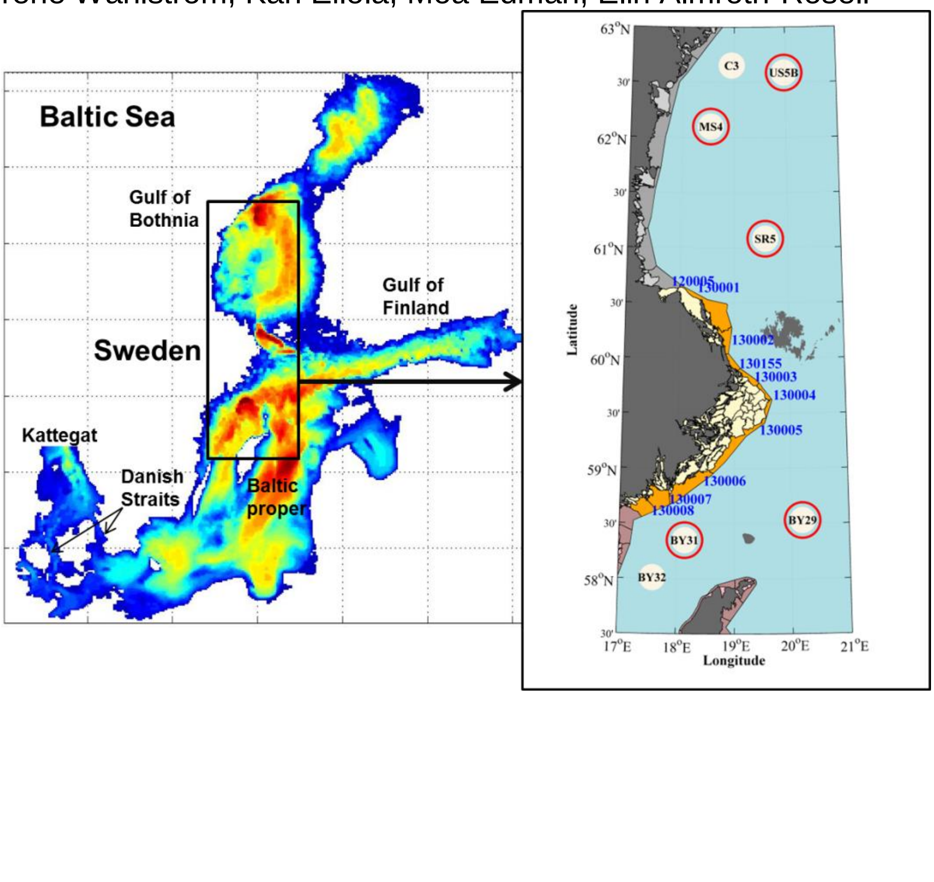
SMHI

REPORT OCEANOGRAPHY No 55

Evaluation of open sea boundary conditions for the coastal zone. A model study in the northern part of the Baltic Proper.

Iréne Wåhlström, Kari Eilola, Moa Edman, Elin Almroth-Rosell



Front: The RCO model domain of the Baltic Sea (left). The figure to the right shows the study area in the northern part of the Baltic proper, including the ten outer basins (indicated by orange area and blue numbers) of the Swedish Coastal zone Model in the Stockholm Archipelago. The monitoring stations are also shown (white circles) where the red circles indicate stations used in the assimilation of the currently used forcing files.

ISSN: 0283-1112

REPORT OCEANOGRAPHY No. 55

Evaluation of open sea boundary conditions for the coastal zone. A model study in the northern part of the Baltic Proper.

Iréne Wåhlström, Kari Eilola, Moa Edman, Elin Almroth-Rosell

Swedish Meteorological and Hydrological Institute, Göteborg, Sweden

Summary

The environmental conditions in the coastal zone are strongly connected with the conditions in the open sea as the transports across the boundaries are extensive. Therefore, it is of critical importance that coastal zone models have lateral boundary forcing of high quality and required parameters with good coverage in space and time.

The Swedish Coastal zone Model (SCM) is developed at SMHI to calculate water quality in the coastal zone. This model is currently forced by the outcome from a one-dimensional model, assimilated to observations along the coast. However, these observations are scarce both in space, time and do usually not include all required parameters. In addition, the variability closer to the coast may be underestimated by the open sea monitoring stations used for the data assimilation. These problems are partly overcome by utilize the one-dimensional model that resolves all the variables used in the SCM. However, the method is not applicable for examine either the past period or future scenario where the latter analyze how climate change might affect the coastal zone. In the present study, we therefore evaluate the possibility to use results from a three-dimensional coupled physical and biogeochemical model of the Baltic Sea as open sea boundary conditions for the coastal zone, primarily to investigate the two periods mentioned above.

Seven sensitivity experiments have been carried out in a pilot area of the coastal zone, the northern part of the Baltic proper, including the Stockholm Archipelago. The sensitivity tests were performed in order to explore methods to extract the outcome from the three-dimensional model, RCO-SCOBI, and apply as lateral boundary forcing for the SCM. RCO-SCOBI is a model for the open Baltic Sea with high horizontal and vertical resolution of the required variables. The results from the different tests were examined and evaluated against observations in the coastal zone. This was executed for both the physical and the biogeochemical variables utilizing a statistical method.

The results from this study concluded that the outcome from the RCO-SCOBI is applicable as forcing files for the SCM. The best results in the tests was obtained with a method extracting depth profiles for the required variables from the RCO-SCOBI at a position 10 nautical miles to the east and 10 nautical miles to the south in the Baltic proper or north in the Gulf of Bothnia outside each of the outer basins.

Sammanfattning

Miljötillståndet i Sveriges kustvatten är starkt kopplat till tillståndet i det öppna havet på grund av det stora vattenutbytet mellan dessa. Det är därför viktigt att modeller utvecklade för kustzonens vatten har drivning från utsjön av god kvalitet med bra täckning i tid och rum samt med information om de variabler som krävs.

För att beräkna vattenkvalitén i kustnära vatten har SMHI utvecklat en modell kallad kustzonsmodellen (SCM). Den drivs för närvarande från öppna havet av resultatfiler från en en-dimensionell modell som med hjälp av observationer har korrigerat och förbättrat modellresultaten. Tyvärr är dessa observationer undermåliga i tid och rum, och saknar nödvändiga variabler för att få bra drivning av SCM modellen. Dessa mätstationer ligger också längre ut i öppna havet och kan därför underskatta variabiliteten närmare kusten för de olika parametrarna. Dessa problem löses delvis med den en-dimensionella modellen som beräknar alla de variabler som är nödvändiga i SCM. Dock är dessa resultat inte användbara om man vill undersöka en historisk period eller framtida klimatförändringar i kustzonen. På grund av dessa tillkortakommanden undersöker vi i denna studie om det är möjligt att istället ersätta dagens drivning från öppna havet med resultat från en tre-dimensionell, kopplad fysisk och biogeokemisk modell för Östersjön som drivning för SCM, framförallt för att undersöka de två ovan nämnda perioder.

I denna studie har sju känslighetsexperiment utförts i en pilotstudie för Norra Östersjön, inklusive Stockholms skärgård. De sju känslighetsexperimenten utfördes för att utvärdera olika metoder att extrahera resultat-filer från den tre-dimensionella modellen RCO-SCOBI med avsikt att användas som drivning för SCM. RCO-SCOBI är en modell för Östersjön med hög horisontell och vertikal upplösning av de variabler som krävs. Resultaten för både de fysiska och biogeokemiska processerna från de olika testen undersöktes och utvärderades mot observationer i kustzonen med hjälp av en statistisk metod.

Slutsaten från dessa test är att resultatfiler från RCO-SCOBI är tillämpbara som utsjödrivning för SCM. Den bästa metoden är att extrahera en djupprofil per variabel för varje ytterbassäng i SCM i en punkt 10 nautiska mil österut och 10 nautiska mil söderut i egentliga Östersjön eller norrut i Bottenhavet för varje ytterbassäng i SCM.

Table of contents

1 Introduction

The Baltic Sea (front figure) is a semi-enclosed sea that can be divided into several sub-basins, which are linked by straits, sills and channels (Feistel et al., 2008; Leppäranta and Myrberg, 2009). This sea is considered to be an estuary, receiving large amounts of fresh water from river discharges along the coastal zones, containing different constituents, including e.g. nutrients. The freshwater mixes with the Baltic Sea water and form the brackish surface water that flow out of the Baltic Sea to the Kattegat through the Danish sounds. The inflows of more saline oceanic waters from the North Sea and Skagerrak, renewing the deepest parts of the Baltic Sea, occur as rare events since they are hampered by the narrow sea entrance to the Baltic Sea (Eilola et al., 2014; Matthäus et al., 2008). The estuarine circulation establishes two water masses with a strong, permanent halocline around 60 m depth, which limits the exchange between the surface water and the deeper water. In addition, a thermocline is formed at about 20 m depth during summertime when the surface water is heated. Furthermore, most of the freshwater to the Baltic Sea enters to the gulfs of Bothnia and Finland, creating a horizontal north-south gradient with lowest salinity at north and in the Gulf of Finland, increasing towards Kattegat.

The Stockholm Archipelago is the largest archipelago in Sweden and the second largest in the Baltic Sea. The archipelago can be divided into basins of different size and depth, separated by the landscape created by rocky islands. Water exchanges between the basins occur through straits where the outflows of low saline water mainly occur in the surface layer and inflows of more saline water mainly occur at larger depth (Engqvist and Andrejev, 2003). Freshwater, containing e.g. nitrogen and phosphorus, enters the archipelago in the innermost part with the Norrström River to the Strömmen basin. There is also large nutrient load from waste water treatments and industries (Lücke, 2015) as the capital of Sweden, Stockholm, is situated here. However, Almroth-Rosell et al. (2016) concluded that about 70 % of the nutrients from land are retained in the coastal zone of the Stockholm archipelago on their way to the open sea, primarily due to denitrification and burial in the sediment. Thus, the coastal zone works as a filter for nitrogen and phosphorous from land (Almroth-Rosell et al., 2016; Karlsson et al., 2010) resulting in that part of the nutrients never reaches the open Baltic Sea. Consequently, the coastal region moderates the eutrophication in the Baltic Sea.

The Swedish Coastal zone Model (SCM) (Almroth-Rosell et al., 2016; Sahlberg et al., 2008) has been developed to simulate the coastal environmental state in the entire Swedish coastal zone. This is a multi-basin one-dimensional set-up coupled to the biogeochemical model, the Swedish Coastal and Ocean Biogeochemical model (SCOBI) (Eilola et al., 2009; Marmefelt et al., 1999). In this study, the aim was to find a method to substitute the currently used SCM open sea forcing files with the outcome from the three-dimensional Rossby Centre Ocean model (RCO), a regional coupled ice-ocean model (Meier, 2007; Meier et al., 2003), which is also coupled to the SCOBI model. The focus in this study is on the coastal zone at the Stockholm Archipelago (front figure) and the primary aim is to utilize the output from the RCO-SCOBI for past and future investigations of the coastal zone. We therefore performed a series of sensitivity tests and investigated the effect from these tests on the physical as well as the biogeochemical variables in this coastal area.

2 Method

2.1 Model

2.1.1 The Swedish Coastal zone Model

The Swedish Coastal zone Model (SCM) used in this study is described in detail by Almroth-Rosell et al. (2016) and parts of the description are repeated below. SCM is a one-dimensional multi-basin model based on the physical model PROBE (Program for Boundary Layers in the Environment) (Svensson, 1998) and is coupled to the biogeochemical model, the Swedish Coastal and Ocean Biogeochemical model (SCOBI) (Eilola et al., 2009; Marmefelt et al., 1999). The model system was developed at SMHI for calculations of water quality in the Swedish coastal zone (Sahlberg et al., 2008) and is divided into five different regions according to the Swedish water districts. One of these regions is the objective of this study, the northern Baltic Proper, including the Stockholm Archipelago. This archipelago consists of 167 sub-basins of diverse size and depth, connected by straits and surrounded by rocky islands. The model separately calculates the status of each of these sub-basins, which are interconnected by the water exchange that is controlled by barotropic and baroclinic pressure gradients through the cross sections in the sounds connecting the basins.

The SCM model is forced by the atmospheric data (weather, atmospheric deposition of nutrients), land data (point sources, discharge from rivers and drainage area and their properties) and data at the outer boundary, which is the open Baltic Sea. The open boundary currently consists of four forcing files with vertical profiles for each of the physical and biogeochemical status variables. Depending on the location of the monitoring station the information from the four files is separately weighted as forcing for each one of the ten outer basins (front figure). These depth profiles were calculated with daily values by a one-dimensional PROBE set up and assimilated against observations from 1990 forward with a maximum depth of the observation stations and then extrapolated to the total depth of the model. The applied monitoring stations for the data assimilation are: MS4, US5B, SR5, BY29 and BY31. Three out of four forcing files are an assembly of assimilation from different monitoring stations as the observations are not only scarce in time but also in space and depth. Both the combination of observation stations and the weighting into the outer basins is utilized to obtain the best representation of the open sea influence on the SCM model domain. The water exchange between the open sea and the outer basins is assumed to be geostrophically balanced as the boundary is open with a width greater than the internal Rossby radius. For further details about the setup and evaluation of the model the reader is referred to Almroth-Rosell et al. (2016); Eilola et al. (2015); Sahlberg et al. (2008).

2.1.2 The Rossby Centre Ocean model and the Swedish Coastal and Ocean Biogeochemical model

The Rossby Centre Ocean model and the Swedish Coastal and Ocean Biogeochemical model (RCO-SCOBI) is a three-dimensional model for the open Baltic Sea with high horizontal and vertically resolution of the variables. It is therefore assumed that RCO-SCOBI will have good effect on the SCM's outer basins calculations. Furthermore, the aim is to use this method to extract and apply results from the RCO-SCOBI model as open boundary conditions for the SCM along the entire Swedish coastline. The RCO-SCOBI has been used for both historical reconstructions starting from year 1850 (Meier et al., 2012a; Meier et al., 2016) and scenarios for the future (Meier et al., 2012a; Meier et al., 2012b), until year 2100. Thus, these simulations are available to be used as forcing for the SCM to achieve historical and future scenarios for the entire Swedish coast.

The Rossby Centre Ocean model (RCO) is a three-dimensional regional coupled ice-ocean model mainly focusing on the open Baltic Sea (Kauker and Meier, 2003; Meier et al., 2003). RCO is used with a horizontal resolution of 2 nm and a maximum depth of 249 m divided into 83 vertical levels with thicknesses of 3 m. For further details of the RCO model the reader is referred to Meier (2001); (2007), Meier et al. (2003) and Vali et al. (2013). The RCO model is coupled to the Swedish Coastal and Ocean Biogeochemical model (SCOBI) (Almroth-Rosell et al., 2011; Eilola et al., 2009). The model system has been used in several applications for the Baltic Sea (e.g. Eilola et al., 2012; Meier et al., 2012b) and has shown good performance in comparison to other Baltic Sea models and to observations (Eilola et al., 2011). The SCOBI model calculates the biogeochemistry in the Baltic Sea with nine pelagic and two benthic variables. The pelagic variables are: nitrate (NO_3), ammonium (NH_4) and phosphate (PO_4); three phytoplankton (diatoms, flagellates and other, cyanobacteria); one bulk zooplankton; detritus and oxygen (O_2). The benthic part consists of pools of nitrogen (N) and phosphorus (P). Phytoplankton assimilates carbon, N and P according to the Redfield molar ratio (carbon:N:P=106:16:1) and the biomass is represented by chlorophyll (Chl) according to a constant carbon to chlorophyll mass ratio (carbon:Chl=50:1). The described processes in the model are: phytoplankton assimilation, nitrogen fixation and mortality; the O_2-dependent mineralization of detritus as well as benthic N and P; nitrification and denitrification; grazing of zooplankton and excretion of detritus and dissolved inorganic nitrogen and phosphorus (DIN and DIP).

The three primary producers are driven by the solar radiation and assimilate the inorganic nutrients but differ in growth and sinking rates. One phytoplankton group has the characteristic of cyanobacteria and therefore, the potential to fixate nitrogen, i.e. to utilize molecular nitrogen (N_2) as a nitrogen source. Consequently, this phytoplankton may continue to grow if PO_4 is available. The phytoplankton sink, die and are grazed by zooplankton. The detritus pool consists of dead organic matter, which is partly mineralized back to inorganic nutrients already in the water column. The sediment receives sinking particles from the water column, which may be remineralized to inorganic forms and released back to the water mass. Parts of the pools of N and P in the sediment are buried and therefore the sediment acts as a permanent sink.

2.2 Sensitivity experiments

The objective of the sensitivity experiments is to evaluate the outcome from the SCM forced from the open boundary by the RCO-SCOBI model. This evaluation is executed relative to the currently used lateral boundary in the reference run (RefRun) previously evaluated by Almroth-Rosell et al. (2016). Seven different sensitivity tests (called TestRuns) were performed with the same temporal (daily values) and vertical resolution (increasing from 0.5 m at the surface to 10 m at the depth) as in the RefRun. The approach was to extract depth profiles for all variables at one or more horizontal grid cells at varying locations outside the SCM outer basins. The profiles were extracted for the period 1990-2008 from the outcome of the historical (1850-2008) reference simulation for the RCO-SCOBI (Meier et al., 2016). The positions of the monitoring stations used in the RefRun of the SCM are shown in Table A1 (See Appendix). Three of the sensitivity experiments, TestRun 3-5 (Table A1), were performed with four forcing files and weighted in the same way as in the RefRun of the SCM. The forcing files of TestRun 3 are extracted at the same locations as the four observation stations (US5B, SR5, BY29, BY37) used for the assimilation in the RefRun, while in TestRun 4 and 5 the profiles from different locations were extracted (See Table A1 for locations). Four of the experiments were executed with ten forcing files, one for each outer basin (TestRun 6-9). For these experiments, the locations from where we extracted RCO-SCOBI profiles are expressed relative to a point on the outer model domain boundary. The outer boundary is constructed from a series of connected nodes with known coordinates. The two outermost nodes (starting and ending points) of each outer basin were averaged and then utilized as a point from where to initiate the calculation of the extracting location of the TestRuns. Profiles for TestRun 6 where extracted 4 nautical miles (nm) to the east and 4 nm to the south in the Baltic proper or north in the Gulf of Bothnia outside the averaged point for each of the outer basins (from now on called +/-2 grid cells) (Fig. 1).

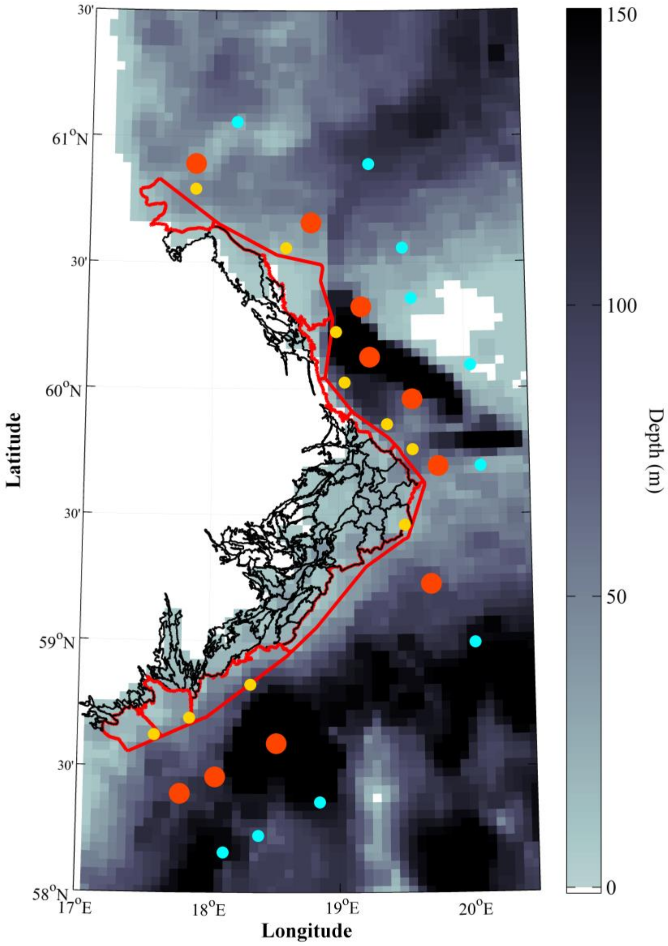


Figure 1. Map of the northern Baltic proper, including the Stockholm Archipelago with different basins in the archipelago (black lines) and the boarder of the outer basins (red line). The positions for the ten extracted RCO-SCOBI forcing files are shown for TestRun 6 (yellow dots), 7 (red dots) and 8 (turquoise dots).

TestRun 7 and 8 used a similar approach as TestRun 6, but the profiles were extracted further out from the boundary, at 5 grid cells (10 nm, called +/-5 grid cells) and 10 grid cells (20 nm, called +/-10 grid cells) east and north/south outside the average nodal point, respectively (Fig. 1). In TestRun 9 the average of nine grid cells around the grid cell selected for TestRun 7 was calculated to examine if a calculation of the average in a larger area could improve the SCM modelling results even further compared to extracting the depth profiles from a single grid cell.

2.3 Evaluation

A systematic analysis was carried out in the coastal zone by comparing the different SCM runs with observations, following the procedure presented by Almroth-Rosell et al. (2016). The results are analysed separately for all the test simulations and the results from the RefRun are evaluated against the different RCO-SCOBI forced SCM runs. Note that due to the limitations in the RCO-SCOBI data set, the time period of the present investigation (1990-2008) is shorter than the time period (1990-2012) studied by Almroth-Rosell et al. (2016).

To quantify how well the model results adapt to observations two statistical parameters are applied, the correlation coefficient (r) and the cost function (C). The sub-basins with good observation data coverage are separately evaluated. The r and C were calculated with regard to the long term average of the vertical distribution of winter (Nov-Feb) and summer (May-Aug) values for salinity, DIN, DIP and O_2. In addition, calculations for the long term average seasonal variation for surface DIN, DIP as well as bottom water O_2 concentration were performed. In order to get a general view of the models performance against observations, a combination of the above r and C are evaluated. For the vertical profiles, the r is a measure how well the average depth-profiles from the observations and model correlate during winter and summer periods. C is a mean bias of the model results relative to observations normalized to the standard deviation of the data. Similarly, the annual cycle is evaluated. For the average seasonal cycle, the r is a measure how well the observations and model correlate during the year and C is the normalized mean bias of the model and data. The limitation values for the two parameters are set to *good*, *acceptable* and *poor*. If C results in a value less than 1, the average model results lies within one standard deviation of observations and the results are considered *good*. If the results are within two standard deviations the results are *acceptable* and larger than 3 it is regarded as *poor*. For r, the limitation values are set to *good* and *acceptable* if the value are higher than two third (0.66) and one third (0.33), respectively. Lesser then 0.33 it is set to *poor*. The value 1-r is used in the discussions, thus, smaller values of C and r indicate less deviation from observed values. For further detailed information about the evaluation, the reader is referred to Almroth-Rosell et al. (2016) and the references therein.

In order to evaluate the overall changes between the different TestRuns and the RefRun the average change of r and C for each variable and all stations was calculated. We also calculated the standard deviation of the changes of all stations to get a measure of how large the variability of model performance between different locations is. A negative change indicates an improvement relative to the reference case. A small standard deviation indicates that the changes are similar at many stations while a large value of the standard deviation compared to the mean value indicates that the change may differ significantly in quality between some stations. For all variables the change between the test value and the reference value are calculated as:

$$\delta V = V_i(x) - V_0(x)$$

Where V_0 and Vi are either the r or the C value at basins x for RefRun and TestRun, respectively. Then, the average (DV) and standard deviation (STDV) where calculated for the δV of all the basins for each TestRun.

3 Results and discussion

In Table 1, the calculations of the total average change in all the basins of r and C between RefRun and the different TestRuns in the period 1990-2008 are shown. The r has been adjusted to 1-r indicating that r values close to zero are *good* model skill, similarly to C. The 1-r for salinity has improved in all the TestRuns (Table 1). However, the cost function differs between the tests. TestRuns 5, 7, 8 and 9 have improved both 1-r and C where TestRuns 7 and 9 gives the best results. The results of one grid point (TestRun 7) compared to the average of 9 grid points at the same position (TestRun 9) give quite similar results, though; TestRun 9 has a slightly higher standard deviation of the cost function. For TestRuns 3, 4 and 6 the cost function are larger than for the RefRun but the results in each basin are still within the C-range of *acceptable* (not shown). These results indicate that four of the new lateral boundary forcing files improves the physics of the SCM compared to the RefRun.

The biogeochemistry variables indicate a variation in 1-r and C results for the parameters DIN, DIP and O_2 (Table 1). For DIN, the results in 1-r have improved for all the tests while the C results have worsened indicating a larger mean bias compared to the RefRun. These results imply that the observed and model DIN has the similar shape but not equivalent concentrations. For DIP, both the 1-r and C results are worsened but an examination of each basin explicitly shows slightly higher 1-r values, but still in the r-range *good* (not shown). The C-value for DIP in almost all basins has deteriorated, which means a larger mean bias compared to the RefRun. The results for the O_2 concentration show that the tests with four forcing files weighted in different ways (TestRun 3-5) display better results for both r and C than the RefRun and the tests with 10 forcing files. However, all the basins C-values in the TestRuns 6-9 are in the range of *good* or *acceptable* except one value that is *poor*, as was the case already in the RefRun (not shown).

Table 1. The results from the calculations of the total average change in r (adjusted to 1-r) and C as well as its standard deviation for each TestRun (3-9) compared to RefRun for parameter (salinity, DIN, DIP and O_2). In TestRun 3-5 the SCM is driven by four open sea forcing files while in 6-9 one forcing file outside each outer basin are applied with the exception for TestRun 9, which is an average of nine grid cells around TestRun 7 grid cell. TestRun better than RefRun is negative values (green colour), TestRun worse than RefRun is positive values (red colour).

1-r

SALINITY	3	4	5	6	7	8	9
DV	-0.008	-0.004	-0.009	-0.007	-0.006	-0.005	-0.006
STDV	0.016	0.011	0.016	0.021	0.019	0.019	0.019

DIN							
DV	-0.036	-0.035	-0.032	-0.019	-0.022	-0.024	-0.022
STDV	0.073	0.071	0.072	0.071	0.077	0.078	0.078

DIP							
DV	0.015	0.016	0.014	0.028	0.029	0.028	0.030
STDV	0.059	0.063	0.064	0.053	0.050	0.048	0.050

O_2							
DV	-0.043	-0.045	-0.038	0.059	0.056	0.054	0.056
STDV	0.106	0.108	0.089	0.145	0.159	0.165	0.158

C

SALINITY	3	4	5	6	7	8	9
DV	0.026	0.062	-0.0004	0.245	-0.064	-0.057	-0.064
STDV	0.437	0.287	0.404	0.427	0.291	0.258	0.294

DIN							
DV	0.099	0.079	0.104	0.162	0.157	0.158	0.157
STDV	0.252	0.222	0.256	0.296	0.303	0.306	0.303

DIP							
DV	0.584	0.607	0.624	0.383	0.524	0.587	0.524
STDV	0.699	0.719	0.749	0.518	0.635	0.705	0.635

O_2							
DV	-0.020	-0.023	-0.021	0.135	0.131	0.128	0.131
STDV	0.045	0.053	0.051	0.212	0.208	0.202	0.207

The less good results for the cost functions (C) of DIN, DIP and O_2 in the SCM model test runs originate from the biases in the forcing coming from the RCO-SCOBI model results in the Baltic Sea. This shortcoming is demonstrated in Fig 2, where the forcing files for salinity, DIN, DIP and O_2 for the RefRun, TestRuns 3 and 7 are shown. The coastal profile is in the figure extrapolated with a constant value below 100 m depth because the maximum depth differs between the coastal grid point and the open sea station. It should be noted that due to the vertical distribution of volume in the boundary basins, very little of the properties below 60 m in the profiles in Fig. 2 are actually received by the coastal zone model. All boundary basins, except for one, have 80 % of their volume above 50 m depth where several of them have 80 % of their volume above 20 m depth.

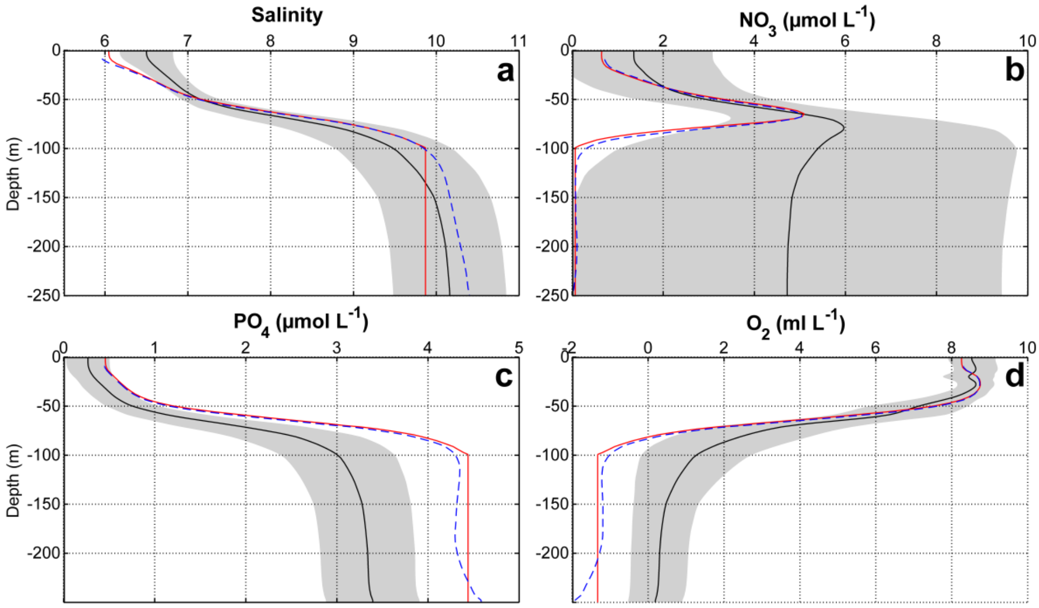


Figure 2. The average depth profiles of the forcing files for salinity (a), NO_3 (b), PO_4 (c) and O_2 (d) for the period 1990-2008. The original forcing file at BY31 (black line) and the standard deviation (grey area). The new forcing files at the same location as the original location but from RCO-SCOBI (TestRun 3; blue, dotted line) and the new forcing file for the same outer basin in TestRun 7 (red).

The average profiles (above 100 m) from a grid point closer to the boundary (TestRun 7) are very similar to the average profiles of a grid point at the open sea station. The biases of the open sea model results are therefore also affecting the coastal regions. There is a stronger stratification in the RCO-SCOBI model with lower salinity at the surface than in the forcing files of the RefRun. The NO_3 in the forcing files of the TestRuns shows lower concentration at the surface and decreases after the peak around 60 m down to zero at 100 m depth. This is in contrary to the RefRun where the concentration is more or less constant with depth. The PO_4 concentration for the TestRuns has elevated concentration through the whole water column with increasing concentration after around 75 m. The concentration of O_2 is lower in the TestRuns except for slightly higher in the depth range of about 20-50 m. There are methods that can be used to deal with biases in the forcing files and the RCO-SCOBI model might be recalibrated to obtain improved results along the coasts but these issues are out of the scope of the present study. The RCO-SCOBI model used for the present analysis has been run with a reconstructed forcing from 1850-2008 and there may be several possible reasons for the biases found at this monitoring station, ranging from large scale processes acting on the internal sources and sinks in the Baltic Sea to regional descriptions of coastal currents and local river runoff and nutrient supplies. An investigation of the causes is also left for future studies.

Altogether, the results are not straightforward and are not pointing directly towards one method that is “best in test”. However, taken all the results into account and emphasis primarily to the physical improvements in the SCM model, the method from TestRun 7 was selected to produce new forcing files for the SCM, primary for examine the past period and future scenario.

The combined results of the RefRun and TestRun 7 from the evaluation of the correlation coefficient and the cost function are shown for eight of the basins in the Stockholm Archipelago (Fig. 3). These results indicate that the model simulates the average vertical winter and summer profiles in *good* or *acceptable* range except in Sandöfjorden where 1-r for O_2 during summer in both RefRun and TestRun 7 are *poor*. In addition, C for DIP in the TestRun 7 in Trälhavet is *poor* for the summer period. The average seasonal variations are *good* or *acceptable* except in two areas, the Kanholmsfjärden and Strömmen. In Kanholmsfjärden, the 1-r for O_2 is *poor* for the TestRun 7 and in Strömmen, the 1-r DIN for both RefRun and TestRun 7 are *poor*.

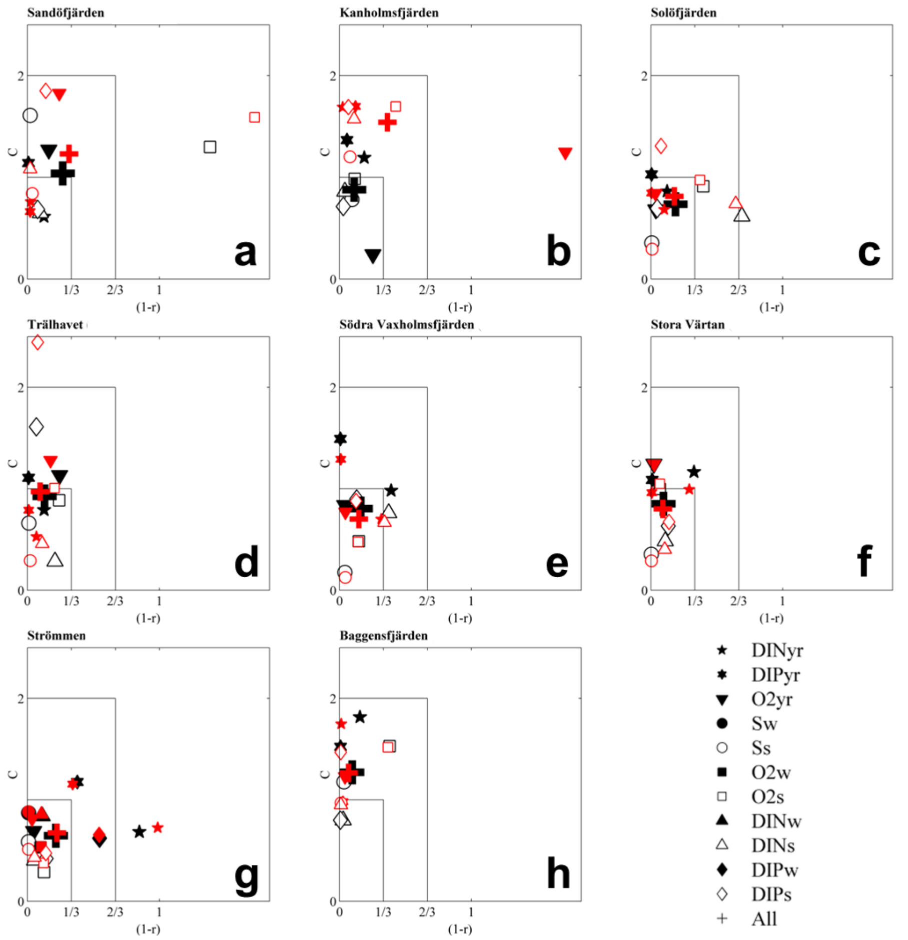


Figure 3. Validation of the outcome from the SCM model with the RefRun (black) and TestRun 7 (red) at eight validation sites (a-h) with the average correlation coefficient (adjusted to 1-r) and the cost function (C). The parameters declaration at the low right refer to horizontal yearly average (yr), average summer profiles (s), average winter profiles (w) and the combined performance for DIN, DIP, salinity (S) and O_2 (All). The variables within the inner square and between the two squares are considered good and acceptable, respectively.

The results from calculating the combined model skill as the average of the individual r and C values (black and red crosses in Fig. 3) reveal five basins with *good* and three with *acceptable* skills for the TestRun 7. The RefRun results in six basins with *good* skills and two *with acceptable* skills. The deviation is the Kanholmsfjärden where the TestRun 7 skill is *acceptable*. The differences between the combined model skills in each basin for the RefRun are calculated (Table 2) where five out of eight basins improved their model skill and three perform worse.

Table 2. The percental change of the TestRun 7 compared to RefRun of the combined model skills (bold crosses) for the basins in Fig. 3. Negative and positive values give better and poorer results, respectively, with new driving files.

Basin name	**Change (%)**	
	1-r	**C**
Sandöfjärden	**18**	**18**
Kanholmsfjärden	**227**	**75**
Solöfjärden	**– 5**	**9**
Trälhavet	**– 26**	**4**
Södra Vaxholmsfjärden	**– 9**	**– 13**
Stora Värtan	**– 4**	**– 6**
Strömmen	**3**	**5**
Baggensfjärden	**– 28**	**0**

In addition to described results, an improvement in the primary productivity in some of the basins occurs with the RCO-SCOBI forcing. In Fig 4, the concentration of phytoplankton for the chosen TestRun 7 is shown for the same basins as in Fig. 3. For these basins, four out of eight shows that the primary productivity has improved, including an increased phytoplankton bloom in the autumn, which is an improvement compared to the RefRun. The autumn bloom, that is usually seen from the observations of chlorophyll-a, was almost absent in some of the basins in the RefRun.

The above robust results, together with the improvement of the primary productivity, strengthen the conclusion that it is feasible to use results from the RCO-SCOBI as forcing for the SCM. The additionally sensitivity experiment with averaging around one grid point (TestRun 9) showed that it is enough to select vertical profiles from one grid point as a representative forcing for the different coastal basins. The tests indicated that results improved if the grid point was chosen not too close or too far from the open boundary of the SCM.

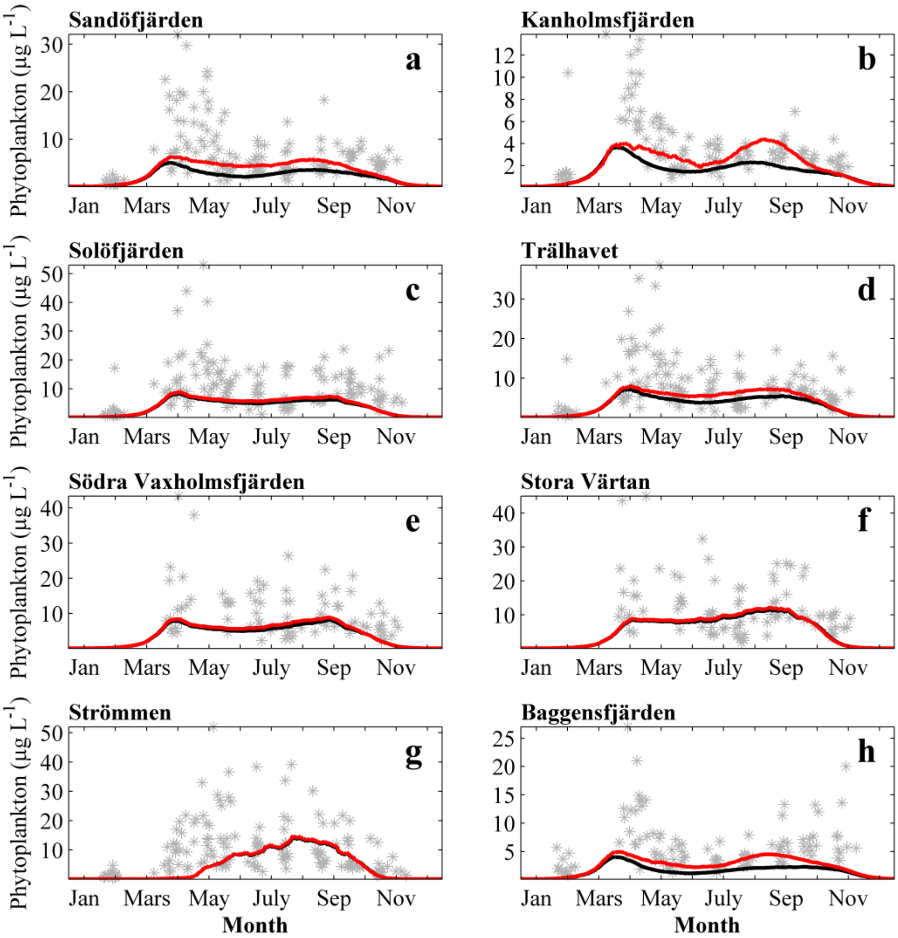


Figure 4. The average surface concentration of phytoplankton (µg Chl a L^{-1}) with the RefRun (black line), TestRun 7 (red line) and observations (grey stars) at the same eight validation sites (a-h) as in Fig. 3.

4 Conclusions

The results indicate that the outcome from a high resolution, three-dimensional coupled physical-biogeochemical model like the RCO-SCOBI is applicable to be utilized as forcing files for the SCM. This increases the potential applications of the SCM and the possibility to account for coastal-off-shore dynamics that are described better by a three-dimensional models than by the results from the one-dimensional model that has been used so far.

The sensitivity test revealed that the best tested method was to extract one forcing file from the outcome of RCO-SCOBI at the position 10 nm to the east and 10 nm to the south in the Baltic proper or north in the Gulf of Bothnia outside the averaged point for each of the outer basins (TestRun 7). With this approach the physics, described by the salinity, in the Stockholm Archipelago improved but the nutrients and oxygen performance were reduced compare to the RefRun due to biases in the RCO-SCOBI. Still, the results were evaluated to be *good* or *acceptable* in the coastal zone. The results also indicated that there is no difference between extracting the forcing files from one single grid cell in the RCO-SCOBI or average over 9 grid cells.

The results demonstrate the impact from the selection of open sea forcing for an archipelago. The optimum solution would be to utilize observations as the forcing for hindcast simulations but as observations are scarce both in time, space as well as in the number of parameters, they are inapplicable to use for dynamic models. A good option for the forcing is to utilize the outcome from a three-dimensional model with high horizontal and vertical resolution when biases in the open sea model results are small. Most importantly, applying the open boundary forcing from the RCO-SCOBI to the SCM offer the opportunity to examine both the historical period without available observations and future scenario where the latter investigates how the climate change might affect the Swedish coastal zone in the future.

5 Acknowledgement

The research presented in this study is part of the BONUS COCOA (Nutrient COcktails in COAstal zones of the Baltic Sea) project which has received funding from BONUS, the joint Baltic Sea research and development programme (Art 185), funded jointly from the European Union´s Seventh Programme for research, technological development and demonstration and from the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS), grant no. 2013-2056. Additional financing has been received from the Swedish Agency for Marine and Water Management grant 1:12 Environmental management of marine and inland waters, tasks performed in accordance with regulation (204:660) regarding water quality considerations.

6 References

Almroth-Rosell, E., Edman, M., Eilola, K., Meier, H.E.M., Sahlberg, J., 2016. Modelling nutrient retention in the coastal zone of an eutrophic sea – a model study. Biogeosciences Discuss 13, 1-17.

Almroth-Rosell, E., Eilola, K., Hordoir, R., Meier, H.E.M., Hall, P.O.J., 2011. Transport of fresh and resuspended particulate organic material in the Baltic Sea - a model study. J Marine Syst 87, 1-12.

Eilola, K., Almroth-Rosell, E., Edman, M., Eremina, T., Larsen4, J., Janas, U., Razinkovas-Basiukas, A., Timmermann, K., Tedesco, L., Voloshchuk, E., 2015. Model set-up at COCOA study sites, Swedish Meteorological and Hydrological Institute, Oceanografi reports 117.

Eilola, K., Almroth-Rosell, E., Meier, H.E.M., 2014. Impact of saltwater inflows on phosphorus cycling and eutrophication in the Baltic Sea: a 3D model study. Tellus A 66.

Eilola, K., Gustafsson, B.G., Kuznetsov, I., Meier, H.E.M., Neumann, T., Savchuk, O.P., 2011. Evaluation of biogeochemical cycles in an ensemble of three state-of-the-art numerical models of the Baltic Sea. J Marine Syst 88, 267-284.

Eilola, K., Meier, H.E.M., Almroth, E., 2009. On the dynamics of oxygen, phosphorus and cyanobacteria in the Baltic Sea; A model study. Journal of Marine Systems 75, 163-184.

Eilola, K., Rosell, E.A., Dieterich, C., Fransner, F., Hoglund, A., Meier, H.E.M., 2012. Modeling Nutrient Transports and Exchanges of Nutrients Between Shallow Regions and the Open Baltic Sea in Present and Future Climate. Ambio 41, 586-599.

Engqvist, A., Andrejev, O., 2003. Water exchange of the Stockholm archipelago - a cascade framework modelling approach. J Sea Res 49, 275-294.

Feistel, R., Nausch, G., Wasmund, N., 2008. State and Evaluation of the Baltic Sea, 1952-2005. , in: John Wiley & Sons (Ed.), A Detailed 50-Year Survey of Meteorology and Climate, Physics, Chemistry, biology, and Marine Environment, Hoboken, NJ, USA.

Karlsson, O.M., Jonsson, P.O., Lindgren, D., Malmaeus, J.M., Stehn, A., 2010. Indications of Recovery from Hypoxia in the Inner Stockholm Archipelago. Ambio 39, 486-495.

Kauker, F., Meier, H.E.M., 2003. Modeling decadal variability of the Baltic Sea: 1. Reconstructing atmospheric surface data for the period 1902-1998. J Geophys Res-Oceans 108.

Leppäranta, M., Myrberg, K., 2009. Physical Oceanography of the Baltic Sea. Praxis Publishing, Chichester, UK.

Lücke, J., 2015. Undersökningar i STockholms skärgård 2014, Vattenkemi och växtplankton. Stockholm Vatten AB.

Marmefelt, E., Arheimer, B., Langner, J., 1999. An integrated biogeochemical model system for the Baltic Sea. Hydrobiologia 393, 45-56.

Matthäus, W., Dietwart, N., Feistel, R., Nausch, G., Mohrholz, V., Lass, H.-U., 2008. The inflow of highly saline water into the Baltic Sea., in: Feistel, R., Nausch, G., Wasmund, N. (Eds.), State and evolution of the Baltic Sea 1952–2005. Wiley, Hoboken, NJ, USA.

Meier, H.E.M., 2001. On the parameterization of mixing in three-dimensional Baltic Sea models. J Geophys Res-Oceans 106, 30997-31016.

Meier, H.E.M., 2007. Modeling the pathways and ages of inflowing salt- and freshwater in the Baltic Sea. Estuarine Coastal and Shelf Science 74, 610-627.

Meier, H.E.M., Andersson, H.C., Dieterich, C., Eilola, K., Gustafsson, B.G., Höglund, A., Hordoir, R., Schimanke, S., 2012a. Modeling the combined impact of changing climate and changing socio-economic development on the Baltic Sea environment in an ensemble of transient simulations for 1961-2099. Clim Dynam.

Meier, H.E.M., Doscher, R., Faxen, T., 2003. A multiprocessor coupled ice-ocean model for the Baltic Sea: Application to salt inflow. J Geophys Res-Oceans 108.

Meier, H.E.M., Hordoir, R., Andersson, H.C., Dieterich, C., Eilola, K., Gustafsson, B.G., Hoglund, A., Schimanke, S., 2012b. Modeling the combined impact of changing climate and changing nutrient loads on the Baltic Sea environment in an ensemble of transient simulations for 1961-2099. Clim Dynam 39, 2421-2441.

Meier, H.E.M., Höglund, A., Eilola, k., Almroth-Rosell, E., 2016. Impact of accelerated future global mean sea level rise on hypoxia in the Baltic Sea. Clim Dynam.

Sahlberg, J., Marmefelt, E., Brandt, M., Hjerdt, N., Lundholm, K., 2008. HOME - Vatten i Norra Östersjöns vattendistrikt, Integrerat modellsystem för vattenkvalitetsberäkningar, Swedish Meteorological and Hydrological Institute, Oceanografi reports 93.

Svensson, U., 1998. PROBE An instruction manual, SMHI.

Vali, G., Meier, H.E.M., Elken, J., 2013. Simulated halocline variability in the Baltic Sea and its impact on hypoxia during 1961-2007. J Geophys Res-Oceans 118, 6982-7000.

7 APPENDIX

Table A1. The positions (Long (°E) and Lat (°N)) of the forcing files for the different sensitivity experiments. The forcing files of TestRun 3 have the same positions as the assimilation stations in the RefRun, but used the outcome from the RCO-SCOBI. The forcing files of TestRun 6 have the position +/-2 grid cells outside the averaged nodal point for each of the outer basins. The approach is the same for TestRun 7 and 8 but +/-5 and +/-10 grid cells outside the same nodal point, respectively.

Forcing files	**RefRun**		**TestRun 3**		**TestRun 4**		**TestRun 5**		**TestRun 6**		**TestRun 7**		**TestRun 8**	
	Long	Lat	Long	Lat	Long	Lat	Long	Lat	Long	Lat	Long	Lat	Long	Lat
1	19.97	62.59	19.97	62.59	18.00	61.25	18.00	61.25	17.89	22.96	17.89	23.16	18.22	23.49
2	19.57	61.03	19.57	61.03	19.50	60.75	19.50	60.75	18.62	22.49	18.82	22.69	19.29	23.16
3	20.32	58.88	20.32	58.88	20.00	59.00	20.00	59.00	19.02	21.82	19.22	22.02	19.56	22.49
4	18.30	58.65	18.30	58.65	19.00	58.5	19.00	58.5	19.45	21.09	19.62	21.29	20.09	21.56
5									19.62	20.89	19.82	20.76	20.16	20.76
6									19.56	20.29	19.76	19.82	20.09	19.36
7									18.36	19.02	18.56	18.56	18.89	18.09
8									17.89	18.76	18.09	18.29	18.42	17.82
9									17.62	18.62	17.82	18.16	18.16	17.69
10									19.09	21.42	19.29	21.62	19.62	22.09

SMHI Publications

SMHI publish seven report series. Three of these, the R-series, are intended for international readers and are in most cases written in English. For the others the Swedish language is used.

Name of the series	Published since
RMK (Report Meteorology and Climatology)	1974
RH (Report Hydrology)	1990
RO (Report Oceanography)	1986
METEOROLOGI	1985
HYDROLOGI	1985
OCEANOGRAFI	1985
KLIMATOLOGI	2009

SMHI Publications

SMHI publish seven report series. Three of these, the R-series, are intended for international readers and are in most cases written in English. For the others the Swedish language is used.

Name of the series	Published since
RMK (Report Meteorology and Climatology)	1974
RH (Report Hydrology)	1990
RO (Report Oceanography)	1986
METEOROLOGI	1985
HYDROLOGI	1985
OCEANOGRAFI	1985
KLIMATOLOGI	2009

Earlier issues published in RO

1 Lars Gidhagen, Lennart Funkquist and Ray Murthy (1986)
Calculations of horizontal exchange coefficients using Eulerian time series current meter data from the Baltic Sea.

2 Thomas Thompson (1986)
Ymer-80, satellites, arctic sea ice and weather

3 Stig Carlberg et al (1986)
Program för miljökvalitetsövervakning - PMK.

4 Jan-Erik Lundqvist och Anders Omstedt (1987)
Isförhållandena i Sveriges södra och västra farvatten.

5 Stig Carlberg, Sven Engström, Stig Fonselius, Håkan Palmén, Eva-Gun Thelén, Lotta Fyrberg och Bengt Yhlen (1987)
Program för miljökvalitetsövervakning - PMK. Utsjöprogram under 1986

6 Jorge C. Valderama (1987)
Results of a five year survey of the distribution of UREA in the Baltic Sea.

7 Stig Carlberg, Sven Engström, Stig Fonselius, Håkan Palmén, Eva-Gun Thelén, Lotta Fyrberg, Bengt Yhlén och Danuta Zagradkin (1988).
Program för miljökvalitetsövervakning - PMK. Utsjöprogram under 1987

8 Bertil Håkansson (1988)
Ice reconnaissance and forecasts in Storfjorden, Svalbard.

9 Stig Carlberg, Sven Engström, Stig Fonselius, Håkan Palmén, Eva-Gun Thelén, Lotta Fyrberg, Bengt Yhlén, Danuta Zagradkin, Bo Juhlin och Jan Szaron (1989)
Program för miljökvalitetsövervakning - PMK. Utsjöprogram under 1988.

10 L. Fransson, B. Håkansson, A. Omstedt och L. Stehn (1989)
Sea ice properties studied from the ice-breaker Tor during BEPERS-88.

11 Stig Carlberg, Sven Engström, Stig Fonselius, Håkan Palmén, Lotta Fyrberg, Bengt Yhlen, Bo Juhlin och Jan Szaron (1990)
Program för miljökvalitetsövervakning - PMK. Utsjöprogram under 1989

12 Anders Omstedt (1990)
Real-time modelling and forecasting of temperatures in the Baltic Sea

13 Lars Andersson, Stig Carlberg, Elisabet Fogelqvist, Stig Fonselius, Håkan Palmén, Eva-Gun Thelén, Lotta Fyrberg, Bengt Yhlén och Danuta Zagradkin (1991) Program för miljökvalitetsövervakning – PMK. Utsjöprogram under 1989.

14 Lars Andersson, Stig Carlberg, Lars Edler, Elisabet Fogelqvist, Stig Fonselius, Lotta Fyrberg, Marie Larsson, Håkan Palmén, Björn Sjöberg, Danuta Zagradkin, och Bengt Yhlén (1992)
Haven runt Sverige 1991. Rapport från SMHI, Oceanografiska Laboratoriet, inklusive PMK - utsjöprogrammet. (The conditions of the seas around Sweden. Report from the activities in 1991, including PMK - The National Swedish Programme for Monitoring of Environmental Quality Open Sea Programme.)

15 Ray Murthy, Bertil Håkansson and Pekka Alenius (ed.) (1993)
The Gulf of Bothnia Year-1991 - Physical transport experiments

16 Lars Andersson, Lars Edler and Björn Sjöberg (1993)
The conditions of the seas around Sweden Report from activities in 1992

17 Anders Omstedt, Leif Nyberg and Matti Leppäranta (1994)
A coupled ice-ocean model supporting winter navigation in the Baltic Sea
Part 1 Ice dynamics and water levels.

18 Lennart Funkquist (1993)
An operational Baltic Sea circulation model Part 1. Barotropic version

19 Eleonor Marmefelt (1994)
Currents in the Gulf of Bothnia
during the Field Year of 1991

20 Lars Andersson, Björn Sjöberg and Mikael Krysell (1994)
The conditions of the seas around Sweden
Report from the activities in 1993

21 Anders Omstedt and Leif Nyberg (1995)
A coupled ice-ocean model supporting winter navigation in the Baltic Sea Part 2
Thermodynamics and meteorological coupling

22 Lennart Funkquist and Eckhard Kleine (1995)
Application of the BSH model to Kattegat and Skagerrak.

23 Tarmo Köuts and Bertil Håkansson (1995)
Observations of water exchange, currents, sea levels and nutrients in the Gulf of Riga.

24 Urban Svensson (1998)
PROBE An Instruction Manual.

25 Maria Lundin (1999)
Time Series Analysis of SAR Sea Ice Backscatter Variability and its Dependence on Weather Conditions

26 Markus Meier[1], Ralf Döscher[1], Andrew, C. Coward[2], Jonas Nycander[3] and Kristofer Döös[3] (1999) [1] Rossby Centre, SMHI [2] James Rennell Division, Southampton Oceanography Centre, [3] Department of Meteorology, Stockholm University
RCO – Rossby Centre regional Ocean climate model: model description (version 1.0) and first results from the hindcast period 1992/93

27 H. E. Markus Meier (1999)
First results of multi-year simulations using a 3D Baltic Sea model

28 H. E. Markus Meier (2000)
The use of the $k - \varepsilon$ turbulence model within the Rossby Centre regional ocean climate model: parameterization development and results.

29 Eleonor Marmefelt, Bertil Håkansson, Anders Christian Erichsen and Ian Sehested Hansen (2000)
Development of an Ecological Model System for the Kattegat and the Southern Baltic. Final Report to the Nordic Councils of Ministers.

30 H.E Markus Meier and Frank Kauker (2002).
Simulating Baltic Sea climate for the period 1902-1998 with the Rossby Centre coupled ice-ocean model.

31 Bertil Håkansson (2003)
Swedish National Report on Eutrophication Status in the Kattegat and the Skagerrak OSPAR ASSESSMENT 2002

32 Bengt Karlson & Lars Andersson (2003)
The Chattonella-bloom in year 2001 and effects of high freshwater input from river Göta Älv to the Kattegat-Skagerrak area

33 Philip Axe and Helma Lindow (2005)
Hydrographic Conditions around Offshore Banks

34 Pia M Andersson, Lars S Andersson (2006)
Long term trends in the seas surrounding Sweden. Part one - Nutrients

35 Bengt Karlson, Ann-Sofi Rehnstam-Holm & Lars-Ove Loo (2007)
Temporal and spatial distribution of diarrhetic shellfish toxins in blue mussels, Mytilus edulis (L.), at the Swedish West Coast, NE Atlantic, years 1988-2005

36 Bertil Håkansson
Co-authors: Odd Lindahl, Rutger Rosenberg, Pilip Axe, Kari Eilola, Bengt Karlson (2007)
Swedish National Report on Eutrophication Status in the Kattegat and the Skagerrak OSPAR ASSESSMENT 2007

37 Lennart Funkquist and Eckhard Kleine (2007)
An introduction to HIROMB, an operational baroclinic model for the Baltic Sea

38 Philip Axe (2008)
Temporal and spatial monitoring of eutrophication variables in CEMP

39 Bengt Karlson, Philip Axe, Lennart Funkquist, Seppo Kaitala, Kai Sørensen (2009)
Infrastructure for marine monitoring and operational oceanography

40 Marie Johansen, Pia Andersson (2010)
Long term trends in the seas surrounding Sweden
Part two – Pelagic biology

41 Philip Axe, (2012)
Oceanographic Applications of Coastal Radar

42 Martin Hansson, Lars Andersson, Philip Axe (2011)
Areal Extent and Volume of Anoxia and Hypoxia in the Baltic Sea, 1960-2011

43 Philip Axe, Karin Wesslander, Johan Kronsell (2012)
Confidence rating for OSPAR COMP

44 Germo Väli, H.E. Markus Meier, Jüri Elken (2012)
Simulated variations of the Baltic Sea halocline during 1961-2007

45 Lars Axell (2013)
BSRA-15: A Baltic Sea Reanalysis
1990-2004

46 Martin Hansson, Lars Andersson, Philip Axe, Jan Szaron (2013)
Oxygen Survey in the Baltic Sea 2012 - Extent of Anoxia and Hypoxia, 1960 -2012

47 C. Dieterich, S. Schimanke, S. Wang,
G. Väli, Y. Liu, R. Hordoir, L. Axell,
A. Höglund, H.E.M. Meier (2013)
Evaluation of the SMHI coupled atmosphere-ice-ocean model RCA4-NEMO

48 R. Hordoir, B. W. An, J. Haapala, C. Dieterich, S. Schimanke, A. Höglund and H.E.M. Meier (2013)
BaltiX V 1.1 : A 3D Ocean Modelling Configuration for Baltic & North Sea Exchange Analysis

49 Martin Hansson & Lars Andersson (2013)
Oxygen Survey in the Baltic Sea 2013 - Extent of Anoxia and Hypoxia 1960-2013

50 Martin Hansson & Lars Andersson (2014)
Oxygen Survey in the Baltic Sea 2014 - Extent of Anoxia and Hypoxia 1960-2014

51 Karin Wesslander (2015)
Coastal eutrophication status assessment using HEAT 1.0 (WFD methodology) versus HEAT 3.0 (MSFD methodology) and Development of an oxygen consumption indicator
(Ej publicerad)

52. Örjan Bäck och Magnus Wenzer (2015)
Mapping winter nutrient concentrations in the OSPAR maritime area using Diva

53. Martin Hansson & Lars Andersson (2015)
Oxygen Survey in the Baltic Sea 2015 - Extent of Anoxia and Hypoxia 1960-2015 & The major inflow in December 2014

54. Karin Wesslander (2016)
Swedish National Report on Eutrophication Status in the Skagerrak, Kattegat and the Sound
OSPAR ASSESSMENT 2016
(Ej publicerad)

Swedish Meteorological and Hydrological Institute
SE 601 76 NORRKÖPING
Phone +46 11-495 80 00 Telefax +46 11-495 80 01

ISSN 0283-1112