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Evaluating hydrography, circulation and transport in a coastal archipelago using a high-resolution 3D hydrodynamic model

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ABSTRACT

We used a 3D hydrodynamic model, COHERENS, to simulate the temperature, salinity and currents in an extremely complicated area, the Archipelago Sea in the Baltic Sea. The high-resolution model domain with approximately 460 m resolution was nested inside a coarser resolution (~3.7 km) grid covering the entire Baltic Sea. The verification of the model results against temperature and salinity measurements showed that the model well captured the seasonal temperature cycle in the surface layer, both in the inner and outer archipelago. In the inner archipelago, the model tended to reproduce higher temperatures in the bottom layer than were measured. The modelled vertical temperature and salinity stratifications were not as pronounced as the measured ones but did describe the overall vertical structure. There was large year-to-year variability in the annual mean surface circulation, both in direction and magnitude. In the deeper channels crossing the Archipelago Sea, there were some year-to-year differences in the magnitudes of the bottom layer currents, but there was very little difference in the directions. These differences were studied by introducing passive tracers into the model through river discharge and as point sources. The results showed that the prevailing wind conditions resulted in southward net transport from the Bothnian Sea towards the Baltic Proper. However, due to the variability in the wind conditions in some years, a significant proportion of transport can also be towards north, from the Baltic Proper to the Bothnian Sea.

1. Introduction

The modelling of the state of coastal waters is a very important and topical issue. Coastal seas are facing multiple stressors and in many places are suffering from heavy eutrophication and pollution. The European Union (EU) Marine Strategy Framework Directive binds EU member countries to introduce measures to achieve and maintain the good environmental status of the European seas. To cost-effectively monitor the environmental status of the seas at regional and national levels, monitoring programmes are currently being evaluated and updated.

In the Baltic Sea, eutrophication is considered one of the main threats to biodiversity (e.g., HELCOM, 2009). The status of the Baltic Sea has been monitored since 1979 via the HELCOM monitoring programme that includes, for example, measuring physical, chemical and biological variables. Although the monitoring programme includes measurements at several stations, the temporal frequency of the visits and the locations of the stations do not provide enough data to adequately resolve the physical characteristics of the Baltic Sea as an entity. The number of automated buoys, floats and gliders in the Baltic Sea (e.g., Alenius et al., 2014; Westerlund and Tuomi, 2016) is continuously increasing and supporting traditional monitoring in open sea areas. Additionally, coastal observatories are being implemented in several countries, for example the German FINO2 research platform (http://www.fino2.de) and the Finnish Utö station (http://en.ilmatieteenlaitos.fi/Uto). There is, however, still a need for more data to evaluate the state of the Baltic Sea and to evaluate the effect of the measures taken (for example those taken to reduce the external inputs of nutrients to the sea) on the health of the Baltic Sea ecosystem.

To improve the ecological state of the Baltic Sea, Helsinki Commission (HELCOM) has set country-vice allocated reduction targets in the Baltic Sea Action Plan (HELCOM, 2013). As modelling is considered to be a good tool for evaluating the effect of the actions on the state of the sea in the future, the Baltic Nest Institute has calculated the maximum allowable annual inputs of nutrients (nitrogen and phosphorus) using the Baltic Sea long-term large-scale eutrophication model (BALTSEM, Savchuk et al., 2012). Although, BALTSEM is a relatively good tool for evaluating the basic nutrient dynamics in the open sea

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areas, more sophisticated tools are needed to evaluate the dynamics of the coastal areas. This can be done by utilising coastal high-resolution models which are able to evaluate the nutrient retention and water exchange between coastal and open sea areas – until now, the latter has not been frequently mentioned.

Model systems that are carefully implemented in coastal regions and verified against a sufficient amount of measurements can bring added value in the evaluation of the Baltic Sea state in the past, present and future, and thus result in a more comprehensive view of the state of the sea. The modelling of the coastal archipelago areas where the topography is extremely complex is a challenging task. Often, the adequate bathymetric data are not available; additionally, the compilation of a model grid in such areas is not an easy task (Tuomi et al., 2014). The large computational cost of high-resolution coastal models also often limits their use. Different solutions have been studied to enable modelling in such areas. For example, Engqvist and Andrejev (2003) used a 0.5 nmi horizontal resolution to model the outer archipelago of Stockholm, but for the inner archipelago, they used a discrete basin model, where the coastal areas were divided into sill-delimited basins of varying size. This type of approach is computationally less demanding than modelling the whole area with a resolution high enough to adequately describe the bathymetry in the inner archipelago and still provides usable information on the dynamics between the inner and outer archipelago. However, the spatial characteristics in the basins of the inner archipelago cannot be reproduced with this method. Additionally, in many areas, unstructured grids can be applied to provide a higher resolution where it is needed. For example, Aleynik et al. (2016) have shown that this type of model was able to give much more accurate and detailed results than the coarse resolution basin-scale models.

Our study area, the Archipelago Sea, is located between the Gulf of Bothnia and the Baltic Sea Proper. The area consists of approximately 40,000 small islands, islets and shoals scattered over a relatively small surface area, approximately 8300 km^2, which is only approximately 2% of the surface area of the Baltic Sea. The smallest islets are just a few metres in diameter, and many of the straits between the islands are very narrow. The estimated mean depth of the area is only 19 m, but the deeper areas are typically up to 50 m deep, and there are some fault lines that are partly deeper than 100 m (Fig. 1). The Archipelago Sea is a transition zone between the Gulf of Bothnia and the Baltic Proper, as well as the coastal inner and outer archipelagos. The surface salinity varies from 4 g/kg in the inner archipelago and close to the river mouths, to 6 g/kg in the outer archipelago. Only in a few deeper areas is there a weak halocline. In summer, a seasonal thermocline develops and reaches depths of 10–20 m. Below the thermocline, there is a colder water layer, the so-called old winter water. In shallow areas in the inner archipelago, there is no thermocline, and the entire water column is heated during the summer. The coastal inner-archipelago is ice-covered even in mild winters, and during an average ice season, most or all of the Archipelago Sea is ice-covered (Seinä and Peltola, 1991). Though the Archipelago Sea is in a nodal point of sea level variations, the amplitude of the short-term (mainly inter-annual) sea level variations range from approximately 1.7 m in the southern part to approximately 2 m in the northern part (Johansson, 2014). Sea level variability is mainly driven by meteorological forcing and seiches, and changes in the total water volume of the Baltic Sea. The tides only contribute to the sea level variation in the order of a few centimetres. The deeper channels (mean depths ~40 m) that cross the Archipelago Sea in the north–south direction steer the water exchange through the archipelago between the Bothnian Sea and the Baltic Proper. The relatively shallow depths of the channels only allow the exchange of Baltic Proper and Bothnian Sea upper layer waters above the halocline. There are estimates that approximately 33% of the transport between the Baltic Proper and the Bothnian Sea goes through the Archipelago Sea, and 24% of that is southward transport; the major part, 67% of the water exchange, goes through the Åland Sea (Ambjörn et al., 1983).

There are only a few published studies of the physical oceanography of the Archipelago Sea (e.g., Ambjörn et al., 1983; Suominen et al., 2010). Most of the studies are either limited to a specific area (e.g., Virtaustutkimuksen neuvottelukunta, 1979) or are a small part in studies that actually handle the whole Baltic Sea. The number of marine biological and chemical studies is larger, for example, studies of fish spawning areas (e.g., Snickars et al., 2015) and bottom oxygen conditions (e.g., Virtasalo et al., 2005). In these studies, physical oceanography is acknowledged as one of the important driving factors. The first high-resolution modelling efforts in the Archipelago Sea were made in the BEVIS project (BEVIS, 2007), which aimed at developing a modelling system for decision support in water quality issues. The system was able to simulate the basic characteristics of the water quality in the Archipelago Sea, and it was demonstrated to adequately simulate the effect of fish farms on the nutrient dynamics in areas close to the main island of Åland. The experience gained from this earlier work encouraged the further development of modelling systems in the SEABED project (Jönsson, 2013), and recently in the "Development of Archipelago Sea nutrient load model assembly" project (Lignell et al., 2016).

In our study, we used a high-resolution implementation of the 3D hydrodynamic model COHERENS (Coupled Hydrodynamical–Ecological Model for Regional Shelf Seas) to calculate the hydrography, circulation and transport in the Archipelago Sea. The high-resolution implementation was validated against temperature and salinity observations from the years 2013–2015. The model implementation was then used to evaluate the annual mean currents in the area. The effect of wind conditions on the year-to-year variability of currents was studied. Passive tracers released as riverine inputs and point sources were introduced to the model to study the effect of the yearly variations in the current fields on the transport of substances in and through the archipelago. Finally, the model implementation was evaluated from the perspective of its future use as forcing for a coastal high-resolution nutrient load model.

2. Materials and methods

2.1. The 3D hydrodynamic model COHERENS

We used a three-dimensional hydrodynamic model, COHERENS (Luyten, 2013), to simulate the hydrography, currents and transport in the Archipelago Sea. COHERENS has been used in several modelling studies of the Baltic Sea, and it has been shown to adequately simulate the dynamics of the Baltic Sea, both at basin and coastal scales (e.g., Bendtsen et al., 2009; Myrberg et al., 2010; Tuomi et al., 2012).

COHERENS solves the momentum equation in an Arakawa C-grid using the Boussinesq approximation and the assumption of vertical hydrostatic equilibrium. The equations of momentum and continuity are solved numerically using the mode-splitting technique (Blumberg and Mellor, 1987), where a first-order explicit Euler scheme was used for the barotropic mode and a semi-implicit TVD scheme was used for the baroclinic mode. For the equation of state, a formulation by McDougall et al. (2003) was used. Surface stress and heat flux formulations are calculated according to Large and Pond (1981, 1982). For vertical mixing, the k-ε parameterisation was applied.

The Archipelago Sea was modelled using a one-way nested approach as follows: a coarse resolution Baltic Sea model provides the boundary conditions for a finer-grid coastal application. The Baltic Sea model has a horizontal resolution of 2 nautical miles and 80 vertical layers, and the nested coastal model has a resolution of 0.25 nautical miles and 40 layers (bathymetries shown in Fig. 1). The Baltic Sea bathymetry is based on the IOW (the Leibniz Institute for Baltic Sea Research, Warnemünde) ocean bottom topography (Seifert et al., 2001). The high-resolution coastal grid was compiled from bathymetric data available in coastal nautical charts of the Finnish Transport Agency after some modifications based on the VELMU depth model (http://www.syke.fi/en-US/Open_information/Spatial_datasets).

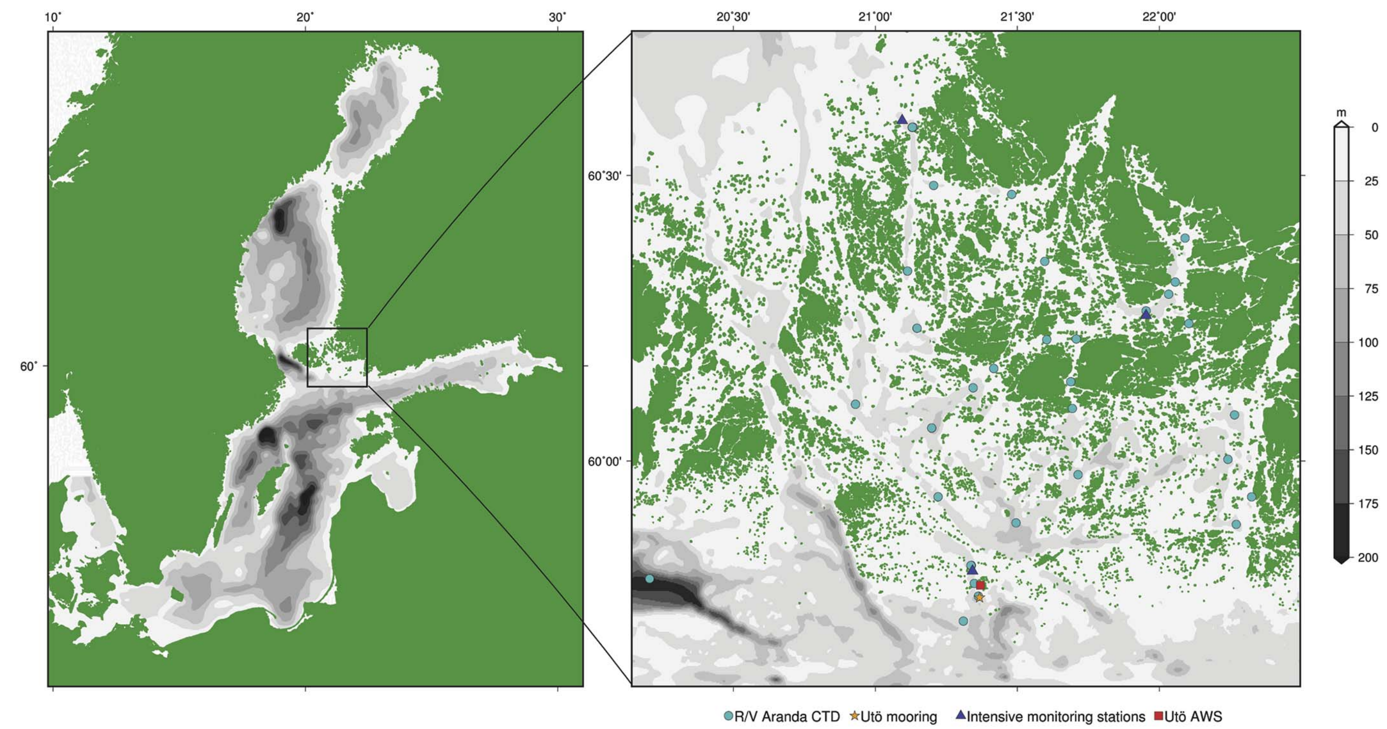

Fig. 1. The bathymetry used in the Baltic Sea (on the left) and the Archipelago Sea (on the right). The locations of the automatic weather station (AWS) and mooring at Utö, the intensive measurement stations (Brändö in the northern, Seili in the centre and Utö in the southern parts of the model domain) and CTD stations measured from R/V *Aranda* are shown on the right panel.

2.2. The vertical coordinate system

COHERENS is a σ-coordinate model, which makes modelling in areas with large depth variations, such as the Archipelago Sea, challenging. To better account for the surface and bottom dynamics, we implemented a vertical coordinate system in COHERENS, introduced by Siddorn and Furner (2013). They defined a formulation called the γ-stretching, which produces terrain-following vertical coordinates with user-defined surface and bottom layer depths.

We set the maximum surface layer thickness to 1 m in both of the model grids. Traditional σ-coordinates were used in grid points with depths less than or equal to 80 m in the Baltic Sea model and 40 m in the Archipelago Sea model. The γ-stretching was then applied to the vertical coordinates at deeper grid points.

2.3. Initial and boundary conditions

2.3.1. Meteorological forcing

The meteorological forcing for the COHERENS model was obtained from the numerical weather prediction (NWP) system HIRLAM (High Resolution Limited Area Model, HIRLAM-B, 2016) of the Finnish Meteorological Institute (FMI). HIRLAM produces short-range weather forecasts for a limited domain covering north-western Europe. The horizontal resolution is approximately 7.5 km, and in the vertical, there are 60 terrain-following hybrid levels. Forcing was gathered from forecast runs produced four times a day (00, 06, 12 and 18 UTC), utilising the first 6 h from each forecast.

2.3.2. Lateral boundaries and initial fields

The COHERENS Baltic Sea implementation has an open boundary at northern Kattegat, and boundary conditions for salinity, temperature and sea level height are applied. We used model data from Copernicus Marine Environment Monitoring Service products for temperature and salinity profiles. On the other hand, we took sea level height data from the measurement of the Swedish Meteorological and Hydrological Institute (SMHI). The initial temperature and salinity fields for the model runs were produced using DAS (Data Assimilation System; Sokolov et al., 1997) software, which utilises data from the Baltic Environment Database (BED).

Monthly mean values for river discharge from 29 major Baltic rivers, based on Bergström and Carlsson (1994), were used in the Baltic Sea grid, providing boundary conditions for the Archipelago Sea grid. In the Archipelago Sea, the river discharge was taken from the watershed model VEMALA. The VEMALA model is an operational, national-scale nutrient loading model for Finnish watersheds (Huttunen et al., 2016). In total, five rivers (Paimionjoki, Aurajoki, Hirvijoki, Mynäjoki and Laajoki) were inside the high-resolution model domain, and the daily values of river discharge were used.

2.3.3. Ice conditions

COHERENS does not include an ice module and thus cannot explicitly account for ice conditions. In the Archipelago Sea, the seasonal ice cover has large year-to-year variations. In severe winters, the whole area has ice cover, and in mild winters, only the small semi-enclosed basins close to the mainland have ice cover. Of the years presented in this study, 2013 was an average ice season. The mainland coast and the inner archipelago started to freeze from the beginning of January. The northern outer archipelago was totally ice-covered by the end of January, and the southern part of the Archipelago Sea by the end of February. The ice season lasted until mid-April in the outer Archipelago and to the end of April in the inner archipelago. The ice winters in 2014 and 2015 were mild. In 2014, there was only ice in the inner archipelago for a two-week period in early January. In both years, there was ice close to the mainland coast.

Although COHERENS does not calculate the ice conditions explicitly, it accounts for ice cover by adjusting the surface temperature to stay above freezing point. Furthermore, FMI-HIRLAM assimilates ice conditions for each forecast cycle, so the ice conditions are indirectly accounted for through the meteorological forcing used. Compared to the open sea conditions, the ice cover increases the surface roughness and typically induces a stable boundary layer, both of which reduce the momentum flux transferred to the ocean. The effect of ice conditions on the modelling and the results presented are further discussed in Subsection 4.1 and Section 5, respectively.

2.4. Observations

2.4.1. Hydrography

Temperature and salinity profiles from three intensive monitoring stations – Brändö (depth 34 m), Seili (depth 50 m) and Utö (depth 70 m, locations shown in Fig. 1) – were used to evaluate the model performance in different areas of the Archipelago Sea. Brändö and Utö represent conditions in the outer archipelago in the northern and southern parts, respectively. Seili is in the inner archipelago, in a sheltered area. Measurements are available at 1, 5, 10, 20 and 40 m depths (except at Brändö, where they were only available up to 20 m) and from the bottom layer. The temporal resolution of measurements is rather low, being only two to three times a month.

In 2013, FMI installed a Metocean inductive mooring system near the Island of Utö. It has seven SBE37 sensors at the depths of 2, 8, 15, 20, 30, 50 and 70 m. The sensors at 8 m and 70 m depths took measurements every 30 min, and the other sensors every 5 min. The data are from the summer seasons of 2013–2015. In 2013, there are data from May 7 till September 12 from depths 10–70 m. The surface buoy data ends on July 19, when the buoy broke loose and started drifting. In 2014, there are data from May 6 till August 30 from the two bottommost sensors (50 and 70 m). The upper layer data (sensors from 2 to 30 m) is from May 6 till June 25, when the mooring chain was broken and the surface instruments dropped to the bottom. In 2015, there are data from all sensors from May 5 till August 12.

We also used CTD[1] data from R/V *Aranda* in the Archipelago Sea during 2013–2015 to evaluate the accuracy of the model simulations. There are 62 profiles altogether from 23 different stations (the locations are shown in Fig. 1).

2.4.2. Measured wind speed and direction

Wind data from an automatic weather station (AWS) on Utö (location shown in Fig. 1) was used to evaluate the differences in the forcing wind field during 2013–2015, as well as to evaluate the accuracy of the HIRLAM forecasts. Furthermore, surface synoptic observations from Utö AWS for the years 1961–2010 were used to evaluate the long-term mean wind conditions.

3. Model validation

To evaluate the accuracy of the high-resolution model setup, we used data from three intensive monitoring stations. We calculated bias (modelled value – measured value) and root mean square error (RMSE) between the modelled and measured values at each station (Table 1). The modelled values, stored as daily means, were directly compared to the measured instantaneous values available 2–3 times a month from each station during the ice-free season. The comparison showed that there is generally a negative bias in the temperature in the upper layer (above thermocline) and positive bias in the lower layers (Table 1). At Brändö and Seili, the bias in the upper layer (1–10 m) was between 0.25 and − 0.6 °C. At both stations, the bias was smallest at a 10 m depth. At Utö, the bias at the surface is − 0.45 °C and grows to − 2 °C at a 10 m depth. In the lower layers (20 m and below), the overestimation of temperatures is highest in the Seili station, where the bias at the 40 m depth is 2.3 °C. The area in which the Seili station is located is represented as too shallow in the model grid. Moreover, the water exchange in the bottom layers between the outer and inner archipelago is more limited in the model since the narrow channels cannot be adequately described with the given resolution. Additionally, the formulation of the optical properties of the water in the COHERENS model is not optimised to the summer conditions in the Archipelago Sea and cannot, for example, account for the variability in the algae concentration in the surface layer. This might affect the results, especially in inner archipelago areas where the water depths and Secchi depths are shallower and vertical mixing is less intensive than in the outer archipelago. In salinity, there is a constant bias at all layers (Table 1). At Brändö, the bias was negative (~ − 0.21), meaning that the model slightly underestimates the salinity. At both Seili and Utö, the salinity is overestimated by the model. The overestimation was quite large at Utö (0.48–0.78 psu) compared to Seili (0.33–0.42 psu).

Table 1
The statistical parameters calculated for temperature and salinity at Seili, Brändö and Utö for the years 2013–2015. *N* denotes the number of profiles during the period at each station. The location of the stations is shown in Fig. 1.

Depth	Bias			RMSE		
	Brändö (N = 53)	Seili (N = 74)	Utö (N = 26)	Brändö	Seili	Utö
Salinity (psu)						
1	− 0.2105	0.3365	0.4829	0.5233	0.5233	0.05523
5	− 0.2114	0.3842	0.5478	0.4234	0.4234	0.5921
10	− 0.2129	0.3938	0.6748	0.4392	0.4392	0.7267
20	− 0.2300	0.3543	0.7841	0.4373	0.4373	0.8424
40	–	0.4109	0.6193	–	0.4556	0.7010
Temperature (°C)						
1	− 0.5215	− 0.3615	− 0.4492	1.2678	1.0242	1.0284
5	− 0.4265	− 0.5984	− 1.6105	1.074	1.2393	2.0742
10	− 0.2467	− 0.2614	− 2.1708	1.4032	0.807	2.7054
20	0.4491	1.2876	− 0.3909	1.9264	2.6727	1.9388
40	–	2.2678	0.8984	–	3.8369	1.7335

The seasonal variations in the surface temperature were fairly well represented by the model (Fig. 2). At Utö station, the heating of the surface layer starts in May and the highest temperatures are reached in late July or August. Of the years presented here, 2014 had the highest measured value of the surface temperature: 23.2 °C. The modelled value for the same instant was 23.8 °C. Also in the other years, the measured maximums were well simulated by the model (Fig. 2). The bottom layer temperatures were simulated with good accuracy during spring and early summer, but typically in July or in August, the modelled temperatures were higher than the measured ones. The model was also able to represent the seasonal variation in bottom and surface salinities, but in 2013 and 2014 the variation was smaller than in the measurements. By the end of the summer season, the surface layer salinities were approximately 0.5 psu higher in the model than in the measurements, and bottom salinities were approximately 0.5–0.8 psu lower. This suggests that the vertical salinity stratification is weaker in the model than in the measured profiles, which is typical for many of the Baltic Sea 3D hydrodynamics models as shown, for example, by Myrberg et al. (2010).

The comparison against CTD measurements showed similar results to the comparison against intensive monitoring stations. There is a positive bias in salinity at all depths (Table 2). The bias is largest at the depth of 40 m and smallest at the 60 m depth. There is a negative bias in temperature from the surface layer down to 10 m, and a positive bias in the lower layers.

Measurements with higher temporal resolution were available from the Utö mooring, which allowed us to better evaluate how the model describes the temporal changes in temperature and salinity. The bias in salinity was positive in all layers, except the lowest one, which is similar to the results presented from the Utö intensive monitoring station. The bias was smallest at a 2 m depth (~ 0.23 psu) and largest at a 20 m depth (~ 0.56 psu). Despite the bias in salinity, the model was able to well simulate the temporal changes in salinity. For example, in 2014, at

[1] The CTD instrument measures conductivity, temperature and depth. The CTD instrument used on R/V *Aranda* is a Sea-Bird SBE 911 plus.

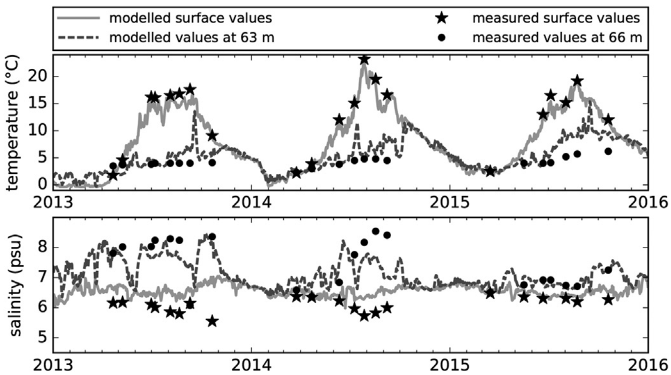

Fig. 2. Modelled surface and bottom temperature (upper panel) and salinity (lower panel) compared against measured values at the Utö intensive monitoring station. Modelled surface temperature and salinity are marked with a light grey solid line, and modelled bottom values with a dark grey dashed line. Surface layer measurements are marked with black stars and bottom layer measurements with black circles.

Table 2
Comparison of model results against CTD measurements from R/V *Aranda* (locations are shown in Fig. 1). *N* denotes the number of observations at each depth.

	N	Salinity (psu)			Temperature (°C)		
		Bias	RMSE	Correlation	Bias	RMSE	Correlation
1	77	0.1353	0.2836	0.6923	− 0.3505	0.8526	0.9929
5	77	0.1544	0.2997	0.6799	− 0.7078	1.2838	0.9868
10	77	0.1736	0.3316	0.6401	− 0.7725	1.6419	0.9718
15	73	0.1609	0.3403	0.6401	0.2991	1.6823	0.9557
20	70	0.1348	0.3277	0.6953	1.3258	2.2053	0.9615
30	63	0.1380	0.3221	0.7140	1.7922	2.8060	0.9418
40	44	0.2188	0.2590	0.7570	1.4405	2.3352	0.9184
50	33	0.1836	0.2525	0.8610	1.2862	2.5125	0.8702
60	24	0.0494	0.3747	0.8162	1.0386	2.3408	0.8107

the 50 m depth, there is an increase in salinity from early June until mid-July, and then there is a sudden drop in salinity combined with an increase in temperature of approximately 4 °C (Fig. 3), which the model is also able to simulate.

4. Transport and circulation

4.1. Annual mean circulation

The annual mean currents in the surface layer of 1 m for 2013–2015 (Fig. 4, upper panel) showed a year-to-year variation in the surface currents. In 2013 and 2015, there is much similarity in the mean surface current fields, especially concerning direction. In the southern and northern parts of the model domain, the flow direction is mainly from the west or west-north-west towards the east. Inside the archipelago, there is more variation in the mean currents between these years. Additionally, in 2015, the mean surface currents are slightly stronger than in 2013. For example, in the south and south-eastern parts of the model domain, the largest mean currents were up to 0.17 ms^{-1}, whereas in 2013, the largest values were only 0.11 ms^{-1}. Additionally, in the inner archipelago, the annual mean current speeds are higher in 2015 (up to 0.11 ms^{-1}) than in 2013 (up to 0.09 ms^{-1}). The higher mean values in 2015 are caused by the higher wind stress in that year. The wind roses from Utö (Fig. 5) show that in 2015, there is higher percentage of high wind speed events from a south-westerly direction than in 2013, and also, the ice season was milder in 2015 than in 2013. In 2014, the mean surface current directions differ a lot from the ones in 2013 and 2015. Both in the southern and northern parts of the domain, the mean directions are mainly from the south-west towards the north-east.

The annual mean currents in the 2–5 m surface layer for 2013–2015 (Fig. 4, middle panel) show the mean circulation in the surface layer, excluding the 0–2 m layer that is most influenced by the forcing wind field. Additionally, here, the years 2013 and 2015 show good resemblance. The highest mean values inside the Archipelago Sea are up to 0.08 ms^{-1}. Inside the Archipelago Sea, the mean currents in the 2–5 m layer are stronger in 2013 and 2015 than in 2014, and the mean flow direction is south and south-east, from the Bothnian Sea towards the Baltic Proper. In 2014, there is much more variation in the current field due to the more variable wind forcing, resulting in the smaller values of mean currents and large variability in the mean current directions.

The bottom currents show a more constant pattern, especially in the deeper channels, where the magnitude of the bottom current is also stronger (Fig. 4, lower panel). The highest mean values, up to 0.18 ms^{-1}, of the bottom currents were in the south-western part of the model domain in the deep basin. In the deeper channels inside the Archipelago Sea, the mean current speeds were up to 0.073 ms^{-1}. The mean bottom currents were stronger in 2013 and 2015 than in 2014 in most of the modelling domain. The mean current direction showed that the transports in the bottom area were mainly towards the north and north-east, through the Archipelago Sea.

There is inter-annual variability in the Baltic Sea wind conditions. Within the period in question, the prevailing wind direction at the Utö coastal weather station (location shown in Fig. 1) was south-west (Fig. 5, left panel). In 2013, and 2015, most of the high wind situations were south-westerly winds, whereas in 2014, there was higher variation in the direction of the high wind situations. Although south-westerly winds also dominated in 2014, there is a significantly larger percentage

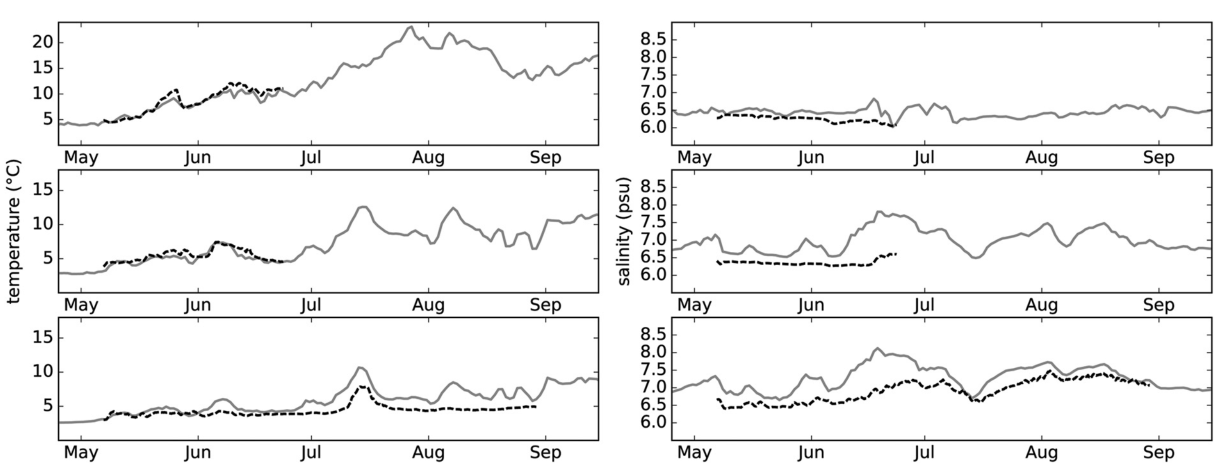

Fig. 3. Modelled temperature (left) and salinity (right) at 2 m, 30 m and 50 m depths compared to observations from the Utö mooring in 2014 (the location of the measurement site is shown in Fig. 1). Modelled temperature and salinity are marked with a solid grey line and measurements with a black dashed line.

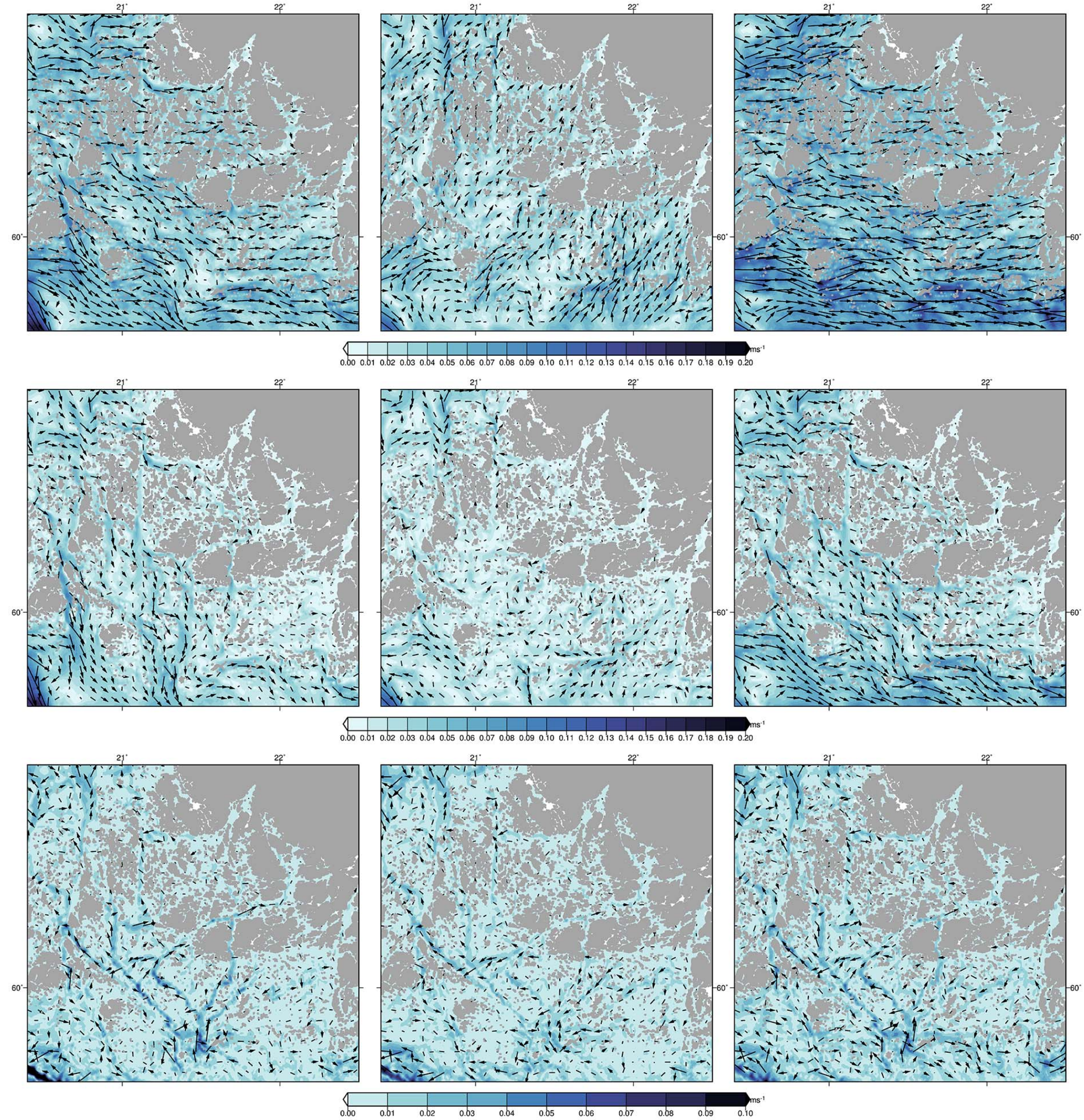

Fig. 4. The annual mean values of surface currents at 1 m depth (upper panel), at 2–5 m depth (middle panel), and in the bottom layer (lower panel) for 2013 (on the left), 2014 (in the middle) and 2015 (on the right). Note the different colour scale in the lower panel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of winds from a south-easterly direction compared to 2013 and 2015. The differences in the wind conditions between the years are reflected to the mean surface current field as described earlier. HIRLAM was able to fairly well represent the wind conditions during 2013–2015 and the differences between the years (Fig. 5, right panel).

4.2. Seasonal variability and maximum values

The maximum values of surface current were strongest in the narrow channels of the northern Archipelago Sea (up to 1.3 ms^{-1}) and in the open sea areas at the southern part of the model domain (up to 1 ms^{-1}). Similar to the mean values, the maximum values were largest in 2015 and smallest in 2014. There was a strong seasonality in both the mean and maximum values of the currents. Typically, the largest values are reached during autumn and winter. Spring and summer had considerably smaller mean and maximum values. The severity of the ice season also affected the results, and the mean and maximum values were slightly smaller in 2013 than in the mild winters of 2014 and 2015.

4.3. The transport of passive tracers

A model configuration was used to study the transport of passive tracers in and through the Archipelago Sea. Tracers were introduced as point sources to the northern and southern parts of the model area and as riverine inputs. The tracer concentrations were set to zero in the beginning of each year, so that the differences in the effect of current and transports between the years on the spreading of the tracer could be studied.

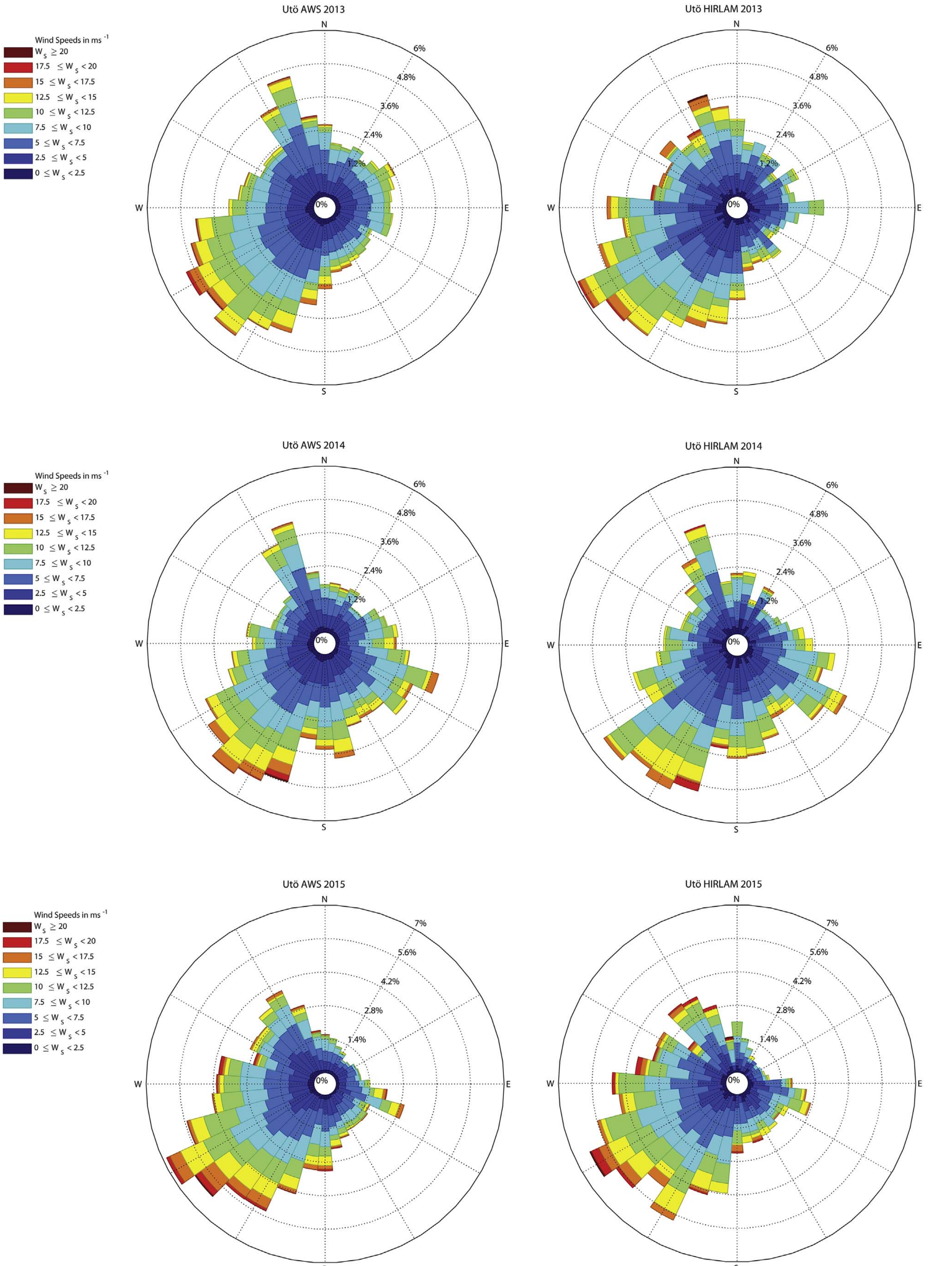

Fig. 5. Wind roses from the Utö automatic coastal weather station (on the left, location shown in Fig. 1) and from HIRLAM for the same location (on the right) for the years 2013 (upper panel), 2014 (middle panel) and 2015 (lower panel).

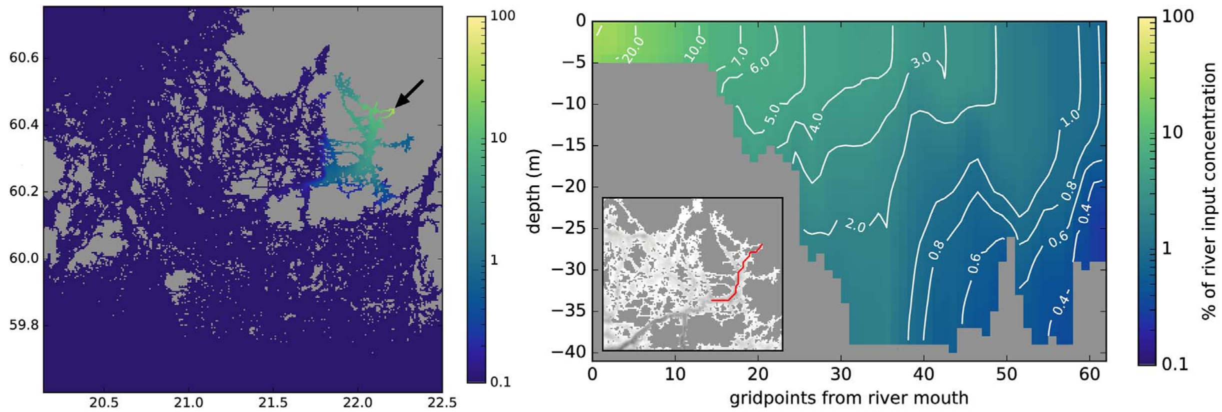

Fig. 6. The spreading of a passive tracer from the River Aurajoki in the 1 m surface layer in 2014 (on the left) and along a transect from the river mouth into the archipelago (on the right). The tracer concentrations are shown as percentages of the original concentration in the river discharge. The location of the river mouth is indicated with the black arrow and the location of the transect with the red line in the small map. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.3.1. Riverine loads

The tracer concentration from the River Aurajoki was set to a constant value for each one-year simulation period. The tracer had a considerably higher concentration in the shallow river estuary (between 10 and 30% of the concentration of the river loading; Fig. 6) than anywhere else in the model domain. When the tracer reached the deeper areas of the inner archipelago, approximately 30 km from the river mouth, the concentrations became considerably lower (less than 1% of the input concentration) as the tracer spread horizontally, as well as mixed vertically in the water column. In the outer archipelago the concentrations were negligible, less than 0.1% of the input concentration. Within a one-year period, the effect of riverine load on the concentrations of the substances in the outer archipelago can therefore be considered relatively small. However, naturally, the present concentrations of nutrients in the Archipelago Sea are the sum of several years of riverine inputs, and background loading from the northern Baltic Sea and the Gulf of Finland.

There is a seasonal cycle in the tracer concentrations in the river estuary. The concentrations are typically highest during spring, when the river discharge is also largest, and lowest during summer and early autumn. The seasonal behaviour in the concentrations is visible up to approximately 50 km from the river mouth. After that, the concentrations become very small (less than 1% of the input concentration), and the seasonality disappears.

4.3.2. The transport of substances through the Archipelago Sea

To evaluate the effect of the annual differences in the mean circulation of the water exchange between the Baltic Proper and Bothnian Sea through the Archipelago Sea, we made model runs with passive tracers located at different locations in the model area. Here, we present data from two locations, namely, near the northern edge of the modelling domain (60° 36.875′ N 21° 7.25′ E) and another in the south-eastern corner of the domain (59° 41.38′ N 22° 21.75′ E): the locations of the point sources are shown in Fig. 7. The southern location was selected to study the possible transfer of substances from the Gulf of Finland to the Bothnian Sea through the Archipelago Sea. The northern location was chosen to simulate the possible transport of substances from the Bothnian Sea towards the Baltic Proper and possibly further to the Gulf of Finland. The tracers were released from these point sources with a constant daily rate for the one-year simulation period.

As the years 2013 and 2015 presented similar characteristics in the mean surface currents, here, we only present the results for 2014 and 2015. The year 2015 was selected instead of 2013 since in 2015, the ice conditions were mild and there was only ice close to the mainland. The spreading of the tracers was quite different for the years 2014 and 2015 (Fig. 7, upper panel). In 2015, the tracer put into the northern part of the domain spread into a much wider area inside the inner archipelago and to the Baltic Proper. In 2014, the tracer mostly spread to the northern part of the archipelago and to the Bothnian Sea. The tracer put in to the southern part of the domain mainly spread to the Baltic Proper and the southern part of the Archipelago Sea in 2015 (Fig. 7, middle panel). In 2014, the tracer spread into a much wider area and the concentrations of the tracer were also quite high in the northern part of the domain in the Bothnian Sea.

The spreading of the tracers in the bottom layer was similar to the spreading in the surface layer. The largest differences in concentration between the surface and the bottom layer were in the vicinity of the point source locations. In shallow areas (less than 30 m depth), the concentrations were of the same order of magnitude throughout the water column. In the deeper channels of the central archipelago, the bottom layer concentration was about half of the surface layer concentration for the tracer released from the point source located in the northern part of the domain. However, the concentrations in the central archipelago were quite small in general, typically less than 0.5% of the daily input concentration.

The wind conditions and the following surface currents were quite different in 2014 and 2015 (Figs. 4 and 5). The long-term mean wind conditions from Utö show that south-west is the prevailing wind direction (Fig. 8), as it was for all the years of 2013–2015. There is also a considerably higher percentage of winds from the southerly and north-westerly sectors than there is from the easterly sectors. In many senses, the years 2013 and 2015 resemble the long-term mean wind conditions more than the year 2014 does. In 2014, the south-easterly winds had a higher percentage of occurrence (of over 3%) than the long-term mean (less than 2.5%).

To evaluate how important the high-resolution model grid is in this type of study, we also ran the point source tracer simulation with the Baltic Sea 2 nmi grid. Generally, the transport was much larger through the Archipelago Sea in the coarse grid model, since most of the archipelago cannot be represented with the given resolutions. For example, after five months of simulation, the transport of a tracer placed in the northern part of the domain produced much higher concentrations in the northern Baltic Proper and at the entrance of the Gulf of Finland than with the high-resolution grid (Fig. 9). In the high-resolution grid, the dense archipelago and narrow channels constrain the transport and restrict the dispersion, thus providing better estimates for the exchange of water and substances between the basins.

4.3.3. The sensitivity of circulation and transport to meteorological forcing

As meteorological forcing is one of the key factors in the modelling of the circulation and transport patterns, we made a sensitivity test using forcing from the FMI's new NWP system, HARMONIE. FMI-HARMONIE has a much higher resolution than HIRLAM, namely, 2.5 km, and should thus be better in describing the land-sea distribution

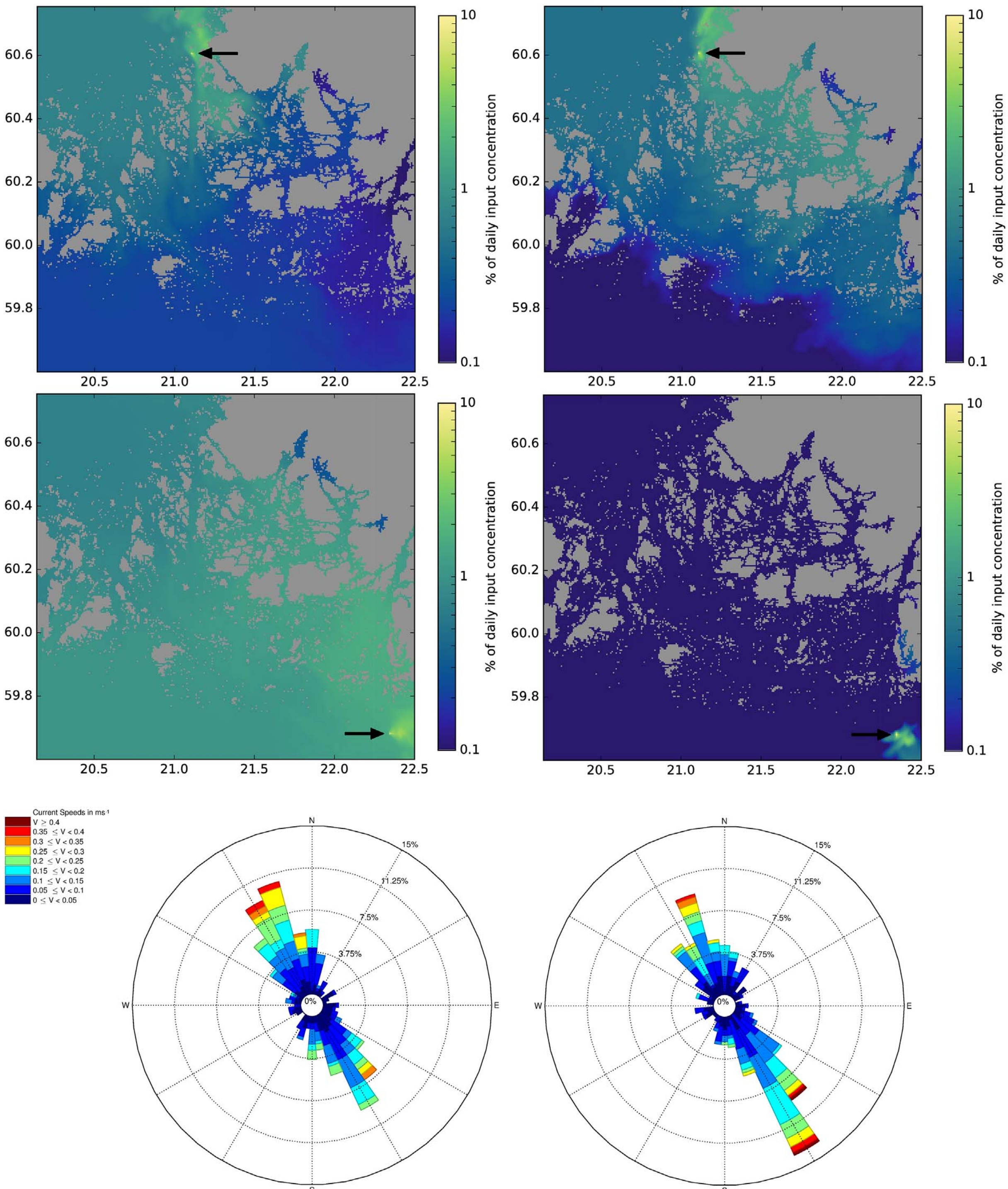

Fig. 7. The spreading of a passive tracer from a location at the northern part of the Archipelago Sea in 2014 (upper left) and 2015 (upper right), and from a location close to the entrance of the Gulf of Finland in the south-eastern boundary of the Archipelago Sea model domain in 2014 (middle left) and 2015 (middle right). The point source locations are indicated with black arrows. The tracer concentrations are shown as percentages of the daily input concentration from the point source. Modelled currents (direction to) in the 2–5 m surface layer in 2014 (lower left) and 2015 (lower right) at the location of the Brändö intensive monitoring station (which is in the vicinity of the northern point source).

in the Archipelago Sea. The forcing fields from FMI-HARMONIE were available for the year 2015.

The mean surface current field calculated using HARMONIE forcing was quite similar to that calculated with HIRLAM forcing in the open sea areas and in the outer archipelago (Fig. 4, upper right panel and Fig. 10, upper panels). In the inner archipelago, the HARMONIE-forced mean surface currents had generally lower magnitudes than the ones run with HIRLAM forcing. There, the high enough resolution of the forcing meteorological fields is of importance. The verification against intensive monitoring stations and the Utö mooring, showed that there are only minor differences in the simulated temperature and salinity between the HIRLAM- and HARMONIE-forced simulations. As the measurements are mainly from the open sea areas and outer archipelago, and the differences between the simulations are mostly in the inner archipelago, this was expected. More measurements from the inner archipelago are needed to further study the effect of the

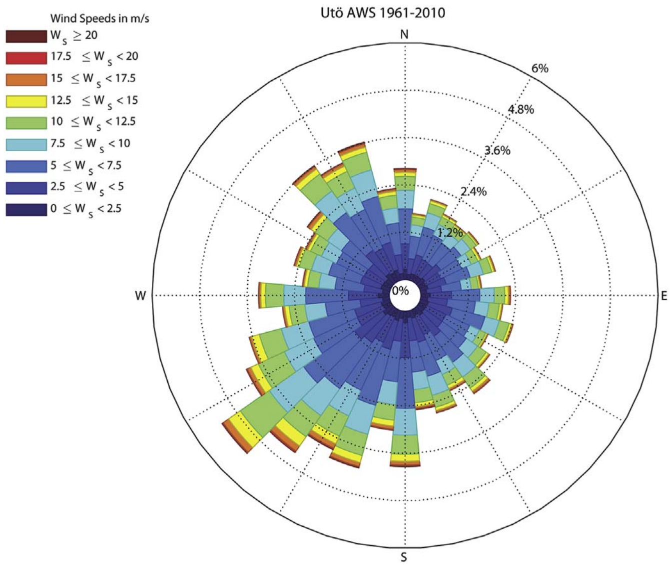

Fig. 8. Synoptic wind observations from the Utö AWS for the years 1961–2010.

meteorological forcing on the accuracy of the simulations. Additionally, the tests with the passive tracers resulted in almost similar distributions of concentrations (Fig. 7, upper right panel and Fig. 10, lower panels).

5. Discussion

The modelling of a complex area, such as the Archipelago Sea, is a way of understanding the details of the processes, but it is challenging in many ways. There are many factors that affect the accuracy of the results and some that leave room for improvement. Although the 0.25 nmi (~460 m) horizontal resolution is high in comparison to the surface area of the model domain, it is still insufficient to solve all the details of the dynamics of the inner archipelago. Some of the channels between the islands, which steer the transports between the outer and inner archipelago, are narrower in the model than in nature or have a shape that is not easily described with a structured grid. Nevertheless, compared to the Baltic Sea modelling grids, which typically have a resolution of one or two nautical miles, it is a significant improvement. With such a coarse resolution, the fine-scale features of the Archipelago Sea cannot be resolved, and the bathymetry is typically left much shallower due to the averaging of the depth data to coarser resolution. For example, in the 2 nmi Baltic Sea grid, the depths in the Archipelago Sea are typically less than 25 m (Fig. 1, left panel), whereas in the high-resolution 0.25 nmi grid, the deepest channels inside the Archipelago are up to 50 m. Furthermore, the measurement locations used to verify the results from the high-resolution grid were typically much too shallow to even consider making a comparison. For example, the depth at the location of the Utö intensive measurement station is only 12 m in the 2 nmi grid, whereas in the high-resolution grid it is 63 m, which is much closer to the actual depth of 70 m.

Considering the use of an unstructured grid in this area also brings some problems; due to the number of small islands scattered all over the model domain, the compiling of such a grid is not trivial. Whichever grid type is used, compromises have to be made. The computational cost of a high-resolution model is big and limits the use of such models to limited areas only.

One important open question is how to define the boundary conditions for the high-resolution grid. The Baltic Sea grid that we used to provide boundary conditions for the Archipelago Sea has a rather coarse horizontal resolution of 2 nmi. Although several modelling studies (e.g., Andrejev et al., 2000; Myrberg et al., 2010; Westerlund and Tuomi, 2016) have shown that with this resolution, the basic features of the Baltic Sea hydrodynamics can be simulated with sufficient accuracy, and the difference between the horizontal resolutions of the coarse- and high-resolution implementations is rather large. We carefully checked that the bathymetries used in both implementations represent the deep channels and shallower areas equally well in both grids at the nest boundary. This led to some modifications in both of the grids to make the shape of the deep channels similar and to avoid spurious 2D transports at boundaries.

The complex bathymetry causes difficulties in the modelling of vertical dynamics. As COHERENS uses σ-coordinates, the depths of the layers in a grid cell depend on the total depth of a grid point and the number of σ-layers. We set the vertical resolution to 40 layers, which leads to 5 m layers in the deepest areas of our model domain and to 10 cm layers in the shallowest areas of our model grid (the minimum bottom depth was set to 5 m). To decrease the depth of the surface and bottom layers in the deeper areas, we applied a modification to the traditional σ-coordinates with a method proposed by Siddorn and Furner (2013), as described in Subsection 2.2. This somewhat increased the accuracy of the surface and bottom layer dynamics compared to the use of traditional coordinates. However, in the narrow deep channels, the depth difference between adjacent grid points grew quite large (up to 47 m) and the use of σ-coordinates introduced over-mixing into these areas.

Evaluating the model performance in such a complex area is also a difficult task. Although measurements exist, these are only from a few areas of the Archipelago Sea, and their temporal resolution is mostly

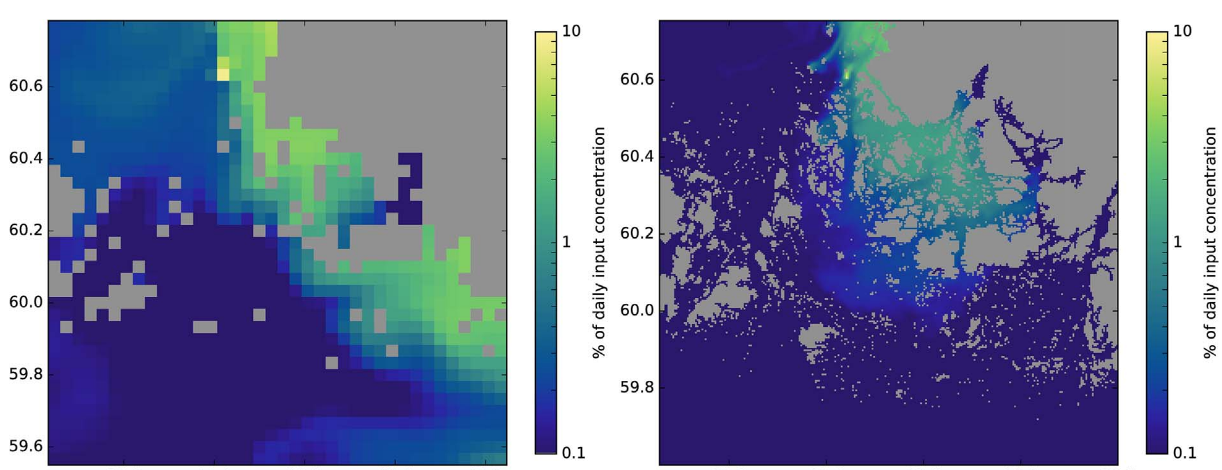

Fig. 9. The spreading of a passive tracer from a location at the northern part of the Archipelago Sea on May 30th, 2015, modelled with a coarse resolution 2 nmi grid (on the left) and with a high-resolution 0.25 nmi grid (on the right).

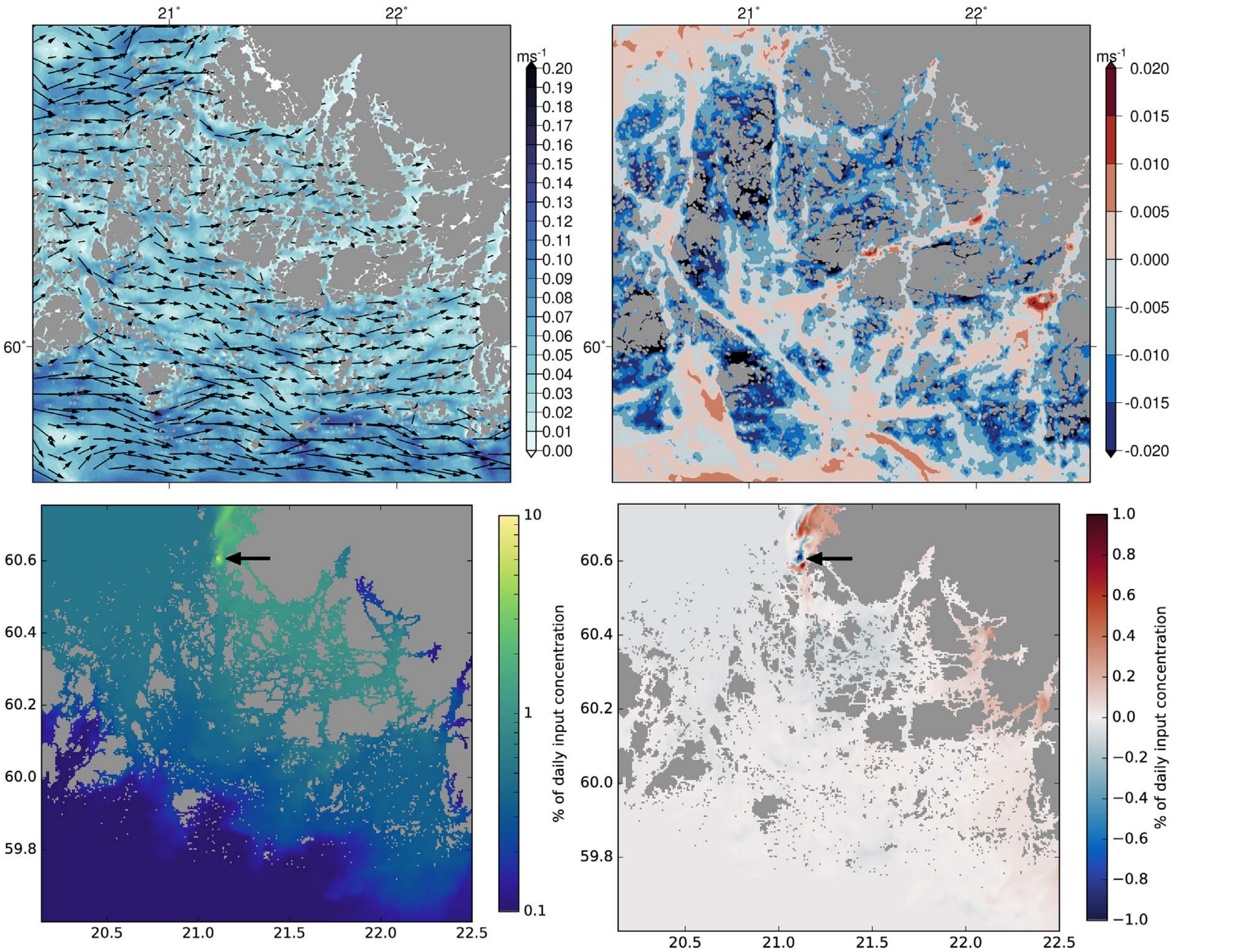

Fig. 10. The mean surface currents in the Archipelago Sea in 2015 with FMI-HARMONIE forcing (upper left) and the difference in the magnitude of the mean currents between HIRLAM and HARMONIE-forced runs (upper right). The spreading of a passive tracer from a location at the northern part of the Archipelago Sea in 2015 (lower left) and the difference in the tracer concentration between the HIRLAM and HARMONIE-forced runs (lower right).

poor. The only measurement site with high temporal resolution that was available for us at this point was the Utö mooring. Although the model performed relatively well when compared against these data, the verification data is too limited to draw very strong conclusions about the model's behaviour in the whole model domain.

The lack of measured data is not limited to hydrographic parameters. There are very few current measurements available from the area for the time period in question. The estimation of the accuracy of the modelled currents and transport is limited to only validating conservative parameters, such as salinity, that indirectly represent the accuracy of the modelled current field and transports, as well as the accuracy of the boundary conditions from the open sea and from river discharge. Although the salinity fields were fairly well represented by the model configuration when compared to the available measurements, the model development in this area would definitely benefit from more in situ current measurements.

Meteorological forcing is one of the key factors in the performance of a 3D hydrodynamic model. We used the FMI's NWP system HIRLAM to provide the meteorological forcing for both of the model grids. For the Baltic Sea 2 nmi grid, the horizontal resolution of HIRLAM (~7.4 km) is sufficient. However, it is rather coarse when the high-resolution (~460 m) grid is considered. Although Tuomi et al. (2014) have shown that the accuracy of higher resolution NWP systems in this area is not necessarily better than the coarser resolution NWP systems, the modelling might benefit from higher-resolution forcing, especially in the inner archipelago. The meteorological forcing of the data set is partially the same as used by Westerlund and Tuomi (2016), who showed that there are some shortages in the data set, which affect the accuracy of at least the surface temperature at certain periods. The sensitivity tests made using FMI-HARMONIE forcing showed that although the use of higher-resolution meteorological forcing leads to some differences in the surface current fields and in the spreading of tracers, essentially there were no significant differences in the results.

COHERENS does not have an ice module, and thus, ice conditions are only taken into account implicitly, as described in Sub-subsection 2.3.3. This might have a considerable effect on the results in severe ice winters, and perhaps also in average winters but can be considered negligible in mild ice winters. As the ice winter was mild in the years 2014 and 2015, the possible effects of this only concern a few months at the beginning of our simulation period (January–March 2013). To evaluate the effect of ice conditions on the circulation and transport, further studies are needed with an ocean-ice model, such as NEMO-LIM3, currently used in basin-scale modelling of the Baltic Sea (Westerlund and Tuomi, 2016 and Westerlund et al., 2017).

The evaluation of tracer concentrations from the River Aurajoki showed that near the river mouth, the concentrations were the largest, up to 30% of the input concentration. Approximately 30 km from the river mouth, the concentrations were less than 1% of the input concentration. In the outer archipelago the concentration of the tracer was very small and negligible when compared against the background nutrient loads entering from the Baltic Proper to the Archipelago Sea. For example, the concentration of total phosphorus in the Archipelago Sea is on average approximately 26% of the total phosphorus loading coming from the River Aurajoki. Whereas the tracer concentration in the outer archipelago was less than 1% of the input concentration. This indicates that measures taken in the watershed area of the Archipelago Sea most likely have a more pronounced impact on the areas close to the mainland and inner archipelago in the short term. However, this needs to be verified with a biogeochemical model, which is able to model the nutrient dynamics of the area as a whole.

The three-year modelling period is relatively short for analysing inter-annual variability in the transport of substances in and through the Archipelago Sea. In our simulations, we had two years – 2013 and 2015 – in which the wind directions were in accordance with the long-term mean directions (south-west being the prevailing wind direction) and one year, 2014, which had a significantly higher percentage of high wind situations from the south-easterly direction than the in the long-term mean conditions. The patterns of mean surface circulation and the transport of tracers were significantly different in 2014 than they were in 2013 and 2015. As 2013 and 2015 more resembled the long-term mean situation, this suggests that the transport of substances through the Archipelago Sea is larger from the Bothnian Sea towards the Baltic Proper rather than the other way around, contrary to the estimates presented by Ambjörn et al. (1983), for example, who estimated that only 24% of transport through the Archipelago Sea is southward transport. However, their analysis was mainly based on observations made during the summer period, which might explain some of the differences between their estimates and the ones presented in this paper. Furthermore, there are years in which the transport from the Baltic Proper to the Bothnian Sea can be significantly larger, as was the case in 2014. A longer simulation period is required in order to analyse the dynamics of water transport between the Baltic Proper and Bothnian Sea through the Archipelago Sea in more detail.

6. Conclusions

We used the 3D hydrodynamic model COHERENS to model the hydrography, circulation and transport of passive tracers in the Archipelago Sea, within the Baltic Sea. A high-resolution setup with 0.25 nmi horizontal resolution and with 40 vertical σ-layers was implemented in the Archipelago Sea area, and it was nested inside a 2 nmi Baltic Sea grid. The model was run for a three-year period (2013–2015), and the results were verified against temperature and salinity measurements in the area.

The verification showed that the model can describe the physical properties of the Archipelago Sea relatively well. The seasonal temperature and salinity variations in the surface layer were simulated with a good accuracy in both the inner and outer archipelago. In the inner archipelago, the resolution and description of the physics and parameterisations were not sufficient to adequately model the bottom temperatures. In the outer archipelago, at Utö station, the model was able to reproduce the temporal changes in parameters, including the advection of warmer and less saline water, in both the upper and near-bottom layers.

The modelled mean surface currents showed large year-to-year variation; in particular, the year 2014 differed from the others. The highest annual mean values of the surface currents inside the Archipelago Sea were up to 0.08 ms^{-1} and were even higher in the southern and northern parts of the model domain. The maximum values were up to 1.3 ms^{-1}, being highest in the narrow channels in the northern part of the Archipelago Sea and in the southern part of the model domain. The large year-to-year variability in the surface layer is due to the variable wind forcing. The prevailing wind direction in this area is southwest, but there can also be high winds from the north-westerly, south and south-easterly sections, as was the case in 2014.

In the bottom layer, there was much less variability in the current speed and direction. The mean current speed was highest in the deeper channels, being up to 0.07 ms^{-1}. Additionally, the current directions in the deep channels were mainly towards the north for all three years.

The year-to-year variability in the wind fields and resulting surface currents also affected the transport of passive tracers in and through the Archipelago Sea. In 2013, and 2015, there was more transport from the Bothnian Sea towards the Baltic Proper. In 2014, the situation was the opposite and there was more transport from the Baltic Proper to the Bothnian Sea. As the wind conditions in the years 2013 and 2015 represented the long-term mean wind directions better, and 2014 was somewhat exceptional, it can be estimated that 2013 and 2015 represent the prevailing conditions in the Archipelago Sea.

The sensitivity test made with the higher resolution meteorological forcing, available for 2015, resulted in smaller values of mean currents in the inner archipelago. The higher resolution forcing was able to better account for the heterogeneity of the surface type in this complex area. In the outer archipelago, the differences in the resulting mean surface current field and in the transport patterns of the passive tracers were negligible.

The model implementation presented in this paper will be used as part of a coastal nutrient load modelling system and has already been used in a study that evaluated the adequacy of the modelling system to estimate the internal loading of phosphorus (Puttonen, 2017). The aim of the modelling system is to manage nutrient load reductions and assess their impact on the state of the Archipelago Sea (Lignell et al., 2016). Although our verification showed that there is still some room for improvement in the model's ability to simulate the temperature and salinity fields, especially in the inner archipelago, we consider that the model has an adequate capability to simulate the physical conditions in the area and to function as a part of the Finnish coastal nutrient load modelling system.

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