Available online at www.sciencedirect.com
ScienceDirect
Ocean Modelling 15 (2006) 124–136
Ocean Modelling
www.elsevier.com/locate/ocemod

Evaluation of a shallow water unstructured mesh model for the North Sea–Baltic Sea

Nicolai Kliem *, Jacob Woge Nielsen, Vibeke Huess

Danish Meteorological Institute, Lyngbyvej 100, DK-2100 Copenhagen Ø, Denmark

Received 14 March 2005; received in revised form 15 June 2006; accepted 15 June 2006
Available online 18 July 2006

Abstract

A two-dimensional shallow water model is used to simulate tide and storm surges for the North Sea–Baltic Sea. In order to resolve the complex coastline, a finite element model using an unstructured mesh is applied. The resolution varies from 300 m in the shallow and narrow Danish straits to approximately 20 km in the deep parts of the domain. The model is forced by tidal elevations along open boundaries, and by atmospheric wind stress and mean sea level pressure obtained from a high resolution NWP model.

The test consist of three simulations: (1) a 10-days simulation of the M_2 tide only, (2) a one-year full tidal simulation, and (3) a one-year predictive simulation including both tides and atmospheric forcing. The simulations are validated against sea level data from a number of coastal tide gauges, using harmonic analysis and direct time series comparison. The tidal simulations are used to calibrate model bathymetry and bed friction. The last simulation is validated in terms of surface elevation, following procedures applied on the operational storm surge system run at the Danish Meteorological Institute. The model gives reasonable sea level predictions, with the quality matching that of an equivalent finite difference model.

Keywords: Storm surge prediction; Tides; Modelling; Finite element method; North Sea; Baltic Sea

1. Introduction

The operational storm surge system for the North Sea–Baltic Sea currently running at the Danish Meteorological Institute (DMI) is based on a two-dimensional shallow water finite difference model (MIKE21; DHI, 1998) using a number of regular, nested computational grids. The model domain covers the entire North Sea–Baltic Sea area, with two open boundaries; one in the North Sea between Norway and Scotland, and another in the English Channel. The model is forced by specified tidal elevations at the open boundaries, and wind stress and atmospheric pressure at the surface. While the finite difference method has some advantages being simple to program and apply, it also has some limitations, such as representing coastlines. The study area has

* Corresponding author. Tel.: +45 39157211; fax: +45 39157300.
E-mail addresses: nk@dmi.dk (N. Kliem), jw@dmi.dk (J.W. Nielsen), vh@dmi.dk (V. Huess).

1463-5003/$ - see front matter
doi:10.1016/j.ocemod.2006.06.003

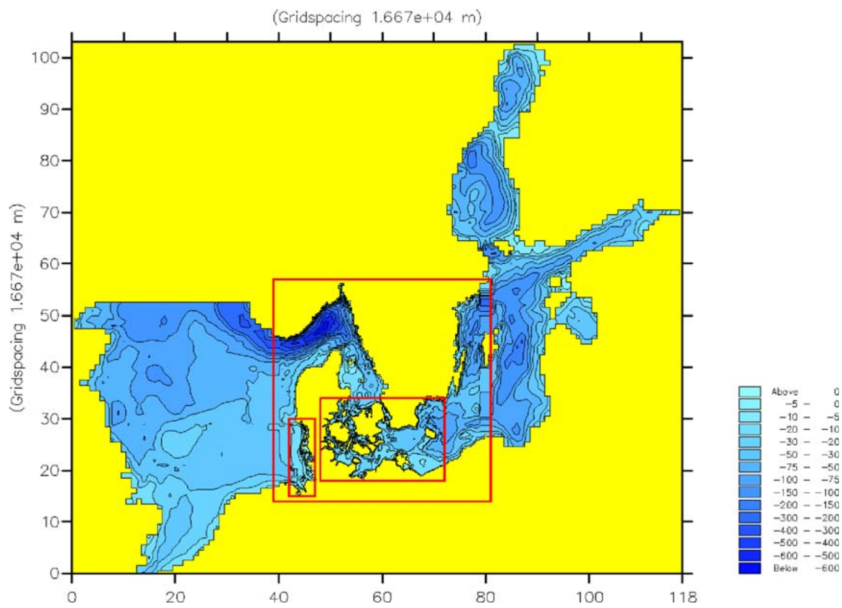

Fig. 1. Nested model domains of the operational finite difference storm surge model.

a complex geometry with a number of narrows and straits, and in order to comply with the different needs for resolution, the model setup has seven domains of different resolution, two-way nested into each other (see Fig. 1). The resolution changes by a factor of 3 between nesting levels, ranging from 9 to 3, 1, 1/3 nautical mile.[1] A fjord model of Limfjorden (see Fig. 2) with a resolution of 750 m is treated using one-way nesting. For a model domain of this complexity, the finite difference method leads to the choice of either having a part of the coastline poorly resolved, or having numerical noise generated at the nesting boundaries. This must then be damped by enhancing the lateral friction or by smoothing procedures.

In order to overcome some of these problems, an alternative model is applied. This model uses the finite element method. The features of finite element and finite difference ocean models have been discussed by for example LeProvost et al. (1994) and Meyers and Weaver (1995). One of the main advantages of the finite element method is that it exploits an irregular mesh and thus nicely handles complex geometry. The setup in this study is similar to the DMI operational storm surge setup with respect to resolution, forcing, and boundary conditions.

Werner (1995) describes a similar shallow water finite element model test. Their purely tidal study covers the English Channel and the southern part of the North Sea. Here, we aim to cover an area of regional scale, and include atmospheric forcing in order to study model performance during storm surges as well.

The test consists of three simulations: (1) a 10-days simulation of the semi-diurnal lunar M_2 tide only, (2) a one-year complete tidal simulation, and (3) a one-year simulation including both tides and atmospheric forcing. The tidal simulations are used to calibrate bathymetry and bed friction. The chosen length of the simulation period is long enough to separate the major tidal constituents, and the validation is done in terms of harmonic analyzed results. The last simulation is a hindcast study of the calendar year 2003, using bathymetry and friction parameters fixed by the tidal simulations. This simulation shows the predictive skill of the model and is validated in terms of actual sea level. Sea level data is obtained from a number of coastal tide gauges, with a time resolution of 10 min. The harmonic analysis has been done by Huess et al. (2002).

The manuscript is organized as follows. Section 2 gives a brief description of the area. In Section 3 the numerical model and the finite element mesh are introduced. The three simulations are discussed in Sections 4–6, and conclusions are given in Section 7.

[1] 1 nautical mile $\sim$ 1852 m.

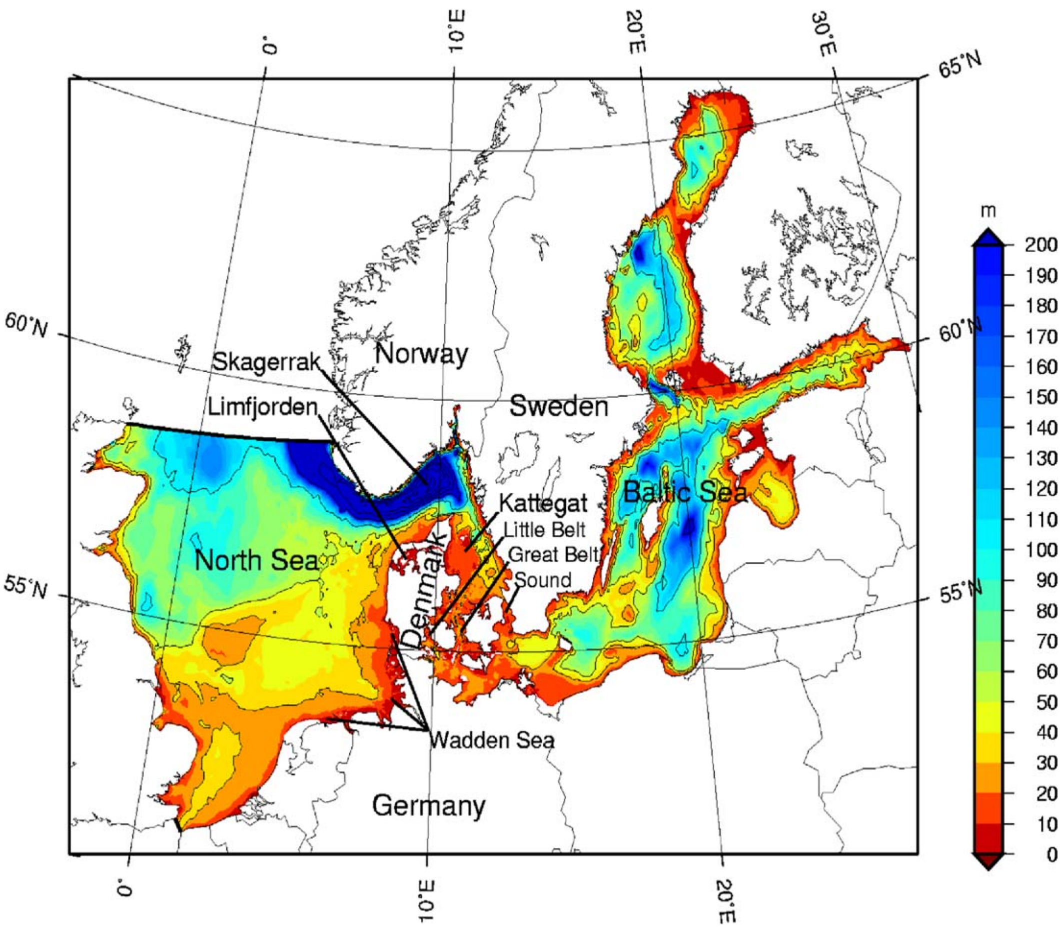

Fig. 2. Map of the model domain. Isobath are drawn at 30 m, 50 m, and every 100 m. Open boundaries of the model domain are shown with thick lines.

2. Model domain

The model domain covers the entire North Sea–Baltic Sea area, with two open boundaries; one in the northern part of the North Sea between Norway and Scotland, and one located in the eastern part of the English Channel. The bathymetry of the model domain is shown in Fig. 2.

The North Sea is a relatively flat shelf sea, with depth increasing gradually from south (30–40 m) to north (150–200 m). One exception is the Norwegian Trench, a submarine canyon following the Norwegian coast into Skagerrak north of Denmark. Maximum depth is approximately 700 m. The North Sea wind fetch is approximately 500–600 km in zonal direction and 1000 km in meridional direction. Strong westerly and northwesterly wind will create storm surges along the low-lying Dutch, German, and Danish coasts of the southeastern part of the North Sea. This whole coastal area is called the Wadden Sea. It is characterized by a system of tidal mud flats and banks separated by narrow trenches of 5–20 m depth. Large parts of the Wadden Sea dry out at low tide and are flooded again during high tide. The trenches play an important role in water exchange between the open sea and the shallow areas, and the current speed in the trenches can be very high.

The Baltic Sea consists of 13–14 basins, separated by submarine sills. The maximum depth is about 500 m and the mean depth 56 m. The Baltic Sea is a semi-enclosed area, it has the characteristics of a huge fjord. The water exchange between the North Sea and the Baltic Sea takes place through Skagerrak, Kattegat, and the Belt Sea, altogether known as the transition area. The Belt Sea is divided on three straits; the Little Belt, the Great Belt, and the Sound. All of these are narrow with minimum widths of approximately 1 km, 15 km, and 4 km, respectively. The Baltic Sea and the Belt Sea are separated by sills of 8–18 m depths.

The tidal wave entering the North Sea from the Atlantic Ocean travels as a Kelvin wave counter-clockwise through the North Sea. The tide enters the North Sea at the Scottish side of the northern open boundary with an amplitude of about 1 m, and through the English Channel with an amplitude of 3–4 m. The wave energy entering through the English Channel is, however, small compared to the amount entering from the north, across the shelf break. The two tidal waves meet just north of the English Channel, but at the German and Danish North Sea coast the tide is almost solely of northern origin. The tidal amplitude in the Wadden Sea region is 1–1.5 m. As the tidal wave moves northward along the Danish west-coast and further into the transition area, it is gradually weakened due to bottom friction. In the Danish Straits the amplitude are about 0.2 m, and in the Baltic Sea the tides are insignificant.

The variation of the mean sea level in the North Sea is small, because the basin is directly connected to the Atlantic Ocean to the north. The water level is increased by storms from the north, but coastal currents quickly bring the surplus away, and the mean sea level increase just has a local effect at the coasts. The Baltic mean sea level varies up to ± 0.7 m due to wind-driven flows through the transition area. The narrow straits act as a low-pass filter, and the largest Baltic sea level variations are due to redistribution of water within the Baltic Sea itself. With the elongated shape of the Baltic Sea and a fetch of more than 1000 km, strong wind

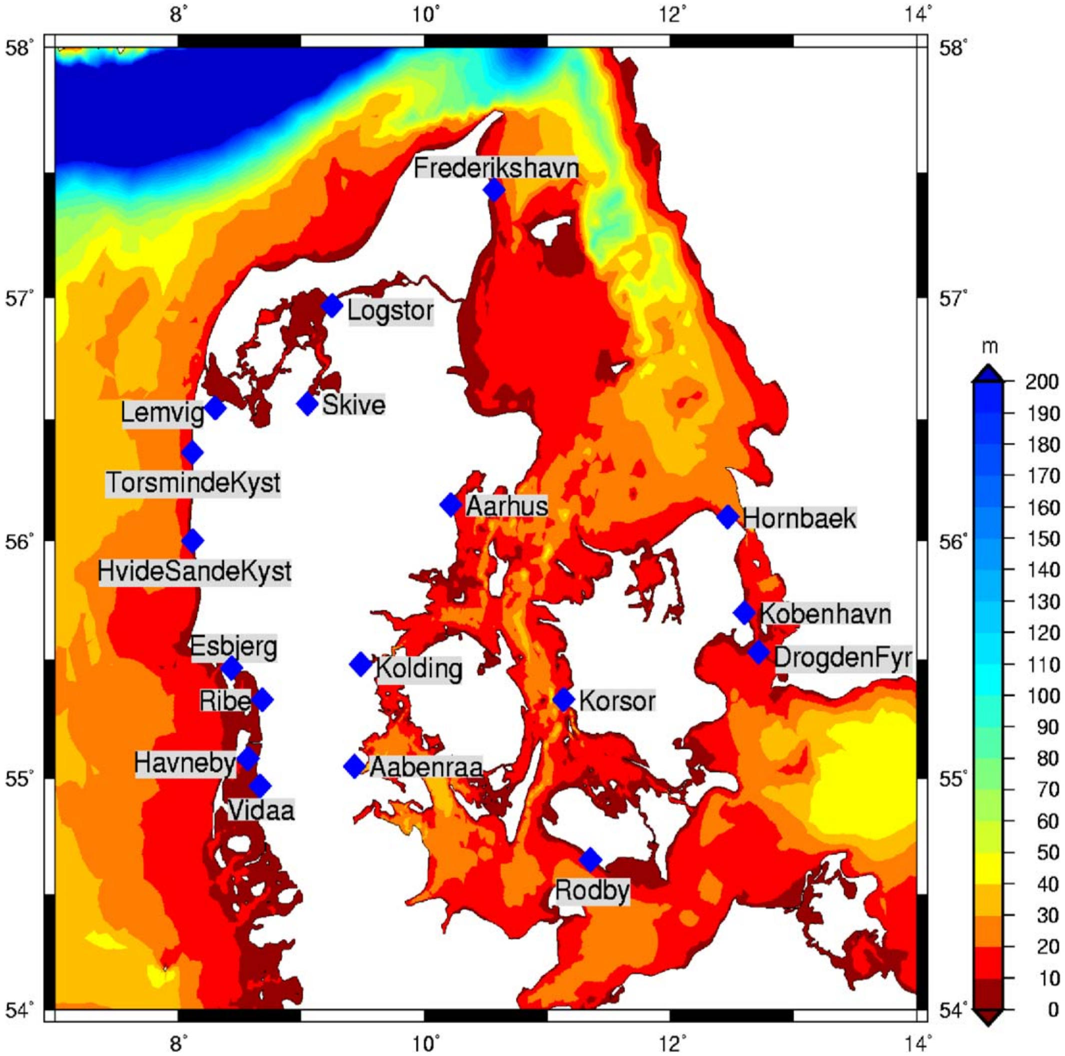

Fig. 3. Location of tide gauge stations.

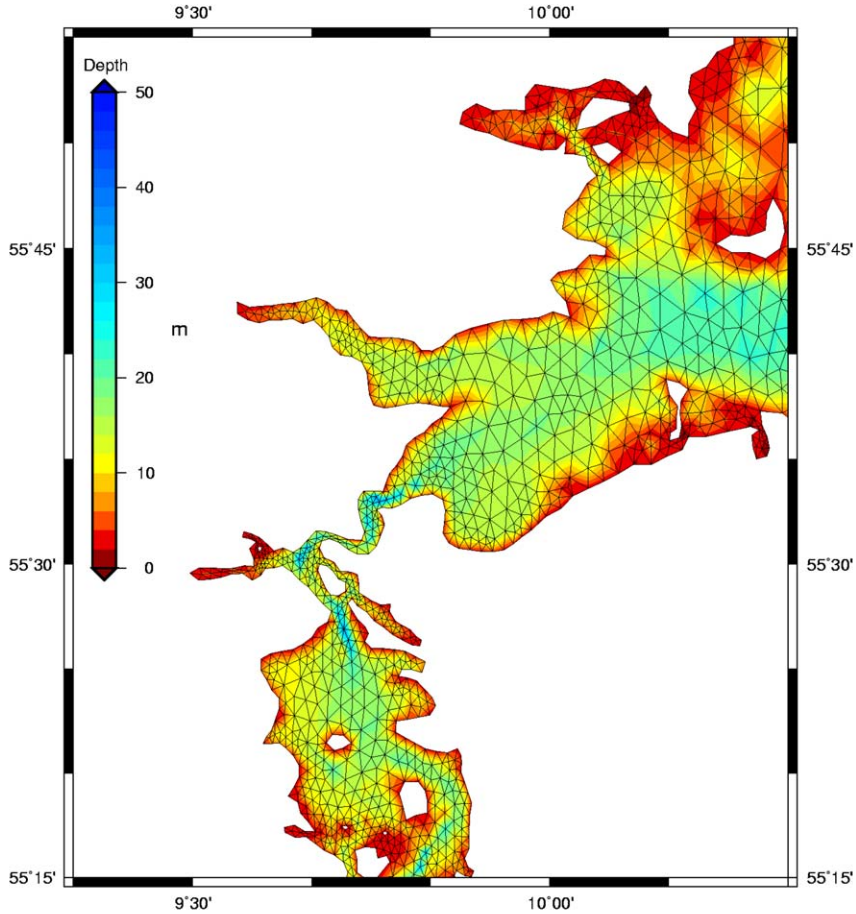

Fig. 4. Part of the mesh showing the high resolution and smooth representation of the coastline in the Little Belt.

may lead to sea level variations of ±3 m in the northeastern and southwestern part of the Baltic Sea. If the forcing wind suddenly abates, the tilt may result in a seiche with a period of about 30 h.

A number of tide gauges are located along the coasts throughout the model domain. Here we shall apply 18 Danish tide gauge stations in the evaluation of the model simulations. The locations of the stations are shown in Fig. 3. This set of stations is used for quality evaluation of DMI's present operational storm surge system, and is chosen due to the data reliability and because they provide a reasonable coverage of the Danish coasts.[2]

3. Model description

The numerical simulations are performed with MOG2D (Carrére and Lyard, 2003; Lyard et al., personal communication). The model is barotropic and non-linear, and it is based on the classical shallow water equations formulated in spherical coordinates. The spatial variations are discretized by the continuous Galerkin finite element method which allows freely varying resolution and facilitates a smoothly resolved coastline. Triangular elements with the P_1P_1 element pair (see e.g. Hanert et al., 2002) are used. To eliminate spurious pressure modes, the continuity and momentum equations are rearranged to produce a wave equation following Lynch and Gray (1979).

In total the mesh consists of 27,910 nodes connected by 49,608 elements. As an example a part of the horizontal triangular mesh is shown in Fig. 4. The resolution (shown in Fig. 5) is proportional to the square root

[2] Except for the island Bornholm in the western Baltic Sea.

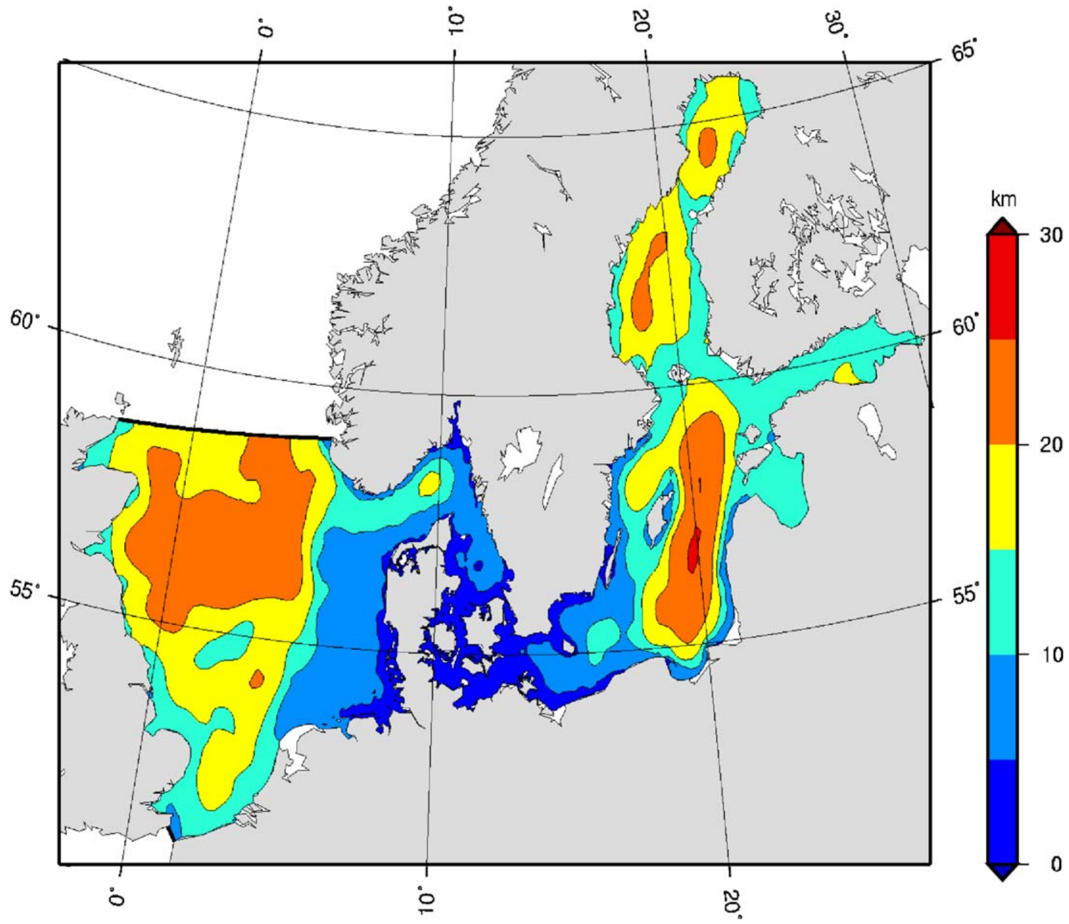

Fig. 5. Resolution (in km) of the computational mesh.

of the depth, i.e. proportional to the phase speed of long gravity waves, with an increased resolution around Denmark. The resolution thus varies from about 20–25 km in the deep parts of the North Sea and the Baltic Sea to approximately 5 km in the Kattegat, and about 300 m as the highest resolution in some of the narrow straits. This roughly corresponds to DMI's present storm surge system which uses nested domains with a resolution of 16.7 km in the large domain, 5.6 km in the Kattegat, 1.9 km in the Great Belt, and 0.6 km in the inner-most nesting level covering the Little Belt and the Sound.

The bathymetry is compiled from different sources. For the Baltic Sea and the transition area a gridded data set (Seifert et al., 2001) with a resolution of $2'$ lon $\times$ $1'$ lat, and double resolution for the transition area, is used, while a gridded data set of 1852 m $\times$ 1852 m (Weiergang and Joensson, 1996) is used for the North Sea. Furthermore, high resolution depth measurements provided by the Danish Coastal Authority and The Royal Danish Administration of Navigation and Hydrography are used for specific near shore areas, e.g. the Danish part of the Wadden Sea and the Danish Straits.

With a resolution of a few hundred meters in the Wadden Sea the computational mesh is too coarse to resolve the narrow trenches, and they do not show up in the model bathymetry after the interpolation to the mesh. In principle, we could resolve the narrow trenches in the Wadden Sea. This would require a resolution of a few tens of meters in the relative deep (approximately 20–30 m) trenches with high wave and current speed, and would require too small time step to be practicable. Since the trenches are important for the dynamics and thus for simulating tidal phases and amplitudes correctly, the Wadden Sea bathymetry is adjusted by increasing the depth at a few nodes in order to restore the trenches. The impact of this adjustment is assessed by the M_2 tide simulation (described in the next section).

In order to simulate tidal phases and amplitudes correctly in the Wadden Sea, the model must be able to reproduce the drying and flooding taking place in that area. The MOG2D implementation of drying and flooding requires the model to apply an explicit time scheme, thus imposing an upper limit on the time step. In order to fulfill the usual CFL criterion a time step of 20 s is used. It is noted that only a small part of the computational nodes may dry out. In a simulation without drying and flooding MOG2D uses an implicit time scheme, allowing for a time step of several minutes and thus a much smaller computational time. From a practical operational point of view the explicit formulation of the drying and flooding algorithm is therefore a severe limitation.

4. Simulation of M_2

The simplest test of the model is a tidal simulation with just one constituent, obtained by specifying the tidal elevation at the open boundaries and no atmospheric forcing. The semi-diurnal lunar M_2 tide is the dominating constituent throughout the North Sea. The tidal boundary forcing is obtained from Lefévre et al. (2002). The simulation is initialized by spinning up the boundary elevation for 24 h and then running the model for another 4 days. The simulations are then performed for 10 days, and the results are harmonic analyzed. The results are validated against observed tidal amplitudes and phases, i.e. harmonic analyzed sea level time series observed at the Danish tide gauge stations.

First, the M_2 simulations are used to adjust the Wadden Sea bathymetry, to obtain the effect of the narrow trenches. When these trenches are absent in the model bathymetry, the model can not get the right volume transport from the open sea to the coastal areas of the Wadden Sea, resulting in a reduced and delayed tidal signal at the coast. Since we are not able to correctly resolve the trenches, they are in principle parameterized by adjusting the bathymetry. This is done in a simple trial and error process by adjusting the bathymetry at a few nodes to obtain a kind of trench to get a best match of the harmonic analyzed tide gauge observations at Esbjerg, Ribe, Havneby, and Vidaa (see Fig. 3).

Secondly, the M_2 simulations are used to calibrate the model with respect to the bottom friction parameter. The bottom friction is calculated using a quadratic friction law:

$$\tau_b = c_d|\mathbf{u}|\mathbf{u} \tag{1}$$

where $\mathbf{u}$ is the current velocity, and c_d is the bottom friction parameter. A constant value of c_d is applied throughout the model domain. Three simulations with c_d set to 0.0015, 0.0020, and 0.0025 are performed. Amplitudes and phases for the stations at the Danish west-coast where the tides are most important, are shown in a polar plot in Fig. 6. Here amplitude is plotted as the radius and the phase as the angle. Observations are shown as solid circles, the simulations as open symbols, and the lines in between represent model error. The best result is obtained using $c_d = 0.0020$.

In order to give a quantitative measure of the quality of the model, the relative error is calculated at each station as the absolute value of the model error (i.e. length of the lines in Fig. 6) divided with observed amplitude

$$\text{Error} = \frac{|A_{\text{obs}}e^{i\phi_{\text{obs}}} - A_{\text{sim}}e^{i\phi_{\text{sim}}}|}{A_{\text{obs}}} \cdot 100\% \tag{2}$$

where A is the tidal amplitude and ϕ is the tidal phase. This is given for each station in Table 1 together with the average over all stations. There is a large variation of the error between the stations. For stations in the transition area, the tides are weak, and an error of a few centimeters might show up as a large relative error. For the North Sea stations where the tides are stronger, and this test is more suitable, the simulation with $c_d = 0.0020$ perform best. This simulation also has the smallest error on average. Therefore, $c_d = 0.0020$ is used for the bottom friction parameter in the following.

The overall picture of the M_2 tidal amplitude and phase for the North Sea is shown in Fig. 7. This looks qualitatively reasonable compared to similar maps based on observations (e.g. Pugh, 1987) and other numerical models (e.g. Huess and Andersen, 2001; Huess, 2001). The main difference is the location of the northern amphidromical point. In our simulations it is located southwest of Norway, while Pugh (1987) place it "on shore". Huess (2001) made tidal simulations using MIKE21 with several constituents similar to the simulation

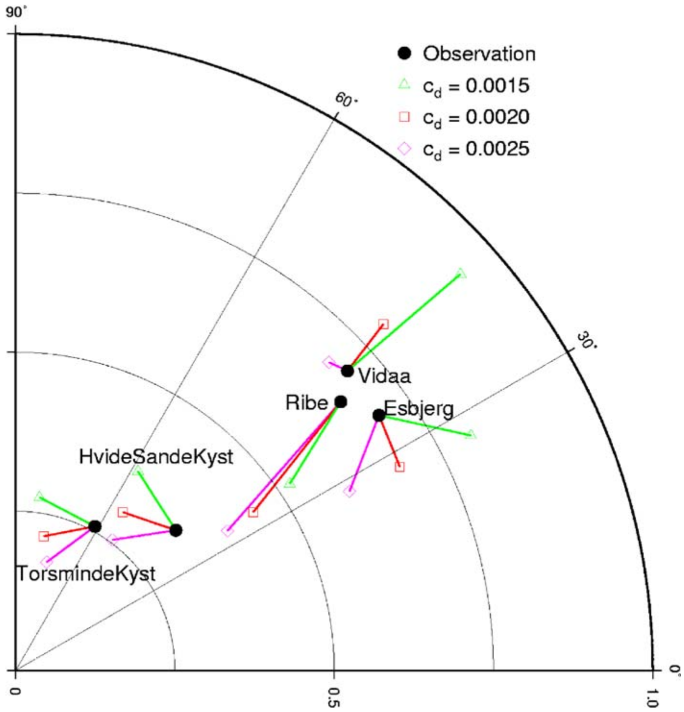

Fig. 6. M_2 tidal amplitude and phase at selected stations for three simulations with bottom friction parameter set to 0.0015 (shown as open triangles), 0.0020 (squares), and 0.0025 (diamonds). Observed values are shown as solid circles.

Table 1
Relative error (in %) of M_2 for three simulations with bottom friction parameter (c_d) set to 0.0015, 0.0020, and 0.0025

Station name	Relative error		
	0.0015	0.0020	0.0025
Vidaa	33.3	13.2	4.5
Havneby	18.0	14.3	21.5
Ribe	22.9	33.4	40.7
Esbjerg	21.2	12.6	18.4
HvideSandeKyst	33.0	26.4	30.1
TorsmindeKyst	38.1	31.8	36.6
Lemvig	45.5	14.5	21.2
Skive	43.6	15.1	12.0
Logstor	57.5	15.2	17.1
Frederikshavn	46.5	51.1	67.6
Aarhus	39.7	28.4	59.3
Kolding	62.8	73.7	85.9
Aabenraa	92.1	13.1	42.2
Korsor	52.1	70.9	97.3
Hornbaek	98.7	85.2	77.6
Kobenhavn	94.0	90.7	87.3
DrogdenFyr	124.0	115.2	107.6
Rodby	117.5	73.4	92.6
Average	57.8	43.2	51.1

described in the next section. She shows that the position of the northern amphidromical point depends of the tidal forcing on the northern open boundary. Simulations with tidal boundary forcing obtained from readings of German tidal maps of the North Sea (Marineobservatorium, 1942) places the amphidromical point on

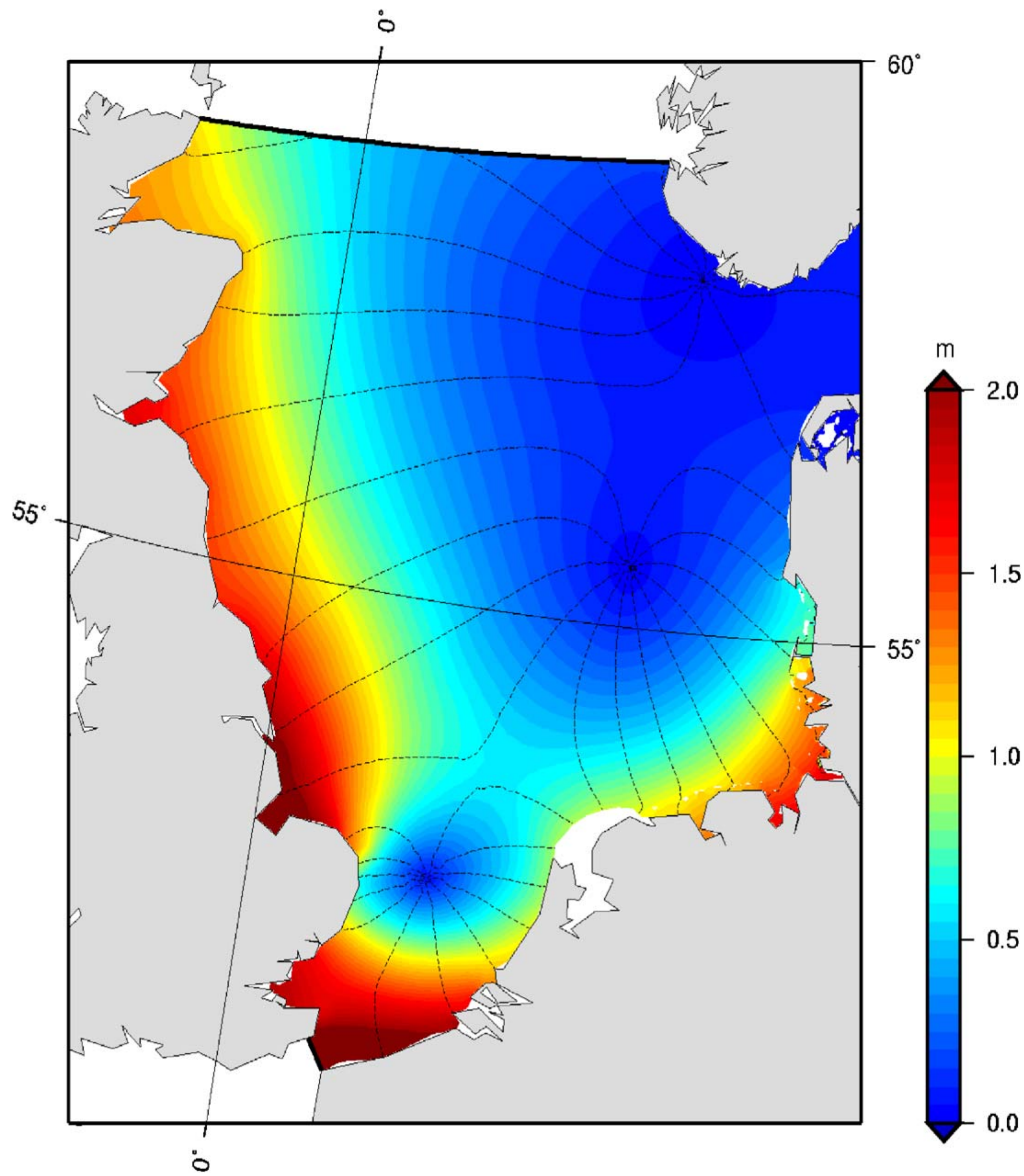

Fig. 7. M_2 tidal amplitude (solid lines) and phase (dotted lines). Phase contour interval is 30°.

shore, while simulations using tidal forcing obtained from a global tidal model assimilating Topex/Poseidon altimetry data (Shum et al., 1997) places the amphidromical point off shore, at approximately the same position as in Fig. 7. This means that the simulation is very sensitive to the tidal phase specified along the northern open boundary. As mentioned above, the model domain was chosen to cover the same area as DMI's present storm surge system, but the findings by Huess (2001) thus suggest that future work should include changes to the model domain, for example to include Great Britain and thus move the open boundaries away and into the North Atlantic Ocean. This is relatively easy to do with an unstructured mesh. The existing mesh does not need to be changed or nested, but a mesh of suitable resolution is created for the new part of the model domain and is then simply merged with the existing mesh.

5. Complete tidal simulation

This tidal simulation has multiple constituents and thus includes non-linear interaction between the different constituents. As in the previous case there is no atmospheric forcing, and tidal elevation is specified at the open boundaries. Nine major constituents, M_2, S_2, N_2, K_2, $2N_2$, O_1, K_1, Q_1, and P_1, are applied, with initialization and spin-up as before, the model is run for a period of one year, and the results are harmonic analyzed.

The relative error for each constituent is calculated as in the previous section and shown in Table 2. As in the M_2 simulation the tides are weak in the transition area, and the relative errors are high in this area. For the

Table 2
Relative error (in %) of the most significant constituents

Station	M_2	S_2	N_2	O_1	M_4	K_1	K_2	Q_1	P_1
Vidaa	8.6	12.0	9.7	13.7	157.8	5.0	18.0	–	25.8
Havneby	15.4	26.4	25.5	25.4	51.5	21.6	36.3	10.6	30.5
Ribe	37.4	49.4	40.0	24.5	258.1	3.9	51.2	–	47.8
Esbjerg	13.8	24.2	17.0	22.3	88.3	13.4	26.5	7.2	16.8
HvideSandeKyst	26.9	44.5	25.4	31.5	70.8	32.6	42.9	9.3	19.6
TorsmindeKyst	32.6	59.0	27.2	35.5	87.0	37.7	62.6	–	–
Lemvig	14.0	77.5	32.5	49.2	97.9	70.1	–	102.3	51.8
Skive	6.9	–	22.8	31.9	–	127.2	–	–	–
Logstor	9.0	–	54.8	32.6	–	167.6	–	–	–
Frederikshavn	53.7	75.8	46.6	36.8	142.8	–	–	–	–
Aarhus	35.3	86.4	56.5	31.9	150.9	–	–	–	–
Kolding	82.0	126.1	102.3	74.5	281.4	–	–	–	–
Aabenraa	10.9	63.1	78.9	134.0	–	103.4	–	–	–
Korsor	74.0	160.1	125.1	–	–	–	–	–	–
Hornbaek	78.8	70.2	27.5	48.7	362.8	–	50.7	–	–
Kobenhavn	85.7	92.9	56.1	59.1	–	–	–	–	–
DrogdenFyr	109.0	105.3	81.7	–	247.2	110.8	–	–	–
Rodby	71.9	–	172.9	–	–	108.3	–	–	–
Average	42.5	71.5	55.7	43.5	166.4	66.8	41.2	32.4	32.1

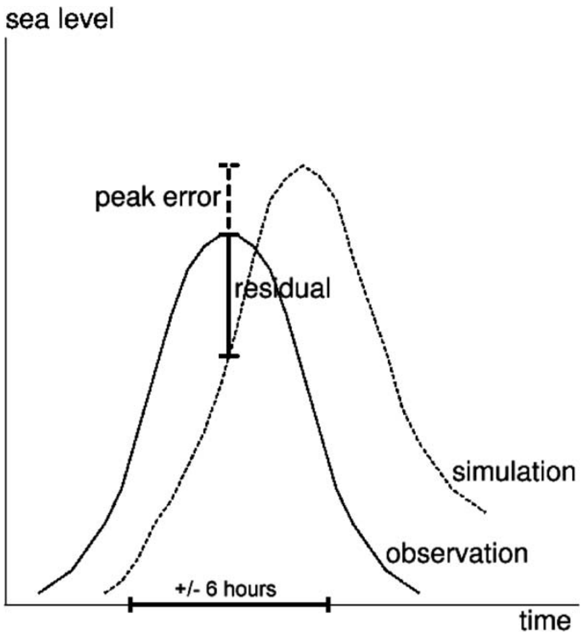

Fig. 8. Sketch of the peak error.

North Sea stations some variations between the constituents are seen. The differences of the first column of Table 2 (M_2) and the second column of Table 1 ($c_d = 0.0020$) are caused by the non-linear effects in the multi-constituent simulation.

6. One year simulation

In the previous two sections, tidal simulations are used to calibrate and evaluate the model. In this section a simulation including tidal and atmospheric forcing is performed for the year 2003 and used to evaluate the predictive skill of the model. The tidal forcing is applied as in the previous section. The atmospheric forcing consists of mean sea level pressure and wind friction. The inverse barometer effect is added to the open boundary condition. The inverse barometer effect is a change of sea level related to the atmospheric pressure by the hydrostatic assumption, such that an increase of atmospheric pressure of 1 hPa will cause a decrease of sea level of approximately 1 cm. This is a reasonable approximation to the sea level on the open ocean where the effect of a coastal setup is not felt, and is used as boundary condition to approximate the increased sea

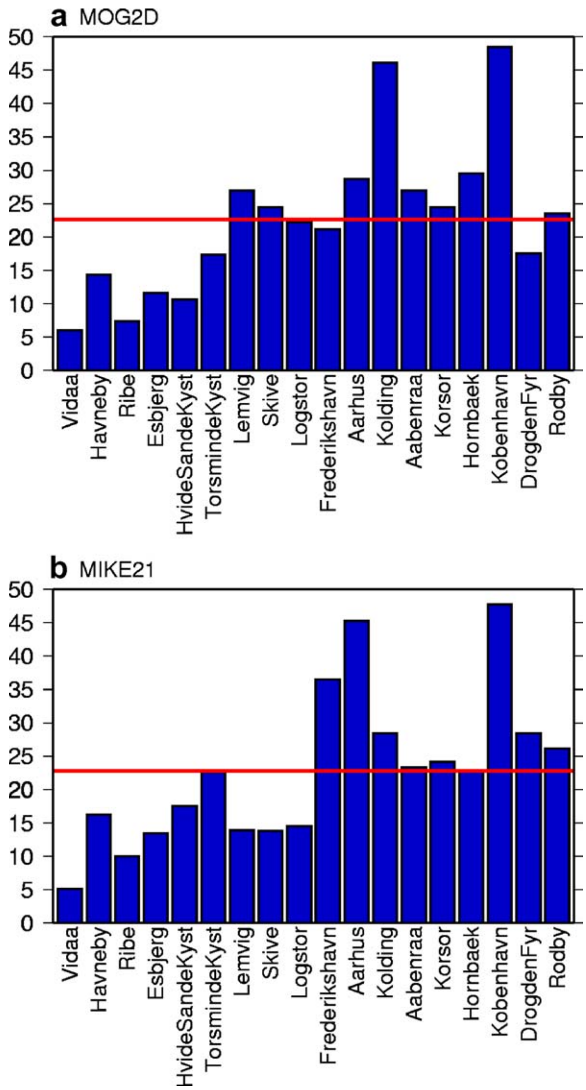

Fig. 9. Absolute relative peak error in percentage for each station (bars) and on average (horizontal line): (a) MOG2D results and (b) result for the same year 2003 obtained from DMI's present storm surge system based on MIKE21.

level related to a low pressure system approaching the model domain. The atmospheric forcing fields are provided by DMI's operational weather forecasting model HIRLAM[3] (Sass et al., 2000).

The simulation is initialized from an ocean at rest, and spun up during a one-month period (December 2002), of which the first 24 h are used to spin-up the forcing fields. The simulation is then performed for the entire year 2003, and the results are evaluated by comparing predicted time series with observed water level records from the selected tide gauge stations.

Since the purpose of this study is to be able to forecast storm surges and extreme water levels, the main focus is on the maximum peaks of the elevation time series, and the validation procedure of DMI's operational storm surge model is adopted for the model evaluation. At each station the three highest peaks are identified from the one year record of observed water level. The peak error is then calculated as the difference between the observed and simulated maximum water level with a maximum time separation of 6 h, as sketched in Fig. 8. From the figure it is noted that the peak error deviates from simply taking the residual between simulation and observation. It might be difficult to distinguish between amplitude and phase errors, and a phase lag produces a large residual even though the amplitude may be correct.

The evaluation is done in terms of the absolute relative peak error, calculated as the absolute value of the peak error relative to the actual maximum elevation. This is calculated for each station as an average of the three highest peaks within the one year simulation. The quality of the model result is then one single number calculated as the average of the absolute relative peak error at the 18 Danish stations. This is shown in Fig. 9. The best results are obtained for the North Sea stations while errors in the transition area are two to three times larger. For comparison the same evaluation for DMI's present storm surge system based on the finite difference model MIKE21 (DHI, 1998) is shown. This model also shows a better performance in the North Sea than in the transition area. The two model simulations have the same overall quality with an average error of 22.6% for MOG2D and 22.7% for MIKE21, but the errors are differently divided among the stations. MOG2D has slightly smaller errors than MIKE21 for the North Sea stations. For other stations like Lemvig, Skive, Logstor, and Kolding, MOG2D performs worse than MIKE21. This is surprising, since these stations are within narrow fjords where the finite element model with its flexible unstructured mesh is expected to be superior to the finite difference model. Furthermore, for Lemvig, Skive, and Logstor which are all in Limfjorden, it is seen from Table 2 that the tides are simulated with a small error.

7. Conclusion

This paper describes the setup and evaluation of a finite element storm surge model for the North Sea and Baltic Sea. The tests include tidal simulations, and a storm surge hindcast simulation of the entire year 2003 including tidal and atmospheric forcing. The tests show that the model is able to simulate tides with a reasonable small error for the North Sea stations while the errors are higher in the transition area. The same general result is found for the storm surge simulation with significantly smaller errors for the North Sea stations than for the other stations.

For Limfjorden it is slightly different. For this region we find that the tide is relatively well modelled while the storm surges are not. Limfjorden is connected to both the North Sea and the Kattegat through narrow straits, of which the opening to the North Sea is the most important with respect to water exchange with the open sea. A direct comparison (not shown) of the modelled and observed sea level time series shows a bias of approximately 20 cm, and the finite element model is thus unable to correctly reproduce the water exchange between the North Sea and Limfjorden.

The result of the storm surge simulation is compared with DMI's present operational storm surge finite difference model MIKE21. The two models show the same overall quality, but with regional differences. For some of the stations like Lemvig, Skive, Logstor, and Kolding, MOG2D performs worse than MIKE21. These stations are located where the irregular coastline is expected to influence the flow, and where the finite element model thus was expected to be superior to the finite difference model.

[3] HIgh Resolution Limited Area Model.

Our study does not offer definite conclusion on why the finite difference model is superior to the finite element model in areas where the opposite was expected. It is not expected to be due to differences in the numerical time schemes or numerical dissipation in the models, since the finite element performs as good as or better than the finite difference model in the North Sea.

The problem appears to be related to resolution. The finite element mesh provides the opportunity to represent almost any strait. As seen in Fig. 4 this is exploited for example in the Little Belt where the strait is just a few hundred meters wide. In the finite difference grid, the strait is at least one grid point wide representing approximately 600 m. In contrast the finite element mesh resolves the correct coastline, and the strait has three nodes and two elements across. Anyway, it is questionable whether this is enough to really resolve the bathymetry and thereby the flow through the channel. Since the coastal nodes only have small depth, the straits will have a v-shaped bottom and the cross-section might have to small an area compared to reality and compared to the finite difference model. The obvious way to solve this problem is to increase the resolution on the expense on computational cost and is left for future work.

Acknowledgment

We thank F. Lyard, F. Dupont, and D. Greenberg for helpful discussions of model input files, and F. Lyard for providing tidal boundary conditions.

References

Carrére, L., Lyard, F., 2003. Modeling the barotropic response of the global ocean to atmospheric wind and pressure forcing – comparisons with observations. Geophys. Res. Lett. 30 (6), 1275. doi:10.1029/2002GL016473.

DHI, 1998. MIKE 21. User Guide and Reference Manual 2.7. Danish Hydraulic Institute, Hørsholm, Denmark.

Hanert, E., Legat, V., Deleersnijder, E., 2002. A comparison of three finite elements to solve the linear shallow water equations. Ocean Modell. 5 (1), 17–35.

Huess, V., 2001. Sea level variations in the North Sea – from tide gauges, altimetry and modelling. Scientific Report 01-08, DMI, Copenhagen, Denmark, Ph.D. Thesis.

Huess, V., Andersen, O.B., 2001. Seasonal variations in the main tidal constituent from altimetry. Geophys. Res. Lett. 28 (4), 567–570.

Huess, V., Nielsen, P.B., Nielsen, J.W., 2002. Tidevand ved de danske vandstandsstationer. Technical Report 02-21, DMI, Copenhagen, Denmark (in Danish).

Lefévre, F., Lyard, F.H., Provost, C.L., Schrama, E.J.O., 2002. FES99: A global tide finite element solution assimilating tide gauge and altimetric information. J. Atmos. Ocean. Technol. 19 (9), 1345–1356.

LeProvost, C., Bernier, C., Blayo, E., 1994. A comparison of two numerical methods for integrating a quasi-geostrophic multilayer model of ocean circulations: finite element and finite difference methods. J. Comp. Phys. 110, 341–359.

Lynch, D.R., Gray, W.R., 1979. A wave equation model for finite element tidal computations. Comput. Fluids 7, 207–228.

Marineobservatorium, 1942. Karten der Harmonischen Gezeitenkonstanten für das Gebietder Nordsee. Oberkommando der Kriegsmarine, Marineobservatorium Wilhemshaven, Germany.

Meyers, P.G., Weaver, A.J., 1995. A diagnostic barotropic finite-element ocean circulation model. J. Atmos. Ocean. Technol. 12, 511–526.

Pugh, D.T., 1987. Tides, Surges and Mean Sea Level. John Wiley and Sons Ltd.

Sass, B.H., Nielsen, N.W., Jørgensen, J.U., Amstrup, B., Kmit, M., 2000. The operational DMI-HIRLAM system. Technical Report 00-26, DMI, Copenhagen, Denmark.

Seifert, T., Tauber, F., Kayser, B., 2001. A high resolution spherical grid topography of the Baltic Sea – 2nd ed. Baltic Sea Science Congress, Stockholm, November 2001, poster 147. Available from: <www.io-warnemuende.de/iowtopo>.

Shum, C.K., Woodworth, P.L., Andersen, O.B., Egbert, G.D., Francis, O., King, C., Klosko, S.M., Provost, C.L., Li, X., Molines, J.-M., Parke, M.E., Ray, R.D., Schlax, M.G., Stammer, D., Tierney, C.C., Vincent, P., Wunsch, C.I., 1997. Accuracy assessment of recent ocean tide models. J. Geophys. Res. 102 (C11), 25173–25194. doi:10.1029/97JC00445.

Weiergang, J., Joensson, M., 1996. DYNOCS technical data report. Tech. Rep. MAS2-CT94-0088, Mast2 project “DYNamics of Connecting Seas”.

Werner, F.E., 1995. A field test case for tidally forced flows: a review of the tidal flow forum. In: Lynch, D.R., Davies, A.M. (Eds.), Quantitative Skill Assessment for Coastal Ocean Models, Coastal and Estuarine Studies, No. 47. AGU, Washington, DC, pp. 269–283.