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Impact of changes in sea ice cover on the wave climate of semi-enclosed, seasonally ice-covered water bodies at temperate latitudes: a case study in the Gulf of Riga

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ABSTRACT

We analyse potential changes in the average and cumulative properties of wind waves owing to the loss of sea ice in regions that are currently seasonally ice-covered. The focus is on the Gulf of Riga, located in the eastern Baltic Sea at higher temperate latitudes. This water body is almost isolated from the rest of the Baltic Sea in terms of wave and ice fields. We compare the statistical properties of wave time series from a hypothetical ice-free wave simulation for the period 1990–2021 with truncated ones in which waves are ignored during the ice season. These simulations are made using the SWAN model with a spatial resolution of about 1 nautical mile for the whole gulf and down to 300 m in its nearshore, and forced with ERA5 wind data. The presence of seasonal ice cover insignificantly impacts the formal average wave properties, but the total loss of sea ice will significantly increase the levels of annual cumulative wave energy and its flux, and will thus add considerable energy to coastal processes in this water body.

Introduction

Sea ice, an inherent phenomenon in polar regions, occupies around one-tenth of the ocean's surface. Most of the seas that are seasonally or year-round covered by ice are located at higher temperate or polar latitudes of the globe, far to the north or south of latitude 60°. Some water bodies at more temperate latitudes, such as the Sea of Japan (which usually has quite thin ice cover; Zhang et al. 2023), the Gulf of St Lawrence (Urrego-Blanco and Sheng 2014), and the Great Lakes (Wang et al. 2012), also regularly experience seasonal ice cover. All these water bodies are impacted by climate change that generally leads to a shortening of the ice season and alternations to ice properties (Ruest et al. 2016; Huang et al. 2021). The loss of ice in such water bodies naturally leads to changes in wave properties: an increase in the significant wave height (Wang et al. 2018) and a substantial intensification of nearshore sediment transport (Manson 2022).

These processes are also characteristic of the Baltic Sea. It is a boreal marginal water body that is completely isolated from wave formation processes in the North Atlantic, has its own wave climate (Soomere 2023), and experiences highly varying seasonal ice cover each year (Vihma and Haapala 2009). As this sea extends almost 1600 km from the south to the north (Leppäranta and Myrberg 2009), its ice cover varies greatly in the different parts of the sea. While the ice season covers about half a year in the northern regions, ice in the open sea is infrequent in the south (SMHI and FIMR 1982).

Ice cover can affect wave climate in several ways. The presence of ice cover reduces the fetch length, hinders the propagation and growth of waves (Liu and Mollo-Christensen 1988), and enhances wave energy attenuation (Wadhams et al. 1986; Squire 2020). The presence of floating ice generally leads to wave energy dissipation (Collins et al. 2015; Mostert and Deike 2020; Tavakoli and Babanin 2021; Thomson 2022). Sea ice protects the nearshore and coastal zones, both directly as a natural breakwater and indirectly via reduction of wind speed over sea ice owing to the increased local atmospheric stability (Alkama et al. 2020; Iwasaki 2022). It can also prevent coastal areas from storm surges and erosion (Orviku et al. 2003; Ryabchuk et al. 2011). This aspect has a particular impact in the Baltic Sea where large variations in water level are caused by atmospheric forcing (Weisse et al. 2021). As a result, the presence of even partial ice cover decreases the impact of waves in the nearshore and at the shoreline. The total decrease in cumulative wave energy due to ice cover can reach up to 80% in the Bohai Sea, the Yellow Sea (Zhang et al. 2020), and up to 82% in the Bay of Bothnia, the Baltic Sea, in single years (Najafzadeh et al. 2022).

Ice extent in the Baltic Sea is strongly linked to large-scale atmospheric circulation patterns in the North Atlantic (Omstedt and Chen 2001). The most dominant teleconnection patterns in this region are the North Atlantic Oscillation (NAO) and the Scandinavian mode (e.g., Tinz 1996; von Storch et al. 2015). These patterns largely not only govern the course of air pressure and temperature but also affect seasonal and decadal variations in wave properties (Najafzadeh et al. 2021; Adell et al. 2023) through their impact on wind speed and direction. An increase in air temperature is apparently the main driver of the gradual decrease in the area and thickness of the ice cover in the Baltic Sea (Palosuo 1953; Hari et al. 2017). An upward trend in the probability of ice occurrence locally in the Gulf of Riga and the Gulf of Finland in the 20th century (Jevrejeva et al. 2004) was probably caused by an increase in freshwater influx to these subbasins (Winsor et al. 2001). The loss of ice is expected to persist (Jylhä et al. 2008; Luomaranta et al. 2014), which is consistent with satellite observations and models that demonstrate a gradual ice loss across the entire planet (Slater et al. 2021).

Despite varying estimates of changes in wind speed in the Baltic Sea region (Pryor and Barthelmie 2003; Hünicke et al. 2015; Torralba et al. 2017), it is likely that no major trend in wind speed exists in this region (Hünicke et al. 2015; Rutgersson et al. 2022). However, notable changes in the direction of strong winds (Bierstedt et al. 2015) that predominantly blow from the west or southwest (Ruosteenoja et al. 2019) have been observed. These changes are evident in spatial variations in the Baltic Sea wave properties (Kudryavtseva and Soomere 2017; Najafzadeh et al. 2021) and extreme water levels (Pindsoo and Soomere 2020), and are most pronounced during autumn and winter seasons (Bierstedt et al. 2015), coinciding with the onset of cold weather and freezing conditions. Therefore, these relevant trends may have changed both the wind-wave and ice climate of the Baltic Sea. Moreover, extreme wave conditions, characterised by significant wave heights of >7 m, usually occur during the period from November to January (Björkqvist et al. 2017). It is thus likely that changes in the beginning time or duration of the ice season due to the described changes not only leave the shoreline unprotected but could also result in a substantial increase in nearshore hydrodynamic loads.

In this paper, we evaluate the nearshore wave loads in response to the climate change-driven loss of sea ice in the Gulf of Riga, the third-largest seasonally ice-covered water body of the Baltic Sea. To a first approximation, we analyse the potential changes in average wave properties and the likely increase in cumulative wave properties, such as total wave energy or its flux, owing to the complete loss of ice. The analysis is performed using time series of wave properties, evaluated with idealised totally ice-free climate and actual ice data from recent decades, similar to Najafzadeh et al. (2022). This approach assumes that waves do not penetrate into ice-covered sea areas. We analyse five characteristic locations: one is used for instrumental wave measurements (Giudici et al. 2023), two for visual wave observations (Eelsalu et al. 2014), one characterises the situation in the offshore of the gulf, and the last one is located near the entrance of the gulf in the eastern Baltic Proper.

Data and method

The basic procedure

The influence of sea ice on wave properties is a multi-faceted process, and different approaches to the presence of sea ice may lead to different ways to evaluating the statistical properties of wave fields in seasonally ice-covered seas (Tuomi et al. 2011). Contemporary wave models usually accurately replicate the impact of sea ice on wave properties in terms of long-term statistics (Björkqvist et al. 2018). However, uncertainties in the specification of the spatial distribution of ice cover may result in large differences in time series and short-term (e.g., monthly) maxima. For example, the use of various sources of ice information led to a 3.2 m difference in the monthly maximum significant wave height in the northern Baltic Sea (Tuomi et al. 2019). For this reason, we focus on the annual average and cumulative properties of wave fields in the Gulf of Riga. Similar to the more northern regions of the Baltic Sea (Najafzadeh et al. 2022), it is likely that these characteristics are less sensitive with respect to uncertainties in ice information.

There are several approaches for estimating the effect of ice cover on wave properties. The most common is Type F approach (also called Type F statistics; Tuomi et al. 2011). It exclusively incorporates wave data during ice-free time at a given location. Type N approach represents the idealised scenario where there is no ice at all in the study area (Tuomi et al. 2011). Type N statistical quantities for seasonally ice-covered regions are usually estimated with wave models that do not involve sea ice during the entire study period. Following Najafzadeh et al. (2022), we perform a comparison of wave properties evaluated using Type F and Type N statistics to develop a first approximation of the impact of the presence of ice on wave climate.

We employ ice information from public databases OSI-450 and OSI-430 (Lavergne et al. 2019) and wave time series from a recent replication of idealised ice-free wave climate in the entire Baltic Sea (Giudici et al. 2023). The procedures of handling ice data are described in detail in Najafzadeh et al. (2022). For this reason, we only explain the main features of these datasets that are directly related to the analysis in this paper.

The basic procedure follows the one employed by Najafzadeh et al. (2022). The potential impact of ice loss on wave loads is evaluated using modelled Type N statistics and satellite-derived information about the duration of the ice season. Wave height is taken from the simulations by Giudici et al. (2023) and is set to zero during the ice season for each ice-covered location. We use only two dates extracted from the ice data: the start and end days of the ice season at each location. As the ice season often extends over two subsequent calendar years, the differences in wave properties in the current climate (for which Type F statistics are used as a proxy) and in the hypothetical ice-free climate (Type N) are evaluated for the so-called windy seasons (Männikus et al. 2020), involving the time period from 1 July to 30 June of the subsequent year. The analysis covers 31 windy seasons from 1990/1991 to 2020/2021, focusing on average wave height as well as cumulative wave energy and wave energy flux during the whole windy season and the ice-free time of such seasons.

Wave data

The time series of wave height and period were extracted from simulations performed using the SWAN wave model (Booij et al. 1999) for the period of 1990–2021. The model setup under idealised ice-free conditions, implemented parameters and features of the output are described in Giudici et al. (2023). The simulations were performed on a three-level nested grid. The coarse grid covers the entire Baltic Sea (Fig. 1) with a horizontal resolution of about 3 nautical miles (nmi). The medium grid covers the Gulf of Riga and its vicinity with a resolution of approximately 1 nmi. A set of fine grids covers the coastal area, with a resolution of 0.32 nmi (about 600 m) along the southern and eastern (mostly straight) shores of the gulf, and with a resolution of about 0.16 nmi (about 300 m) in the northern side of the gulf, to meet the complicated shape and irregular bathymetry in this region.

The simulations were forced with wind information matching the latest WMO climatological standard normals from 1991 to 2020, with an extension from 1990 until 2022, using the state-of-the-art global atmospheric reanalysis ERA5 (Hersbach et al. 2020) developed by the European Centre for Medium-Range Weather Forecasts (ECMWF 2006). More detailed information about the bathymetry and other features of the grid, as well as the particular setup, is provided in Giudici et al. (2023) and Najafzadeh et al. (2024).

The output of the model was validated against wave measurements at one location in the Baltic Proper (Harilaid, Fig. 1) near the entrance to the Gulf of Riga and four locations in the interior of the gulf (Table 1; Najafzadeh et al. 2024). Wave properties at Kõiguste, Matsi and Kihnu (Fig. 1) were evaluated with a bottom-mounted Recording Doppler Current Profiler (RDCP) during a few months at each location. Here, the RDCP is a medium range (600 kHz) device

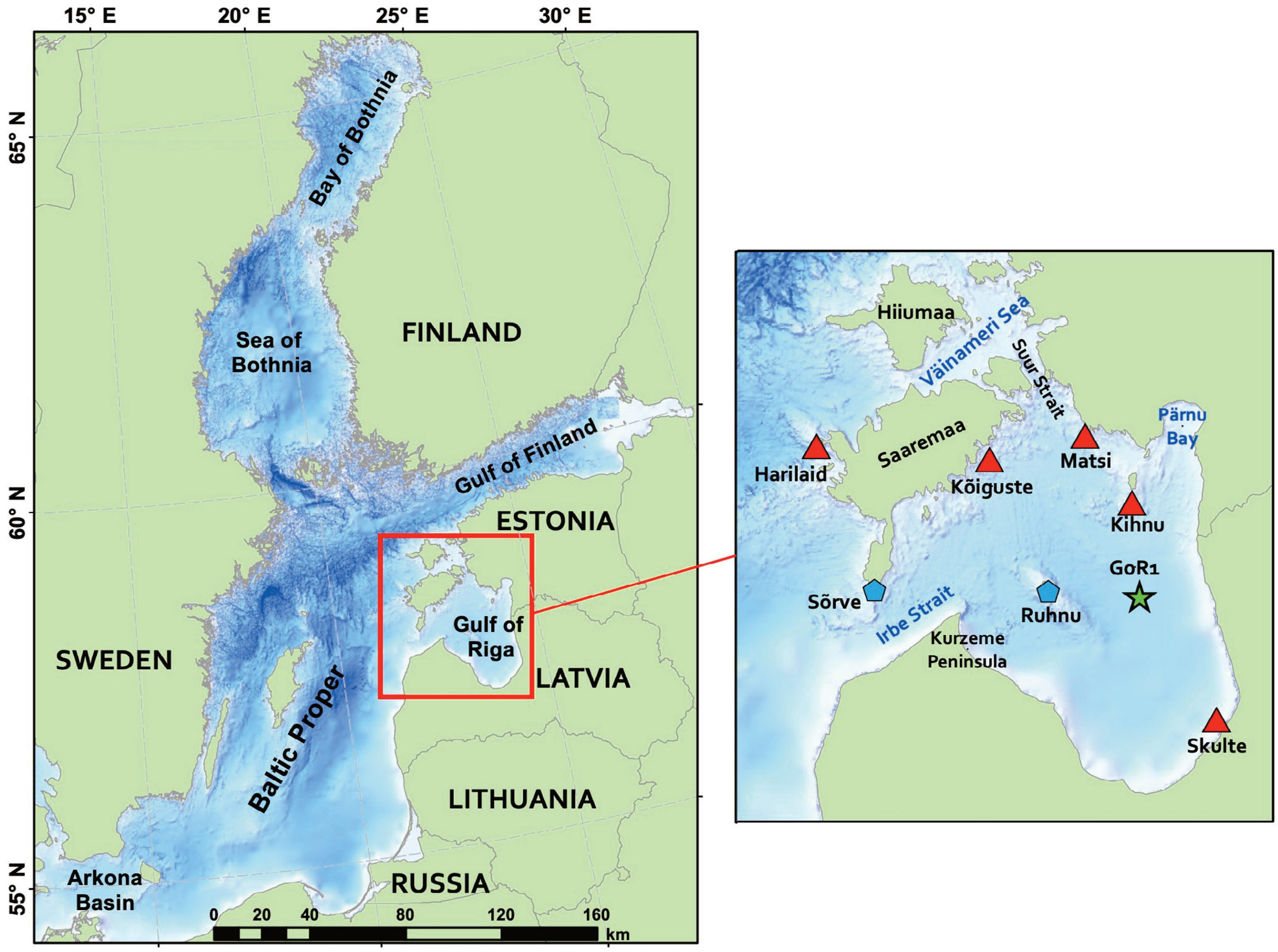

Fig. 1. Scheme of the study area and the wave measurements (red triangles) and observations (cyan pentagons) used to validate the wave model in Najafzadeh et al. (2024).

that calculates wave parameters based on the dynamic pressure of wave motion. The temporal courses of measured wave heights and periods were adequately replicated by the model. The correlation coefficients between the measured and modelled wave heights are in the range of 0.89–0.92 for the data from the innermost grid and 0.71–0.8 for the 1 nmi grid (Najafzadeh et al. 2024). The associated bias is in the range of –0.19 to –0.23 m, and the root mean square deviation (RMSD) of the measured and modelled values is 0.24–0.30 m. These estimates are almost the same as for the simulations of Björkqvist et al. (2018) for the Gulf of Finland, which are considered state-of-the-art in wave modelling in the Baltic Sea (Soomere 2023). This comparison indicates that the employed wave data appropriately reflect the actual wave conditions in the Gulf of Riga.

The match of wave heights is even better for wave buoy measurements near the Skulte Harbour at 57°19.199′ N and 24°21.813′ E at a water depth of 15 m over 8.5 months, where the bias was 0.02(0.03) m, the RMSD was 0.19(0.20) m, and the correlation coefficient was 0.88(0.92) for the 1 nmi (0.32 nmi) grid (Najafzadeh et al. 2024). Wave properties at this location were acquired using the Wave and Tide Sensor 5218 (Aanderaa, Norway) once an hour, and the pressure time series were measured over a time period of 120 s. More importantly, there was almost no difference in the quality of replication of wave properties between using the 1 nmi and 0.32 nmi grids. For this reason, we use below the results for the 1 nmi grid.

The mismatch between modelled and measured periods was larger, with an average bias ranging from –0.41 to 1.04 s and RMSD from 1.21 to 2.51 s. This level of mismatch is usual in the simulations of the Baltic Sea waves in nearshore conditions. While it does not affect the estimates of average wave height and cumulative wave energy, it adds uncertainty to the estimates of cumulative wave energy flux (wave power).

Sea ice

The sea ice dataset was retrieved from the second release of EUMETSAT Ocean and Sea Ice Satellite Application Facility OSI-450 (v2.0, 2017; Lavergne et al. 2019) and its extension, OSI-430-b. These datasets are provided by the Norwegian Meteorological Institute and the Danish Meteorological Institute via an open data interface at http://osisaf.met.no (accessed in May 2023).

The OSI-450 dataset offers worldwide information on sea ice concentrations and encompasses records from 1979 to 2015, while OSI-430-b covers data from 2016 onwards. Both datasets have a spatial resolution of 25 × 25 km, with each spatial grid cell containing daily ice concentration as a percentage of the grid cell covered by sea ice. Every record is further characterised by a flag that indicates the level of uncertainty for this record. Following Najafzadeh et al. (2022), we employ only records with a flag of 0, which signifies the highest reliability.

A comparison of remote sensing-based ice data and corresponding estimates derived from ice charts provided by the Swedish Meteorological and Hydrological Institute (SMHI) was performed for the Baltic Proper in Najafzadeh et al. (2022).

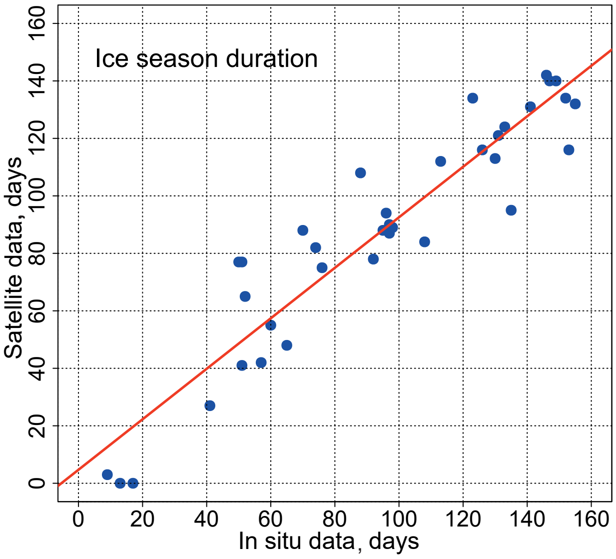

Fig. 2. Comparison of ice season duration provided by SMHI ice charts and retrieved from OSI-450 with ice concentration >50% at southwest Nordvalen. The red line represents the linear regression line. From Najafzadeh et al. (2022).

An estimate of the ice season duration by the SMHI at southwest Nordvalen (63.54° N, 20.73° E) was compared with a similar estimate at the nearest OSI-450 satellite ice measurements location (63.54° E, 20.76° E; Fig. 2). By considering ice concentration >50%, these two estimates resulted in the most accurate agreement with a correlation coefficient of 0.94 and a bias of around five days. The analysis in Najafzadeh et al. (2022) also showed that satellite-derived data tend to miss small ice concentrations. From the retrieved time series of ice concentrations, we evaluate the length of the ice season (Fig. 3) from its start and end days for each windy season. These days are defined as the first and last days of a windy season where ice concentration exceeds 50% at the selected location (Najafzadeh et al. 2022).

The analysis is applied to four locations in the Gulf of Riga and one location close to the entrance of the gulf in the eastern Baltic Proper (Harilaid, Table 1). While satellite ice data are not available for three wave measurement locations (Matsi, Kõiguste and Skulte, provided in Table 1) close to the coastline, ice data could be retrieved for areas near the locations of historical visual wave observations at Sõrve and Ruhnu. The length of the ice season varies considerably between years and selected locations. It typically lasts for

Table 1. Geographical coordinates and water depth of stations used to validate the wave model (Najafzadeh et al. 2024) and estimate the impact of ice on wave properties

Station	Longitude (°E)	Latitude (°N)	Depth (m)
Kihnu	23.95	58.05	11.5
Matsi	23.72	58.33	9.4
Kõiguste	23.02	58.32	6.3
Harilaid	21.82	58.47	13.7
Skulte	24.36	57.32	15.9
GoR1	23.87	57.70	42.4
Sõrve	22.06	57.90	4.8
Ruhnu	23.34	57.77	23.2

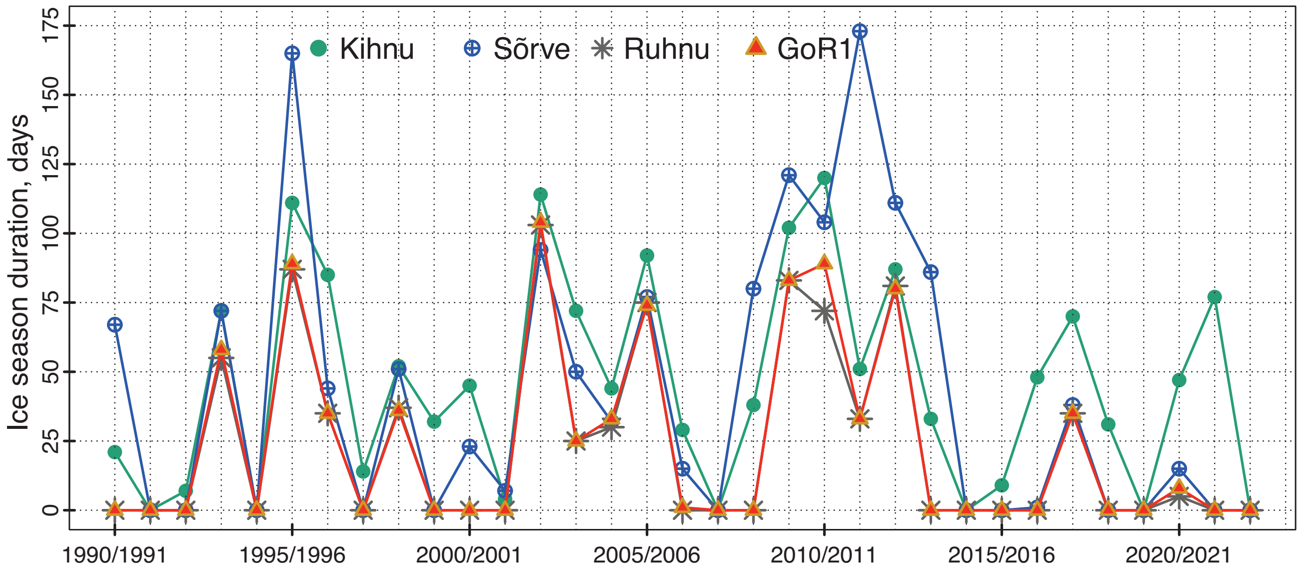

Fig. 3. Ice season duration at Kihnu, Sõrve, Ruhnu and GoR1 based on OSI-450 and OSI-430 satellite data. Harilaid has had notable ice cover only in five years since 1990 (1993/1994, 1995/1996, 2002/2003, 2009/2010, 2010/2011). The ice season duration (not shown) for this location ranged from 13 days in 1993/1994 to 59 days in 2002/2003.

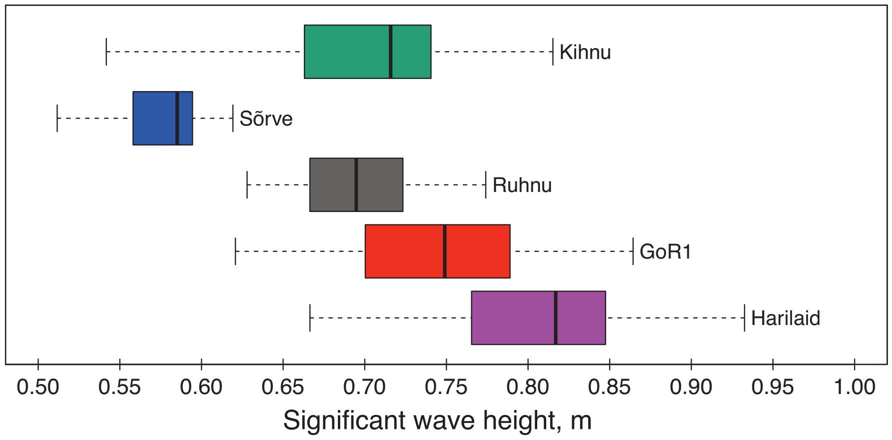

Fig. 4. Boxplot of ice-free modelled mean significant wave height H_S (Type F statistics according to Tuomi et al. 2011) during 31 windy seasons from 1990/1991 to 2020/2021. The coloured area reflects the two middle quartiles of the windy season mean H_S. The vertical line in this area represents the median H_S (in terms of mean H_S in single windy seasons). The sections denoted by dashed lines represent the lowest and highest quartiles. The maximum and minimum H_S at a particular location are shown by small vertical lines.

about two months but may reach five and a half months (e.g., at Sõrve) in severe winters, whereas substantial ice cover is virtually missing in about half of the winters at the observed locations. Harilaid has the shortest ice season that does not allow for sensible comparison with locations in the interior of the Gulf of Riga. The location GoR1 in the offshore of the Gulf of Riga has good quality ice information but only modelled wave data. However, the above comparison of modelled and measured wave data at this location demonstrates that the modelled wave properties adequately match the measured ones.

Results

Average wave properties

The median values of the average significant wave height H_S for single windy seasons in terms of idealised ice-free statistics (Type N in terms of Tuomi et al. 2011) range from 0.7 to 0.75 m at Kihnu, Ruhnu and GoR1 (Fig. 4). The median value is much lower, 0.58 m at Sõrve. It is expected that these values almost exactly match the estimates of long-term H_S at the relevant locations (Giudici et al. 2023; Najafzadeh et al. 2024), even though having slightly different interpretations. The lower value of H_S at Sõrve compared to the ones at other locations reflects the well-known west-east anisotropy of wind and wave fields in the Gulf of Riga, where the largest wave heights occur in the northeastern part of the water body and the western nearshore has a clearly milder wave regime (Eelsalu et al. 2014; Giudici et al. 2023). The difference in the medians of the windy season average H_S at Sõrve and Ruhnu is almost equal to the similar difference in long-term observed wave heights at these locations (Eelsalu et al. 2014). It is also expected that the wave climate near Harilaid in the Baltic Proper is clearly rougher in terms of annual averages as well as their minima and maxima (Fig. 4).

The temporal courses of the windy season average wave energy (Fig. 5) qualitatively replicate the similar courses of average H_S (not shown) but have much larger amplitudes. The temporal course of this quantity is almost the same at Harilaid, Ruhnu, Kihnu and GoR1. As expected, wave fields are more energetic at Harilaid than in the interior of the Gulf of Riga, where the GoF1 location has more wave energy than

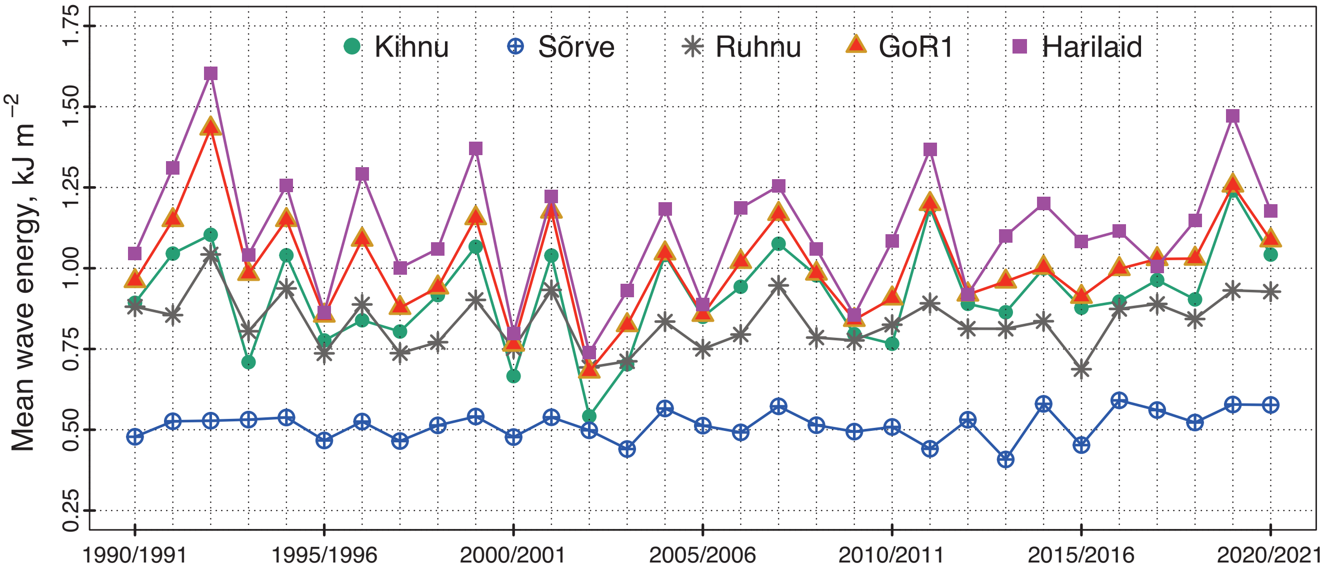

Fig. 5. Average ice-free wave energy (Type F statistics) evaluated from the SWAN model hindcast for single windy seasons in 1990/1991–2020/2021.

other locations for the reasons explained above. Interestingly, this quantity varies insignificantly at Sõrve. This feature indicates that wave fields at this location, on average, only weakly depend on the storminess of the particular windy season. Even though the average wave energy decreased at Harilaid, Ruhnu, Kihnu and GoR1 from 1990/1991 to 2002/2003, there is no evident long-term trend in this quantity. Instead, the temporal course suggests the presence of decadal-scale variations, with a decrease in the 1990s and a less rapid increase in the 2000s and 2010s.

The temporal course of the windy season average wave energy flux (Fig. 6) is qualitatively similar to the one for the average wave energy. Wave energy flux is much more powerful at Harilaid than in the Gulf of Riga. Different from wave energy that is relatively large at GoR1, the vicinity of Kihnu tends to have larger energy flux than other locations in the gulf. Interestingly, this quantity at Sõrve is only slightly smaller than at other locations. In some years, it reached the same level as the wave energy flux at Ruhnu that has almost 21% higher average H_S.

This pattern signals the importance of wave periods in the formation of wave loads in different parts of the gulf. The wave periods are clearly larger at Harilaid than in the Gulf of Riga because of the systematically longer fetch in the Baltic Proper. Note that the higher level of wave energy flux at Harilaid in our estimates compared to the results of Soomere and Eelsalu (2014) apparently reflects a systematic underestimation of wave heights by about 15% in the early simulations of Räämet and Soomere (2010).

It is likely that the systematically longer fetch is the reason for the larger wave energy flux at Kihnu compared to Ruhnu. The relatively large wave energy flux at GoR1 com-

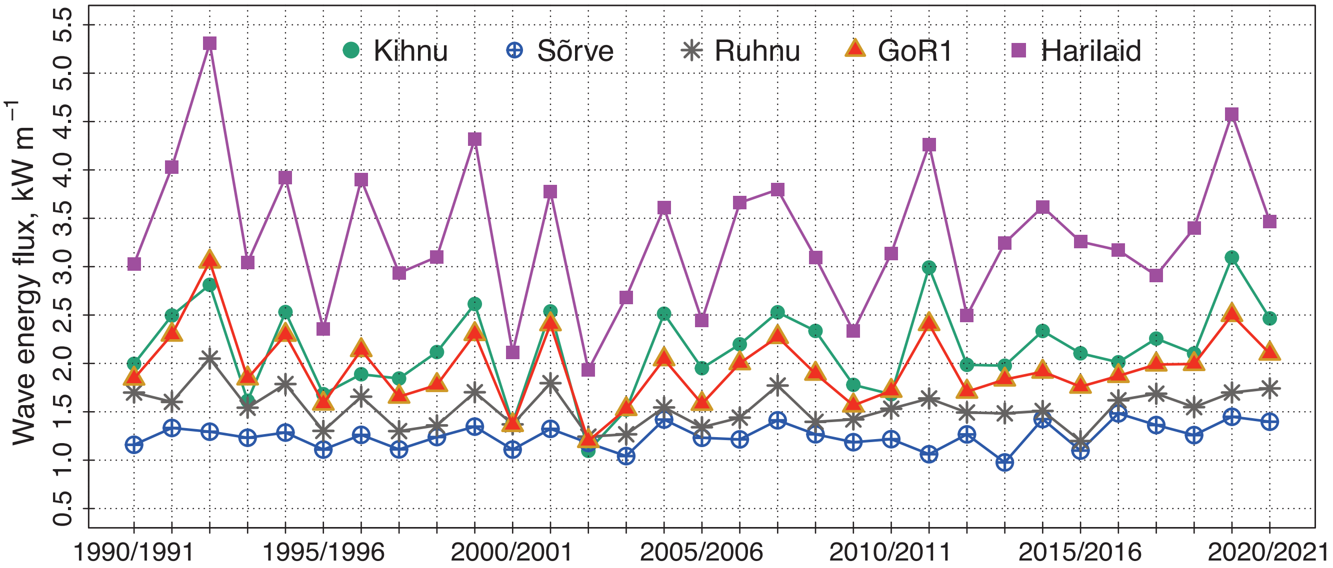

Fig. 6. Average ice-free wave energy flux (Type F statistics) evaluated with the SWAN model during windy seasons in 1990/1991–2020/2021.

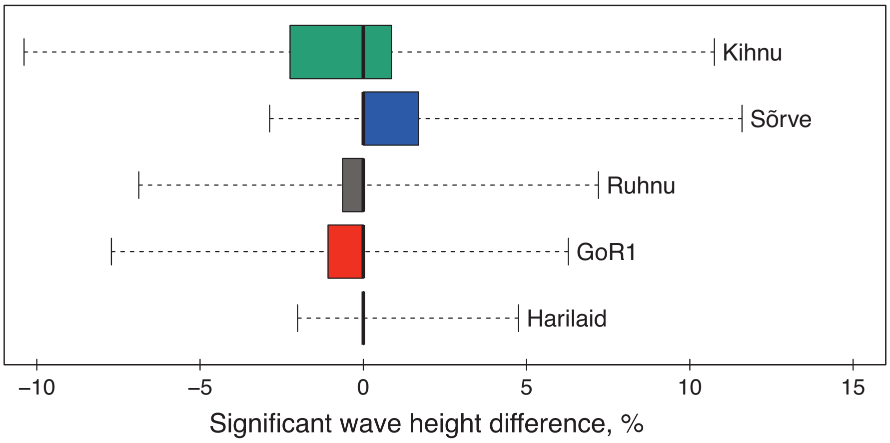

Fig. 7. Difference of Type F and N estimates of average H_S in single windy seasons in 1990/1991–2020/2021. See the explanation of the diagram in the caption to Fig. 4.

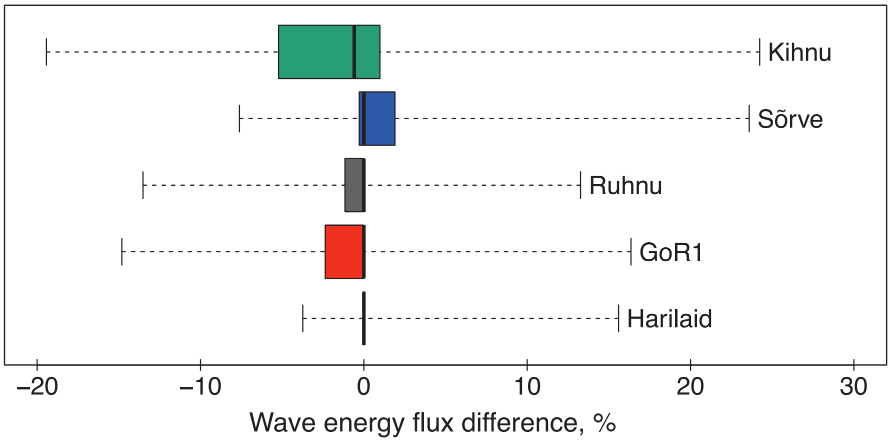

Fig. 8. Difference of Type F and N estimates of mean wave energy flux in single windy seasons in 1990/1991–2020/2021. See the explanation of the diagram in the caption to Fig. 4.

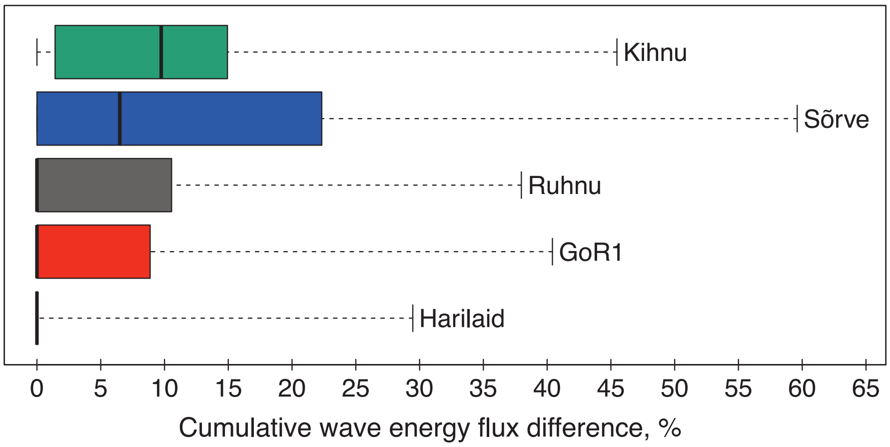

Fig. 9. Difference of Type F and N estimates of cumulative wave energy flux in single windy seasons in 1990/1991–2020/2021. See the explanation of the diagram in the caption to Fig. 4.

pared to Ruhnu may stem from the presence of relatively infrequent but comparatively strong north-northwestern winds in this region (Soomere 2003) that have a longer fetch at this location. The relatively high level of wave energy flux at Sõrve signals that this location may often receive relatively long waves from the Baltic Proper. Similar to above, there is no evident long-term trend in the windy season average wave energy flux.

The impact of ice loss

The potential impact of total ice loss can be quantified, to a first approximation, using a comparison of Type N (idealised ice-free) statistics for the entire windy season, with estimates where the wave height time series is omitted during the ice season (a proxy of Type F according to Tuomi et al. 2011). The difference between wave climate parameters calculated using Type F and Type N approaches depends on the match of the windy season and ice-free time. Type F statistics underestimate average wave height when the ice season is windier than ice-free time, and overestimate it in the opposite case. This comparison (Figs 7, 8) signals that the loss of ice insignificantly impacts the Type F statistics of average H_S and mean wave energy flux in the Gulf of Riga, and practically does not affect these statistics at Harilaid (which had ice only in five windy seasons out of 33; Fig. 3).

The situation is, as expected, greatly different in terms of cumulative wave properties in the interior of the Gulf of Riga. Figure 9 first of all signals, not unexpectedly, that any loss of sea ice will lead to an increase in total wave energy flux at any location in the gulf. The changes are the largest at Sõrve, where an increase in wave energy flux by 8% in average and up to 60% in single windy seasons is likely. A large number of years with no notable ice cover is apparently the main reason why the loss of sea ice will not affect the median of

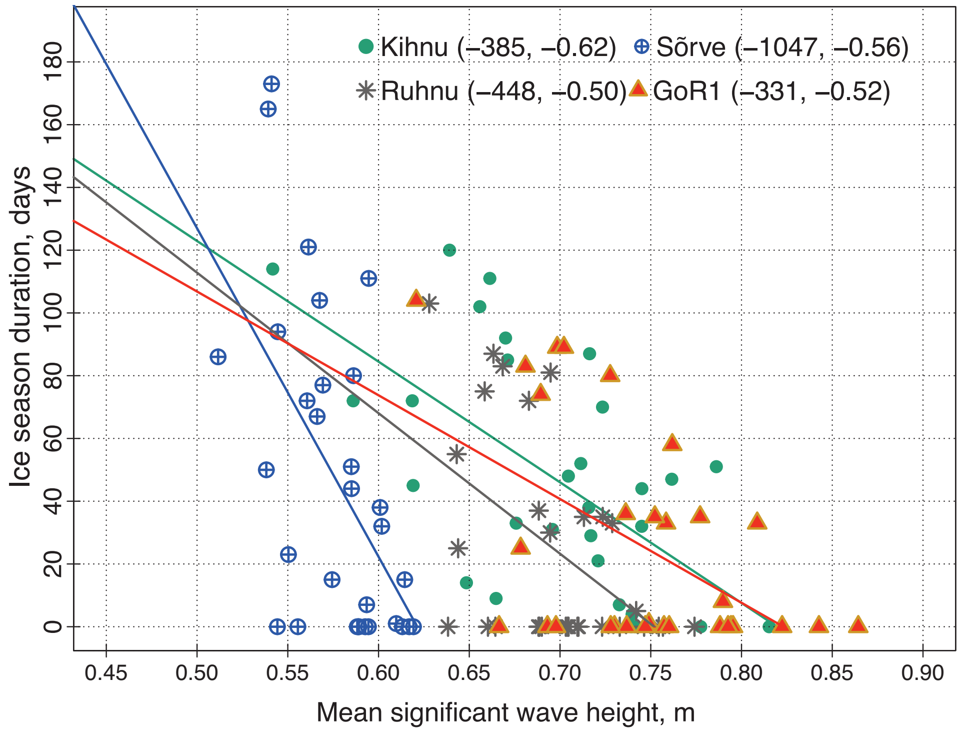

Fig. 10. Scatter diagram of ice season duration and mean H_S during ice-free times in single windy seasons at four locations of Fig. 1. The slopes and the correlation coefficients of the relevant regression lines are presented in the legend. Note that most of these data points that define the location of the median in Fig. 7 lie on the horizontal axis. These data points also affect the location of the trendlines.

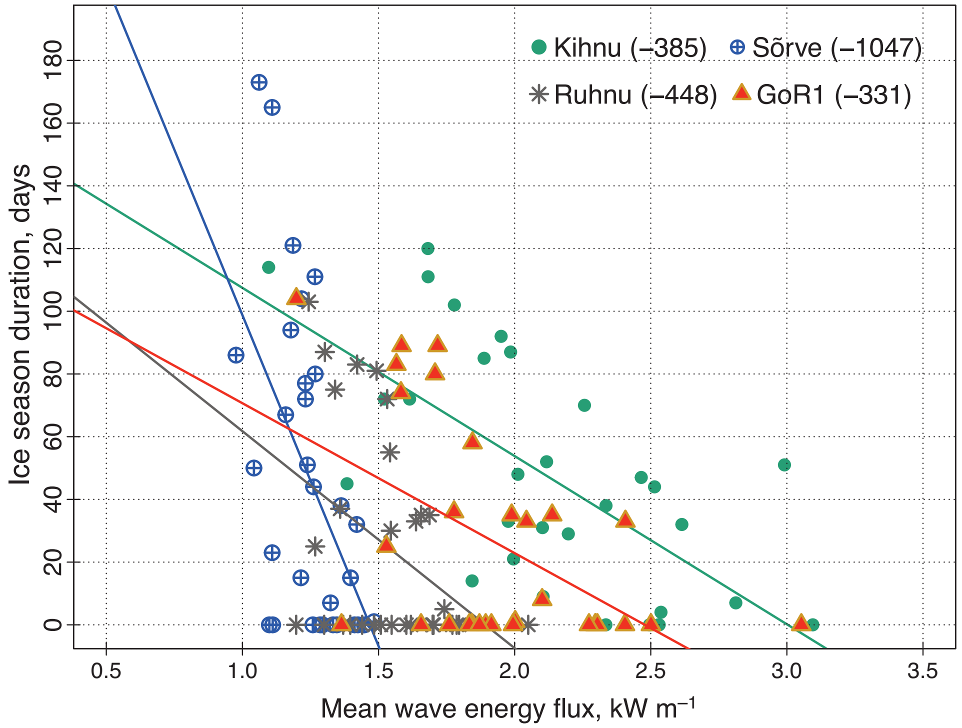

Fig. 11. Scatter diagram of ice season duration and mean wave energy flux during ice-free times in single windy seasons at four locations of Fig. 1. The slopes and the correlation coefficients of the relevant regression lines are presented in the legend. Note that most of these data points that define the location of the median in Fig. 8 lie on the horizontal axis.

windy season cumulative wave energy flux at Harilaid. The actual increase is, of course, inevitable, should sea ice be completely lost, but it is still much smaller than in the Gulf of Finland or the Sea of Bothnia, where the ice season is currently much longer.

Figures 7 and 8 present a generalised view of the changes in average wave properties that focuses on the ranges of the presented values. A more detailed inspection of the interrelations between the duration of the ice season and average wave properties during the associated windy season demonstrates that a decrease in the ice season duration will eventually lead to a substantial increase in the average significant wave height (Fig. 10) and average wave energy flux (Fig. 11). This increase is fairly small at Sõrve but may reach up to 0.2 m (i.e., about 30% of the long-term average) in the interior of the Gulf of Riga.

Figures 10 and 11 also reiterate the representation of the range of ice season durations at different locations presented in Fig. 3 in a different context. While the ice season duration varies much more at Sõrve than at other locations of the Gulf of Riga, the ranges of variation in the windy season significant wave height and wave energy flux are much smaller at Sõrve than at other locations. This feature signals that ice formation and breakup at Sõrve is only weakly correlated with the severity of wave conditions in the Gulf of Riga. The similar range for the windy season average wave energy flux is also small for Sõrve. Consistently with Fig. 9, the ranges in question reached the long-term average values of these quantities in the interior of the gulf, where changes in the ice season duration have, therefore, a much larger impact on both the average and cumulative wave properties.

Discussion and conclusion

We have performed a simple exercise to evaluate some consequences of the loss of sea ice on the wave regime and hydrodynamic loads in the Gulf of Riga, based on simulated wave climate and satellite data about ice concentration. This water body is the southernmost large subbasin of the Baltic Sea that has at least some amount of sea ice each year under the current climate. Climate change will likely lead to substantial variations in the ice regime of this region. The sea ice cover and its duration are more persistent in the Gulf of Riga compared to neighbouring areas (e.g., Harilaid in the northeastern part of the Saaremaa Island that is washed by the waters of the Baltic Proper; Jevrejeva et al. 2004). The ice season usually lasts about two months but can cover up to five and a half months in severe winters at some locations (Sõrve) in this gulf. Therefore, the Gulf of Riga is obviously vulnerable to climate warming and its consequences, such as changing stratification. The altered behaviour of sea waves can affect coastal regions, shipping routes and various industries, depending on wave conditions.

The analysis also reiterates several known features of the wave climate in the Gulf of Riga. It is generally mild, with the average significant wave height over windy seasons (from July to June of the subsequent year) reaching maximally 0.9 m and usually being about 0.7–0.75 m. The anisotropy of wind conditions and the different exposure of different locations to predominant winds have created a situation where the spatial distribution of annual average wave energy flux does not exactly match the similar distribution of average wave height. In particular, in some years at locations such as Sõrve with a low median significant wave height (0.58 m), the wave energy flux (during ice-free time) can reach values characteristic of locations where the average wave height is much higher (e.g., Ruhnu with the median significant wave height of 0.7 m).

The analysis of ice impact is performed by comparing average and cumulative wave properties during ice-free time with those in an idealised totally ice-free climate. This approach ignores possible changes in the wind regime in the absence of sea ice owing to different surface roughness and changes in the stability of air flow, and thus serves only as a rough, first-order estimate of the future wave properties and associated loads. Furthermore, within the scope of our investigation, the multifaceted aspects of sea ice and waves interaction, such as the penetration of waves into the sea ice cover (Wadhams 1986), have not been addressed. Ignoring the wave dispersion and attenuation in the ice may lead to biases in wave statistics.

First of all, it is likely that even total ice loss will lead to insignificant changes in average wave properties, such as average significant wave height or average wave energy. This feature is consistent with the outcome of a similar analysis of more northern regions (Najafzadeh et al. 2022) and signals that the classical statistical properties of wave climate in seasonally ice-covered seas must be interpreted with caution.

However, cumulative wave properties, such as annual wave energy and wave energy flux, are expected to increase significantly. Changes during a typical ice season make up about 10% of the annual wave energy flux in the current climate, and are thus clearly smaller than similar changes observed in the Gulf of Finland and the Sea of Bothnia (Najafzadeh et al. 2022). The future is still threatening, as changes may be much larger, reaching 40–60% of the existing typical levels in terms of cumulative wave energy flux in single years and at single locations. Such changes, if associated with elevated water levels that are typical of windy months, may lead to a particularly rapid evolution and erosion of certain coastal sections that are no longer protected by ice (Orviku et al. 2003; Ryabchuk et al. 2011).

It is thus likely that the projected climate changes, especially the continuing warming of the Baltic Sea region, will lead to a gradual increase in hydrodynamic loads on the shores of the Gulf of Riga. These loads may be particularly large during single relatively windy years, the analogues of which had extensive ice cover in the past. The signal of the global sea level rise adds to the increasing susceptibility of the Gulf of Riga's shores and calls for careful monitoring of their vulnerable sections and preparation of necessary management solutions.

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Jääolude muutumise mõju parasvöötme veekogude lainekliimale Liivi lahe näitel

Fatemeh Najafzadeh ja Tarmo Soomere

Kuigi talvise merejää kadumisel võib lainekliima oluliselt muutuda, ei pruugi see kajastuda lainetuse omadusi peegeldavates formaalsetes suurustes. Aasta keskmine lainekõrgus ei pruugi muutuda, kuid näiteks kogu aasta jooksul randa jõudev lainetuse energia üldjuhul kasvab. Võimalikke muutusi analüüsitakse parasvöötme külmemas osas paikneva Liivi lahe näitel, kus nii lainetuse omadused kui ka jääolud on suures osas sõltumatud Läänemere avaosa lainetusest ja jäätingimustest. Aluseks on lainemudeliga SWAN aastatel 1990–2021 ERA5 süsteemis modelleeritud tuuleinformatsiooni abil rekonstrueeritud lainetuse parameetrid 1-miilise (*ca* 1,86 km) lahutusvõimega kogu Liivi lahes ja 300-meetrise lahutusvõimega lahe rannalähedastes osades. Võrreldakse lainetuse omadusi idealiseeritud jäävabas lahes ja satelliidiinfo alusel määratletud jääolude korral, mil lainetust jääga kaetud merealadel ignoreeritakse. Mõneti ootamatult kattuvad idealiseeritud jäävaba mere jaoks leitud lainetuse keskmised omadused suuresti tegelikke jääolusid arvestavate hinnangutega. Sisuliselt tähendab see, et tüüpiline tuule tugevus ja lainete omadused jääperioodil ja jäävabal ajal oluliselt ei erine. Küll aga suureneb jää kadumisel märkimisväärselt lainete poolt randa kantav energiavoog ning eeldatavasti kiirenevad märgatavalt lainete põhjustatud rannaprotsessid.