model computations without ice. Further in the lagoon, in Nida and Ventė, differences are much lower – less than 1 and 3 days per year, respectively.

3.4. Water residence time

The average WRT values for the specified areas (north, south, and whole lagoon domain) are shown in Table 2. These values indicate that in the northern part of the lagoon the WRT is around 55 days, and in the southern – 150 days, considering the real ice cover conditions (WRT_{ice}^{real}), which are very similar to the ones averaged over the meteorological winter season (WRT_{winter}^{real}). The difference

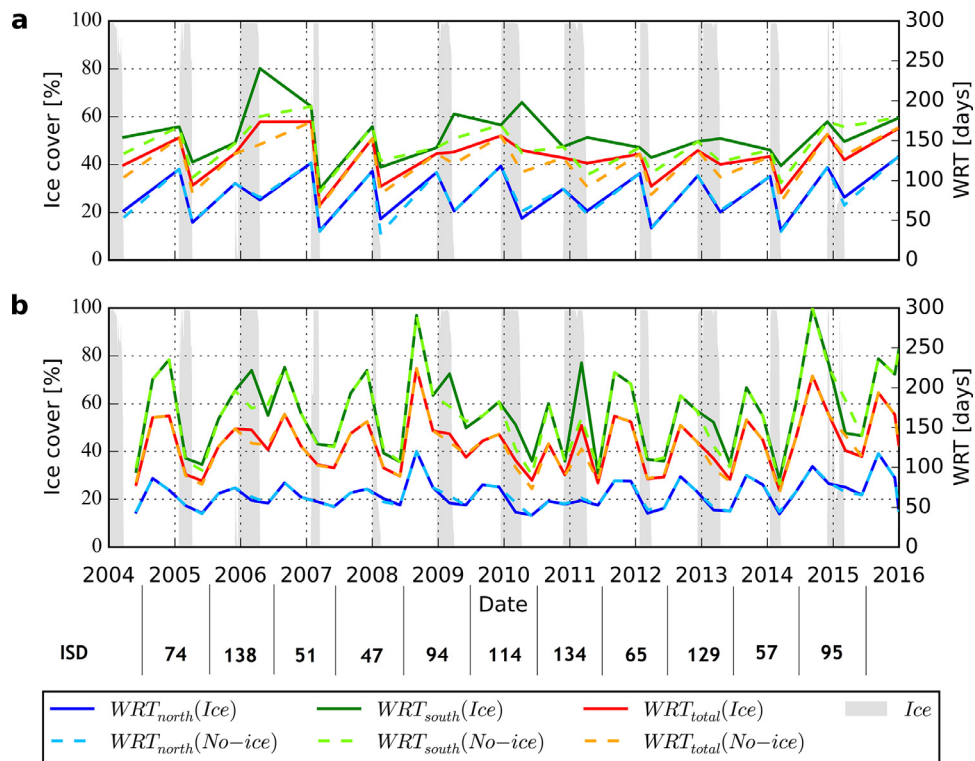


Figure 8 Water residence time in the northern (WRT_{north}), southern (WRT_{south}) parts, and in the whole lagoon area (WRT_{total}) computed with and without the real ice cover: (a) for the ice-free period of the year and the real ice-cover season, (b) seasonally every 3 months. Grey columns indicate ice cover percentage over the lagoon. At the bottom of the graph, the ice season duration (ISD) in days is shown. Please note that in panel (a) only two values per year were available due to the way the WRT was computed. In figure b four values per year were computed.

Table 1 The number of hours per year when salinity difference between bottom and top layers of the water column in the Klaipėda Strait exceeds the threshold of 1 and 3 PSU in simulations with ice and without ice.

Year	Number of hours with salinity [PSU] above threshold			
	> 1 with ice	> 1 without ice	> 3 with ice	> 3 without ice
2005	170	138	24	15
2006	190	107	20	12
2007	135	134	18	18
2008	116	114	8	7
2009	112	122	17	27
2010	156	119	12	7
2011	42	32	1	1
2012	75	90	0	12
2013	85	83	9	11
2014	202	172	15	22
2015	149	145	33	27
Mean	130	114	14	14

between WRT values in the simulations with and without real ice cover (WRT_{winter}^{real} and WRT_{ice}^{no-ice}) is around 1.5 days in the northern part and around 24 days in the southern part. Results of simulation with the idealized ice cover

(WRT_{ice}^{ideal}) show that in the southern part of the lagoon the WRT increases by around 40 and 63 days compared with WRT_{ice}^{ideal} and WRT_{ice}^{no-ice} , respectively. However, in the northern part of the lagoon WRT_{ice}^{ideal} is lower.

The differences of the results averaged over the meteorological winter season (WRT_{winter}^{real} and WRT_{winter}^{no-ice}) are slightly higher in the northern part, due to the variability of the ice season duration (ISD) in this area, and the difference in the southern part is slightly smaller, compared to WRT_{ice}^{real} and WRT_{ice}^{no-ice} .

ISD and different WRT computation periods show a high correlation (from 0.71 to 0.84), denoting a significant ice cover effect on water residence time. However, when considering water residence during the meteorological winter season (WRT_{winter}^{real}), there is no correlation with ISD in the northern part of the lagoon, as mentioned, due to the fact that the ice is more dynamic in this area during the winter season.

The 11-year average water residence time in the Curonian Lagoon (averaged over all meteorological seasons, WRT_{season}^{real}) is around 130 days when the ice cover is switched on in the model, which is a ~1.5 days longer compared to the theoretical period without ice (WRT_{season}^{no-ice}). Higher WRT values can be found in the southern part of the lagoon. In the north, the difference between ice and no-ice simulations is rather small.

The variability of the WRT computation periods can be seen in Figure 8, where the difference between simulation

Table 2 Averaged water residence time (WRT) computed for the northern (WRT_{north}), southern (WRT_{south}) parts and for the total (WRT_{total}) lagoon area as well as correlation between the ice season duration (ISD) and WRT during the ice cover and winter seasons computed in simulations with real ice cover. Subscript indicates different WRT computation periods (ice – ice cover season, winter – December, January, February, and season – every meteorological season), superscript indicates the model set-up type (real – satellite ice cover data, ideal – idealized ice cover data, no-ice – without ice), all described in Section 2.4.

Simulation	WRT_{north} [days]	WRT_{south} [days]	WRT_{total} [days]
WRT_{ice}^{real}	55.48 ± 13.72	150.54 ± 41.10	113.79 ± 28.68
WRT_{ice}^{ideal}	50.01 ± 13.16	190.10 ± 97.92	124.22 ± 43.85
WRT_{ice}^{no-ice}	53.09 ± 14.53	126.52 ± 28.79	99.67 ± 23.97
WRT_{ice}^{real} correlation with ISD:	0.71	0.79	0.84
WRT_{winter}^{real}	53.81 ± 9.94	152.47 ± 50.16	112.15 ± 26.33
WRT_{winter}^{no-ice}	56.44 ± 7.60	135.62 ± 33.91	106.43 ± 22.20
WRT_{winter}^{real} correlation with ISD:	0.09	0.79	0.75
WRT_{season}^{real}	66.66 ± 18.93	170.53 ± 52.67	129.96 ± 36.09
WRT_{season}^{no-ice}	67.24 ± 18.39	166.60 ± 52.07	128.58 ± 36.49

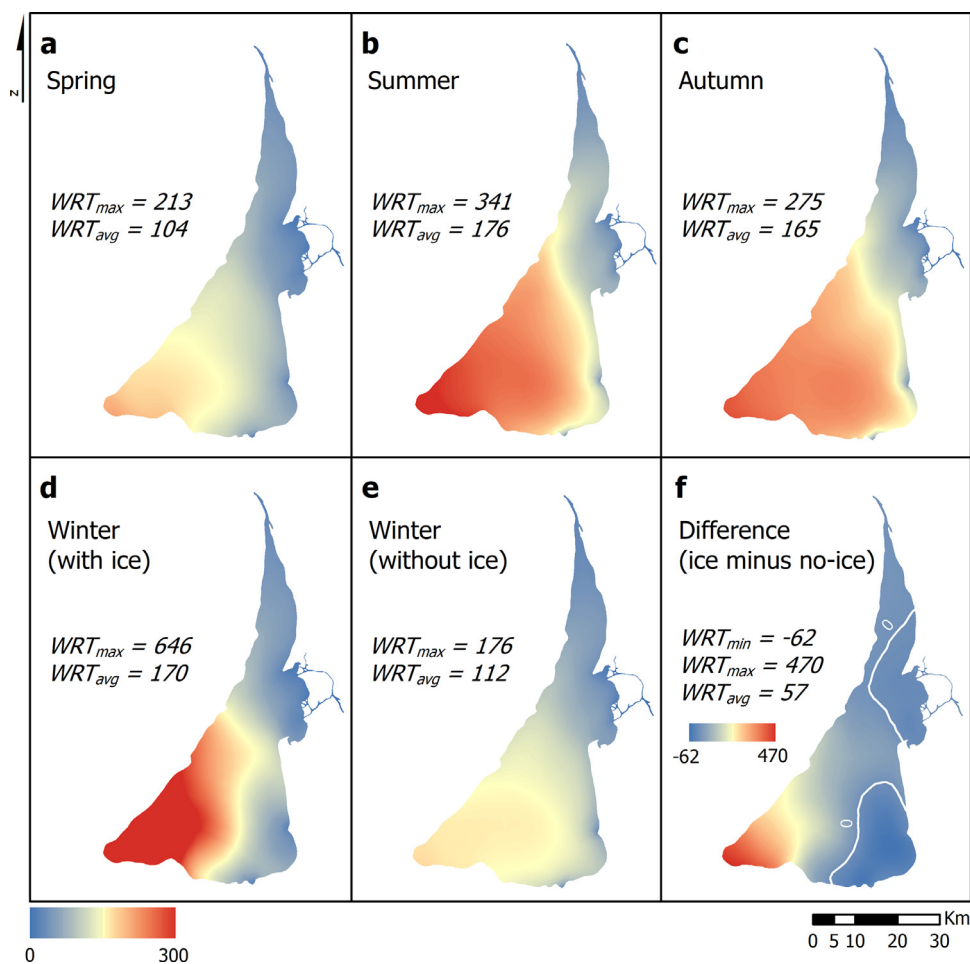


Figure 9 Seasonal water residence time maps (in days) averaged over the whole simulation period of computations with ice data (WRT_{season}^{real}) in (a) spring, (b) summer, (c) autumn, (d) winter, and (e) without ice in winter, as well as the difference of winter simulations (ice minus no-ice, f). Contour lines in the difference map indicate the zero value (no difference) and numbers indicate the maximum (WRT_{max}) and average (WRT_{avg}) water residence time.

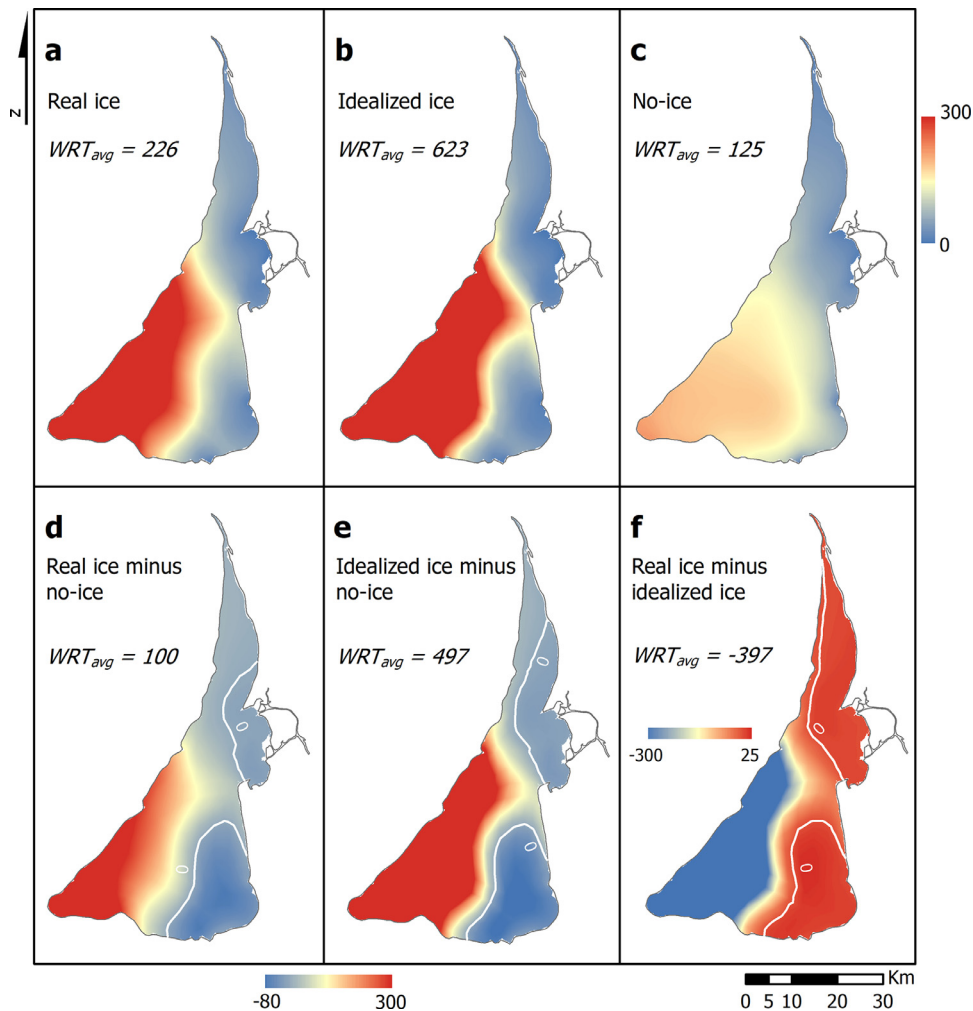


Figure 10 Water residence time distribution in days averaged over the all ice cover seasons in simulation with (a) real ice cover, (b) idealized ice cover, and (c) no-ice season set-up, as well as the difference between the simulations: (d) real ice cover minus no-ice, (e) idealized ice cover minus no-ice, and (f) real minus idealized ice cover. Contour lines indicate the zero value (no difference). The numbers indicate the spatial average (WRT_{avg}) of water residence time.

with and without ice is higher after the long and severe winters, e.g., in 2006, 2009, 2010, 2011 and 2013, when the ice season duration was the longest over the analyzed period (on average 122 days). Again, the higher difference is visible in the southern part of the lagoon, where the ice cover is less dynamic compared to the northern part.

The water residence time throughout the seasons of the year is displayed in Figure 9 (a–d). The values slightly differ throughout the ice-free season, being highest in summer, when the wind and water inflow from the rivers decrease. However, the same overall pattern is observed – high WRT values in the southern part of the lagoon and especially in the southwestern corner. During winter (Figure 9d) in the model runs with real ice the water residence time values are observed to be much higher in the southwestern corner of the lagoon (Figure 9f) than in the reference simulation without ice (Figure 9e), which is much more similar to the spring WRT distribution (Figure 9a). The residence time of nearly 2 years during the winter season means that if the ice

conditions had been prolonged to two years, then the water circulation in 2 years would have renewed only $1/e$ of the initial concentration.

The simulation results of idealized ice cover (Figure 10b) show that the prolonged full ice cover has a much higher impact on the WRT in the southwestern corner of the lagoon compared with the simulation with real ice cover data (Figure 10a). In this area, there are no inflowing rivers, and therefore there are no additional sources of fresh water. Overall, ice affects WRT over the majority of the lagoon area. In the southeastern corner and in Nemunas Delta, where the main river outlets are situated, simulation without ice (Figure 10d and e) shows higher values, meaning that under the ice water is renewing faster than it would be if ice were not present. This difference in the northern part stretches further along the eastern shoreline compared to the no-ice simulations with the idealized ice cover (Figure 10e) than compared to the simulation with the real ice cover (Figure 10d).

4. Discussion and conclusions

The most important drivers of the hydrodynamic processes, when no ice is covering the Curonian Lagoon, is a combination of wind force and Nemunas discharge. However, when ice is present, only the Nemunas River discharge is primarily responsible for accelerating the water masses. Throughout the seasons of the year, we can observe different circulation patterns in the lagoon. In spring, a two-gyre system is observed in the southern part of the lagoon, of which one of them during summer shifts further to the center of the lagoon and another system is observed to form in Nemunas Delta, however, with much lower current speed. The increased wind conditions in autumn force one additional gyre to form near the delta area. However, the highest number of gyre systems are observed during the winter period, when the water surface is sheltered by the ice cover from the wind forcing. The rotation of the gyre systems in and near the Nemunas Delta (along the southeastern shoreline) is anticlockwise, the gyre in the central part of the lagoon is clockwise, and in the southwestern part of the lagoon it is anticlockwise. During the winter season, another clockwise gyre in the south can be observed. These results do not precisely match with the previous study of [Umgiesser et al. \(2016\)](#), because of the ice cover data used, which previously was interpolated from four ground observation stations and available for only for 4 years. In our study, we have used ice data from satellite images, which covered the whole 11-year simulation period.

The comparison of circulation during the real and idealized ice cover seasons reveals that the prolonged full ice cover can diminish the development of gyres in the lagoon. Ice does not only alter the structure of the circulation of the water masses, but also the speed of the currents. When ice cover decomposes and refreezes several times throughout the winter season, it leads to slightly higher current speeds, due to the wind-stress on the ice-free water surface. In the Klaipėda Strait area and approximately 5 km southward from it, the current speed is always higher compared to the rest of the lagoon, however, if this area is fully covered by ice for longer, then this difference slightly decreases.

Since the circulation decreases under the ice cover, there is less exchange between different parts of the lagoon. Therefore, all the water fluxes through the specified four cross-sections are affected by the presence of the ice cover. However, there is a lower impact observed in the northern part of the lagoon contrary to the southern part. It is noticeable that, in the northern part, the fluxes stay nearly the same, just wind is making them fluctuate. In the Klaipėda Strait area, the exchanges are mainly driven by water level fluctuations in the Baltic Sea and are much less wind-driven. However, the situation in the cross-section of Nemunas Delta and along Lithuanian-Russian border is different. Water exits the Nemunas Delta more steadily, without cycling between the delta and the lagoon and less water is diverted to the south, because, during the ice cover season, wind-driven circulation is inhibited and the prolonged full ice cover has the biggest impact on fluxes through the Lithuanian-Russian border.

In the southern part of the lagoon, salinity is small and negligible throughout the year. In the northern part, the concentration is higher, but highly depending on the season. The lowest salinity concentration is observed during spring and the highest during the autumn season when the westerly winds increase allowing for the Baltic Sea water to inflow into the Curonian Lagoon. During the period when ice is covering the lagoon, salinity decreases by up to around 1 PSU. Overall, the highest differences between the results of simulations with ice and without it are observed in the northern part of the lagoon where salinity decreases during the ice cover season, reducing the saltwater intrusion events. For instance, in Juodkrantė (approximately 20 km southward from Klaipėda Strait) saltwater intrusions (overpassing 2 PSU threshold) can be found on average around 90 days per year, which is on average nearly 14 days less when the ice cover was not considered in the model simulations. The simulation results of idealized ice cover show that this difference is even higher – 16.3 days. Thus, we can conclude that when there is ice, it markedly decreases the frequency of saltwater intrusions into the Curonian Lagoon.

The water column is uniform, however, in Klaipėda Strait a slight salt concentration increase is observed in the bottom layers. The difference of bottom and top layers of the water column can exceed the 1 PSU threshold for 130 hours per year on average, which is 16 hours more than it would be if the ice would not be covering the lagoon. [Zemlys et al. \(2013\)](#) have already shown that in the Klaipėda Strait area strong salinity gradients create conditions for three types of water flow: one-directional freshwater outflow to the Baltic Sea, one-directional saline water inflow into the Curonian Lagoon, and two-directional flow with a lagoon water outflow in the surface layers and saline water intrusion in the bottom. However, in their study ice cover was not taken into account, [Umgiesser et al. \(2016\)](#) later did this, showing the more accurate results for salinity validation; yet, they concluded that a high-resolution model used in [Zemlys et al. \(2013\)](#) does a better job in describing salinity variations, even if the ice cover is not included. Since in our study we wanted to present the long-term analysis of model simulation results, we also used a coarser resolution model grid, thus in the future, for a fully updated analysis of salinity variations in the Klaipėda Strait area, including the ice cover data in the model computations, a finer grid should be used.

Ice cover and its duration likewise affect the water residence time (WRT) in the Curonian Lagoon. When ice is present, it takes longer for the water to be renewed. This is especially evident after the long ice cover seasons (e.g., in 2006, 2009, 2010, 2011, and 2013) in the southern part of the lagoon. WRT computations during the ice cover season (WRT_{ice}^{real}), show a high correlation with ice season duration (from 0.71 to 0.84), however, when computing it only during the winter season (WRT_{winter}^{real}) there is no correlation in the northern part of the lagoon. This is due to the fact that the ice season duration in this area is shorter than in the southern part and the computation of WRT during the winter season is limited to only three months (Dec, Jan, Feb), while ice can be observed to start forming, often only in the middle of January and can last much longer than February.

The increased WRT under the ice is true for analyzing water residence in the whole area of the Curonian Lagoon (north, south, and the whole domain) for the real ice cover conditions (WRT_{ice}^{real}). However, computations for the meteorological winter season (WRT_{winter}^{real}) show that it is not the same in the northern part of the lagoon, where simulation results with no ice cover show longer WRT than simulation results with ice. However, the difference is quite small (just 4%), and probably does not exceed the uncertainty of the evaluation of WRT by the model. Comparing the real and idealized ice cover simulation results shows that prolonged full ice cover can lead to an increase of WRT in the southern part of the lagoon. However, in the north, it decreases due to the cutting-off the exchanges between the northern and southern part. Therefore, more water from the Nemunas River stays in the north and does not mix with water in the southern areas. This mechanism contributes to a decrease of WRTs in the northern part.

Our computed WRT values slightly differ from those described in Umgiesser et al. (2016), supposedly as a result of satellite ice cover data used in the model representing more realistic ice distribution with respect to the data interpolated from the observations from coastal stations. The melt-off occurrences during the ice cover season observed in satellite images have a small, but noticeable impact on the WRT by slightly increasing it in the northern part, and decreasing the WRT in the southern part compared to the previous study results with ice.

WRT throughout the seasons is varying. During the ice-free period, the longest time required for water to renew is in summer, due to the decreased wind speed and river water input. The pattern in summer and spring are similar, with the highest WRT being in the southern part of the lagoon. During the winter period, the WRT increases much more in the southwestern corner of the lagoon, which is far away from the rivers inflowing the lagoon, hence the water renewal is very slow. The model results with the idealized ice cover (lagoon fully covered by ice during the entire ice cover season) show that it has a much higher impact to the WRT in the southwestern part of the lagoon. Water near the river outlets – in the southeastern corner of the lagoon and in Nemunas Delta, tends to renew faster under the ice cover and the prolonged full ice cover in the northern part stretches this area further along the eastern shoreline. If ice would not be present during the ice cover season, then the WRT distribution would be much more similar to the situation during the spring.

To conclude, with this study we show how the ice data derived from satellite observations improve the representation of the real conditions of the circulation, saltwater intrusions, and water residence time in the Curonian Lagoon. Currently, an ice model is still not yet integrated in the modelling system SHYFEM, which will be done and will be presented in future publications.

References

- Ambrosetti, W., Barbanti, L., Sala, N., 2003. Residence time and physical processes in lakes. *J. Limnol.* 62, 1–15.
- Baušys, J., 1978. Ledo Režimas. In: Rainys, A. (Ed.), *Kuršių Marios II. Mokslas, Vilnius, Lithuania*, 34–49.
- Bellafore, D., Umgiesser, G., 2010. Hydrodynamic coastal processes in the North Adriatic investigated with a 3D finite element model. *Ocean Dyn.* 60, 255–273, <https://doi.org/10.1007/s10236-009-0254-x>.
- Bengtsson, L., 2012. Ice Covered Lakes. In: Bengtsson, L., Herschy, R.W., Fairbridge, R.W. (Eds.), *Encyclopedia of Lakes and Reservoirs*. Springer, Netherlands, Dordrecht, 357–360.
- Bengtsson, L., 1996. Mixing in ice-covered lakes. *Hydrobiologia* 322, 91–97, <https://doi.org/10.1007/BF00031811>.
- Cañedo-Argüelles, M., Kefford, B., Schäfer, R., 2019. Salt in freshwaters: Causes, effects and prospects - Introduction to the theme issue. *Philos. Trans. R. Soc. B Biol. Sci.* 374, art. no. 20180002, 6 pp., <https://doi.org/10.1098/rstb.2018.0002>.
- Carrasco, A.R., Ferreira, O., Roelvink, D., 2016. Coastal lagoons and rising sea level: A review. *Earth-Science Rev.* 154, 356–368, <https://doi.org/10.1016/j.earscirev.2015.11.007>.
- Cushman-Roisin, B., 2019. *Environmental Fluid Mechanics*. John Wiley & Sons Ltd, New York, 406 pp.
- Dailidienė, I., 2007. Hidroklimatinių sąlygų kaitos ypatumai Baltijos jūros Lietuvos priekrantėje ir Kuršių mariose. *Klaipėda University*.
- Dailidienė, I., Davulienė, L., 2008. Salinity trend and variation in the Baltic Sea near the Lithuanian coast and in the Curonian Lagoon in 1984–2005. *J. Marine Syst.* 74, 20–29, <https://doi.org/10.1016/j.jmarsys.2008.01.014>.
- De Pascalis, F., Pérez-Ruzafa, A., Gilabert, J., Marcos, C., Umgiesser, G., 2011. Climate change response of the Mar Menor coastal lagoon (Spain) using a hydrodynamic finite element model. *Estuar. Coast. Shelf Sci.* 114, 118–129, <https://doi.org/10.1016/j.ecss.2011.12.002>.
- Ertürk, A., Razinkovas, A., Zemlys, P., Pilkaitytė, R., Gasiunaitė, Z., 2015. Linking NPZD and Foodweb Models of an Estuarine Lagoon Ecosystem. *Comput. Sci. Tech.* 3, 350–412, <https://doi.org/10.15181/csat.v3i1.1093>.
- Ferrarin, C., Cucco, A., Umgiesser, G., Bellafore, D., Amos, C.L., 2010a. Modelling fluxes of water and sediment between Venice Lagoon and the sea. *Cont. Shelf Res.* 30, 904–914, <https://doi.org/10.1016/j.csr.2009.08.014>.
- Ferrarin, C., Maicu, F., Umgiesser, G., 2017. The effect of lagoons on Adriatic Sea tidal dynamics. *Ocean Model.* 119, 57–71, <https://doi.org/10.1016/j.ocemod.2017.09.009>.
- Ferrarin, C., Razinkovas, A., Gulbinskas, S., Umgiesser, G., Bliudžiute, L., 2008. Hydraulic regime-based zonation scheme of the Curonian Lagoon. *Hydrobiologia* 611, 133–146, <https://doi.org/10.1007/s10750-008-9454-5>.
- Ferrarin, C., Umgiesser, G., Bajo, M., Bellafore, D., De Pascalis, F., Ghezzi, M., Mattassi, G., Scroccaro, I., 2010b. Hydraulic zonation of the lagoons of Marano and Grado, Italy. A modelling approach. *Estuar. Coast. Shelf Sci.* 87, 561–572, <https://doi.org/10.1016/j.ecss.2010.02.012>.
- Ferrarin, C., Zaggia, L., Paschini, E., Scirocco, T., Lorenzetti, G., Bajo, M., Penna, P., Francavilla, M., D'Adamo, R., Guerzoni, S., 2013. Hydrological Regime and Renewal Capacity of the Microtidal Lesina Lagoon. *Estuar. Coast.* 37, 79–93, <https://doi.org/10.1007/s12237-013-9660-x>.
- Gasiūnaitė, Z.R., Daunys, D., Olenin, S., Razinkovas, A., 2008. The Curonian Lagoon. In: Schiewer, U. (Ed.), *Ecology of Baltic Coastal Waters*. Springer, Berlin/Heidelberg, 197–215.
- Hampton, S.E., Galloway, A.W.E., Powers, S.M., Ozersky, T., Woo, K.H., Batt, R.D., Labou, S.G., O'Reilly, C.M., Sharma, S., Lottig, N.R., Stanley, E.H., North, R.L., Stockwell, J.D., Adrian, R., Weyhenmeyer, G.A., Arvola, L., Baulch, H.M., Bertani, I., Bowman, L.L., Carey, C.C., Catalan, J., Colom-Montero, W., Domine, L.M., Felip, M., Granados, I., Gries, C., Grossart, H.P., Haberman, J., Haldna, M., Hayden, B., Higgins, S.N., Jolley, J.C., Kahilainen, K.K., Kaup, E., Kehoe, M.J., MacIntyre, S., Mackay, A.W., Mariash, H.L., McKay, R.M., Nixdorf, B., Nöges, P., Nöges, T., Palmer, M., Pierson, D.C.,

- Post, D.M., Pruet, M.J., Rautio, M., Read, J.S., Roberts, S.L., Rücker, J., Sadro, S., Silow, E.A., Smith, D.E., Sterner, R.W., Swann, G.E.A., Timofeyev, M.A., Toro, M., Twiss, M.R., Vogt, R.J., Watson, S.B., Whiteford, E.J., Xenopoulos, M.A., 2017. Ecology under lake ice. *Ecol. Lett.* 20, 98–111, <https://doi.org/10.1111/ele.12699>.
- Idzelytė, R., Kozlov, I.E., Umgiesser, G., 2019. Remote Sensing of Ice Phenology and Dynamics of Europe's Largest Coastal Lagoon (The Curonian Lagoon). *Remote Sens* 11 (17), art. no. 2059, 27 pp., <https://doi.org/10.3390/rs11172059>.
- Jakimavičius, D., 2012. Changes of water balance elements of the Curonian Lagoon and their forecast due to anthropogenic and natural factors. *Kaunas University of Technology*.
- Jakimavičius, D., Kriauciūnienė, J., Šarauskiene, D., 2018. Impact of climate change on the Curonian Lagoon water balance components, salinity and water temperature in the 21st century. *Oceanologia* 60 (3), 378–389, <https://doi.org/10.1016/j.oceano.2018.02.003>.
- Jakimavičius, D., Šarauskiene, D., Kriauciūnienė, J., 2019. Influence of climate change on the ice conditions of the Curonian Lagoon. *Oceanologia* 62 (2), 164–172, <https://doi.org/10.1016/J.OCEANO.2019.10.003>.
- Jankovič, V., Schultz, D.M., 2017. Atmosfear: Communicating the effects of climate change on extreme weather. *Weather. Clim. Soc.* 9, 27–37, <https://doi.org/10.1175/WCAS-D-16-0030.1>.
- Jarmalavičius, D., 2007. Jūrinis krantas. In: Bukantis, A., Šinkūnas, P., Taločkaitė, E. (Eds.), *Klimato Kaita: Pristatymai Prie Jos Poveikio Lietuvos Pajūryje*. Vilniaus Universiteto Leidykla, Vilnius, 25–31.
- Maicu, F., De Pascalis, F., Ferrarin, C., Umgiesser, G., 2018. Hydrodynamics of the Po River-Delta-Sea System. *J. Geophys. Res.* 123, 6349–6372, <https://doi.org/10.1029/2017JC013601>.
- Mėžinė, J., Ferrarin, C., Vaičiūtė, D., Idzelytė, R., Zemlys, P., Umgiesser, G., 2019. Sediment Transport Mechanisms in a Lagoon with High River Discharge and Sediment Loading. *Water* 11 (10), art. no. 1970, 24 pp., <https://doi.org/10.3390/w11101970>.
- Molinaroli, E., Sarretta, A., Ferrarin, C., Masiero, E., Specchiulli, A., Guerzoni, S., 2014. Sediment grain size and hydrodynamics in Mediterranean coastal lagoons: Integrated classification of abiotic parameters. *J. Earth Syst. Sci.* 123, 1097–1114, <https://doi.org/10.1007/s12040-014-0445-9>.
- Müller, S., Jessen, S., Duque, C., Sebök, E., Neilson, B., Engesgaard, P., 2018. Assessing seasonal flow dynamics at a lagoon saltwater–freshwater interface using a dual tracer approach. *J. Hydrol. Reg. Stud.* 17, 24–35, <https://doi.org/10.1016/j.ejrh.2018.03.005>.
- Nguyen, T.D., Hawley, N., Phanikumar, M.S., 2017. Ice cover, winter circulation, and exchange in Saginaw Bay and Lake Huron. *Limnol. Oceanogr.* 62, 376–393, <https://doi.org/10.1002/lno.10431>.
- Twiss, M.R., Smith, D.E., Cafferty, E.M., Carrick, H.J., 2014. Phytoplankton growth dynamics in offshore Lake Erie during mid-winter. *J. Great Lakes Res.* 40, 449–454, <https://doi.org/10.1016/j.jglr.2014.03.010>.
- Umgiesser, G., Canu, D.M., Cucco, A., Solidoro, C., 2004. A finite element model for the Venice Lagoon. Development, set up, calibration and validation. *J. Marine Syst.* 51, 123–145, <https://doi.org/10.1016/j.jmarsys.2004.05.009>.
- Umgiesser, G., Zemlys, P., Ertürk, A., Razinkovas-Baziukas, A., Mezine, J., Ferrarin, C., 2016. Seasonal renewal time variability in the Curonian Lagoon caused by atmospheric and hydrographical forcing. *Ocean Sci.* 12, 391–402, <https://doi.org/10.5194/os-12-391-2016>.
- Ummerhofer, C.C., Meehl, G.A., 2017. Extreme weather and climate events with ecological relevance: A review. *Philos. Trans. R. Soc. B Biol. Sci.* 372, <https://doi.org/10.1098/rstb.2016.0135>.
- Vincent, W.F., 2009. Effects of Climate Change on Lakes. In: *Encyclopedia of Inland Waters*. Acad. Press, Elsevier, 55–60.
- Wang, J., Haoguo, H., Schwab, D., Leshkevich, G., Beletsky, D., Hawley, N., Clites, A., 2010. Development of the Great Lakes Ice-circulation Model (GLIM): Application to Lake Erie in 2003–2004. *J. Great Lakes Res.* 36, 425–436, <https://doi.org/10.1016/j.jglr.2010.04.002>.
- Wolanski, E., Day, J.W., Elliott, M., Ramesh, R., 2019. *Coasts and Estuaries*. Elsevier, Amsterdam, 726 pp.
- Wotton, R.S., 1995. Temperature, Organic Matter and the Sustainability of Aquatic Systems. *Freshw. Forum* 5, 39–47.
- Yuan, R., Zhu, J., 2015. The Effects of Dredging on Tidal Range and Saltwater Intrusion in the Pearl River Estuary. *J. Coast. Res.* 316, 1357–1362, <https://doi.org/10.2112/jcoastres-d-14-00224.1>.
- Žaromskis, R., 1996. *Oceans, Seas, Estuaries*. Debesija. Vilnius, 293 pp., (in Lithuanian).
- Zemlys, P., Ertürk, A., Razinkovas, A., 2008. 2D finite element ecological model for the Curonian lagoon. *Hydrobiologia* 611, 167–179, <https://doi.org/10.1007/s10750-008-9452-7>.
- Zemlys, P., Ferrarin, C., Umgiesser, G., Gulbinskas, S., Bellafiore, D., 2013. Investigation of saline water intrusions into the Curonian Lagoon (Lithuania) and two-layer flow in the Klaipėda Strait using finite element hydrodynamic model. *Ocean Sci.* 9, 573–584, <https://doi.org/10.5194/os-9-573-2013>.