

Seasonal renewal  
time variability in the  
Curonian Lagoon

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# Seasonal renewal time variability in the Curonian Lagoon caused by atmospheric and hydrographical forcing

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## Abstract

The aim of this study was to investigate the variability of the water exchanges in the Curonian Lagoon based on the hydraulic regime and the atmospheric forcings. A finite element hydrodynamic model has been applied to the Curonian Lagoon to simulate the circulation patterns for ten years. With the help of a transport-diffusion model the salinity distribution and the renewal times of the Curonian Lagoon have been investigated when forced by river runoff, wind and Baltic Sea level fluctuations. The hydrodynamic model has been validated using in situ salinity measurements.

Model results show that the variability depends mainly on seasonal changes in hydrographic forcing and on the dominant wind regimes that prevail over the Curonian Lagoon. Exchanges between the southern and the northern part of the lagoon are mostly depended on the wind forcing and are much less influenced by the river discharge.

However, when looking at the water renewal time, the most important factor is the river discharge into the lagoon. Other physical forcings are only marginally determining the renewal time, and not even ice cover is able to influence it. Even if ice cover is strongly inhibiting the exchanges between southern and northern lagoon, it is basically not able to change the absolute value of the renewal times.

## 1 Introduction

Lagoons are the most productive coastal habitats on earth. They are, however, also considered to be extremely vulnerable due to human impact and future climate change. They have crucial relevance what concerns ecological, social and economical importance, both in a historical and present day (Gonenc and Wolflin, 2005). Lagoons show extremely varying settings what concerns hydrological and biological characteristics.

Lagoons are crucially depending on the exchange of their waters with the open sea. Especially in lagoons where direct fresh water input is not available because no rivers

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part. The total area of the lagoon is approximately 1584 km<sup>2</sup>, the volume is 6.3 km<sup>3</sup>, its length is 93 km, maximum width is 46 km in its southern part, and mean depth is 3.8 m (Žaromskis, 1996).

The dynamics is dominated by the river discharge with a climatological average of 21.8 km<sup>3</sup> yr<sup>-1</sup> (700 m<sup>3</sup> s<sup>-1</sup>) (Jakimavičius, 2012). More than 90 % of this amount is contributed by the Nemunas River that discharges into the central and northern part of the lagoon.

Every year the rivers carry the amount of fresh water about four times the lagoon volume. Therefore, the southern and central parts of the lagoon are freshwater (average annual water salinity is 0.08 ‰), while the northern part has an average annual water salinity of 2.45 ‰, with irregular salinity fluctuations of up to 7 ‰ due to Baltic water intrusion (Dailidienė and Davulienė, 2008).

Therefore the Curonian Lagoon is a transitory freshwater basin; and due to the inflowing rivers the average water level in the lagoon is normally higher compared to the sea level of the Baltic Sea.

## 2.2 Data

For the calibration and validation results of salinity a data set of daily measurements performed by the Marine Research Department of Lithuanian Environmental Protection Agency, linked to the Lithuanian Ministry of Environment, for the period 2004–2010 for the northern part of the Curonian Lagoon (Juodkrantė and Klaipėda Strait) were used. Daily river discharges were provided by Lithuanian hydro-meteorological service. The fresh water input into the Curonian Lagoon was considered as the sum of the discharge of its major rivers (Nemunas near Smalininkai, Minija, Šešupė, Jūra, Šešuvis, Deima) (Jakimavičius, 2012).

Open sea boundary water temperature, salinity and water levels were obtained by three different sources. For the year 2004–2006 the boundary data was taken from the operational hydrodynamic model MIKE21 provided by the Danish Hydraulic Insti-

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fitting the logarithm of the tracer value in every point to a straight line (Umgiesser and Cucco, 2011). The second method gives the possibility of shortening the simulations and stopping them before the concentration arrives at very small values. This procedure allows also restarting the computation at given time periods. In our case we have  
5 repeated the computation every 3 months trying to resolve the seasonal variability of the Curonian Lagoon.

## 2.5 Simulation setup

In this application the numerical grid consists of 2027 elements and 1309 nodes. The resolution is much finer in the vicinity of the Klaipėda strait. A part of the Baltic Sea shelf  
10 has also been included in the numerical grid in order to not disturb the computations of the exchanges through the Klaipėda strait. In the vertical a total of 12 sigma layers have been inserted.

Several numerical simulations have been carried out in this study:

- Idealized simulations to investigate the role of different forcing on the water exchange and energy content distribution.  
15
- 10 years realistic simulations using hydro meteorological forcing for the time period between 1 January 2004 and 31 December of the year 2013.

The characteristics of the performed simulations are summarized in Table 1.

The simulations have been carried out using a maximum time step of 100 s, and the model adopts automatic sub-stepping over time to enforce numerical stability with respect to advection and diffusion terms. The vertical viscosity and diffusivity are computed by the  $k$ -epsilon model GOTM, and the horizontal ones by a Smagorinsky type closure with a parameter of 0.2. The bottom drag coefficient has been set to a constant standard value of  $2.5 \times 10^{-3}$ . Finally, the wind drag is being computed by the sea-air interaction model COARE (Fairall et al., 2003).  
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### 3 Results

#### 3.1 Calibration and validation through salinity

Even if the calibration and validation has already been carried out in a former work (Ferrarin et al., 2008; Zemlys et al., 2013) we show one more time the validation for the salinity, because the numerical grid has been changed between the two applications. In Zemlys et al. (2013) the resolution of the grid was much finer. In the present application a coarser resolution has been used because of the need to run the model for longer time periods.

To drive the model realistic forcing of boundary conditions (water levels, salinity, temperature) and meteorological input has been used for the year 2004–2013. For the calibration and validation of modeled salinity a data set of daily measurements performed by the Marine Research Department of Lithuania Environment Ministry for the period 2004–2010 for the northern part of the Curonian Lagoon (Juodkrantė and Klaipėda Strait) were available.

Statistical analysis results for salinity are reported in Table 2 in terms of root-mean-square error (RMSE, in ‰) and correlation coefficient between model results and observations ( $R$ ). The results showed that the model with ice gives much better results compared to the reference simulation. The correlation coefficient between model results and observations for the period 2007–2010 (when the realistic ice data were used) is 0.641 (RMSE = 2.3 ‰) in Klaipėda Strait and 0.427 (RMSE = 2.1 ‰) in Juodkrantė. Still the comparison of results with previous studies showed that the high resolution model does a better job in describing salinity variations.

#### 3.2 Exchange mechanisms between the northern and the southern lagoon

In a first set of sensitivity simulations the exchange mechanisms between the northern and southern part of the lagoon have been explored. It has been studied how the physical forcing influences and determines the circulation and exchange in the lagoon.

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A first simulation explores the dependence on wind direction. The wind speed has been fixed to  $5 \text{ m s}^{-1}$  which corresponds approximately to the long term average of winds from all directions. No Nemunas River water discharge has been imposed. Energy content (kinetic and potential) and fluxes between different sub-basins have been computed. The section over which these fluxes have been taken is plotted with a black continuous line in Fig. 1. The results of this experiment are shown in Fig. 2.

Energy has been computed by excluding the grid area of the Baltic Sea, so only the water circulation and setup of the water level inside the lagoon have been taken into account. Energy is not equally distributed between its kinetic and potential part. The potential energy is normally much higher than its kinetic counterpart. This means that due to the shallow nature of the lagoon the currents contribute much less to the energy budget with respect to the change in water level which accumulates potential energy inside the lagoon.

The energy budget is symmetric with wind speeds of opposite directions (Fig. 2). The minimum of potential energy correspond to around  $90$  and  $270^\circ$ , which are easterly and westerly winds. This direction corresponds to a minimum fetch over the lagoon where the wind can act to pile up the water on one side or the other. On the other side wind directions of  $0$  and  $180^\circ$  (northerly and southerly winds respectively) show highest accumulation of potential energy. In this case the potential energy is 50 times higher than in case of minimum potential energy (please note the logarithmic scale in the figure).

Kinetic energy is differently distributed with wind speed. Its maximum is at around  $50$  and  $230^\circ$ , which corresponds to NE and SW winds. Kinetic energy is much less variable when compared with the potential energy, and it is higher than potential energy only close to where the minimum of potential energy occurs.

In the bottom panel of Fig. 2 fluxes over selected sections are presented. Shown are absolute fluxes, so positive and negative fluxes add up to each other. Fluxes through the Klaipėda strait are maximum at around  $100$  and  $270^\circ$ , which corresponds roughly to the direction of the inlet that connects to the Baltic Sea. Minimum fluxes occur with

northerly and southerly winds. The more southerly situated section of Ventė shows a similar form with higher fluxes, due to being much wider. Fluxes through the Nemunas section and the South lagoon section show much higher values, with maxima at around 30 and 200°. This is the wind direction which favors highest exchange between the northern and southern sub-basin in the Curonian Lagoon.

In another simulation only the Nemunas discharge has been taken into account. The simulation has a duration of 250 days, while the Nemunas discharge is continuously increased until reaching the value of  $2500 \text{ m}^3 \text{ s}^{-1}$ . No wind forcing has been applied. Results are shown in Fig. 3. With a low Nemunas discharge the kinetic energy is higher than the potential energy. This means that with low discharges there is little piling up of the water in front of the Nemunas delta and the water flows freely in direction of the strait. At higher discharges the ratio is reversed, and potential energy becomes more important, and at very high discharges total energy consists basically only in potential energy. This means that due to the big water masses inflowing the water cannot freely flow to the strait but accumulates close to the Nemunas Delta, contributing to a rise in potential energy.

Fluxes for the same simulation are shown in Fig. 3. Not surprisingly, the discharges through Klaipėda strait, Ventė and Nemunas sections show exactly the same value than the Nemunas discharge. It is however surprising that this Nemunas discharge only influences marginally the fluxes through the south section. Fluxes still grow linearly with discharge, but are much lower than through the other sections. The ratio between Nemunas and south section is about 1/8.

### 3.3 Renewal time variability

As described above the model has been applied to the Curonian Lagoon computing the water renewal time (WRT). The renewal time has been computed for 3 months and after this period concentrations have been re-initialized for a new computation. Renewal times have been computed separately for the northern and southern sub-basin,

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WRT is barely changing (149.5 days with respect to the reference value of 148.0 days). In the southern basin changes are a bit higher (192.6 days with respect to 188.8 days).

The seasonal variability during the 4 years can be seen in Fig. 5. In the figure, the actual ice cover has been inserted as a black line. The winters in 2007 and 2008 are less severe and hardly any difference in WRT can be found between the results without and with ice cover. The winters of 2009 and 2010 led to a longer period of ice cover, and especially in 2010 some differences in WRT can be seen. As expected WRT, when considering ice cover, goes up in the southern basin, but at the same time lower WRTs can be found in the northern basin.

Finally, analyzing the frequency curves created only for the years 2007–2010, where ice cover was available (Fig. 6, bottom panel), it becomes clear that the first peak identifying the northern basin is not changing, but the second peak at around 150 days is lower and the distribution is shifting to longer WRTs. This can be seen especially in the very long tail of the winter with ice distribution that is very similar to the distribution in summer times.

### 3.5 Dependence on other physical forcings

Since ice cover (and therefore wind forcing) did not show a strong impact on WRT it was reasonable to check what other factors would determine the renewal capabilities of the Curonian Lagoon. We decided to test two other physical forcing mechanisms that are influencing the WRT, namely water level variations in the Baltic Sea and the inflow of the Nemunas River.

The results of simulation, when the water level variations in the Baltic Sea are set to zero, can be seen in Table 3 and in Fig. 7. Strongest changes in WRT can be found in the northern lagoon (5%) and less so in the southern one (2%). Fluxes through the southern section are a little more sensitive to the changes and amount to around 11%. However, as can be seen also in Fig. 8, the changes are slight.

However, if the Nemunas River discharge is switched off, the picture changes radically. Both from Table 3 and Fig. 7 it can be seen that WRTs shift to much higher levels.

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The WRT in the northern basin becomes similar to the value in the southern one of the reference situation (212 days), and the southern basin shows WRTs of more than 5 years on average, with strong inter-annual changes. However, the exchange between the northern and the southern basin only changes by as little as 2%.

## 4 Discussion and conclusions

The simulations that were carried out to study the dynamics of the Curonian Lagoon under changing wind conditions indicated that there are two mechanisms that have to be taken into account. Minimum exchange between northern and southern sub-basin takes place with winds from N or S. These winds correspond to a minimum exchange through the Klaipėda Strait. This indicates that winds act in two ways: either they enhance the water exchange with the Baltic Sea, or they contribute to the internal mixing and redistribution of the water masses inside the lagoon.

The influence of the Nemunas on the internal water circulation is quite low, and it only marginally influences the exchanges between the southern and northern part. The Nemunas River contributes mostly to kinetic energy under lower discharges, but with high discharges a water level gradient is building up and potential energy is becoming the major energy contribution. The discharge where potential and kinetic energy become similar is at around  $900 \text{ m}^3 \text{ s}^{-1}$  which is close to the climatological average of the river discharge of  $700 \text{ m}^3 \text{ s}^{-1}$  (Jakimavičius, 2012). Therefore average kinetic and potential energy due to the Nemunas discharge are nearly equi-distributed.

The pattern of the WRT distribution between different seasons is very similar between each other. The absolute numbers depend on the season, with spring showing low WRT close to the Nemunas outflow and highest WRT in the southern basin during summer time. This confirms the strong influence of the Nemunas forcing on the WRT, especially in the northern basin.

The inter-annual changes of the WRT show a coherent picture. Lowest WRTs are always during winter and spring, and highest during summer (Fig. 5). The variability

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is much lower in the northern basin, where the inflow of the Nemunas is stabilizing the water exchange. On the other hand, the southern basin is really depending on the meteorological forcing which may vary between different years. As can be seen from the figure, the summer of 2012 leads to large WRTs in the southern basin, whereas the northern part only showed a minor increase.

Ice cover, even if important for the exchange in the inside of the lagoon, does not influence too much the WRT. Only during strong winters, when ice cover is lasting for a considerable amount of time, the ice cover will be able to change the WRT. Two different effects can be seen. While the WRT increases in the south, in the north it decreases. This can be explained by the fact that water exchange between the north and the south is decreasing. Less fresh water from the Nemunas goes to the south, increasing the WRT there. However, the fresh water that stays in the north contributes to lower WRTs there. Summarizing, the WRT in the whole basin is changing very little, showing that ice cover may inhibit the exchanges inside the lagoon, but does not too much influence the exchanges with the Baltic Sea.

The other two physical factors that may influence the WRT distribution are water level variations in the Baltic Sea and the Nemunas discharge. Switching off the water level variation did result in slightly smaller WRTs in the basin (2–5%), and exchanges between the southern and northern basin were decreasing by around 10%. Again this result is astonishing. Most lagoons throughout the world are dominated by tidal exchange. Even in Mediterranean lagoons, where tides can be classified as micro-tidal, it is still the tide which mostly controls the exchange with the open sea (Umgiesser et al., 2014). However, in the eastern Baltic Sea tides are negligible, and intermittent water level changes are not strong enough (or not frequent enough) to influence the water exchange with the Baltic Sea.

The strongest impact on the WRT distribution is exerted by the Nemunas inflow. The northern part of the lagoon shows WRTs of around 7 months, whereas the in the southern part the WRT increases to around 5 years on average between the years. As already mentioned this is only due to the missing fresh water input of the Nemunas, and





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**Table 2.** Model validation results for salinity. Given are correlation coefficients and root mean square error in ‰. The results refer to the reference simulation, the simulation with ice cover (10 years), only the 4 years where ice cover was available, only 2009 with ice cover and results from the article Zemlys et al. (2013).

	Reference (without ice) 2004–2010	Ice 2004–2010	Ice 2007–2010	Ice 2009	2009 from Zemlys et al. (2013)
Klaipėda Strait	$R = 0.584$ RMSE = 2.433	$R = 0.596$ RMSE = 2.386	$R = 0.641$ RMSE = 2.312	$R = 0.675$ RMSE = 2.131	$R = 0.74$ RMSE = 2.3
Juodkrantė	$R = 0.398$ RMSE = 2.068	$R = 0.410$ RMSE = 2.024	$R = 0.427$ RMSE = 2.063	$R = 0.499$ RMSE = 1.759	$R = 0.67$ RMSE = 1.6

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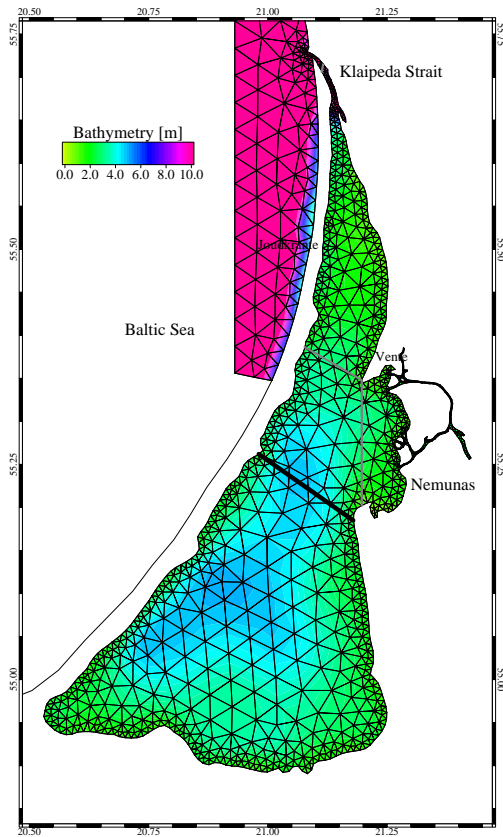
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**Figure 1.** The setting of the Curonian Lagoon showing its bathymetry. Superimposed is the used numerical grid. The thick black line indicates the section, named Southern Lagoon, considered for computing the fluxes between the north and the south basins. It also indicates the division into northern and southern sub-basin when computing the WRT. The three gray lines are the other flux sections and are named (from north to south) Klaipėda Strait, Ventė, and Nemunas.

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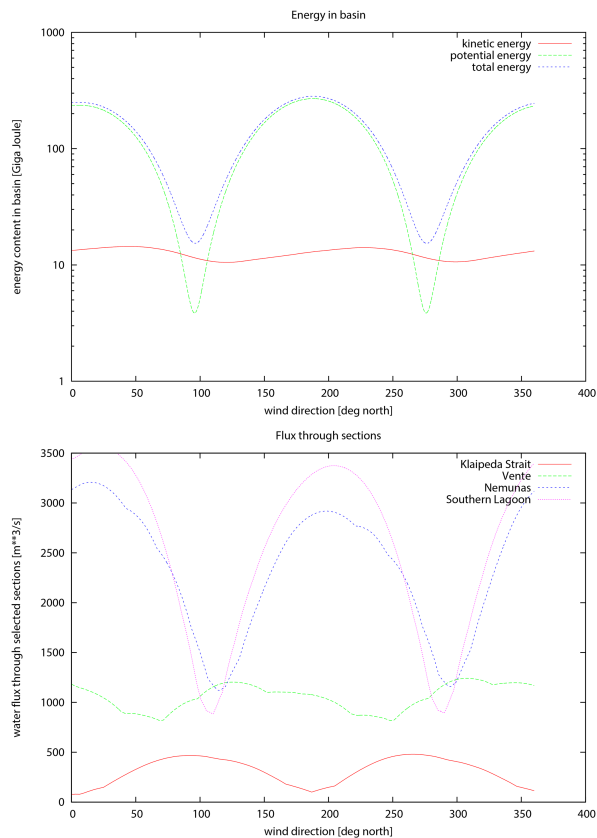
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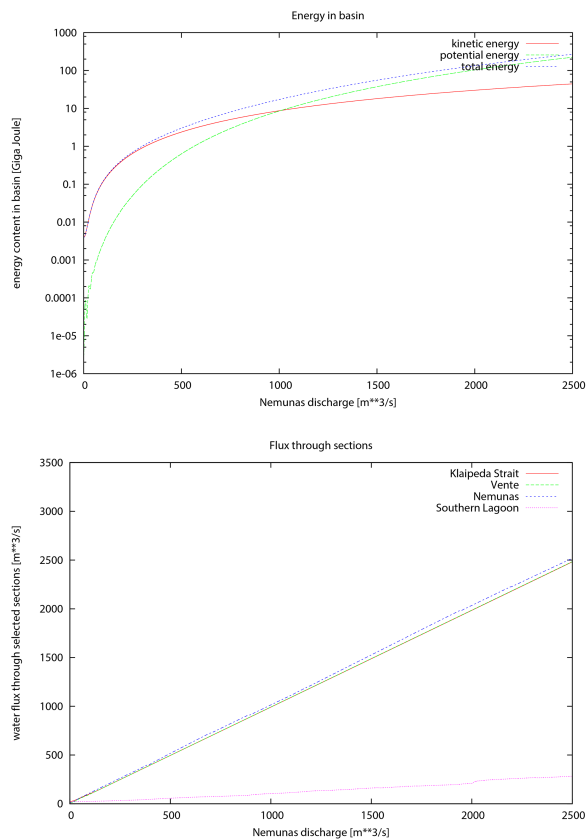


**Figure 2.** Energy content in basin (top) and fluxes through selected sections (bottom) depend on the wind direction.



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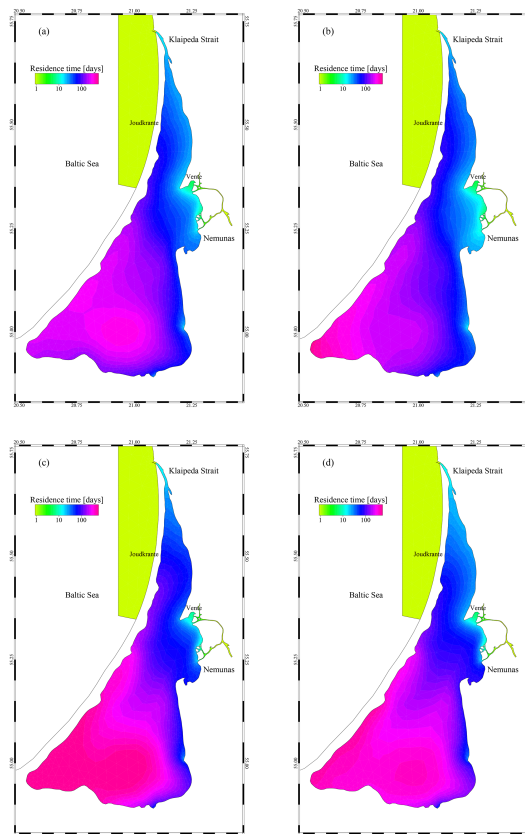


**Figure 3.** Energy content in basin (top) and fluxes through selected sections (bottom) depend on the Nemunas discharge.

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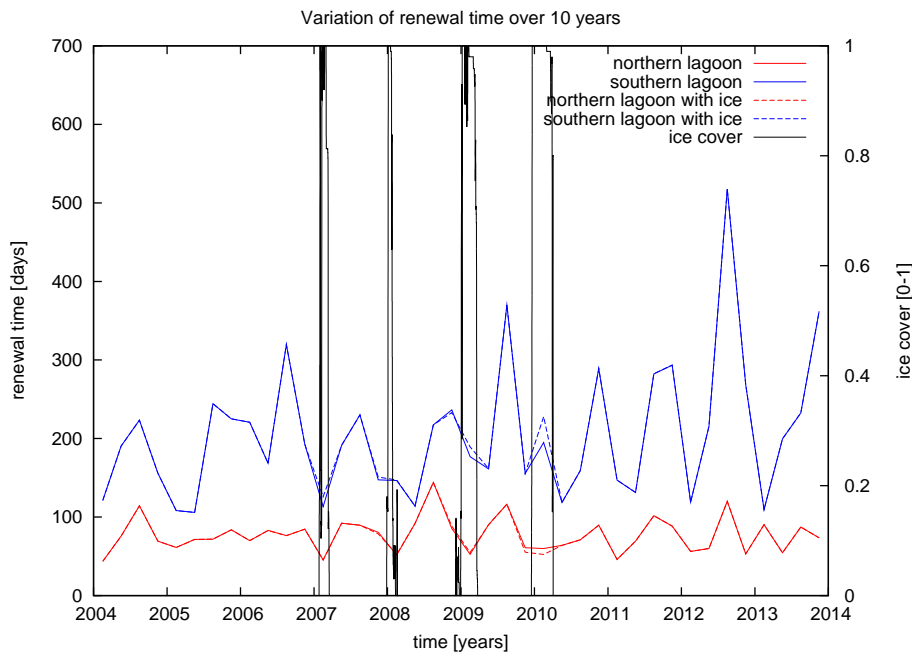


**Figure 4.** Seasonal residence time maps averaged over the years 2004–2014. The residence time is only computed inside the Curonian Lagoon and not in the Baltic Sea. Maps show winter (a), spring (b), summer (c) and autumn (d). Please note the logarithmic color scale.

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**Figure 5.** Water renewal times for the northern, southern basin. The WRT is computed every 3 months to obtain a seasonal estimate. WRT is computed with and without ice cover for the years 2007–2010. The black curve shows the actual ice cover in the Curonian Lagoon.

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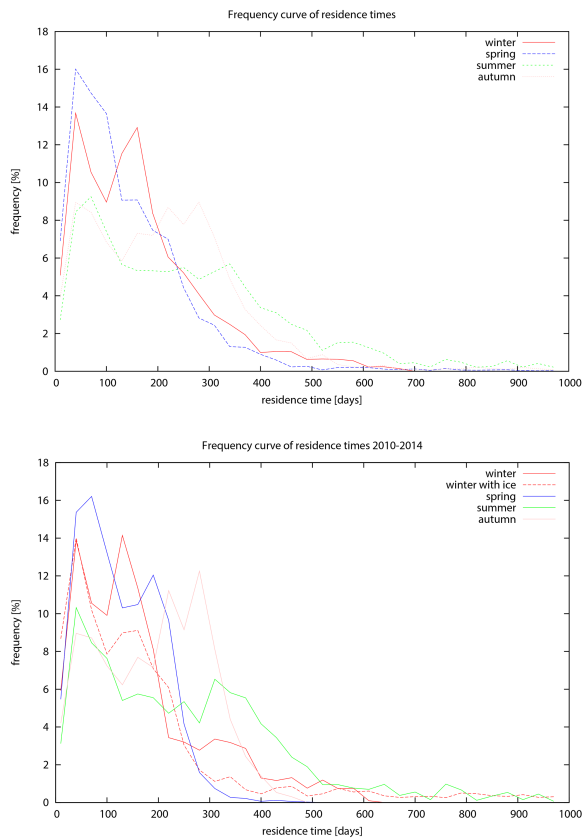
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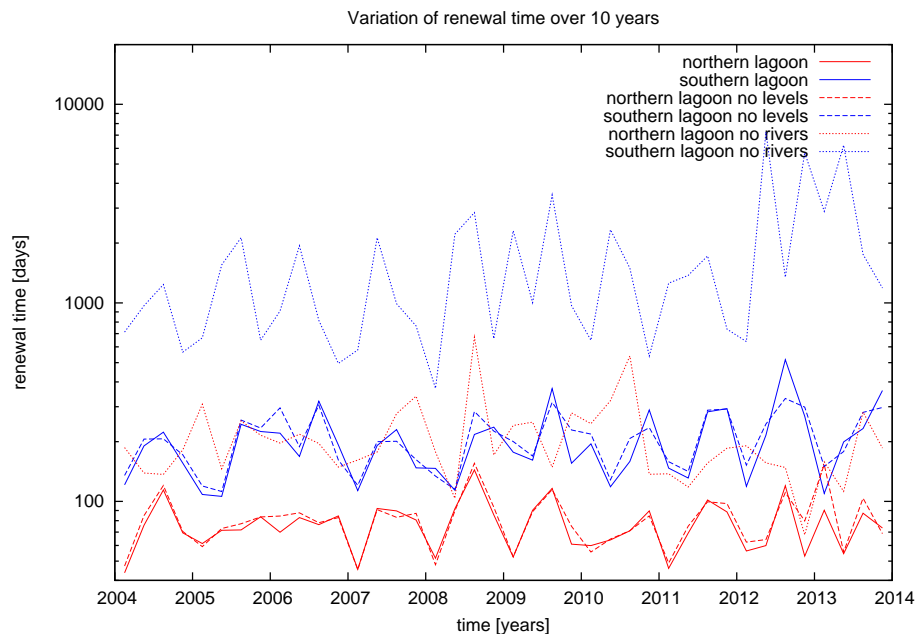


**Figure 6.** Seasonal frequency curves of WRT. Top: Results for 10 years (2004–2014), no ice cover considered. Bottom: As above but with and without ice cover in winter only for years 2007–2010.

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**Figure 7.** Water renewal times for the northern, southern basin. The WRT is computed every 3 months to obtain a seasonal estimate. WRT is computed for the reference run (continuous line), with no water level variation in the Baltic Sea (dashed line) and with no river discharge (dotted line). The northern lagoon is in red, the southern lagoon in blue.

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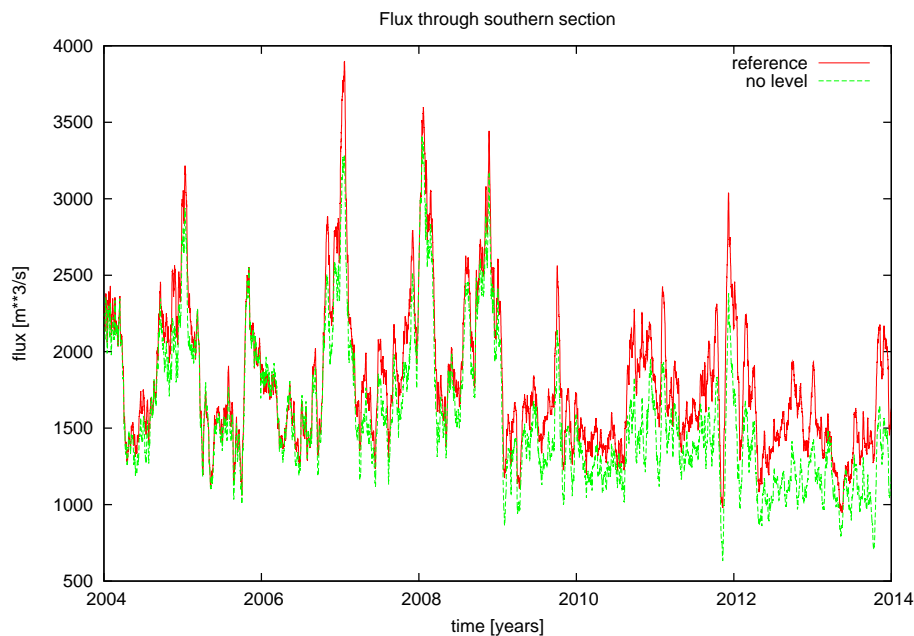
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**Figure 8.** Absolute fluxes through the south section. Results are shown for the reference run compared.

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