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High waves with high sea levels - sensitivity test in the Olkiluoto region

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Contents

Abstract

In this Report, we discuss co-occurring high waves and high sea levels in the Olkiluoto region on the eastern coast of the Bothnian Sea using uniform wind fields as atmospheric forcing for the wave simulations. Our simulations represent estimates of the sea surface wave fields that may be reached under different wind conditions and under typical sea level in the area, as well as during an extreme sea level of 2 m above the mean sea level. Wave fields were calculated using the wave model WAVEWATCH III® with high (0.1 nautical mile) resolution around the Olkiluoto nuclear power plant (NPP) site. Our results show that westerly winds grow the highest waves at the western shoreline of the Olkiluoto study site, whereas the southern shoreline is open to high waves both for southeastern and southwestern winds. As the southern sea area is deeper, waves in this area do not grow significantly higher with higher sea levels. In the shallower western sea area an sea level of 2 m can allow for even 0.5 m higher significant wave heights with extreme wind speeds of 32 m s^{-1}. With lower wind speeds, significant wave heights are under 1.0 m near the Olkiluoto NPP site both for mean sea level and extreme sea level.

1 Introduction

Coastal flooding is affected by both sea level and waves on the coast. The effect of waves depends on the bathymetry near the shoreline and the structures (such as piers and walls) at the shoreline. To study the risks of coastal flooding, it is important to study the simultaneous occurrence of high sea level and high waves near the coast, even if a more detailed analysis is needed to have estimates of the height of the combined effect of sea level and waves (Leijala et al. (2018)). The probability of a simultaneous high sea level with high waves in the Baltic Sea is shown to be highest on the eastern coast of the Bothnian Sea by Kudryavtseva et al. (2020), where the Olkiluoto nuclear power plant (NPP) is located. However, on the Finnish coast, the complex coastline and numerous islands together with shoals limit wave growth in varying ways with winds of different speeds and directions. Therefore, the highest waves might not occur simultaneously with the most extreme sea levels. Wave growth is affected by the fetch, i.e., the distance the wind affects the sea surface from the shore/island, as well as the duration and strength of the wind (Kahma (1981), Tuomi et al. (2012)). These conditions for the fetch can vary greatly locally, and the length of the fetch can have an effect if the waves grow long enough to start to interact with the seafloor (see Young et al. (1996)).

Modern wave models account for depth variation and wave interaction with the sea floor when waves are long enough in relation to the depth of the water. Nowadays, water level variation is routinely used as a forcing for many wave model setups. For example, the wave forecasts of the Copernicus Marine Service and therefore also the Baltic Sea Analysis and Forecast Product (BALTICSEA_ANALYSISFORECAST_WAV_003_010, `https://doi.org/10.48670/moi-00011`) include sea level variation in their wave forecasts. In the Baltic Sea, the influence of sea level variation on wave fields is mainly limited to coastal areas, and sea level effects that change significant wave height more than 10 cm are rather rare (Tuomi et al. (2023)).

Waves in connection with an extreme sea level in the Baltic Sea have been evaluated by Apukhtin et al. (2017) and Gordeeva et al. (2020). In Apukhtin et al. (2017), wave simulations have been performed in high resolution near Sosnovyi Bor NPP, estimating significant wave heights near the shoreline. In Gordeeva et al. (2020), waves have been simulated in lower resolution in the Bothnian Bay, without applying higher resolution near the planned Hanhikivi NPP site in Pyhäjoki.

Extreme sea levels in the future are affected both by natural climate variability and by changes in mean sea levels and short-term sea level variations due to climate change. On the Finnish coast of the Baltic Sea, the post-glacial rebound of the Earth's crust leads to a decline of mean sea level that counteracts the effect of global mean sea level rise. Estimates of extreme sea level are useful for the protection of the population and infrastructure in the vicinity of the coast, especially for NPPs. A comprehensive investigation of the present-day sea level variability and the scenarios for mean sea level in the future is needed for the determination of coastal flooding risks on the

Finnish coast (Leijala et al. (2018); Pellikka et al. (2018); Pellikka et al. (2023)). In the MAWECLI project, the effect of clustered cyclones on sea level has been studied by Rantanen et al. (2024) based on historical atmospheric and sea level data. Also, a more theoretical approach has been used, where the effect of local and deep synthetic cyclones on sea level was investigated (Särkkä et al. (2024b)).

In this study, we investigate how high sea level affects surface waves in the vicinity of Olkiluoto NPP, continuing the work started in Särkkä et al. (2024a). According to the original research plan, the wind fields from synthetic cyclones should have been used as input both for the sea level and wave models. It turned out that for the wave model, the quickly moving low pressure systems with high wind speeds (over 40 m/s) combined with the special features of the Baltic Sea, produced unrealistic wave heights in the simulations. In the end, we changed the plan so that waves are simulated using all together 90 different uniform wind fields that were combined with 18 different wind directions and 5 different wind magnitudes. This study examines plausible wave fields around Olkiluoto NPP site, when wave growth is not limited by the duration of the wind. Since the shallowness of the area occasionally affects waves and the purpose of the analysis is to look for the worst possible flood situations (which are not caused solely by waves), the same analysis is carried out with a situation where the static water level in the area is 2 m higher than usual, corresponding to an extreme sea level estimate at Olkiluoto (Särkkä et al. (2024a)).

2 Data and methods

2.1 WAVEWATCH III® model setup for the Baltic Sea

We used the third-generation spectral wave model WAVEWATCH III® (Tolman et al. (2002)) to perform wave simulations. The spectral wave models are built to represent the chaotic nature of sea surface waves by not solving individual waves on the sea surface but rather using a statistic approach in which the wave field, consisting of waves with different directions and frequencies, is described with power spectrum. The WAVEWATCH III® model solves the spectral action density balance equation for wavenumber-direction spectra in time and space. The wave spectrum used in our simulations has 35 frequencies (0.05–1.2774 Hz) and 36 directions. We used source terms for wind input and dissipation by Ardhuin et al. (2010), bottom friction by Komen et al. (1994), depth-induced wave breaking by Battjes et al. (1978), and weak non-linear wave-wave interactions by Hasselmann et al. (1985).

To account for the effects of smaller scale depth variations and coastline, we created a 0.1 nmi (around 200 m) model grid around Olkiluoto island with obstruction fields as proposed in Tuomi et al. (2014), using an open-access EMODnet Bathymetry (EMODnet Bathymetry Consortium (2020)). With obstruction grids, we account for some of the islands smaller than the model grid by dampening the wave energy in the model grid. The two-way nested setup was run with gradually increasing model resolution from the initial 1 nmi Baltic Sea grid to 0.5 nmi and 0.25 nmi surrounding the Olkiluoto area (Fig. 1). The minimum depth in the wave model was set up as 1 m.

The model setup was validated against operational wave buoys in the open sea and two research wave buoys in the higher resolution grid areas as part of a separate master's thesis work using the same model configuration. The model setup was run for 11 years with a high resolution setup using weather forcing from CERRA reanalysis (Ridal et al. (2024)). Validation against wave buoy observations in the area (shown in Fig. 1) showed that the model setup had the same order of accuracy as the other wave model setups in the Baltic Sea.

The high-resolution model setup was only created around the Olkiluoto NPP site as there were no available wave buoy measurements near the Loviisa NPP site that could have been used to validate the high-resolution setup in this area.

2.2 Model forcing with uniform wind fields

To study the effect of different wind conditions on high waves in the Olkiluoto area, we generated a set of uniform homogeneous wind fields from all wind directions with 20° intervals between 0° and 340° (all together 18 directions). The model was run with 5 different wind magnitudes for each direction: 14 m s^{-1}, 18 m s^{-1}, 21 m s^{-1}, 24 m s^{-1}

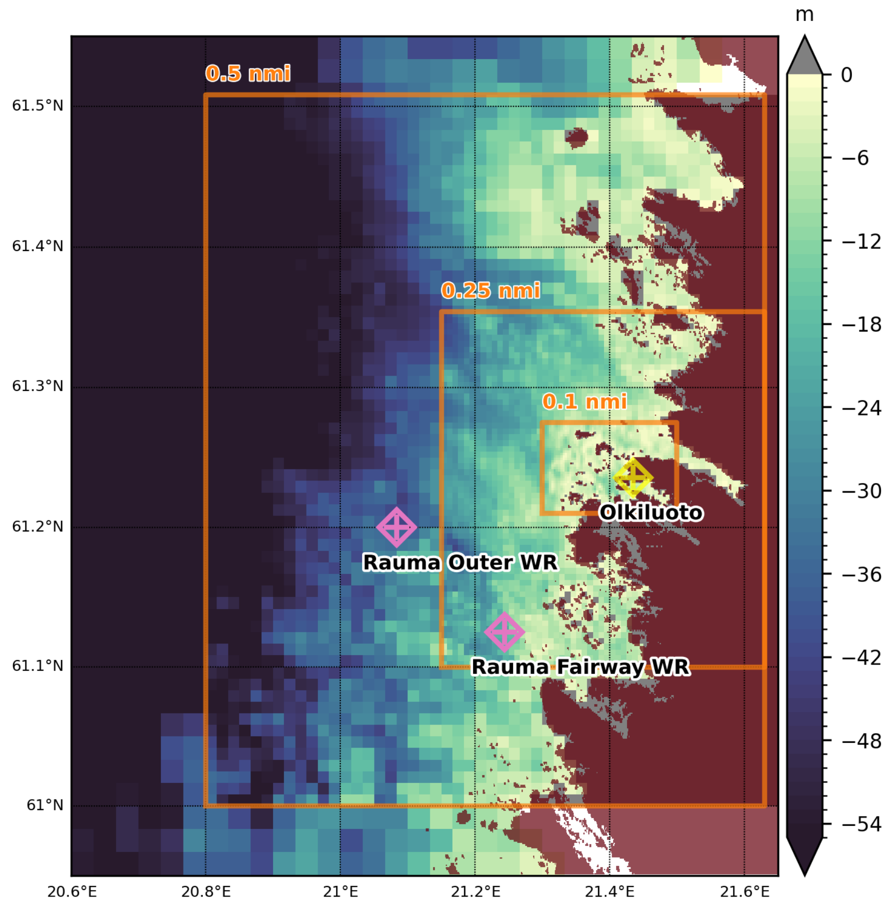

Figure 1: Two-way nested model grid setup. Pink diamonds highlight research wave buoys (WR) in the area where waves were measured during year 2020, yellow highlights Olkiluoto site. Colorbar represents model bathymetry and the size of the coloured squares represents the size of the model grid in latitude/longitude direction. The wave model bathymerty is calculated from the EMODnet Bathymetry (EMODnet Bathymetry Consortium (2020)). Dark red areas mark the land mask from the EMODnet Bathymetry.

and 32 m s^{-1}. The first four wind speeds represent higher wind speeds that can be expected in the region, although winds of more than 20 m s^{-1} in this region are rare (see e.g. Laurila et al. (2025)). The 32 m s^{-1} winds were chosen as an extreme worst case scenario.

The presented results are from the time when the wave fields reached a stationary state from each run, meaning that the wave growth was limited by the wind speed and fetch from the set direction, but not by the duration. By the shallow coast, waves can also be restricted by bottom friction and wave breaking due to interactions with the sea floor. Also, the refraction of waves toward shallow regions affects the propagation direction of the waves. However, these interactions are present only when the waves are long enough so that they interact with the sea floor. Based on linear wave theory, at 5 m depth waves need to be at least 10 m long to not interact with the sea floor, which corresponds to wave period of 2.5 s.

To account for the effect of higher sea level, we made identical runs with 2.00 m increase in sea level compared to the original depths of the model grid throughout the model domain. The depths of the original wave model grid are presented in Figures 1 and 2.

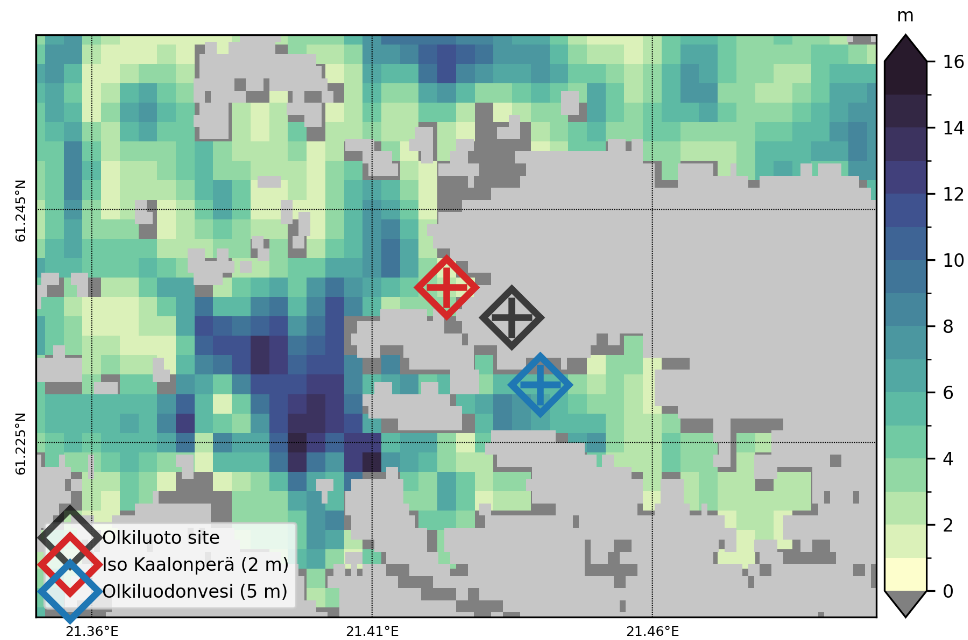

Figure 2: Zoomed bathymetry of the study area in the 0.1 nmi model grid. Colorbar shows the used model bathymetry and values below 0 m have been marked as land in the wave model setup. Lighter gray colours show the land mask in the EMODnet Bathymetry (EMODnet Bathymetry Consortium (2020)) used to generate model grid. Olkiluoto area as well as the two coastal sites (Iso Kaalonperä and Olkiluodonvesi) have been marked with a diamond.

2.3 Estimate for the extreme sea level at Olkiluoto

The estimates of high sea level at Olkiluoto have been calculated based on synthetic cyclone methods, presented in detail in Särkkä et al. (2024b). With this method, having winds and air pressures from synthetic cyclones at atmospheric input, we obtained an estimate of 144 cm for extreme sea level at Olkiluoto (Särkkä et al. (2024a)). This high sea level was due to synthetic cyclone propagating from Sweden and heading in a northeastern direction, when westerly winds push water towards the coast. Sea level at Olkiluoto is over 100 cm for 10 hours before it recedes rapidly to the mean sea level. The variations in the water volume of the Baltic Sea are mainly caused by the flow of the water in and out of the Baltic Sea through the Danish Straits. The contribution of the water volume to the local sea level (also called preconditioning) is termed the water balance component. This component can be estimated with a statistical model, based on wind speeds at a single coordinate point at (55° N, 15° E) (Johansson et al. (2014); Särkkä et al. (2017)). The extreme value of the water balance component can be estimated to be 100 cm. We estimate the extreme total sea level at Olkiluoto by adding water balance value 100 cm and the 100 cm sea level from the short-term sea level (that is exceeded during 10 hours) leading to static extreme sea level of 200 cm above mean sea level in the Olkiluoto region. In general, the high sea levels at Olkiluoto are related to cyclones arriving from the south or the west, whereas cyclones arriving from north or the east lead to lower sea levels. Therefore, the high sea levels at Olkiluoto are usually connected to simultaneous local southern or western winds.

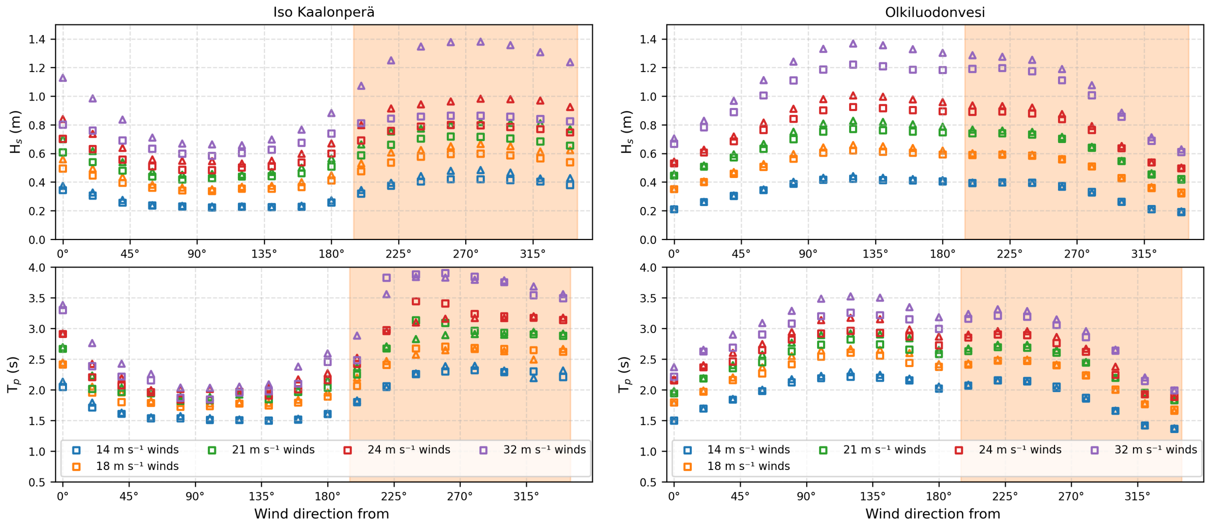

Figure 3: Maximum significant wave height (H_s, upper panels) and corresponding dominant wave period (T_p lower panels) with different wind speeds (colors) against different directions of the winds. Square markers show the wave simulations with the standard model bathymetry (shown in Fig. 1) and triangles show the corresponding value when sea level in the overall area was set 2.00 m higher. Wind directions, where high sea levels are most likely in this region (200° to 340°) are highlighted with light orange.

3 Results

Significant wave height (H_s) and dominant wave period (T_p) are presented at the two coastal sites surrounding Olkiluoto NPP: 1) western Iso Kaalonperä which is more separated from the open sea with shoals and islands around it and 2) Olkiluodonvesi which is connected to the open sea through some narrow passages through the islands in the west (Fig. 2) but has a rather long fetch from the south-east.

Western Iso Kaalonperä site is most open to high waves for wind directions from 230° (SW) to 320° (NW) (Figures 3, left panels, square markers). Winds of 14 m s^{-1} resulted in significant wave height (H_s) up to 0.4 m s^{-1} with peak periods (T_s) up to 2.3 s. Higher 24 m s^{-1} winds were able to grow H_s to 0.8 m with T_p varying between 3.2 s and 3.5 s with longest waves arriving from 240°–260° (WSW). Extreme wind speeds of 32 m s^{-1} generate around 0.1 m higher H_s values than 24 m s^{-1} winds, but T_p is even 0.6 s longer with western winds (280°).

The waves by the Iso Kaalonperä site were increasingly limited by the depth of the area with increased wind speeds, when the wind was blowing from the direction of the longer fetch that allowed waves to grow longer (i.e. higher T_p values). This is visible when comparing the run with an additional 2 m water level (triangle markers) against the wave height H_s during typical depth fields (square markers) in Figures 3 (left panels). A higher sea level of 2 m allowed H_s to grow up to 0.20 m higher with 24 m s^{-1} winds resulting in H_s values up to 1 m, while the most extreme 32 m s^{-1} winds together with increased sea level resulted up to 0.5 m higher H_s values resulting to H_s of 1.4 m. The wind directions with the most notable increase of H_s by higher sea level are also the same wind directions known to induce high sea level in the Olkiluoto region (Figures 3, highlighted areas).

The analysis of the wave fields surrounding the Iso Kaalonperä site (Figure 4) show that the western side of Olkiluoto NPP is well sheltered not only by the surrounding archipelago but also by the shoals between the islands that attenuate the waves quickly between longitudes 21.36° E and 21.39° E. Higher sea level outside of the archipelago allowed much higher (and longer, not shown: T_p of 9 s with increased sea level, compared to 3 s in reference run) waves to form already outside of the surrounding archipelago resulting in different refraction patterns in the sheltered western coast. The growth of waves in Iso Kaalonperä with 280° western winds is limited by the fetch from the western islands (around 1.8 to 2.5 km from the study site).

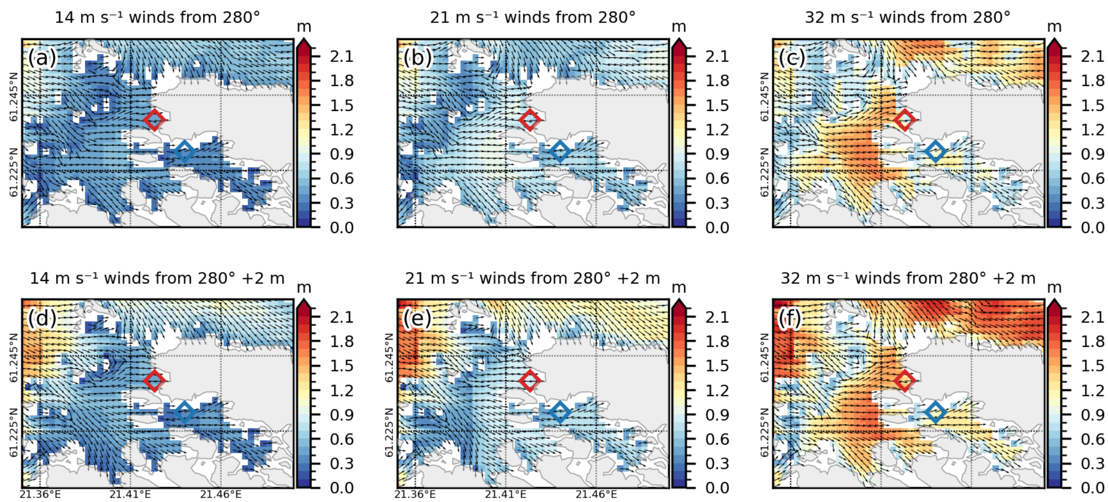

Figure 4: Significant wave height (H_s, colorbar) and the dominant wave direction (arrows) generated by the uniform winds of 14 m s^{-1} (left panels), 21 m s^{-1} (middle panels) and 32 m s^{-1} (right panels) from 280° (W). Upper panels show the wave fields in the reference run of the original model depths (Figure 2) and lower panels show the run with 2 m higher sea level. Presented wind direction generated the highest waves in Iso Kaalonperä site (orange marker).

The second site, southern Olkiluodonvesi, is more open to high waves from a wider range of wind directions compared to the Iso Kaalonperä site (Figures 3, right panels). The maximum H_s is reached with winds from 120° (SE), which corresponds to the orientation of the open water in the area (Fig. 2). However, high and long waves were also simulated from 220° (SW), where the study site again has a longer fetch and deeper bathymetry. Like in Iso Kaalonperä, winds of 14 m s^{-1} increased the significant wave height (H_s) up to 0.4 m with peak periods up to 2.3 s and 18 m s^{-1} wind resulted up to 0.6 m H_s and 2.6 s T_p. With 24 m s^{-1} winds, H_s reached to 0.9 m and T_p to 3 s, which corresponded more to the wave conditions during the higher sea level in Iso Kaalonperä site. With 24 m s^{-1} winds, an increase in sea level of 2 m (triangle markers) increased the H_s less than 0.1 m but with 32 m s^{-1} winds H_s increased up to 0.2 m.

The Olkiluodonvesi site was deeper (5 m, see Fig. 2) than Iso Kaalonperä site (2 m). The wave growth in the Olkiluodonvesi was only slightly limited by the depth of the region with the highest winds speeds that grew the longest waves. Based on linear wave theory, waves with periods up to 2.5 s are considered deep sea waves at a depth of 5 m, and they do not interact with the sea floor. At the 2 m deep Iso Kaalonperä site, waves with periods below 1.6 s are deep sea waves. The largest increase in H_s, caused by the increase in sea level, was seen with winds from 120° (SE); however, this direction of wind is not likely to occur with simultaneous high sea levels in Olkiluoto region. Wave fields during the 120° (SE) winds (Fig. 5) show how the waves would grow higher already earlier in the long channel with higher sea level.

3.1 Wind directions at the study site

We checked the distribution of the 10 m wind directions and magnitude distribution by the Iso Kaalonperä site using CERRA reanalysis data (Ridal et al. (2024)) with 5.5 km spatial resolution over 11 years (2010–2020, Fig. 6). The wind rose shows that in this region,the winds blow most commonly between S and SW (170°–240°) and are most of the time below 15 m s^{-1}. However, the highest winds are from the WNW (275°).

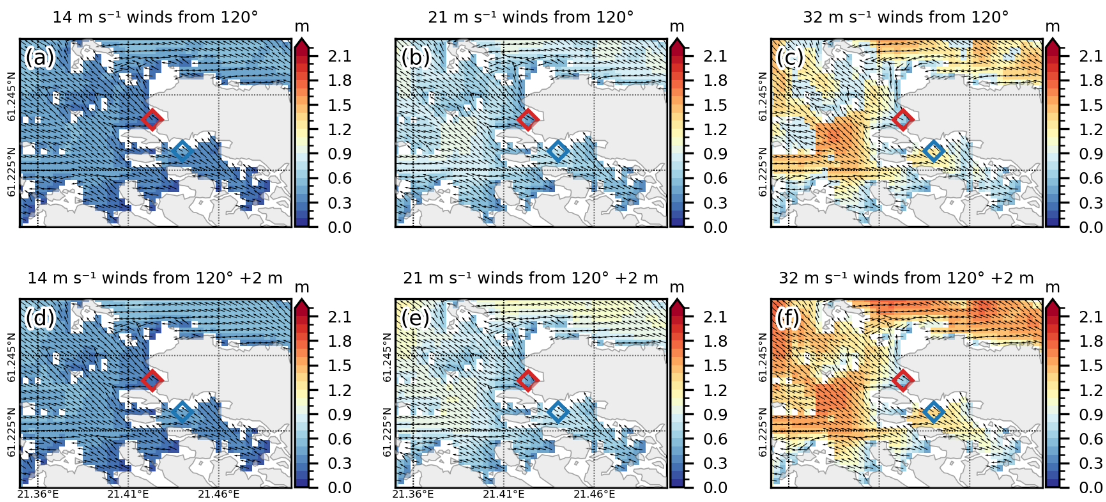

Figure 5: Significant wave height (H$_s$, colorbar) and the dominant wave direction (arrows) generated by the uniform winds of 14 ms^{-1} (left panels), 21 ms^{-1} (middle panels) and 32 ms^{-1} (right panels) from 120° (W). Upper panels show the wave fields in the reference run of the original model depths (Figure 2) and lower panels show the run with 2 m higher sea level. Presented wind direction generated the highest waves in Olkiluodonvesi site (blue marker).

4 Discussion

The presented analysis in this fetch-limited finite depth area is very sensitive to correct representation of the depth and the coastline of the area. Our analysis is based on open access EMODnet Bathymetry (EMODnet Bathymetry Consortium (2020)) that was used to calculate model bathymetry. The input depth information used had an apparent horizontal resolution of around 200 m, but the original information that was interpolated to the EMODnet grid can be much coarser than the one given through the database, and thus it might not represent all of the shoals that this model resolution could otherwise account for. The coastline was in some regions hand-tuned to better fit the actual coastline; however, even more detailed edits could be considered if the model grid would be used again in future. The complexity of the coastline and bathymetry of the area is still rather far from being completely represented with 0.1 nmi model grid. In this study, we did not aim to find the optimum model resolution to model the Olkiluoto area, but the 0.1 nmi resolution was chosen based on previous research on modelling waves in the Finnish archipelago (e.g. Tuomi et al. (2012),Tuomi et al. (2014)). Comparing the model coastline to the EMODnet coastline in areas with coarser resolutions to the 0.1 nmi resolutions in Fig.1) clearly shows how much more detail can be attained with higher resolution to model the true fetch felt by the waves. It is notable that typical Baltic Sea wave models that use 1 nmi grid resolution are too coarse to have any information on the Olkiluodonvesi area. Simulations could have, however, been made computationally lighter by lowering the model resolution outside of the Gulf of Bothnia.

The chosen approach of using static uniform wind fields over the whole area still represents quite unrealistic wind conditions, as winds blowing over the land would be affected by landmasses, and thus would be weaker than the ones blowing from open sea directions. Also, realistic wind fields would have variation in wind speed and direction. However, this approach gives an estimate of the limits the wave growth has due to the fetch of the area with given wind speed while taking into account many other interactions of the waves like the interaction with the sea floor and refractions over shoals.

Increasing the sea level by 2 m also reveals some of the areas where waves have a strong interaction with sea floor by showing the changes in wave fields. However, a bulk increase of sea level by 2 m throughout the whole model area is not very realistic as sea level is typically tilted so that the largest increases or decreases occur by

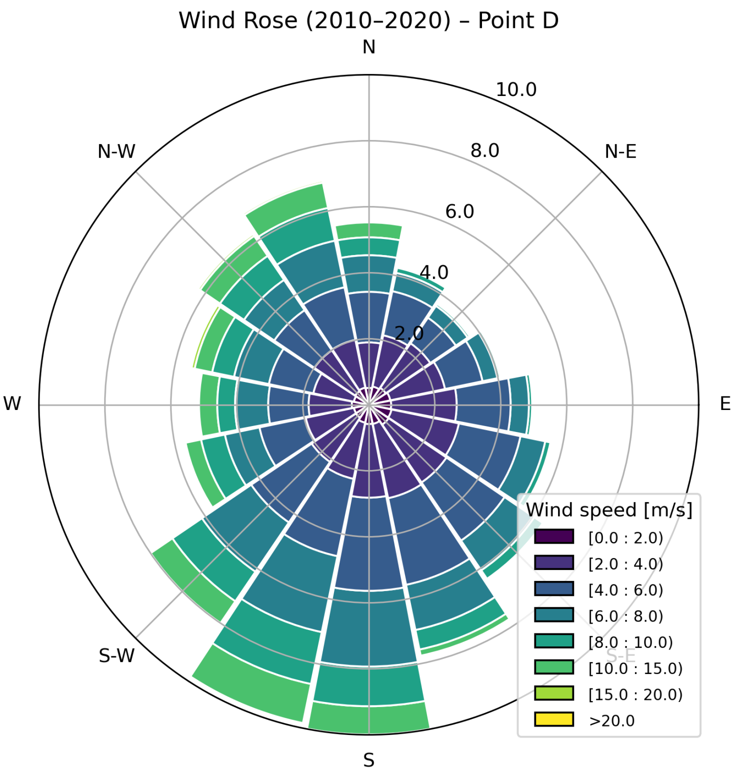

Figure 6: Wind rose of 10 m winds 2010-2020 by the Iso Kaalonperä site from CERRA reanalysis.

the coast. Used approach might have allowed too long waves to travel from open sea to the presented Olkiluoto region. However, the shallows around the Olkiluoto region blocked most of the open sea waves in the study area (see wave fields around 21.36° E in Figs. 4 and 5) which made this approach still usable in this region. However, even if the uniform 2 m increase of sea level in the entire model domain is not entirely realistic, it gives a conservative upper limit estimate for the maximum sea level in the domain.

The combined occurrence of both high sea levels and high waves at Olkiluoto can be related to the local wind direction. The extreme sea levels at Olkiluoto are caused by southerly and westerly winds. They push the water from the Baltic Sea to the Gulf of Bothnia and consecutively push the water towards the eastern coast of the Bothnian Sea. Northerly winds have an opposite effect, pushing water out of the Gulf of Bothnia and away from the coast, and are less likely to lead to extreme sea levels in the Olkiluoto region. Thus, it is expected that the southerly and westerly winds are related to the high sea levels near the Olkiluoto NPP. As westerly winds grow the highest waves in the Iso Kaalonperä site, the highest waves can occur simultaneously with high sea levels in the area. Although the wind rose shows that the westerly winds are not the most common in the area, the highest winds have blown from that direction. In the Olkiluodonvesi site, highest waves are generated both by western and southern winds (leading to high sea levels) and eastern winds (leading to low sea levels). Therefore, high waves are not always connected to high local sea levels.

5 Conclusions

The significant wave height (H_s) can grow highest in the shallower (2 m) sea area west of the Olkiluoto NPP site (Iso Kaalonperä) with the western winds, but the wave heights are nearly as high with the wind directions from SWS through west to north. In this region, even extreme 32 m s^{-1} winds are not shown to be able to grow H_s to more than 0.9 m with the typical sea level in the area, but that wave heights could grow up to 1.4 m if extremely high westerly winds occurred with simultaneous 2 m high sea level.

In the deeper (5 m) sea area south of the NPP site (Olkiluodonvesi), waves can grow to higher magnitudes with winds from SW and SE, but only waves generated by the SW winds grow slightly higher with increased sea level. The H_s can grow up to 1.4 m with SE winds and 2 m higher sea level, but also up to 1.2 m both with SE and SW winds if they blow up to 32 m s^{-1}.

In Iso Kaalonperä, the winds between the south and the west lead to a simultanous high sea level and high wave heights, making this combination realistic. In Olkiluodonvesi, high waves are generated by both winds between the south and the west (leading to high sea level) and winds between the south and the east (leading to lower local sea level). Therefore, the co-occurrence of high sea level and waves is more likely in Iso Kaalonperä than in Olkiluodonvesi.

Summarizing the results of this study, it was shown that the extreme sea level of 2 m has a small effect on wave heights near the Olkiluoto NPP site for wind speeds up to 24 m s^{-1}. Therefore, the estimates for wave heights using water depths in mean sea level are valid also for higher sea levels. The combined effect of high sea level and high waves can be estimated by combining independent high sea level estimates and high wave estimates.

In the MAWECLI project plan, the original objective of this task was to study sea level and waves generated by synthetic cyclones. As the extreme sea level from the synthetic cyclone has a short duration (less than 12 hours over 100 cm), the effect of high sea level on waves would likely have been smaller than in the used method with static uniform wind fields. Consequently, it is evident that the extreme sea level events are unlikely to lead to high waves near Olkiluoto NPP site.

Our report studied only Olkiluoto NPP site, but a similar analysis could possibly be extended to the Loviisa NPP site now that there is an operational wave buoy by the Orrengrund piloting site in the eastern Gulf of Finland since summer 2025. Wave buoy measurements allow us to validate the created model grid before using it in the sensitivity study.

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