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Operational Ocean Forecasting for German Coastal Waters

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Summary

A numerical ocean forecasting system for the North and Baltic Seas has been applied at the Federal Maritime and Hydrographic Agency (BSH) since several decades. The model system is under permanent revision and the latest development – the implementation of the ocean circulation model BSH-HBM – is presented here. The circulation model is of particular importance because it provides the basic information for a couple of services at the German coast, like e.g. the sea level prediction and storm surge warning service, or oil spill forecasting and search-and-rescue applications.

An overview on the basic components of the model system will be given. The main part is the presentation of validation results and some applications of the new system which still is in the final calibration phase. An outlook on future developments both scientific and more technical, including completely new model components especially for data assimilation of ecosystem modelling completes the presentation.

Keywords

HBM, ocean forecast, operational ocean circulation model, North Sea, Baltic Sea

Zusammenfassung

Am Bundesamt für Seeschifffahrt und Hydrographie ist bereits seit einigen Jahrzehnten ein numerisches Ozeanvorhersagesystem für Nord- und Ostsee mit Fokus auf dem deutschen Küstenbereich in der operationellen Anwendung. Alle Modellkomponenten befinden sich dabei in ständiger Weiterentwicklung. Hier wird die jüngste Modellentwicklung – die Einführung des Zirkulationsmodells BSH-HBM – beschrieben. Das Zirkulationsmodell ist eine wesentliche Informationsquelle für eine Reihe von Diensten an Deutschen Küsten (z.B. Wasserstandsvorhersage- und Sturmflutwarndienst, Öldriftvorhersage und Seenotrettung) und damit von zentraler Bedeutung in der Ozeanvorhersage.

Nach einem Überblick über das Modellsystem liegt der Schwerpunkt dieser Arbeit in der Darstellung der Modellergebnisse aus Validation und Anwendung des sich derzeit am Ende der Kalibrationsphase befindlichen Modells. Den Abschluss bildet ein Ausblick auf zukünftige Arbeiten sowohl in Bezug auf die inhaltliche als auch auf die technische Weiterentwicklung inklusive einiger neuer Modellkomponenten z.B. zur Ökosystemmodellierung und Datenassimilation.

Schlagwörter

HBM, Ozeanvorhersage, operationelles Ozeanzirkulationsmodel, Nordsee, Ostsee

Contents

1 Introduction

The Federal Maritime and Hydrographic Agency (BSH) has a large need for ocean forecasting data to run its internal operational services, e.g. the sea level prediction and storm surge warning service and the ice service, and to support external customers like the national search-and-rescue centres, the Central Command for Maritime Emergencies or the German Navy. In order to fulfill all these operational obligations BSH runs and maintains a comprehensive numerical ocean forecasting system which is under permanent revision.

Operational modelling at BSH has already a considerable history starting at the predecessor institution DHI in the early 1980s and was in the beginning focused on the North Sea. Storm surge forecasting at the German Coast was – and still is – an important issue and thus was one of the applications that was tackled first. Later on the region of interest was extended to include the Baltic Sea which led to a fruitful cooperation in the Baltic area. As part of this cooperation the model code developed at BSH – called BSHcmod – was spread in the Baltic Sea community. One branch (HIROMB) was installed and further developed at the Swedish Meteorological and Hydrological Institute (SMHI) and is until today the basis for the official HELCOM oil spill response system in the Baltic. Another branch started a few years later at Danish Meteorological Institute (DMI) where it founded the Danish storm surge warning system. All three model lines where actively development over several years and somehow diverged over time. During recent years and with support of the MyOcean projects an effort was made to merge the three development lines into one. The outcome of this effort is the HIROMB-BOOS-Model (HBM) nowadays jointly development by BSH, DMI, the Finnish Meteorological Institute (FMI) and the Marine Systems Intitute at Tallinn University (MSI). At BSH the transition from the current operational model code BSHcmod towards HBM is not yet fully completed, so this publication, in which for the first time results from the future operational model HBM are presented, describes partly work in progress and mostly results from the ongoing calibration phase.

2 Model system

2.1 Equations

The equations of the physical kernel of HBM are mostly the same as those of BSHcmod which are described in DICK et al. 2001 and DICK et al. 2008. An important difference to the BSHcmod versions is the possibility to choose between dynamical vertical co-ordinates (KLEINE 2004) and z-co-ordinates with a free surface by a compiler flag. For operational use at BSH dynamical vertical co-ordinates are chosen.

Changes with the largest impact on the physical kernel (in comparison to the latest BSHcmod version 4) are the implementation of a new turbulence scheme – now a k-omega model is used, which is described in BERG 2012 – and the grid nesting. In HBM a fully dynamical two-way nesting is implemented. This means that the nested grid is a continuation of the grid into which it is nested. Therefore, areas which are covered by more than one grid within one setup are just calculated in one - the finest - grid. In all coarser grids the finer grid area is non-active. In the BSH NOKU-setup (see Fig 2) this is realized in the inner German Bight and the Western Baltic, where only the so-called KU-grid (the fine grid) is active, whereas the corresponding points in so-called NO-grid (the coarse grid) are non-active (grey area in the NO-grid shown in Fig. 2). However, the products from NO-grid still cover the whole area. A more detailed description of the nesting equations and a very detailed description of the technical implementation with a focus on parallelization in HBM can be found in BERG and POULSEN 2012.

Furthermore some parameterizations were adjusted whereby especially the wind stress parameterization is noteworthy, because in contrast to BSHcmod-versions which use a linear approach, a quadratic approach for calculating the wind drag coefficient is chosen.

2.2 Setups / bathymetry

The BSH model system consists of four model grids which are calculated in three different setups. The first setup of the model chain is a 2D-model of the North East Atlantic

(NA, Fig. 1) with a horizontal resolution of about 10 km. Boundary values for the North- and Baltic Sea grid (NO, Fig. 2) are extracted from this setup. The North- and Baltic Sea grid has a horizontal resolution of about 5 km and 36 vertical layers at the maximum. Through the mentioned fully dynamical two-way nesting the finer coastal grid (KU, Fig. 3) with a horizontal resolution of about 900 m and a maximum of 24 vertical layers, which covers the inner German Bight and the Western Baltic, is integrated into the North- and Baltic Sea grid. Together these two grids form the second setup (this setup will be called NOKU henceforth) of the model chain. The third set up is formed by the Elbe grid (EL, Fig. 4), which was mainly developed in the OPTEL-project (BORK and MÜLLER-NAVARRA 2011; MÜLLER-NAVARRA and BORK 2012). It has a horizontal resolution of 90 m and a maximum of 7 vertical layers. In contrast to the calculations within the OPTEL-project which used a two-way nesting to the coastal grid, the Elbe-grid is calculated as a standalone setup in operational mode. The boundary values are provided by the NOKU setup.

The number of vertical layers in the three 3D-grids NO, KU and EL are a result of the same vertical partition. The upper 20 m are divided in ten layers of 2 m thickness. Between 20 m and 100 m water depth there are five layers of 3 m thickness and fourteen layers with a thickness of 5 m. In water depths below 100 m the resolution is relatively coarse with layer thicknesses up to 200 m.

The described setups are the 4th version, which has been developed and applied at BSH, so that the whole system of setups will be called V4 subsequently.

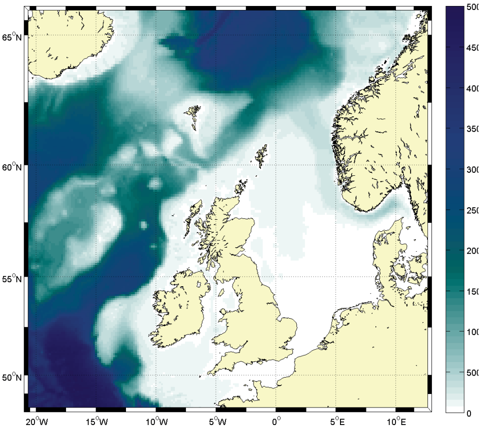

Figure 1: water depth of the NA-grid.

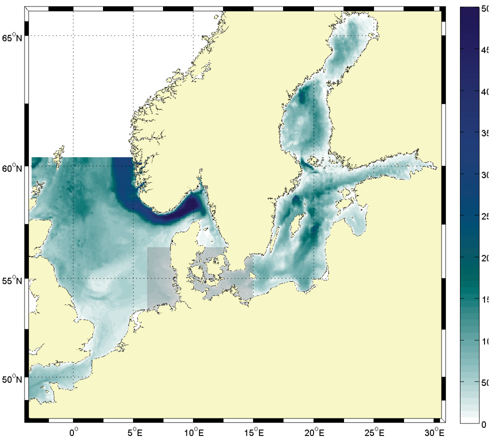

Figure 2: water depth of the NO-grid, during calculation the grey shaded area is non-active due to the nesting.

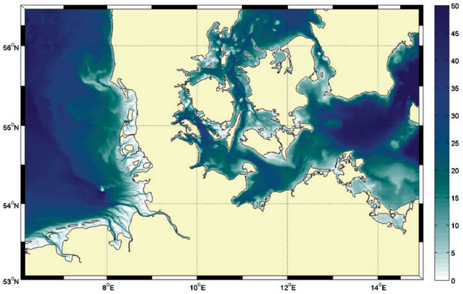

Figure 3: water depth of the KU-grid.

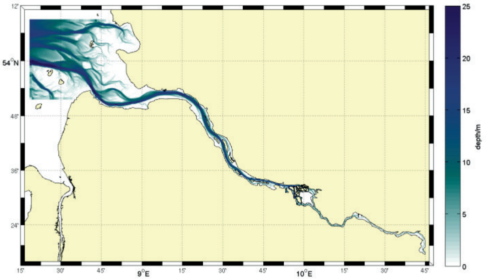

Figure 4: water depth of the EL-grid.

2.3 Forcing

Atmospheric forcing for all BSH model-setups is provided by the operational forecasts of the German Weather Service (DWD). The meteorological input parameters 10m-wind, air pressure, humidity, cloudiness and 2m-air temperature are received by BSH four times a day. Whereas the NA-setup needs forcing fields which are a combination of output from the global model GME (MAJEWSKI et al. 2012) with an effective horizontal resolution of 20 km and the European model COSMO-EU (SCHULZ and SCHÄTTLER 2011) with a horizontal resolution of currently 7 km, the NOKU- and the EL-setup are driven only by COSMO-EU data.

A radiation boundary condition is applied in the NA-setup, so that no external data for the open boundary is needed. At the open boundary of the NOKU-setup the sum of surge data from the NA-setup and tides based on 19 partial constituents are used. The EL-setup finally gets its open boundary data from the NOKU-setup.

Moreover eighty rivers are considered in the NOKU- and one (the Elbe) in the EL-setup. Whereas data of the German rivers is provided operational by the German Federal Institute of Hydrology (BfG), data for all Baltic rivers (except the Odra) is taken from the operational HBV model (BERGSTRÖM 1995) running at the SMHI. Because of a lack of data all the remaining rivers in the North Sea (mostly from the UK) are based on climatological data.

2.4 Operational schedule / Computer facilities

The described model system runs currently once per day on an IBM P7 755 server (4x8 core, 3.6 Ghz Power7 processors) with 16 openMP-threads and without MPI parallelisation. The HBM-code was compiled with the IBM-xlf-compiler. For illustrating results both MATLAB and GMT are used.

2.5 Archive

BSH maintains an extensive archive of model forecasts which includes data since 2000. All archived data are available free of charge. The longest consistent data set is the output of the former V3-NOKU-setup calculated by the previous version of the BSHcmod model, which covers the 14 years from 2000 to 2013. The resolution of that setup was half of the resolution of the currently used V4 NOKU-setup. Data from the V4-NOKU-setup calculated by the BSHcmod V4 is archived from 2008 onwards.

Because both the NA- and the NOKU-setup of the described BSH-HBM model system are still in pre-operational mode, only results from the EL-setup calculated by HBM is archived at the moment. From this setup the output is available since April 2013.

3 Validation

A quantitative comparison of model results with different kinds of observations – often referred to as validation - is an important step in the operational model development cycle. Even though the model version presented here is still at a pre-operational stage and some calibration steps need further iteration, the results presented below already give an estimate of the lower limit of the quality of the upcoming operational model version.

The year 2008 was chosen as the main validation period because a comprehensive observational data set was already available for this year. A hindcast run initialized in November 2007 was carried out as basis for the validation. Some results of the validation of water level, currents, water temperature, salinity and sea ice will be presented in this section.

3.1 Water level

To analyse the simulated water levels it is sensible to split the analysis into two parts, respectively subsections: The first one on the North Sea, where tides are the main component of the local sea level elevation, so that the quality of the model output depends mainly on the quality of the simulated tides. Therefore both tides and total water levels were analysed in this subsection. The second subsection is focused on the Baltic Sea, where tides are virtually absent and only the total water levels are considered.

3.1.1 North Sea

As outlined in section 2.3 the tidal boundary conditions in the applied NOKU-setup are based on the 19 dominating tidal constituents. Moreover the validation period is only one year, so that a complete tidal analysis of the data is not feasible. Instead the analysis will be restricted to the two dominating semi-diurnal tidal constituents M2 and S2. A harmonic analysis of the modeled data yields the results given in Tab. 1 when compared with harmonic constants analysed from observations by the French Service Hydrographique et Océanographique de la Marine (SHOM 1982).

Table 1: Amplitude and phase calculated from BSH-HBM output as well as the error compared to data taken from SHOM (1982) for M2- and S2-tide at selected stations at the German coast.

Station	**M2 amp [cm]**	**M2 amp err [cm]**	**M2 pha [deg]**	**M2 pha err [deg]**	**S2 amp [cm]**	**S2 amp err [cm]**	**S2 pha [deg]**	**S2 pha err [deg]**
Borkum	107.6	2.8	278	8	28.1	1.0	338	5
Helgoland	113.2	4.6	312	0	30.8	1.9	13	-5
Cuhaven	147.9	13.5	340	-4	37.1	2.7	46	-7
Buesum	154.7	-1.5	341	4	41.0	-1.1	47	0

The results in Tab. 1 show that both the amplitude as well as the phase of M2 and S2 is represented quite well by the model at the considered stations. Only the amplitude at Cuxhaven has a significant error in comparison with the SHOM data, but it should be kept in mind that there is also an uncertainty in the observed data. A recent analysis of a 19 year time series at tide gauge Cuxhaven by BSH (personal communication Patrick Goffinet) gave a M2 amplitude of 138 cm, which would reduce the model error to about 10 cm. Nevertheless the modeled M2 amplitude at Cuxhaven fails the BSH internal quality criteria at the moment and further calibration work is presently carried out.

When validating the water levels in the North Sea, the analysis is restricted to the peak values at high and low water because these are the values of highest interest. The exact timing of the peak values is not considered by this method.

Table 2: Bias and bias-corrected root mean square deviation from observations (RMSD) of total water level peaks during high and low water at selected stations at the German coast.

Station	**Total water level**			
	High water		**Low water**	
	Bias [cm]	**RMSD [cm]**	**Bias [cm]**	**RMSD [cm]**
Borkum	-3	11	10	14
Helgoland	3	14	10	11
Cuxhaven	19	18	5	14
Buesum	15	18	6	17

Whereas the bias' shown in Tab. 2 at the stations Borkum, Helgoland and Cuxhaven are mainly explainable by the error in tides, the bias in Buesum can partly be explained by the very difficult local topographic conditions around that station. The bias-corrected root mean square deviation from observations (RMSD) which is lower than 20 cm at all stations, is already sufficiently but there is of course potential for improvements in the future. The RMSD is, however, at the same level as it is in the current operational model BSHcmod.

For station Cuxhaven Fig. 5 shows the frequency distribution of high and low water level differences. If the bias is considered, the rate of events which are reproduced in a range of ±10 cm is 39 % for high water and 49 % for low water. In a range of ±20 cm it is 69 % for high and 85 % for low water. In the range of ±30 cm more than 90 % of both high and low water events are reproduced.

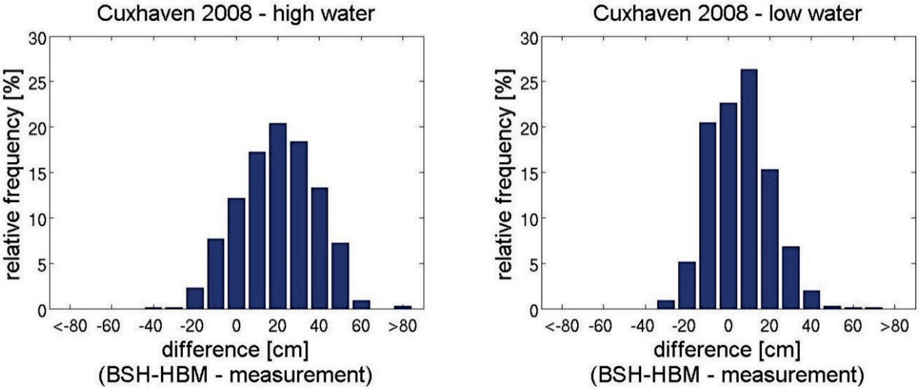

Figure 5: Frequency distribution of high (left) and low (right) water level differences at station Cuxhaven for the year 2008.

3.1.2 Baltic Sea

In the Baltic Sea, water level variations are caused mainly by wind effects and seiches, whereas the tidal signal is relatively small, so that water level predictions for the Baltic differ markedly from those for the North Sea. Therefore, the direct model-water level output is validated here. As it can be seen from the examples presented in Fig. 6, in which the results at station Warnemuende are shown, the model describes both the absolute water level elevation and the variability of it rather good.

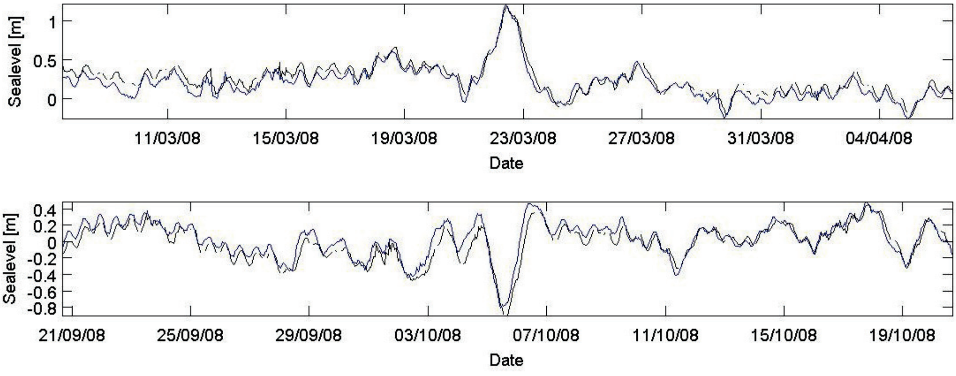

Figure 6: Water level time series during two storm events in 2008 at Warnemuende station. Observations are shown in black, BSH-HBM data in blue.

Tab. 3 indicates that the results at Warnemuende are representative for all German stations where correlations of about 90 % and RMSDs of about 10 cm are to be found. Moreover the simulated standard deviation equals nearly the observed one in all places.

Table 3: Overview of statistical metrics for water level elevation at German stations – N describes the total number of measurements, σ is the standard deviation from mean, RMSD is the bias-corrected root mean square deviation from measurements and r the correlation coefficient.

Station	**Water level elevation**						
	Observations			**BSH-HBM**			
	N	**σ [m]**	**mean [m]**	**Bias [m]**	**σ [m]**	**RMSD [m]**	**r**
Kiel-Holtenau	8158	0.25	0.05	0.07	0.28	0.12	0.90
Koserow	8301	0.21	0.10	0.18	0.23	0.10	0.90
Sassnitz	5792	0.21	0.13	0.15	0.22	0.10	0.89
Travemuende	8472	0.24	0.07	0.08	0.28	0.12	0.90
Warnemuende	7477	0.22	0.08	0.11	0.25	0.11	0.89

3.2 Currents

Due to the very high natural local variability of currents – caused e.g. by local topographic effects – on the one hand, and the model immanent spatial averaging on the other hand, it is always challenging to do direct model-observation comparisons. In addition to that, only a sparse set of measurements is available. For 2008 only data from a few stations in the Baltic can be used. A comparison between observed current speed and the current speed of the appropriate model cell shows for most part a good agreement, indicated by a modelled standard deviation that is in the same range than the observed one at all stations and a bias that is lower than 10 cm/s at most stations. As an example the time series for surface- and bottom current velocity at station Arkona is shown in Fig. 7.

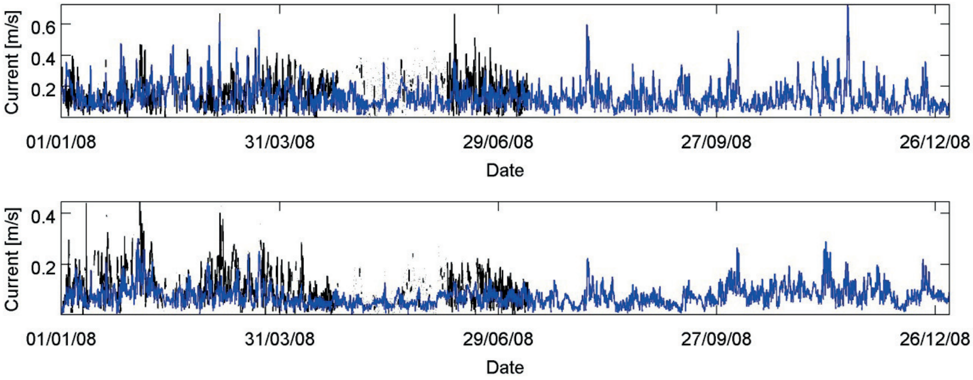

Figure 7: Current velocity time series at surface (above) and bottom (below) at Arkona station. Observations are shown in black, BSH-HBM data in blue.

3.3 Water temperature

With respect to water temperature, there is both a ‘supercollated’ L3 satellite product for validating the sea surface temperature (SST) and profile data in North and Baltic Sea available.

Regarding the SST, BSH-HBM shows a very accurate reproduction of the satellite data. Over the whole year 2008, the bias is almost in the whole NOKU-area less than 1° C and also the RMSD between BSH-HBM and satellite data is mostly less than 1° C (Fig. 8).

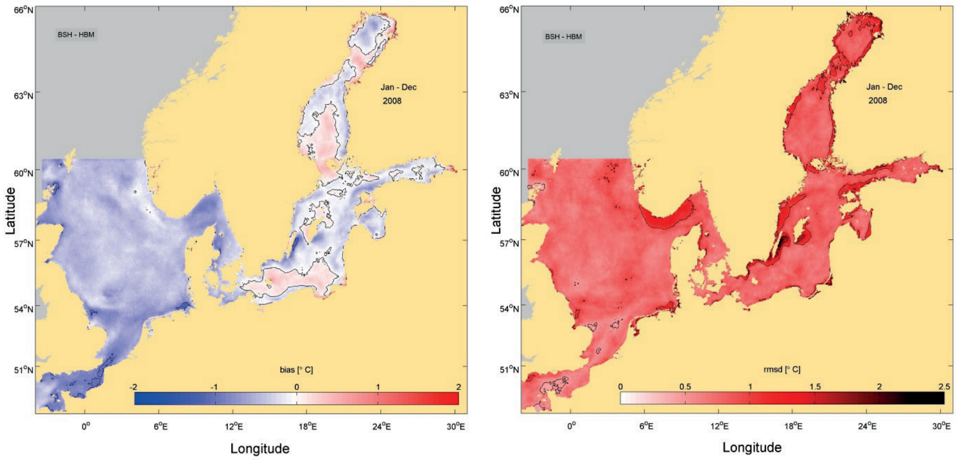

Figure 8: Bias (left) and RMSD (right) of BSH-HBM SST compared with 'supercollated' L3-satellite SST in 2008.

A more detailed analysis of modelled water temperature is possible at in-situ stations with larger water depth where sensors are available at different depth levels. Near-surface and near-bottom data have been taken into account at these stations.

The near-surface results confirm the results from the satellite based SST analysis. At the German stations the bias is less than 0.5° C, the RMSD is smaller than 0.7° C and the correlation is above 97 %.

At larger water depth, more pronounced deviations from observation are found. At large depth of more than 80 metres in the Baltic Sea the temperature is not well captured in the simulation. Due to the very long time scales of the deep water properties in the Baltic it is hard to say if there is really a severe model deficit e.g. due to a too coarse vertical resolution, or if most of the observed differences are due to the short one year validation-period which make the results prone to problems in the initialization and spin-up procedure.

Nevertheless, at German stations both in the North Sea and in the Baltic the correlation at bottom is mostly still more than 90 %, the RMSD is between 0.5° and 1.5° C and the bias is between 0.2° and 2° C. All in all there is a good overall agreement between HBM and the observed data at these stations as shown exemplarily in Fig. 9.

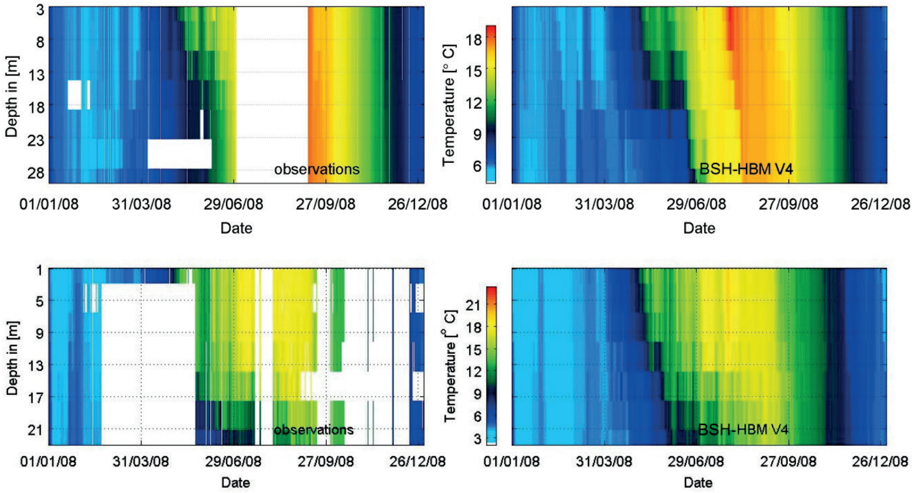

Figure 9: Temperature time-depth maps at station UFS Deutsche Bucht / North Sea (above) and at station Fehmarn Belt / Baltic Sea (below). In each case observation is shown on the left, BSH-HBM on the right.

3.4 Salinity

Unfortunately only few observations were available in the chosen calibration period, so only salinity at some Baltic stations has been analyzed. Generally the model captured the surface salinity quite well. Moreover, due to good initial conditions, the salinity below the halocline i.e. at depths greater than 60-80m, shows also a good agreement. At depths above the permanent halocline and below the surface like the bottom of all German Baltic stations measurements show generally stronger fluctuations than the model does and the bias and the RMSD are also relatively high. This is most probably owed to a combination of the complicated bathymetry of the Baltic Sea and the (probably too) coarse vertical resolution of the applied model setups. As an example Fig. 10 shows the salinity time series at station Fehmarn Belt.

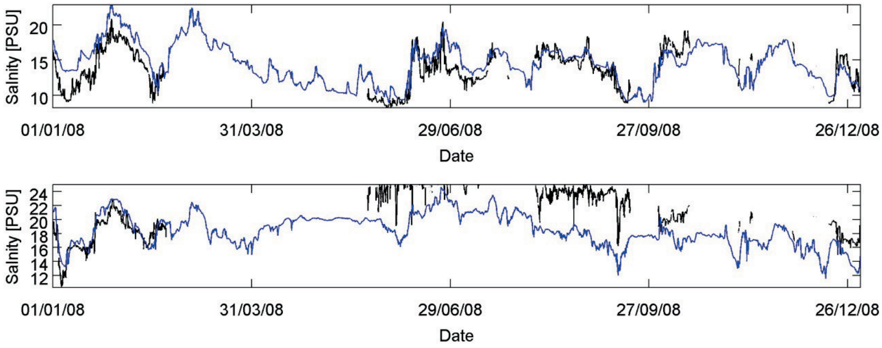

Figure 10: Salinity time series at surface (above) and bottom (below) at Fehmarn Belt station. Observations are shown in black, BSH-HBM data in blue.

In any case salinity is a parameter with a high potential for improvements in future model versions with higher (vertical) resolution and applied data assimilation.

3.5 Sea Ice

The winter of the year 2008 was relatively mild, so that only little sea ice was observed. Fig. 11 shows a comparison of computed and observed sea ice concentration on 01.03.2008 - the time with maximum sea ice extent in 2008. The sea ice extent and general distribution are quite similar. However, locally the concentrations differ significantly.

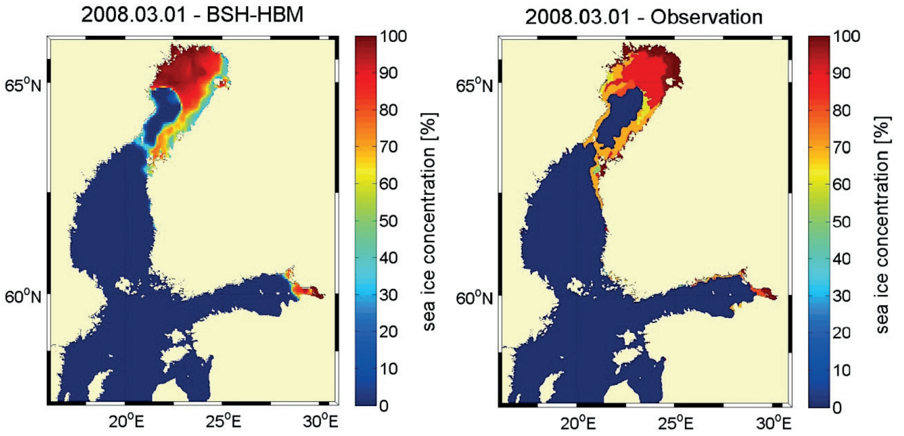

Figure 11: Comparison of predicted (left) and observed (right) sea ice concentration in the Baltic Sea on 1 March 2008.

4 Results

In this section some recent results will be presented which demonstrate that the new BSH-HBM model system could simulate special events of strong public interest. Two events which took place in 2013 are highlighted – on the one hand the "Elbe flood" in June and on the other hand the impact of cyclone "Xaver" from 5th to 7th December. During both events a strong increase in water levels had been experienced and as precise as possible forecasts were needed to minimize the consequences of these events for the affected population.

4.1 Elbe flood in June 2013

Heavy rainfall in south-east Middle Europe in May and June 2013 caused a flood at various rivers in that region. At the river Elbe water levels along the river were measured which were never observed before. Of course these enormous water masses caused also very high water levels in the tidal influenced part of the Elbe estuary between St.Pauli and the weir in Geesthacht which is influenced significantly by the river discharge anyway.

The forecast of the river discharge was characterized by high uncertainties and therefore a high variability from forecast to forecast. Indeed the best estimate forecast of BSH-

HBM works with discharge calculations from water level measurements in Neu Darchau which lies outside the EL-model region. Because the calculated river discharges of more than 4000 m³/s, which were nearly five times as high as the medium discharge, never occurred before, also these values were fraught with uncertainty.

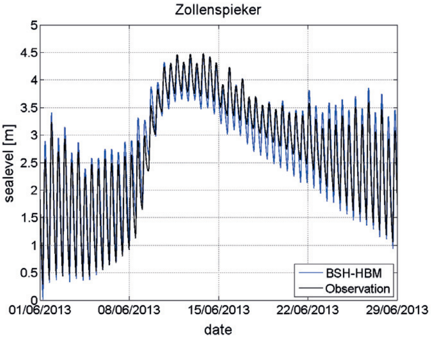

Figure 12: Water levels during Elbe flood at station Zollenspieker.

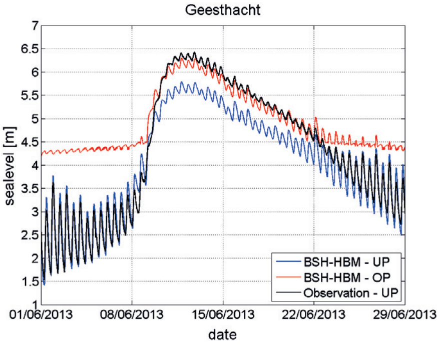

Figure 13: Water levels during Elbe flood at station Geesthacht-UP. Additionally model results at station Geesthacht-OP are shown.

In spite of these uncertainties BSH-HBM captured the Elbe flood very well at most stations between St.Pauli and Geesthacht like for example Zollenspieker (Fig. 12). Only directly below the weir in Geesthacht ("Unterpegel" - UP) the absolute peak was modelled about 0.5 m to low. However this could be explained with difficulties in modelling the weir itself, because during the flood the weir was completely opened and directly above the weir ("Oberpegel" – OP) the modelled water level matched very good to the observations (Fig. 13).

4.2 Cyclone Xaver at 5th and 6th December 2013

At 5th and 6th December 2013 the cyclone Xaver reached the inner German Bight with very high middle wind speeds between 45 and 55 knots (9-10 Beaufort) from northwesterly directions (Fig. 15). Because of these high middle winds and gales up to 12 Beaufort over almost the whole two days, up to four storm surges and up to two strong storm surges in a row could be observed at almost all German North Sea stations. The highest water level elevation during Xaver could be observed at station St.Pauli with a deviation of 3.98 m above the mean high water, which means a water level of 6.09 m above mean sea level – a very strong storm surge and the second highest observed value ever.

Even if the low waters were overestimated by BSH-HBM during Xaver, the model turned out to be a very useful tool for the scientists of the storm surge forecasting center because the storm surges were captured very well. At station Cuxhaven the errors of the maximum water levels during high waters were below 10 cm and at station St.Pauli they were below 25 cm (Fig. 14), which is a very good result taking the extraordinary high observed values into account.

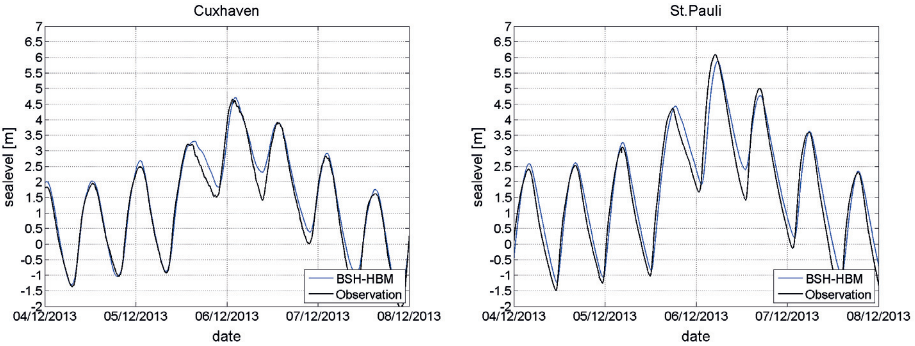

Figure 14: Water levels during Cyclone Xaver at stations Cuxhaven (left) and St.Pauli (right).

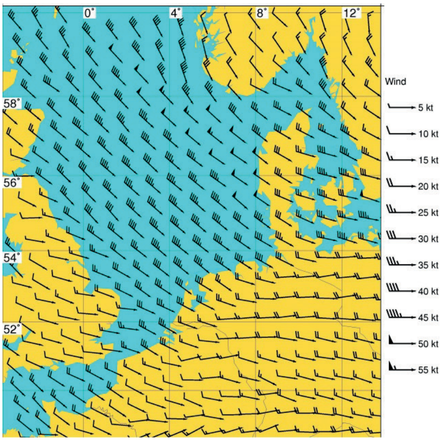

Figure 15: COSMO-EU middle 10m-wind at 6th December 2013 00 UTC.

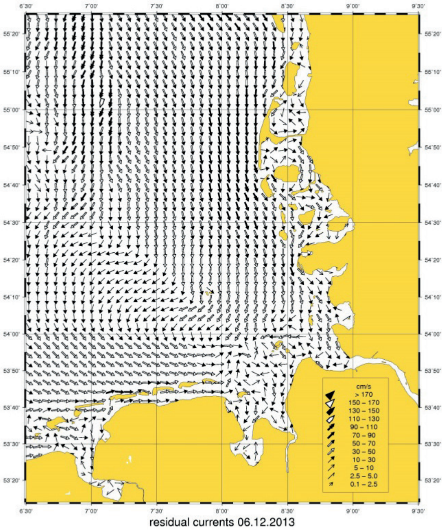

Figure 16: BSH-HBM residual currents at surface in the German Bight at 6th December 2013.

Very impressive were also the modelled residual currents which were at surface between 30 and 90 cm/s in almost the whole German Bight (Fig. 16). Hence it was three times as high as compared to a situation with stable wind conditions of 4-5 Beaufort from one direction over a whole day.

5 Outlook

The model system in under permanent revision and steps to upgrade, adapt or extend the model system on the scientific as well the technical level are continuously taken according to the changing and typically growing customer demands. The main points of further development are listed below:

5.1 Operational schedule/Computer facilities

The latest hardware upgrade at BSH towards three IBM P7 755 servers (4x8 core, 3.6 Ghz Power7 processors) in combination which the strongly increased computing efficiency of the HBM code give a substantial speedup in the model runs compared to the former system. It is planned to use the free resources primarily for an improvement in operational schedule. The current status is that only the 2D storm surge model runs 4 times per day based on the latest meteorological forcing. The 3D circulation model is only run once a day. The final stage of the planned upgrade of the operational schedule will allow also for 4 runs per day with both the 3D NOKU and the 3D EL setup with a forecast lead time of at least 78 hours. As an intermediate step 2 runs per day are aimed at. Along with these changes goes an optimization of the data provision for internal and external customers, which will lead to a reduced delay between model run and data delivery as well as an increase in system robustness.

5.2 Data assimilation

All model runs carried out at BSH today are completely "free" model runs, i.e. there is no direct connection from model space to observational space, besides the indirect connection via the use of observational data in the boundary conditions. This lack of connection to observations has the strongest implication for physical processes in the ocean which are not directly connected to the atmospheric forcing like haline stratification. In order to overcome this limitation, data assimilation procedures have been developed over the last decades, first in meteorology and later on also in ocean modelling. BSH has started to build up a data assimilation capacity in close cooperation with the Alfred-Wegener-Institute (AWI). The first step was the implementation of a data assimilation scheme for sea surface temperature (SST) which resulted in a substantial error reduction in temperature (LOZA et al. 2012; LOZA et al. 2014). The assimilation of satellite born SST data was extended towards the use of temperature and salinity profiles (LOZA et al. 2013). In the next steps it is planned to include further sources of temperature and salinity data, i.e. from FerryBox lines, and extend the methods to handle also ocean currents, sea ice and water level. To make the data assimilation scheme - which is in a pre-operational stage at the moment - fully operational demands for a further upgrade of computational facilities at BSH mentioned above.

5.3 High resolution estuary setups

A very high spatial resolution is needed to attain accurate forecast of currents, water level and other parameters in complicated coastal areas like the German North Sea estuaries. A first step towards high resolution forecasts was made in the development of a setup with 90m horizontal grid spacing for the Elbe estuary in the OPTEL project. The further development of the Elbe model became operational in the beginning of 2013. There are plans to extend the coverage of the high resolution setup towards the Jade/Weser and the Ems estuary with spatial resolution of at least 100m.

5.4 Ecosystem modelling

Several fields, among them the implementation of the European marine directives, e.g. the Water Framework Directive or the Marine Strategy Framework Directive, have an increasing demand for marine information which are not limited to the physical environment. In order to build up a capacity for providing biogeochemical information to a broad range of customers an ecosystem component is under development. Based on a coupling of HBM and the well-established ecosystem model ERGOM (NEUMANN 2000; MAAR et al. 2011) an operational setup for the North Sea and the Baltic Sea has been created which is in the calibration phase at the moment.

5.5 Coupled models

Another area of intensive development is the further integration of different model components into one coupled system.

Although the integration of ocean and ice has been established several years ago and runs fully operational at BSH there is still large room for improvements. Especially the simulation of ice rheology and related dynamics of sea ice is under further investigation.

Other areas of model coupling have already come a long way, too. The coupling of ocean currents and surface waves had entered a pre-operational stage already some years ago (MURAWSKI 2007) and is now reinvestigated based on the latest development of the single components (HBM for ocean circulation, WAM (KOMEN et al. 1994; KIESER et al. 2012) for surface waves). The next step in coupling, which has not been addressed at BSH so far, is the coupling of ocean and atmosphere where a coupled system based on COSMO (2013) and HBM is planned.

5.6 Upgrade of computing facilities/massive parallelization

Running an operational ocean forecasting system is a computationally expensive task. Steadily increasing user demands make a continuous upgrade of the computational facilities a necessity. In order to better support massive parallelization needed for future high resolution setups and especially the data assimilation the next computer generation at BSH will be a Linux cluster which will give a boost in scalability of the system and a strong reduction in computing costs.

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