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Hydrodynamic Numerical Models Suitable for Application to the German Fairways and Ports at the Baltic Sea Coast

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Summary

Since the early 1990s there has been a growing demand for fairways to the ports along the German Baltic Sea coast to be adapted for modern types of vessels. Practical planning by fairway management authorities is also influenced by a growing and broadly shared understanding of climate change.

This has resulted in new assessment requirements during planning processes and the consultations of the Federal fairway management authorities. It was necessary to adapt modelling tools to fit them to deal with issues concerning the Baltic Sea coast. The highly baroclinic nature of the system required inclusion of thermic processes. Long-term modelling requires faster models and the limited staff of the institute required a flexible, efficient modelling toolbox.

In parallel to the development of a modelling framework for the Baltic Sea coast, issues relating to the entrance of the Peenestrom, the ports of Wismar and Rostock and the Schlei estuary also needed to be addressed. Further insights on the reaction of inner coastal waters to changes in sea level were also tackled in the context of the KLIWAS project. Some of these project highlights are presented here.

Keywords

Baltic Sea, port entry, toolbox, numerical models, climate change, fairway, adaption

Zusammenfassung

Seit den frühen 1990er-Jahren besteht ein wachsender Bedarf der Anpassung der Häfen der Deutschen Ostseeküste an moderne Schiffstypen. Die neuen Erkenntnisse der Gesellschaft über den Klimawandel beeinflussen ebenfalls die praktische Planung der Wasserstraßenverwaltung.

Diese Entwicklungen führten zu neuen Anforderungen in der Begutachtung während der Planungsprozesse und der Beratung der Wasserstraßenbehörden des Bundes. Die Werkzeuge zur Modellierung mussten angepasst werden, um die Fragen betreffend die Ostseeküste abdecken zu können. Die stark barokline Natur des Systems machte es erforderlich, thermische Prozesse zu berücksichtigen. Modellierung über lange Zeiträume erfordert schnellere Modelle und die begrenzte Zahl der Mitarbeiter einen flexiblen, effizienten Modellbaukasten.

Parallel zur Entwicklung des Baukastens für die Ostseeküste mussten Fragen an den Zufahrten zum Peenestrom, der Schlei und der Häfen von Wismar und Rostock beantwortet werden. Innerhalb des Projektes KLIWAS wurden weitere Erkenntnisse zur Reaktion der inneren Küstengewässer auf einen Anstieg des Meeresspiegels erarbeitet. Von diesen Projekten werden hier Schlaglichter präsentiert.

Schlagwörter

Ostsee, Hafenzufahrt, Werkzeugkasten, numerische Modelle, Klimawandel, Fahrwasser, Anpassung

Contents

1 Introduction

Since the early 1990s there has been increasing demand for the modernisation and adaption of the waterway infrastructure of the new federal states of Germany in the eastern part of the country which joined the Federal Republic of Germany following reunion with the territories of the former German Democratic Republic. The depth of fairways has required alteration as the size of vessels built in the shipyards of Wolgast and Wismar has grown. The draft and width of ship units which will enter the ports of Rostock and Wismar in the future will also require further adaption of fairways.

The inner coastal waters are valuable natural habitats and recreational regions. The increasing availability of public information has sharpened the general public's awareness of environmental issues. Conflicts between growing volumes of commercial traffic and other competing interests are consequently becoming more and more apparent and need to be solved in a constructive manner in the planning phase.

The need to find acceptable solutions to environmental conflicts results in new assessment requirements and consequently the decision to develop a modelling framework for the Baltic Sea with a focus on the German coast.

2 Challenges

The fairways planning process needs to address several types of issues. The most important of these with regard to the Baltic Sea coast are:

- Changes in local mean sea level and its variability
- Changes in local salinity and temperature
- Spreading of dumped substances
- Changes in wave characteristics and wave induced stresses

Even if there is not always a benefit in precisely reproducing the physical system in order to answer the issues which arise during an approval procedure, any opponents of a traffic measure will negate the credibility of model results if the accuracy of the modelling systems used clearly fail to provide a natural view of their area of interest.

High modelling standards for the approval of traffic planning in Germany include the following topics:

- Small-scale bathymetric structures, such as fairways or islands, must be geometrically approximated sufficiently well enough in the area of interest.
- The seaward open model boundary should be kept as far away as possible to avoid the influence of model reactions on bathymetry changes reaching that boundary.
- The dynamics driven by temperature, salinity and sediments must be included.

The dynamics of the Baltic Sea are characterised by long-term circulation, driven by wind and density changes. A permanent halocline is present in the deeper basins of the Baltic. Singular events, such as storm surges and salt water inflows from the North Sea, are added to this basic state. In the winter, cooling causes strong convection and leads to a partial ice cover. In the summer, heating leads to a sharp thermocline. All these processes have a strong influence on spatial and time resolution and model calibration.

3 Model description

In order to fulfil all the requirements required for the approval processes we chose to develop a modelling framework for the Baltic Sea (SEIß 2012, RAHLF and SEIß 2012). The framework is a modular system containing the following components, which are independently variable:

- Numerical solver software
- Pre-processing tools
- Post-processing and presentation tools
- Model grids
- High resolution digital bathymetry models
- Boundary forcing data
- Calibration data

Only the model grids and boundary forcing data depend on the numerical solver software used. Basic datasets, such as digital bathymetries, gauge data for validation or geographic information used to illustrate result pictures, are provided in a central place. These datasets can be used by any model. Pre- and post- processing software tools are provided by the BAW modelling group (BAW 1996-2014).

The model grids are derived from a basic grid which covers the whole Baltic Sea with an open boundary at the Skagerrak. Spatial resolution becomes more detailed from the inner Baltic Sea to the coastline. For the regions of interest, the basic grid is substituted with an inlay grid which is suitable for resolving the details of the bathymetry subject for a specific issue (Fig. 1). High resolution inlay grids are part of the framework database and currently exist for the Warnow mouth, the Kiel Fjord and the Schlei Fjord. They can also be run as standalone models with a limited area of application, e.g. fast prediction of accurate water levels or currents.

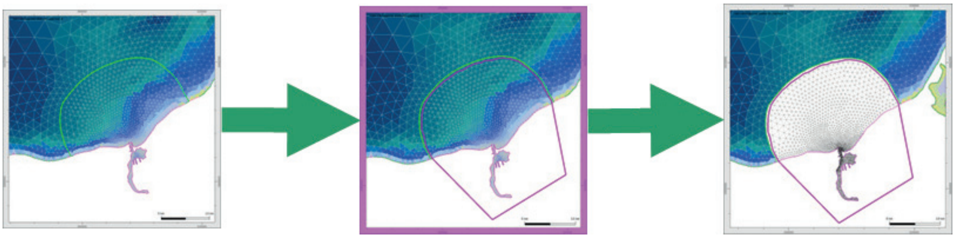

Figure 1: Principle of generation of a regionally refined grid by substitution of an area by an inlay grid.

In our institute we usually apply the UNTRIM model code as the numerical solver of the hydrodynamic equations (CASULLI und WALTERS 2000) (CASULLI und ZANOLLI 2002).

Atmospheric boundary data were originally provided by the German Weather Forecast system and were pre-processed to fit the input format of the modelling software. Data from 01/2005 to 11/2012 are currently available for use. In this case, the model software must be adapted to the common data format NetCDF (UNIDATA PROGRAM CENTER).

Gauge data from Smögen, a village approximately 120 km north to northwest of Gothenburg, can be used for steering of the sea level at the open boundary if a time shift of 30 minutes is applied to the time series (Fig. 2).

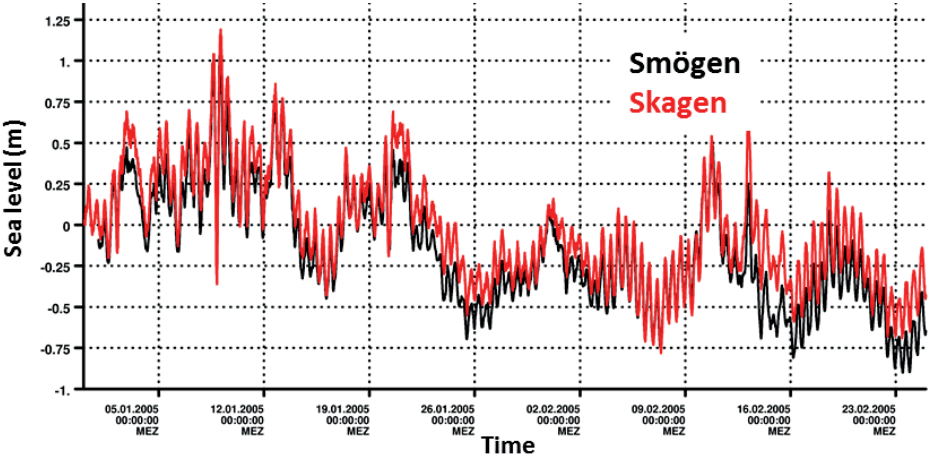

Figure 2: Typical time series at the open boundary.

This approximation is good enough to reproduce the tidal signal and the long-term development of the mean sea level in the interior. These data are available for the period 2001 to 2012. Precompiled boundary data are already available for several years. The boundary conditions can be reconstructed for previous years using the long-term signal of the gauge of Gothenburg and the tidal harmonics of Smögen or by using the gauge of Skagen directly. Several software tools are available to support the generation of realistic boundary time series (BAW 1996-2014).

The current version of the UNTRIM simulation software still uses proprietary data formats of BAW to import boundary conditions. Support of the internationally distributed NetCDF (UNIDATA PROGRAM CENTER) data format is in progress and will represent a huge technical step forward in the use of existing datasets provided by other institutions.

The model state can be initialised using the dataset of (JANSSEN et al. 1999). However, some programming effort will still be required in order to use these NetCDF data (UNIDATA PROGRAM CENTER) in the model software UNTRIM as they are provided.

Models are validated by comparing measured water levels at several gauges with the time series simulated by the model. Some data sources are available for gauge data via the internet for the Baltic Sea. Additionally, the database of the German Waterway Management Authorities provides high resolution time series of all their supported gauges from 1989 to the present. Fig. 3 shows a typical example of such a gauge station. Historical measurements from paper archives are now being continuously digitized and integrated into this database resource. A standard procedure is applied to recompile in the BAW all the data provided from different sources. This guarantees comparable quality and provides a data format which is readable by post-processing tools.

Figure 3: Modern gauge equipment, which is indicated by the smallness of the gauge house, at "Wismar Baumhaus" provides high resolution time series of water levels (photo: Seiß, 2009).

A typical validation step is to visually compare the simulated curve with the one provided by the gauge at the same location. Differences are calculated to estimate the maximum range of error in instantaneous water levels. Deviations may result from an energy distribution in the model domain which deviates from reality and which is indicated by the amplitudes of the extreme events. Phase shifts indicate that the spectra of the model differ from nature. Different mean sea levels are not normally so important for validation. They often indicate systematic deviation of the reference level of the seaward boundary condition, and a constant correction is therefore applied.

Fig. 4 shows the measured and the simulated time series at the Schleswig gauge lying at the end of the Fjord for an extreme low water situation. In this simulation the high resolution Schlei Fjord grid is used, driven by the local wind derived from Schleswig weather station. The water level at the open boundary was steered with the gauge Schleimünde.

The comparison clearly shows that, because the boundary values and bathymetry are represented well enough, the model is able to reproduce the hydrodynamics inside this very complex geometry. In this case in particular there was no need to adapt parameters to achieve this high-quality result. All the physical forces (advection, pressure, dissipation, external forces) appear to be of the right order inside the model. The result suggests that it may always be possible to obtain a good representation of hydrodynamics with a numerical model if the relevant processes are resolved in the time-space domain.

Even the two extreme low water level events are reproduced. These events depend critically on the quality of the local wind field, which could be represented by using the wind speed of the meteorological station Schleswig multiplied by a suitable factor. The factor is needed to emphasise the fact that the wind speed is higher over the water surface due to reduced friction.

Figure 4: comparison of simulated water level (red curve) with gauge values (black curve) at Schleswig.

4 History of the Baltic Sea modelling kit

The first projects were performed with a model grid with open boundaries at Fehmarn, Bornholm and to the south of the Sound (BAW 2009/2010). This approach was good enough to deal with the issues arising within the project context, but failed to represent absolute salinity in a realistic manner as the errors in boundary conditions could be rather large on the open boundaries which intersect a zone of a relatively large salinity gradient. Providing sufficient data for salinity became a considerable issue.

These experiences resulted in the decision to develop a grid covering the whole Baltic Sea. Only one open boundary at Skagen made it easier to provide sufficient boundary values for water level, salinity and temperature.

The first modular grid was built for a consultation project on the region of the Warnow mouth (BAW 2011). Example results from this study are shown in Fig. 5. The picture shows the change in the variability of the parameter salinity due to a dredging measure. The analysis is based on a period of four weeks with extreme events of high and low water levels. The colours can be interpreted as follows:

- The blue colours in the northern part indicate a damping of salinity variability because the zone of the highest salinity variability has been shifted to the south.
- The red colours indicate the increase of variability in the southern part, which is increasingly influenced by the sea and the advective transport of seawater.

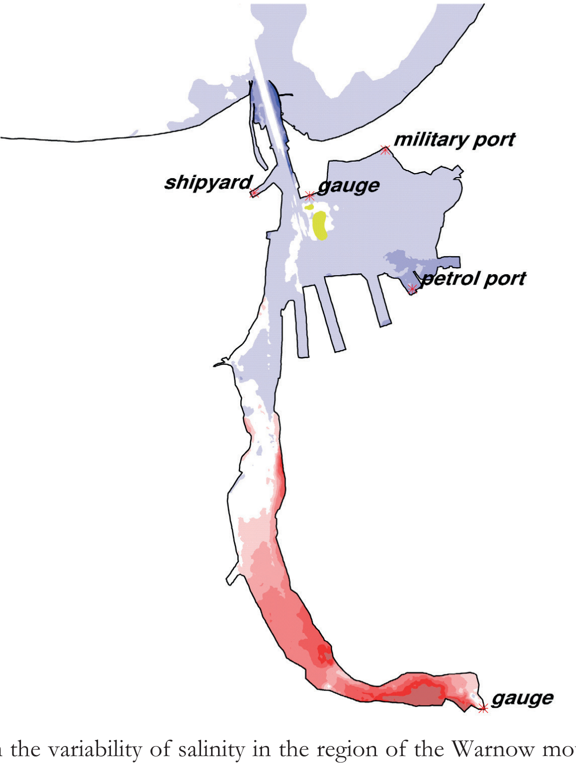

Figure 5: Change in the variability of salinity in the region of the Warnow mouth due to a deepening of the fairway.

This example indicated that the concept of using a complete Baltic Sea model with refinement only in the region of interest works quite well.

However, one important process - temperature driven dynamics – was still missing. Forcing by space-dependent surface air temperature was realised in subsequent years. The data pool was reorganised and completed. New strategies have been developed to create sufficient boundary values for water level even if the gauges Skagen and Smögen are not available by using spectral information of tides and long term signals of other nearby gauges.

5 Further applications

A study of tracer spreading has been undertaken in the Schlei Fjord. This study was performed with a high resolution inlay model which was run as a standalone model with boundary values created from the basic Baltic Sea model. The configuration in the inner part is shown in Fig. 6. A tracer source near Schleswig simulates the inflow of polluted water.

To evaluate the typical time scales until the Fjord has been adapted to a dynamic steady state, the tracer concentration of a single point in the inner fjord was fit to an exponential function. This procedure is illustrated by Fig. 7 for a position in the inner Schlei Fjord. The average time series of tracer concentration clearly shows exponential characteristics. The derived typical exponential time scale of the red curve fit is about 142 days within which the concentration reaches 90% of the equilibrium state value.

The Schlei Fjord model was also used in KLIWAS as part of a sensitivity study dealing with the influence of a rising sea level on the variability of short-term water level changes due to meteorological events. This study compared the results generated by a low resolution inlay model with the results provided by the high resolution version. The signal characteristic in the change of water level variability is the same in both models. But the finer resolution model shows less pronounced changes in sea level variation compared with the coarse resolution model. The step from qualitative answers to quantitative values is determined by the sufficient time-space resolution of the model used, as is also shown in the validation example.

6 Conclusion

The concept of a Baltic Sea model construction kit appears to fulfil the needs of the BAW in modelling coastal processes for the practical purpose of supporting the management of German fairways. A wide range of practical applications shows the flexibility and strength of the concept of a modular modelling framework. The quality of the results depends mainly on the quality of the input data used by the simulation software. Real events can be reproduced to a high standard, if the grid resolution is appropriate.

Efforts should be made to press ahead with the use of common data format standards within the modelling software to provide easier and more cost-effective access to the third-party proofed datasets which are already available.

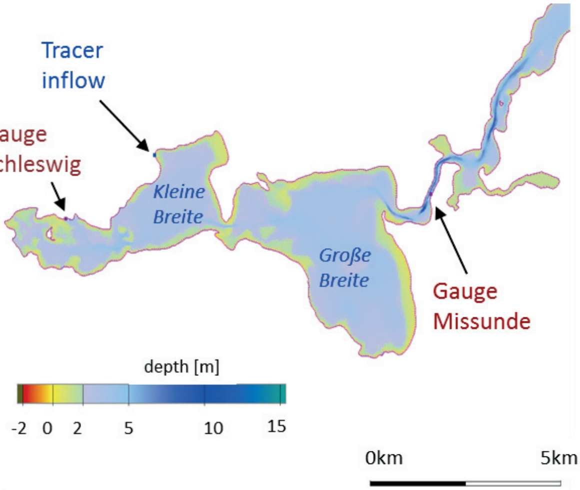

Figure 6: Model bathymetry of the inner Schlei Fjord with inflow position and gauge positions.

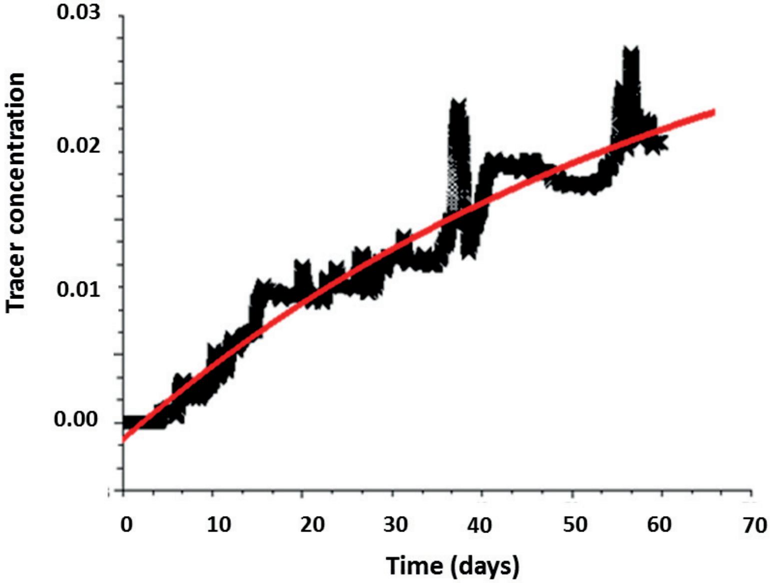

Figure 7: Evaluation of tracer concentration at a station in the inner Schlei Fjord due to entrainment. The markers show the modelled values, the strait line the exponential fitting curve.

Several physical aspects will still need to be improved or integrated into the software part of the Baltic Sea modelling kit in the future, but the high quality data part is now ready for use. The next steps in software improvement could be to include a simple ice model and eventually test other modelling software products which use unstructured grids.

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