Robinson Hordoir, PhD
Institute of Marine Research
P.O. Box 1870 Nordnes, 5817 Bergen, Norway
Mobile: +47 906 27 189
robinson.hordoir@hi.no

Prof. James R. Madisson
Editor for Geosciences Model Development
University of Edinburgh
United Kingdom

Bergen, October 29th 2018

Dear Prof. Madisson,

Please find attached a revised version of the manuscript entitled “Nemo-Nordic: A NEMO based ocean model for Baltic & North Seas, research and operational applications”. We have taken into account most of the comments made by the two reviewers, comments which were very constructive and helpful. Some comments were sometimes aimed more towards a scientific discussion, which although very relevant, were difficult to answer in the framework of this article, but which are good suggestions of model developed or process studies.
I have now relocated from Sweden to Norway, and I am very grateful for the extra time I was given to provide a revised version of this manuscript, the latest months have been very intense indeed.

My co-authors and myself also wish to thank you and the two reviewers for the work done on our manuscript.

Best regards,

Robinson Hordoir

Response to reviewer #1 comments :

First we want to thank you for the constructive comments and the general work done on our manuscript. We answer each comment below. You ask a lot of question and show a great interest for our model and manuscript, which we appreciate very much of course. But sometimes we can not do all the work which you suggest, either for time related questions or because some questions (like for what generates the inflows for example) are still a subject of debate.

lines 40-55: a figure with a map of the main currents and key elements of local dynamics could be welcome

Indeed. We will add them. However, since such maps have been produced numerous times in many articles, we will just reproduce pre-existing one and cite their origin accordingly.

line 55-65: the authors emphasize the importance of the transition between the two seas (North and Baltic). Is the horizontal resolution sufficient to represent all these small straits? A mesh of almost 4km seems a bit coarse to achieve this goal.

It is too coarse to make any detailed study of the Danish straits, but an appropriate tuning can reproduce the « impedance » of the Danish straits so that the transfers of volume, salt and heat between the two basins are represented. We mentioned this briefly in the text, but we will make it more clear.

line 67: if possible I would suggest replacing the nauticmiles by the metric system

We will put both.

line 96: I think we could be more specific: for example explain what are the physical processes represented by NEMO that allow NEMO to be better adapted than these other models cited in lines 95.96

We will detailed this part to a larger extent. Beyond the features present today in NEMO that other non-community models will likely never have, it's also about the yet non-exploited possibilities like wave coupling for example, or the future ones.

line 96: " the dense overflows that feed its very specific sill bounded estuarine circulation ". Unclear. . .. Detail a little more.

Done.

line 101: the authors specify that they use version 3.6 of NEMO. If this seems relevant to the authors, I would suggest to say what this version brings compared to previous versions.

The biggest improvement was the new coupling between barotropic/baroclinic modes which enables a much better SSH representation, and since SSH variability is the driver of the entire system a better representation of almost everything. XIOS, and the ability to have only one output file and not one per processor anymore, made the model a lot nicer to handle for everyone. This is not a scientific argument but having motivated scientists to work on a model does help a lot. We will add more details about the scientific aspect in the text.

line 105: This area has a large overlap with the NEMO-IBI operational system domain (Maraldi et al, 2013). The horizontal resolution is ultimately worse than that of IBI but NEMO-NORDIC brings the connection with the Baltic, missing from IBI. The overlapping zone also offers interesting intercomparison possibilities between the two models. The authors could say a few words about the respective interests and the complementarity of NEMO-NORDIC and NEMO-IBI and if possible make a reference to the validation study of NEMO IBI by Maraldi et al, 2013.

Yes. The idea is that to have good North Sea baroclinic dynamics, you need a good Baltic Sea freshwater outflow, which most models don't have. And to get good Baltic Sea dynamics you need the North Sea variability. Not to mention the most interesting area of Nemo-Nordic which is Kattegat/Skaggerak. We have mentioned this aspect and added the relevant citation.

line 108: NEMO's recent advances on the sigma coordinate could be cited here. I think for example to the paper of Shapiro 2013 (or other if the authors see a reference more relevant)

Indeed, we have added this reference.

line 112 "adopted" "adapted"

Yes, thanks.

L132: the word "decouples" seems clumsy to the extent that there is in fact a coupling between baroclinic and barotropic modes.

Indeed, we'll correct this.

L135: the term "degree of conservation" implies that the conservation properties of tracers may not be strictly respected, which seems a priori not very compatible with the study of climate. If the model really respects the conservation properties of tracers the authors should say it more clearly (or can refrain from commenting on a fairly basic property).

Quite so. I think we shall refrain from commenting on this aspect.

L140: Is the roughness given by a length of roughness? Is it a constant or a mapped parameter? Since this parameter seems important it would be interesting to give its value, or its order of magnitude if it is not a constant.

In operational mode (1nm resolution), the roughness is mapped. It is constant for the longer term simulations. We will add a better description.

L145-150: without doubting the proper functioning of the BBL, is it still not unsatisfactory to have to completely remove the advective component of this parameterization? Independently of the numerical considerations that one has well understood, is it not less realistic from the point of view of physics? Would that not finally plead for the use of the sigma coordinate referred to online 107?

Actually the transition times of Baltic flows are several months, so a small advection speed might help. We need to investigate this matter further. Sigma coordinates would help for the overflows but would create many other problems, like destroying completely the Baltic Sea halocline. The best would be hybrid coordinates like in Getm. We'll add more lines about this.

lines 150-160 What is "tuning" mentioned by the authors is not very clear. Do the authors refer to the value of the Galperin coefficient? In this respect, the reference to Galperin's paper is too vague. One could for example think that one refers to the functions of stability of Galperin? Is that the case? According to Reffray et al 2015 the choice of Canuto seems the most judicious... Or do you refer to the limitation of the mixing length (eq22 of Galperin)? What exactly is this coef mentioned above? The problem raised by the authors also refers to the choice of the thresholds of minimum values for the TKE of the closure scheme and their possible regionalization. Can the authors say a few words about the values used by NEMO?

We refer to the mixing length limitation, itself tuned with the Galperin's coefficient. We have made this more precise.

lines 165-175 The authors mention the drawbacks of the calculation of the horizontal mixing in z coordinate, which, even taking into account the NEMO rotation tensor, tends to introduce a significant diapycnal mixing. The authors correct this defect by means of a spatial adaptation of the coefficients of viscosity / diffusivity which seems a little artificial but which has the merit of working. There is certainly room for discussion of possible future improvement prospects for NEMO-NORDIC. Insofar as the saline intrusions evoked by the authors would follow the bottom, one can for example wonder if the sigma coordinate would not be better adapted. The work of Shapiro 2013 on the different forms that the sigma coordinates can take in NEMO could be a source of inspiration for a possible evolution of NEMO-NORDIC in this direction.

As said before, sigma would be better for the overflows, but would have dire consequences for the frontal structures and the permanent stratification. The best would be hybrid coordinates, but this is for the future. Meanwhile, we believe there are possible improvements to do with our viscosity/diffusivity coefficient.

line 183: the tide is apparently introduced as a boundary condition only. Does this mean that the internal generating forces in the numerical domain (astronomical potential and loading self attraction present in the NEMO version used by Kodaira et al, 2016) are not used here? If yes, why? Are they negligible in comparison with the influence of boundary conditions?

Yes, we have neglected the tidal potential. NOAA on its website says US great lakes have a maximum spring tide of 5cm so it could be worth trying. So far our tidal signal is actually too strong, but we will try this sensitivity experiment in the future.

lines 184 The open boundary conditions seem to have a fairly high level of elaboration with respect to the barotropic processes (tide, storm surge). On the other hand, I am surprised, given the possible operational purpose, and also given the Copernicus context in which the NEMO-NORDIC model seems to be developed, by the great simplicity of the boundary conditions for the general 3D circulation. Only temperature and salinity seem to be concerned (nothing specific is said about SSH and currents, apparently). In addition, T and S would be climatological. This simplicity can be understood in the context of a climate projection, but for operational applications it is expected that the Coperninus operational system will serve to provide boundary conditions for regional models such as NEMO-NORDIC. I may have misunderstood the text which in this case should be a little clarified. Note also that the IBI operating system seems to have the capacity to forecast storm surges according to Maraldi et al 2013. Can the authors discuss a little more about their choices?

Indeed, thanks for this remark, this is a mistake of ours when drafting the manuscript. In operational mode, having proper OBCs has been a subject of great concern, especially for the barotropic mode. We will add more details.

line 185. The authors apparently use the TPXO tide atlas of Egbert et al 1994. In Maraldi 2013, the accuracy of altas FES is widely commented and finally used as a reference to validate the quality of the tide simulation obtained with NEMO. The present study could have been an opportunity to make a comparison between the different tidal atlases usable as boundary conditions. Which produces the best result? etc etc. . . That would be useful I think. This is a minor remark but if the authors deem it appropriate they might mention this fact as a possible prospect in future work.

Absolutely, it is just a question of time: one of the co-authors of this article has suggested we use FES. We just did not have the time to try, but will mention it.

line 195-205 The introduction and the abstract of the article suggest that NEMO-NORDIC is used for both climate studies and short-term operational forecasting. The description of the atmospheric forcing seems to correspond to the first point only. What is the authors' strategy for short-term operational forecasting? Does the hourly forecast of the sea level for example impose particular constraints with regard to the frequency of the atmospheric forcing? We can also think that the precise prediction of the sea level requires taking into account the effect of the waves. Preliminary developments have been made in NEMO on this subject (see, for example, NEMO and WW3 coupling by Clementi et al, 2017 for a better representation of the drag coefficient). What is the authors' strategy for this question?

Indeed, we had forgot to mention the forcing used in operational mode. This is now corrected.
There has not been a thorough investigation on the influence of the frequency of the atmospheric forcing so far, the goal has been to find the best accessible data to obtain results which fit the quality requirements of the model in forecast mode, through a benchmark.
About the coupling with wind waves, this work is ongoing at the Finnish Meteorological Institute.

lines 208-215 About taking into account a constant concentration of chlorophyll to improve the essential point of the penetration of light. Would there be an interest (perspective) in using Copernicus' global predictions of chlorophyll?

It would be interesting for future studies but we have not pushed our investigation so far. Basically we provided a value which is different than the NEMO default value to take into account the Baltic & North Sea turbidity.

line 243: I am surprised when the authors say that the correlation is mostly close to 0.99. I would have rather said 0.95. This difference of appreciation is probably subjective and attributable to the lack of readability of Figures 2-3-4. In fact it seems to me that Taylor diagrams are not very suitable here. Figures 2-3-4 indeed occupy a lot of space for little information (only two points, a yellow, a blue) with a very low level of readability since each individual figure per tide station is finally tiny. We therefore lose a lot of time trying to see what are the RMS values, Standard deviation, correlation, when a simple table would immediately give this information, and allow a quick comparison with other authors (see for example Table 1 in Maraldi 2013). It seems to me that Taylor diagrams are appropriate when a single reference is compared to a scatter plot. For example, in Toublanc et al (2018) Figure 7, it is immediately understood that the simulations corresponding to green and blue point clouds are better than the simulation

We have converted this data into arrays.

line 247: The issue of the horizontal resolution is appropriately addressed in the Strait of Denmark. Some passages are indeed so narrow that a resolution of 2nm (almost 4km) seems clearly insufficient. For example the passage between Elsinore and Helsingborg barely fits a mesh. However, in NEMO, there is possibility for local increase in horizontal resolution, either by using an AGRIF nesting (Waldmann et al, 2016), or by using the NEMO curvilinear grid (Madec Imbard, 1996). To what extent can either of these two possibilities constitute a NEMO-NORDIC development perspective?

AGRIF is the way to go, but that is for the future…. Actually I am right now just back from the Nemo User's Meeting and it seems finally that Agrif works with the non-linear free surface in Nemo (key_vvl), which was not the case so far. The non linear free surface being an essential feature of Nemo Nordic, we did not spend too much time investigating Agrif before being should it would work.

The thresholding of the bathy (note that Maraldi 2013 also uses a threshold and discusses its consequences) also seems problematic: is not it a handicap for the forecast of surges? What is the technical reason that prevents lower bathymetry? Could the sigma coordinate overcome this problem?

We are not sure to understand, we do not limit the value of the bathymetry: the only treatment of the original database we perform is to interpolate it on the Nemo-Nordic grid.

Table 1: Northern boundary, the "Inflow Observations" bounds are given in descending order. Is it correct?

It was not very clear indeed, and there was a bug in one of the values. We changed that. The values given are a range, and are now in ascending order.

Line 328. My next question is motivated by the authors' commentary on the Galperin coefficient and the fact that NEMO has two types of turbulent closure (TKE, k-epsilon, Reffray 2015). In the manner of Reffray et al 2005, have the authors made a sensitivity test of the SST bias to the turbulent closure scheme (TKE or K-epsilon)?

We have not made such an experiment with Nemo-Nordic, but we tried different values of the Galperin coefficient.

lines 353-355: In the description of the model it would therefore be interesting to say a few words about the state equation used.

Indeed, we have added a line when providing the runoff description.

line 370. It seems to me that the mechanisms responsible for the Major Baltic Inflows of 1993 and 2003 could be explained in more detail if possible (would there be no more things to say outside of the sea level? ?). Do these mechanisms come from open boundary conditions, or are they generated inside the modeling domain etc etc ...?

This is a very nice remark, but still a subject of intense debate among researchers. We have added a line

l***ine 393. Specify the number of the Figure***

Corrected.

line 415: the authors evoke the possibility of a validation of their boundary conditions. But what exactly are the boundary conditions for T and S? How are the T and S fields constructed that force the open-border model? Climatology, ORCA25? Same remark for baroclinic currents.

The sentence is not very clear indeed, we changed it. The data source for T&S at the open boundary is a climatology for our long term hindcast, but can be anything else depending on the simulation. We do not use baroclinic currents data for the open boundary conditions, but a simple radiation condition.

Figure 14: Would a single color palette (as in Figure 15) be preferable?

We have tried to adapt the color scale to the salinity range, the idea was to visualize as best as possible the biases of the model when comparing with observations.

line 481: it seems to me that the acronym BSH is not defined.

Yes, this is corrected.

Response to reviewer #2 comments :

First, we want to thank you for your work on our manuscript, we have tried to correct the many typos and hope this latest version will meet the quality standard expected for publication in GMD.

I think within the introduction (L85) or the Model set up needs mentioning of the two differing resolution models that are referred to later in the paper. It is not immediately obvious which version of Nemo-Nordic is being assessed at any one time, especially as both are later compared against each other. I think it would help the reader if there was some way to make this clearer, e.g. Nemo-Nordic 1nm/2nm etc. or some other similar labelling strategy early in the paper and a description of these. In the model description there is only a description of the 2nm version. Perhaps restricting nautical miles to metric equivalents will be more in line with GMD.

Yes, indeed. We have now written clearly in the introduction that there are two configurations of different resolutions. Each time nautical miles units are used then the equivalent resolution in meters is now also written.

L105. With regards to the 2nm grid description, it might be useful to state if the grid is rotated, otherwise it would be hard to see how the stated grid resolution would be retained at a relatively high latitude.

We have made this more precise. The grid is un-rotated, it is a simple geographical grid.

L113-L116 The stated vertical resolution is surprisingly coarse in a regional model. I appreciate there is a need to focus resolution with regards to the overflows but 3 m surface resolution seems quite low. I refer the authors to Stewart et al. with regards to what would be an optimal vertical resolution for a z-level model in a global context. K.D. Stewart, A.McC. Hogg, S.M. Griffies, A.P. Heerdegen, M.L. Ward, P. Spence, M.H. England,Vertical resolution of baroclinic modes in global ocean models,Ocean Modelling,Volume 113, 2017,Pages 50-65,https://doi.org/10.1016/j.ocemod.2017.03.012. Towards the end of the paper there is an analysis compared to an SST product. The bias is surprisingly large and cold given the warm bias in the atmospheric forcing, could the surface resolution play a part? What is defined as SST in this context ?

The vertical resolution is a compromise, which allows to have an acceptable resolution close to the surface but also closer to the bottom in order to resolve as best as possible the Baltic overflows. The overflows are driven by barotropic processes, and the halocline/thermocline is usually located far below the level the first grid cells, so we do not believe this kind of bias is linked with the resolution. However there is a clear problem linked with the Galperin parameterization, which we believe needs to be applied only to haline stratification, we are working with this issue.

L124 The issue of model resolution and the Danish straits is correctly brought to the attention of the reader and the method by which the barotropic flux can be maintained by retaining the same cross-sectional area. However, this must be problematic with regards to the baroclinic part of the flow. Particularly so as one of the main motivations of having the interconnect is to model bottom saline intrusions form the North Sea that enter the Baltic. Perhaps there is justification here for some more comment on the effects on the baroclinic flows by attempting to retain the barotropic flux.

Indeed, we have added a few lines about this specific issue.

L136 It is mentioned that ‘tuning’ is done with regards to optimizing model SSH. It is not clear what the optimization is, perhaps this could be elaborated as it could potentially save others time in the future or suggest useful strategies. I wonder could the authors supply a graphic/map in the supplementary material with regards to the 2d varying bottom friction “following the barotropic Kelvin wave”, what is the physical grounds for this?

We can provide the input file that is used for this tuning, but the entire model is available on demand actually, including this file. The underlying idea is that barotropic waves entering the North Sea have a high energy that they lose while propagating cyclonically along the coastline. The bottom roughness tuning is done to fit the loss of energy.

L174-L175 The use of variable diffusivity and viscosity appears to be an interesting pragmatic engineering solution to the model difficulties concerning mixing and the dense water overflows. That is an interesting solution and appropriate for short time scale like a forecast model, but I wonder if it is appropriate for climate scales? That is this strategy assumes a-priori what the structure of the water column is, but on climate time scale that could change but the model may in effect be imposing it as it is, could the authors comment on this. It seems that as the authors note, a hybrid z* with sigma at the bottom is a much better vertical framework for the problem at hand. Could the authors comment on why such a huge viscosity is required at the boundary region? This is likely to cause severe issues for any coupled biogeochemistry model here. I suggest it is worth investigating what is happening to vertical velocity and tke here.

Actually this idea is made more for climate time scales (i.e.: several decades) which affect the Baltic Sea salinity. As long as the Baltic Sea is a semi enclosed basin with low turbulence this would work. We have added a few lines in the manuscript.
Sigma coordinates would be better at the bottom indeed but would have dire consequences at the level of the halocline, the best would be hybrid coordinates but long term simulations would be very costly. z* coordinates are not perfect but a good compromise.
High viscosity at the OBCs does not affect areas of concern for biogeochemistry so far, which we always manage as for the physics to be far away from these OBCs.

L210 There are a number of chl products that are available. Do the authors consider using say even just a monthly climatology rather than a uniform value domain wise.

Indeed, but we have not investigated this issue yet. So far our only concern with chlorophyll data is to get a light penetration that corresponds to reality, especially in the Baltic Sea.

Fig 2,3,4 I think the use of Taylor plots here is not appropriate, as there are only two data points. It could save a lot of space to reduce the Taylor plots to numerical tables. Taylor plots are beneficial when analysing a large 'cloud' of data. In a model sensitivity, they are useful if tuning say one parameter a number of times. In this case, there are just 2 model resolutions, it might be more appropriate if there are several model resolutions to intercompare. Enabling the modeller to visualise if there are say competing trends between rms, correlation and standard deviation. However, with just two data points there can be no trend to discern. In conclusion, a table might be quicker to interpret and save considerable space I do not think the Taylor plots here bring any advantage. With regard to the tides in the North Sea, the inclusion of a Co-tidal amp/phase plot of say M2 could be useful to give a quick look at how overall the model is doing in space with regards to tides.

The other reviewer made the same remark, we replaced the Taylor diagrams by arrays.

Fig 5 The climatological currents from North to South along the boundary in the English channel are very odd and suggest some problem in the bdy implementation here. Could the problem be related to using clim. TS in a highly tidal area? Ignoring the general cold bias in Fig 17, there is still an obvious bdy issue both in the north and in the south in JJA, again perhaps relates to the bdys provided. Too much vertical mixing??

Basically what the figure shows are the mean currents of a place where there is a huge variability compared with the mean value. Along the Western side of the English channel opening towards the Atlantic ocean, the mean currents are not entirely along the main direction of the channel as it is the case in many places in the channel itself. The flow being almost entirely barotropic in such a region, if there was such a mistake in the model it would show immediately in the sea level.

L256 It is noted that the north sea underestimate lower frequencies but these are unbiased in the Baltic. (due to amplification?) Is there a case to be made that the model Is overdoing amplification of waves that are initially underestimated in the North Sea? If so could that have other adverse effects?

This is a very interesting question, which is difficult to answer here because it is a research topic in itself. Basically our understanding is that some low frequency waves coming from the Atlantic ocean enter the domain and are not included in our set of open boundary conditions.
The effects on the Baltic Sea are difficult to estimate, so far it seems we are able to reproduce all the major Baltic inflows.

L 425 the authors show a large freshwater bias at the Frisian front location. May I also suggest that the riverine input from HYPE could be a possible issue here, Have the authors made an assessment of the HYPE model along this coastline? The accuracy is assessed for the Baltic Basin but not for the North Sea?

Actually we have computed the mean value of of the E-Hype flow for the North Sea and it looked quite correct although there was a positive bias indeed. We have tried a lot of different forcing datasets for hydrology, including trying to correct biases in HYPE, all lead the same salinity bias (too fresh) . We believe a bias of circulation and/or mixing is the cause of this issue.

3 Minor Technical points/errata These are likely but a subsection of minor points that need further editing.

Thanks for this re-reading work, which helps a lot to correct the manuscript. We have taken one by one all the points and corrected them.

30/10/2018, 10:43:38

Compare Results

Old File:		New File:
gmd-2018-2.pdf	versus	**NEMO-Nordic_validation.pdf**
29 pages (14,08 MB)		**31 pages (9,86 MB)**
05/04/2018, 08:47:38		29/10/2018, 17:13:03

Total Changes

688

Text only comparison

Content

301	Replacements
187	Insertions
200	Deletions

Styling and Annotations

0	Styling
0	Annotations

Go to First Change (page 1)

Manuscript prepared for Geosci. Model Dev.
with version 4.2 of the LaTeX class copernicus.cls.
Date: 29 October 2018

Nemo-Nordic 1.0: A NEMO Based Ocean Model for Baltic & North Seas, Research and Operational Applications

Robinson Hordoir[1,2], Lars Axell[3], Anders Höglund[3], Christian Dieterich[3], Filippa Fransner[2,4,5], Matthias Gröger[3], Ye Liu[3], Per Pemberton[3], Semjon Schimanke[3], Helen Andersson[3], Patrik Ljungemyr[3], Petter Nygren[3], Saeed Falahat[3], Adam Nord[3], Anette Jönsson[3], Iréne Lake[3], Kristofer Döös[5], Magnus Hieronymus[3], Heiner Dietze[6], Ulrike Löptien[6], Ivan Kuznetsov[7], Antti Westerlund[8], Laura Tuomi[8], and Jari Haapala[8]

[1] Institute of Marine Research, Bergen, Norway
[2] Bjerknes Centre for Climate Research, Bergen, Norway
[3] Swedish Meteorological and Hydrological Institute, Norrköping, Sweden
[4] Geophysical Institute, Bergen University, Norway
[5] Department of Meteorology, Stockholm University, Sweden
[6] GEOMAR, Helmholtz Centre for Ocean Research, Kiel, Germany
[7] Institute of Coastal Research, Helmholtz-Zentrum, Geesthacht, Germany
[8] Finnish Meteorological Institute, Helsinki, Finland

Correspondence to: Robinson Hordoir
(robinson.hordoir@hi.no)

Abstract. We present Nemo-Nordic, a Baltic & North Sea model based on the NEMO ocean engine. Surrounded by highly industrialised countries, the Baltic and North seas, and their assets associated with shipping, fishing and tourism; are vulnerable to anthropogenic pressure and climate change. Ocean models providing reliable forecasts, and enabling climatic studies, are important tools for the shipping infrastructure and to get a better understanding of effects of climate change on the marine ecosystems. Nemo-Nordic is intended to come as a tool for both short term and long term simulations, and to be used for ocean forecasting as well as process and climatic studies. Here, the scientific and technical choices within Nemo-Nordic are introduced, and the reasons behind the design of the model and its domain, and the inclusions of the two seas, are explained. The model's ability to represent barotropic and baroclinic dynamics, as well as the vertical structure of the water column, is presented. Biases are shown and discussed. The short term capabilities of the model are presented, and especially its capabilities to represent sea level on an hourly timescale with a high degree of accuracy. We also show that the model can represent longer time scales, with a focus on the Major Baltic Inflows and the variability of deep water salinity in the Baltic Sea.

---

1 Introduction

The Baltic Sea is a semi-enclosed sea that is heavily influenced by freshwater input from large continental rivers. The large freshwater input, and the narrow connection with the North Sea and the Atlantic Ocean through the Danish straits (Figure 1), gives the Baltic Sea its brackish characteristics with a strongly stratified water column, and a water residence time of ca. 40 years (Döös et al., 2004).

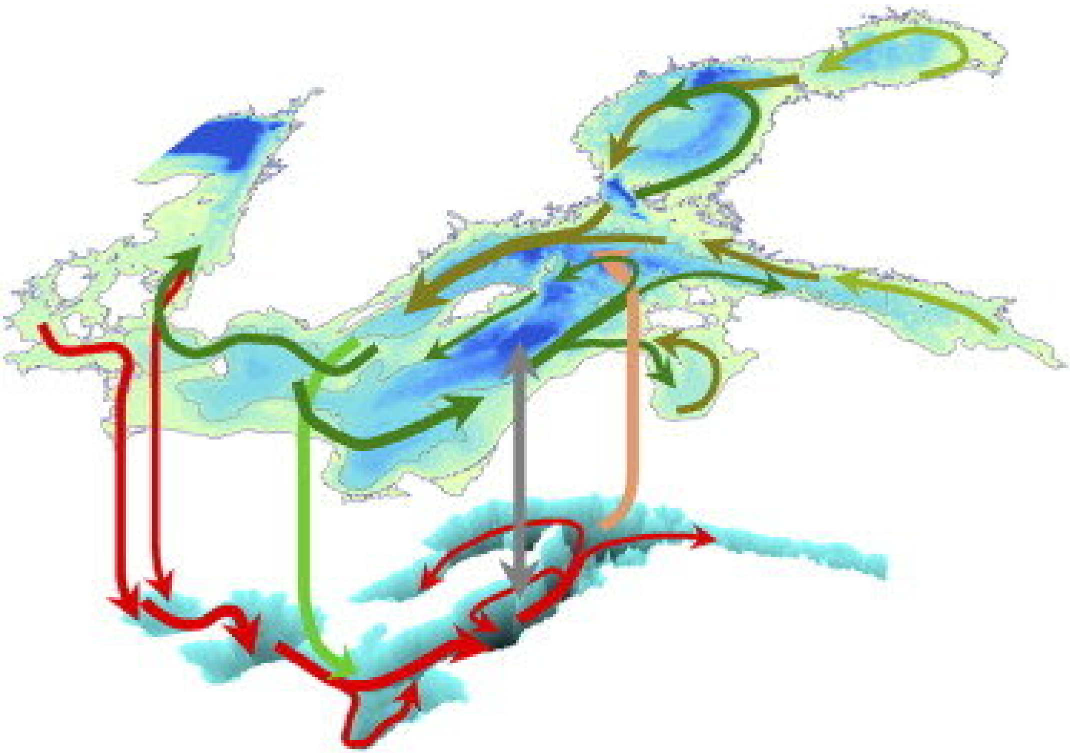

Fig. 1. Schematic view of the Baltic Sea circulation (From Elken and Matthäus (2008)). The Baltic Sea can be considered as a large sill estuary in which salty water masses from the North Sea may manage to flow towards the bottom. These water masses eventually mix with lighter and fresher water masses. Sub-estuarine circulations take place in the Gulf of Finland and in the Gulf of Bothnia.

Due to the long residence time and the strong stratification, the Baltic Sea ecosystem is vulnerable to antropogenic pressure. As a result of large nutrient inputs the sea is today classified as eutrophied (Andersen et al., 2017), and a spreading of anoxic bottom waters has been observed during the last century (Carstensen et al., 2014). Eutrophication and anoxia can have severe impacts on the ecosystem. The cod, for example, which is a economically important fish species (Köster et al., 2003; Wieland et al., 1994), suffers from anoxic deep waters as its eggs reside in the Baltic Sea deep waters. Further, although all underlying mechanisms are still not clear, increases in cyanobacteria blooms are often related to eutrophication (Vahtera et al., 2007).

The vertical structure of the Baltic Sea, and its ecosystem, is on the long term influenced by inflows of salt water masses from the North Sea through the Danish Straits (e.g Boesch et al., 2006; Eilola et al., 2009; Fonselius and Valderrama, 2003; Neumann et al., 2012; Pawlak. et al., 2009; Wasmund and Uhlig, 2003; Fredrik Wulff, 1990). The time scale of a typical "Major Baltic Inflow" (MBI hereafter), which provides salt and oxygen to the deepest parts of the Baltic Sea and fuels the Baltic Sea baroclinic circulation (Döös et al., 2004), is on the order of 40 days (Schimanke et al., 2014). MBIs are barotropic in nature, and the variability of the barotropic circulation on time scales of hours to days can affect the Baltic Sea ecosystem on time scales up to several decades or a whole century.

Fueled by advances in computer hardware, the quest towards a more comprehensive understanding of the crucial ventilation of the Baltic Sea has been aided by simulations of inflows with numerical general ocean circulation models (Hordoir et al., 2015), and it has been shown that these inflows are closely correlated to the sea surface height (SSH hereafter) variability in both the Baltic and the North Sea (Gustafsson and Andersson, 2001). An ocean model that provides a consistent representation of the Baltic Sea long term ecosystem with its specific haline dynamics and stratification on one side, and that allows to make an accurate forecast of SSH for the Baltic & North Sea basin, is not incompatible: it is complementary.

The North Sea is, compared to the Baltic Sea, a dynamical region with a water residence time of only a few years (Otto et al., 1990). It is characterized by strong tidal currents and a general cyclonic large scale circulation pattern (Winther and Johannessen, 2006) with major inflow along the British Isles in the western part of northern boundary and an outflow along the Norwegian Channel in the East (Figure 2).

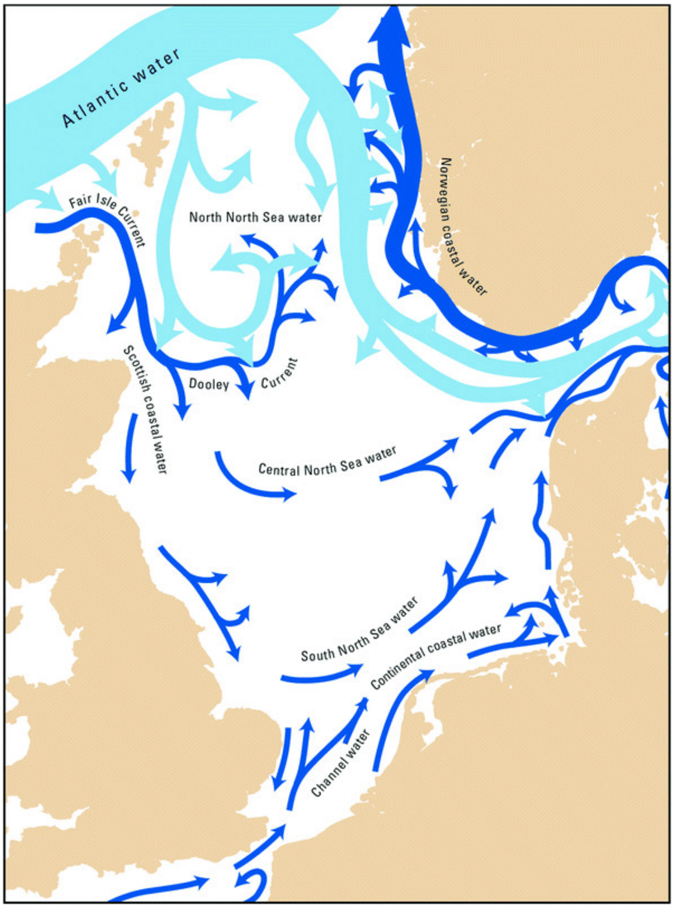

Fig. 2. Schematic view of the North Sea circulation (From OSPAR (2000)). The North Sea is a dominated by a cyclonic circulation (blue arrows) driven by wind and tidal forcing. The input of freshwater along South-Eastern coasts and from the Baltic Sea also creates a strong baroclinic circulation along the Eastern Side that brings Northern Atlantic water masses (green arrows) that eventually mix with fresher water masses to eventually create the Norwegian coastal current.

Strong local inflow of 0.29 Sv occurs via the straits of Pentland Firth and Faire Isle, and 1.33 Sv are obtained east of the Shetland Islands (Thomas et al., 2005). Besides this, around 0.15 Sv come through the English Channel (Otto et al., 1990; Thomas et al., 2005) and around 0.016 Sv are received from the Baltic Sea (Stigebrandt, 2001). Outflow to the North Atlantic at the Northern end of the Norwegian Channel amounts to 1.79 Sv. Unlike the Baltic Sea, the North Sea is not permanently stratified. During winter, enhanced wind induced mixing in combination with convective mixing maintain well mixed conditions almost everywhere with the exception of the Norwegian Channel region where fresh outflow waters from the Baltic Sea dominate (Schrum, 2001; Schrum et al., 2003; Ådlandsvik and Bentsen, 2007; Huthnance et al., 2009; Holt et al., 2010; Mathis et al., 2013; Emeis et al., 2015; Mathis et al., 2015). During summer, the deeper parts of the central and northern North Sea experience a strong thermal stratification (Mathis et al., 2013) whereas the shallow Southern North Sea remains mostly well mixed around the year though short term stratified periods are possible, (Baretta-Bekker et al., 2009). The timing and intensity of the seasonal stratification plays an important role for biogeochemical processes as it influences primary production, the start of the spring phytoplankton bloom, and the nutrient cycling in the North Sea (Pätsch and Kühn, 2008; Holt et al., 2012; Daewel and Schrum, 2013; Gröger et al., 2013).

For both the North Sea (Mathis et al., 2013; Graham et al., 2017), and the Baltic Sea (Meier et al., 2003; Burchard et al., 2009; Hordoir et al., 2015), there is a number of models of different complexity. Because the two seas differ so much in their oceanographical and biogeochemical characteristics it is plausible to setup separate models specific for each region, and to prescribe lateral boundaries at a reasonable location in the transition zone between the two seas. However, recent studies provide evidence that the simulation of the Skagerrak and Kattegat hydrography are often problematic in these model setups (Pätsch et al., 2017). As the dynamics in this transition zone between the Baltic and the North Sea are essential for a realistic simulation of major Baltic Sea inflows (MBIs), a combined Baltic-North Sea model is necessary to better understand their dynamics and their impact on the Baltic and North Sea physics and ecosystem. Especially for climate scenario simulations it is more appropriate to explicitly simulate potential changes in the Kattegat/Skagerrak region, than relying on a present day climatological prescription. Further, ocean models that include only the North Sea do not take into account the interaction with the Baltic Sea, and therefore rely on a freshwater provision to the North Sea that is not accurate in strength nor in time (Hordoir et al., 2013).

Early attempts of combined North Sea - Baltic Sea modelling were limited by a relative coarse resolution (approx. 11000 m, or 6 nm) and constrained on short term simulations of one year (Schrum and Backhaus, 2011). Only recently, attempts have been done to include the two seas in one model setup for longer periods and in high resolution. Daewel and Schrum (2013) used a coupled hydrodynamic-biogeochemical model and concluded that coupled Baltic and North Sea model setups can help to improve the performance in the Skagerrak area. Moreover, the model reasonably simulated the major MBIs during the hindcast period (Daewel and Schrum, 2013). Gräwe et al. (2015) presented a hydrodynamic model using adaptive vertical coordinates and with a resolution of 1852 m (or 1 nm). The authors found the mean state for the period 1997-2012 as well as the timing and amplitude of MBIs were well represented by the model. Tian et al. (2013) as well as Pham et al. (2014) presented each a hydrodynamic model coupled to an atmospheric model but they focused more on atmospheric dynamics and air sea interactions than on oceanographic topics.

In the present article, we provide a description and validation of Nemo-Nordic in its first mature version, Nemo-Nordic 1.0, based on Nemo 3.6. Nemo-Nordic is declined into two resolutions of 2 nautical miles (3704 m) and 1 nautical mile (1852 m). First prototype versions were already used for process studies in (Hordoir et al., 2013, 2015) or to specifically investigate the added value of interactive air-sea exchange of mass and energy fluxes (Gröger et al., 2015). The present version is the first reference, used both for research and forecast. This article provides a full validation of both barotropic and baroclinic dynamics, it shows the qualities and biases of the model. It is also a milestone that will be used for further development at a time when Nemo-Nordic extends beyond SMHI in different European institutions within the Copernicus framework for operational applications for example, but also for research.

Nemo-Nordic is a NEMO (Madec and the NEMO system team, 2015) based ocean model for Baltic & North Sea that can be used for climate, oceanographic process study, and operational oceanographic applications. Nemo-Nordic has been designed to be an advanced compromise to provide forecast or study Baltic and/or North Sea dynamics, at various time scales (operational or climate time scales), with a representation of processes occurring in both basins including overflows and sea-ice, within a reasonable range of computing resource. The inclusion of the both seas makes it possible to study the exchange between the two seas because its boundary condition is far enough from where this exchange occurs, unlike for example a Baltic Sea only ocean model (Meier et al., 2003). Unlike Nemo-Nordic, this latest model being in any case limited by its linear free surface, which produce conservation errors for the Baltic Sea in long term simulations, and forbids any possibility of representing properly ocean dynamics in any region of higher sea level variability, such as Kattegat, Skagerrak and the entire North Sea. Nemo-Nordic is also not the first model to include both Baltic and North-Sea basins, one could cite (Funkquist and Kleine, 2007) or (Madsen et al., 2015) as examples of models who already do. However these models do not permit to represent the main driver of the Baltic Sea ecosystem, the dense overflows that feed its very specific sill bounded estuarine circulation: this circulation is difficult to represent in z coordinates since such coordinate systems do not represent well dense overflows. In addition, the Baltic Sea halocline is tilted, and is featured in a very low turbulence environment. Representing the Baltic Sea halocline therefore requires a possibility to rotate the diffusion tensor to avoid diapycnal mixing, and to limit the vertical mixing length in case of low turbulence. The NEMO ocean engine allows to have tools such as bottom boundary layer parametrization, isopycnal diffusion in z coordinates, or advanced vertical turbulence schemes, that permit a better representation of such circulations. From a more general point of view, using a community engine such as NEMO means having the latest available developments in ocean and sea ice modelling. Further developments are now being made into Nemo-Nordic, such as wind wave coupling for example, that will keep this ocean modelling configuration to a state of the art level when it comes to Baltic and North Sea modelling.

2 Model setup: Nemo-Nordic

Nemo-Nordic is an ocean model setup for Baltic & North Sea. It is based on the "Nemo ocean engine", a set of ocean modeling tools supported by a large community, and in constant watch towards developments done in other community ocean models. More specifically, we apply the stable Nemo 3.6 version (Madec and the NEMO system team, 2015). The ocean component is coupled to the sea ice model LIM3 (Vancoppenolle et al., 2009). The first version of Nemo-Nordic were based on Nemo 3.3.1, switching to Nemo 3.6 which features a new coupling between barotropic and baroclinic modes ensures a much better representation of the barotropic mode, with a sea level representation of a higher quality. Technically, Nemo 3.6 and the use of the XIOS server was a key element to a more user friendly version of Nemo-Nordic.

2.1 Grid and bathymetry

The model domain of Nemo Nordic covers the English Channel, the North Sea and the Baltic Sea (Fig. 3). This domain bears similarities with that used in the Nemo based configuration described by Maraldi et al. (2013). The resolution of this latest configuration is higher than that of Nemo-Nordic, but also uses the features of the Nemo ocean engine to build regional and coastal configurations. The main interest of the two configurations is different: that of Maraldi et al. (2013) aims at resolving the European shelf dynamics, whereas the purpose of Nemo-Nordic is to represent the interaction between two basins with different dynamical features.

The area of Nemo-Nordic reaches from 4.15278 W to 30.1802 E and 48.4917 N to 65.8914 N. The grid is geographical, and in its 2 nautical version the horizontal grid has zonal/meridional increments of 0.05°, which corresponds to a horizontal resolution of approximately 2 nautical miles (3704 m). The resolutions of approximately 1 or 2 nautical miles are given as approximations, especially at these high latitudes where zonal scale factors differ between the Southern and Northern parts of the domain.

This resolution does not permit a proper description of the Danish Straits, which is a critical area of this configuration. However, in order to insure a proper communication between the Baltic and the North Sea, we tune a proper “impedance” of the Danish Straits in the model so that the flow between the two areas is consistent. We never checked if this feature allows a proper representation of the baroclinic flow within the straits, but since major Baltic inflows are mostly barotropic events we believe this is of secondary importance. However a higher resolution of the Danish straits will be implemented in the future using the AGRIF tool.

Nemo-Nordic uses z^* vertical coordinates, which is more simple than some other Baltic Sea models such as Gräwe et al. (2015) or the configurations develloped by Shapiro et al. (2013). Advanced hybrid coordinates permit a better representation of dense overflows to the Baltic Sea, but have a higher computational cost. However, the salinity biases based on the latest advances made in Nemo-Nordic show very acceptable range, as shown in Section 4, and the benefit of z^* coordinates from a vertical point of view allow multiple long term simulations with realistic computing power. Our model setup comprises 56 vertical levels. The vertical resolution is adapted to the physical properties of the Baltic and North Seas: the upper levels have a thickness of approximately 3 m until the typical level of the halocline is reached at 60 m. Below 60 m the layer thickness increases substantially: the layer thickness is 10 m at a 100 m depth, which is the typical halocline depth of the Norwegian Coastal Current (NCC hereafter) (Skagseth et al., 2011). Maximum values of 22 m are reached below 200 m. Note that the maximum decrease in resolution between two consecutive vertical levels is below 11%. With these increments, the vertical resolution of Nemo-Nordic is adapted to Baltic Sea conditions and less optimal to resolve the halocline of the NCC. However the NCC is a baroclinic Kelvin wave which has a permanent renewal of stratification coming from the constant runoff flux of the Baltic Sea and all the river inputs located along the Western Swedish and Norwegian coasts. Thus the NCC halocline is less sensitive to coarse vertical resolution than the halocline of the Baltic Sea, which is not permanently renewed and is suspected to impact spurious salt water inflows in ocean models. Partial steps are used at bottom level to ensure a proper fit between the input bathymetry and the vertical grid.

The cross sectional area of the Danish Straits is critical as it ensures the exchange between Baltic and North Seas. The resolution of the model does not permit to have a proper representation of the Danish Straits. However, it is possible to represent each cross-section so that it has the same hydraulic impedance as in reality. This was achieved by fitting the area of each critical cross-section of the model with its equivalent area in the real world. More precisely, this means that the area of each critical "numerical cross-section" of the model is made to fit with the surface of the real cross-sections of the Danish Straits.

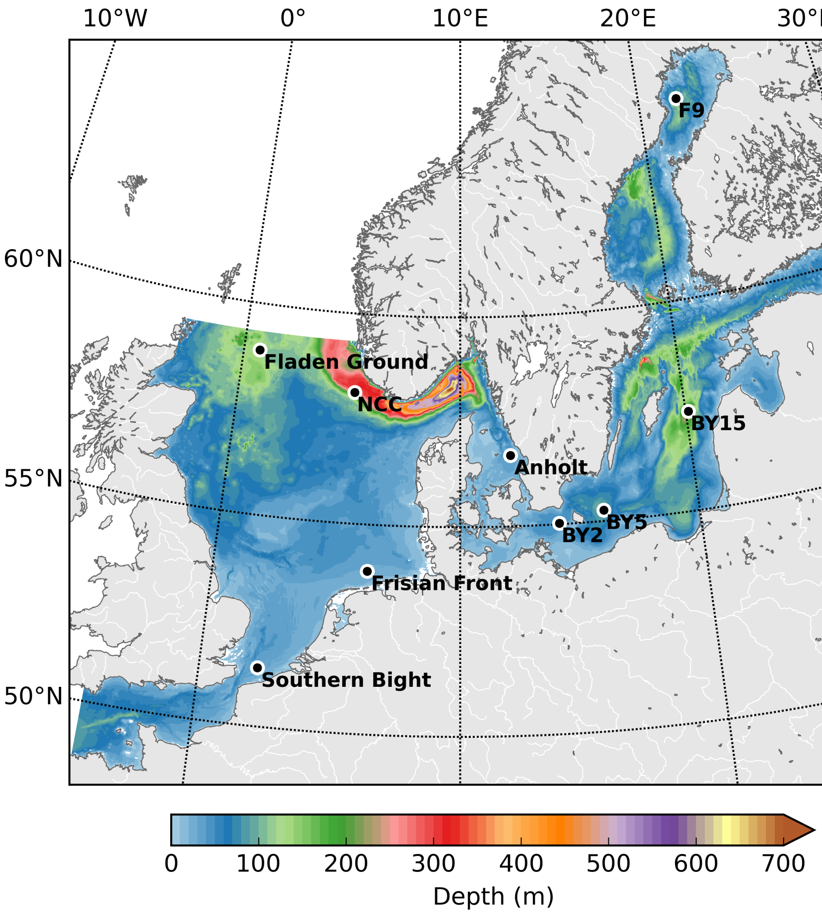

Fig. 3. The model domain and bathymetry of Nemo-Nordic. The filled circles show the locations of validation stations for salinity and temperature.

2.2 Physical Settings

2.2.1 Free Surface and Time Stepping

Nemo-Nordic uses a non-linear free surface (`key_vvl`) with a (`key_dynspg_ts`) option to split the computation of barotropic and baroclinic modes. In comparisons with previous ocean models such as that used by Meier (2004) for example which used a linear free surface, these features enable Nemo-Nordic to run in regions of high tidal amplitude like the North Sea and the English Channel. Tuning is done in order to obtain an accurate SSH representation. We use a variable bottom roughness (`ln_bfr2d = .true.`) along the cyclonic pathway of barotropic Kelvin waves in the North Sea. This roughness is optimized to obtain the best possible SSH amplitude. Nemo-Nordic runs with a baroclinic time step of 360 s, which proved to be the best compromise between stability and computational speed. The barotropic time step is set to be 30 times smaller.

2.2.2 Mixing and Dense Overflows Representation

Vertical and horizontal mixing (and the connections between each of them) is a critical element when it comes to a Baltic & North Sea configuration. The major difficulty is to simulate the crucial dense water overflows in the Baltic Sea (Hordoir et al., 2015). In order to ease this process, Nemo-Nordic uses a bottom-boundary-layer parametrization (Beckmann and Döscher, 1997) for tracers (`key_trabbl`) in order to reduce the biases of a z-coordinate ocean models when it comes to the representation of dense overflows. In NEMO, the bottom-boundary-layer can be used with an upstream advection scheme or with a purely diffusive scheme, or with a mixture of both. For Nemo-Nordic, sensitivity experiments have shown that the use of a purely diffusive scheme results in more realistic deep salinity in the Baltic Sea. Using an advective scheme results in a lower deep salinity, most likely due to a higher entrainment rate during major Baltic inflow events. One could object rightly that using sigma coordinates could have solved this issue without the use of such a parameterization. But using such a coordinate system would on the other hand create a strong diapycnal mixing of the Baltic Sea halocline, and most likely pressure gradient errors in the steepest places of the North Sea such as the Norwegian trench.

However, the use of the bottom-boundary-layer parametrization is not enough to achieve a correct representation of the overflows. The tuning of the mixing was a major issue and required a tuning process. Nemo-Nordic includes two basins which have very different dynamical features: The North Sea is strongly influenced by tides, tidal mixing and relatively strong winds. In the North Sea, the stratification is relatively weak, with the exception of a summer thermocline in some regions, regions of freshwater influence (Simpson and Souza, 1995) and the region of the Norwegian Coastal current (Hordoir et al., 2013). In contrast, the Baltic Sea has almost no tides, is less exposed to wind forcing and has a strong permanent stratification. Nemo-Nordic uses a two equation turbulence closure, based on a $k-\epsilon$ turbulence scheme (`key_zdfgls`). In addition, the Galperin parameterization is used (Galperin et al., 1988), in order to preserve the Baltic Sea permanent stratification. This parameterization limits the mixing length computed by the vertical turbulence model in case of low turbulence and high stratification, which fits perfectly with the Baltic Sea halocline environment. Experiments done on the configuration without this latest parameterization yield a Baltic Sea permanent halocline that vanishes in a few years only. The Galperin coefficient is set to 0.17 which proves to be a good compromise between deep salinity and seasonal thermal stratification. A too high Galperin coefficient produces a higher deep salinity, but also a very thin and un-realistic seasonal thermocline. In addition to the Galperin parameterization, the background levels of turbulent kinetic energy are turned to their minimum values, the goal being always to limit as much as possible mixing at the level of the Baltic Sea halocline.

Horizontal mixing is based on a Laplacian approach combined with the rotation of the horizontal diffusion tensor (`key_ldfslp`). However, this does not result in a real isopycnal diffusion in the sense that Nemo-Nordic is still based on a z coordinate system and not on isopycnal coordinates. Close to the bottom, sensitivity experiments have demonstrated that the rotation of the diffusion tensor did not enable to follow dense salt inflows: increasing horizontal diffusivity resulted in lower deep salinity, or even no penetration of dense inflows at all, showing that diapycnal mixing is created by horizontal diffusion, even when the rotation of the diffusion tensor is activated. The first versions of Nemo-Nordic used a Smagorinsky approach in order to limit horizontal mixing as much as possible, but this approach finally resulted in very weak Baltic Sea salt inflows, and a diffusivity impossible to control. Our final strategy has therefore been to create a viscosity/diffusivity coefficient which is high where model stability requires it the most (i.e.: above the halocline), and low where it is crucial for diffusivity to be as low as possible to avoid diapycnal mixing. After a suite of sensitivity runs we decided on using spatially varying values for viscosity and diffusivity. From the surface to a depth of 30 m the viscosity is set to values ranging from 30 to 50 $m^2\ s^{-1}$ for the Baltic and the North Sea respectively, while we set diffusivity to a tenth of this value. Below this depth the values of viscosity is reduced to 0.1 $m^2\ s^{-1}$. The same increase was applied to the diffusivity which is still set to a tenth of the value for viscosity. This feature works as long as the Baltic Sea halocline is located at this precise depth, but should be changed if the halocline depth changes. Along the open boundaries, the viscosity is increased to 800 $m^2\ s^{-1}$ over the entire water column, decreasing rapidly to standard values within a few grid points inside the domain.

A free slip option is taken for the lateral boundary conditions.

2.3 Boundary Conditions

2.3.1 Open Boundaries

Nemo-Nordic has two open boundaries, a meridional one in the western part of the English Channel, and a zonal one set between Scotland and Norway. The setting of the boundary conditions uses the open boundary condition module of Nemo (`key_bdy`), as well as the tide module (`key_tide`).

Several settings can be used for boundary conditions. Tidal harmonics are taken from Egbert and Erofeeva (2002); Egbert et al. (1994) although further investigation is also being made using the FES tidal model (Lyard et al., 2006). Harmonical values for SSH are interpolated on the open boundaries of Nemo-Nordic. Harmonical tidal transports (in $m^2\ s^{-1}$) are also interpolated in the same manner and then divided by the local depth of the Nemo-Nordic domain. In research mode, temperature and salinity boundary conditions may come from climatological data or from climate simulations, and a simple storm surge model is used, model itself corrected by a global ORCA0.25 configuration to take into account seasonal variability due to temperature and salinity variations. In operational mode, Nemo-Nordic uses ECMWF forecasted data for its SSH, temperature and salinity boundary conditions.

2.3.2 Atmospheric forcing

Nemo-Nordic has been so far used in forced mode using prescribed atmospheric conditions and the CORE bulk formulation (Large and Yeager, 2009).

To cover a long period, the atmospheric forcing is based on different sources. The driving data of the period 1961-1978 is based on downscaled ERA40 data (Uppala et al., 2005). The ERA40 reanalysis is downscaled with the Rossby Centre regional atmospheric model version 4 (RCA4) with spectral nudging (Berg et al., 2013). The downscaling is necessary to improve the horizontal resolution of the global reanalysis data set. Here, we use data from an RCA4 set-up with a horizontal resolution of 11km. The frequency of the driving data is hourly.

With the beginning of 1979 we change the atmospheric forcing to the SMHI reanalysis product EURO4M which is available until the end of 2013 (Dahlgren et al., 2016; Landelius et al., 2016). The EURO4M data is available 3 hourly and with a horizontal resolution of 22km. EURO4M incorporates data assimilation which assures the best quality for our driving data. In operational mode (Nemo-Nordic 1nm), the simulations were forced by HIRLAM C11 (hirlam.org).

In forecast mode, Nemo-Nordic uses a combination of hourly ECMWF LL01 (9 km) data and Arome-data (2.5km).

2.3.3 Light Penetration

A proper light penetration parameterization proved to be an important feature in order to reproduce the proper thermal structure, and especially the formation of a summer "Cold Intermediate Layer". The Baltic Sea has turbid waters which prevent deep light penetration, concentrating the summer heat input close to the surface, and hence easing the autumn cooling. Nemo-Nordic uses a Red-Green-Blue light penetration parameterization, together with a constant chlorophyll value of 0.5 mg m^{-3} to represent the turbid Baltic Sea waters. Failing to use chlorophyll concentration results in a too thin and too shallow cold intermediate layer. This chlorophyll concentration does not pretend to be realistic from a biogeochemical point of view, it corresponds to a mean value for both basins which allow a realistic light penetration in an area which has a water turbidity higher than that of the global ocean.

2.3.4 River discharge

The Baltic Sea salinity is sensitive to the accumulated freshwater input since the exchange with the open ocean is very limited (e.g. Meier and Kauker, 2003). Freshwater supply to the Baltic Sea in the simulation must therefore be handled with care. Here, we are using data from the HYdrological Predictions for the Environment (HYPE) model (Donnelly et al., 2016). The model simulates a mean runoff to the Baltic Sea of roughly 16000 $m^3\ s^{-1}$ for the period 1981-1998. However, Meier and Kauker (2003) state that the observed runoff for the same period is 15053 $m^3\ s^{-1}$ with an even lower value (14085 $m^3\ s^{-1}$) for the period 1902-1998. Consequently, we reduced the freshwater supply computed by HYPE. We have chosen a general reduction of 10% which gives more realistic runoff for the Baltic Sea. Moreover, this improved the Baltic Sea salinity (not shown). The freshwater input to the North Sea including the Skagerrak and Kattegat area amounts to 11515 $m^3\ s^{-1}$ after the reduction by 10%. The river runoff is spread over 424 river mouths in the entire model domain whereas more than 250 are

Table 1. SSH representation, in terms of correlation, standard deviation (meters) and root-mean-square-deviation (meters), made by Nemo-Nordic for 9 Baltic Sea stations. The diagrams are based on a 18 months period, starting on July 1st 2011, and based on hourly output SSH.

	Std. Obs	1nm std	Corr. 1nm	RMSE 1nm	Std. 2nm	Corr. 2nm	RMSE 2nm
Kalix	0.28	0.27	0.97	0.07	0.24	0.96	0.076
Furögrund	0.24	0.23	0.96	0.07	0.21	0.95	0.075
Spikarna	0.2	0.2	0.95	0.06	0.18	0.94	0.07
Forsmark	0.19	0.19	0.95	0.06	0.17	0.94	0.07
Landsort	0.18	0.18	0.95	0.06	0.16	0.95	0.07
Kronstadt	0.29	0.29	0.95	0.09	0.27	0.95	0.09
Öland	0.17	0.17	0.95	0.06	0.16	0.94	0.06
Simrishamn	0.19	0.19	0.94	0.06	0.18	0.94	0.06
Skanor	0.2	0.20	0.92	0.08	0.19	0.92	0.08

Table 2. SSH representation, in terms of correlation, standard deviation (meters) and root-mean-square-deviation (meters), made by Nemo-Nordic for 9 stations located in the Danish Straits, Kattegat and Skaggerak. The diagrams are based on a 18 months period, starting on July 1st 2011, and based on hourly output SSH.

	Std. Obs	1nm std	Corr. 1nm	RMSE 1nm	Std. 2nm	Corr. 2nm	RMSE 2nm
Gedser	0.23	0.21	0.93	0.08	0.21	0.94	0.08
Barsebäck	0.18	0.19	0.88	0.09	0.14	0.68	0.13
Klagshamn	0.18	0.18	0.91	0.08	0.19	0.92	0.08
Rödvig	0.21	0.2	0.93	0.08	0.19	0.92	0.08
Göteborg	0.22	0.21	0.91	0.09	0.18	0.93	0.08
Smögen	0.22	0.23	0.91	0.1	0.2	0.93	0.08
Viken	0.21	0.19	0.90	0.1	0.18	0.90	0.1
Skagen	0.24	0.26	0.90	0.11	0.225	0.91	0.1
Kungsvik	0.24	0.25	0.92	0.1	0.22	0.93	0.09

located in the Baltic Sea (excluding the Skagerrak and Kattegat area). The UNESCO equation of state for sea water is used. The reference density is set to 1035 $kg\ sm^{-3}$, which is most likely over estimated. Further experiments should be done on this point.

2.3.5 Sea-Ice

Nemo-Nordic benefits from the use of the Nemo ocean engine and of its advanced sea ice model LIM3. Sea ice is a Baltic Sea specific feature that owes to the Baltic Sea low salinity. Being able to represent sea ice dynamics properly is compulsory when it comes to a Baltic Sea ocean model. Models such as Gräwe et al. (2015) do not include this feature. The sea ice in the Nemo-Nordic is validated in Pemberton et al. (2017). Comparison done with (Funkquist and Kleine, 2007) suggest that Nemo-Nordic reaches so far the highest accuracy of sea ice representation for the Baltic Sea.

3 Validation of barotropic mode and surface currents

3.1 Sea Level

To model and forecast SSH is one of the major aims of Nemo-Nordic. This section provides a statistical comparison between measured and modeled SSH at different tide gauges in the Baltic & North Seas.

We have chosen tide gauges which are as representative as possible for the respective regions. The Figures are subdivided into tide gauges in the Baltic Sea, the Danish Straits plus Kattegat and Skagerrak and the North Sea, including the English Channel. The comparisons, are based on a 18 month period, lasting from July 1st 2011 and ends on December 31st 2012 on an hourly frequency. The respective model simulation was started one month before to allow for a spinup time. Each area is presented in a specific array.

The Taylor diagrams show generally very high correlations between model and observations in almost all regions. In the North Sea and the English Channel, correlations are highest and mostly close to 0.99, with the one exception of Hanstholm,

Table 3. SSH representation, in terms of correlation, standard deviation (meters) and root-mean-square-deviation (meters), made by Nemo-Nordic for 6 stations located in the North Sea. The diagrams are based on a 18 months period, starting on July 1st 2011, and based on hourly output SSH.

	Std. Obs	1nm std	Corr. 1nm	RMSE 1nm	Std. 2nm	Corr. 2nm	RMSE 2nm
Calais	1.95	1.5	0.99	0.55	1.65	0.98	0.4
Dover	1.8	1.4	0.99	0.4	1.5	0.99	0.3
Aberdeen	1.05	0.95	0.99	0.15	0.95	0.99	0.15
Plymouth	1.35	1.25	0.98	0.25	1.3	0.98	0.25
Helgoland	0.9	0.74	0.98	0.2	0.82	0.97	0.2
Hanstholm	0.28	0.24	0.93	0.11	0.26	0.98	0.1

where correlations are around 0.94. In the Baltic Sea, correlations are always close to 0.95. In the narrow Danish Straits and the Kattegat, regions with complicated topography, the correlations are lowest, but still exceed generally 0.9. Exceptionally low correlations (0.6) are obtained in Barseback and only when Nemo-Nordic 2nm is used. When Nemo-Nordic 1nm is used, the minimum depth of the ocean model is set to 3 m, compared to 9 m, which gives a better representation of the shallow banks located in the Öresund area, and of the amplification of barotropic waves. This feature was not implemented in Nemo-Nordic 2nm where the main focus is the Baltic / North Sea exchange. Using wetting and drying in the future should help better representations of SSH in shallow areas affected by strong sea level variability.

The Taylor diagrams illustrate also that the amplitude of the simulated SSH variations are close to the observed one.

Biases in terms of SSH representation can be summarised as follows. Nemo-Nordic usually has a negative bias in terms of representation of the low frequencies in the North Sea, Skagerrak and Kattegat. In the same regions, the opposite bias can be noticed when it comes to higher frequencies: tidally driven SSH can present overshoots in some places. In the Baltic Sea, one can notice that the tidal signal is usually a bit too high, but since its amplitude remains very small in comparison of other frequencies it does not affect the quality of the SSH representation significantly. The representation of lower frequencies does not reveal any significant bias in the Baltic Sea.

Nemo-Nordic 1nm represents SSH better than Nemo-Nordic 2nm, which partially is due to the higher resolution for most features. For example in the Danish Straits, the representation of shallow banks has been taken into account in Nemo-Nordic 1nm, and the size of the cross sections has been adapted to represent the North Sea / Baltic Sea exchange. This allows to amplify incoming barotropic waves which is essential in order to get the right SSH variability in the Danish Straits tide gauges. In Nemo-Nordic 2nm, the main concern has been to insure the right Baltic / North Sea exchange which is crucial for having a correct representation of Baltic Sea salt inflows, which are one of the main drivers of the Baltic Sea ecosystem, and of its long term thermo-haline structure.

In summary, we identified the following key processes to model realistic SSH variations:

- In Nemo-Nordic, the SSH and SSH variability in the North Sea is to a first order barotropicaly driven, and is built by a combination of tidal waves entering through the Northern boundary and Western Boundaries, wind driven SSH built over the Northern Atlantic, and wind driven SSH over the North Sea. To get a correct representation of the SSH variability and the cyclonic circulation in the North Sea, it is important to have high frequency (hourly) boundary conditions that takes into account all these aspects.

- In the Kattegat/Skagerrak region, as one moves further towards the entrance of the Baltic Sea, the effect of tides and of high frequency waves generated in the Northern Atlantic or the North Sea becomes less important. The low frequencies, on the other hand, generated by the storm surge model over the North Atlantic turned out to be important for this region. The shelf break along the coast amplifies the effect of coasts on barotropic waves arriving from the North Sea and helps representing the SSH variability and its extremes. A higher vertical resolution in the shallow areas improves the representation of the SSH variability, especially in the Skagerrak-Kattegat. This last effect becomes crucial in the Danish Straits where the shallow banks need to be represented.

- The SSH variability in the Baltic Sea is barely influenced by any tidal variability, but is highly influenced by low frequency forcing coming from the Northern Atlantic and the North Sea. In addition, local wind forcing over the Baltic Sea explains higher frequencies. The only communication between the Baltic and the North Sea being the Danish Straits, the adjustment of cross-sections and of the friction in this area are of crucial importance to chose which barotropic frequencies can penetrate the Baltic Sea. The Danish Straits should act as a well tuned low pass filter which allows low frequency waves to penetrate the Baltic Sea, but lets little high frequency power enter the Baltic Sea.

3.2 Surface Currents

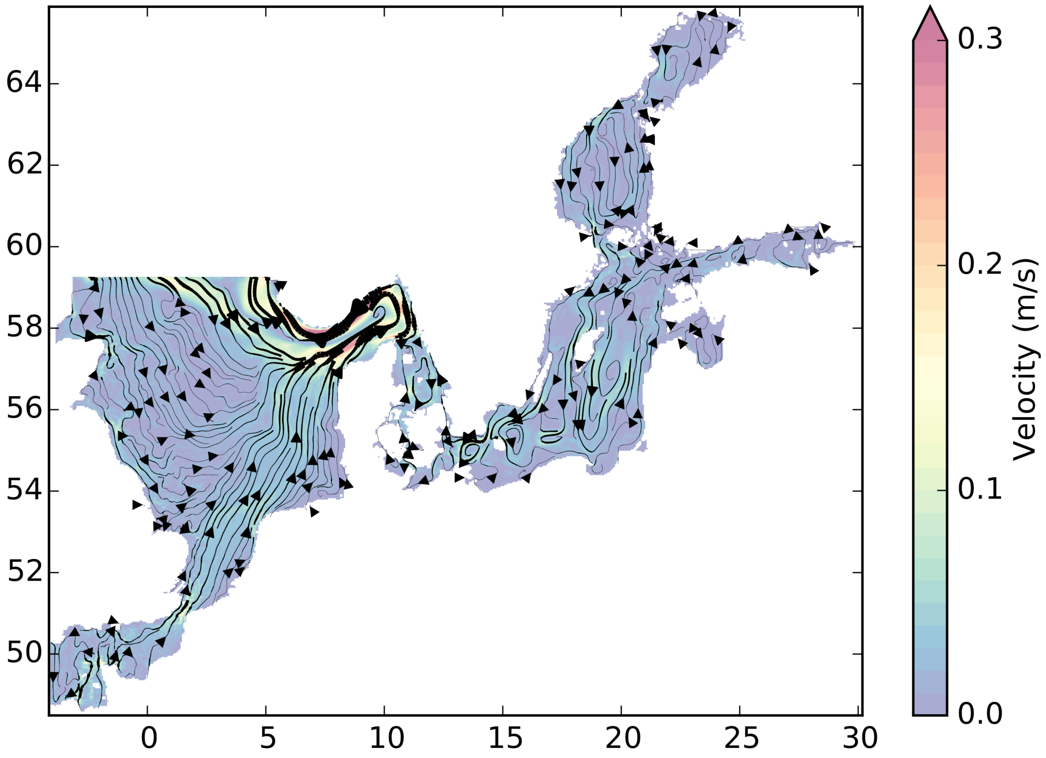

Fig. 4. Simulated surface (0-30 m) currents, climatology for 1979-2010. The lines and arrows show the streamlines and directions of the current vector field. The thickness of the line is scaled with respect to the speed of the current. The filled contours show the current speed in m/s

3.2.1 General circulation

The model reproduces the general cyclonic surface circulation pattern in the North Sea (OSPAR, 2000), with a southward flow in the western part of the basin, a northeastward flow along the southern coast, and a northward flow along the Norwegian coast in the Norwegian coastal current (Fig. 4). The strongest modelled southward flow of Atlantic water through the Northern boundary occurs just next to the NCC. This flow forms a current that flows South-East and enters the well known cyclonic circulation pattern in the Skagerrak, in good agreement with the observed surface currents in the North Sea (OSPAR, 2000). A part of the southward flow along the British Isles also deviates eastward to directly join the eastward flow towards the Skagerrak. Another part flows further to the South and mixes with inflow from the English channel. The larger part of inflowing Atlantic water from the Northern boundary is restricted to north of 54 °N and then recirculates mainly following the topography of the Dogger Bank. The southern North Sea is dominated by inflows waters from the English Channel.

In the Baltic Sea and its sub-basins the model reproduces the observed general cyclonic circulation patterns (Elken and Matthäus, 2008), with a Southward flow in its Western part, and a Northward flow in its Eastern part. In the Gotland basin the model reproduces the Southward flow on both sides of Gotland, and the Northward flow along the coast of Baltic, giving rise to the cyclonic structure over the Gotland deep (Fig. 4). In the Kattegat the model simulates a general anticyclonic flow in agreement with Nielsen (2005), and resolves the northward flowing Baltic Current along the Swedish coast, that feeds low saline waters into the NCC.

3.3 Overturning circulation

The inflows and outflows through critical cross-sections, where observational estimates exists, have been calculated for the period 1979-2010. Inflows are defined as volume transports directed inwards to the domain, and outflows are defined as transports directed outwards. For the Baltic Sea a longitudinal cross section has been taken along 12.90 °E, and inflowing waters are defined as transports in the positive x-direction, and outflows in the negative. For the strait of Dover a longitudinal cross-section has been taken along 50.99 °N. Here the flow is barotropic and there is only a mean inflow to the North Sea. For the Northern Boundary, taken along 58.06 °N, the inflow is all transports in the negative y-direction, and the outflow is all transports in the positive y-direction.

As shown in table 4, the modelled transports agrees well with observational estimates, which is an additional indication that the general circulation of the North and the Baltic Sea is well reproduced by the model. The modelled flows gives a water residence time of 23 and 1.8 years in the Baltic Sea and the North Sea, respectively.

The circulation in the North Sea is mainly of a barotropic feature. Barotropic stream functions of the horizontal overturning circulation, showing the general cyclonic circulation of the North Sea, are displayed in Figure 5. The largest flows are found in the Norwegian trench, where the overturning barotropic circulation amounts to 0.9 Sv, in good agreement with the calculated fluxes in Table 4

Table 4. Volume flow (Sv) through cross-sections, climatological mean for 1979-2010.

	Model		Observations		
Cross section	Inflow	Outflow	Inflow	Outflow	Reference
Strait of Dover	0.110	-	0.11-0.17	-	Otto et al. (1990), and references therein
Northern boundary	0.794	0.928	0.93-1.73	1.34-1.8	Otto et al. (1990), and references therein
Baltic Sea	0.029	0.044	0.027	0.043	Savchuk (2005)

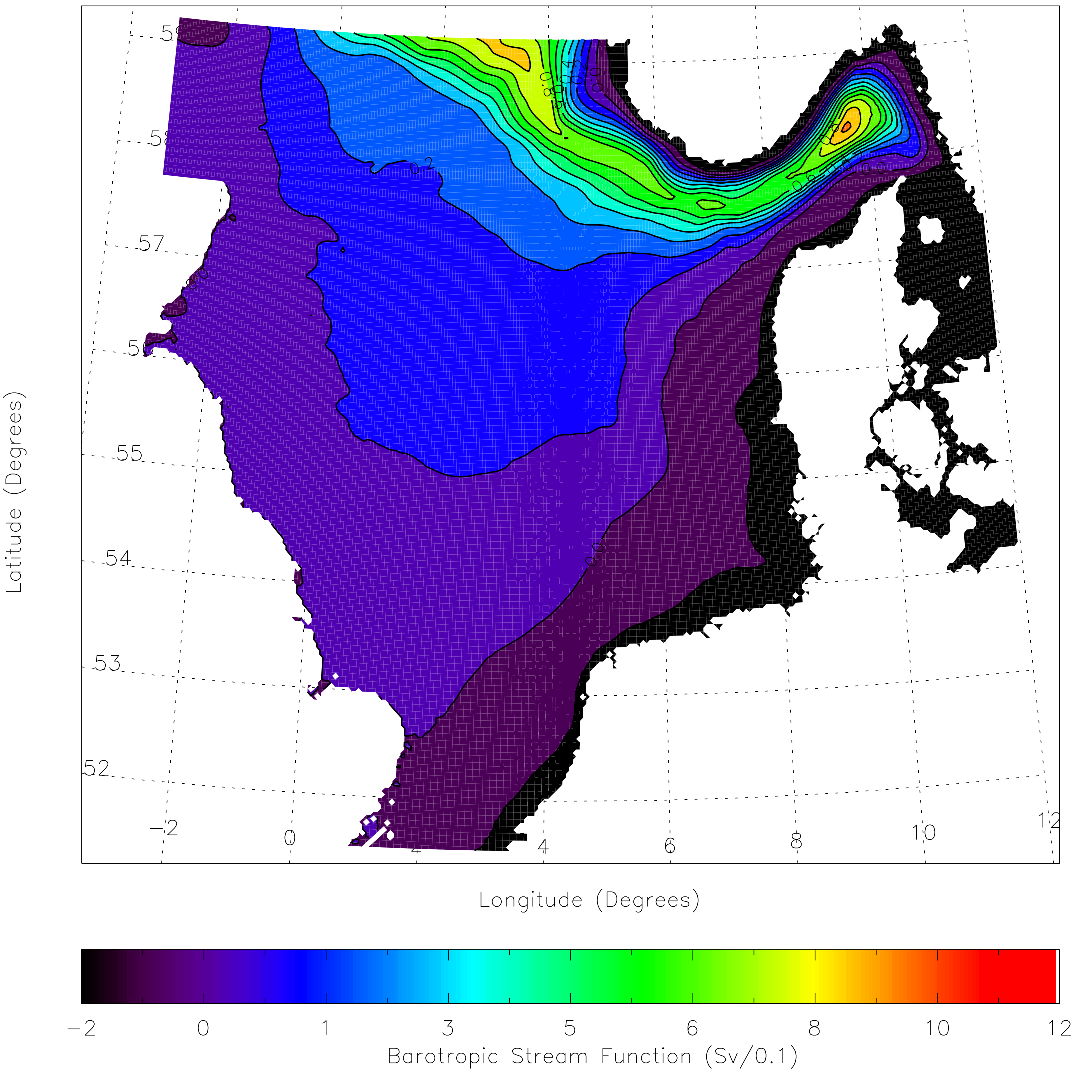

Fig. 5. Barotropic stream function (Sv), climatology for 1979-2010.

4 Salinity and temperature

4.1 Surface temperature and salinity

A validation of the simulated mean surface salinity and temperature is made (Figures 6 and 7) using the Janssen et al. (1999) climatology. The values are computed as a mean value over the first ten meters. For the Baltic and North Sea, the overall surface salinity is well reproduced. There is, however, a positive surface bias in the Baltic Sea. Especially one can notice that the penetration of the 8 PSU iso-haline within the estuary is too high. The 7 PSU iso-haline is also located a few nautical miles too far North. In the North Sea there is a negative bias in freshwater-influenced areas (the NCC and in the Southern German Bight). For Sea Surface Temperature (SST), the structure is similar to observations but there is a positive bias of less than 1 degree over all the domain. This bias seems to partially come from a warm bias in the atmopheric forcing (in winter) (Landelius et al., 2016), and partially from surface overshoots during the summer period. Sensitivity experiments have shown that the positive SST bias during summer time is lower if the Galperin coefficient used to maintain a stable haline stratification is lowered. In order to avoid these effects, further development is being made to decouple the Galperin parameterisation from thermal effects.

4.2 Thermohaline structure of the Baltic Sea

The thermohaline structure of the Baltic Sea exhibits two types of variability. First, a spatial variability which makes that the Baltic Sea has strong salinity gradients from the surface towards the bottom, but also presents estuarine features which results in a decreasing salinity from South towards North. Strong temperature gradients also exist as the Northern regions of the Baltic Sea have a much colder climate than those located in its Southern part. From a temporal point of view, surface salinity exhibits a seasonal variability (Hordoir and Meier, 2010), and deep salinity has a lower variability highly related to the occurrence of deep salt inflows (Hordoir et al., 2015). Surface temperature has a strong seasonal cycle related with summer stratification and its destruction during autumn. The models ability to reproduce the thermohaline structure and its variability on different time scales will be validated below.

4.2.1 Vertical structure and seasonal variability

The haline vertical structure of the Baltic Sea is in general well reproduced by Nemo Nordic (Fig. 8), with a distinct halocline separating the surface waters from the deeper waters. In the Bothnian Bay and the Kattegat (F9-A13 and Anholt), the modeled depth (50 and 20 meters, respectively) and strength of the halocline, corresponds well to observations. There is a small negative salinity bias over the whole water column in the Bothnian Bay, while the overall salinity is well reproduced in the Kattegat. In the Baltic Proper and the Bornholm Basin (BY15 and BY5), the modeled halocline is weaker and shallower than the observed one. The surface water at these stations tend to have a positive bias, while the deeper waters tend to have a negative bias, suggesting a too strong mixing between surface and deep waters. No stronger seasonal cycles exist in the haline structure, except for a freshwater pulse arriving in the surface waters during summer months, which is captured by the model at all stations.

The thermal vertical structure is dominated by the seasonal thermocline. In the Kattegat, Bornholm Basin and the Baltic proper (Anholt, BY5 and BY15), it starts forming earlier than in the Bothnian Bay (F9-A13), both in the model and in the observations (Fig. 9). The later formation of the thermocline in the Bothnian Bay is partially due to the lower insolation at higher latitudes, but also due to the non-linearity of the equation of state at low salinities. The temperature of maximum density is higher at lower salinities, meaning that the water column has to completely mix before the formation of the thermocline can start, which is well reproduced by the model. The model's development of the seasonal thermocline and its deepening agrees well with observations in the Kattegat, the Bornholm basin and in the Baltic proper. In the Bothnian Bay no conclusions can be drawn on this aspect due to a lack of measurements between 15 and 40 meters, where the thermocline is situated. The break up of the thermocline is also well represented in the model. The model has on the other hand difficulties in representing the colder intermediate waters in the Bornholm basin and the Baltic Proper, which have a warm bias. This might be related to biases in the atmospheric forcing (Landelius et al., 2016), as these waters are formed during winter convection. Indeed, the simulated winter surface temperatures at BY5 and BY15 tend to have a warm bias. The modelled cold intermediate waters also descend too deep towards the end of the year. This might be related to the weaker halocline, and thus probably stronger mixing, in the model. The deep waters below the halocline are warmer than the intermediate waters, which is reproduced by the model. In the model it is, however, about 0.5 degrees warmer than in the observations at the BY15 station.

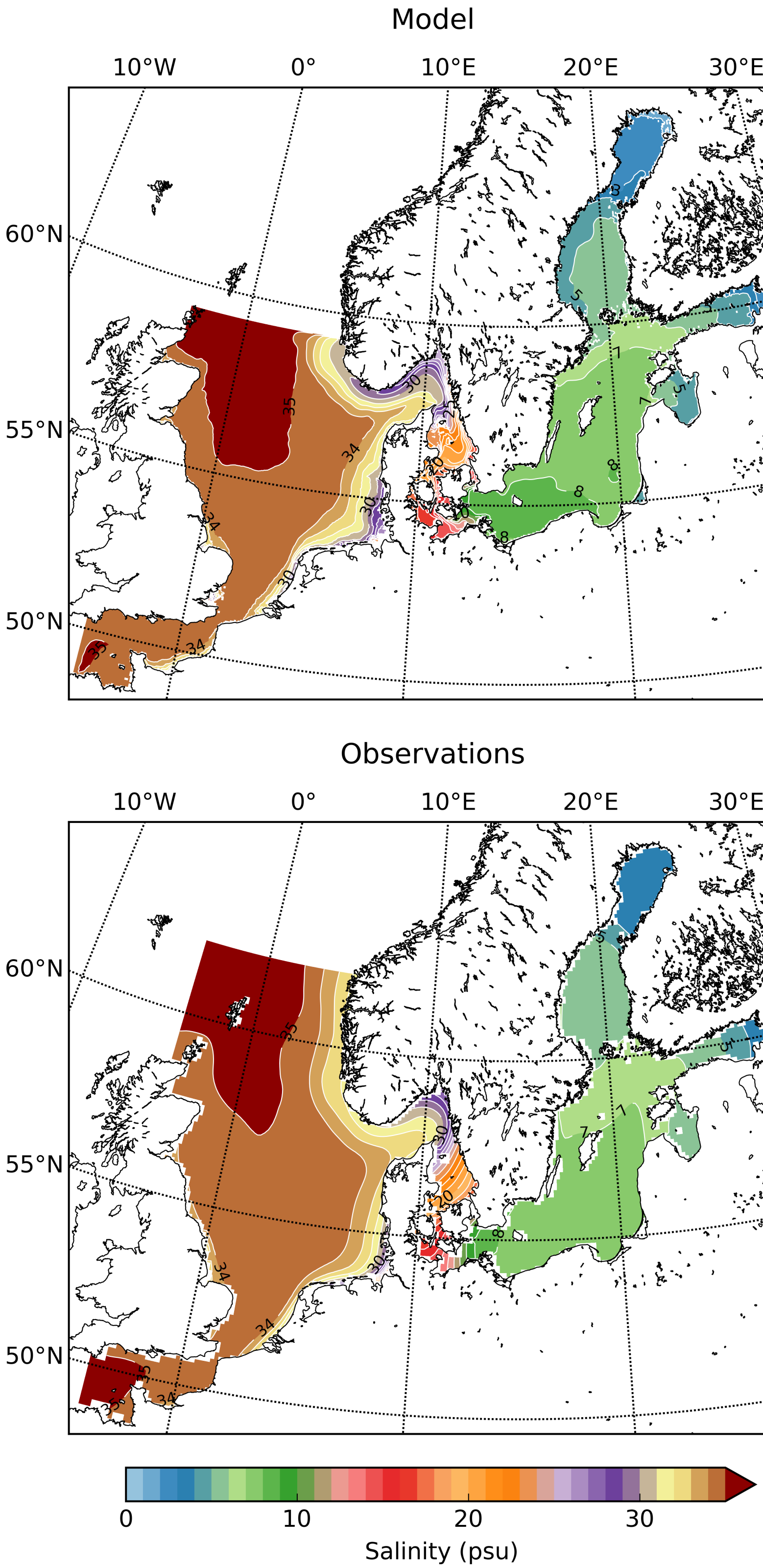

Fig. 6. Mean surface (0-10 m) salinity for Baltic, North Sea and English Channel, as simulated by Nemo-Nordic for the period 1979-2010 (upper figure) and from observations (lower figure) from Janssen et al. (1999).

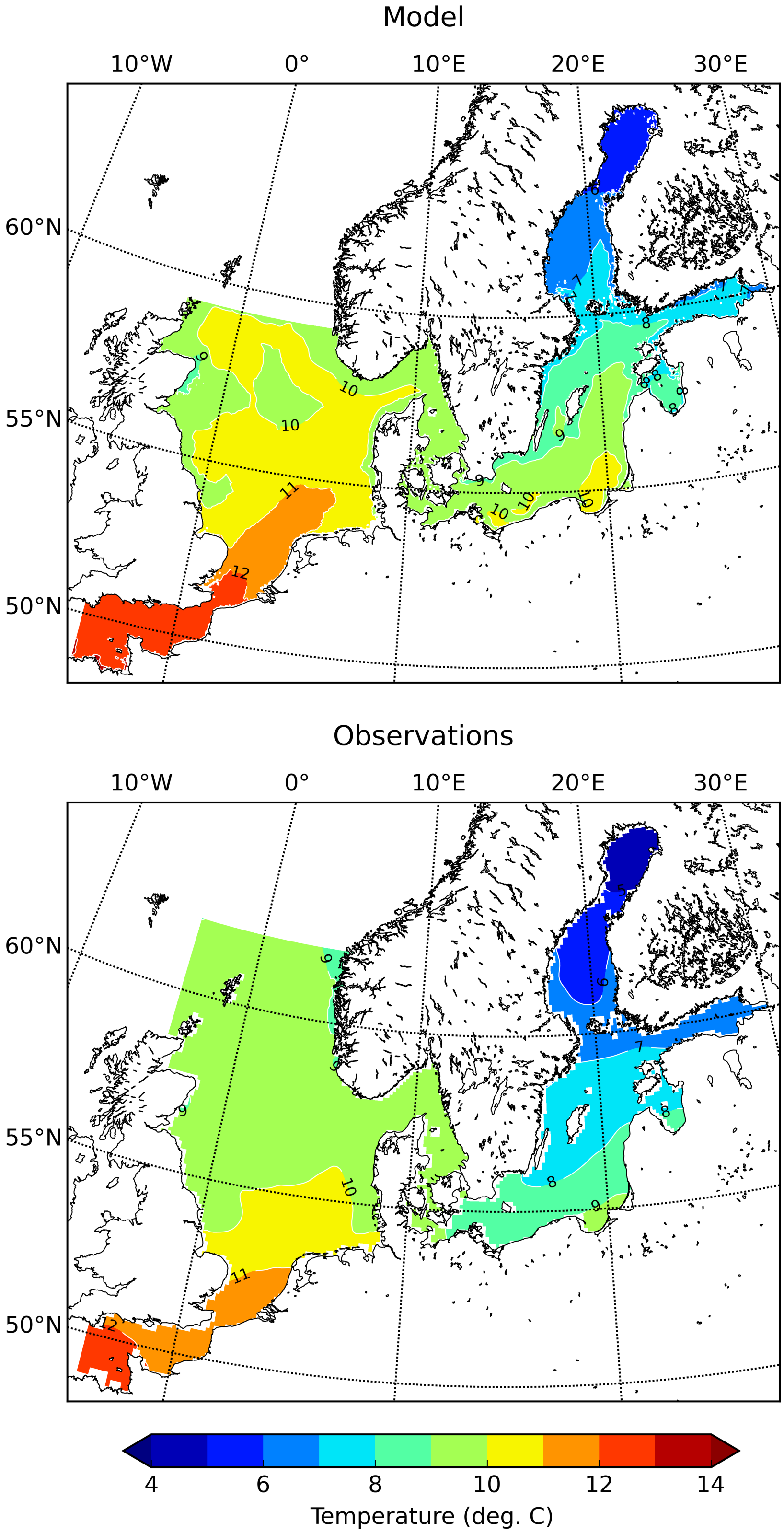

Fig. 7. Mean surface (0-10 m) temperature for Baltic, North Sea and English Channel, as simulated by Nemo-Nordic for the period 1979-2010 (upper figure) and from observations (lower figure) from Janssen et al. (1999).

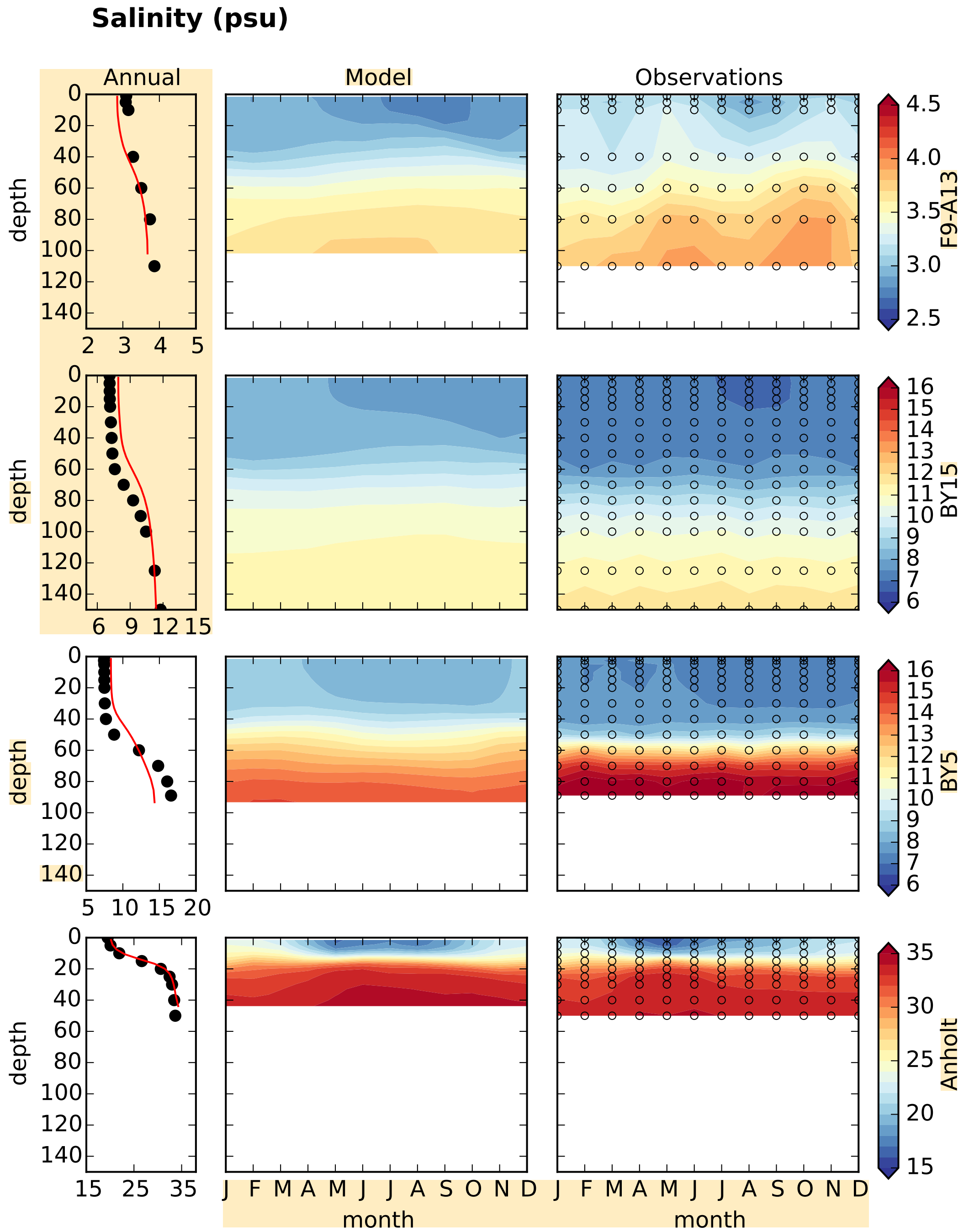

Fig. 8. Haline structure for four different stations of the Baltic Sea, from top to bottom F9-A13 station in the Bothnian Bay, BY14 station in the Baltic Proper, BY5 station in the Bornholm Basin and Anholt station in Kattegat. The left column displays annual mean depth profiles, where the red line is simulated salinity and black dots are observations. The middle and the left columns show seasonal variations in the model and the observations, respectively. In the left column the transparent circles show sample depths, the observations are based on a 1979-2010 climatology.

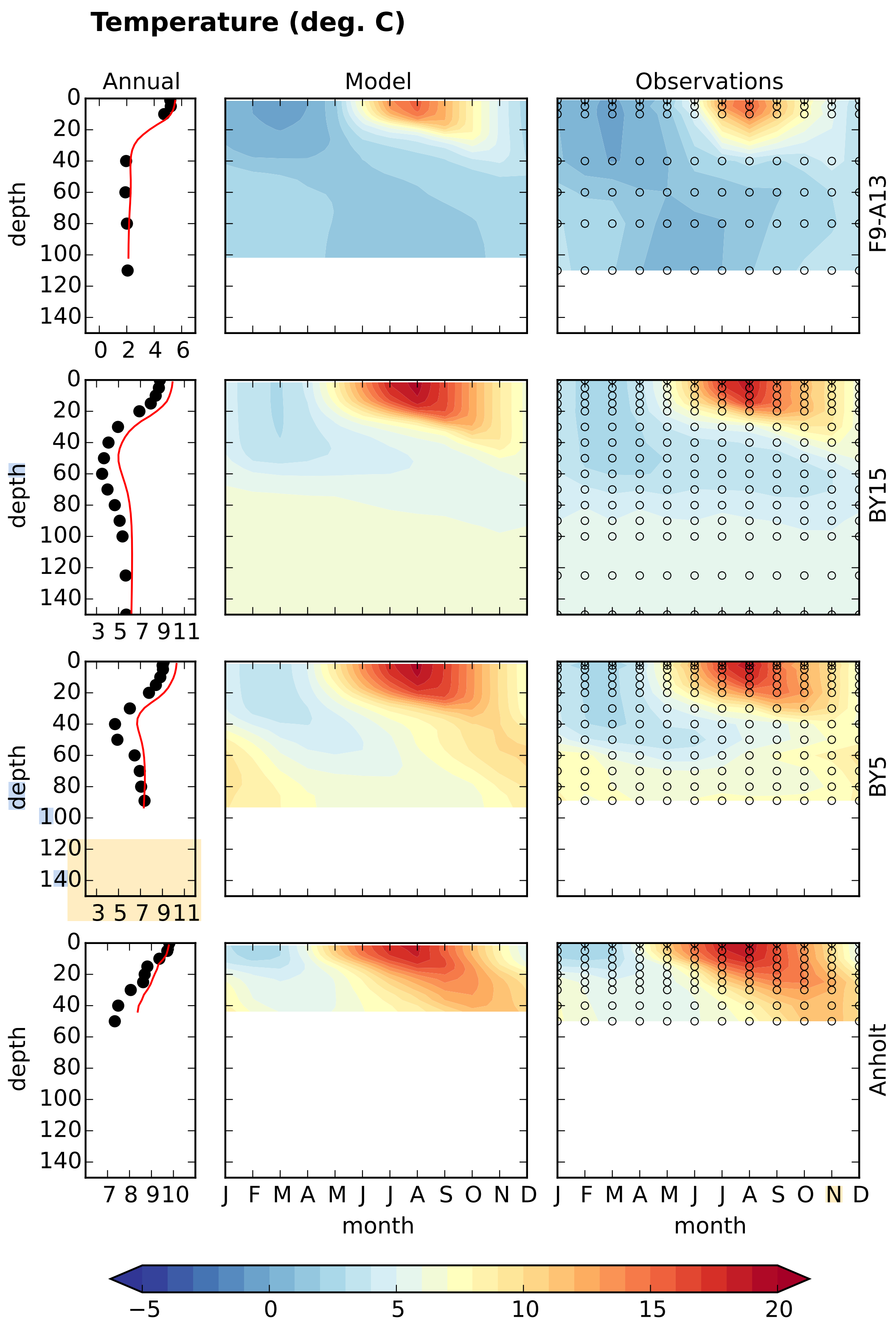

Fig. 9. Thermal structure for four different stations of the Baltic Sea, from top to bottom F9-A13 station in the Bothnian Bay, BY14 station in the Baltic Proper, BY5 station in the Bornholm Basin and Anholt station in Kattegat. The left column displays annual mean depth profiles, where the red line is simulated temperature and black dots are observations. The middle and the left columns show seasonal variations in the model and the observations, respectively. In the left column the transparent circles show sample depths, the observations are based on a 1979-2010 climatology.

4.2.2 Interannual variability

From the comparison between the observations and their variability (Figure 10), one notices that Nemo-Nordic in general well reproduces the variability in the deep water salinity close to the bottom, both in the Kattegat and in the Baltic Sea, despite the constant background bias in the salinity. Especially, it is interesting to note from the BY15 salinity that the model is able to reproduce the Major Baltic Inflows of 1993 and 2003. A comparison of the modelled and measured sea level differences during the recorded durations these inflows shows the models accuracy to represent the underlying barotropic processes. During the duration of the 1993 major Baltic inflow, the sea level at Landsort increases by 1 m in observations against 1.02 m in the model, while during the 2003 major Baltic inflow, the sea level at Landsort increases by 0.58 m both in the model and in the observations. This further suggests that a miss-represented baroclinic process must be responsible for the negative bias in deep water salinity in the Baltic Sea. Even though this model uses a bottom boundary layer parameterisation (Beckmann and Döscher, 1997), it is still a z coordinate model which makes that the representation of dense overflows is not as accurate as it would be in a sigma or generalized vertical coordinate model. It is also interesting to note that Nemo-Nordic tends to overestimate the variability in deep water salinity at the Anholt station in the Kattegat, while it slightly underestimates the variability at the BY2 station.

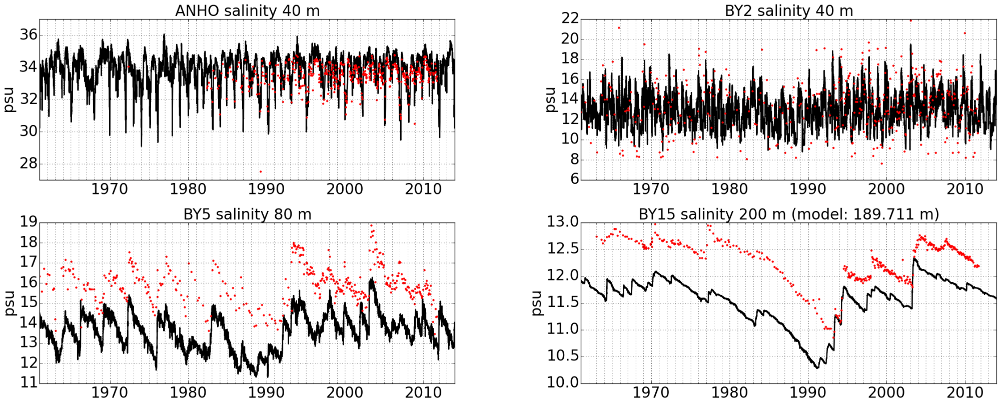

Fig. 10. Time series of modeled salinity (black) and observations (red) for different stations. The stations are from top to bottom Anholt, BY2, BY5 and BY15 (check Fig 3 for their location). All stations are relevant for inflowing salty water masses from the North Sea to the Baltic Sea. The chosen levels are all close to the bottom of the corresponding location.

4.2.3 Short term variability - Comparison with Argo Floats Data

As an example of Nemo-Nordic's performance on shorter term, we compared the model results to temperature observations from an autonomous Argo buoy. Over 100 profiles were collected during a mission in the Bothnian Sea, which lasted from 13 Jun 2013 to 2 Oct 2013. The profiles were taken from between 61.57°N and 62.47°N in latitude and between 19.59°E and 20.42°E in longitude. This dataset has been described in detail by (Westerlund and Tuomi, 2016), who also provided an illustration of the buoy route. From a comparison of observed and modelled temperature profiles we see that the seasonal thermocline is visible throughout the summer (Figure 11). The vertical structure of temperature was relatively well reproduced by Nemo-Nordic near the surface. In August the thermocline reached maximum depth and temperature. The model was able to describe well how the mixed layer deepened during the summer. The temperature gradient of the thermocline was also well represented. The surface layer responded to atmospheric forcing in a similar way in observations and model. In layers under the thermocline, model temperatures were somewhat too high. This bias increased in late summer. Deeper, the dicothermal (old winter water) layer was not as pronounced in the model as it was in the observations. In late August, model predicted larger thermocline depths than were observed. In general, temperature profiles were smoother in the model than in observations. Furthermore, some finer scale features were not completely reproduced by the model.

Observed and modelled near-surface temperatures, along with estimated thermocline depths, are shown in Figure 12. Near-surface temperature was taken to be the temperature of the model point at the depth of the topmost data point in the observations, which was typically around 4 metres, depending on the profile. In most cases this is very close to the surface temperature. Location of the thermocline was taken as the place of the maximum temperature gradient along the z-axis. Near-surface temperature in the model reproduced overall seasonal temperature cycle, although in early September surface temperatures were around 1 degree greater in the model than in observations. Thermocline depths were represented in the model quite well, except for the aforementioned time in late August. (Westerlund and Tuomi, 2016) presented a similar comparison to a different model configuration, derived from an earlier version of Nemo-Nordic. That model used different atmospheric forcing fields taken from an operational HIRLAM forecast from the FMI (Finnish Meteorological institute), climatological boundary conditions, climatological river runoffs and initial conditions from FMI's operational Baltic Sea forecast. Furthermore, it did not have the light penetration parameterization present in the official Nemo-Nordic configuration described in this paper. Compared to those results, the near-surface temperature in the official Nemo-Nordic results differs more from the observations in autumn, but shows less bias in early summer. Thermocline depths were quite similar in both configurations.

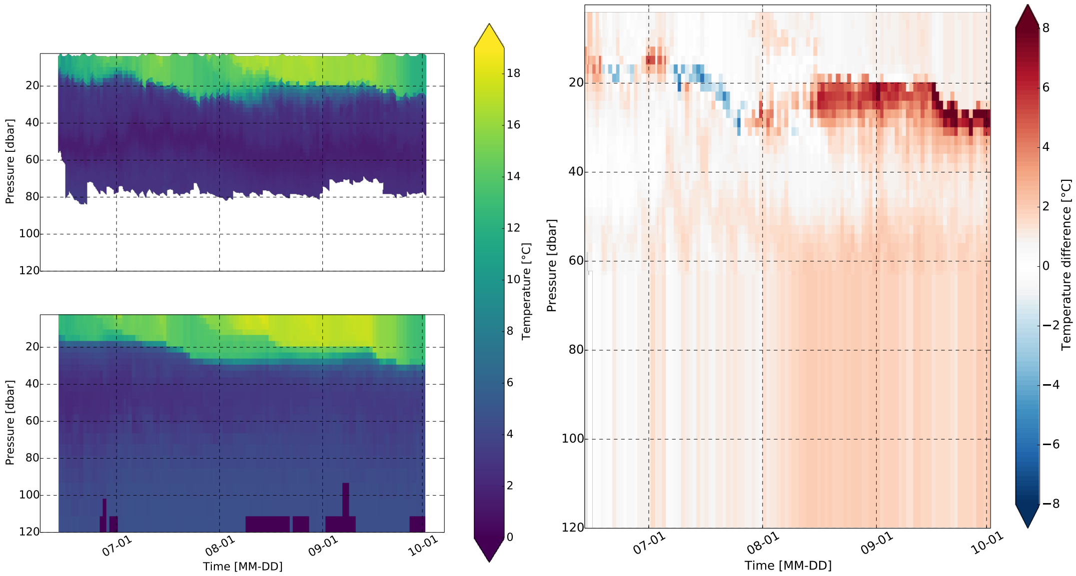

Fig. 11. Comparison of temperature profiles from an Argo float (upper left panel) and Nemo-Nordic. Observational data in the upper panel has been redrawn from the dataset used by Westerlund and Tuomi (2016). The panel on the right hand side shows the difference between the observation and model run. The model was larger than the measurement where the difference is positive. Model results have been taken along the buoy route in the Bothnian Sea in 2013.

4.3 Thermohaline structure of the North Sea

Compared to the Baltic Sea, the North Sea is more homogeneous regarding its thermohaline structure. It exhibits mostly seasonal variations in the form of the formation of the seasonal thermocline and seasonal variations in freshwater forcing. Haline fronts between coastal and offshore areas are found in the Southern and Eastern North Sea due to the relatively large river runoff from continental rivers at the Southern shore of the North Sea, and the Norwegian Coastal Current carrying low saline waters from the Baltic Sea.

4.3.1 Vertical structure and seasonal variability

In this section we validate the vertical structure and seasonal variability at four stations representative for different hydrological regimes in the North Sea. Two stations are located near the boundaries towards the Atlantic Ocean (Fladen Ground and the Southern Bight). Validating the temperature and salinity structure in these areas also gives a validation of the boundary conditions and the properties of the inflowing water. The two other stations (NCC and Frisian Front), are located in areas where there are relatively large horizontal and vertical (only NCC) salinity gradients due to the freshwater forcing from the Baltic Sea and the continental rivers draining into the Southern North Sea. The observational data comes from the KLIWAS dataset provided by the University of Hamburg (Bersch et al., 2013). It is composed of all available measurements between 1970 and 2013 in the North Sea, that have been put into a 1x1 grid.

The haline vertical structure at the four stations in the North Sea is displayed in Figure 13. The only station with a distinct permanent haline stratification is the NCC station. The vertical haline structure at this station is well reproduced by the model, although the surface waters are less saline than the observations by about 1 PSU. The other stations are rather homogeneous in the vertical with respect to salinity. In the Southern Bight and the Fladen Ground the model captures the overall mean

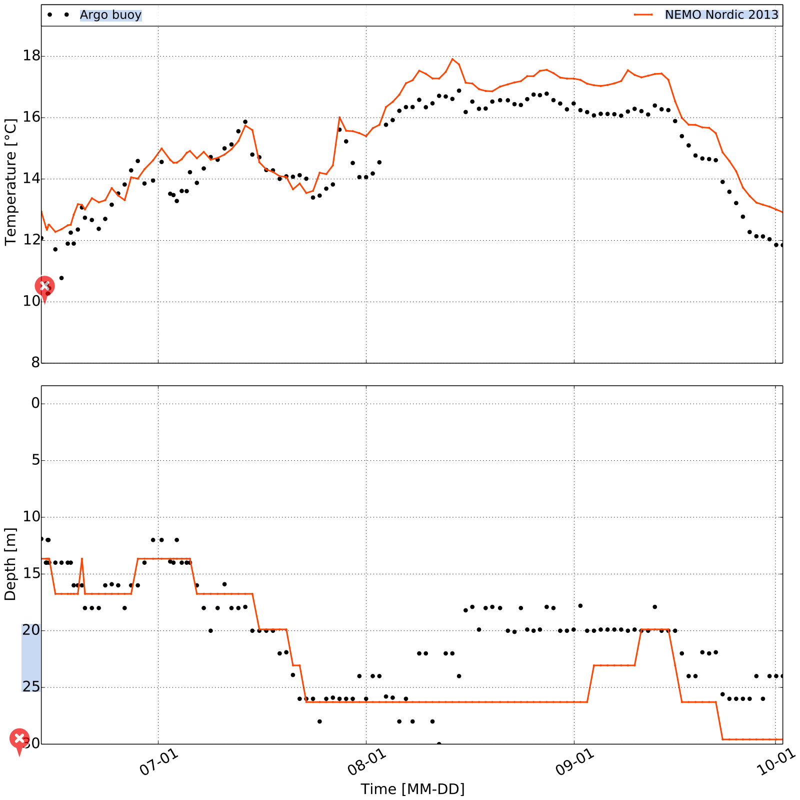

Fig. 12. Near-surface temperature in 2013 from the Argo float data and from Nemo-Nordic. Thermocline depth estimated as the maximum of vertical temperature gradient in the lower panel.

salinity. At the Frisian Front the modelled salinity is about 1.5 PSU too low, which probably is related to a displacement of the front between coastal waters with lower salinity and offshore waters. At all stations the model simulates a seasonal cycle in the surface salinity with a freshening during the summer months, in agreement with the observations. The timing and the amplitude of this summer freshening is however subject to some biases. Because the dataset does not contain regular measurements from these positions it can on the other hand give rise to biases in the observational estimates of the seasonal cycle.

The thermal vertical and seasonal structure is, as for the Baltic Sea, dominated by the seasonal warming and cooling of the surface waters (Fig. 14). In the Southern Bight and at the Frisian Front the waters are well mixed from surface to bottom throughout the year, and no seasonal thermocline develops, which is well reproduced by the model. In the Southern Bight there is a warm bias in the order of 0.5 °C (annual mean) in the model throughout the water column. At the Frisian front there is a warm bias of about 0.3 °C in the surface waters. At the two deeper stations, the seasonal development, and the depth, of the thermocline is well reproduced in the model, although the start of the thermocline formation is somewhat too early in the model. This is the case especially at the Fladen Ground, where it starts almost one month too early. Also the winter SST's are too warm in the model, resulting in a too weak winter convection/ too warm temperatures of the convecting water, which in its turn gives a warm bias in the deep waters. At both stations there is a warm bias of about 0.5 °C (annual mean) in the surface waters.

4.3.2 Modelled thermocline dynamics

For biogeochemical processes summer thermal conditions are important when water temperature and light intensity stimulate the growth of phytoplankton. Contemporaneously, thermal stratification develops in the deeper basin of the northern North Sea and the inflow of Atlantic water weakens (Skogen et al., 2011) and accordingly atmospheric forcing at the surface becomes more important. This leads to substantially better reproduction of interannual variability even in the North (Fig. 16b). We analyze in the following the modelled thermocline dynamics following previous approaches for the North Sea (Pohlmann, 1996; Meyer et al., 2011; Mathis and Pohlmann, 2014), which define the presence of thermocline conditions when a certain

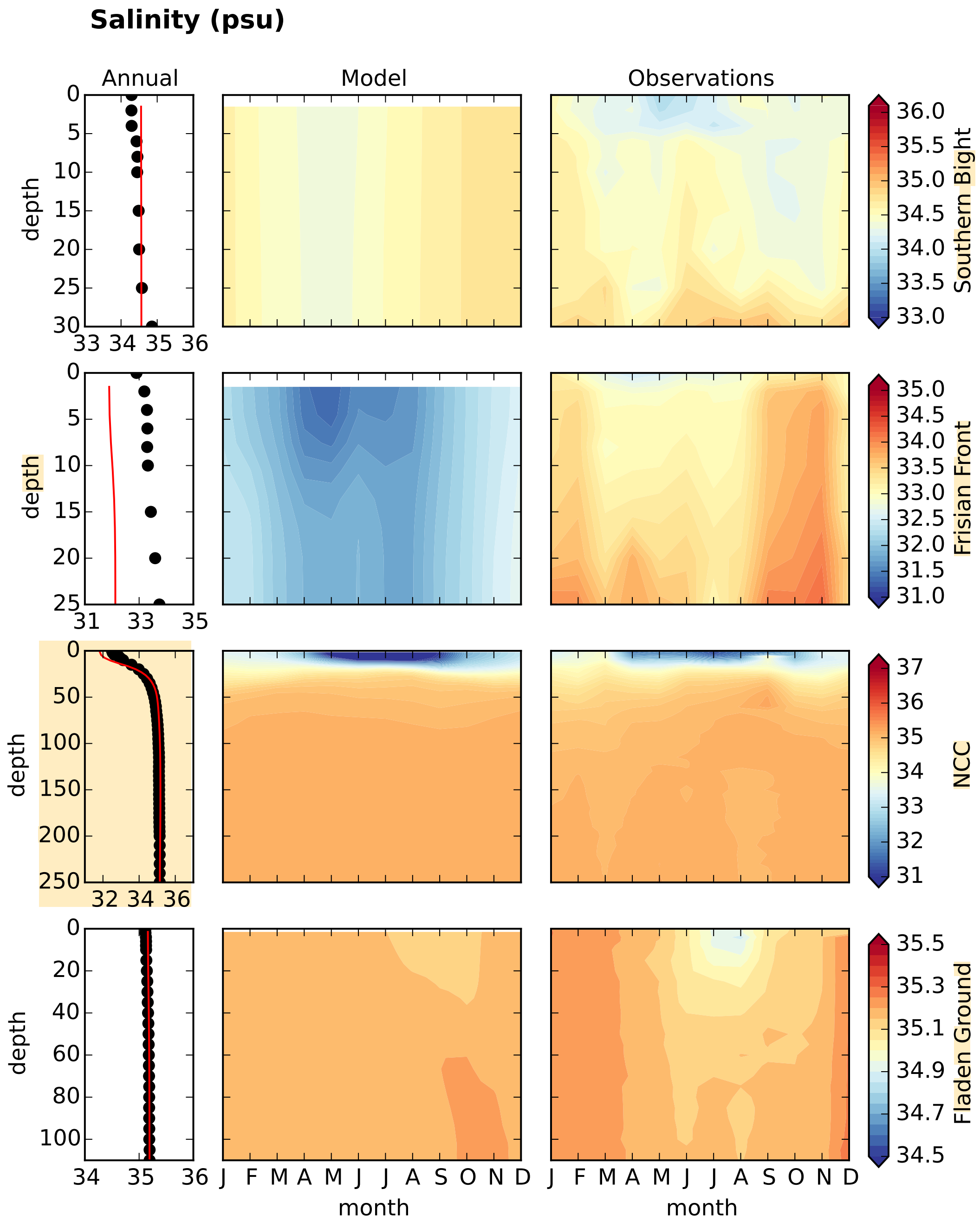

Fig. 13. Haline structure for four different stations of the North Sea, from top to bottom Southern Bight station, Frisian Front station, NCC station, and Fladen Ground station. The left column displays annual mean depth profiles, where the red line is simulated salinity and black dots are observations. The middle and the left columns show seasonal variations in the model and the observations, respectively. In the left column the transparent circles show sample depths, the observations are based on a 1979-2010 climatology.

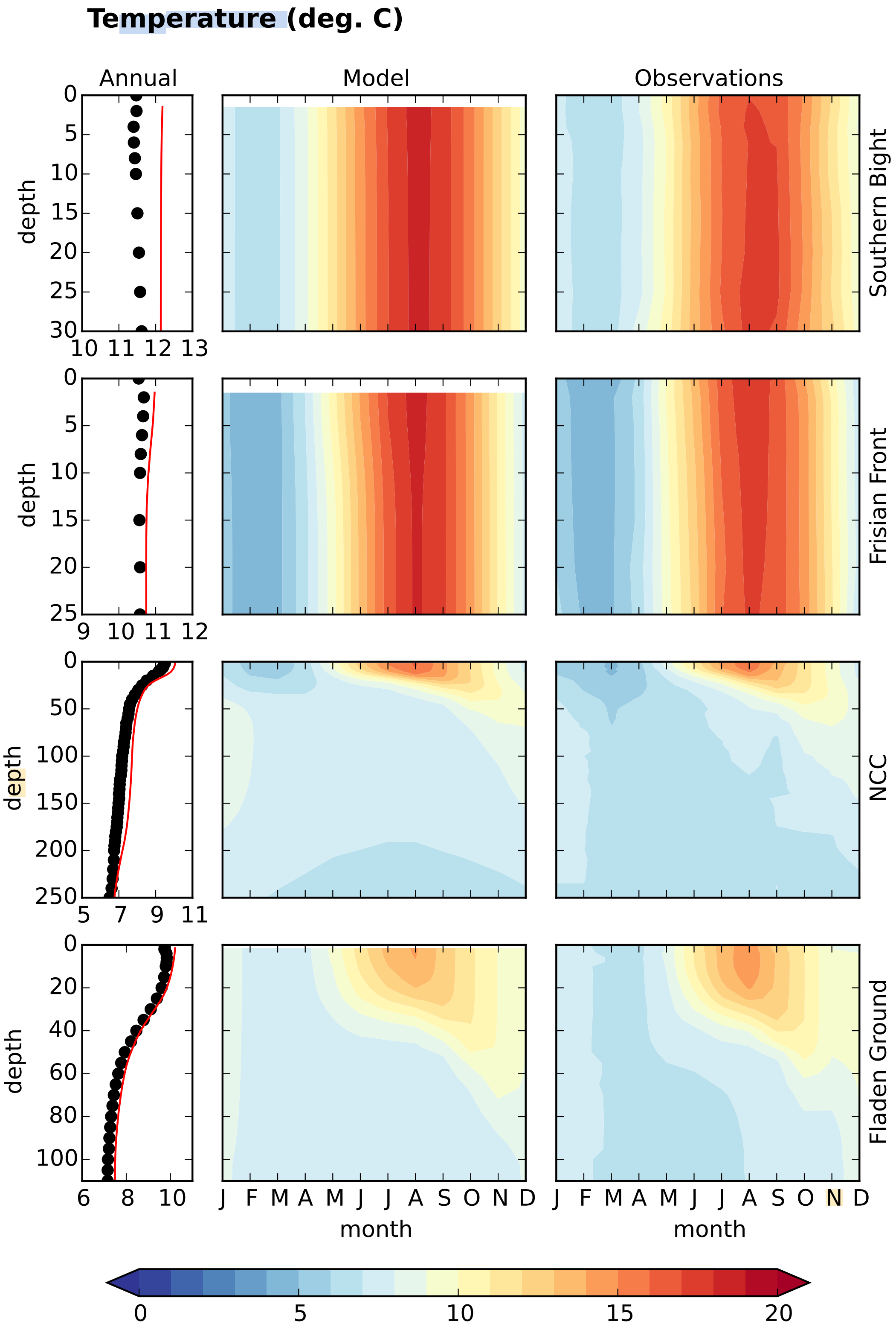

Fig. 14. Thermal structure for four different stations of the North Sea, from top to bottom Southern Bight station, Frisian Front station, NCC station, and Fladen Ground station. The left column displays annual mean depth profiles, where the red line is simulated temperature and black dots are observations. The middle and the left columns show seasonal variations in the model and the observations, respectively. In the left column the transparent circles show sample depths, the observations are based on a 1979-2010 climatology.

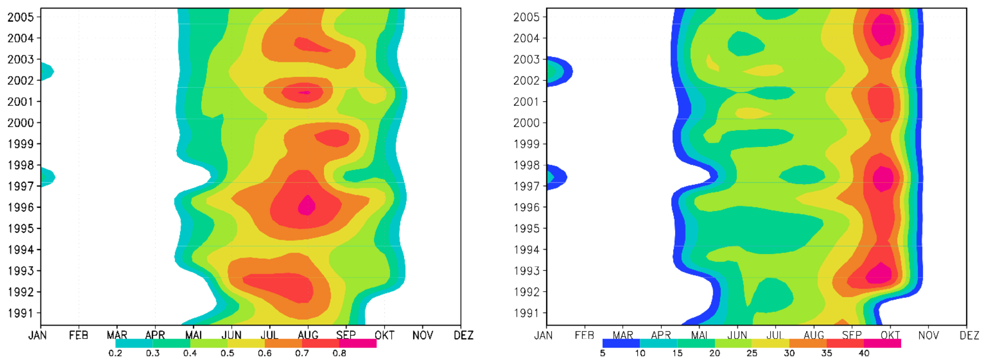

Fig. 15. Seasonal cycle of thermocline structure. Left: thermocline intensity (K m^{-1}) averaged over the entire thermal stratified area. Right same as left but for for thermocline depth (m).

vertical temperature gradient is exceeded. We here chose a critical gradient of 0.25 K/m. The yearly maximum extent of stratified areas is primarily governed by topography and wind stress (Mathis and Pohlmann, 2014) and varies between 1990 and 2005 between 100,000 and 185,000 km^2. Stratified conditions begin to develop in May and reaches its maximal intensity during July and August. Already during September wind stress strengthens and temperatures lower which increases mixing. The thermocline weakens then and is shifted downward. As a result, nutrient rich water reaches the euphotic zone. During this time a second phytoplankton bloom can be sometimes observed in the North Sea (van Haren et al., 2003; Moll, 1998).

4.3.3 Interannual variability

Surface properties are in many cases dominated by local meteorological forcing (Skogen et al., 2011). Therefore, its important to validate also subsurface properties which are also influenced also the by circulation dynamics (like e.g. Atlantic inflow). For this, we use the KLIWAS observational data set (Bersch et al., 2013). We here follow previous approaches and subdivide the North Sea into 1° x 1° boxes for which for each month, at each box and standard level Taylor statistics (Taylor, 2001) is calculated (for details see Raddach and Moll, 2006, Gröger et al. 2013). In order to estimate the interannual variability of seasonal signals we chose January and July as representative for winter and summer as in these month observations were most abundant in the observational data set. The results are shown in table 5. In total 25619 observations were used for the analysis.

Overall good correlation with the temperature and salinity observations for summer and winter indicates the models skill to capture interannual variability and thus, the ability to realistically respond to low frequency modes of climate variations such as decadal variability or the NAO which likely influence the North Sea hydrography (e.g. Hjøllo et al.2009, Mathis et al. 2015). The root mean square values lie well within the standard deviation of the observations (with the exception of January salinities where rms is slightly higher,table 5). The models salinity variability (as indicated by standard deviation) is too high (∼50%), but the spatial distribution of the observations is much coarser than the model grid which explains this result.

Table 5. Quantitative comparison of simulated and observed state variables derived from Taylor statistics (Taylor, 2001). rms = root mean squared, corr = Pearson's correlation, stddev = standard deviation, N = number of observations. The statistics have been derived from all 1° x 1° boxes. See text for details about data set and data handling.

State variable	rms	corr	stddev observation	stddev simulation	N
			Winter		
Temperature	0.74	0.78	0.86	1.18	6139
Salinity	0.56	0.79	0.54	0.88	6034
			Summer		
Temperature	1.10	0.94	3.06	3.15	6808
Salinity	0.56	0.83	0.72	0.98	6638

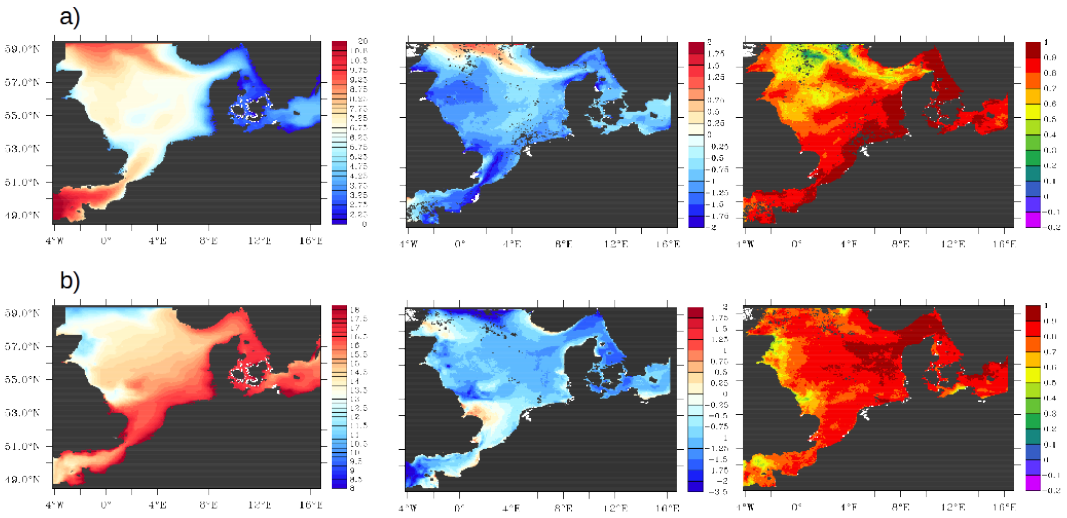

Fig. 16. a) left: Nemo-Nordic multiyear (1990-2005) DJF average sst. middle: Nemo-Nordic minus BSH sst. right: Correlation between Nemo-Nordic sst and BSH sst. Note regions where not enough observational data were present have been coloured grey. b) same as a) but for JJA.

4.3.4 Comparison with satellite data

In the following we compare the modelled SST with a widely used satellite product provided by the Federal Maritime and Hydrographic Agency of Germany, Hamburg (Bundesamt für Seeschifffahrt und Hydrographie, BSH hereafter). By this we are able to investigate how the modelled SST reproduces interannual variability which is important for the application of the model for climate services and the simulation of various climate scenarios.

In contrast to the warm bias relative to the in-situ temperature measurements, the simulated winter SST (Fig.16) is almost everywhere colder than the satellite estimations of SST. Cold biases relative to satellite measurements were also obtained in other ocean models driven by the ERA40 reanalysis dataset in (Tian et al., 2013); (Gröger et al., 2015)). Given that in-situ temperature measurements give a more direct measure than satellite estimations of SST's, and that the atmospheric forcing used for these simulations has a warm bias, especially in the North Sea during winter (Landelius et al., 2016), it is likely that the satellite underestimates the SST. Despite this, the satellite SSTs can be used for validation of spatial and temporal variability.

Figure 16 (a) shows an overall good correlation of modelled interannual SST variations with the BSH data set. Likewise the lower correlation in the Northern deeper parts could indicate problems with convective and/or wind induced mixing which would influence the heat transfer from the deeper layers to the surface. In contrast, in the Southern and shallower parts, SSTs are dominated largely by the atmospheric forcing (Skogen et al., 2011) and, thus correlation increases. Good correlation is also seen along the Norwegian coast where the effective heat capacity is limited due to haline stratification which make SSTs more sensitive to the atmospheric forcing. The same is true for nearly the entire Baltic Sea where correlation almost nowhere drops below 0.8.

5 Conclusions

In this article we provide a detailed description of the dynamic features of Nemo-Nordic, a newly developed joint setup for the Baltic Sea and the North Sea. Its performance when it comes to sea-ice is the subject of a specific article on its own (Pemberton et al., 2017). We have shown that Nemo-Nordic is able to reproduce the barotropic and baroclinic dynamics, as well as the thermohaline structure, of Baltic & North Sea basins. The key to achieve this overall good representation of the physics in the Baltic Sea and the North Sea has been to get a representation of the barotropic dynamics as good as possible. This ability, which is detailed in the present article, has been validated with the most demanding procedure: Nemo-Nordic is used as the official forecast model of SMHI for Baltic & North Seas, including for SSH for which the model does not benefit of any data assimilation. In forecast mode, Nemo-Nordic is used with a higher resolution (1nm or 1852 m), compared to longer integrations where the setup is used with a 2nm (or 3704 m) resolution. The ability of the model to represent barotropic dynamics at high frequency time scales (hours to several days) is the main reason for its good representation of transports and water exchanges in and between the Baltic Sea and the North Sea. It also allows for an accurate representation of the Baltic Sea inflows, and the initiation of the Baltic Sea baroclinic dynamics. In order for Nemo-Nordic to proper represent baroclinic dynamics in both basins, a specific tuning of mixing is done from both horizontal and vertical points of view. For example a limitation of the vertical mixing length in order to help the model keep the Baltic Sea halocline at a realistic level.

Although Nemo-Nordic well reproduces the overall physics of Baltic & North Sea, some biases can be noticed. The sea level representation is better in forecast mode than that of the previous SMHI operational model HIROMB, but some improvements are still needed to better represent extreme events. Regarding this precise point, a coupling with wind waves appears to be the next step, as it was recently shown that the contribution of wind waves has a major impact on extreme sea levels (Staneva et al., 2016). Ongoing development based on the new implementations within the NEMO ocean engine concerns the inclusion of wetting and drying processes which can also affect sea level in shallow areas. Further, an important margin of improvements exist in atmospheric forcing, bottom friction and bathymetry. A margin that should lead to an even greater accuracy in sea level representation: recent tests done with a bathymetry computed from the GEBCO database (The GEBCO-2014 Grid, version 20150318, http://www.gebco.net) show a high improvement of sea level representation in the North Sea and along the Swedish West coast.

From a baroclinic perspective, several aspects can be improved in the model. First, even though we could show that the barotropic variability of the Baltic & North Sea basins allows the Baltic Sea MBIs, there is still a bias in the deep salinity due to an over ventilation of the intermediate layers. So far, the only solutions which were found to solve this bias is to increase resolution. But a major future development would be the use of a hybrid vertical coordinate system with z^* close to the surface and σ coordinates close to the bottom. A minor development concerns the Galperin parameterization as mentioned before, which needs to be decoupled from thermal dynamics. Ongoing tests are being made concerning this latest point. The geometry of the horizontal diffusivity is to be improved as well in order to limit its effect on Baltic Sea inflows. The underlying idea is to avoid any horizontal diffusivity close to the bottom. Other developments in Nemo-Nordic concern its coupling with biogeochemical models. Nemo-Nordic has been coupled with the SCOBI model (Eilola et al., 2009), for which a validation work is ongoing. Nemo-Nordic has also been coupled with the BFM model (Vichi et al., 2007, 2015) on a part of its domain (Fransner et al., 2017).

Nemo-Nordic, and spin-off configurations, provide a tool not only for ocean forecasting, but also for a wide variety of ocean research. It can be used for long term simulations either for process purpose studies (Hordoir et al., 2013; Godhe et al., 2013; Moksnes et al., 2014; Westerlund and Tuomi, 2016, e.g.) or climate change related studies (Hordoir et al., 2015; Höglund et al., 2017). It can be also used for biogeochemical-ecosystem studies, using a simple passive tracer with a decay rate (Fransner et al., 2016) or coupled with a complex biogeochemical model (Fransner et al., 2017). Nemo-Nordic is also the ocean component of an RCA4-NEMO coupled model which is the basis of a regional climate model used in several studies (Wang et al., 2015; Pätsch et al., 2017).

Finally, Nemo-Nordic has also been used as a boundary condition for high-resolution sub-basin scale setups (Westerlund et al., 2017).

6 Code and data availability

Nemo-Nordic builds on the standard NEMO code (`nemo_v3_6_STABLE`, revision 5628) with only minor changes, including the fast-ice parametrization and a spatial varying background viscosity/diffusivity that could be read in from the file. The standard NEMO code can be downloaded from the NEMO web site (http://www.nemo-ocean. eu/). The `nemo_v3_6_STABLE` version is available from the following link: http://forge.ipsl.jussieu.fr/nemo/vn/branches/2015/`nemo_v3_6_STABLE`. The new code blocks that are introduced (relative to the standard NEMO code `nemo_v3_6_STABLE`, revision 5628) into our Nemo-Nordic code are included as supplemental material. The full Nemo-Nordic code is in a Subversion revision control system repository, available under http://54.73.141.37/subversion/repository/source_code/trunk/NEMOGCM. However, a user account is needed to gain full access. This work used revision 339 of the Nemo-Nordic code. Access to the Nemo-Nordic code and all input data, analysis scripts, and data used to produce the figures in this study can be made available upon request to the corresponding author.

Acknowledgements. The research presented in this study is part of the project BONUS STORMWINDS and 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, agriculture sciences and spatial planning (FORMAS). This work has been also supported by the Strategic Research Council at the Academy of Finland, project SmartSea (grant number 292 985).

References

Ådlandsvik, B. and Bentsen, M.: Downscaling a twentieth century global climate simulation to the North Sea, Ocean Dynamics, 57, 453–466, 2007.

Andersen, J. H., Carstensen, J., Conley, D. J., Dromph, K., Fleming-Lehtinen, V., Gustafsson, B. G., Josefson, A. B., Norkko, A., Villnäs, A., and Murray, C.: Long-term temporal and spatial trends in eutrophication status of the Baltic Sea, Biological Reviews, 92, 135–149, doi:10.1111/brv.12221, http://dx.doi.org/10.1111/brv.12221, 2017.

Baretta-Bekker, J., Baretta, J., Latuhihin, M., Desmit, X., and Prins, T.: Description of the long-term (1991–2005) temporal and spatial distribution of phytoplankton carbon biomass in the Dutch North Sea, Journal of Sea Research, 61, 50 – 59, doi:http://dx.doi.org/10.1016/j.seares.2008.10.007, http://www.sciencedirect.com/science/article/pii/S1385110108001159, long-term Phytoplankton Time SeriesTime Series Data Relevant to Eutrophication and Ecological Quality Indicators [WKEUT], 2009.

Beckmann, A. and Döscher, R.: A method for improved representation of dense water spreading over topography in geopotential-coordinate models, J. Phys. Oceanogr., 27, 581–591, 1997.

Berg, P., Doscher, R., and Koenigk, T.: Impacts of using spectral nudging on regional climate model RCA4 simulations of the Arctic, GEOSCIENTIFIC MODEL DEVELOPMENT, 6, 849–859, doi:10.5194/gmd-6-849-2013, 2013.

Bersch, M., Gouretski, V., Sadikni, R., and Hinrichs, I.: Hydrographic climatology of the North Sea and surrounding regions, Centre for Earth System Research and Sustainability (CEN), University of Hamburg, http://icdc.zmaw.de/1/daten/ocean/knsc-hydrographic.html, 2013.

Boesch, D., R., H., C., O., D., S., and S, S.: Eutrophication of Swedish seas, Swedish Environmental Protection Agency Report, pp. 1–72, 2006.

Burchard, H., Janssen, F., Bolding, K., Umlauf, L., and Rennau, H.: Model simulations of dense bottom currents in the Western Baltic Sea, Continental Shelf Research, 29, 205 – 220, doi:https://doi.org/10.1016/j.csr.2007.09.010, http://www.sciencedirect.com/science/article/pii/S0278434307002920, physics of Estuaries and Coastal Seas: Papers from the PECS 2006 Conference, 2009.

Carstensen, J., Andersen, J. H., Gustafsson, B. G., and Conley, D. J.: Deoxygenation of the Baltic Sea during the last century, Proceedings of the National Academy of Sciences, 111, 5628–5633, doi:10.1073/pnas.1323156111, http://www.pnas.org/content/111/15/5628.abstract, 2014.

Daewel, U. and Schrum, C.: Simulating long-term dynamics of the coupled North Sea and Baltic Sea ecosystem with {ECOSMO} II: Model description and validation, Journal of Marine Systems, 119–120, 30 – 49, doi:http://dx.doi.org/10.1016/j.jmarsys.2013.03.008, http://www.sciencedirect.com/science/article/pii/S0924796313000705, 2013.

Dahlgren, P., Landelius, T., Kallberg, P., and Gollvik, S.: A high resolution regional reanalysis for Europe Part 1: 3-dimensional reanalysis with the regional HIgh Resolution Limited Area Model (HIRLAM), Q. J. R. Meteorol. Soc., 2016.

Donnelly, C., Andersson, J. C., and Arheimer, B.: Using flow signatures and catchment similarities to evaluate the E-HYPE multi-basin model across Europe, Hydrological Sciences Journal, 61, 255–273, doi:10.1080/02626667.2015.1027710, http://dx.doi.org/10.1080/02626667.2015.1027710, 2016.

Döös, K., Meier, M., and Döscher, R.: The Baltic Haline Conveyor Belt or The Overturning Circulation and Mixing in the Baltic, Ambio, 33, doi:10.1357/002224006777606506, 2004.

Egbert, G., Bennett, A., and Foreman, M.: TOPEX/Poseidon tides estimated using a global inverse model, J. of Geophys. Res., 99, 24,821 – 24, 852, doi:10.1029/94JC01 894, 1994.

Egbert, G. D. and Erofeeva, S. Y.: Efficient Inverse Modeling of Barotropic Ocean Tides, Journal of Atmospheric and Oceanic Technology, 19, 183–204, doi:10.1175/1520-0426, http://journals.ametsoc.org/doi/abs/10.1175/1520-0426282002%29019%3C01833AEIMOBOE2.0.CO3B2, 2002.

Eilola, K., Meier, H. M., and Almroth, E.: On the dynamics of oxygen, phosphorus and cyanobacteria in the Baltic Sea; A model study, Journal of Marine Systems, 75, 163 – 184, doi:http://dx.doi.org/10.1016/j.jmarsys.2008.08.009, http://www.sciencedirect.com/science/article/pii/S0924796308002182, 2009.

Elken, J. and Matthäus, W.: Physical system Description, in: Assmesment of Climate Change for the Baltic Sea Basin, edited by author team, T. B., chap. Annex A1, pp. 379–386, Springer-Verlag, Berlin, 2008.

Emeis, K.-C., van Beusekom, J., Callies, U., Ebinghaus, R., Kannen, A., Kraus, G., Kröncke, I., Lenhart, H., Lorkowski, I., Matthias, V., Möllmann, C., Pätsch, J., Scharfe, M., Thomas, H., Weisse, R., and Zorita, E.: The North Sea — A shelf sea in the Anthropocene, Journal of Marine Systems, 141, 18 – 33, doi:http://dx.doi.org/10.1016/j.jmarsys.2014.03.012, http://www.sciencedirect.com/science/article/pii/S0924796314000724, biogeochemistry-ecosystem interaction on changing continental margins in the Anthropocene, 2015.

Fonselius, S. and Valderrama, J.: One hundred years of hydrographic measurements in the Baltic Sea, Journal of Sea Research, 49, 229 – 241, doi:http://dx.doi.org/10.1016/S1385-1101(03)00035-2, http://www.sciencedirect.com/science/article/pii/S1385110103000352, proceedings of the 22nd Conference of the Baltic Oceanographers (CBO), Stockholm 2001, 2003.

Fransner, F., Nycander, J., Mörth, C.-M., Humborg, C., Markus Meier, H. E., Hordoir, R., Gustafsson, E., and Deutsch, B.: Tracing terrestrial DOC in the Baltic Sea—A 3-D model study, Global Biogeochemical Cycles, 30, 134–148, doi:10.1002/2014GB005078, http://dx.doi.org/10.1002/2014GB005078, 2014GB005078, 2016.

Fransner, F., Gustafsson, E., Tedesco, L., Vichi, M., Hordoir, R., Roquet, F., Spilling, K., Kuznetsov, I., Eilola, K., Mörth, C. M., Humborg, C., and Nycander, J.: Non-Redfieldian dynamics explain seasonal pCO2 drawdown in the Gulf of Bothnia, J. Geophys. Res. Oceans., In revision, 2017.

Fredrik Wulff, Anders Stigebrandt, L. R.: Nutrient Dynamics of the Baltic Sea, Ambio, 19, 126–133, http://www.jstor.org/stable/4313678, 1990.

Funkquist, L. and Kleine, E.: HIROMB - An introduction to HIROMB, an operational baroclinic model for the Baltic Sea, Tech. rep., SMHI, 2007.

Galperin, B., Kantha, L. H., Hassid, S., and Rosati, A.: A Quasi-equilibrium Turbulent Energy Model for Geophysical Flows, J. of the Atmospheric Sciences, 45, 55–62, 1988.

Godhe, A., Egardt, J., Kleinhans, D., Sundqvist, L., Hordoir, R., and Jonsson, P.: Seascape analysis reveals regional gene flow patterns among populations of a marine planktonic diatom, Proc R Soc B, doi:10.1098/rspb.2013.1599, 2013.

Graham, J. A., O'Dea, E., Holt, J., Polton, J., Hewitt, H. T., Furner, R., Guihou, K., Brereton, A., Arnold, A., Wakelin, S., Castillo Sanchez, J. M., and Mayorga Adame, C. G.: AMM15: A new high resolution NEMO configuration for operational simulation of the European North West Shelf, Geoscientific Model Development Discussions, 2017, 1–23, doi:10.5194/gmd-2017-127, https://www.geosci-model-dev-discuss.net/gmd-2017-127/, 2017.

Gräwe, U., Burchard, H., Naumann, M., and Mohrholz, V.: Anatomizing one of the largest saltwater inflows into the Baltic Sea in December 2014, Journal of Geophysical Research: Oceans, 120, 7676–7697, doi:10.1002/2015JC011269, 2015.

Gräwe, U., Holtermann, P., Klingbeil, K., and Burchard, H.: Advantages of vertically adaptive coordinates in numerical models of stratified shelf seas, Ocean Modelling, 92, 56 – 68, doi:https://doi.org/10.1016/j.ocemod.2015.05.008, http://www.sciencedirect.com/science/article/pii/S1463500315000979, 2015.

Gröger, M., Maier-Reimer, E., Mikolajewicz, U., Moll, A., and Sein, D.: NW European shelf under climate warming: implications for open ocean-shelf exchange, primary production, and carbon absorption, Biogeosciences, 10, 3767–3792, 2013.

Gröger, M., Dieterich, C., Meier, M., and Schimanke, S.: Thermal air–sea coupling in hindcast simulations for the North Sea and Baltic Sea on the NW European shelf, Tellus A, 67, http://www.tellusa.net/index.php/tellusa/article/view/26911, 2015.

Gustafsson, B. G. and Andersson, H. C.: Modeling the exchange of the Baltic Sea from the meridional atmospheric pressure difference across the North Sea, Journal of Geophysical Research: Oceans, 106, 19 731–19 744, doi:10.1029/2000JC000593, http://dx.doi.org/10.1029/2000JC000593, 2001.

Höglund, A., Pemberton, P., Hordoir, R., and Schimanke, S.: Ice conditions for maritime traffic in the Baltic Sea in future climate, Boreal Env. Res., 22, 245–265, 2017.

Holt, J., Wakelin, S., Lowe, J., and Tinker, J.: The potential impacts of climate change on the hydrography of the northwest European continental shelf, Progress in Oceanography, 86, 361–379, 2010.

Holt, J., Butenschön, M., Wakelin, S. L., Artioli, Y., and Allen, J. I.: Oceanic controls on the primary production of the northwest European continental shelf: model experiments under recent past conditions and a potential future scenario, Biogeosciences, 9, 97–117, doi:10.5194/bg-9-97-2012, http://www.biogeosciences.net/9/97/2012/, 2012.

Hordoir, R. and Meier, H. E. M.: Freshwater Fluxes in the Baltic Sea - A Model Study, J. Geophys. Res., 10.1029/2009JC005604, http://onlinelibrary.wiley.com/doi/10.1029/2009JC005604/full, 2010.

Hordoir, R., Dieterich, C., Basu, C., Dietze, H., and Meier, M.: Freshwater outflow of the Baltic Sea and transport in the Norwegian current: A statistical correlation analysis based on a numerical experiment, Continental Shelf Research, 64, 1 – 9, doi:http://dx.doi.org/10.1016/j.csr.2013.05.006, http://www.sciencedirect.com/science/article/pii/S0278434313001532, 2013.

Hordoir, R., Axell, L., Löptien, U., Dietze, H., and Kuznetsov, I.: Influence of sea level rise on the dynamics of salt inflows in the Baltic Sea, Journal of Geophysical Research: Oceans, doi:10.1002/2014JC010642, http://dx.doi.org/10.1002/2014JC010642, 2015.

Huthnance, J. M., Holt, J. T., and Wakelin, S. L.: Deep ocean exchange with west-European shelf seas, Ocean Science, 5, 621–634, doi:10.5194/os-5-621-2009, http://www.ocean-sci.net/5/621/2009/, 2009.

Janssen, F., Schrum, C., and Backhaus, J. O.: A climatological data set of temperature and salinity for the Baltic Sea and the North Sea, Deutsche Hydrografische Zeitschrift, 51, 5, doi:10.1007/BF02933676, https://doi.org/10.1007/BF02933676, 1999.

Köster, F. W., Möllmann, C., Neuenfeldt, S., Vinther, M., Kraus, G., and Voss, R.: Fish stock development in the central Baltic Sea (1974–1999) in relation to variability in the environment, ICES Marine Science Symposia, 219, 2003.

Landelius, T., Dahlgren, P., Gollvik, S., Jansson, A., and Olsson, E.: A high resolution regional reanalysis for Europe Part 2: 2D analysis of surface temperature, precipitation and wind, Q. J. R. Meteorol. Soc., 2016.

Large, W. and Yeager, S.: The global climatology of an interannually varying air-sea flux data set, Climate Dynamics, 33, 341–364, http://dx.doi.org/10.1007/s00382-008-0441-3, 10.1007/s00382-008-0441-3, 2009.

Lyard, F., Lefevre, F., Letellier, T., and Francis, O.: Modelling the global ocean tides: modern insights from FES2004, Ocean Dynamics, 56, 394–415, doi:10.1007/s10236-006-0086-x, https://doi.org/10.1007/s10236-006-0086-x, 2006.

Madec, G. and the NEMO system team: NEMO Ocean Engine, Version 3.6 Stable, Tech. rep., IPSL, http://www.nemo-ocean.eu/, note du Pôle de modélisation de l'Institut Pierre-Simon Laplace No 27, 2015.

Madsen, K. S., Høyer, J. L., Fu, W., and Donlon, C.: Blending of satellite and tide gauge sea level observations and its assimilation in a storm surge model of the North Sea and Baltic Sea, Journal of Geophysical Research: Oceans, 120, 6405–6418, doi:10.1002/2015JC011070, http://dx.doi.org/10.1002/2015JC011070, 2015.

Maraldi, C., Chanut, J., Levier, B., Ayoub, N., De Mey, P., Reffray, G., Lyard, F., Cailleau, S., Drévillon, M., Fanjul, E. A., Sotillo, M. G., Marsaleix, P., the Mercator Research, and Team, D.: NEMO on the shelf: assessment of the Iberia-Biscay-Ireland configuration, Ocean Science, 9, 745–771, doi:10.5194/os-9-745-2013, https://www.ocean-sci.net/9/745/2013/, 2013.

Mathis, M. and Pohlmann, T.: Projection of physical conditions in the North Sea for the 21st century, Climate Research, 61, 1–17, doi:10.3354/cr01232, http://www.int-res.com/abstracts/cr/v61/n1/p1-17/, 2014.

Mathis, M., Mayer, B., and Pohlmann, T.: An uncoupled dynamical downscaling for the North Sea: Method and evaluation, Ocean Modelling, 72, 153 – 166, doi:http://dx.doi.org/10.1016/j.ocemod.2013.09.004, http://www.sciencedirect.com/science/article/pii/S1463500313001662, 2013.

Mathis, M., Elizalde, A., Mikolajewicz, U., and Pohlmann, T.: Variability patterns of the general circulation and sea water temperature in the North Sea, Progress in Oceanography, 135, 91 – 112, doi:http://dx.doi.org/10.1016/j.pocean.2015.04.009, http://www.sciencedirect.com/science/article/pii/S0079661115000695, 2015.

Meier, H. and Kauker, F.: Sensitivity of the Baltic Sea salinity to the freshwater supply, CLIMATE RESEARCH, 24, 231–242, 2003.

Meier, H. E. M. and Kauker, F.: Modeling decadal variability of the Baltic Sea: 2. Role of freshwater inflow and large-scale atmospheric circulation for salinity, Journal of Geophysical Research, 108, 3368, doi:10.1029/2003JC001799, 2003.

Meier, H. E. M., Döscher, R., and Faxén, T.: A multiprocessor coupled ice-ocean model for the Baltic Sea: Application to salt inflow, J. Geophys. Res., 108(C8), 3273, doi:10.1029/2000JC000 521, 2003.

Meier, M.: Simulated sea level in past and future climates of the Baltic Sea, Climate Research, 27, 59–75, http://www.int-res.com/abstracts/cr/v27/n1/p59-75/, 2004.

Meyer, E. M., Pohlmann, T., and Weisse, R.: Thermodynamic variability and change in the North Sea (1948–2007) derived from a multidecadal hindcast, Journal of Marine Systems, 86, 35 – 44, doi:http://dx.doi.org/10.1016/j.jmarsys.2011.02.001, http://www.sciencedirect.com/science/article/pii/S0924796311000145, 2011.

Moksnes, P.-O., Corell, H., Tryman, K., Hordoir, R., and Jonsson, P. R.: Larval behavior and dispersal mechanisms in shore crab larvae (Carcinus maenas): Local adaptations to different tidal environments?, Limnology and Oceanography, 59, 588–602, doi:10.4319/lo.2014.59.2.0588, http://dx.doi.org/10.4319/lo.2014.59.2.0588, 2014.

Moll, A.: Regional distribution of primary production simulated by a three dimensional model, Journal of Marine Systems, 16, 150–170, 1998.

Neumann, T., Eilola, K., Gustafsson, B., Müller-Karulis, B., Kuznetsov, I., Meier, H. E. M., and Savchuk, O. P.: Extremes of Temperature, Oxygen and Blooms in the Baltic Sea in a Changing Climate, AMBIO, 41, 574–585, doi:10.1007/s13280-012-0321-2, http://dx.doi.org/10.1007/s13280-012-0321-2, 2012.

Nielsen, M. H.: The baroclinic surface currents in the Kattegat, Journal of Marine Systems, 55, 97 – 121, doi:https://doi.org/10.1016/j.jmarsys.2004.08.004, http://www.sciencedirect.com/science/article/pii/S0924796304002921, 2005.

OSPAR: Quality Status Report 2000 Region II - Greater North Sea, OSPAR Commission for the Protection of the Marine Environment of the North-East Atlantic, London, 2000.

Otto, L., Zimmerman, J., Furnes, G., Mork, M., Saetre, R., and Becker, G.: Review of the physical oceanography of the North Sea, Netherlands Journal of Sea Research, 26, 161 – 238, doi:http://dx.doi.org/10.1016/0077-7579(90)90091-T, http://www.sciencedirect.com/science/article/pii/007775799090091T, 1990.

Pätsch, J. and Kühn, W.: Nitrogen and carbon cycling in the North Sea and exchange with the North Atlantic—A model study. Part I. Nitrogen budget and fluxes, Continental Shelf Research, 28, 767 – 787, doi:http://dx.doi.org/10.1016/j.csr.2007.12.013, http://www.sciencedirect.com/science/article/pii/S0278434307003470, 2008.

Pätsch, J., Burchard, H., Dieterich, C., Gräwe, U., Gröger, M., Mathis, M., Kapitza, H., Bersch, M., Moll, A., Pohlmann, T., Su, J., Ho-Hagemann, H. T., Schulz, A., Elizalde, A., and Eden, C.: An evaluation of the North Sea circulation in global and regional models relevant for ecosystem simulations, Ocean Modelling, 116, 70 – 95, 2017.

Pawlak., J., Laamanen, M., and Andersen, J.: Eutrophication in the Baltic Sea — an integrated thematic assessment of the effects of nutrient enrichment in the Baltic Sea region. An executive summary., Baltic Sea Environment Proceedings, Helsinki Commision, 2009.

Pemberton, P., Löptien, U., Hordoir, R., Höglund, A., Schimanke, S., Axell, L., and Haapala, J.: Sea-ice evaluation of NEMO-Nordic 1.0: a NEMO–LIM3.6-based ocean–sea-ice model setup for the North Sea and Baltic Sea, Geoscientific Model Development, 10, 3105–3123, doi:10.5194/gmd-10-3105-2017, https://www.geosci-model-dev.net/10/3105/2017/, 2017.

Pham, T. V., Brauch, J., Dieterich, C., Frueh, B., and Ahrens, B.: New coupled atmosphere-ocean-ice system COSMO-CLM/NEMO: assessing air temperature sensitivity over the North and Baltic Seas, Oceanologia, 56, 167 – 189, doi:https://doi.org/10.5697/oc.56-2.167, http://www.sciencedirect.com/science/article/pii/S0078323414500115, 2014.

Pohlmann, T.: Calculating the development of the thermal vertical stratification in the North Sea with a three-dimensional baroclinic circulation model, Continental Shelf Research, 16, 163 – 194, doi:http://dx.doi.org/10.1016/0278-4343(95)00018-V, http://www.sciencedirect.com/science/article/pii/027843439500018V, 1996.

Savchuk, O. P.: Resolving the Baltic Sea into seven subbasins: N and P budgets for 1991–1999, Journal of Marine Systems, 56, 1–15, 2005.

Schimanke, S., Dieterich, C., and Meier, H. E. M.: An algorithm based on sea-level pressure fluctuations to identify major Baltic inflow events, Tellus A, 66, doi:http://dx.doi.org/10.3402/tellusa.v66.23452, http://www.tellusa.net/index.php/tellusa/article/view/23452, 2014.

Schrum, C.: Regionalization of climate change for the North Sea and Baltic Sea, Climate Research, 18, 31–37, 2001.

Schrum, C. and Backhaus, J.: Sensitivity of atmosphere–ocean heat exchange and heat content in the North Sea and the Baltic Sea, Tellus A, 51, http://www.tellusa.net/index.php/tellusa/article/view/13825, 2011.

Schrum, C., Hübner, U., Jacob, D., and Podzun, R.: A coupled atmosphere/ice/ocean model for the North Sea and the Baltic Sea, Climate Dynamics, 21, 131–151, doi:10.1007/s00382-003-0322-8, http://dx.doi.org/10.1007/s00382-003-0322-8, 2003.

Shapiro, G., Luneva, M., Pickering, J., and Storkey, D.: The effect of various vertical discretization schemes and horizontal diffusion parameterization on the performance of a 3-D ocean model: the Black Sea case study, Ocean Science, 9, 377–390, doi:10.5194/os-9-377-2013, https://www.ocean-sci.net/9/377/2013/, 2013.

Simpson, J. and Souza, A.: Semidiurnal switching of stratification in the region of freshwater influence of the Rhine, J. Geophys. Res., 100, 7037–7044, 1995.

Skagseth, Ø., Drinkwater, K. F., and Terrile, E.: Wind- and buoyancy-induced transport of the Norwegian Coastal Current in the Barents Sea, Journal of Geophysical Research: Oceans, 116, n/a–n/a, doi:10.1029/2011JC006996, http://dx.doi.org/10.1029/2011JC006996, c08007, 2011.

Skogen, M. D., Drinkwater, K., Hjøllo, S. S., and Schrum, C.: North Sea sensitivity to atmospheric forcing, Journal of Marine Systems, 85, 106 – 114, doi:http://dx.doi.org/10.1016/j.jmarsys.2010.12.008, http://www.sciencedirect.com/science/article/pii/S0924796310002241, 2011.

Staneva, J., Wahle, K., Günther, H., and Stanev, E.: Coupling of wave and circulation models in coastal ocean predicting systems: a case study for the German Bight, Ocean Science, 12, 797–806, doi:10.5194/os-12-797-2016, https://www.ocean-sci.net/12/797/2016/, 2016.

Stigebrandt, A.: Physical Oceanography of the Baltic Sea, pp. 19–74, Springer Berlin Heidelberg, Berlin, Heidelberg, doi:10.1007/978-3-662-04453-7_2, http://dx.doi.org/10.1007/978-3-662-04453-7_2, 2001.

Taylor, K. E.: Summarizing multiple aspects of model performance in a single diagram, Journal of Geophysical Research: Atmospheres, 106, 7183–7192, 2001.

Thomas, H., Bozec, Y., de Baar, H. J. W., Elkalay, K., Frankignoulle, M., Schiettecatte, L.-S., Kattner, G., and Borges, A. V.: The carbon budget of the North Sea, Biogeosciences, 2, 87–96, doi:10.5194/bg-2-87-2005, http://www.biogeosciences.net/2/87/2005/, 2005.

Tian, T., Boberg, F., Christensen, O., Christensen, J., She, J., and Vihma, T.: Resolved complex coastlines and land-sea contrasts in a high-resolution regional climate model: a comparative study using prescribed and modelled SSTs, Tellus A, 65, http://www.tellusa.net/index.php/tellusa/article/view/19951, 2013.

Uppala, S. M., Kallberg, P. W., Simmons, A. J., Andrae, U., añd M. Fiorino, V. D. C. B., Gibson, J. K., Haseler, J., Kelly, A. H. G. A., Li, X., Onogi, K., Saarinen, S., Sokka, N., Allan, R. P., Andersson, E., Arpe, K., Balmaseda, M. A., Beljaars, A. C. M., Berg, L. V. D., Bidlot, J. ., Bormann, N., Caires, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M., Fuentes, M., Hagemann, S. ., Holm, E., Hoskins, B. J., Isaksen, L., Janssen, P. A. E. M., Jenne, R., Mcnally, A. P., Mahfouf, J.-F., Morcrette, J.-J., Rayner, N. A., Saunders, R. W., Simon, P., Sterl, A., Trenberth, K. E., tch, A. U., Vasiljevic, D., Viterbo, P., and Woollen, J.: The ERA-40 re-analysis, Quaterly Journal of the Royal Meteorological Society, 131, 2961–3012, doi:10.1256/qj.04.176, 2005.

Vahtera, E., Conley, D. J., Gustafsson, B. G., Kuosa, H., Pitkänen, H., Savchuk, O. P., Tamminen, T., Viitasalo, M., Voss, M., Wasmund, N., et al.: Internal ecosystem feedbacks enhance nitrogen-fixing cyanobacteria blooms and complicate management in the Baltic Sea, AMBIO: A journal of the Human Environment, 36, 186–194, 2007.

van Haren, H., Howarth, M., Jones, K., and Ezzi, I.: Autumnal reduction of stratification in the northern North Sea and its impact, Continental Shelf Research, 23, 177–191, 2003.

Vancoppenolle, M., Fichefet, T., Goosse, H., Bouillon, S., Madec, G., and Maqueda, M. A. M.: Simulating the mass balance and salinity of Arctic and Antarctic sea ice. 1. Model description and validation, Ocean Modelling, 27, 33 – 53, doi:http://dx.doi.org/10.1016/j.ocemod.2008.10.005, http://www.sciencedirect.com/science/article/pii/S1463500308001613, 2009.

Vichi, M., Masina, S., and Navarra, A.: A generalized model of pelagic biogeochemistry for the global ocean ecosystem. Part II: Numerical simulations, Journal of Marine Systems, 64, 110 – 134, doi:https://doi.org/10.1016/j.jmarsys.2006.03.014, http://www.sciencedirect.com/science/article/pii/S0924796306001096, contributions from Advances in Marine Ecosystem Modelling Research, 27-29 June, 2005, Plymouth, UK, 2007.

Vichi, M., Lovato, T., Lazzari, P., Cossarini, G., Gutierrez Mlot, E., Mattia, G., Masina, S., McKiver, W. J., Pinardi, N., Solidoro, C., Tedesco, L., and Zavatarelli, M.: The Biogeochemical Flux Model (BFM): Equation Description and User Manual. BFM version 5.1, BFM Consortium, 2015.

Wang, S., Dieterich, C., Döscher, R., Höglund, A., Hordoir, R., Meier, H. E. M., Samuelsson, P., and Schimanke, S.: Development and evaluation of a new regional coupled atmosphere–ocean model in the North Sea and Baltic Sea, Tellus A: Dynamic Meteorology and Oceanography, 67, 24 284, doi:10.3402/tellusa.v67.24284, 2015.

Wasmund, N. and Uhlig, S.: Phytoplankton trends in the Baltic Sea, ICES Journal of Marine Science: Journal du Conseil, 60, 177–186, doi:10.1016/S1054-3139(02)00280-1, http://icesjms.oxfordjournals.org/content/60/2/177.abstract, 2003.

Westerlund, A. and Tuomi, L.: Vertical temperature dynamics in the Northern Baltic Sea based on 3D modelling and data from shallow-water Argo floats, Journal of Marine Systems, 158, 34 – 44, doi:https://doi.org/10.1016/j.jmarsys.2016.01.006, http://www.sciencedirect.com/science/article/pii/S0924796316000191, 2016.

Westerlund, A., Tuomi, L., Alenius, P., Miettunen, E., and Vankevich, R. E.: Attributing mean circulation patterns to physical phenomena in the Gulf of Finland, Oceanologia, doi:http://dx.doi.org/10.1016/j.oceano.2017.05.003, in press, 2017.

Wieland, K., Waller, U., and Schnack, D.: Development of Baltic cod eggs at different levels of temperature and oxygen content, Dana, 10, 163–177, 1994.

Winther, N. G. and Johannessen, J. A.: North Sea circulation: Atlantic inflow and its destination, Journal of Geophysical Research: Oceans, 111, n/a–n/a, doi:10.1029/2005JC003310, http://dx.doi.org/10.1029/2005JC003310, c12018, 2006.