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Validation of hydrostatic and non-hydrostatic versions of the hydrodynamical model MIKE 3 applied for the Baltic Sea

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Abstract. Hydrostatic and non-hydrostatic versions of the hydrodynamic model MIKE 3 were used to hindcast hydrophysical fields in the Baltic Sea for the period 1 April–1 November 1996. The model results were compared with observed sea level at Helsinki station and with temperature and salinity measured at monitoring stations in the Gulf of Finland and the Baltic Proper for the period 1 June–1 November 1996. The comparison was quite good for the sea level and the differences between the results of two model versions were insignificant for temperature and salinity stratification. In general, the results were better for the Baltic Proper than for the Gulf of Finland.

Key words: Baltic Sea, Gulf of Finland, hydrodynamics, salinity, temperature, sea level, modelling.

1. INTRODUCTION

The Baltic Sea is one of the largest brackish water areas in the world. It has very limited water exchange with the open ocean via the narrow and shallow Danish Sounds, and is characterized by a significant fresh water surplus due to river runoffs. This leads to a two-layer salinity stratification which plays an important role in physical processes [1].

The Gulf of Finland is a sub-basin, located in the north-eastern area of the Baltic Sea. It is a complicated hydrographic region, having saline water input from the Baltic Proper in the west and a large fresh water input from the rivers in the east [2,3]. Salinity increases from east to west and from north to south. The surface salinity typically varies from 5‰–7‰ in the western Gulf of Finland (the Hanko–Osmussaar line at the mouth of the gulf) to about 0–3‰ in the east (Neva Bay) [4,5]. Bottom salinity in the western Gulf of Finland can typically reach values of 8‰–9‰. In the eastern Gulf of Finland and in the eastern part of the central Gulf of Finland, there is no permanent halocline. In the western Gulf of Finland a permanent halocline exists throughout the year between depths of 60–80 m [4].

Annual variations in the sea-surface temperature are large in the Gulf of Finland. A seasonal thermocline usually forms at the beginning of May and starts eroding by the end of August due to the cooling of surface waters [1]. The thermocline is usually situated at a depth of 10–15 m and is at its strongest in July–August when the temperature difference between the warm upper and the cold intermediate layer below the thermocline lies in the range of 12–20 °C [6]. Variations in the sea level are caused by three main factors: changes in the wind direction and speed, fluctuations in the air pressure and changes in the density of sea water [7,8]. In Helsinki the sea level variability is smallest in July (between –36 and +79 cm compared to the mean sea level), and largest in January (between –92 and +151 cm) [4,9].

Nowadays numerical models are common tools for the hindcasting and forecasting of the hydrophysical situation in natural water basins and for process-oriented studies. Usually, a variety of models is applied for the same region with similar or different purposes. The models can differ in many aspects, e.g. in implemented numerical schemes, parameterization of horizontal and vertical turbulence, calculation of heat fluxes at the air–sea interface, etc. One option for the selection of the models is hydrostatic versus non-hydrostatic version. The majority of marine models implement a hydrostatic pressure assumption in their physical formulation, but non-hydrostatic models have shown an advantage over the hydrostatic model in simulating open ocean deep convection [10], sinking of dense water outflows [11], internal waves at a discharge plume [12] and sub-meso-scale vertical motion at ocean fronts [13].

Selection of the non-hydrostatic version of the model is usually justified when high-resolution hydrodynamic models are applied. A non-hydrostatic model explicitly incorporates the effect of vertical acceleration, which is important in water basins with complex topography where dense water overflow can occur, and in case of convective mixing forced by cooling of the water surface. Both processes are essential in the spatio-temporal evolution of hydrographic fields in the Baltic Sea.

This study aims at the validation and comparison of hydrostatic (HS) and non-hydrostatic (NHS) versions of the hydrodynamic model MIKE 3 [14,15] in the Gulf of Finland and Baltic Proper. Both model versions are verified against measurements of salinity, temperature and sea level for the period June–November 1996. The validation results indicate the ability and advantages of the different model versions in simulating hydrographic conditions in the Gulf of Finland and in the Baltic Proper, which can facilitate selection of model versions for future applications.

2. MODEL DESCRIPTION AND SET-UP

The classical version of the model MIKE 3 is non-hydrostatic and applies an artificial compressibility method (ACM). The mathematical foundation in MIKE 3 is the mass conservation equation for compressible fluid, the Reynolds-averaged Navier–Stokes equations in x-, y-, and z-directions, including the effects of turbulence and variable density, together with conservation equations for salinity and temperature [14]. The model applies a Cartesian grid representation for the Baltic Sea.

The non-hydrostatic model, where the full vertical momentum equation is retained, requires that the fluid is compressible. To solve the equation system, the artificial compressibility must be chosen so that it does not interfere with the hydrodynamical processes to be simulated. Thus, the resultant artificial speed of sound must be higher than the celerity of free surface waves.

The HS version of the hydrodynamical model consists of the same set of equations as the non-hydrostatic model [15]. The main difference is due to the application of the hydrostatic pressure assumption. This results in the omission of vertical acceleration and exclusion of the artificial compressibility term. The pressure is split up into two parts, the external pressure and the internal one. In the hydrostatical version the external pressure is directly linked to the free surface, and the internal pressure is due to the density differences. In the HS version, a semi-implicit numerical scheme is used as compared to the alternating direction implicit (ADI) scheme, used in the NHS version. Both the NHS and HS versions of MIKE 3 apply the same grid (Arakawa C) and use time staggering.

The model MIKE 3 has been applied for the investigation of several hydrodynamical and eutrophication problems in natural water basins [16–20].

The modelling domain covers the whole Baltic Sea area (Fig. 1). The open boundary is along Skagerrak–Kattegat front at 57°43′ N. The model has a grid with a horizontal resolution of 2′, which means about 1×2 nautical miles (approximately 1852×3704 m). Vertical resolution is equal to 2 m, except for the surface layer, which is 3 m thick. High vertical resolution is used for obtaining good representation of the seasonal thermocline and permanent halocline in the Baltic Sea. The set-up specifications make it possible to use a model time step of 200 s without stability problems. The Smagorinsky formulation was used for horizontal eddy viscosity, while κ–ε formulation was used for vertical turbulent closure model. Several test runs with different sets of model parameters were performed. In the presented results, the horizontal non-dimensional calibration parameter was set to 0.2. The eddy diffusivities for temperature and salinity were taken to be proportional to the eddy viscosity. The non-dimensional proportionality coefficients were taken as 0.05.

The modelling period was from 1 April to 1 November 1996. The model set-up is consistent with the Eutrophication-Maps project where the other five models were compared with the non-hydrostatic MIKE 3 model [21]. Thus initial fields, atmospheric forcing, river discharge and boundary conditions were pre-

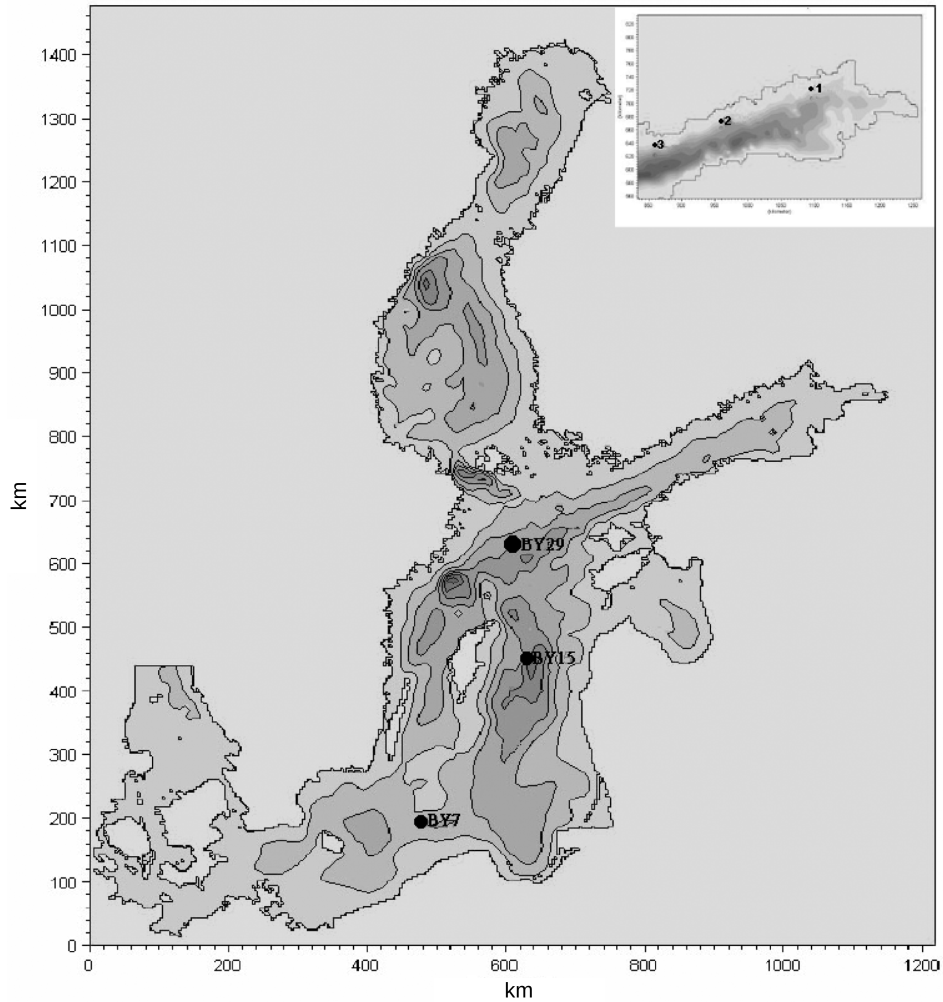

Fig. 1. The location of the HELCOM monitoring stations (BY7, BY15, BY29) in the Baltic Proper and of the Finnish coastal monitoring stations (1 – Huovari, 2 – Länsi-Tonttu, 3 – Längden).

pared in the frame of the Eutrophication-Maps project. The initial condition includes zero current velocity and sea level. Initial temperature and salinity were constructed from the data available in the Baltic Environmental Database [22] for January–March in 1995 and 1996.

Atmospheric forcing data (air temperature, wind fields, relative humidity, precipitation, cloudiness and atmospheric pressure) was prepared based on the meteorological database created by the Swedish Meteorological and Hydrological Institute. The meteorological data set covers the whole Baltic Sea drainage basin with a grid of $1° \times 1°$ squares. The grid extends over the area of the latitude 49°30′–71°30′ N and longitude 7°30′–39°30′ E. Air pressure, wind fields, air temperature, relative humidity and total cloud cover data were prepared at 3-h intervals. Accumulated precipitation data was prepared at 12-h intervals. The parameters were interpolated to the model grid using two-dimensional univariate optimum interpolation scheme. A quality control algorithm to reject erroneous data was built into the objective analysis scheme. Wind stress was calculated from the quadratic law with the linear wind drag coefficient. Also air pressure was used as external forcing. Heat exchange between the atmosphere and the sea was calculated on the basis of sensible and latent heat flux and the net short- and long-wave radiation. No heat and salt exchange through the sea bottom occurs. The lateral boundary conditions involve no slip for velocity and insulation for temperature and salinity on sidewalls. A quadratic drag law was used for bottom stress.

Land-based freshwater sources consist of river discharges from 29 major rivers of the Baltic Sea. The input data of rivers were compiled relying on the database of a monthly time resolution [23]. The long-term monthly mean values were calculated as sample means for each month using all available data for a particular source and month over the year 1992. Prescribed sea level, temperature and salinity distributions were applied at the open boundary. The open boundary data was obtained from the HIROMB model. Time series consist of sea level values at 1-h intervals and temperature and salinity distributions at 3-h intervals.

3. RESULTS

The model results for the period 1 June–1 November 1996 were compared with the observed sea level at Helsinki as well as the temperature and salinity profiles from monitoring stations Huovari, Längden and Länsi-Tonttu near the Finnish coast and three HELCOM monitoring stations (BY7, BY15, BY29) in the Baltic Proper. The first two months of the simulation period were excluded from the comparison. Observed sea level at Helsinki for the year 1996 was prepared by Finnish Institute of Marine Research with 1-h time resolution. The time series of salinity and temperature profiles for three Finnish coastal stations were prepared by Finnish Environment Institute, based on irregular observations of temperature and salinity.

3.1. Helsinki sea level

Comparison between the modelled and observed sea levels from Helsinki mareograph during the period of 1 June–1 November 1996 showed quite good agreement for both versions of the model (Fig. 2). The modelled sea level is about 40 cm higher on average due to the inability of the models to correctly reproduce long-term mean sea level. This value was subtracted from modelled results.

The maximum sea level in Helsinki (49 cm) for the considered period was measured on July 13, 1996 and the minimum value (–49 cm) on September 28, 1996. Both models give slightly overestimated sea level values for these events.

(a)

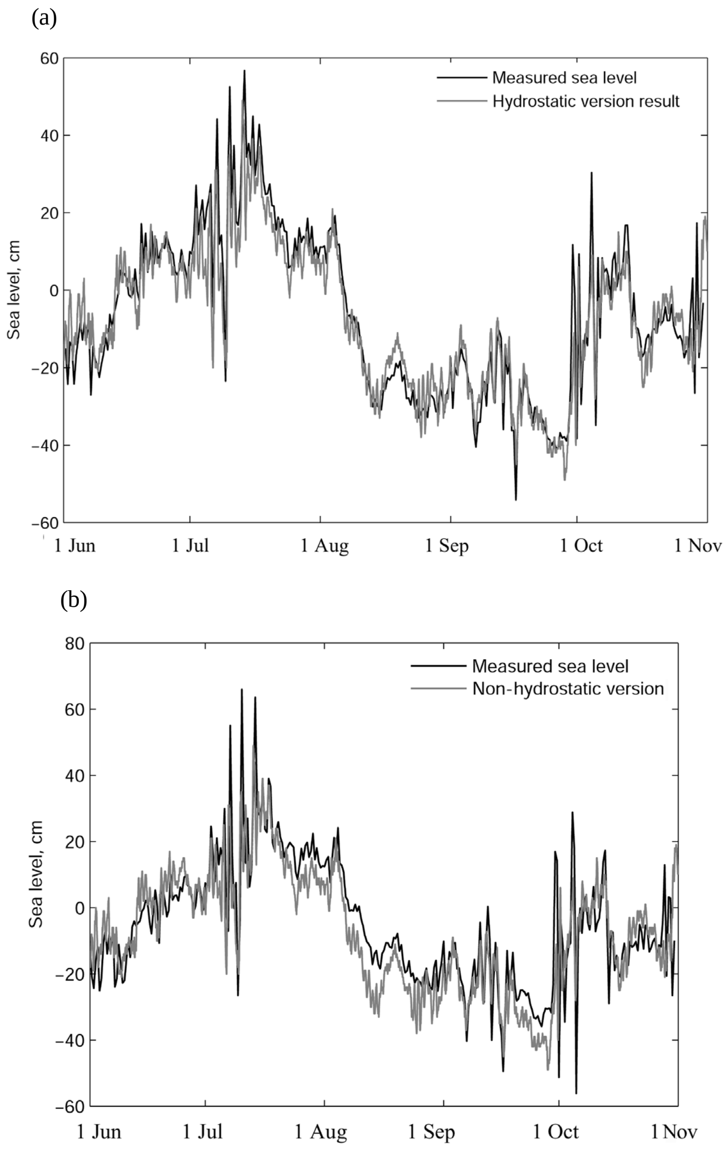

Fig. 2. Sea level time series from the hydrostatic (a) and non-hydrostatic (b) model compared with measurements at Helsinki. The measurement data were made available by the Eutrophication-Maps project [[21]].

3.2. Huovari monitoring station

Comparison of HS and NHS model results with measured temperature at Huovari monitoring station is presented in Fig. 3. During the period of 1 June–1 November 1996 the surface temperature measured at Huovari station varied between 8 and 19 °C, with the highest temperature values occurring at the end of

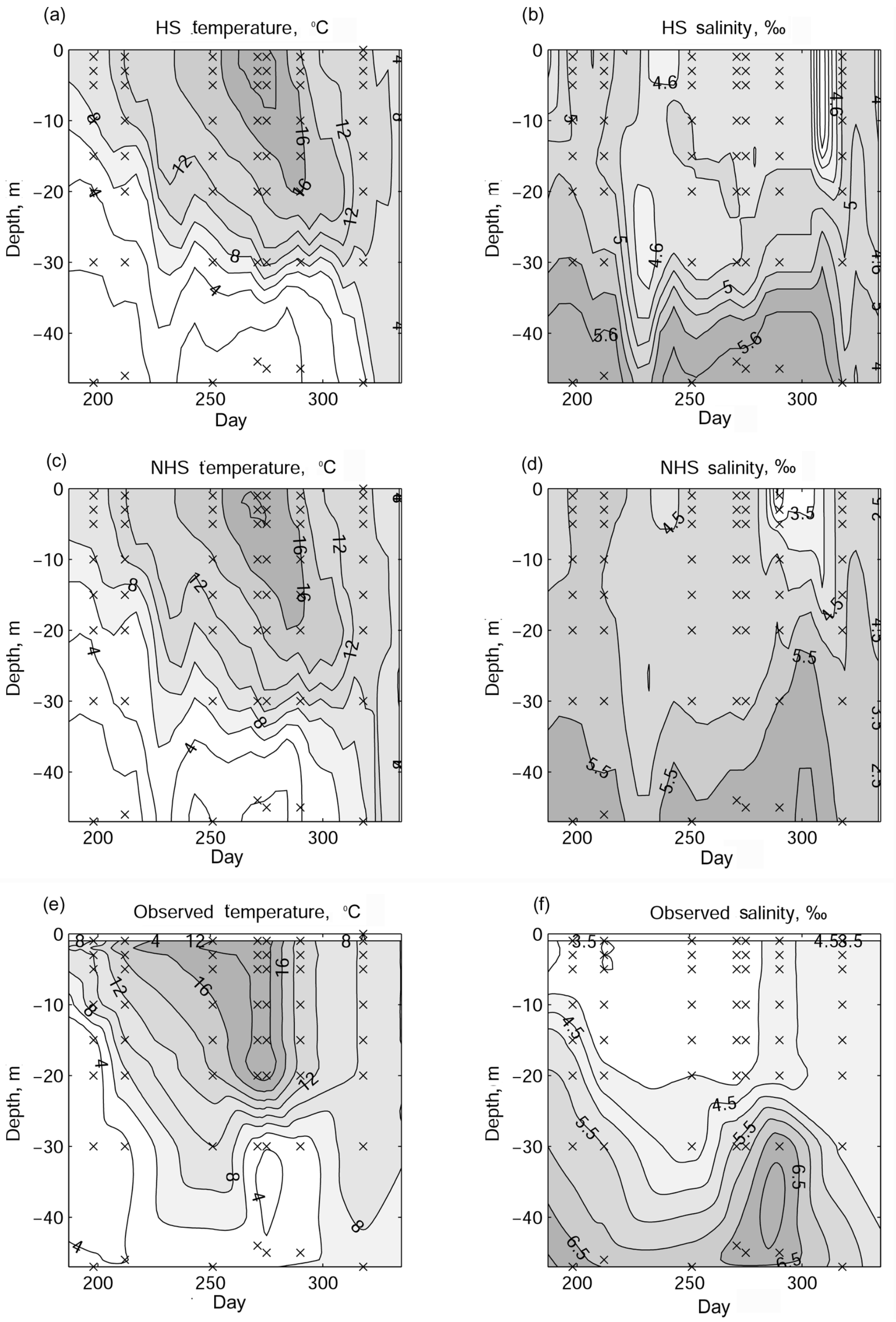

Fig. 3. Modelled HS temperature (a) and salinity (b), NHS temperature (c) and salinity (d) and observed temperature (e) and salinity (f) at the Huovari monitoring station. The measurement data were made available by the Eutrophication-Maps project [21].

August. Near bottom temperatures were more or less homogeneous with the mean value of 4 °C. The thermocline formed at a depth of 20 to 30 m. Stratification in the gulf is strongest in August and early September. During autumn, the water column is thoroughly mixed and the thermocline is eroded.

There were disparities in the temporal temperature distribution from the model results and measured data in the both HS and NHS model versions. According to the models, warming of the water column started one month later than was recorded by measurements. In the bottom layer both models show temperatures 2 °C less than were measured. Both models were able to reproduce temperature stratification, thermocline depth and the upper mixing layer accurately. For instance, the modelled thermocline was at the same depth (20–30 m) as was measured.

Surface salinity at Huovari monitoring station was more or less homogeneous and equal to about 4‰ from June to early September. At the end of September and October, surface salinity was about 5‰. The vertical distribution of salinity was from 4‰ near the surface to about 7‰ at the bottom. Salinity stratification was strongest in September. In August there was an inflow of colder and saltier water masses.

Modelled surface salinity was higher than measured, except in September and October. Underestimation of surface salinity is clearly seen in the NHS model during September and October, where surface layer salinity is only 3‰. Bottom salinity was reproduced more or less satisfactorily. In the HS model the variability of the bottom salinity is less than shown by the measurements and by the NHS model. The difference between the measurements and the NHS model near-bottom salinity is 1‰, while that of the HS model it is 1.5‰. None of the models simulated vertical salinity stratification accurately.

3.3. Gotland Deep

The surface temperature measured at the monitoring station BY29 (Fig. 4) during the simulated period varied between 6 and 20 °C with the maximum occurring in August. The thermocline lies in the range of 20–40 m. During the whole period, there was a colder water layer at a depth of 20–80 m, where water temperature was below 4 °C. Below this, there was a warmer layer, where temperature was about 5 °C (depth between 100–120 m). The near-bottom water temperature was about 5 °C. HS and NHS versions of the model simulate temporal variability of temperatures and stratification quite well and with similar accuracy. Both models reproduce intermediate colder water layer.

Measured surface layer salinity distribution was homogeneous up to the depth of 45 m during the whole period, with a mean value of about 6.5‰. The halocline at the monitoring station BY29 was between 70–110 m. Below the depth of 110 m, salinity increased monotonically from about 10‰ to 11‰. The HS and NHS models described the bottom salinity better than the surface salinity.

HS model gives a sharper seasonal thermocline and seasonal halocline in the Gulf of Finland. Temporal development of surface mixed layer and corresponding

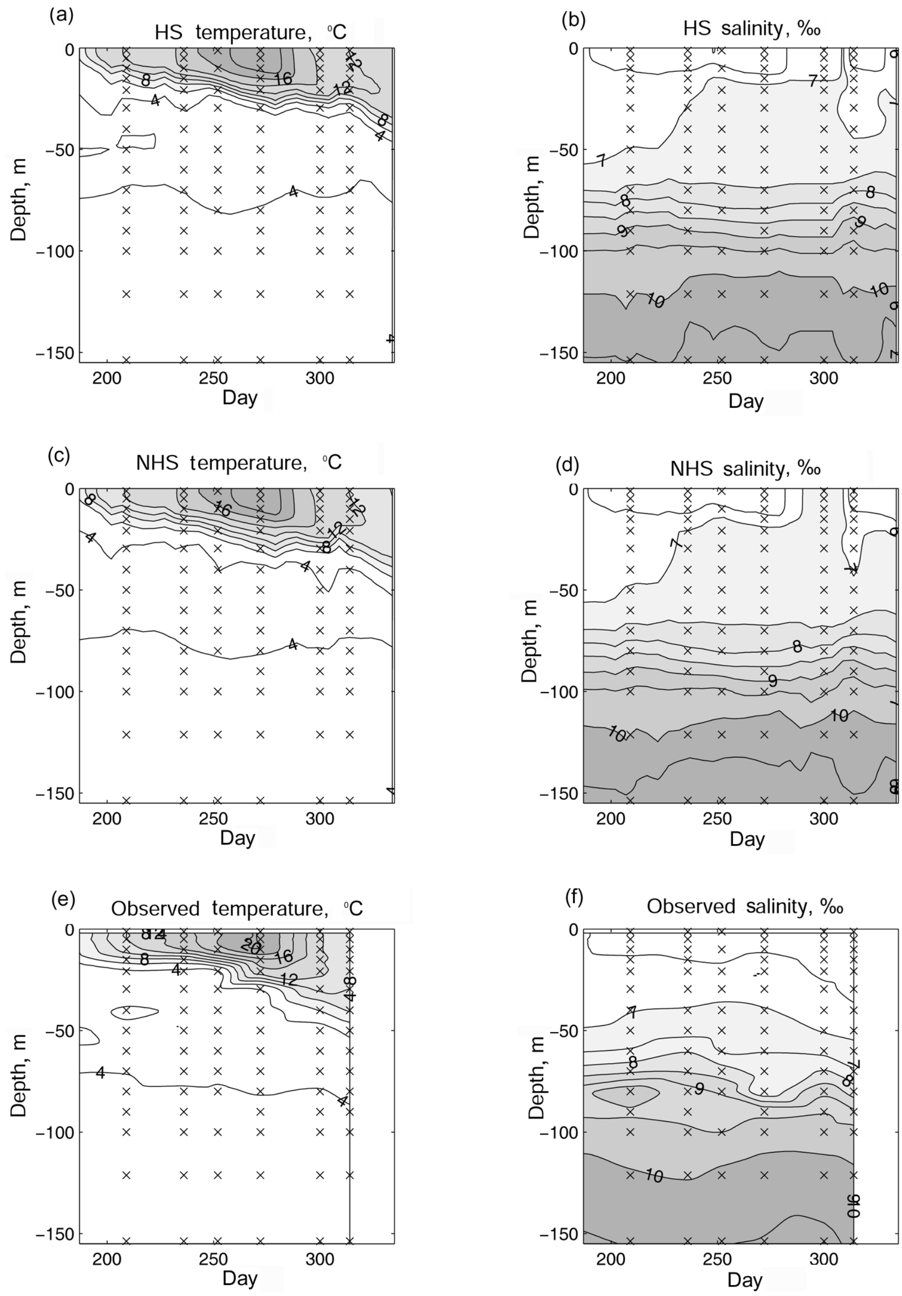

Fig. 4. Modelled HS temperature (a) and salinity (b), NHS temperature (c) and salinity (d), observed data for temperature (e) and salinity (f) at the monitoring station BY29. The measurement data were made available by the Eutrophication-Maps project [21].

erosion of seasonal thermocline occurs faster in the NHS model, which is more consistent with the measurements.

4. DISCUSSION

Statistical analysis was made to quantify how accurately the results of each hydrodynamical model match the measurement data. For this purpose the difference between measurement data and modelled results was analysed. A positive value of the difference denotes overestimation, while a negative value indicates an underestimation of modelled results compared to the observed data. In order to estimate which model fits measurement data more accurately, the root mean square error (RMSE) was calculated for both HS and NHS model results at different depths.

At Huovari station (Fig. 5), model results and measured data for temperature fit best in the beginning of the investigated period and in late August and early September, when temperature was at its highest. On average, both models showed the best performance (and, consequently, smallest RMSE values) at the depth of 3–15 m. The greatest overestimation of temperature by the models is apparent at intermediate depths during late summer and early autumn due to longer persistence of warm water. The HS model was slightly more accurate. Temperature was mostly underestimated in the near-bottom layer and more so by the HS than by the NHS model, as seen from RMSE data.

In the case of salinity, overly strong mixing led to the overestimation of near-surface results in the models during the first half of the period. The over-estimation diminished with depth. Both models showed similar behaviour, as seen in the RMSE data. Salinity in the deep layers was underestimated during the entire period, except for October. The RMSE was smallest at the intermediate layers (depth around 25 m), where the HS model performed slightly better. Below that level (to the depth of approximately 40 m) the NHS model was more precise than the HS model.

The temperature at Gotland Deep station (Fig. 6) was reproduced with the highest inaccuracy at the depth of 20–40 m, where thermocline existed. The temperature was overestimated at the beginning and middle of the period, but was underestimated later. Both models behaved similarly, but the NHS version was less accurate at around 40 m depth. Below 80 m the temperature was reproduced accurately, as confirmed by very low RMSE values.

The modelled salinity showed the best match with data at depths of 40–60 m and 100–120 m, i.e. above and below the halocline. Since the modelled halocline depth was lower than measured, both versions of the model underestimated salinity around 80 m water depth (corresponding to highest RMSE values). The models overestimate upper layer salinity in October. Also, the modelled salinity is too high near the bottom. These discrepancies are reflected in the values of RMSE. On average, the HS model reproduced salinity at the station more accurately.

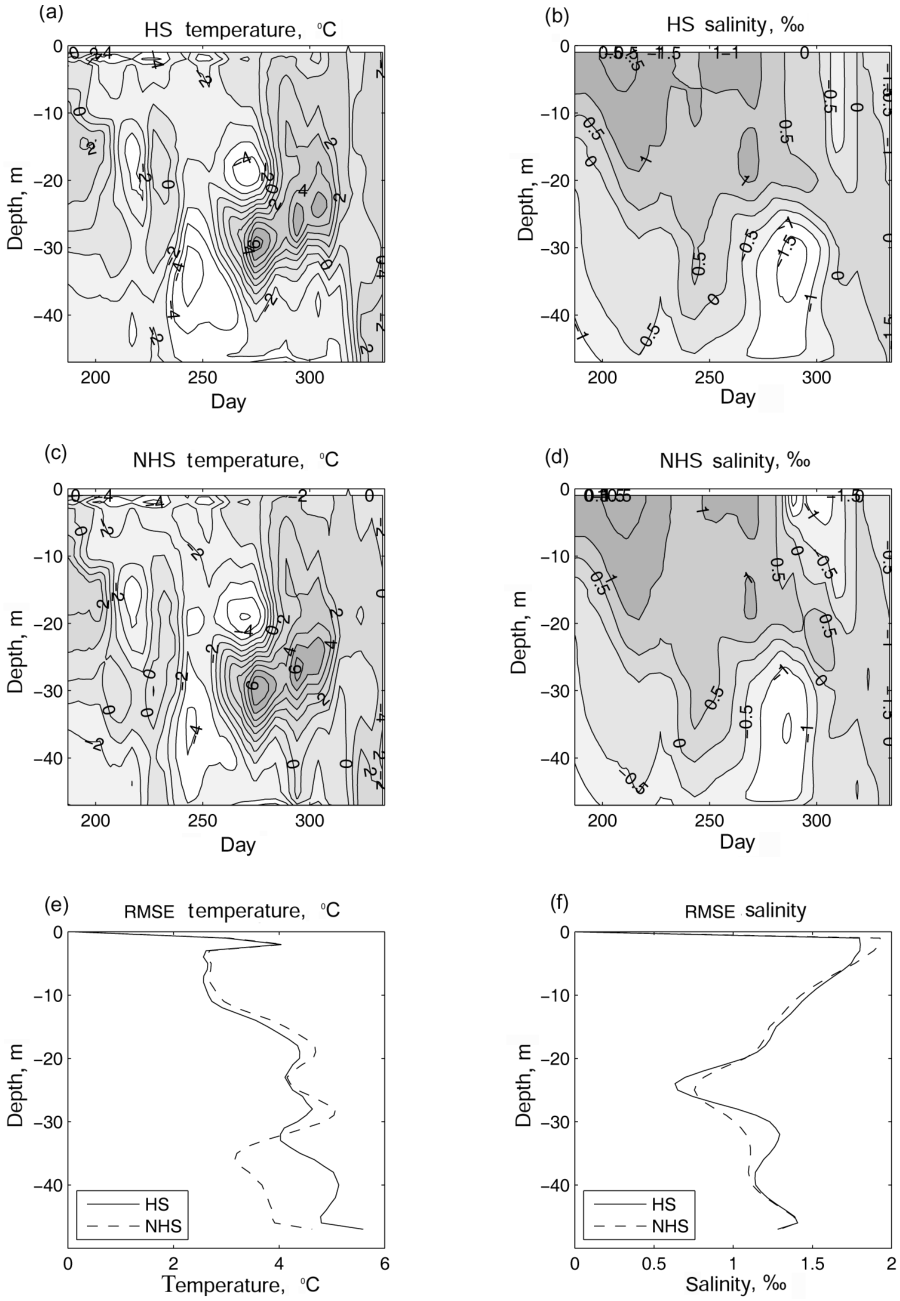

Fig. 5. Difference between the measurement data and model results at the Huovari monitoring station: HS temperature (a) and salinity (b), NHS temperature (c) and salinity (d), RMSE for temperature (e) and salinity (f). The measurement data were made available by the Eutrophication-Maps project [21].

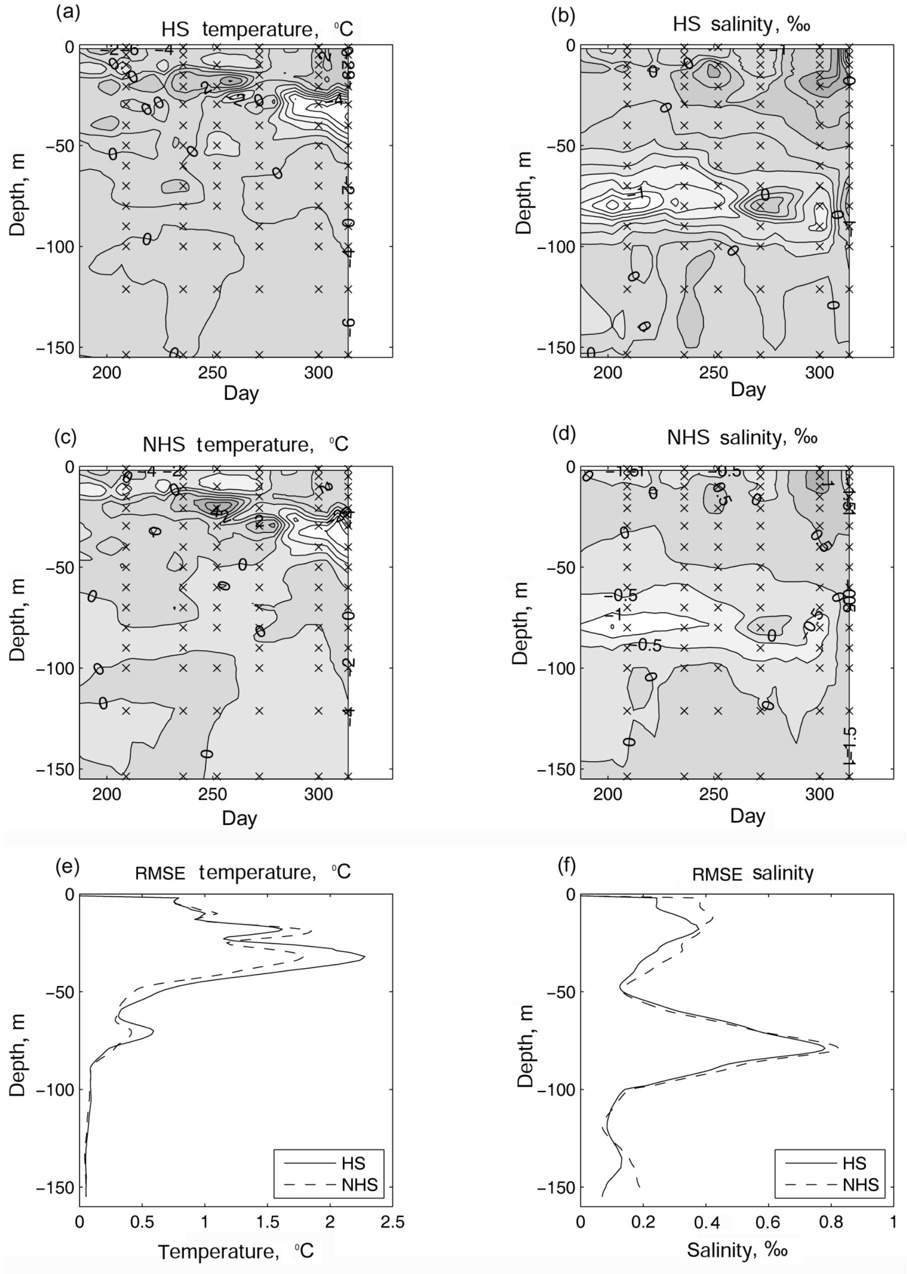

Fig. 6. Difference between the measurement data and model results at the monitoring station BY29: HS temperature (a) and salinity (b), NHS temperature (c) and salinity (d), RMSE for temperature (e) and salinity (f). The measurement data were made available by the Eutrophication-Maps project [21].

Table 1 gives an overview of the RMSE values for all the stations where a comparison of modelled and measured results was performed. The RMSE profiles were calculated for temperature (T) and salinity (S) at each station. The profiles were then divided into three depth intervals: the upper layer, the intermediate layer and the near-bottom layer. For temperature, the upper layer was defined as the depth range from the surface to the upper boundary of the seasonal termocline. The intermediate layer consisted of the thermocline only and the near bottom layer was defined as the layer below the seasonal thermocline. For salinity, in the stations where a permanent halocline existed, the layers were defined as the layer above the halocline, the halocline layer and the layer below the halocline, respectively. In the shallow stations, i.e. the stations in the Gulf of Finland, the layers were defined according to the vertical temperature distribution. The range of RMSE values was estimated visually for each depth interval. Thus the range is given when the RMSE values vary in the respective layer. Both models reproduced temperature and salinity with a similar accuracy. Moreover, modelling of the vertical and temporal distributions of temperature and salinity in the Baltic Proper gave results with higher accuracies than in the Gulf of Finland. This could be a result of the greater depths at the monitoring station in the Baltic Proper and by higher stability of deeper layers. The upper layer in the Gulf of Finland is better reproduced than the intermediate and near-bottom layers. In the Baltic Proper, the opposite situation occurs. The modelled upper layer was less accurate than the intermediate and near-bottom layers. This could be explained by the fact that the Gulf of Finland is shallower than the Baltic Proper. Alternately, stronger mixing in the water column in the gulf could explain the model inaccuracies.

Table 1. The RMSE values for monitoring stations in the Gulf of Finland and the Baltic Proper

Station	NHS			HS		
	Upper	Intermediate	Near bottom	Upper	Intermediate	Near bottom
Huovari, T	2.5	3–5	3–4	2.5	3–5	4–5
Huovari, S	1.6–1.8	0.7–1.1	1.1–1.4	1.6–1.8	0.6–1.3	1.1–1.4
Länsi-Tonttu, T	4.8–6.4	5.3–5.9	5.3–6.4	4.8–6.4	5.7–6.1	5.3–6.3
Länsi-Tonttu, S	1.3	0.6–1.3	0.6–0.9	1.4	0.6–1.4	0.6–0.9
Längden, T	3.5	3–4	1.2–3.5	3.5	3.5–5	0.5–3.5
Längden, S	0.8	0.4–0.8	0.6–1	0.8	0.5–0.8	0.6–1
BY7, T	2–4	1–5	1–2.5	2–4	1.2–6	1.2–3.1
BY7, S	0.25	0.3	0.3–2.1	0.25	0.3	0.3–1.5
BY15, T	1–5	0.3–1	0.2	1–5	0.3–1	0.2
BY15, S	0.15–0.25	0.1–0.4	0.02–0.2	0.15–0.25	0.1–0.45	0.02–0.2
BY29, T	0.7–1.5	0.5–1.7	0.2	0.7–1.5	0.5–2.3	0.2
BY29, S	0.1–0.25	0.1–0.8	0.2	0.35	0.1–0.8	0.1

5. CONCLUSIONS

Results of the hydrostatic and non-hydrostatic models showed quite good agreement with the measured sea level at Helsinki mareograph. However, both models give slightly overestimated values for extreme water levels.

Quantitative and qualitative analyses of temperature and salinity stratification at monitoring stations show that the differences between hydrostatic and non-hydrostatic models are insignificant. In several cases the NHS model showed a slightly better performance.

In general, the models underestimate water temperature in the first half of the modelled period and overestimate it in the second half. The reason for this disparity is that the warming of the water column in both models started about one month later than in the measurements. Overly strong mixing in the models has also influenced the accuracy of the results. Modelled salinity was generally overestimated in the upper layer and underestimated in deeper layers. This could also be caused by overly strong water mixing in the shallow Gulf of Finland.

Modelling of the vertical and temporal distribution of temperature and salinity in the Baltic Proper gave results with a higher accuracy than in the Gulf of Finland. This could be caused by the greater depths at the monitoring station in the Baltic Proper and the higher stability of deeper layers. However, there were temporal shifts as well. Besides this, measured thermocline and halocline were deeper compared to the results of both models.

Modelled results from all monitoring stations supported the assumption that the water column is more intensively mixed in the non-hydrostatic version than in the hydrostatic version due to the prognostic equation for the vertical velocity component.

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Läänemerele rakendatud hüdrodünaamika mudeli MIKE 3 hüdrostaatilise ja mittehüdrostaatilise versiooni sobivuse kontroll

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Hüdrodünaamika mudeli MIKE 3 hüdrostaatilist ja mittehüdrostaatilist versiooni on kasutatud Läänemere hüdrofüüsikaliste väljade modelleerimiseks perioodil 1. aprillist kuni 1. novembrini 1996. Perioodil 1. juunist kuni 1. novembrini 1996 mõõdetud Helsingi meretaseme ja Soome lahe ning Läänemere avaosa monitooringujaamade temperatuuri ja soolsuse väärtusi on võrreldud modelleerimistulemustega. Meretaseme kokkulangevus on rahuldav mudeli mõlema versiooni puhul. Samuti on temperatuuri ja soolsuse stratifikatsiooni erinevused kahe mudeli versiooni tulemuste vahel ebaolulised. Läänemere avaosas on kokkulangevus parem kui Soome lahes.