Earth Syst. Dynam. Discuss., doi:10.5194/esd-2016-69, 2016
Manuscript under review for journal Earth Syst. Dynam.
Published: 9 December 2016

Earth System Dynamics
Discussions
Open Access

Assessment of the nuclear power plant "Hanhikivi-1" influence on the local hydrological conditions in the Bothnian Bay, Baltic Sea

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Abstract. The results of the study aimed to assess the influence of future nuclear power plant "Hanhikivi-1" upon the local hydrological conditions in the Bothnian Bay in the Baltic Sea are presented. A number of experiments with different numerical models were also carried out in order to estimate the extreme hydro-meteorological conditions in the area of the construction. The numerical experiments were fulfilled both with analytically-specified external forcing and with real external forcing for two years: a cold year (2010) and a warm year (2014). The study has shown that the extreme values of sea level, water temperature, the characteristics of wind waves and sea ice in the vicinity of the future nuclear power plant can be significant and sometimes catastrophic. Permanent release of heat into the marine environment from operating nuclear power plant will lead to a strong increase in temperature and the disappearance of ice cover around 2 km vicinity of the station. These effects should be taken into account when assessing local climate changes in the future.

1 Introduction

The environmental impact of nuclear power plant (NPP) results from the nuclear fuel cycle, the effects of nuclear accidents, and NPP operation. It is known that the greenhouse gas emissions from nuclear fission power are much smaller than those associated with coal, oil and gas, and the routine health risks are much smaller than those associated with coal. However, there is a "catastrophic risk" potential if containment fails (von Hippel, 2010), which in nuclear reactors can be brought about by over-heated fuels melting and releasing large quantities of fission products into the environment. This potential risk could wipe out the benefits.

The environmental impact of NPP due to operation has been studied less than nuclear fission effects. During the process of nuclear power generation large volumes of water are used. The uranium fuel inside reactors undergoes induced nuclear fission which releases great amounts of energy that is used to heat water. The water turns into steam and rotates a turbine, creating electricity. Nuclear plants must collect around 600 gallons/MWh for this process (Tellinghuisen), so the plants are built near bodies of water.

As with all thermoelectric plants, NPPs need cooling systems. The most common systems for thermal power plants, including nuclear, are:

- Once-through cooling, in which water is drawn from a large water body, passes through the cooling system, and then flows back into the water body.
- Cooling pond, in which water is drawn from a pond dedicated to the purpose, passes through the cooling system, and then returns to the pond.
- Cooling towers, in which water recirculates through the cooling system until it evaporates from the tower.

Nuclear plants exchange 60 to 70 % of their thermal energy by cycling with a body of water or by the evaporation of water through a cooling tower. According to the World Nuclear Association data (http://www.world-nuclear.org), this thermal efficiency is somewhat lower than that of coal-fired power plants, thus creating more waste heat.

When intaking water for cooling, nuclear plants, like all thermal power plants, use special structures. Water is often drawn through screens to minimize the entry of debris. The problem is that many aquatic organisms are trapped and killed against the screens, through a process known as impingement. Aquatic organisms small enough to pass through the screens are subject to toxic stress in a process known as entrainment. Billions of marine organisms, such as fish, seals, shellfish, and turtles, essential to the food chain, are sucked into the cooling systems and destroyed.

On January 19, 2016, the construction of NPP "Hanhikivi-1" was started. This event had been preceded by examination of hydro-meteorological conditions in the area of construction, which included not only the estimation of extreme conditions in the vicinity of Peninsula Hanhikivi (Pyhäjoki municipality) in the Bothnian Bay in the Baltic Sea, but also the possible impact of future plant on the marine environment in this area.

The long-term experience related to the world-wide operating of NPPs shows that, under normal safe operating conditions, the non-radiological impact on the environment becomes dominating. One of the major factors is the heat pollution of the surface water bodies due to the discharge of waste heat from the condensers of NPPs. If heated condenser water is not cooled for re-use in a cooling tower, the waste heat may be discharged either into artificial reservoirs (ponds) or directly into surface waters like rivers, lakes, and sea bays.

The purpose of this study was two-fold: 1) to estimate possible extreme marine phenomena in this region (wind waves, sea level changes); 2) to estimate the adverse thermal effect of NPP on marine environment in future. To do this we used different hydrodynamic models. Results of this examination are presented below.

2 Methods

2.1 Circulation model

A three-dimensional numerical model based on the Princeton Ocean Model (POM) (Blumberg & Mellor, 1987; Mellor, 2004) was used to simulate the circulation pattern and thermal regime in the Bothnian Bay. It is a model with a σ-coordinate in the vertical direction that allows it to represent the bathymetry smoothly and provides a better simulation of the currents in the bottom boundary layer as compared with some z- and isopycnal models. Also such σ-models reproduce different thermodynamical effects caused by the non-linearity of the equation of state rather well. That is why such models have been widely used for the simulations of coastal areas and estuaries dynamics. As for the turbulence closure parameterization, POM makes use of the well-tested and reliable schemes of Mellor-Yamada 2.5 (Mellor & Yamada, 1982) for the vertical, and Smagorinsky (Smagorinsky et al., 1965) for the horizontal turbulent mixing, respectively. The above-mentioned advantages of the model along with the significant experience of the authors with its use in a number of successful applications for other basins in similar studies (Ryabchenko et al., 2008) were the main reasons why POM was chosen for the present study. The model allows to simulate three-dimensional fields of currents, water temperature and salinity, two-dimensional elevation field in an area of interest when external influence is specified. This influence includes wind forcing, sea-surface atmospheric pressure, air temperature and humidity in the near-water layer, cloudiness, precipitation rate and open boundary conditions.

2.2 Sea-ice and snow model

To model ice and snow distribution in any area an advanced sea-ice model with several different categories of ice was used (Haapala et. al., 2005; Ryabchenko et al., 2010). The model distinguishes the sea ice as two main types: deformed and non-deformed. The non-deformed ice is divided into several sub-categories, while the deformed ice consists of only ridged and rafted ice. The rafted ice exists when the ice thickness is equal or less than 17 cm, otherwise the ice is considered to be ridged. Evolution of each type is described by ice concentration and mass equations. The ice thickness of each category varies due to advection, deformation and thermodynamical processes. It is assumed that the fast ice exists in the areas with the depth less than some specified value. But in the present study the fast ice was not considered, and the model operated with 7 different categories of sea ice.

The evolution of snow cover thickness can be described as the interaction of the following main mechanisms (Lepparanta, 1983): precipitation, surface melting, compaction, and the formation of slush, which further transforms into snow-ice. In the present model only the precipitation and surface melting were taken into account (Ryabchenko et al., 2010).

2.3 Wind waves model

The wind waves model SWAN (**S**imulating WAves Nearshore) (Booij et al., 1999; Ris et al., 1999) was used in the present study. SWAN is a third-generation spectral wave model specifically developed for wind waves simulation in shelf and shallow coastal areas with complex shore line configuration. The model can take into account wind forcing, depth-induced wave breaking, refraction, diffraction, ambient currents and sea-level oscillations, bottom friction, whitecapping, wave quadruplets and triads, wave-induced set-up, presence of sub-grid obstacles, vegetation and bottom mud layer, and also the turbulent viscosity. The core element of SWAN is the numerical and efficient solving of the spectral wave action balance equation, which includes source terms representing the effects of generation, dissipation and nonlinear wave-wave interactions.

During all model runs SWAN was working in a non-stationary mode with a time step equal to 10 minutes, with maximal iterations at each time step set equal to 10. According to the recommendations presented in the official SWAN manual, the directional resolution was set equal to 10 degrees, minimal and maximal frequencies were set equal to 0.04 and 1.0 Hz, respectively.

2.4 Areas of interest and model domains

The present study focuses on the assessment of main hydrological features of the Bothnian Bay (a northern part of the Gulf of Bothnia in the Baltic Sea) and the relatively small area off the Hanhikivi peninsula located at the eastern coast of the Bothnian Bay (Fig. 1). The bathymetry data were collected from different marine navigational charts, from Baltic Sea Bathymetry Database (Baltic Sea Hydrographic Commission, 2013), and were provided from field observations. These data were linearly interpolated into grid nodes with further making use of low-frequency filter.

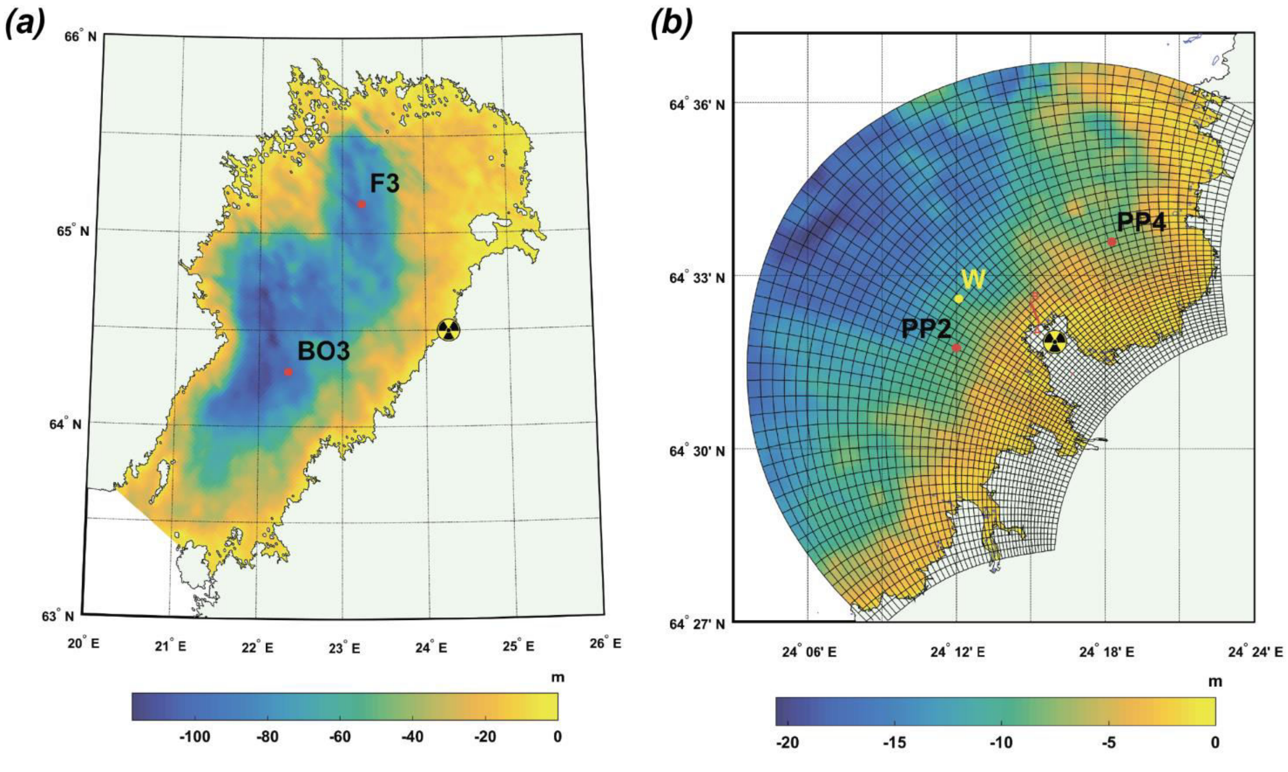


Figure 1: Bathymenty of the Bothnian Bay (a) and the area off the Hanhikivi peninsula (b). The location of the NPP, observation sites (BO3, F3, PP2, PP4), and also the position of cross-section (red line) and SWAN output point (W) are presented

The Bothnian Bay model grid consists of 107×175 nodes in horizontal and 25 sigma-levels in vertical direction, horizontal resolution being 1 nautical mile and minimum depth being 3 m. The model time step was set equal to 300 seconds.

The Hanhikivi area model grid is much more curvilinear in its shape (see Fig. 1b), consists of 142×193 nodes in horizontal and 12 sigma-levels in vertical direction. Its horizontal resolution is rather variable, the minimum and maximum horizontal resolution being 35 and 180 m, respectively. The minimum depth was set equal to 1.5 m and model time step was 0.5 second. The Hanhikivi model grid covers the area with radius app. 9000 m from the future NPP "Hanhikivi-1".

In addition to these above-mentioned main model domains and their grids we also built and used another grid which covered the entire Gulf of Bothnia in order to assess the impact of incoming wind waves traveling from the Bothnian Sea northward into the Bothnian Bay through the open south boundary. The Gulf of Bothnia model grid (not shown) consisted of 101×250 nodes, the minimum depth was limited by the 3 m isobath, horizontal resolution: minimum 2.2 km, maximum 5.3 km. The main outcome obtained from the numerical experiments performed on this grid was that the impact of the incoming wind waves plays an important role only in the southern part of the Bothnian Bay and that its contribution to the wind waves pattern in the vicinity of Hanhikivi peninsula is negligible. Such result allowed us to concentrate only on the modeling efforts inside the Bothnian Bay without any need to include the entire Gulf of Bothnia into the model domain in all subsequent model runs, thus enhancing the model resolution and reducing the model total integration time.

2.5 Atmospherical forcing, boundary and initial conditions

Atmospherical forcing included air temperature and humidity, wind speed and direction, cloudiness, which were obtained from the results of atmospherical model HIRLAM (High Resolution Limited Area Model) (http://hirlam.org) provided to Russian State Hydrometeorological University by the Danish Meteorological Institute. HIRLAM's horizontal resolution is 11 km and the model's domain covers the North Atlantic and Northern Europe regions. Comparison of HIRLAM's results with observational data collected near the future NPP location showed their good agreement.

The circulation model used in the present study calculates the momentum, heat and salt fluxes at the air-sea and air-ice interfaces. The momentum fluxes are calculated traditionally as a quadratic friction law with making use of different drag coefficients for air-water, air-ice and ice-water boundaries. The heat and salt fluxes are parameterized by taking into account the diurnal cycle of short-wave solar radiation (Parkinson & Washington, 1979; Ryabchenko et al., 2010).

At the open boundaries the coupled circulation and sea-ice model assimilates the sea level, current velocity, water temperature and salinity, sea ice thickness and concentration, snow thickness obtained from the results of HIROMB (High Resolution Operational Model for the Baltic) (Funkquist, 2001; http://www.smhi.se/en/research/research-departments/oceanography/hiromb-1.8372), a high-quality prognostic 3D ocean circulation model recommended for all states in the Baltic Sea region by Helsinki commission (HELCOM). HIROMB covers the North Sea and the Baltic Sea with horizontal resolution in the latter being one nautical mile and vertical resolution being 4 m (24 vertical levels). HIROMB data also include river runoff in the Baltic Sea region.

At the solid lateral boundaries (coasts) a no-slip condition and zero fluxes are specified for horizontal velocity, heat and salt, respectively.

At the bottom the vertical component of current velocity, heat and salt fluxes are set to zero. Bed shear stress is parameterized as a function of horizontal velocity at the near-bed model sigma level.

All the above-described hydrological boundary conditions were applied for the Bothnian Bay circulation model, while for the Hanhikivi area circulation model the results obtained from the previous Bothnian Bay model runs were used as the boundary conditions, implementing nesting technique.

It should also be noted that the hydrological regime of the area located relatively close to the Hanhikivi peninsula is considerably affected by the river Pohjoishaara situated nearby and with an annual runoff equal to 103×10^7 m^3. In the present study, for the Hanhikivi model the river Pohjoishaara runoff was distributed into 12 months in accordance with the known monthly averages of the nearest large rivers' runoff. The Pohjoishaara's water temperature was set to the nearest coastal area water temperature, while salinity was set to zero.

The initial conditions for the coupled circulation and sea-ice model for the entire Bothnian Bay domain included water temperature, salinity and sea level fields obtained from the HIROMB model.

For the SWAN model the initial condition of no waves in the entire domain was adopted. At the solid boundaries the model sets the condition of full wave energy absorption and no wave energy generation. At the open boundaries in the case of outgoing waves they can leave the area freely (radiation condition), while in the case of incoming waves there can be two options: 1) either no waves come into the model domain (an option used for the Bothnian Bay model) or 2) incoming wave spectrum is specified along the open boundary which has been obtained from the previous Bothnian Bay simulations (an option used for the Hanhikivi model).

2.6 Verification of the models

2.6.1 Circulation model verification

Sea level. Model verification with respect to the sea level was carried out for the period 5–7.12.2015. The maximum level was reached at 18:00 on Dec 5, 2015. Comparison of POM and HIROMB calculated sea levels at four stations located around the coast of the Bothnian Bay (Kemi, Oulu, Pietarsaari, Raahe) and presented on Fig. 2 showed that the models gave the consistent results and reproduced the sea level changes correctly. The greatest differences in the maximum levels were observed in Kemi and Oulu (5 and 9 cm).

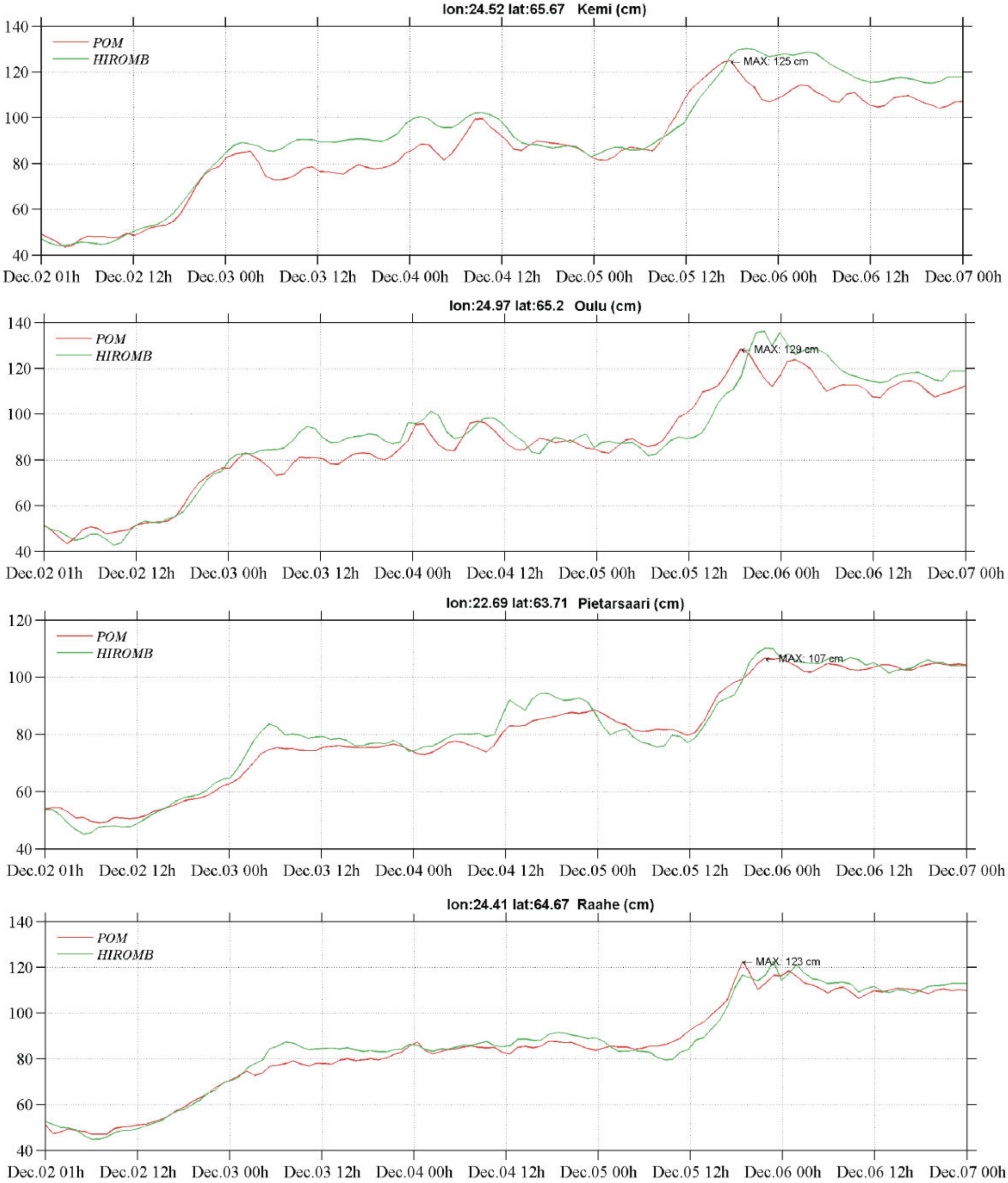
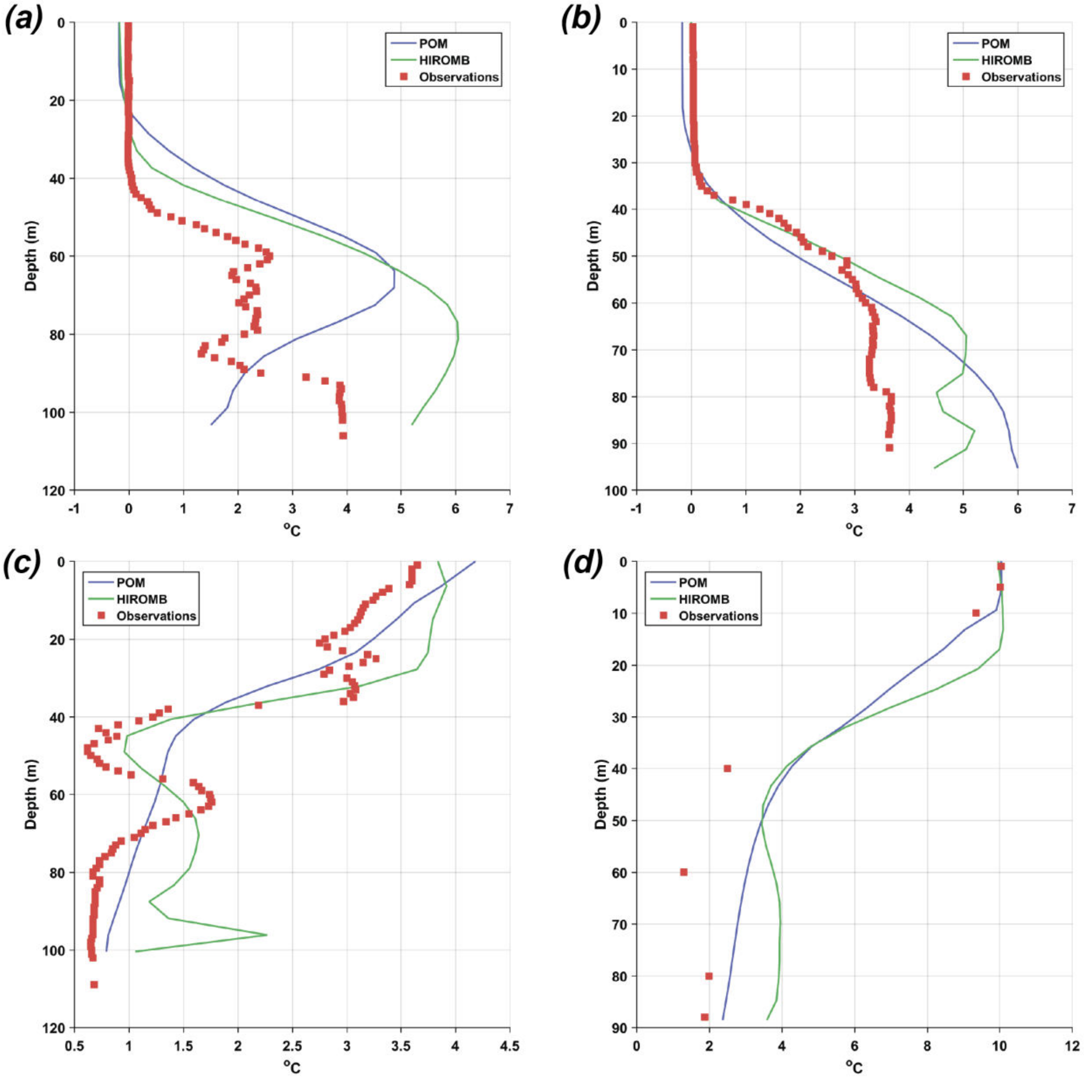


Figure 2: Comparison of POM and HIROMB calculated sea levels at four stations located around the coast of the Bothnian Bay for the period 5–7.12.2015

Temperature. Setting up and verification of the coupled circulation model were carried out by comparing the results of calculations in the Bothnian Bay with observations of temperature provided by the Baltic Environmental Database (BED) (http://www.balticnest.org/bed) and the results of calculations of these characteristics produced by HIROMB. Figure 3 shows these profiles.



5 **Figure 3: Comparison of the computed temperature profiles by POM and HIROMB with observations provided by BED in the Bothnian Bay. Location of stations are presented in Fig. 1a. (a) Station BO3, 2010-01-18; (b) Station F3, 2010-01-19; (c) Station BO3, 2010-06-06; (d) Station F3, 2010-06-30**

From these figures it can be concluded that POM reproduces the observed vertical profiles of temperature slightly better than HIROMB.

2.6.2 Sea ice model verification

The comparison of computed sea ice thickness and compactness showed that the model results were in general accordance with observed values (http://www.aari.ru/) though some overestimation in ice thickness can be observed (Fig. 4)

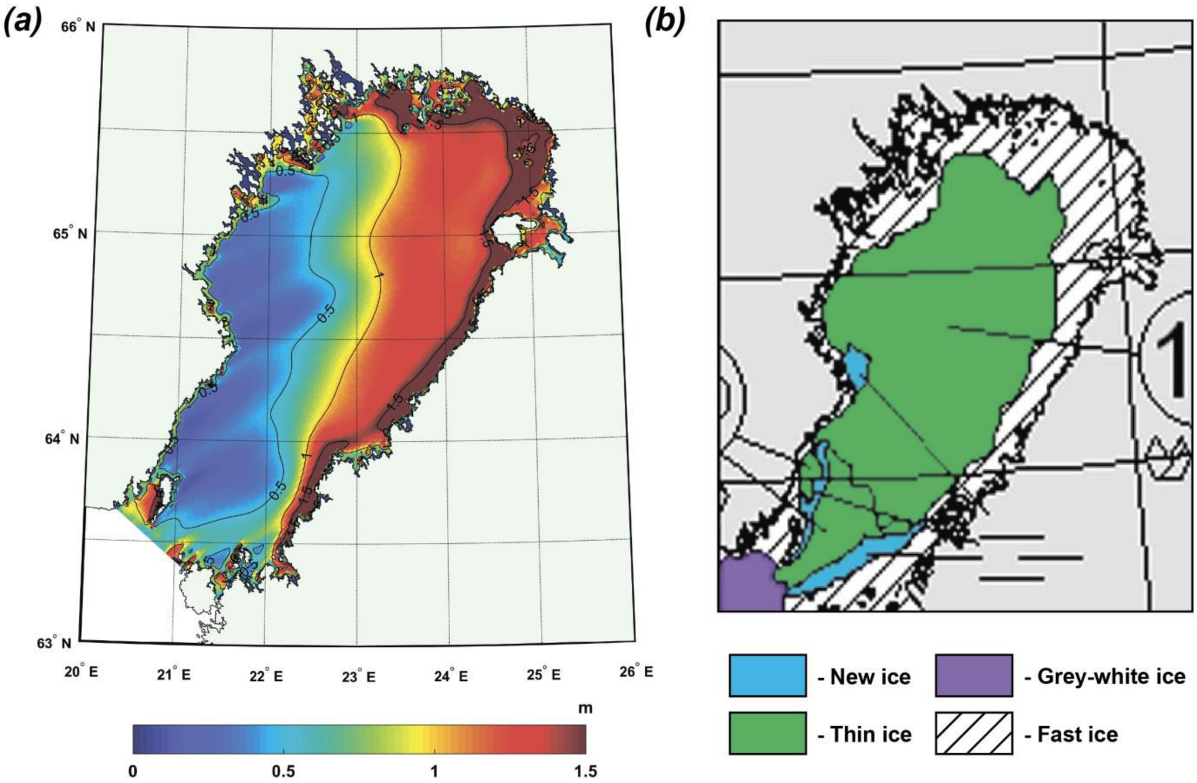


Figure 4: Modeled (a) and observed (b) distribution of sea ice thickness in the Bothnian Bay

2.6.3 Wind waves model verification

Verification of the results of the SWAN model (in terms of significant wave height – SWH) against observational data (Fennovoima report, 2013) for two points (PP2 and PP4) located in the vicinity of the peninsula Hanhikivi showed that in general the model correctly simulated wind waves' characteristics (Fig. 5). The main discrepancies could be caused by the inaccuracy in dealing with the ice cover in wave model and/or ice cover modeling itself.

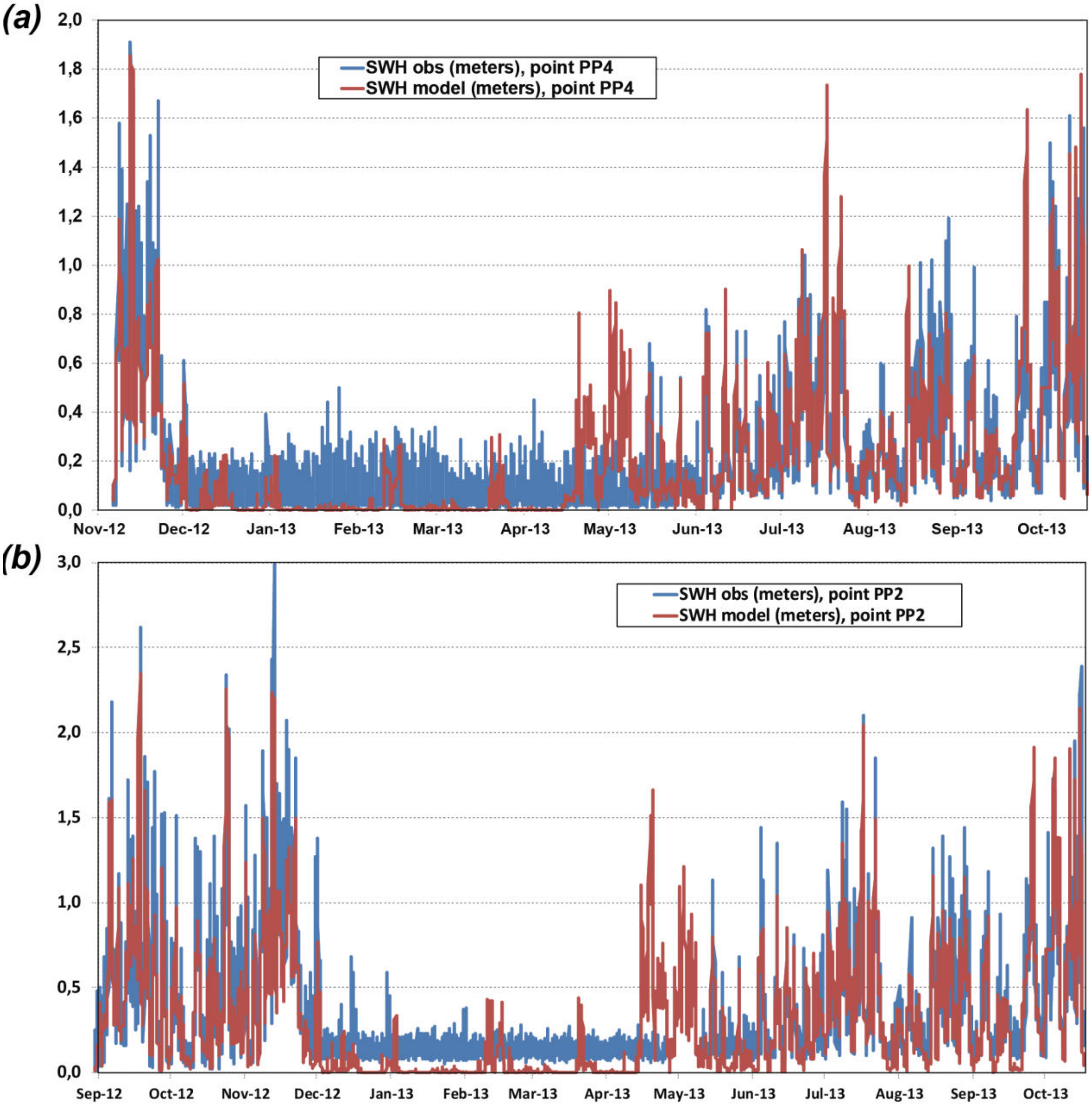


Figure 5: Comparison of SWH observations and model results for the period: (a) 06.11.12–17.10.13 and (b) 30.08.12–17.10.13

3 Results

3.1 Modeling of storm events in the vicinity of the future NPP

3.1.1 Wind waves

With an aim to assess the maximal possible significant wave heights (SWH) in the area off the Hanhikivi peninsula and to investigate the main features of wind waves field in different hydrometeorological situations a number of numerical experiments with analytically specified different wind speeds and directions was carried out. The area of interest is located along the eastern coast in the Bothnian Bay so we expected that the maximal wind waves would be generated by western winds. If one drew a hypothetical line along the Bothnian Bay than it would have the direction from south-west to north-east with the angle equal approximately 50 degrees relative to the geographical west-east parallel. Using such line as a coordinate axis we performed 7 main numerical experiments (A-G) with making use of the SWAN model for wind directions varying from 0 to 180 degrees relative to this basic line with angle discretization equal to 30 degrees, wind speed being constant and equal to 10 m s^{-1} (Fig. 6a).

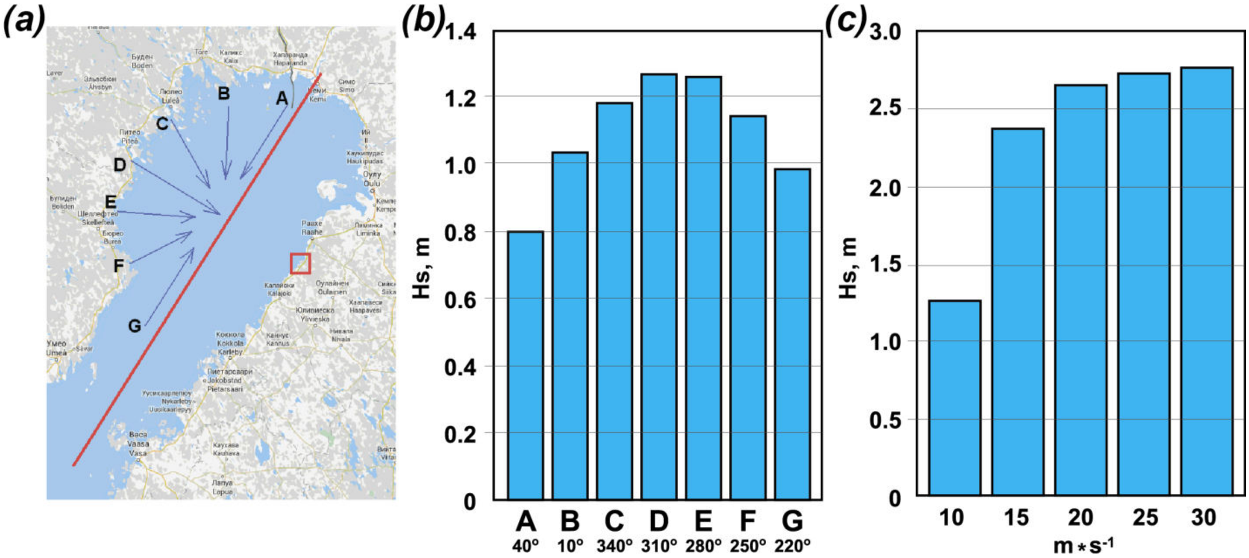


Figure 6: (a) Bothnian Bay imaginary axis (red line), wind direction in numerical experiments (blue arrows) and Hanhikivi peninsula loation (red square); (b) Dependence of modeled SWH near NPP upon wind direction; (c) Dependence of modeled SWH near NPP upon wind speed for the most dangerous wind direction (310^{0})

These wind directions cover the entire range of possible directions capable to produce high waves in the vicinity of the future NPP "Hanhikivi-1". All other wind directions outside the above-mentioned range will lead to the occurrence of wave shadow zone near the Hanhikivi peninsula. The wind speed was set constant and equal to 10 m s^{-1}. Wind duration was

24 h. After the most dangerous wind direction had been determined we used that direction and varied wind speeds holding the direction constant. For that experiment the wind duration was also 24 h.

Model calculations of wind waves have shown that the most dangerous in terms of the generation of wind waves in the NPP area is the west and north-west wind with the directions of 280° and 310° (experiments E and D, respectively, Fig. 6b). Maximal SWH in the Gulf of Bothnia near NPP for that wind direction at a wind speed of 10 m s^{-1} is about 1.2-1.4 m after 24 hours of wind. Changing the wind speed for the determined most dangerous wind direction (310°) allowed to assess the values of the highest possible wind waves near the NPP (Fig. 4c).

The model results allowed to estimate the values of SWH in both the entire Bothnian Bay and in the small area near Hanhikivi peninsula during different external wind forcing. SWH for the most dangerous wind direction and wind speed of 15 m s^{-1} was 2.5–3.0 m and increased up to 7.0 m in the open part of the Bothnian Bay for the wind speed of 30 m s^{-1} (not shown). Nevertheless in the very vicinity of the coast near the Hanhikivi peninsula the SWH decreases dramatically due to relatively shallow detphs (see Fig. 1b). It is also interesting to note that considerable increase of SWH in this area in the model experiments appeared during the increase of wind speed from 10 to 15 m s^{-1} while further wind speed increase did not such rapid SWH growth (Fig. 6c).

Besides the model experiments with theoretical atmospherical forcing, a model run for the real meteorological forcing of 2014 was carried out for the whole year. Just as in all other numerical experiments, the both models (Bothnian Bay model and Hanhikivi area model) were used: the Bothnian Bay model produced all required wind wave characteristics to be used as boundary conditions in the Hanhikivi area model. The results obtained for 2014 have shown that the highest waves in the Bothnian Bay occurred during the autumn period, SWH reaching 4.0 m. During the winter period of 2014 SWH reached 1.5–2.0 m at ice-free areas of the Bothnian Bay. But the most time during moderate wind speeds SWH was 0.5–1.5 m and less.

A situation with rather large simulated SWH, occurred on the 27 of September 2014, is presented on Fig 7 in order to show in detail the spatial distribution of waves heights in this area and the influence of bathymetry upon them. The region of the reduction of SWH due to wave breaking and bottom friction is clearly visible and in general coincides with the 5m-isobath. It should be noted that we used the parameterization for bottom friction implemented in the SWAN model, which takes into account the size of bed ripples calculated with making use of available field measurements of grain sizes.

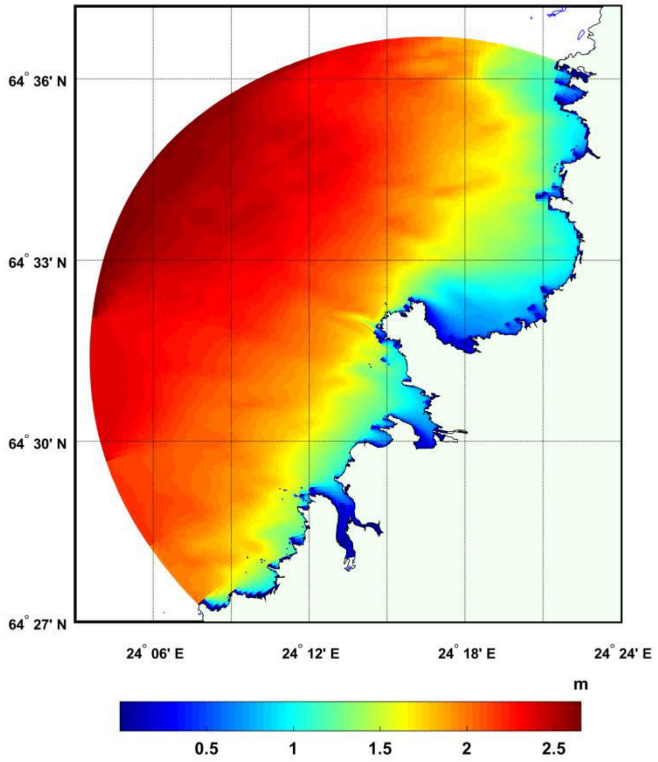


Figure 7: Modeled SWH distribution on the 27 of September, 2014

Wind waves in the area near the Hanhikivi peninsula can be characterized by the time-series of SWH at the location marked by letter "W" in Fig. 1b. The time-series of SWH in the Hanhikivi area for the whole 2014 is presented on Fig. 8.

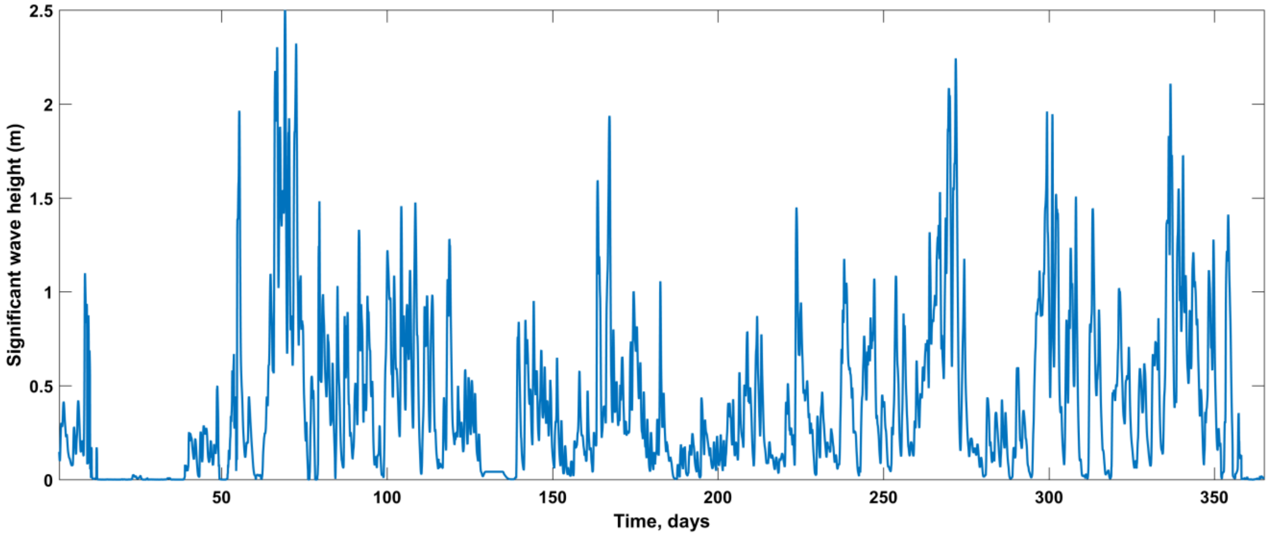


Figure 8: Modeled SWH time-series in the Hanhikivi area at the location mark with "W" on Fig. 1b

3.1.2 Extreme sea levels

To calculate the extreme sea levels in the vicinity of the NPP "Hanhikivi-1" the maximum possible wind velocity was set equal to 30.2 m s^{-1} (having 0.01 repeatability) defined according to the observations in the NPP area (Fennovoima Report, 2015). The wind velocity field calculated using the HIRLAM model was enhanced to reach this maximum wind velocity without any changes in wind direction. The periods of 5–7.12.2015 and 14–16.10.2010 were chosen to simulate the storm surges causing the extreme high and low sea level rise, respectively. The results for the entire Bothnian Bay are presented on Fig. 9 for the high level of the storm surge and in Fig 10 for the low level of the storm surge. All computations were performed with making use of the Bothnian Bay coupled circulation model only, without using the nesting technique and the Hanhikivi area model.

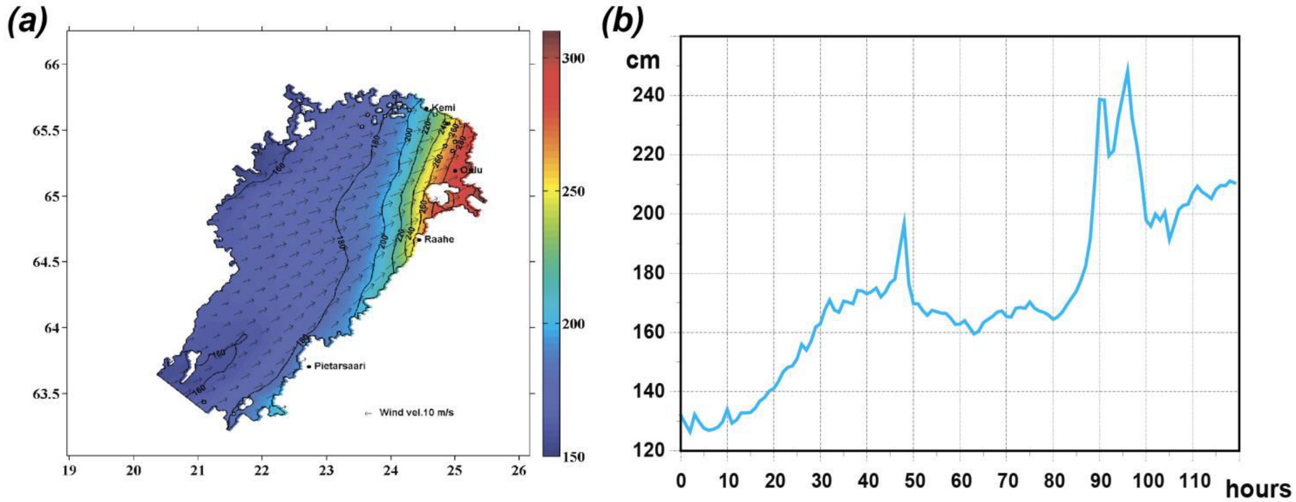


Figure 9: (a) Sea level rise in the Bothnian Bay during the model run with the wind speed 30.2 m s^{-1} and high level of the storm surge; (b) Temporal evolution of sea level rise near the NPP area. X-axis corresponds to the time in hours from the start of the wind

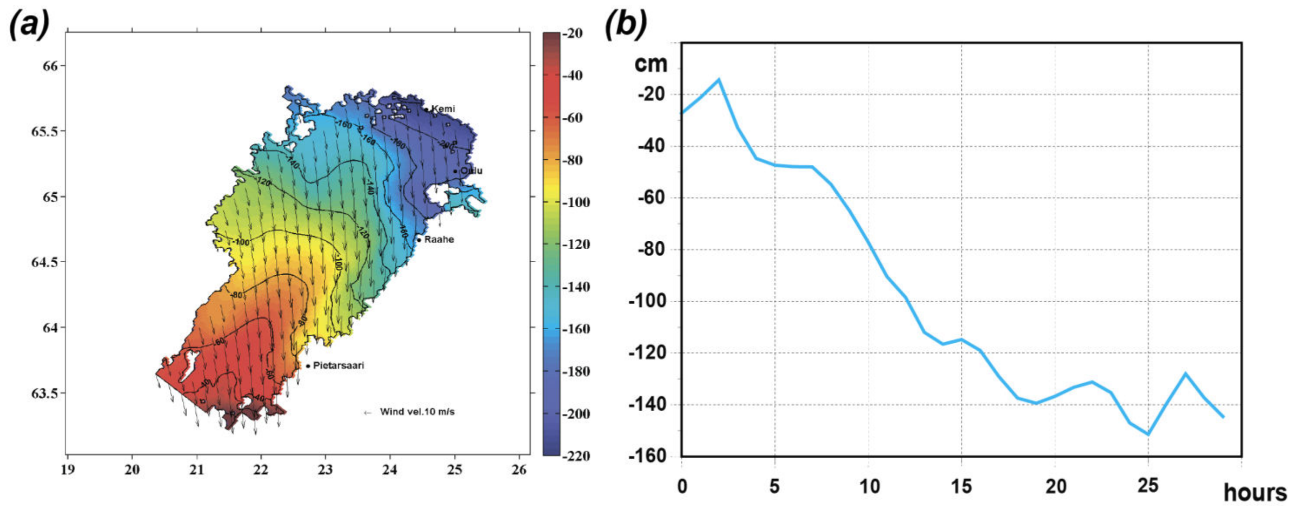


Figure 10: (a) Sea level rise in the Bothnian Bay during the model run with the wind speed 30.2 m s^{-1} and low level of the storm surge; (b) Temporal evolution of sea level rise near the NPP area. X-axis corresponds to the time in hours from the start of the wind

According to the simulations of possible sea level changes in the Bothnian Bay, extreme sea level values in the vicinity of the future NPP at a constant wind of 30.2 m s^{-1} were: maximum of 248 cm and minimum of -151 cm (see Fig. 9b and Fig. 10b). This is in a good agreement with the sea level data for the period 1922-2015 at the station Raahe (Finland) according to the estimates of SMHI (SMHI, 2014) in which the maximal and minimal sea level there could reach up to 250.4 cm and 150 cm, respectively, once in 10^8 years.

3.2 Assessment of the thermal pollution of water by the NPP

To assess the possible impacts of the NPP "Hanhikivi -1" on the marine environment two scenario runs were performed:

1) "background" scenario: simulating the natural conditions in the absence of the NPP;

2) "predictive" scenario: the NPP has been built and is operating with the temperature of heated discharged water set equal to 12 °C above the ambient water temperature at the point of water discharge, the discharge being 45 m^3s^{-1}.

Runs were performed for a cold year (2010) and a warm year (2014). The atmospheric characteristics necessary for calculating the fluxes of moment, heat and moisture at the air-water boundary were set according to the atmospherical HIRLAM model with a time resolution of 1 hour. To set the boundary conditions on the open boundary of the Bothnian Bay we used the data from HIROMB model (sea level, water and ice current velocities, temperature, salinity, ice thickness and compactness, snow thickness). The annual discharge of river Pohjoishaara was set equal to 33 m^3s^{-1}.

In natural conditions, the water of the Gulf around the Peninsula Hanhikivi was covered with ice since the beginning of December to the beginning of May in 2010 (the cold year), and since the beginning of January to the beginning of April in 2014 (the warm year). The highest "background" temperature in the cold and warm year was achieved respectively in July and August. The thermal regime of the basin in the vicinity of the points of water intake and water discharge is almost identical. In general, the spatial variations of mean monthly temperature in the area of the Hanhikivi peninsula limited by radius of 2 km are small, not exceeding 0.6 °C for the sea surface temperature (SST) and 1.2 °C for the temperature of the deep layer. The main difference between the cold 2010 and the warm 2014 is a longer winter period in 2010.

Permanent discharge of warm water in the case of operating NPP will lead to a permanent polynya near the northern tip of the peninsula Hanhikivi resembling in warm winter conditions an ellipse with axes 1.5×6 km, which stretches to the north (Fig. 11b). In cold winter conditions the polynya has a rounded shape, the boundary of which is located from the water discharge point at 2-3 km (Fig. 12b).

The difference between "background" and "predictive"' model runs is clear. A thermal plume (plume of heated water) emerges in the area of water discharge. Its spatial expansion and propagation mainly depends upon the wind speed and direction above the ice-free water surface and upon the current velocity and direction during ice-cover periods. Figures 11-12 demonstrate the influence of the heated water discharge upon the ice-cover distribution and thickness for both warm (2014) and cold (2010) years, respectively.

Earth Syst. Dynam. Discuss., doi:10.5194/esd-2016-69, 2016
Manuscript under review for journal Earth Syst. Dynam.
Published: 9 December 2016

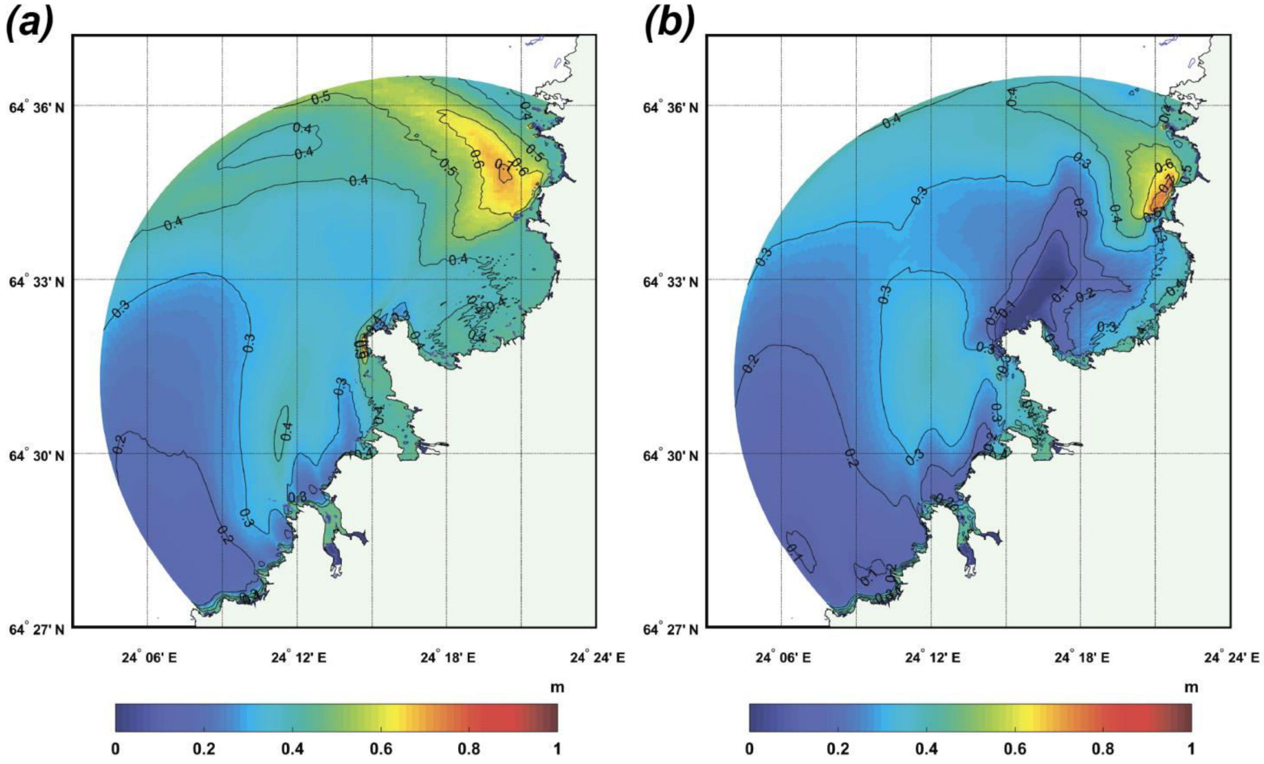


Figure 11: Ice thickness distribution (monthly-mean) in the vicinity of NPP "Hanhikivi-1" in February for conditions of warm year 2014. (a) "background" scenario; (b) "predictive" scenario

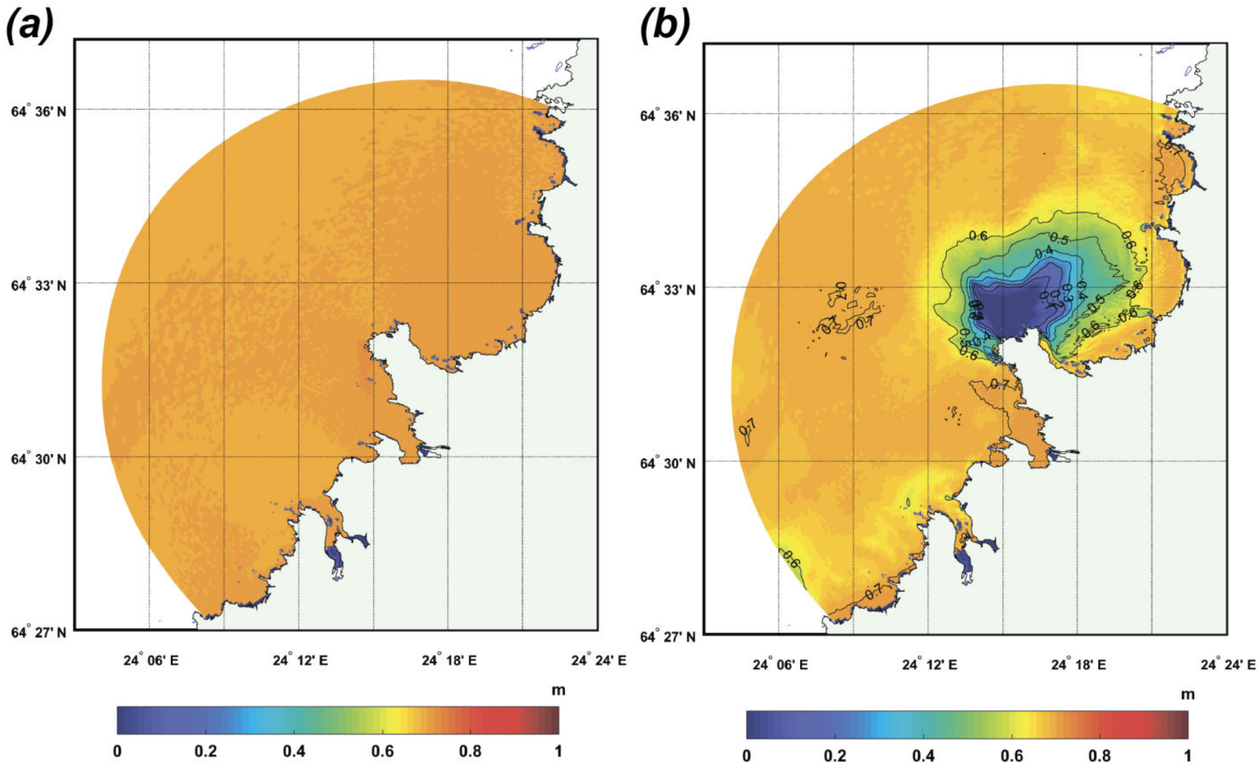


Figure 12 Ice thickness distribution (monthly-mean) in the vicinity of NPP "Hanhikivi-1" in February for conditions of cold year 2010. (a) "background" scenario; (b) "predictive" scenario

A vertical structure of water both in natural conditions and after the construction of the NPP was also investigated. A vertical structure changes significantly when large amounts of heated water have been discharged. Figure 13 shows the example of vertical cross-sections of the temperature field calculated for the cold year conditions. The position of the cross-section is presented on Fig. 1b, it starts from the heated-water discharge point and stretches to the north. The difference in depth for this one and the same profile is due to the changes in bathymetry caused by the planning hydrotechnical works near the future station.

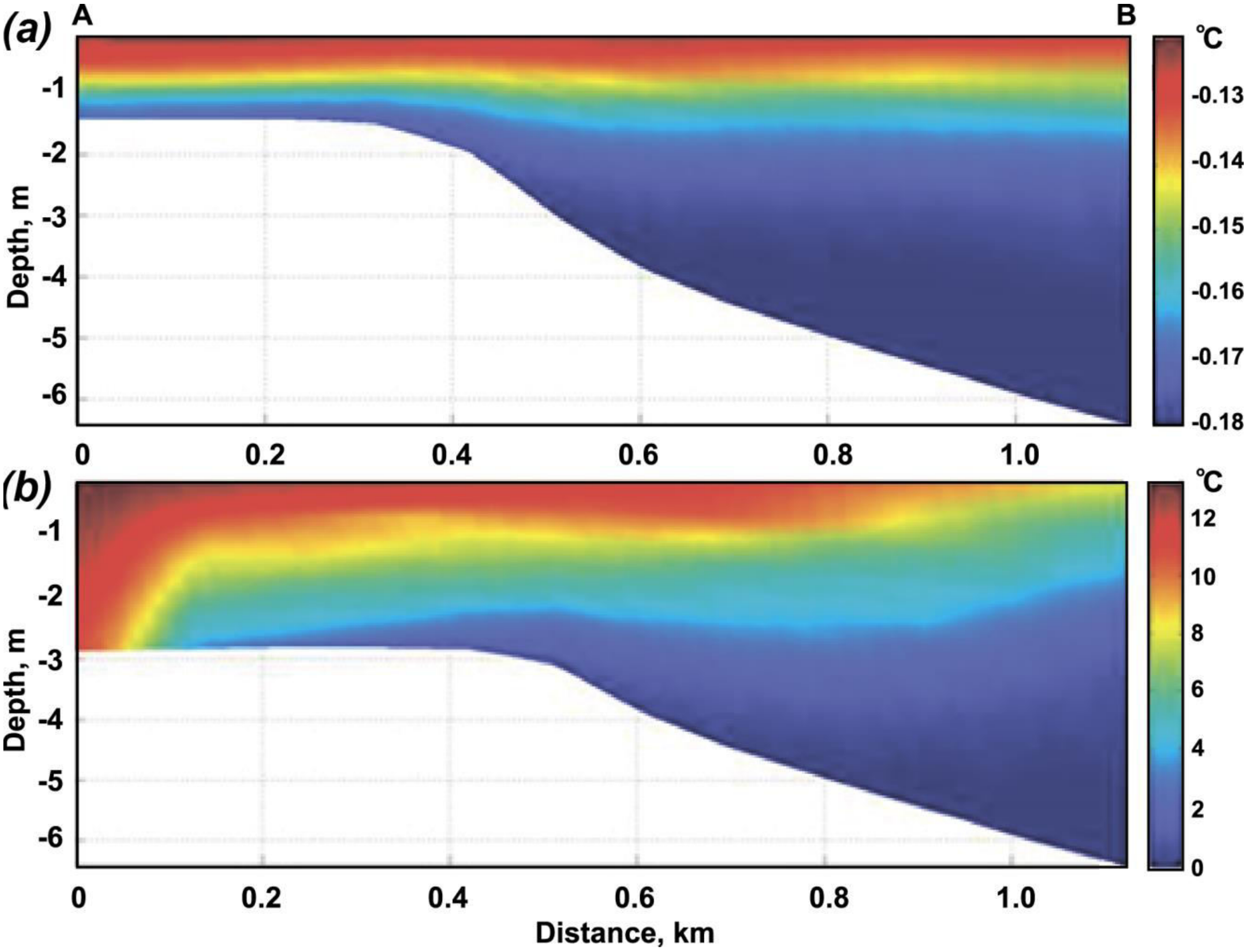


Figure 13: The vertical structure of the temperature field along the section from the discharge point to the north for 04.04.2010: (a) "background" scenario; (b) "predictive" scenario. Temperature scales for (a) and (b) are very different

Thermal regime in the vicinity of the water discharge point becomes completely different: SST deviations from background values are maximal in the 0-250 m zone, where they reach approximately 10 °C in winter and spring and 8 °C in summer and early autumn in cold year (2010). SST deviations decrease with the increasing distance from the water discharge point and reach the minimum value of 0.3 °C in the zone of 1500-2000 m. The bottom water temperature is also maximal in 0-250 m zone, where its deviations amount to 5 °C in winter and spring and 3 °C in summer and early autumn. In the cold year conditions the thermal regime in the case of operating NPP will be changed qualitatively as well as in warm year, but these changes (compared to the background scenario) in the vicinity of both the intake point and the discharge point will be stronger.

4 Discussion

1. The above model estimates of wind waves characteristics took into account the possible presence of the sea-ice cover in the Bothnian Bay, which in reality hinders or prevents the free generation and propagation of surface waves and limits the wave fetch if some part of the basin is covered with ice. The model run for 2014 was fulfilled for the entire year that is why the inclusion of sea-ice into the wind waves model was necessary. We assumed the isoline of ice concentration equal to 0.5 as an edge of the ice cover that in fact was some kind of simplification but still appeared as an effective way to limit the wave fetch in the presence of sea-ice in the Bothnian Bay. All required data for the SWAN model (sea level oscillations, currents, sea-ice) had been calculated in advance by the coupled circulation model before being used in the SWAN model.

2. Generally speaking, extreme sea levels in the Bothnian Bay are caused by storm winds, long waves, tides, low atmospheric pressure, seiches, and sea level rise of the World Ocean. Tidal level oscillations in the Gulf of Bothnia are negligible (Lepparanta & Myrberg, 2009) and can be omitted in the above model simulations. The influence of moving centers of the low atmospheric pressure has not been investigated in the present study, still it can be assumed that their impact is commonly appears jointly with the wind impact (SMHI, 2014). In order to simulate extreme sea level oscillations in the vicinity of the NPP "Hanhikivi-1" we considered the situations with constant (both in speed and direction) maximal possible wind blowing long enough to establish an equilibrium state and under the influence of sea level change caused by the long wave coming from the Baltic Sea. As indicated above, such a simplistic approach to the evaluation of extreme sea level in the area of interest gives results in good agreement with the estimates of extreme values of sea level according to the observations during almost 100 years.

3. Assessment of the scale of the thermal effects which could arise due to the work of NPP "Hanhikivi-1" on the marine environment has been obtained for the anomalously warm and cold years. These years for Hanhikivi’s area were identified as a result of the statistical analysis of long-term variability of meteorological parameters (with 3-hour resolution) for the period from 1993 to 2014, observed at the meteorological station Raahe Lapaluoto (the data were provided by Fennovoima (Fennovoima report, 2015). It was found that the coldest winter for the period was observed in 2010. The hottest summer for the period 1993 to 2014 was observed in 2002, for the period 2004 to 2014 – in 2014. Choosing 2014 as the abnormally warm year was dictated by the availability of observational data needed for verification of the models used: the number of available data for 2014 was greater than for 2002. If 2002 would be considered as an abnormally warm year, the difference between the cold and warm years would be more. In any case, the resulting estimates should be viewed only as typical ones that determine the order of magnitude.

4. Another restriction of this study is connected with prescribing the constant temperature difference (12 °C) between the discharged cooling water and the water temperature in the bay. This assumption not taking into account seasonal variations in the temperature of water environment can significantly affect the final result. For example, at the Beloyarsk

NPP operating in the Ural Region in the Russian Federation, this difference varies between 9 °C in summer to 12-13 °C in the winter (Vereshchagina et al., 2013). Finally, this temperature difference can be set when the plant is operating.

5 Conclusions

As shown above, the extreme values of sea level, water temperature, significant wave height in the vicinity of the future NPP "Hanhikivi-1" can be significant and sometimes catastrophic. Permanent release of heat into the marine environment from the operating NPP will lead to a strong increase in temperature and the disappearance of ice cover around 2 km vicinity of the NPP. These effects should be taken into account when assessing local climate changes in the future.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

This study was supported by the Grant N 14-50-00095 of the Russian Science Foundation and also by the Grant N 16-55-76021 of the Russian Foundation for Basic Research. The authors would like to thank the Fennovoima Company for providing the observational data needed for the present study.

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