Coupled hydrological and hydrodynamic modelling application for climate change impact assessment in the Nemunas River watershed–Curonian Lagoon–south-eastern Baltic Sea continuum

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Abstract. We analyse the cumulative impacts of climate change in a complex basin-lagoon-sea system continuum, which covers the Nemunas River basin, Curonian Lagoon, and the south-eastern part of the Baltic Sea. A unique state-of-the-art coupled modelling system, consisting of hydrological and hydrodynamic models, has been developed and used for this purpose. Results of four regional downscaled models from the Rossby Centre high-resolution regional atmospheric climate model have been bias-corrected using in situ measurements, and were used as forcing to assess the changes that the continuum will undergo until the end of this century.

Results show that the Curonian Lagoon will be subjected to higher river discharges that in turn increase the outgoing fluxes into the Baltic Sea. Through these higher fluxes, both the water residence time and saltwater intrusion event frequency will decrease. Most of these changes will be more pronounced in the northern part of the lagoon, which is more likely to be influenced by the variations in the Nemunas River discharge. The southern part of the lagoon will experience lesser changes. Water temperatures in the entire lagoon and the south-eastern Baltic Sea will steadily increase, and salinity values will decrease. However, the foreseen changes in physical characteristics are not of the scale suggesting significant shifts in the ecosystem functioning, but are expected to manifest in some quantitative alterations in the nutrient retention capacity. However, some ecosystem services such as ice fishing are expected to vanish completely due to the loss of ice cover.

1 Introduction

Climate change and increasing anthropogenic pressures are expected to cause drastic changes in the global environment in the near future, and thus may affect the discharge and hydrological regime of rivers (Middelkoop et al., 2001), lagoons (Jakimavičius and Kriaučiūnienė, 2020; Anthony et al., 2009) and regional seas (Holt et al., 2016). The Baltic Sea, together with its largest lagoon, the Curonian Lagoon, and the Nemunas River watershed are no exceptions to this trend. The impact of climate change is already evident here through the changes in ice conditions in the sea (Merkouriadi and Leppäranta, 2014)

and the lagoon (Idzelytė et al., 2019), increase in sea surface temperature (Kniebusch et al., 2019; Belkin, 2009) or redistribution of river runoff over the year (Meier et al., 2022a).

Additional climate change impacts might manifest themselves slowly over decades (Lillebø, 2015) making the management of freshwater and transitional waters a challenge for policymakers, decision makers, and scientists. Hence, modelling becomes
35   increasingly important for understanding and projecting climate change impacts, also for supporting the formulation of management measures (Vohland et al., 2014).

The first climate change scenario simulations for the Baltic Sea were carried out more than 20 years ago (Meier, 2002a, b; Omstedt et al., 2000). ln 2008, the first assessment of the climate change in the Baltic Sea region was prepared with the main conclusions that by the end of 2100 the annual mean sea surface temperature will be 2–4 °C higher while the ice cover and
40   salinity values will decrease (BACC Author Team, 2008). One of the new key findings of the 2nd climate change assessment (BACC II Author Team, 2015) was that due to the large bias in the water balance projections the projected changes of the Baltic Sea salinity remained uncertain, i.e., it is unclear if the Baltic Sea becomes more or less saline (von Storch et al., 2015). Nevertheless, climate change is consequently going to affect marine ecosystem and may reduce its resilience.

The magnitude and severity of climate change impacts will vary considerably within the Baltic Sea region (Graham, 2004)
45   making basin-specific studies of high importance for understanding climate change induced impacts on a local scale. Likewise, with increasing computational capacity, the multidisciplinary modelling studies were progressively evolving during the past few decades (Rodrigues et al., 2015). Thus, the need for a combination of different aquatic processes became essential. The coupling of different numerical models allows researchers to replicate the environmental processes for better assessment of the physical parameters' response to changing climate.

50   In this article, we present a framework of coupled hydrological and hydrodynamic models that are able to simulate the contribution of the entire Nemunas River watershed to the Curonian Lagoon. Moreover, the Curonian Lagoon and the south-eastern Baltic Sea are covered by a finite element grid that resolves its hydrodynamic and physical parameters. A seamless integration of two models represents the watershed–lagoon–sea continuum for the simulations of the present state and future scenarios based on the ensemble of meteorological datasets produced by climate models.

55   2 Materials and methods

2.1 Study area

The study site covers part of the south-eastern Baltic Sea region together with the Curonian Lagoon and the Nemunas River watershed (Fig. 1). The drainage basin is shared by five countries: Belarus (48%), Lithuania (46%) and the other 6% is shared by Kaliningrad region of Russian Federation, Poland and Latvia (Gailiušis et al., 2001). The river enters the Curonian Lagoon
60   at its central-eastern part and divides the system into two sub-basins; its southern part belongs to the Russian Federation (Kaliningrad region, 76%) and its northern part to Lithuania (24%).

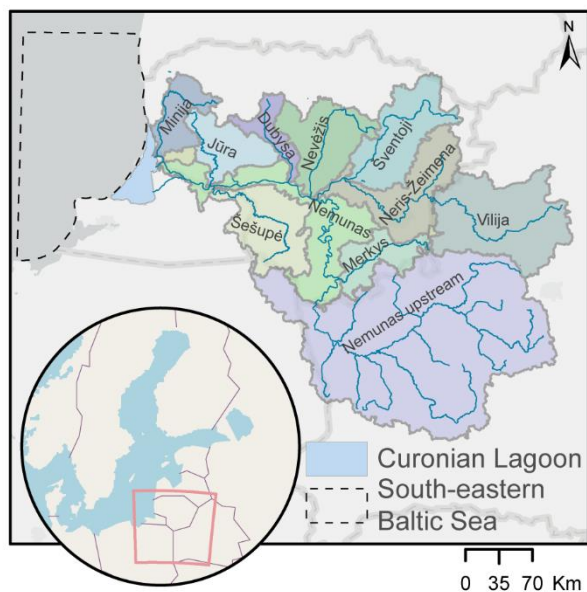



Figure 1. The Nemunas River watershed (coloured polygons in the mainland are major sub-basins), Curonian Lagoon, and south-eastern Baltic Sea with respect to the entire sea area. Basemap source: ESRI.

65   The Nemunas River is the fourth largest river draining into the Baltic Sea and the largest tributary entering the Curonian Lagoon, accounting for ~96% of the total freshwater input into it (Jakimavičius and Kovalenkovienė, 2010). The annual average discharge is 16.4 km^3 yr^{-1} (518.3 m^3 s^{-1}), calculated for the period 2012–2016 (Vybernaite-Lubiene et al., 2018), and the long-term average of 21.847 km^3 yr^{-1} (692 m^3 s^{-1}) for the period 1960–2007 (Jakimavičius and Kovalenkovienė, 2010).

The Curonian Lagoon is a shallow water body with an average depth of 3.8 m (Gasiūnaitė et al., 2008) located on the south-

70   eastern coast of the Baltic Sea. With a total area of ~1584 km^2 (Žaromskis, 1996), it is considered the largest lagoon in Europe. It is a transnational lagoon whose northern part is influenced by the Nemunas River flow and brackish water intrusions from the Baltic Sea, while the southern part is more stagnant, where hydrodynamics are influenced by the wind (Vybernaite-Lubiene et al., 2022; Ferrarin et al., 2008). The intrusions of the sea water through the narrow (0.4–1.1 km) Klaipėda Strait occur in the northern part of the lagoon and reach up to 20 km southward from the strait (Zemlys et al., 2013).

75   The coastal area of the south-eastern Baltic Sea is relatively shallow, up to 20 m depth. The lowest water temperatures here are observed in winter months (in Jan and Feb the average water temperature is ~2 °C), while in summer months, e.g., Jul and Aug, the average water temperature is ~18–19 °C (Kozlov et al., 2014). The salinity in the coastal zone is varying between 6–7 g kg^{-1}, although in the plume affected waters from the Curonian Lagoon it can drop drastically to nearly fresh water (0–3 g kg^{-1}) (Olenin and Daunys, 2004).

2.2 Data

2.2.1 Climate projection data

To feed our developed modelling system we used meteorological forcing data acquired from CORDEX (Coordinated Regional Downscaling Experiment) scenarios for Europe from the Rossby Centre high-resolution regional atmospheric climate model (RCA4), which consisted of four sets of simulations (downscaling) driven by four global climate models (specified in Table 1). The datasets consist of cloud cover, solar radiation, precipitation, surface air pressure, relative humidity, air temperature, and wind speed and direction, and covers a historical period of 1970–2005 and projection period of 2006–2100. The projections are derived according to two Representative Concentration Pathway (RCP) scenarios: RCP4.5 and RCP8.5.

Abbreviation	Model	Institution
ICHEC	EC-Earth	Irish Centre for High-End Computing
IPSL	IPSL-CM 5A-MR	The Institut Pierre-Simon Laplace
MOHC	HadGEM2-ES	Met Office Hadley Centre
MPI	MPI-ESM-LR	Max Planck Institute for Meteorology

Table 1. Summary of the global climate model data sources.

The applied modelling system uses standard Gregorian calendar, however, MOHC uses 360-day calendar and IPSL 365-day calendar. Therefore, correction was applied to harmonize the input data. MOHC calendar was adjusted by deleting 30 Feb and 29 Feb (if not leap year), and interpolating the 31st of respective months. IPSL was corrected by interpolating the 29 Feb during the leap years.

The bias correction of air temperature and precipitation datasets were done separately for the hydrological and hydrodynamic models by applying the climate data bias correction tool (Gupta et al., 2019), which uses the quantile mapping approach by fitting the daily values to normal distribution function for the air temperature and gamma distribution function for the precipitation. Due to the availability of measurement data, provided by Lithuanian Hydrometeorological Service, the correction period was from 1993 to 2005.

The data from 18 meteorological stations, which are scattered throughout the Republic of Lithuania, were used for the bias correction of the climate data and used as inputs for the hydrological model. For the Belarus region the meteorological grid was constructed according to the methodology presented in the "Renewal of a River Basin Districts Management Plans and Programmes of Measures" project report (PAIC, 2015) and were split in three groups corresponding to the closest meteorological stations in Lithuania of which measured data were used for bias correction. The bias correction of climate input data for the hydrodynamic model was performed from the averaged data of three meteorological stations closest to the northern part of the lagoon that describe the coastal climate conditions.

2.2.2 Boundary data

Water level, temperature, and salinity data for the sea boundary of the hydrodynamic model were acquired from a high resolution regional coupled ocean–sea ice–atmosphere model RCA4–NEMO (Gröger et al., 2019; Wang et al., 2015)

developed by the Rossby Centre and the Oceanographic research group at Swedish Meteorological and Hydrological Institute (SMHI). This model was run by the same before-mentioned global climate projections (Table 1).

110 The bias correction for the data of RCA4-NEMO model was done by using Copernicus Marine Environment Monitoring Service (CMEMS) Baltic Sea Physical Reanalysis product data for the period of 1993–2005. The correction was done by simply adding the difference between the average values of CMEMS, C_O, and RCA4–NEMO data, C_m, (Lenderink et al., 2007):

$$C_{BC}(t) = C_m(t) + (C_O - C_m) \,, \tag{1}$$

115 Bathymetry data of a high-resolution spherical grid topography of the Baltic Sea were used as a bottom boundary (Seifert et al., 2001). Data of ice thickness from ice thermodynamic model ESIM2, run using the meteorological data specified in Table 1, were used as a top boundary during the ice cover season (Idzelytė and Umgiesser, 2021; Tedesco et al., 2009).

2.2.3 Watershed-scale data

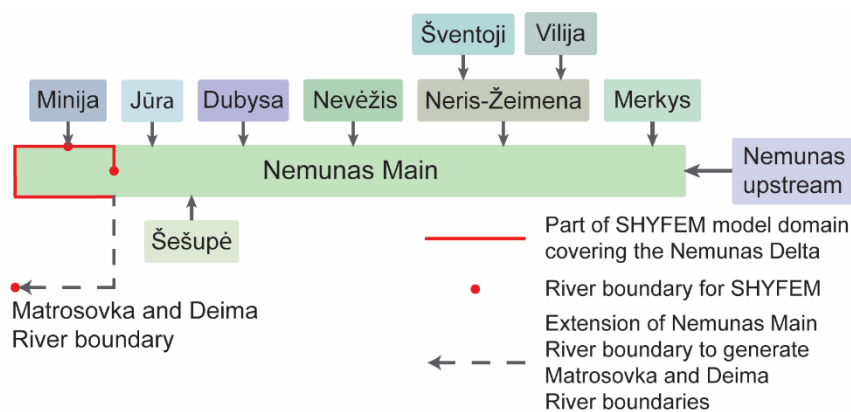
For the development of the hydrological model many basin-scale datasets are required, i.e., the digital elevation model (DEM),
120 land use and management data, hydrologic grid, soil maps, etc. We obtained the data from several governmental sources in different countries as well as public open access databases. For a full list of datasets and their sources, we refer the reader to Čerkasova et al. (2021), where the acquired datasets are described in depth. Observed discharge data with varying time step (daily, weekly, by-weekly, and monthly) for the majority of the Nemunas River tributaries as well as the main branch were obtained from the Lithuanian Hydrometeorological Service. Observed nutrient (TN and TP) concentration values for the
125 overlapping periods were provided by the Lithuanian Environmental Protection Agency.

Large parts of the watershed are outside of Lithuania, hence open-access data for those regions were identified and used (Čerkasova et al., 2021). Some data had to be manually digitized, i.e., the stream network of the Nemunas watershed outside of the territory of Lithuania. Unfortunately, due to political reasons, we could not acquire any observational data from the Republic of Belarus and the Kaliningrad Region. We resolved the issue by calibrating the model against observed data at the
130 nearest border locations within the territory of Lithuania, provided by abovementioned governmental institutions.

2.3 Models

2.3.1 Hydrological model

High-resolution basin-scale model has been developed for the entire Nemunas watershed (Fig. 1) and implemented using Soil and Water Assessment Tool (SWAT) using a set of custom tools and scripts. To set up a comprehensive model, we incorporated
135 the topographic information of the area, land use and soil properties, information on water bodies, land management, water use, crop growth, livestock production, administrative units, etc. The model was calibrated, validated, and proved to reliably represent the water balance components as well as nutrient and sediment load estimates, and was used in previous studies (Čerkasova et al., 2021, 2019, 2018).

The basin-scale hydrological model consists of 11 sub-models, each representing one of the tributaries of the Nemunas River,
140   connected to the main branch (Fig. 2). In total, the model consists of 9012 sub-basins, and 148 212 Hydrologic Response Units.
These sub-models are linked from upstream to downstream, where the outputs of two downstream models are directly used as
river boundaries for the hydrodynamic model. Discharge and temperature outputs were extracted from the list of variables,
provided by the Nemunas drainage basin modelling framework.

145   **Figure 2. SWAT models for the Nemunas River watershed and their linkage with SHYFEM through river boundaries.**

2.3.2 Hydrodynamic model

Hydrodynamics of the Curonian Lagoon and the south-eastern Baltic Sea were modelled with an open-source shallow water
hydrodynamic finite element model SHYFEM (http://www.ismar.cnr.it/shyfem, Umgiesser et al., 2004), which consists of a
finite element 3-D hydrodynamic model, a transport and diffusion model, and a radiation transfer model of heat at the water
150   surface. The model resolves the 3-D primitive equations, vertically integrated over each layer, in their formulations with water
levels and transports. Horizontal spatial discretization of the model is based on an unstructured triangular grid and carried out
using a finite element method, which makes it suitable for applications to coastal systems with complicated geometry and
bathymetry.

This model has already been successfully applied to many coastal environments (Umgiesser et al., 2014; De Pascalis et al.,
155   2011; Ferrarin et al., 2013, 2010; Bellafiore and Umgiesser, 2010; Ferrarin and Umgiesser, 2005), as well as validated for the
Curonian Lagoon case study in previous works (Mėžinė et al., 2019; Umgiesser et al., 2016; Zemlys et al., 2013; Ferrarin et
al., 2008). For this study, SHYFEM was applied in its 2-D version, which is sufficient considering the shallow nature of this
lagoon. The computational grid consists of 3292 triangular elements with 1986 nodes having a much finer resolution in the
Klaipėda Strait area (Fig. 3). Model produced output data of hydrodynamic properties every 6 hours.

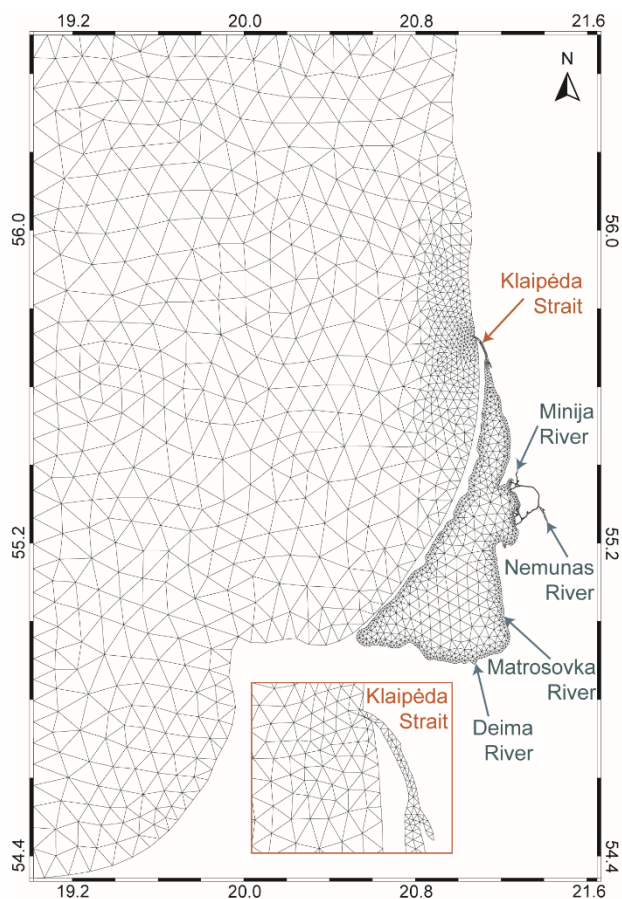



Figure 3. Computational grid of the hydrodynamic model SHYFEM. Dark blue arrows denote the location of the river boundaries (modelling system connectivity points), where the hydrological model outputs (water temperature and discharge) are used as inputs to the hydrodynamic model.

2.3.3 Coupling of models

A better representation of hydrodynamic conditions in the Nemunas Delta region is achieved with a hydrodynamic model, thus the overlapping parts of SHYFEM and SWAT models were modelled entirely by SHYFEM. The daily water temperature and discharge data from the SWAT model were directly used as Minija and Nemunas river boundaries (Fig. 3). However, other two main rivers discharging in the southern part of the lagoon (Matrosovka, branch of the Nemunas, and Deima) are not part of the Nemunas River watershed model, thus the SWAT output data of the Nemunas River were scaled by the ratio between Matrosovka-Nemunas and Deima-Šešupė calculated from the data presented in Jakimavičius (2012).

2.4 Methods of data analysis

Model results based on four global climate model forcings (Table 1) were averaged, therefore the final analysis was done for three aggregated outputs referring to the historical and projection (RCP4.5 and RCP8.5) scenarios. The analysis periods were

divided into historical (1975–2005), short-term (2020–2050) and long-term (2070–2100), and the results were compared by
175 averaging over these timespans. The period of 1970–1975 was discarded from analysis as it was used for the model spin-up.
The main air temperature and precipitation patterns were determined. The parameters of the hydrological model (water
discharge) and parameters of the hydrodynamic model (water temperature, salinity, level, residence time, and fluxes through
predefined cross sections), as well as ice thickness, were assessed. The analysis was done using standard statistical methods,
and computing the percentage of change from the historical period.

3 Results

3.1 Bias correction

Even though the meteorological data from the global climate models were already downscaled by the regional climate model,
there was still some bias remaining in comparison with the local measurement data – underestimation of air temperature and
overestimation of precipitation. Therefore, an additional correction was applied (Fig. 4). The correlation between the modelled
185 and measured air temperature datasets was strong (~0.8), however after bias correction there was an evident improvement of
the standard deviation. Similar change is also equivalent to the monthly precipitation, although here we observe that the climate
models have their own internal dynamics, thus the correlation with measurements is weak (~0.25).

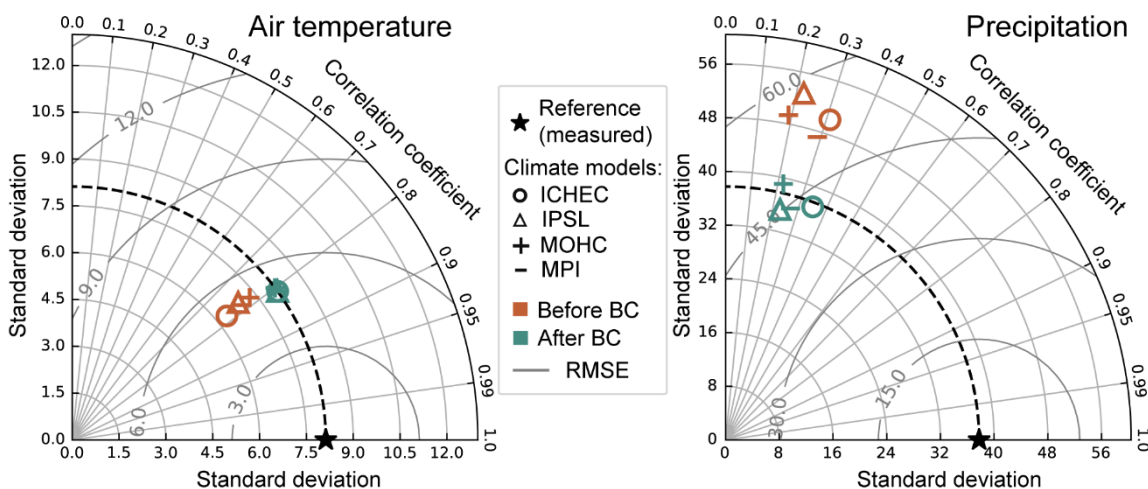



Figure 4. Taylor diagram showing a statistical comparison of air temperature (daily mean) and precipitation (monthly sum) before
190 **and after bias correction (BC) with respect to the reference measurement data. Statistics were computed for the period of 1990-**
2005.

3.2 Meteorological changes

The bias-corrected statistics of both RCP scenarios show a distinct increase in the projected monthly and annual average
precipitation and air temperature (Table 2). The differences between the scenarios in the short-term are smaller than in the
195 long-term by an average of 49% under RCP4.5 and ~123% under RCP8.5. Considering precipitation, the monthly

wetness/dryness pattern is similar between the analysis periods and scenarios. The average air temperature in the long-term has the highest increase, especially in the months from November to April. The highest changes of these parameters are projected under RCP8.5 scenario.

Air temperature (ºC)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Historical (1975-2005)		-2.6	-2.6	0.3	5.3	10.7	14.6	17.9	17.5	13.2	8.1	1.8	-2.3	6.8
Short-term (2020-2050)	RCP4.5	-0.5	0.4	2.4	7.4	12.2	15.9	19.2	18.7	14.6	9.7	3.8	0.0	8.6
	RCP8.5	-0.6	0.5	2.8	7.5	12.4	16.1	19.2	18.8	14.6	10.0	4.2	-0.2	8.8
Long-term (2070-2100)	RCP4.5	0.9	1.4	3.4	8.4	13.3	16.9	20.1	19.7	15.5	10.9	4.7	1.0	9.7
	RCP8.5	2.9	3.4	5.0	10.0	14.7	18.1	21.8	21.5	17.6	12.4	6.7	3.3	11.5
Precipitation (mm month^{-1})		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Historical (1975-2005)		42.8	36.5	43.1	36.9	55.9	87.1	57.5	57.9	48.7	63.7	39.0	48.7	617.7
Short-term (2020-2050)	RCP4.5	54.4	47.6	53.7	41.1	53.1	83.4	69.9	64.7	55.6	72.7	49.9	56.4	702.5
	RCP8.5	53.1	46.9	50.1	43.1	61.0	83.1	75.4	69.1	54.2	71.2	50.5	58.4	716.2
Long-term (2070-2100)	RCP4.5	56.9	46.5	53.7	44.8	58.8	83.3	69.2	70.0	54.0	78.2	53.6	59.3	727.3
	RCP8.5	72.3	52.2	65.4	49.5	67.7	93.2	73.6	77.9	60.6	85.3	62.7	70.3	830.8

Table 2. Monthly and yearly mean of air temperature and precipitation over the study region derived by averaging four bias-corrected climate models' datasets.

Considering the differences between marine and terrestrial parts of the study area, there is a clear pattern of lower air temperatures (on average by ~1–1.5 °C) over the Baltic Sea and the Curonian Lagoon during March through June, while during the rest of the year it is warmer (on average by ~2.2 °C), compared with that of the Nemunas River watershed. During February through August and December months, less precipitation over the marine part (on average by 10 mm month^{-1}) is observed, while during the rest of the months it is higher by the same amount compared with the terrestrial area. Therefore, annual precipitation is similar to both areas.

3.3 Interactions between domains

The historical discharges of the Nemunas River watershed to the Curonian Lagoon were compared to the projected averaged discharges under RCP4.5 and RCP8.5 climate change scenarios for all seasons (Fig. 5). The most noticeable change is the projected drastic increase in runoff during winter, which will almost double in the long-term period under both RCPs. This result is a combination of increased projected average precipitation and temperatures, which will likely result in warmer winters with reduced snow cover throughout the basin. The increased liquid precipitation in winter will likely lead to an increased soil erosion and nutrient wash-off, when the soil is bare and exposed to the elements.

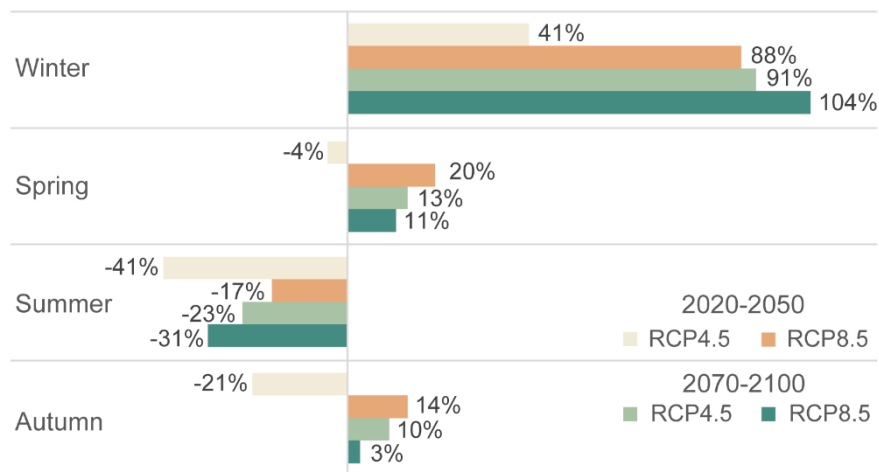



Figure 5. The percentage of change of seasonal average discharge from the Nemunas River for the RCP4.5 and RCP8.5 scenario runs during the short-term (2020–2050) and long-term periods (2070–2100), compared with the historical period (1975–2005).

In contrast, a decrease in average summer outflow is projected under both RCP scenarios, despite an increase in precipitation across the region. The increased average temperatures in summer months will impact the evapotranspiration (ET) over the basin, where an increase in both potential ET and ET is projected, which will lead to lower discharges at the stream gages during this period. Stable and mostly unchanged Nemunas River discharge will continue to supply the lagoon over the rest of the season, in spring and autumn.

Noteworthy are the differences between the RCP scenarios. We see a stronger shift in the increased winter discharges in the RCP8.5 scenario in the short-term period, and a stronger shift towards lesser summer flows in the RCP4.5 scenario (Fig. 5). The RCP8.5 in the short-term can be considered as "wetter" scenario, whereas RCP4.5 is "dryer". In the long-term, however, both RCPs simulate similar outcomes with slightly different magnitudes.

The interactions between the study domains can be defined by the water fluxes from the main discharging rivers into the Curonian Lagoon, eventually into the Baltic Sea (water outflow), and vice versa (water inflow). The volume of inflowing water is much lower than that of the outflowing (Fig. 6), especially in the northern part of the Curonian Lagoon, meaning that the outflow is already dominating and this study shows that it will prevail and even increase in the analysed continuum system.

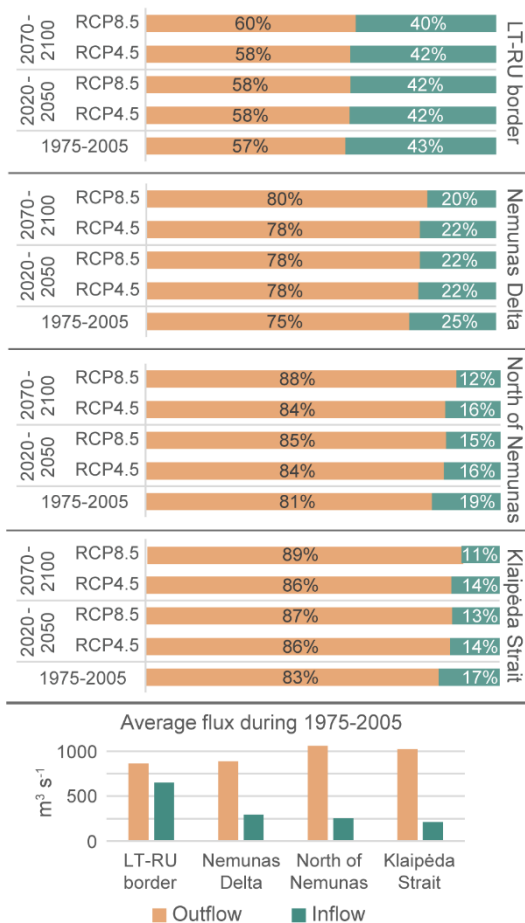



Figure 6. The percentage of the average outflowing and inflowing water volume of the absolute flux of each analysis period – historical (1975–2005), short-term (2020–2050), and long-term (2070–2100) under RCP4.5 and RCP8.5 scenarios. The locations of cross-section are shown in Fig. 7. The bottom graph is for reference, indicating the average water flux in m³ s⁻¹ during the historical period (1975–2005).

Comparing the simulation results of the scenario runs (short- and long-term) with the historical period, it is evident that the water inflow in the northern part of the lagoon (cross-sections 1 and 2 in Fig. 7) is projected to decrease. The change of water inflow in the centre of the lagoon (cross-sections 3 and 4 in Fig. 7) is very small and can be considered negligible. The outflowing water flux is projected to increase and is related to the growing outflow from the Nemunas River and will increase along the pathway towards the Baltic Sea (cross-sections 1, 2, and 3 in Fig. 7). In the southern part of the lagoon, near the Lithuanian–Russian border, the changes in water fluxes are less evident, due to the fact that water circulation in this area is mostly determined by the wind induced currents.

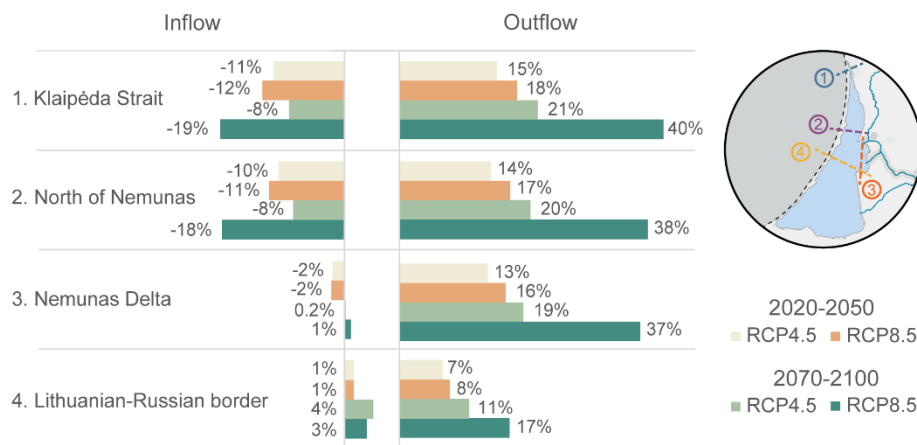



Figure 7. The percentage of change of projected (under RCP4.5 and RCP8.5 scenarios) inflowing and outflowing water flux from the historical period (1975–2005). The map insert shows the locations of the predefined cross-sections: 1 – Klaipėda Strait, 2 – North of Nemunas, 3 – Nemunas Delta, 4 – Lithuanian–Russian border. Outflow is from south to north (sections 1,2,4), and from east to west (section 3), inflow - vice versa.

The change of water flow through all cross-sections display a similar pattern in all scenarios, the water flux changes from the historical are very similar in each analysed cross-section and for each flow type. For both the outflow and inflow the highest change from the historical period is observed in the long-term under RCP8.5 scenario.

Looking at the water exchange seasonal dynamics, we can see that the highest inflowing water deviations from the historical period are predicted during winter and spring, being lower by 10–28% (Table 3). The water exchange is expected to increase in summer by 12–22% while in the autumn the changes are very small and similar throughout the analysis periods and scenarios.

		1975-2005	2020-2050		2070-2100	
		Historical	RCP4.5	RCP8.5	RCP4.5	RCP8.5
OUTFLOW	Winter	1017	1291 (27%)	1324 (30%)	1388 (36%)	1663 (63%)
	Spring	1046	1210 (15%)	1213 (15%)	1214 (16%)	1356 (29%)
	Summer	858	814 (-5%)	850 (-1%)	856 (0.3%)	923 (8%)
	Autumn	924	1007 (9%)	1030 (12%)	1076 (17%)	1190 (29%)
INFLOW	Winter	452	387 (-19%)	383 (-20%)	380 (-21%)	357 (-28%)
	Spring	246	225 (-13%)	220 (-16%)	233 (-10%)	225 (-14%)
	Summer	277	309 (13%)	308 (12%)	331 (22%)	315 (14%)
	Autumn	439	449 (2%)	450 (2%)	461 (4%)	456 (2%)

Table 3. Seasonal water flux in m³ s⁻¹ averaged over historical (1975–2005), short-term (2020–2050), and long-term (2070–2100) periods under RCP4.5 and RCP8.5 scenarios. Percentage in the brackets shows the change compared with the historical period. The values are averaged over four cross-sections in the Curonian Lagoon: Klaipėda Strait, North of Nemunas, Nemunas Delta, and Lithuanian Russian border (see map insert in Fig. 7).

The changes of the outflow during winter, spring, and autumn are expected to increase (Table 3). In the short-term, the changes
260   between the scenarios are similar, while in the long-term, the change increases nearly twice under RCP8.5, compared with
RCP4.5. During summer the outflow changes are negligible, apart from the long-term scenario under RCP8.5 (-8%).

3.4 Salinity

The modelling results show that the Baltic Sea saltwater intrusions into the Curonian Lagoon will likely decrease in the future.
During the historical period 48 days year[-1] of salt water intrusions were observed, i.e., the average yearly number of days when
265   salinity exceeds the 2 g kg^{-1} threshold, approximately 20 km below the lagoon sea connection. In the short-term, this number
will decrease by 60% under RCP4.5 scenario (19 days year[-1]) and 65% under RCP8.5 scenario (17 days year[-1]) compared with
the historical period. While in the long-term, it will decrease by ~67% under RCP4.5 (16 days year[-1]) and 83% under RCP8.5
scenario (8 days year[-1]).

Seasonally, the highest change of saltwater intrusion days is observed during winter and especially spring, when the outflow
270   of the lagoon is dominating and there are no water intrusions from the Baltic Sea (right side of Fig. 8). Saltwater intrusions
during summer season have a larger decrease under RCP8.5 scenario than RCP4.5, which does not have a distinct pattern in
the future. In autumn, the changes in the short-term are similar under both scenarios ~27% decrease compared with the
historical period, and it continues to decline in the long-term as well.

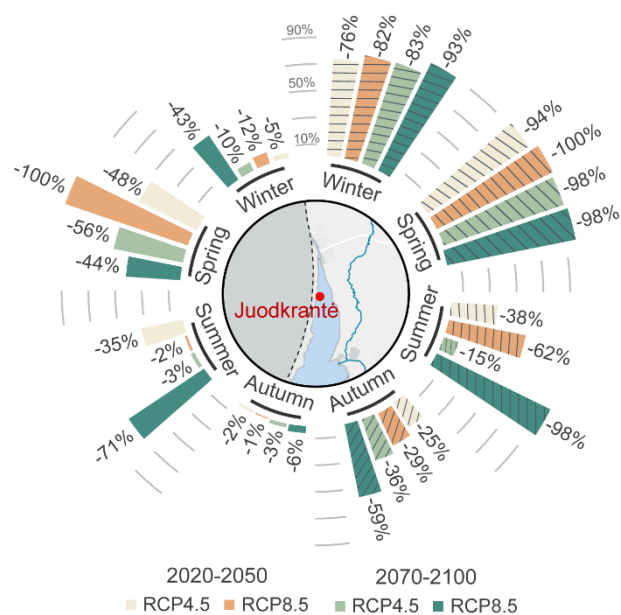



**Figure 8. The percentage of change of seasonal average salinity of saltwater intrusions (solid pattern – left) and number of days
when salinity exceeded the 2 g kg⁻¹ threshold (hatched pattern – right) in Juodkrantė, approximately 20 km below the strait
connecting the Baltic Sea and the Curonian Lagoon. Values denote the percentage of difference of the scenario runs compared with
the historical period (1975–2005).**

The severity of the saltwater intrusions is also predicted to decrease (left side of Fig. 8). The pattern is similar to that of the
280   number of days of saltwater intrusions. Due to the increased outflow from the lagoon during spring, the changes are the highest
in the same period.

Salinity in the south-eastern Baltic Sea show a decreasing pattern throughout the analysis periods. Under RCP4.5 scenario,
there is a small salt content decrease projected – 5–6% less in the short-term and 11–18% in the long-term (Table 4), compared
with the historical period. Difference between the RCP scenarios are only apparent in the long-term, where the change is
285   projected to be higher under RCP8.5 scenario. In the Baltic Sea there is no difference of average salinity throughout the seasons.

| | | 1975-2005 | 2020-2050 | | 2070-2100 | |
		Historical	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Coastal waters	Winter	6.6	5.9 (-11%)	5.8 (-13%)	5.4 (-18%)	4.8 (-27%)
	Spring	5.4	4.9 (-11%)	4.8 (-12%)	4.4 (-18%)	4.0 (-26%)
	Summer	5.4	5.1 (-4%)	5.0 (-7%)	4.8 (-12%)	4.3 (-20%)
	Autumn	6.3	5.9 (-6%)	5.8 (-8%)	5.5 (-13%)	5.0 (-21%)
Baltic Sea	Winter	7.8	7.4 (-5%)	7.3 (-6%)	6.9 (-11%)	6.4 (-18%)
	Spring	7.7	7.4 (-5%)	7.3 (-6%)	6.9 (-11%)	6.3 (-18%)
	Summer	7.8	7.4 (-5%)	7.3 (-6%)	7.0 (-11%)	6.4 (-18%)
	Autumn	7.8	7.4 (-5%)	7.3 (-6%)	7.0 (-11%)	6.4 (-18%)

**Table 4. Average seasonal salinity in the Baltic Sea and along the south-eastern Baltic coast. Percentage in the brackets shows the
change of the scenario runs compared with the historical period (1975–2005).**

Salinity in the coastal area is slightly lower compared to that of the Baltic Sea. However, here the difference of seasons is more
apparent, having a higher decease of salinity values during winter and spring when the discharge of freshwater from the
290   Curonian Lagoon increases. In the coastal waters the highest change, compared with the historical period, is also projected to
be under RCP8.5 scenario. Notably, the highest decrease is projected northward of Klaipėda Strait (lagoon outlet), while
southward the change is lower and salinity values are similar to that of south-eastern Baltic Sea

3.5 Water temperature

The water temperature in the Curonian Lagoon is relatively homogeneous throughout its area with slightly warmer water (by
295   on average 0.4 °C) in the northern part of the lagoon. Considering the seasonal dynamics, water temperature is projected to
increase the most during winter, by ~60% in the short-term and more than twice in the long-term (Table 5). During spring and
autumn, the increase is lower – ~17% in the short-term and 19–27% in the long-term. The lowest increase is projected during
summer season – 5–6% in the short-term and 9–13% in the long-term. The more apparent difference between the RCP
scenarios is observed during the long-term, where RCP8.5 displays a higher temperature increase.

300

| | | 1975-2005 | 2020-2050 | | 2070-2100 | |
		Historical	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Lagoon	Winter	1.5	2.5 (60%)	2.5 (61%)	3.1 (102%)	3.9 (151%)
	Spring	8.3	9.6 (16%)	9.8 (18%)	9.9 (19%)	10.5 (27%)
	Summer	19.8	20.8 (5%)	20.9 (6%)	21.6 (9%)	22.3 (13%)
	Autumn	10.5	11.7 (11%)	12.0 (14%)	13.1 (24%)	13.8 (32%)
Coastal waters	Winter	2.6	3.7 (42%)	3.7 (42%)	4.4 (72%)	5.9 (129%)
	Spring	5.4	6.7 (24%)	6.8 (26%)	7.0 (30%)	8.4 (56%)
	Summer	16.0	17.0 (7%)	17.2 (8%)	17.7 (11%)	19.2 (20%)
	Autumn	12.0	13.1 (9%)	13.4 (11%)	14.4 (20%)	15.8 (31%)
Baltic Sea	Winter	4.2	5.2 (24%)	5.3 (26%)	5.9 (41%)	7.2 (71%)
	Spring	3.4	4.5 (30%)	4.6 (33%)	5.1 (50%)	6.3 (85%)
	Summer	7.4	8.5 (14%)	8.6 (16%)	9.2 (23%)	10.4 (40%)
	Autumn	8.3	9.3 (12%)	9.4 (13%)	10.1 (21%)	11.3 (35%)

Table 5. Average seasonal water temperature (in °C) in the Curonian Lagoon and Baltic Sea. Percentage in the brackets shows the change of the scenario runs compared with the historical period (1975–2005).

In general, in the Baltic Sea the highest change of water temperature is projected in the long-term than in the short-term (Table 5). Seasonally, the highest increase is estimated in winter and spring during both analysis periods, of which the highest change is under RCP8.5 scenario, compared with the historical period. The smallest change throughout the analysis periods is projected in summer and autumn. There is no apparent difference between the RCP scenarios in the short-term, contrary to the long-term, when the RCP8.5 scenario displays a higher water temperature increase.

The seasonal dynamics in the coastal area (nearshore temperature) is very similar to the whole south-eastern Baltic Sea. Although, the water temperature is slightly lower during the winter season, on average by 1.5 °C, and higher during other seasons, on average by 4.9 °C. The changes between the analysis periods and RCPs scenarios comparing with the historical period are higher than that of the south-eastern Baltic Sea.

3.6 Water level

The water level in the Curonian Lagoon usually varies between -0.2–0 m during the historical period. In the short-term projections, the model estimates a water level increase by 17–20 cm compared with the historical period (Table 6). The highest increase can be estimated in the long-term, when the water level in the lagoon increases by 32 cm under RCP4.5 and 41 cm under RCP8.5 scenario, compared with the historical period. For the latter, the highest increase is observed in the Nemunas Delta and northern part of the lagoon.

	1975-2005	2020-2050		2070-2100	
	Historical	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Baltic Sea	-0.15	0.01	0.03	0.17	0.23
1 Klaipėda Strait	-0.13	0.04	0.06	0.19	0.26
2 Northern CL	-0.06	0.11	0.13	0.26	0.35
3 Nemunas Delta	-0.06	0.11	0.14	0.26	0.35
4 Central CL	-0.07	0.10	0.12	0.25	0.33
5 Southern CL	-0.08	0.09	0.11	0.24	0.33

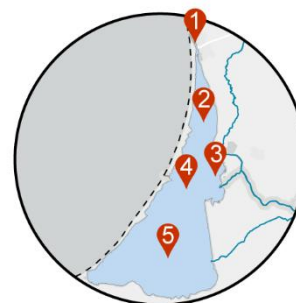



Table 6. The average water level during the historical (1975–2005) and the short- (2020–2050) and long-term (2070–2100) periods under RCP4.5 and RCP8.5 scenarios. Data were averaged over south-eastern Baltic Sea and five selected points in the Curonian Lagoon (CL) as shown in the map insert.

330 The water level in the Baltic Sea, as well as the coastal area, is homogeneous and most of the time staying below the sea level during the historical period. The water level in the sea is expected to rise by 16–19 cm in the short-term and by 32–39 cm in the long -term, compared with the historical period (Table 6). This change is one half of that in the Curonian Lagoon. At the domains' connective area – Klaipėda Strait, the water level corresponds mostly to the dynamics of it in the sea.

3.7 Water residence time

335 The water residence time (WRT) generally is likely to have a decreasing tendency, apart from the summer season, when it slightly increases (Table 7). In the northern part of the lagoon WRT is always shorter, while the southern part has higher values, because the water movement in this area is more driven by wind than by the outflowing rivers (e.g., Nemunas). There is no apparent difference between the climate scenarios in the short-term. The highest decrease, compared with the historical period, is observed in the long-term under RCP8.5 scenario.

		1975-2005	2020-2050		2070-2100	
		Historical	RCP45	RCP85	RCP45	RCP85
North	Winter	61	49 (-21%)	48 (-21%)	46 (-24%)	41 (-32%)
	Spring	44	39 (-11%)	40 (-9%)	41 (-7%)	39 (-12%)
	Summer	59	63 (7%)	63 (6%)	66 (11%)	61 (4%)
	Autumn	67	66 (-1%)	66 (-1%)	67 (0.03%)	62 (-7%)
South	Winter	174	123 (-29%)	119 (-32%)	112 (-36%)	88 (-49%)
	Spring	122	96 (-22%)	99 (-19%)	101 (-17%)	94 (-23%)
	Summer	179	196 (9%)	199 (11%)	217 (21%)	192 (7%)
	Autumn	180	178 (-1%)	178 (-1%)	176 (-2%)	158 (-12%)
Total	Winter	127	95 (-25%)	93 (-27%)	88 (-30%)	73 (-43%)
	Spring	94	76 (-18%)	79 (-16%)	80 (-14%)	75 (-20%)
	Summer	129	140 (8%)	140 (8%)	147 (14%)	134 (4%)
	Autumn	135	133 (-1%)	133 (-1%)	133 (-2%)	120 (-11%)

340 **Table 7. Seasonal water residence time (in days) in the northern, southern, and total lagoon area under RCP4.5 and RCP8.5 scenarios, averaged over historical (1975–2005), short-term (2020–2050), and long-term (2070–2100) periods. Percentage in the brackets shows the change compared with the historical period.**

The highest WRT in the Curonian Lagoon is during summer and autumn when the discharge from the surrounding rivers decreases. Seasonal changes compared with the WRT during the historical period revealed that the highest decrease is observed

345 during winter, followed by spring. During summer WRT slightly increases under both RCP scenarios and both analysis periods, while in autumn the changes are negligible, apart from RCP8.5 scenario in the long-term, when the WRT decreases by ~10%, compared to the historical period.

3.8 Ice thickness

Ice thickness in the Curonian Lagoon is projected to decrease steadily. The average maximum ice thickness during the short-

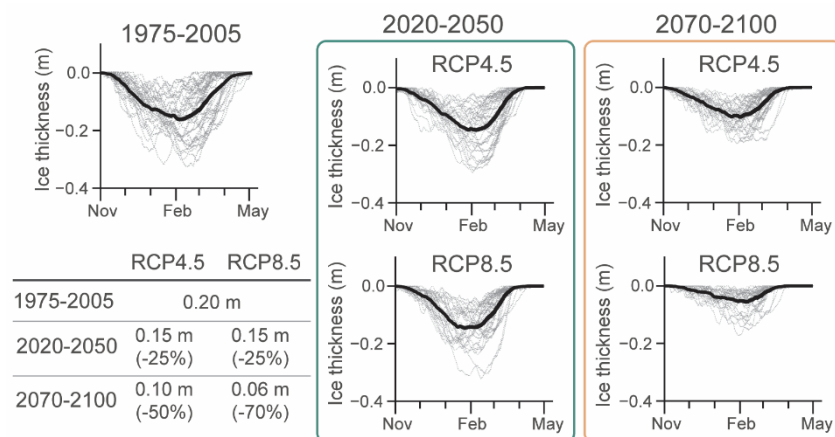
350 term period can decrease by 25% compared with the historical period. Additionally, there is no apparent difference between the RCP scenarios (Fig. 9). Adverse case is with long-term projections, for which the average maximum ice thickness under RCP4.5 scenario is estimated to decrease by half and by 70% under RCP8.5 scenario, compared with the historical period. These changes indicate a possible severe modification of ice regime in the lagoon, leading to winter seasons with a more likely unstable thin ice cover.

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Figure 9. Average ice thickness in the Curonian Lagoon. Black line indicates the average ice thickness of each analysis period – historical (1975–2005), short-term (2020–2050), and long-term (2070–2100) under RCP4.5 and RCP8.5 scenarios. Table shows the average maximum ice thickness and a percentage of change of the scenario runs compared with the historical period.

4 Discussion

360 The results above give an indication on the variation of the physical parameters that the Nemunas River watershed, Curonian Lagoon, and south-eastern part of the Baltic Sea will be subjected to. All parameters indicate a change, more or less strong, until the end of this century. These changes will be discussed hereafter.

4.1 Local climate insights

The results of this study have been achieved with regional climate models that have been downscaled from global models. The
365 quality of the model output was generally good, but a comparison with local observed data showed the need to ultimately
correct the downscaled data by applying a bias correction. This was needed because some variables (precipitation suffices as
one example) were far from being well produced by the regional climate models (Tapiador et al., 2019).

As summarized in the BACC assessments – the Baltic Sea region is warming and it will continue to warm throughout the 21st
century (Meier et al., 2022a). Accordingly, our study results show a considerable increase in the projected air temperatures as
370 well (Table 8). These changes will likely result in warmer conditions during winters, less snow and ice cover as well as higher
river discharge in winter, while the increase of air temperature during other seasons might have a severe impact on the crop
production, increase the occurrence of hydrological and/or agricultural droughts and impact changes in the crop calendar of
the region.

Parameter	Domain	2020-2050		2070-2100	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
Air temperature	Marine area	21%	23%	34%	57%
	Terrestrial area	33%	35%	51%	81%
Precipitation	Marine area	14%	15%	18%	34%
	Terrestrial area	14%	16%	18%	35%
Water inflow	Nemunas River to Lagoon	13%	16%	19%	37%
Water outflow	Lagoon to sea	15%	18%	21%	40%
Salinity	Coastal area	-8%	-10%	-15%	-24%
	Sea	-5%	-6%	-11%	-18%
Saltwater intrusions (No of days year^{-1})	Juodkrantė	-30%	-34%	-34%	-51%
Water temperature	Lagoon	11%	13%	19%	26%
	Coastal area	13%	14%	21%	37%
	Sea	17%	19%	30%	50%
Water residence time	Norther part of the lagoon	-6%	-6%	-5%	-12%
	Southern part of the lagoon	-10%	-9%	-8%	-19%
	Total lagoon area	-8%	-8%	-8%	-17%

Table 8. Summary of the percentage change of projected average annual changes (under RCP4.5 and RCP8.5 scenarios) during
375 **short-term (2020–2050) and long-term (2070–2100) periods compared with the historical period (1975–2005).**

With increasing mean temperatures, a distinct increase in the projected monthly and annual average precipitation is also
expected. Our results show that by the end of the century an increase of the total annual precipitation by 18 to 34% (~100–200

mm) according to RCP4.5 and RCP 8.5 scenarios respectively, is projected. In comparison with a neighbour country, this is considerably higher than the projected precipitation for the Latvian case, where the total annual increase was estimated to be

380   13 to 16% (~80–100 mm) under the same scenarios (Avotniece et al., 2017).

4.2 Water flow

The driving force of changes in the lagoon are the boundaries – the Nemunas River inputs and the influence of the Baltic Sea through the Klaipėda Strait. Historically every year on average Nemunas River supplies three times the volume of water to the lagoon (Žilinskas et al., 2012), which is subject to change in the future. The projections indicate a 13–16% (in the short-term)

385   and 19–37% (in the long-term) increase in water discharge from the river, which coincides with the projected precipitation increase (Table 8). This projected change alone will strongly influence the hydrodynamic conditions of the lagoon.

Due to the enhanced Nemunas discharge, the fluxes from the Curonian Lagoon into the Baltic Sea will also increase. The outflow to the sea is already dominating, especially in the northern part of the lagoon and it will remain so in the future. The water flow will increase in all its path towards the Baltic Sea by 13–18% in the short-term and by ~20% under RCP4.5 scenario

390   in the long-term, while the changes under RCP8.5 scenario can be expected to increase by up to 40% by the end of the century, compared with the historical period (Table 8).

The volume of discharging river water into the Baltic Sea is projected to be dependent on the season and the region (Graham, 2004; Meier et al., 2022a). With this, the increase of riverine nutrient loads is also anticipated (Pihlainen et al., 2020), likewise suggesting that "land based nutrient management will have greater effect on nutrient loads than greenhouse gas emissions"

395   (Climate Change in the Baltic Sea: 2021 Fact Sheet).

The seasonal river discharge changes in the Baltic Sea correspond with our study noting that a more likely increase in winter and decrease in summer can be expected by the end of this century (Donnelly et al., 2014). The magnitude of changes of freshwater inflow within different subregions of the Baltic Sea has a considerable variation, i.e., an increased outflow in the northern part of the Baltic Sea and a decreased in the southern part (Graham, 2004). Although the combined uncertainties from

400   the climate models, their bias correction, and applied models make it difficult to draw conclusions about the magnitude of change (Donnelly et al., 2014).

The most alarming are the projected hydrologic changes in the Nemunas River watershed during the winter season in the long-term period. As supported by other studies (Čerkasova et al., 2021; Stonevičius et al., 2017), both RCPs point toward a drastic increase in winter discharges, which might lead to severe flooding of the delta region, which suffers from annual floods of

405   different magnitude (Valiuškevičius et al., 2018). Currently these flood events occur in spring, but will likely occur in winter in the future, and with increased severity, which will pose a serious concern to the local population and stakeholders. The currently functioning polder system in the Nemunas River delta (Lesutienė et al., 2022) region might not withstand such changes.

4.3 Water level dynamics

410 Water levels are the main drivers, together with the Nemunas discharge, of the exchanges through the Klaipėda Strait. In the strait and particularly in the Curonian Lagoon water levels are higher than in the Baltic Sea, which leads to an increase in outflow periods through the strait. Since 1960 until 2008, the average measured water level in the Curonian Lagoon has been rising at a rate of approximately 3.0 mm year^{-1}, leading to increase by 18 cm during this period (Čepienė et al., 2022, and references therein). Our modelling results showed that in the future, water level is projected to increase by 16–20 cm in the

415 short-term and by 32–41 cm in the long-term, compared with the historical period.

Since the projected water level will be above the mean sea level, it could affect the infrastructure and residents living in the coastal area leading to a significant social and economic damages (Vousdoukas et al., 2020). The low elevation wetland areas covering the southern and eastern part of the lagoon (especially Nemunas Delta area) are more likely of getting flooded. However, the Klaipėda city and the Curonian Spit are located higher and the mean water level rise should not permanently

420 affect these areas. It is worth mentioning, that the hydrodynamic model has a fixed boundary, thus the increase could be overestimated especially considering the role of coastal wetlands in mediation of global change induced water level changes.

4.4 Salinity dynamics

When looking at the saltwater intrusion events, it can be clearly seen that the intrusion periods are decreasing and the outflow from the lagoon becomes dominant, simply because the outflowing water fluxes will stop the salty seawater from entering the

425 Curonian Lagoon. This is clearly evident for both climate change scenarios – periods where values higher than the threshold of 2 g kg^{-1} in Juodkrantė drops by 30–50% compared with the historical period (Table 8). This will lead to some alteration of the ecosystem in the northern part of the Curonian lagoon, which is now considered as oligohaline.

As seen and suggested from other Baltic Sea salinity projection studies, the salinity in the Baltic does not have a distinct pattern of changing in the future and the projections have a lot of uncertainties (Lehmann et al., 2022; Meier et al., 2022b). Our study

430 of salinity changes in the south-eastern Baltic Sea demonstrates a decreasing tendency, especially in the coastal area, northward from the lagoon outlet, where the sea water is diluted by discharging freshwater from the lagoon (Table 8).

4.5 Water temperature dynamics

The mean temperature of the water column in the Klaipėda Strait is less sensitive to changes. In the lagoon water temperature is projected to increase under both RCP scenarios compared with the historical period. The highest changes are projected in

435 the long-term under RCP8.5 scenario (Table 8).

The increasing temperature patterns are also evident in the south-eastern Baltic Sea, having a higher increase in the long-term than in the short-term. The highest change, compared with the historical period, is mostly occurring during winter and spring. Considering only the coastal area, it represents similar dynamics of the sea, although, having higher changes compared with

the historical period. Additionally, the coastal average water temperature is lower by 1.5 °C during the winter and higher by
440 4.9 °C during the rest of the year than that of the south-eastern Baltic Sea.

Our study supports the findings of projected increasing water temperature in the Baltic Sea (Meier et al., 2022b). In this article
we focused only on the average water temperature of the water column, however, there are many studies revealing the warming
patterns of the sea surface temperature in the Baltic (Dutheil et al., 2022; Zhu et al., 2022).

4.6 Water residence time in the lagoon

445 Water residence time (WRT) is generally decreasing with climate change (Table 8), although the decline is small in the short-
term and in the long-term under RCP4.5 scenario (5–10% less). A general decrease can be found in the whole area of the
lagoon in the long-term under RCP8.5 (17%). As in the case with saltwater intrusions, this is due to the increased outflow from
the lagoon to the sea, where WRT are less varying in the north, whereas it decreased sensibly in the south.

When looking at seasonal changes, WRT becomes lower in summer due to decreasing river discharge. Comparing the changes
450 from the historical period it revealed that the highest decrease is observed during winter and spring, presumably due to the
increased outflowing water fluxes and change of the ice cover regime.

4.7 Ice thickness in the lagoon

Ice thickness projections in the lagoon will become thinner for a longer period during the ice season compared to the historical
period. The projected changes of 25% decreased maximum ice thickness in the short-term and 50–70% in the long-term, could
455 presume leading to severe alteration of the ice season regime in the future. This pattern corresponds to the trends in the southern
Baltic lagoons (Girjatowicz and Świątek, 2021) and gulf of Riga (Siitam et al., 2017; Kļaviņš et al., 2016;), as well as Baltic
Sea itself (Luomaranta et al., 2014).

Ice in the Curonian Lagoon has become a trending topic in the recent years, due to its already evident changes as seen from
the historical observations (Jakimavičius et al., 2019), remote sensing (Kozlov et al., 2020; Idzelytė et al., 2019), as well as
460 modelling studies of future projections (Idzelytė and Umgiesser, 2021; Jakimavičius et al., 2019). The decreasing ice
parameters impact on the hydrodynamics of the lagoon suggest a possible increase of water flow and saltwater intrusions, as
well as shorter WRT during the ice cover season (Idzelytė et al., 2020; Umgiesser et al., 2016). Although, the role of ice for
controlling WRT is far less than the increased fluxes from the discharging rivers.

4.8 Impacts on the ecosystem structure and functions

465 Despite clear trends for physical indicators, the actual consequences of climate change for the functioning of the Curonian
Lagoon ecosystem are much more complicated to predict. The foreseen salinity changes in the mostly freshwater ecosystem
are not of the scale suggesting significant shifts in the ecosystem functioning even in the northern part of the lagoon. However,
some decrease in distribution areas of some estuarine species (mysids, barnacles) could be foreseen.

A recent analysis (Ivanauskas et al., 2022) indicated statistical relationship between WRT and salinity and both catches and
470   populations of main commercial fish populations. This is in stark contrast to the predictions for the Baltic Sea fishery, where
catches are expected to be decreasing in quantity, and especially in the quality (Climate Change in the Baltic Sea, 2021). This
could be explained by the fact that commercial catches in the Curonian Lagoon already are dominated by eutrophication
tolerant species like bream and pikeperch, which are also known to prefer higher water temperatures. However, projected ice
cover decrease will inevitably negatively affect the winter ice fishing practices in the lagoon.

475   The latest studies, revealing the mechanisms of nutrient cycling and eutrophication processes (Bartoli et al., 2018), point
toward the expected reduction of the role of the Curonian Lagoon as a coastal filter. The shortening of the ice cover period
will reduce the system denitrification capacity while the decrease of WRT will lead to substantial reduction of nutrient
retention. So far, the only difference is the more favourable conditions for the cage aquaculture in the lagoon, where the
decreased WRT and increased flushing in combination with modern practices of multi trophic aquaculture (e.g. floating
480   vegetable gardens) could remove some of the constraints existing at present.

5 Conclusions

The setup of the complex Nemunas River–Curonian Lagoon–Baltic Sea model has been successfully used in the climate change
studies presented in this paper. The high-resolution hydrological model for the Nemunas River and hydrodynamic model for
the Curonian Lagoon and the Baltic Sea were used. The finite element approach has allowed us to achieve a good compromise
485   of needed resolution and computer efficiency to carry out all needed hydrodynamic simulations. With the help of downscaled
climate models, which have been ultimately bias-corrected with observations, the tendency of changes was inferred.

The study results showed that the Curonian Lagoon will be subject to higher Nemunas discharges that will in turn increase the
outgoing fluxes into the Baltic Sea. Through these higher fluxes both water residence times and saltwater intrusion events will
decrease. Most of these changes will however be only noticeable in the northern part of the lagoon, which are more likely to
490   be influenced by the Nemunas discharge. The southern part of the lagoon will experience much less changes.

The foreseen changes in physical characteristics are not of the scale suggesting significant shifts in the ecosystem functioning,
but expected rather to manifest in some quantitative alterations in the nutrient retention capacity. However, some ecosystem
services such as ice fishing are expected to be completely vanishing due to the physical constraints.

Whereas tendencies could be identified in our analysis, it was yet not possible to discuss the uncertainty of the results achieved.
495   This can be done only through extensive sensitivity analysis, and was not part of the scope of this research article. It will
however be part of another investigation that will be carried out in the near future.

Data availability

All numerical modelling results created during this study are openly available in the Zenodo open data repository (https://doi.org/10.5281/zenodo.7500744) as cited in Idzelytė et al. (2023).

500 **Author contribution**

GU and NC initiated the conceptualization and funding acquisition of the research project. RI, NC, and JM performed the analysis and drafted the paper. RI curated the visualization of the results. RI, NC, JM, TD, ARB, AE prepared the original manuscript draft with the assistance of GU. All co-authors reviewed the paper and contributed to the scientific interpretation and discussion.

505 **Competing interests.**

The authors declare that they have no conflict of interest.

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