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ORIGINAL RESEARCH ARTICLE

Impact of climate change on the Curonian Lagoon water balance components, salinity and water temperature in the 21st century

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Summary The Curonian Lagoon is a shallow water body connected to the Baltic Sea by a narrow navigable strait, which enables an exchange of water of different salinity. The projected climate change together with the peculiarities of mixing water will undoubtedly alter hydrological regime of this lagoon. The study uses three climate model outputs under four RCP scenarios, four sea level rise scenarios and hydrological modelling in order to project the extent to which water balance components, salinity and temperature may change in the future. In order to simulate river inflow, the Nemunas River hydrological model was created using HBV software. In general, the changes of the lagoon water balance components, salinity and temperature are expected to be more significant in 2081—2100 than in 2016—2035. It was estimated that in the reference period (1986—2005) the river inflow was 22.1 km^3, inflow from the sea was 6.8 km^3, salinity (at Juodkrantė) was 1.2 ppt and average water temperature of the lagoon was 9.2°C. It was projected that in 2081—2100 the river inflow may change from 22.1 km^3 (RCP2.6) to 15.9 km^3 (RCP8.5), whereas inflow from the sea is expected to vary from 8.5 km^3 (RCP2.6) to 11.0 km^3 (RCP8.5). The lagoon salinity at Juodkrantė is likely to grow from 1.4 ppt (RCP2.6) to 2.6 ppt (RCP8.5) by the end of the century due to global sea level rise and river inflow decrease. The lagoon water temperature is projected to increase by 2—6°C by the year 2100.

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1. Introduction

Lagoons represent a complex and unique coastal environment which requires special attention in the context of climate change (Lillebo et al., 2015). These water bodies are especially sensitive to any environmental changes. Water temperature and sea level rise that in turn leads to an increase in water salinity are fundamental environmental descriptors that play a vital role in sustainability of lagoon ecosystems. Both of them are projected to change in the future (Anthony et al., 2009).

The rise of sea surface temperature (SST) is tightly connected with the effects of climate change. According to observation data beginning in 1880, the global ocean warms by 0.005°C year^{-1} (Huang et al., 2014; Liu et al., 2014). Considerably stronger growth tendencies of SST were estimated in 1986—2005: 0.02°C year^{-1} (Huang et al., 2015a). SST in European seas is increasing more rapidly than in the global oceans. The rate of increase is higher in the northern European seas and lower in the Mediterranean Sea (Coppini et al., 2007). The results obtained by Stramska and Białogrodzka (2015) also revealed that this process takes place slightly faster in inner and relatively close seas, e.g. according to the data of 1982—2013, SST increased from 0.03 to 0.06°C year^{-1} in the Baltic Sea (depending on location). In the 21st century, the generally expected warming of the annual Mediterranean SST ranges from 0.45°C in the RCP2.6 scenario, through 1.15°C in the RCP4.5 scenario and 1.42°C in the RCP6.0 scenario, to 2.56°C in the RCP8.5 scenario (Shaltout and Omstedt, 2014). The rises of global surface temperature by the year 2100 projected by the IPCC should range from about 1.3°C for RCP 2.6 to 4.4°C for RCP 8.5 (IPCC, 2013).

According to the data of 1880—2009, the global mean sea level rise (SLR) was 1.6 mm year^{-1} (Church and White, 2011). As reported by Navrotskaya and Chubarenko (2013), over the past 150 years, the rate of SLR in the lagoons and coastal areas of the Southeast Baltic Sea (1.7—1.8 mm year^{-1}) is close to the SLR rate in the World Ocean. In the second half of the 20th century, the rate of SLR in the lagoons and marine areas became stronger: up to 3.6 mm year^{-1} in the Vistula Lagoon and in 1959—2006 in the Baltic Sea, exceeding the rate of the global ocean SLR. Similar tendencies of water level changes are identified for the Curonian Lagoon, but they depend on the length of available data series. For example, in the period of 1986—2005 (the reference period), the Curonian Lagoon water level grew 1.64 mm year^{-1}. If other data series are used (e.g. 1961—1990), the rate of this growth may reach 4 mm year^{-1} (Dailidienė et al., 2011; Jakimavičius and Kriaučiūnienė, 2013). Projections of relative SLR indicate a statistically significant increase in mean sea level along the entire European coastline: by around 21 and 24 cm by the 2050s under RCP4.5 and RCP8.5 respectively to reach 53 and 74 cm by the end of the century (Vousdoukas et al., 2017). However, according to Grinsted et al. (2015), SLR is not uniform globally but is affected by a range of regional factors: the median 21st century relative SLR projection is 80 cm near London and Hamburg, with a relative sea level drop of 0.1 m in the Bay of Bothnia (near Oulu, Finland).

As a consequence of sea level rise, the increase of seawater intrusion to transitional water bodies (lagoons and estuaries) is supposed to occur (Chen et al., 2016; Liu and Liu, 2014; Vargas et al., 2017). Less fresh water might also reach such water bodies due to reduced river inflow (Dailidienė and Davulienė, 2008; Jakimavičius and Kovalenkovienė, 2010; Vargas et al., 2017). Water salinity of the Curonian Lagoon also mainly depends on fresh (inflowing from rivers) and brackish (entering from the Baltic Sea) water exchange, which is a complex process with many driving factors. Zemlys et al. (2013) developed a 3D model to reveal characteristic features of water exchange between these two water bodies and related vertical and horizontal salinity distributions. The later study (Umgiesser et al., 2016) showed that the most important physical force that influences the water renewal time in the Curonian Lagoon is the Nemunas River discharge. The investigation by Dailidienė and Davulienė (2008) proved that the mean water salinity in the Klaipėda Strait and in the northern part of the Curonian Lagoon in 1984—2005 was increasing, but whether it is going to increase in the future has not yet been assessed.

Sea surface temperature, level rise and salinity are closely related with each other and with water balance elements. All of these variables are changing and are expected to change in the future as direct or indirect consequences of global climate warming. SST and salinity have a considerable importance for marine organisms, may directly affect the state of ecosystem, limit the number of species, and are very important for juveniles' incubation period. Surveys, such as the ones conducted by Gasiūnaitė (2000), Gasiūnaitė and Razinkovas (2002), have shown that zooplankton in the northern part of the Curonian Lagoon is very sensitive to salinity variation. Effects of different salinity conditions on the abundance and community composition of some aquatic macrophytes and microorganisms in the Curonian Lagoon were assessed by Kataržytė et al. (2017). Increased summer water temperature causes ongoing eutrophication and algae blooms in the Curonian Lagoon. Harmful algal blooms in July—October result in the deterioration of water chemical parameters, death of fish in the coastal zone and pollution with toxins (Aleksandrov et al., 2015).

The Curonian Lagoon is regarded as a water body abundant with fish, temporarily or permanently inhabited by around 50 fish species. This unique and valuable lagoon ecosystem is going to experience the impact of climate change due to increased water salinity and higher water temperature. There is an increasing concern that this ecosystem may be strongly modified or destroyed in the future by the projected changes.

This study intends to use climate model outputs under RCP scenarios and hydrological modelling in order to project the extent to which water balance components, salinity and temperature of the Curonian Lagoon will change in two future periods: 2016—2035 and 2081—2100.

The expected future changes were projected according to a new set of scenarios (called the Representative Concentration Pathways (RCPs)) presented in the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC, 2013). When climate model outputs of the new generation (Representative Concentration Pathways — RCP) scenarios are used, hydrological modelling may be applied to assess the future environmental changes that are likely to happen in case any scenario occurs.

2. Material and methods

2.1. Study area

The Curonian Lagoon is a shallow water body that is separated from the Baltic Sea by a narrow, dune-covered sand spit (the Curonian Spit) (Fig. 1). At its north end, the lagoon is connected to the Baltic Sea by the navigable Klaipėda Strait. The east coast of the lagoon is low, forested wetland, part of which forms the Nemunas River delta.

The Curonian Lagoon is a territory of high international environmental value. The Nemunas delta has a regional park status and belongs to the Ramsar Convention sites. The lagoon meets the requirements of the Bonn Convention and is one of the most valuable and important bird areas in Lithuania. In 1929, in a headland of the Nemunas delta — Ventė Cape, a famous Lithuanian ornithologist professor T. Ivanauskas opened an ornithology station, where each year about 60—80 thousand birds are ringed. The Curonian Lagoon is famous for its abundance of fish as well. The Curonian Spit is declared a national park and is included in the UNESCO World Heritage List.

The whole surface area of the lagoon is 1584 km^2 (Červinskas, 1972). Lithuania owns only 381.6 km^2 of its northern part (Žilinskas and Petrokas, 1998). The average depth of this shallow lagoon is 3.8 m. The greatest depth is in the northern part, where the Klaipėda Seaport is located and the water territory is dredged up to 16 m. The total volume of the lagoon is 6.2 km^3 (Gailiušis et al., 2001). The residence time of lagoon water in the northern basin is about 77 days, while the average for the southern basin is nearly 200 days (Umgiesser et al., 2016).

On average, the Nemunas discharged 22.1 km^3 year^{-1} of fresh water to the eastern part of the lagoon in the period of 1986—2005. Depending on the ratio of brackish water inflow from the Baltic Sea through the Klaipėda Strait and fresh water coming from the Nemunas River, salinity of the entire Curonian Lagoon changes. According to the data of 1986—2005, salinity in the Curonian Lagoon is 2.5 ppt at Klaipėda, 1.2 ppt at Juodkrantė, and less than 0.1 ppt at Ventė and Nida.

2.2. Methodology and data

Water balance of the Curonian Lagoon consists of the following components: river inflow (Q_R), precipitation on the surface of the lagoon (P), evaporation from the lagoon (E), inflow from the sea (Q_{BS}) and outflow from the lagoon (Q_{CL}). The main steps for evaluation of projections of water balance components, salinity and water temperature of the Curonian Lagoon in the 21st century were (Fig. 2): 1. Adaptation of climate scenarios for Lithuanian territory according to three climate models and 4 scenarios; 2. Evaluation of projections of water balance components of the Curonian Lagoon according to climate scenarios for near (2016—2035) and far (2081—2100) future periods; 3. Evaluation of projections of water temperature and salinity in the 21st century.

The data outputs of projected precipitation and air temperature were acquired from global climate models presented in the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC, 2013) according to a new set of RCP (Representative Concentration Pathways) scenarios (Moss et al., 2010; van Vuuren et al., 2011). Values of the daily mean air temperature T (°C) and daily amount of precipitation P (mm) in the near-future (2016—2035) and far-future (2081—2100) periods were estimated according to three climate models (GFDL-CM3, HadGEM2-ES, NorESM1-M) and four RCP scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5). The climate model cells are large (up to $2.5 \times 1.895°$). Since Lithuanian territory falls into 5 climate model cells, P and T values derived from the climate models were recalculated for 16 meteorological stations using the quantile mapping

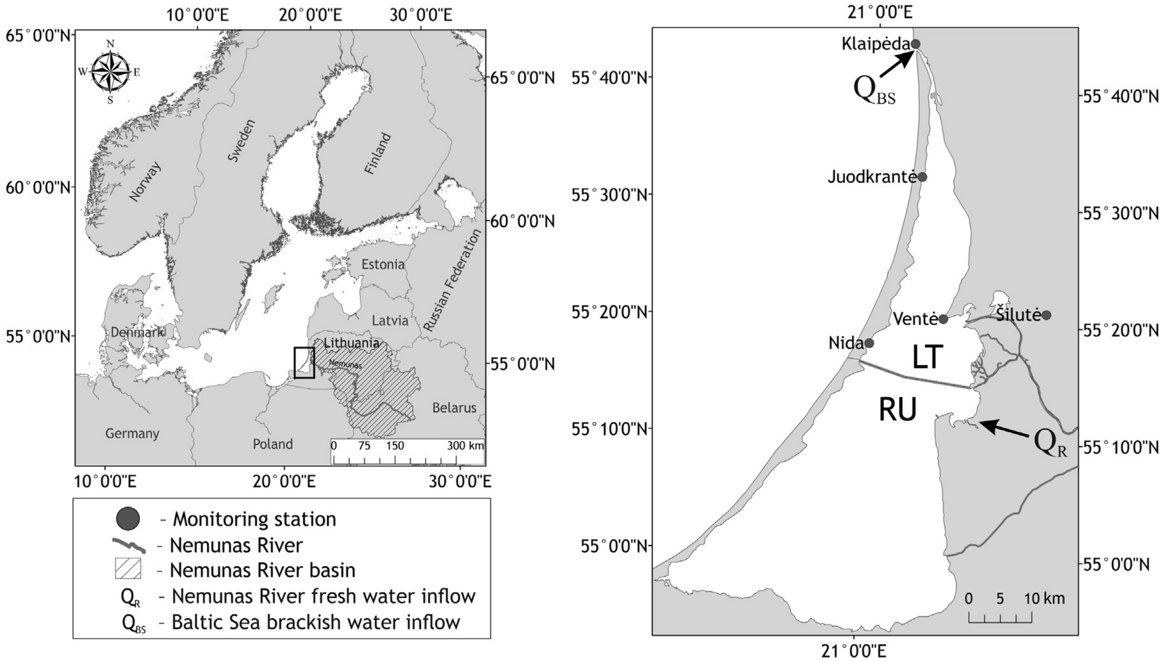

Figure 1 Location of the Curonian Lagoon and measurement stations.

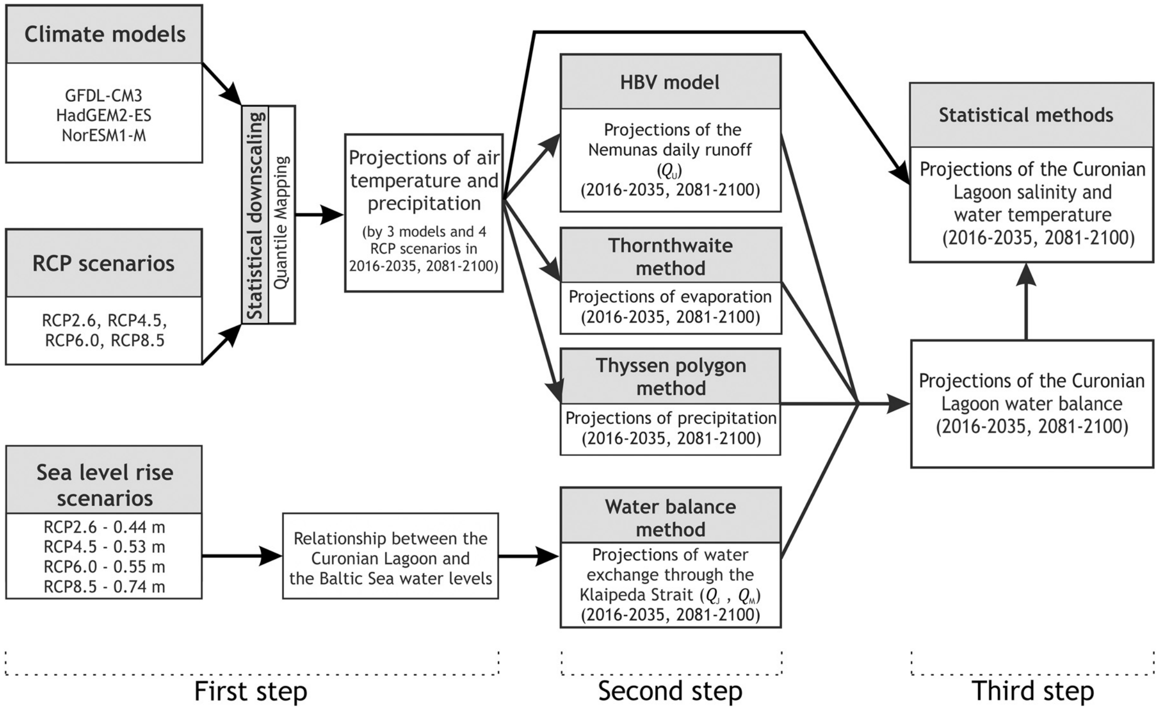

Figure 2 The principal scheme of the study.

statistical downscaling method (Teutschbein and Seibert, 2013).

The nonparametric empirical quantile method is based on the concept that there is a transformation h, which can be described by the following equation (Gudmundsson et al., 2012; Sunyer et al., 2015):

$$St^{Obs} = h\left(St^{CM\,RP}\right) = ECDF^{Obs-1}\left(ECDF^{CM\,RP}\left(St^{CM\,Fut}\right)\right), \qquad (1)$$

where St^{Obs} is an observed meteorological parameter, $St^{CM\ RP}$ is the climate model output for the reference period, $ECDF^{Obs}$ is an empirical cumulative distribution function for the observed period, $ECDF^{CM\ RP}$ is an empirical cumulative distribution function for the climate model reference period, $St^{CM\ Fut}$ is a meteorological parameter which is modelled by the climate model for the future period. All estimated results are compared with the values of the reference period (1986—2005).

Estimation of the Curonian Lagoon's future water level was performed according to 4 sea water level rise scenarios which project a water level rise of 0.44 m (RCP2.6), 0.53 m (RCP4.5), 0.55 m (RCP6.0) and 0.74 m (RCP8.5) from 2005 to 2100. Projections of the Curonian Lagoon's water level for the periods of 2016—2035 and 2081—2100 were accomplished using the lagoon level data (1986—2005) at Juodkrantė and considering the water level rising tendencies described by the scenarios.

In order to simulate river inflow to the lagoon, the Nemunas River hydrological model was created using the HBV modelling software (Integrated ..., 2005) based on the following water balance equation:

$$P - E - Q = \frac{d}{dt}[SP + SM + UZ + LZ + V], \qquad (2)$$

where P is the precipitation, E is an evaporation, Q is the runoff, SM is the soil moisture, SP is the snow pack, UZ is an upper groundwater zone, LZ is the lower groundwater zone, V is the lake or dam volume.

The daily values of river discharges (Q) in the Nemunas catchment from 10 water gauging stations (WGS) as well as T and P from 14 meteorological stations (MS) (Fig. 3) were necessary for model creation. Information about the modelled catchment area, the presence of lakes and forests, mean elevation (above sea level) of the area, WGS and MS was required as well. The created hydrological model was calibrated according to the data of 1986—1995 and validated using the data of 1996—2005. The projection of the Nemunas runoff at its mouth was estimated in daily steps for 2016—2035 and 2081—2100 using the calibrated model as well as the output data from the selected climate models and RCP scenarios.

The amount of evaporation and precipitation was calculated using the data of Klaipėda, Nida and Šilutė MS. Input of each MS was evaluated according to the Thiessen polygon method (Balany, 2011). The Thornthwaite equation was used to calculate the amount of evaporation (Thornthwaite, 1948):

$$E = 16\times\left(\frac{10\times T}{I}\right)^{a}\times\frac{\mu\times N}{360}, \qquad (3)$$

where E is the evaporation per month, (mm month^{-1}), T is the mean monthly air temperature (°C), I is an empirical annual heat index, a is an empirical I exponent, μ is the number of days in a particular month, N is the mean number of sunny hours per month (depends on a latitude). This equation was introduced quite a long time ago, but recent comprehensive scientific studies (Jakimavičius et al., 2013;

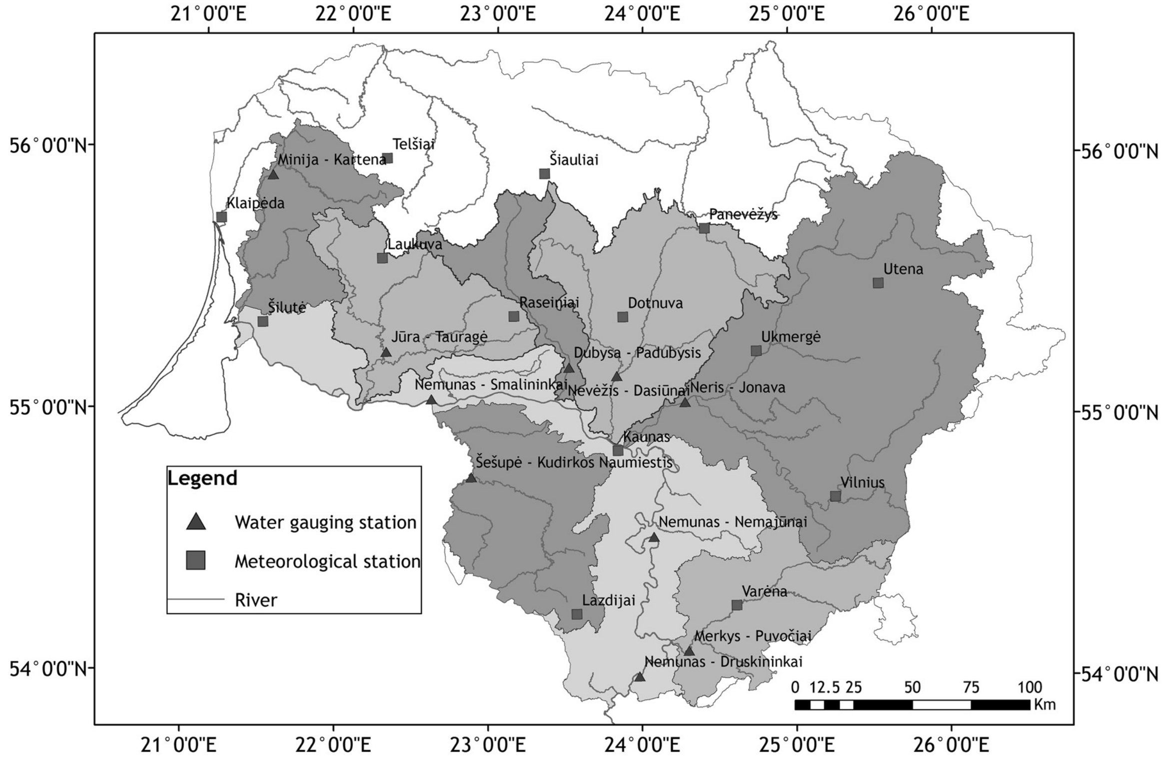

Figure 3 Location of water gauging and meteorological stations in the investigated territory of the Nemunas River catchment.

Lu et al., 2005) showed that it can still be successfully applied to estimate the evaporation rate.

Water exchange through the Klaipėda Strait was calculated using a water balance method. A modified equation of water balance created by Gailiušis et al. (1992) was applied:

$$(Q_R + P - E) + Q_{exch} = \Delta V, \tag{4}$$

$$\text{if } Q_{exch} > 0, Q_{exch} = Q_{BS}, \tag{5}$$

$$\text{if } Q_{exch} < 0, Q_{exch} = Q_{CL}, \tag{6}$$

where Q_R is the river inflow, km^3, P is the precipitation on the surface of the lagoon, km^3, E is an evaporation from the lagoon, km^3, Q_{exch} is the water exchange between the Curonian Lagoon and the Baltic Sea, km^3, Q_{BS} is an inflow from the sea, km^3, Q_{CL} is an outflow from the lagoon, km^3, ΔV is the change in the volume of the lagoon, km^3.

Change of the Curonian Lagoon volume was estimated according to the water level projection. Daily volume changes and modelled river inflow were used to estimate flow discharges between the sea and the lagoon. Values of Q_{BS} and Q_{CL} were assessed as a difference between the volume change in the Curonian Lagoon and the sum of river inflow. The negative discharge indicated a flow from the Curonian Lagoon to the Baltic Sea, while the positive discharge showed a flow of the opposite direction.

Projections of the Curonian Lagoon salinity were performed using statistical relations between water salinity at Juodkrantė (S_J) and the ratio of inflow from the sea (Q_{BS}) and the river inflow (Q_R). Monthly values of Q_{BS} and Q_R were estimated according to the multiannual water balance of the lagoon (1986—2005). Such structure of Eq. (7) was selected deliberately. Large inflow from the Baltic Sea (Q_{BS}) increases the salinity of the Curonian Lagoon, while significant inflow from the Nemunas River (Q_R) has an opposite effect. That is why the ratio of these two variables was chosen. A constant of 0.036 was selected in case if there is no inflow from the sea in a particular (modelled) month, i.e. Q_{BS} = 0. Such cases may occur in the presence of the significant discharge from the Nemunas (e.g. during floods). These phenomena are very rare: there were only 3 of them observed in 1986—2005. The constant value of 0.036 is the least monthly salinity value (ppt) in the lagoon at Juodkrantė in 1986—2005. The rest of constants (0.066, 0.635, 0.025 and 1.062) were generated using the statistical software package Statistica 10.

$$S_J = 0.036 + \left(\frac{0.066 \times Q_{BS}^{0.635}}{0.025 \times Q_R^{1.062}}\right), \tag{7}$$

where S_J is the monthly water salinity at Juodkrantė, ppt; Q_{BS} is the monthly inflow from the sea, km^3; Q_R is the monthly river inflow, km^3.

The estimated correlation coefficient between the measured salinity values and the calculated ones according to Eq. (7) was equal to 0.75. This coefficient is statistically significant when $p < 0.05$.

To project the mean monthly water temperatures of the Curonian Lagoon, statistical relations between water and air temperatures were created using the data of 1986—2005. Water temperatures at Klaipėda, Juodkrantė, Nida and Ventė were calculated using the following equations:

$$T_{\mathrm{KW}} = (0.95\times T_{\mathrm{KA}}) + 1.02, \tag{8}$$

$$T_{\mathrm{JW}} = (1.10\times T_{\mathrm{NA}})-0.31, \tag{9}$$

$$T_{\mathrm{NW}} = (1.13\times T_{\mathrm{NA}})-0.45, \tag{10}$$

$$T_{\mathrm{VW}} = \left(1.12\times T_{\substack{\text{Ï}\\ \text{ŠA}}}\right) + 0.29, \tag{11}$$

where T_{KW}, T_{JW}, T_{NW}, T_{VW} is the water temperature at Klaipėda, Juodkrantė, Nida and Ventė, °C, T_{KA}, T_{NA}, $T_{\text{ŠA}}$ is an air temperature at Klaipėda, Nida and Šilutė, °C.

Eqs. (8)—(11) are valid only for the positive air temperature. When air temperature reaches 0°C, it is assumed that in a given territory water temperature reaches 0.2°C and stabilizes. This threshold water temperature (0.2°C) was estimated as an average of minimal monthly temperatures at Klaipėda, Juodkrantė, Ventė and Nida in 1986—2005.

Correlation between the values of air and water temperatures was very high: from 0.98 (Eq. (8)) to 0.99 (Eq. (10)). These coefficients are statistically significant when $p < 0.05$.

Weighted coefficients for each WGS were estimated using the Thiessen polygon method. The mean water temperature of the Curonian Lagoon was projected according to the created statistical relations as well as air temperature projections under three climate models and four RCP scenarios for the periods of 2016—2035 and 2081—2100:

$$T_{\mathrm{CLW}} = (0.006\times T_{\mathrm{KW}}) + (0.066\times T_{\mathrm{JW}}) + (0.160\times T_{\mathrm{VW}}) + (0.768\times T_{\mathrm{NW}}), \tag{12}$$

where T_{CLW} is the mean water temperature of the Curonian Lagoon, °C.

3. Results

3.1. Calibration and validation of the Nemunas River runoff model

When creating the Nemunas catchment hydrological model, the Nemunas River from the selected starting point (Druskininkai) to the mouth (the Curonian Lagoon) was divided into separate parts sequentially attaching the catchments of: Nemunas to Druskininkai, Merkys, Nemunas from Druskininkai to Nemajūnai, Neris, Nevėžis, Dubysa, Nemunas from Nemajūnai to Smalininkai, Šešupė, Jūra, Minija and Nemunas from Smalininkai to the Curonian Lagoon (Fig. 4).

The separate subbasins were merged together into a single Nemunas River runoff model. Each subbasin was calibrated separately, using the main sixteen calibration parameters which were adapted to each subbasin. The calibration parameters were divided into four groups and calibration was started from the first group parameters (volume changes). The entire process of calibration is described in more detail in (Integrated . . ., 2005; Kriaučiūnienė et al., 2013). The model calibration was performed in the period of 1986—1995 (correlation coefficient (R) — 0.88, Nash—Sutcliffe efficiency (NSE) — 0.78, accumulated difference between the calculated and the observed discharge (Accdiff) — 7.4%), while the model validation was carried out in the period of 1996—2005 (R — 0.75, NSE — 0.62, Accdiff — 5.7%) (Fig. 5). The created hydrological model was calibrated (1986—1995) and validated (1996—2005) according to the observed hydrological and meteorological data. Meteorological and water gauging station network, which data are used to develop the hydrological model, are presented in Fig. 3.

The calibrated model was then used to simulate the Nemunas inflow to the Curonian Lagoon in a historical period. In Fig. 6, the observed runoff values are compared to the simulated ones (the outputs of three climate models (average of GFDL-CM3, HadGEM2-ES and NorESM1-M) for the period of 1986—2005). This modelling is necessary to perform in order to find out how precisely the selected models reflect the historical climate conditions. Since the hydrographs of the observed and simulated historical runoff were very similar (the mean annual discharges were 700 $\mathrm{m^3\,s^{-1}}$ and 696 $\mathrm{m^3\,s^{-1}}$), the selected climate models can be used for future runoff simulation.

3.2. Changes of water balance components of the Curonian Lagoon

The water balance components of the reference period are analyzed in Table 1. The water balance income consists of the following components: river inflow (Q_{R}) — 22.1 $\mathrm{km^3\,year^{-1}}$ (from 15.4 to 30.0 $\mathrm{km^3\,year^{-1}}$), inflow from the sea (Q_{BS}) — 6.8 $\mathrm{km^3\,year^{-1}}$ (from 5.4 to 9.0 $\mathrm{km^3\,year^{-1}}$) and precipitation (P) — 1.3 $\mathrm{km^3\,year^{-1}}$ (from 0.9 to 1.7 $\mathrm{km^3\,year^{-1}}$). The balance losses include outflow from the lagoon (Q_{CL}) — 28.6 $\mathrm{km^3\,year^{-1}}$ (from 20.9 to 36.8 $\mathrm{km^3\,year^{-1}}$) and evaporation (E) — 1.0 $\mathrm{km^3\,year^{-1}}$ (from 0.9 to 1.1 $\mathrm{km^3\,year^{-1}}$). All of these components have seasonal variation. The greatest values of Q_{R} and Q_{CL} are characteristic for spring (April),

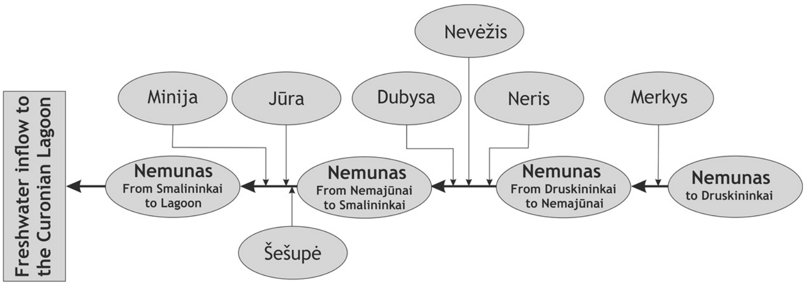

Figure 4 The scheme of the Nemunas River hydrological model.

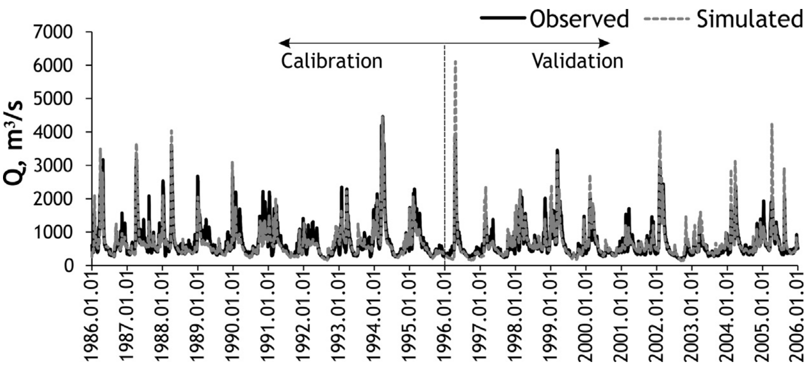

Figure 5 Comparison of observed and simulated runoff of the Nemunas River in the periods of calibration (1986—1995) and validation (1996—2005).

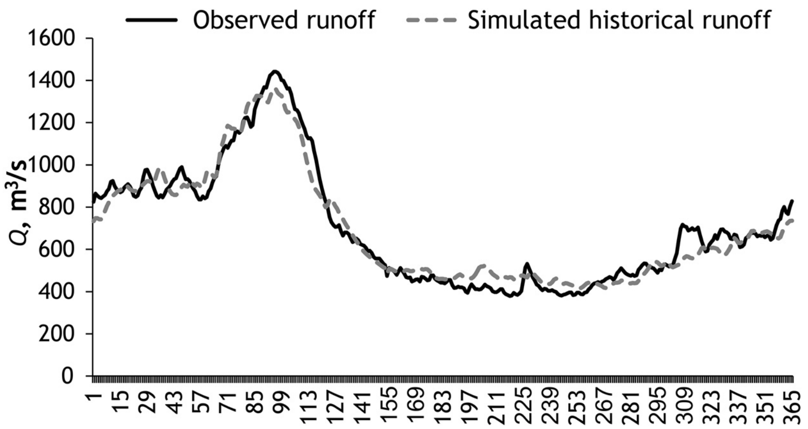

Figure 6 Comparison of observed average runoff at the mouth of the Nemunas River in historical period (1986—2005) with simulated historical runoff according to average data of three climate models (GFDL—CM3, HadGEM2—ES and NorESM1—M).

while the smallest ones are observed in summer (July). On the contrary, Q_{BS} is the smallest in spring (April) and the largest at the end of autumn (November). E increases in summer (July) and decreases in winter months, whereas P decreases in spring and is the most intensive in the autumn season.

Fig. 7 outlines that under four RCP scenarios, the components of the lagoon water balance are not expected to change significantly in the nearest future (2016—2035). The analysis indicated that in this period, Q_R and Q_{CL} averaged by all RCPs should decrease by 6.8% and 2.1% respectively, whereas Q_{BS}, E and P should increase by 13.9%, 10.8%, 6.1% respectively in relation to the reference period (1986—2005).

Considerably larger changes are projected in the far-future period (2081—2100). Q_R is going to decrease from 0.1% (RCP2.6) to 28.2% (RCP8.5), and will on average be 13.4% smaller than in the reference period. Q_R values should redistribute among the seasons. The greatest annual inflow changes are projected in winter and spring. Q_R in winter is expected to be greater from 1.9% (RCP2.6) to 10.3% (RCP8.5), while Q_R in the spring season should get smaller from 5.0% (RCP2.6) to 9.7% (RCP8.5) in comparison with the reference period. Because of rising global sea level and decreasing river inflow, the water exchange through the Klaipėda Strait (Q_{CL} and Q_{BS}) is expected to change. Q_{CL} should decline from 30.2 km^3 (RCP2.6) to 26.5 km^3 (RCP8.5), which, according to all four RCPs, constitutes an average decrease of only 0.7% if compared to the reference value of 1986—2005. Inflow from the sea (Q_{BS}) is projected to increase quite significantly (i.e. from 24.8% to 61.3%) due to several reasons, including decreased river inflow (projected to shrink from 0.1 to 28.2% according to different scenarios) and rising sea level (expected to grow by 0.44—0.74 m from 2005). Inflow from the sea has seasonal patterns. The projections indicate that it will get smaller by 3.4% in winter and greater by 4.5% in spring, on average, whereas in other seasons it will remain almost the same. Depending on the scenario, precipitation is expected to grow by 8.7—15.1%, while evaporation is expected to increase by 14.9—41.1% in comparison with the reference period amounts.

3.3. Changes of the Curonian Lagoon salinity

In the reference period, the average salinity of the Curonian Lagoon at Juodkrantė (S_J) was 1.2 ppt. Its smallest values were observed in spring (0.5 ppt), while the largest ones were detected in autumn (1.9 ppt). The average annual salinity data at Juodkrantė demonstrates an upward trend equal to 0.08 ppt over a decade. The comparison of S_J values and both Q_R and Q_{BS} values presented in Table 1 indicated that S_J at Juodkrantė is directly proportional to inflow from the sea and inversely proportional to river inflow. Based on

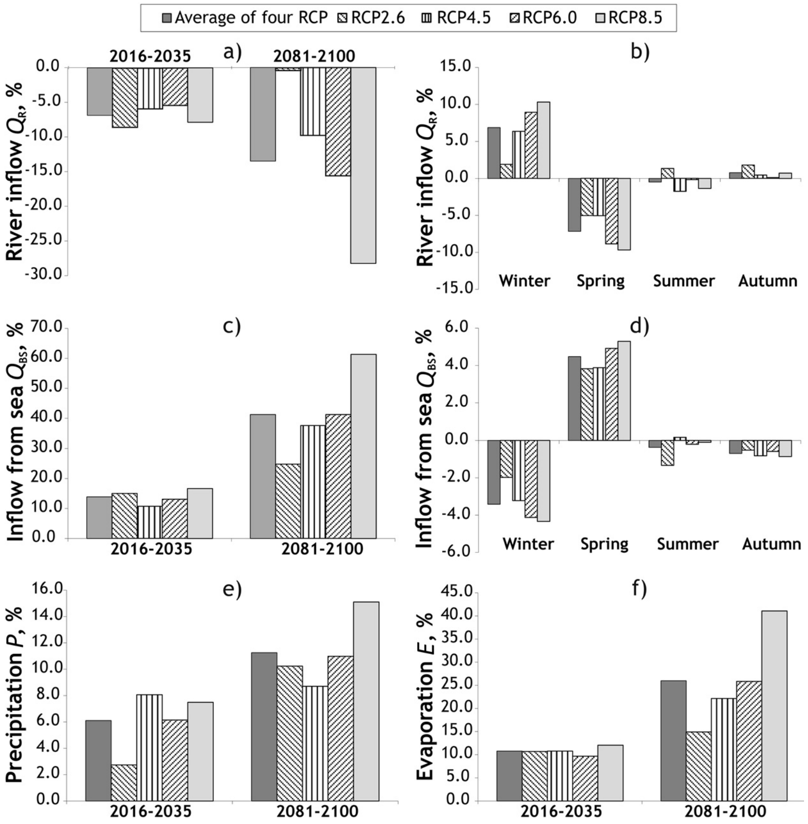

Figure 7 Changes of the components of the Curonian Lagoon water balance (in % comparing projections of 2016–2035 and 2081–2100 with average values of 1986–2005): (a) river inflow, (b) seasonal river runoff in 2081–2100, (c) inflow from the sea, (d) seasonal inflow from the sea in 2081–2100, (e) precipitation on the surface of the lagoon, (f) evaporation from the lagoon.

Table 1 The water balance of the Curonian Lagoon in the reference period (1986–2005) (km^3 year^{-1}).

Balance component	Month												Annual
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
Q_R	2.4	2.2	3.0	3.2	1.8	1.2	1.1	1.1	1.1	1.4	1.7	1.9	22.1
Q_{BS}	0.6	0.4	0.4	0.2	0.4	0.6	0.5	0.6	0.6	0.8	0.9	0.9	6.8
P	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	1.3
Income	**3.0**	**2.7**	**3.5**	**3.5**	**2.3**	**1.9**	**1.7**	**1.9**	**1.9**	**2.3**	**2.8**	**2.9**	**30.2**
Q_{CL}	2.8	2.7	3.5	3.8	2.2	1.6	1.6	1.7	1.7	2.1	2.5	2.5	28.6
E	0.0	0.0	0.0	0.1	0.1	0.2	0.2	0.2	0.1	0.1	0.0	0.0	1.0
Losses	**2.8**	**2.7**	**3.5**	**3.8**	**2.3**	**1.8**	**1.8**	**1.9**	**1.9**	**2.2**	**2.5**	**2.5**	**29.6**
ΔV	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
Error	0.3	0.0	0.0	−0.3	−0.1	0.1	−0.1	0.1	0.0	0.1	0.3	0.3	0.5

this dependence, Eq. (7) was created and used to estimate S_J in the selected future twenty-year period (2016–2035 and 2081–2100).

The projections revealed an increase of the lagoon water salinity at Juodkrantė (Fig. 8) which can be attributed to changes of water exchange through the Klaipėda Strait and the Nemunas inflow. In the nearest future, the projected changes will probably be insignificant (up to 1.3 ppt, i.e. by 0.1 ppt larger than in the reference period) according to RCP4.5 and RCP6.0 scenarios, whereas other scenarios indicate a slightly greater increase of the average salinity values (1.5 ppt), i.e. by 0.3 ppt larger than in 1986–2005. Fig. 8a presents that a greater variation is possible in summer and autumn. During these seasons, salinity is projected to be larger than in the reference period, while a smaller variation is expected during the rest of the seasons. In winter and spring, salinity values will likely be similar to or somewhat less than those in the past. At the end of the 21st century, salinity changes are projected to be more significant and grow depending on scenario severity (they can reach as much as 2.6 ppt according to RCP8.5) (Fig. 8b). It is important to mention that these changes would occur in case of a

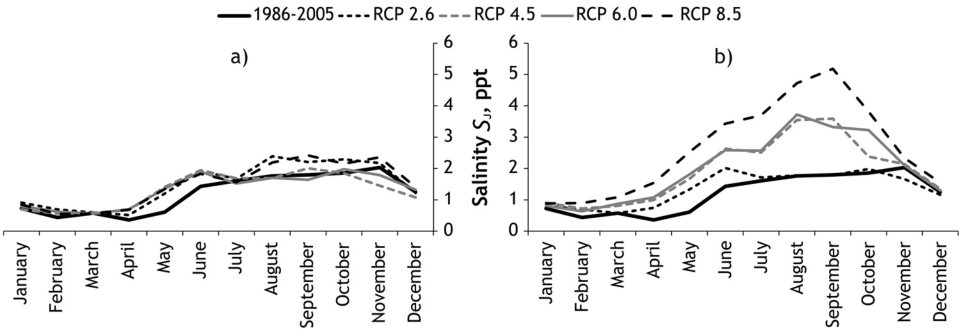

Figure 8 Projections of the Curonian Lagoon salinity (at Juodkrantė) in: (a) 2016—2035, (b) 2081—2100.

considerable decrease of the Nemunas inflow and rising sea level.

3.4. Changes of water temperature of the Curonian Lagoon

Fig. 9 outlines the water temperature of the Curonian Lagoon. Its annual variation at Klaipėda differs from the one at Juodkrantė, Nida or Ventė. The reason for such phenomenon is the position of Klaipėda, i.e. it is located at the junction of the sea and the lagoon. Since the volume of the Baltic Sea is many times greater than the Curonian Lagoon, its water warms up more gradually and cools down slower. In the reference period, the average annual water temperature was 8.8°C at Klaipėda, 9.1°C at Juodkrantė, 9.2°C at Nida and 9.3°C at Ventė. The average water temperature of the entire Curonian Lagoon, calculated according to Eq. (12) was 9.2°C, which is very similar to the measured one at Nida. This variable had an upward trend in the period of 1986—2005: it rose up by 0.7°C at Klaipėda, by 0.8°C at Nida, by 0.9°C at Juodkrantė and by 1.0°C at Ventė. It was estimated that the average annual water temperature of the Curonian Lagoon rose at an average rate of 0.04 degrees per year.

Projections of water temperature of the Curonian Lagoon were performed using Eqs. (8)—(12) of four WGS and for two selected future periods (Fig. 10). In the nearest future, considerable differences among the projected water temperature values according to the selected scenarios were not identified; this variable is expected to grow by 1.7°C on average (Fig. 10a). As usual, in the far-future period, the projected changes are going to be more significant: the mean annual water temperature may grow by at least 2.3°C (according to RCP2.6) or even by 6.3°C (according to the most severe RCP8.5 scenario) compared to the reference period values. On average, the annual water temperature is projected to be higher by 4.1°C than in the reference period: it will rise by 2.3°C in winter, 4.2°C in spring, 5.0°C in summer and 4.3°C in autumn. The warmer lagoon water is likely to create unfavourable conditions for forming a permanent ice cover in winter.

4. Discussion and conclusions

The performed analysis presented in this paper attempted to cover the full complexity of the potential impact of climate change on the Curonian Lagoon water balance components, salinity and temperature. Projections were performed using three global climate models and four RCP scenarios. Values of the projected variables were compared with the ones in the reference period of 1986—2005. The estimated water balance of the Curonian Lagoon (in 1986—2005) and projections of the Nemunas inflow revealed that considerable variations should be expected in the future. In all cases, the projected changes are going to be much more significant in the second period (2081—2100) than in the first one (2016—2035). In the

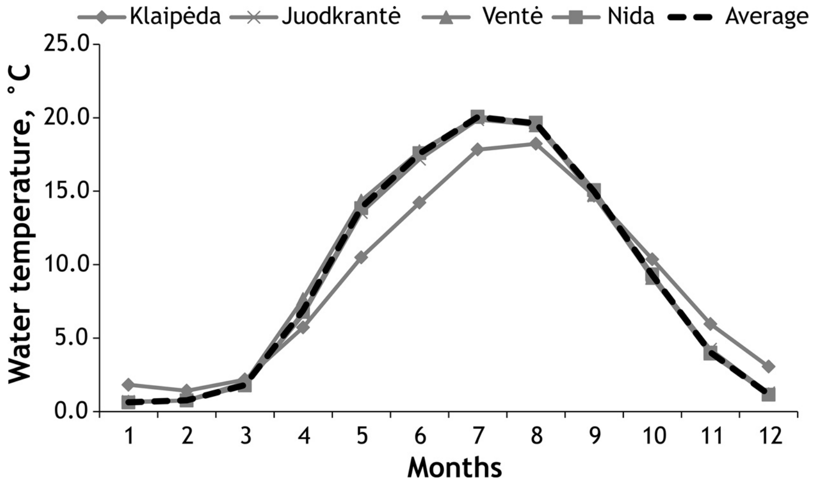

Figure 9 Water temperature of the Curonian Lagoon in the reference period (1986—2005).

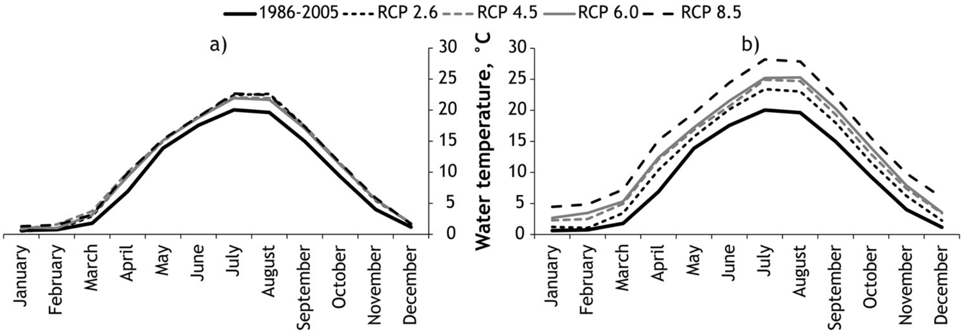

Figure 10 Projections of water temperature of the Curonian Lagoon in: (a) 2016—2035, (b) 2081—2100.

nearest future, the Nemunas annual inflow may decline to 20.3 km^3 (RCP2.6). In the far-future period, it is expected to decrease to 15.9 km^3 (RCP8.5), while in the reference period it was 22.1 km^3. In the period of 2081—2100, considerable seasonal redistribution of the Nemunas annual inflow is expected. According to climate scenarios, the river inflow will increase by an average of 6.9% in winter and 0.8% in autumn, whereas it is expected to decrease by 7.1% in spring and 0.5% in summer. Due to rising sea water level and smaller amounts of river inflow, inflow from the sea annual input is expected to increase up to 8.0 km^3 in the nearest future and up to 11.0 km^3 in the far future according to RCP8.5 (the scenario which projects the most drastic changes), while in the past (1986—2005) it was 6.8 km^3. According to RCP8.5, the major changes of annual precipitation and evaporation are likely to occur in the far-future period as well: evaporation should intensify by 41.1%, while precipitation should increase by 15.1%.

As inflow from the sea is expected to increase, the same will happen to salinity values. In the nearest future, salinity at Juodkrantė is projected to reach 1.4 ppt on average (from 1.3 ppt by RCP2.6 to 1.5 ppt by RCP8.5). At the end of the century, salinity will gain significantly higher values: from 1.4 ppt (RCP2.6) to 2.6 ppt (RCP8.5). On average, it is projected to reach 2.0 ppt, whereas the reference period value was 1.2 ppt. If future changes projected by RCP8.5 scenario come true, salinity would reach the reference values (2.6 ppt according to Dailidienė and Davulienė, 2008) of the Curonian Lagoon at Klaipėda (i.e. very close to the Baltic Sea). This outcome is contrary to that of Vuorinen et al. (2015) who found that unchanged salinity conditions at the end of the 21st century are possible as well.

In the reference period (1986—2005), water temperature of the Curonian Lagoon grew by 0.04°C year^{-1}. These results are in line with those of previous studies, indicating that the warming trend of the mean surface water temperature in the Curonian lagoons was 0.03°C year^{-1} in the period of 1961—2008 (Dailidienė et al., 2011). Similar temperature growth tendencies were determined for the Baltic Sea as well. SST averaged over the entire Baltic Sea increased at the rate of 0.05°C year^{-1} (Stramska and Białogrodzka, 2015). Smaller seas and especially shallow lagoons are getting warmer much faster than the global ocean temperature (0.02°C year^{-1} over the reference period) (Huang et al., 2015b).

This study shows that in the nearest future, the inflow from the sea, evaporation, water temperature and salinity are projected to increase more under the RCP2.6 scenario than the rest of scenarios. These findings are in agreement with other results (Westervelt et al., 2015). The most likely explanation of this is the increase of meteorological parameters, such as air temperature and precipitation projected according to the RCP2.6 scenario until the middle of the 21st century, as well as the decrease of these variables that is expected to occur in the second half of the century. In the far-future period, the most significant changes of all investigated variables are expected according to the RCP 8.5 scenario.

This study does not rule out the presence of other factors that may have an influence on the state of the Curonian Lagoon in the future. It is difficult to project anthropogenic activities, such as land use changes in river catchments, Klaipeda Strait permeability changes, etc., that may alter the results of this study, creating a degree of additional uncertainty. However, there is a strong possibility that in the long term period (the end of 21st century), the projected changes will have the estimated tendencies.

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