https://doi.org/10.5194/os-2019-84
Preprint. Discussion started: 18 July 2019

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The significance of coastal bathymetry representation for modelling the tidal response to mean sea level rise in the German Bight

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Abstract. Due to climate change an accelerated mean sea level rise is expected. One key question for the development of adaptation measures is how mean sea level rise affects tidal dynamics in shelf seas such as the North Sea. Owing to its flat coastal areas, especially the German Bight (located in the south-east of the North Sea) will be affected. Numerical hydrodynamic models help to understand how mean sea level rise changes tidal dynamics. By definition models cannot represent all processes in overall detail. One limiting factor is the resolution of the model grid. In this study we investigate which role the representation of the coastal bathymetry plays when analysing the response of tidal dynamics to mean sea level rise.

Using a shelf model including the whole North Sea and a high-resolution hydrodynamic model of the German Bight we investigate the changes in M2 amplitude due to a mean sea level rise of 0.8 m and 10 m. To the mean sea level rise of 0.8 m the shelf model and the German Bight Model react in different ways. In the shelf model the M2 amplitude generally increases in the region of the German Bight. In contrast, the M2 amplitude in the German Bight Model increases only in some coastal areas and decreases in the northern part of the German Bight. In two case studies we adjust the German Bight Model in order to more closely resemble the shelf model. We find that a different resolution of the bathymetry results in different energy dissipation changes in response to mean sea level rise. Our results show that the resolution of the bathymetry especially in flat intertidal areas plays a crucial role for modelling the impact of mean sea level rise in the order of 1 m. For higher mean sea level rise scenarios (10 m) the resolution of the bathymetry is less important.

1 Introduction

Due to climate change an accelerated mean sea level rise (MSLR) is expected. During the 20th century an increase in global mean sea level rise of about 1.7 mm/year is observed (Church and White, 2006), (Holgate, 2007). For the recent past (1993-2010) a further increase is detected with a rate of 3.2 mm/year. In future projections a range of rates of 8-16 mm/year between 2081 and 2100 is estimated (Church et al., 2013). Many coastal areas will be affected by an accelerated MSLR. The German Bight located in the south-east of the North Sea with its flat coastal areas could be especially vulnerable.

Mean sea level rise will not only influence water levels (i.e. coastal protection), it also changes tidal dynamics in the North Sea and its adjacent estuaries. Altered sediment transport lead to sea level rise-induced morphological changes in the

Wadden Sea (Dissanayake et al., 2012; Becherer et al., 2018). Furthermore, salt intrusion into the estuaries will be affected (Seiffert and Hesser, 2014). Thus, future challenges related to mean sea level rise include not only coastal protection issues, but also other aspects such as sediment management in the estuaries. Some of the largest ports in Europe like Rotterdam, Hamburg and Antwerp are based in the south-east of the North Sea. Other challenges involve drainage of the hinterland and the protection of the UNESCO World Natural Heritage Site Wadden Sea that provides a unique habitat for flora and fauna. For the development of potential adaptation measures it is important to understand how mean sea level rise changes tidal dynamics.

Several previous studies investigate the impact of mean sea level rise on tidal dynamics in the North Sea, especially on the M2 amplitude which is the most energetic component (e.g. Ward et al., 2012, Pickering et al., 2012, Idier et al., 2017). Some of these studies come to contradictory results. Ward et al. (2012) analyse a mean sea level rise (MSLR) of 2 m with the shelf model KUTM and obtain a decrease of M2 amplitude in the German Bight whereas Pickering et al. (2012) find an increase of M2 amplitude with the same MSLR of 2 m using the shelf model DCSMv5.

Pelling et al. (2013) provide an explanation for these contrasting results. They show that the differences are due to the way of implementing the landward model boundary in the model simulations. In Pickering et al. (2012) the model has a fixed vertical wall at the boundaries whereas in the study of Ward et al. (2012) new cells of the former hinterland are allowed to flood with MSLR. These new cells provide additional shallow areas of high dissipation resulting in a dampening effect that works against the general decrease of dissipation due to MSLR. In the model allowing new cells to flood less energy reaches the northern German Bight because of the higher dissipation on the shallower parts of the Dutch coast and the East Frisian Wadden Sea. In the model with a fixed boundary, more energy remains in the M2 tide due to the lack of additional dissipative area, leading to an increase of M2 amplitude with mean sea level rise. Another study with similar model setups using smaller levels of MSLR (up to 1m) by Pelling and Green (2014) supports the theory of Pelling et al. (2013). They also suggest that higher resolution simulations with up to date and realistic flood defence are needed to estimate changed tidal dynamics due to MSLR. Not only the adequate representation of flood defence but also the correct representation of topographical details and shallow intertidal regions could be important for the estimation of the system's response to MSLR. In this context the question arises whether the resolution of shelf models is sufficient to assess the response of tidal dynamics in the North Sea to MSLR. Especially, shallow areas of high dissipation might be insufficiently represented in the models.

Due to the relatively coarse resolution of shelf models with a cell size of about 2 km to 7 km, topographic features such as estuaries or the details of tidal flats and channels in the Wadden Sea cannot be represented in these models. Thus potentially important factors like missing oscillation volume or inadequately resolved topographical structures might lead to misleading results. The aim of our study is to investigate whether the response of tidal dynamics in the North Sea to MSLR is sensitive to the resolution-dependent simplifications of shelf models. For this purpose we perform hydrodynamic numerical model simulations with different levels of resolution and different model domains.

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2. Methods

In this study we use two different models. The Dutch Continental Shelf Model DCSMv6FM that simulates the tidal dynamics in the entire North Sea and the German Bight Model (GBM), a higher resolved model that covers the German Bight and its estuaries. The GBM uses boundary conditions from the DCSMv6FM and simulates the tidal dynamics in the German Bight on a more detailed level.

2.1 Shelf Model: DCSMv6FM

The Dutch Continental Shelf Model DCSMv6FM is a further development of the Dutch Continental Shelf Model DCSMv6 (Zijl et al., 2013; Zijl et al., 2015) using the new flexible mesh technology D-Flow FM (Donchyts et al., 2014). The model domain covers the northwest European shelf (Figure 1). In the North Sea the resolution of the model grid is 1.5´ in east-west direction. The resolution in north-south direction is 1´. This leads to a grid cell size of 1.9 by 1.9 km. Beyond the shelf the resolution is coarser with a grid size of about 7.4 by 7.4 km.
The bathymetry is based on data from the North-West Shelf Operational Oceanographic System (NOOS). These data are supplemented by data from ETOPO2 (National Oceanic and Atmospheric Administration). During the calibration process using the OPENDA-DUD algorithm (Garcia et al., 2015), the bathymetry was adjusted in some areas to achieve an improved propagation of the tidal wave. The OPENDA-DUD algorithm defines the calibration as an optimization problem. It takes the bathymetry and the bottom friction coefficient as calibration factors.
The model is forced by astronomical tides (22 constituents). The amplitudes and phases of the main diurnal und semi-diurnal constituents are derived by interpolation from the dataset generated by GOT00.2 global ocean tide model (Ray R., 1999). 16 additional partial tides are adopted from FES2012 (Carrere et al., 2013). External surge is forced as an inverse barometer correction based on time and space varying pressure fields. As atmospheric forcing (wind at 10 m and atmospheric surface pressure) we use the reanalysis data COSMO-REA6 (Hans-Ertel-Centre for Weather Research, Bollmeyer et al., 2015).

2.2 Regional Model: German Bight Model

The regional German Bight Model covers the German Bight from Terschelling in the Netherlands to Hvide Sande in Denmark (Figure 2). The estuaries of the rivers Elbe, Weser, and Ems are included with their main tributaries up to the tidal weirs.

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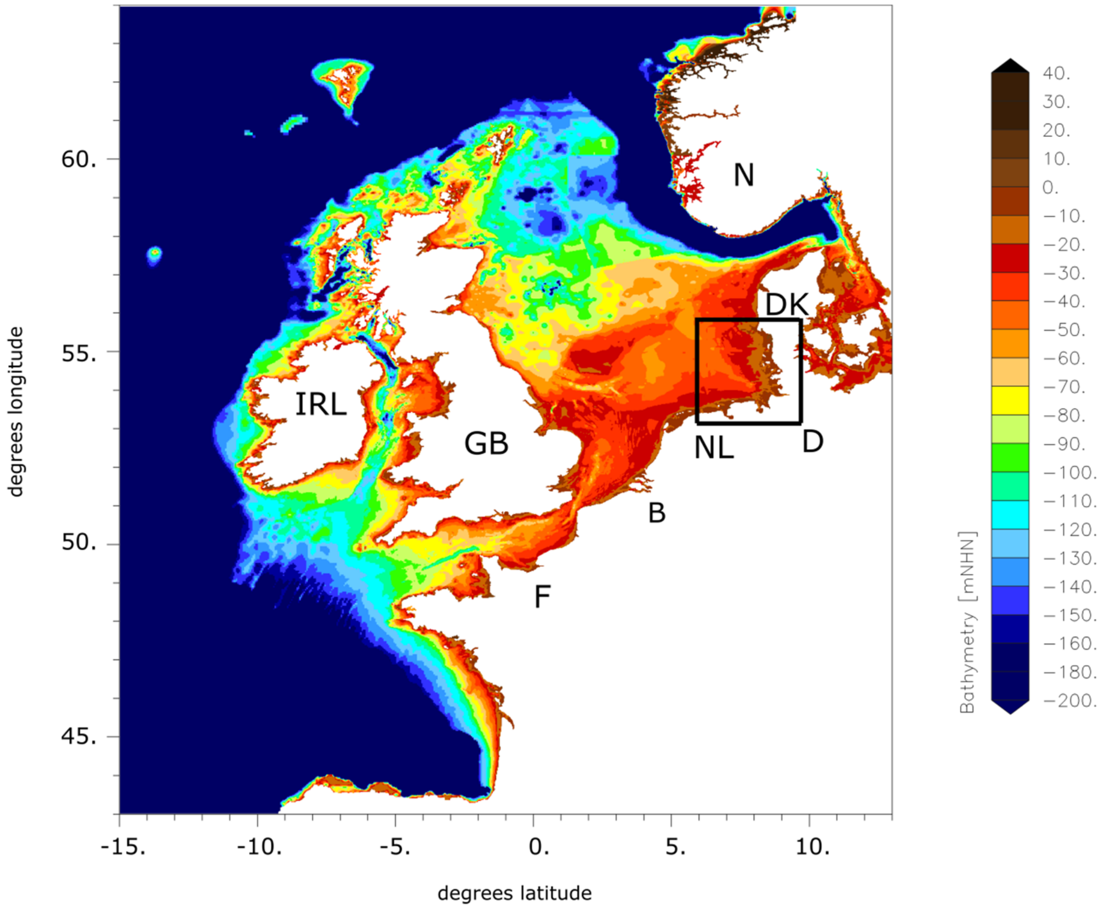

Figure 1: Model domain of the DCSMv6FM. The black box marks the German Bight.

The model is based on the hydrodynamic numerical model UnTRIM² (Casulli, 2008), which solves the three-dimensional shallow water equation and the three-dimensional transport equation for salt, suspended sediment and heat on an orthogonal unstructured grid (Casulli and Walters, 2000). In the model set-up used here the transport of suspended sediment is not calculated. One advantage of the UnTRIM²-method compared to its predecessor UnTRIM is the option to specify bathymetric details on subgrid level. This allows to describe the bathymetry at a higher resolution compared to the computational grid. Due to the subgrid the volume of the domain, especially on the tidal flats, can be reproduced with higher accuracy (Sehili et al., 2014).

The computational grid has an edge length of 5 km at the open boundary, an edge length of 300 m in the coastal areas and 100 m in the estuaries. The subgrid technology is used in the estuaries and the coastal zone with a resolution of 40 m in the finest parts. Due to the high resolution of the intertidal zone, flooding and drying can be well reproduced in the model (Sehili et al., 2014).

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At the open boundary to the North Sea water level is derived from DCSMv6FM. In this way shallow water effects caused by the shelf are taken into account in the boundary values. Salinity at the open boundary is provided by results of a North Sea model used in the project AufMod (Milbradt et al., 2015).

At the upstream boundaries of the estuaries measured river discharge is applied. As atmospheric forcing (wind at 10 m and atmospheric surface pressure) the same reanalysis data COSMO-REA6 (Hans-Ertel-Centre for Weather Research, Bollmeyer et al., 2015) as for the shelf model DCSM6vFM are used. The bathymetric data used in the German Bight Model are mainly based on data provided by the DHI (Danish Hydrological Institute) and the BSH (Federal Maritime and Hydrographic Agency Germany). Near the coast bathymetric data is updated with results provided by the project AufMod (Milbradt et al., 2015).

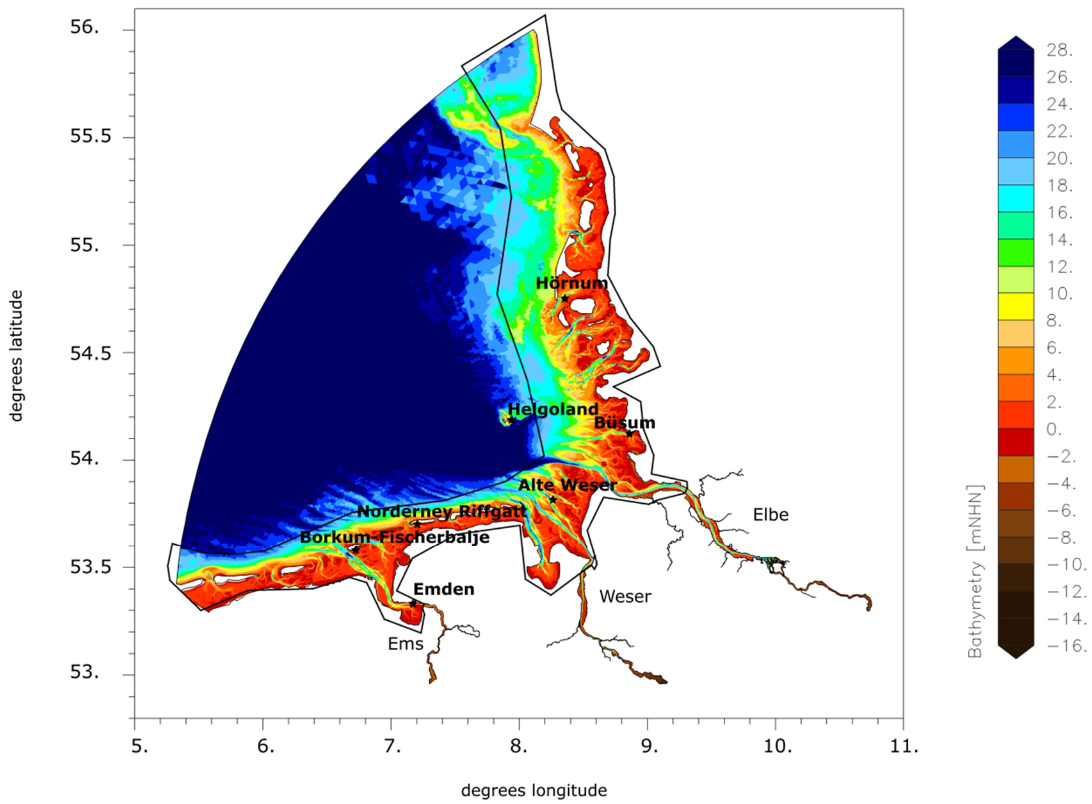

Figure 2: Model domain of the German Bight Model. Area within black polygon is used for spatial averages.

2.3 Model validation

In Table 1 the bias (mean deviation between measurement and model) of the two models compared to measurements for tidal high water, tidal low water and tidal mean water are listed at different stations along the German Bight. The stations are marked in Figure 2. The comparison shows that both models are able to represent basic characteristics of the tidal dynamics. In general, tidal high water is simulated in higher accuracy than tidal low water. The comparable shape of the water level

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curves between the two models and measurements can be seen exemplarily in Figure 3 at the station "Borkum Fischerbalje". Figure 4 shows a Target-Diagram in which the water levels of the DCSMv6FM and the German Bight Model are compared with measured data. The seven spots are located along the German Bight. The Target-Diagram relates the uRMSD* (unbiased Root-Mean-Square-Difference normalized with the standard deviation) and the bias* (mean deviation between measurement and model normalized with the standard deviation) (Jolliff et al., 2009). The closer the individual points are positioned to the centre, the higher is the models accuracy. The modelled water levels at the displayed stations are for both models almost all within the inner circle with a range of -0.25 to 0.25 which resembles a RMSE* of 0.25.

Table 1: Bias for three tidal parameters at different stations along the German Bight for the German Bight Model and the DCSMv6FM (stations marked in Figure 2).

	Borkum Fischerbalje		Norderney Riffgat		Alte Weser		Helgoland		Hörnum	
	GBM	DCSM v6FM	GBM	DCSM v6FM	GBM	DCSM v6FM	GBM	DCSM v6FM	GBM	DCSM v6FM
Tidal high water [m]	-0,02	-0,02	-0,04	-0,05	-0,10	-0,07	-0,13	-0,22	-0,12	0,10
Tidal low water [m]	0,23	0,18	0,32	0,23	0,28	0,22	0,31	0,25	0,20	0,00
Tidal mean water [m]	0,06	0,05	0,10	0,09	0,08	0,06	0,07	0,06	0,06	-0,01

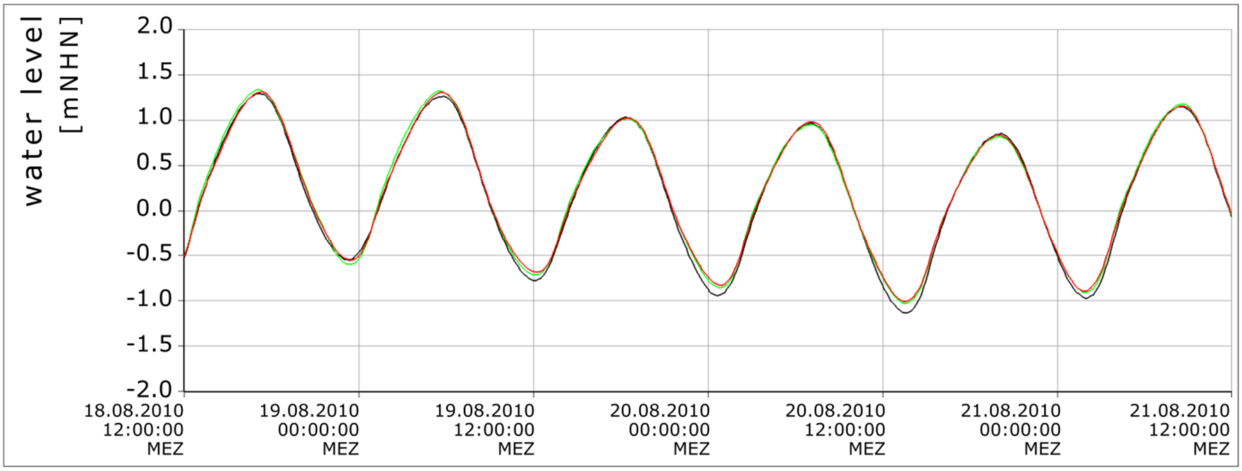

Figure 3: Water level at the station "Borkum Fischerbalje" (see Figure 2): Black: Measured data, red: Simulated data with the German Bight Model, green: Simulated data with the DCSMv6FM.

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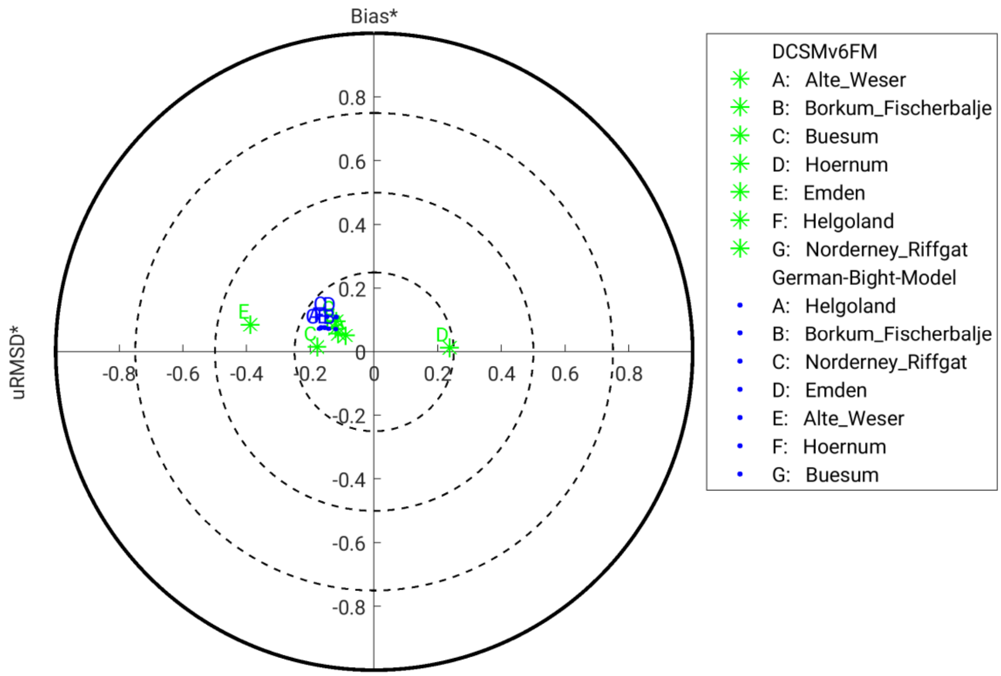

Figure 4: Target-Diagram for the comparison of the German Bight Model and the DCSMv6FM with measured water levels at seven locations along the German Bight (stations marked in Figure 2).

3.4 Numerical simulations

To investigate the impact of mean sea level rise on tidal dynamics in the North Sea we perform simulations with and without mean sea level rise using the shelf model DCSM6vFM and the German Bight Model (Table 2). For the simulations a period of 3 months (June, July and August 2010) is modelled. The summer periods ensure that the results are not influenced by storm surges or extraordinary high river discharge. Two different mean sea level rises are simulated: 0.8 m and 10 m. The value of 0.8 m lies within the projected range of global mean sea level rise in 2100 of the scenario RCP8.5 reported in the 5th IPCC report (Stocker et al., 2013). To gain a better understanding of the systems response to high water levels we use additionally the mean sea level rise of 10 m. The mean sea level rises are added as constant values at the open boundary of the shelf model DCSM6vFM.

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In addition to the above mentioned simulations we examine two case studies using the German Bight Model. With the help of these case studies we investigate the effects of resolution-dependent simplifications of shelf models. In case study 1 the estuaries of the rivers Elbe, Weser and Ems are removed from the German Bight Model at the locations where the shelf model DCSMv6FM ends. In these runs (GBM_ref_CS1 and GBM_80_CS1) and the corresponding reference run (GBM_ref_noQ) no river discharge is included (Table 2). Thus the only difference is the varied oscillation volume.

In case study 2 the coarser bathymetry of the shelf model DCSMv6FM is mapped onto the model grid of the German Bight Model without estuaries. This simulation is compared to the simulations from case study 1. In this way the only difference is the resolution of the bathymetry. The model still has a high resolution grid, but with a coarse bathymetry mapped onto it as shown in Figure 5. The topography of the coarse bathymetry contains artificial shoals and barriers even in deep channels like the mouth of the Elbe estuary. In some areas the water depth is underestimated and in other parts overestimated (Figure 5).

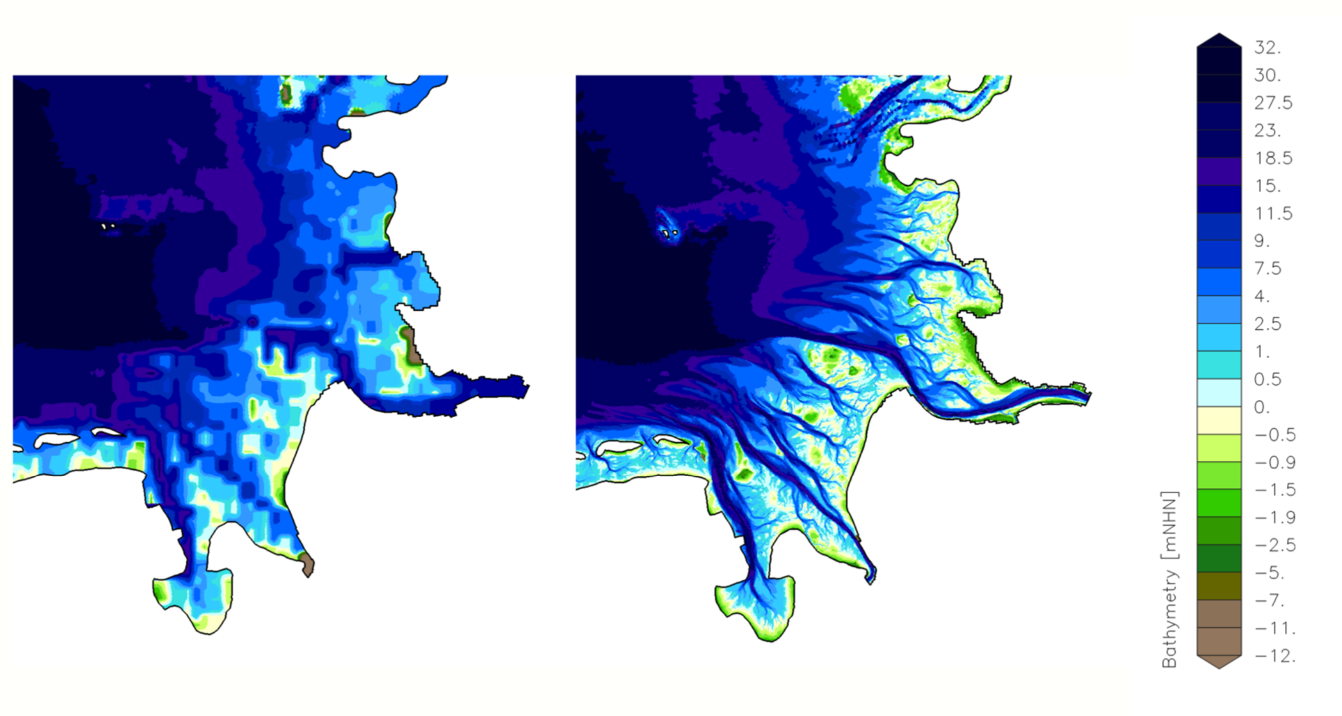

Figure 5: Bathymetry in the German Bight, left: coarse model bathymetry on the high resolution grid, right: highly resolved bathymetry.

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Table 2: Overview of simulations carried out.

Name	Model setup	MSLR
Shelf_ref	DCSMv6FM	-
Shelf_80	DCSMv6FM	0.8 m
Shelf_1000	DCSMv6FM	10 m
GBM_ref	German Bight Model	-
GBM_80	German Bight Model	0.8 m
GBM_1000	German Bight Model	10 m
GBM_ref_noQ	German Bight Model, no river discharge	-
GBM_ref_CS1	German Bight Model, no estuaries	-
GBM_80_CS1	German Bight Model, no estuaries	0.8 m
GBM_ref_CS2	German Bight Model, no estuaries, coarse bathymetry	-
GBM_80_CS2	German Bight Model, no estuaries, coarse bathymetry	0.8 m

2.5 Analysis

The analyses of the numerical model simulations shown in this paper concentrate on the M2 amplitude, mean current velocities, wet area and dissipation rate. The amplitude of the largest tidal constituent M2 (lunar semi-diurnal tide) in the North Sea is estimated by a harmonic analysis applied over the simulation period. The results of wet areas, dissipation rate and mean current velocities are averages over a full spring-neap cycle (6 July – 21 July). To evaluate wet areas in the model simulations we analyse the mean flooded area at tidal high water. The estimation of the dissipation rate is based on the assumption that a loss of barotropic energy (sum of kinetic and potential energy) is mainly caused by barotropic dissipation. We estimate the dissipation rate ϵ by computing the divergence of the depth-integrated barotropic energy flux $\nabla_H \overline{F_0}$ where

$$\overline{F_0} = \frac{1}{2}\rho H U^3 + \rho g \eta H U$$

and ρ denotes density, H the total water depth, U the depth-averaged velocity, g the gravitational acceleration, η the deviation from the mean water level. The first term on the right hand side represents the advection of kinetic energy. The second term estimates the barotropic pressure work. For a comprehensive derivation and description of tidal energetics see Kang (2011).

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3 Results

3.1 M2 amplitude

Figure 6 shows for both numerical models the M2 amplitude and its changes in response to mean sea level rise in the region of the German Bight. The first row pictures the M2 amplitude in the reference case, the second row the changes due to MSLR of 0.8 m and the third row the changes due to MSLR of 10 m with respect to the reference case.
The shelf model DCSMv6FM resembles the results from Pickering et al. (2012). It shows an increase of the M2 amplitude in the German Bight for the two mean sea level rise scenarios. The German Bight Model shows for the higher MSLR of 10 m also an increase of the M2 amplitude. The results of the simulation with MSLR of 0.8 m, however, differ considerably in comparison to the results of the shelf model. The amplitude increases in the German Bight Model only in small areas on the Wadden Sea and decreases offshore of the North Frisian Wadden Sea. This behaviour is comparable to the results of Ward et al. (2012).
To explore the reasons for the observed differences between the shelf model and the German Bight Model two case studies are conducted that are described in the following.

3.2 Case Study 1: Removing the estuaries

Since the estuaries are not included in the shelf model the two models have different oscillation volumes in the German Bight. To study the effect of this difference the estuaries are removed from the German Bight Model. They are cut at the locations where the DCSMv6FM ends.
Figure 7 gives the results of the changes in M2 amplitude due to the removal of the estuaries. In this figure no mean sea level rise is considered. The M2 amplitude shows differences only in the mouth of the Elbe due to the removal of the estuaries. The removal leads to an increase of the M2 amplitude.
The response of the German Bight Model without estuaries to MSLR of 0.8 m is displayed in Figure 8. The comparison to Figure 6d (GBM with estuaries and MSLR of 0.8 m) shows that only in the outer estuary of the Weser some differences can be spotted but the general pattern of the changes in M2 amplitude stays the same. Thus the different oscillation volume due to the missing estuaries in the shelf model DCSMv6FM is not the main reason for the differences of the two models for MSLR of 0.8 m seen in Figure 6.

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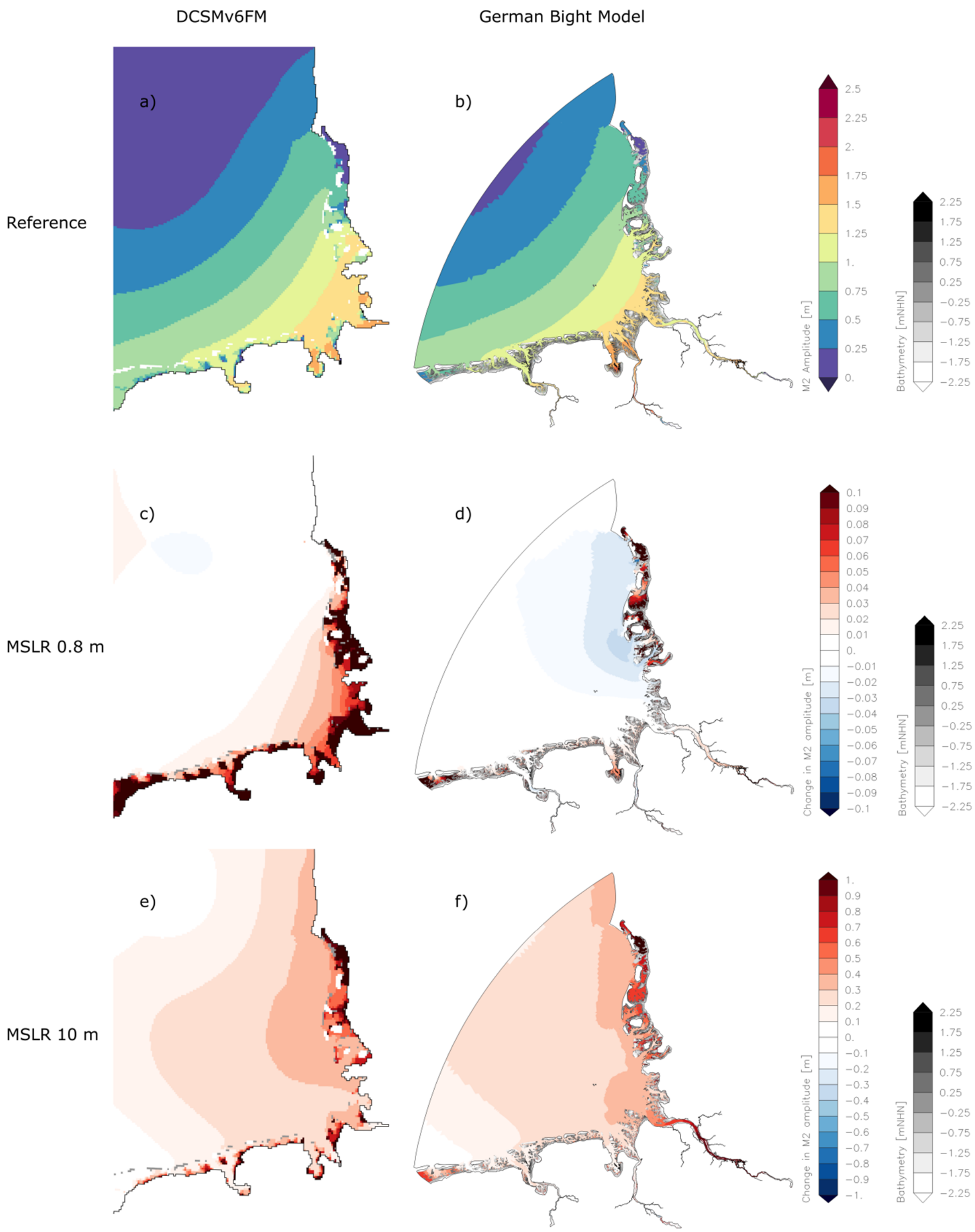

Figure 6: M2 amplitude and response of M2 amplitude to MSLR (increase in red, decrease in blue), left: DCSMv6FM (a, c, e), right: German Bight Model (b, d, f); first row: Reference; second row: MSLR of 0.8 m; third row; MSLR of 10 m; a) Shelf_ref, b) GBM_ref, c) Shelf_80 - Shelf_ref, d) GBM_80 - GBM_ref, e) Shelf_1000 - Shelf_ref, f) GBM_1000 - GBM_ref.

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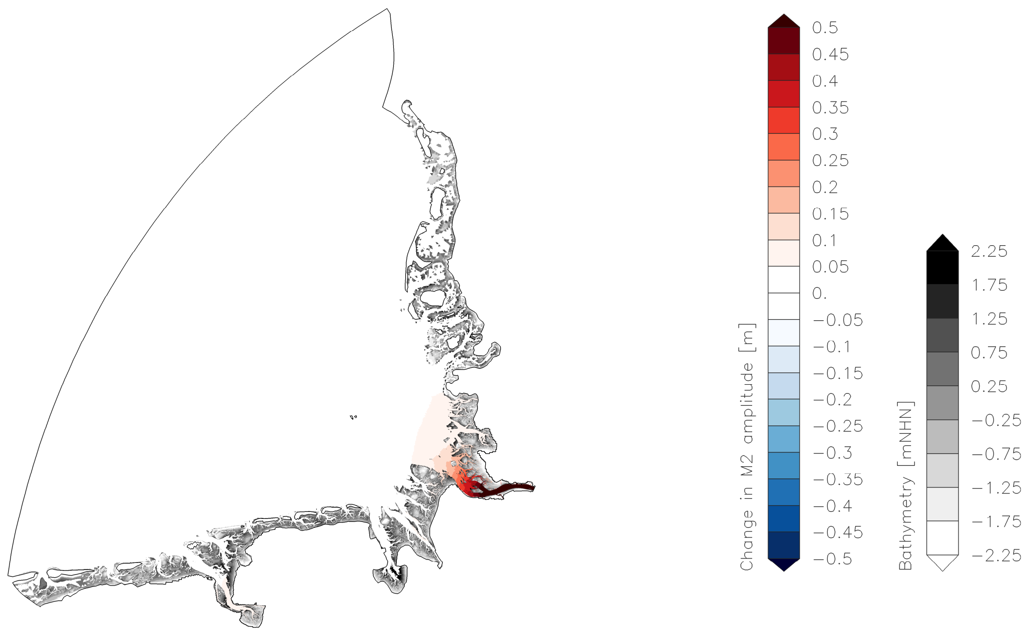

Figure 7: Changes in M2 amplitude due to the removed estuaries (increase in red, decrease in blue) (GBM_ref_CS1 – GBM_ref_noQ).

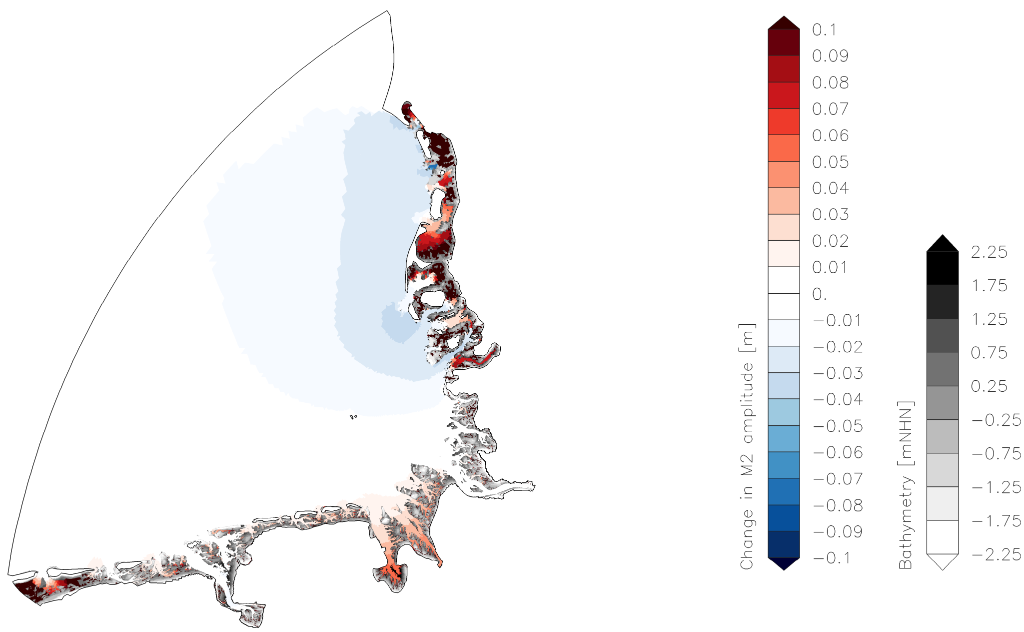

Figure 8: Changes in M2 amplitude due to MSLR 0.8 m in the German Bight Model without the estuaries (increase in red, decrease in blue) (GBM_80_CS1 - GBM_ref_CS1).

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3.3 Case Study 2: coarse shelf model bathymetry

Due to the limited resolution of the shelf model the complex bathymetry in the coastal zone cannot be represented in detail. In this second case study the effect of a coarse bathymetry is investigated by interpolating the coarser shelf model bathymetry onto the high resolution model grid of the German Bight Model.

Figure 9 shows the changes in M2 amplitude due to the coarser resolution of the adopted shelf model bathymetry. As a result of the altered bathymetry the M2 amplitude decreases in the inner German Bight. The largest decrease can be detected in the mouth of the Elbe estuary. In contrast to case study 1 the changes are not locally restricted.

The response to MSLR of 0.8 m is shown in Figure 10. Similar to the shelf model the M2 amplitude increases in this case study in the German Bight.

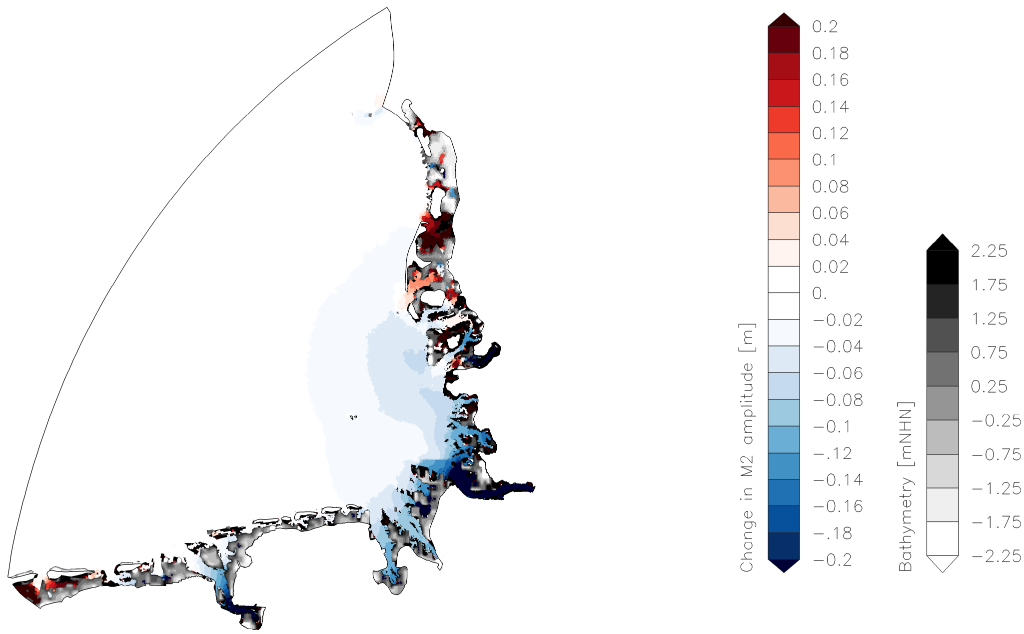

Figure 9: Changes in M2 amplitude due to the coarser bathymetry (increase in red, decrease in blue) (GBM_ref_CS2 – GBM_ref_CS1).

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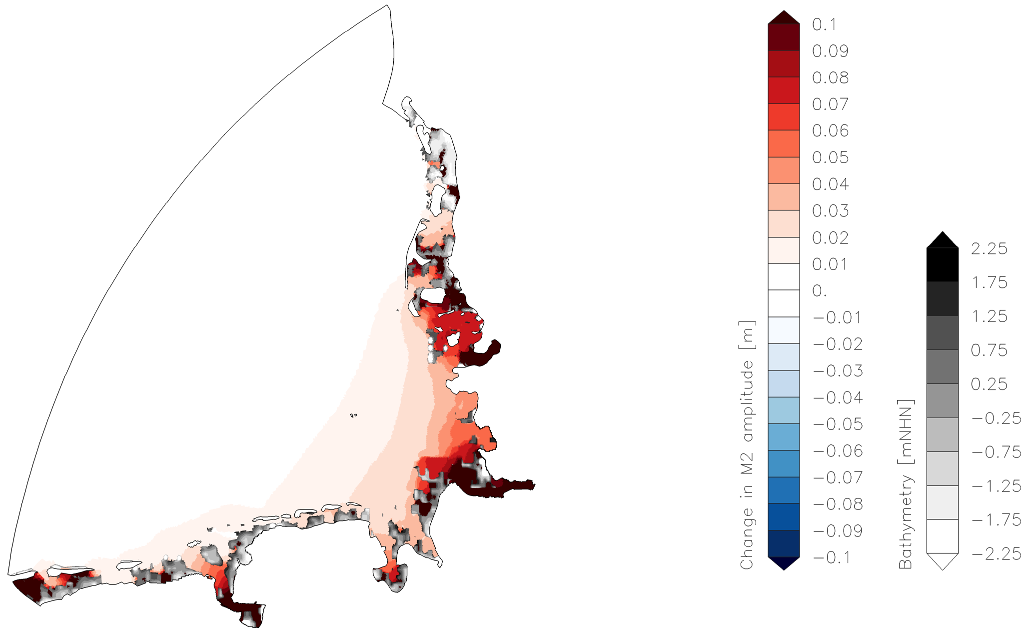

Figure 10: Changes in M2 amplitude due to MSLR 0.8 m in the German Bight Model with coarse bathymetry (increase in red, decrease in blue) (GBM_80_CS2 – GBM_ref_CS2).

3.4 Wet areas, dissipation rate and current velocities

To further investigate the reasons for the similar response of case study 2 compared to the shelf model DCSMv6FM we analyse the mean flooded area at tidal high water (wet areas) and the dissipation rate in both case studies (Table 3). Since we expect main differences in the shallow part of the German Bight, we determine the average values within the area of the Wadden Sea including shallow parts up to the 20 m depth line (shown as polygon in Figure 2). Case study 1 serves now as reference. In this way the pure effect of the different resolutions of bathymetry is considered.

The numbers in Table 3 show that wet areas enlarge due to mean sea level rise. In both case studies, i.e. in the highly resolved bathymetry and in the coarsely resolved bathymetry, the gain of wet areas due to MSLR of 0.8 m is about the same. In contrast, the change in dissipation rate due to mean sea level rise differs in both case studies. In case study 1 (fine bathymetry) the dissipation rate increases by about 21 % (0.6×10^{-3} W/m^2) whereas in case study 2 (coarse bathymetry) it increases only by about 7% (0.2×10^{-3} W/m^2).

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Table 3: Mean flooded area at tidal high water (wet area) in the shallow part of the German Bight up to the 20 m depth line and dissipation rate averaged over that region.

	wet area [10^9 m^2]	dissipation rate [10^{-3} W/m^2]
GBM_ref_CS1	15.90	2.9
GBM_80_CS1 - GBM_ref_CS1	0.22	0.6
GBM_ref_CS2	15.91	3.0
GBM_80_CS2 - GBM_ref_CS2	0.24	0.2

Figure 11 shows the mean current velocity in the reference case (a) and the change of mean current velocity due to MSLR of 0.8 m in case study 1 (fine bathymetry) (b). Figure 12 shows the same for case study 2 (coarse bathymetry). In case study 1 the mean current velocity increases due to mean sea level rise in coastal areas, especially in the tidal channels, almost everywhere in the German Bight. In case study 2 the change of mean current velocity has a different pattern. In general the course of the channels is less distinctively represented and increases in mean current velocity are not as pronounced as in case study 1. These results coincide with the smaller increase of dissipation rate in case study 2 compared to case study 1, since dissipation rate strongly depends on velocity.

The significance of the shallow areas near the coast for the dissipation of energy is illustrated in Table 4. Besides the dissipation rate averaged over the shallow part of the German Bight up to the 20 m depth line (area within the black polygon in Figure 2) the table contains also dissipation rates averaged over the entire model domain of the German Bight Model excluding the estuaries (global). In general, the globally averaged dissipation rates are smaller than dissipation rates averaged over the shallow parts. In the reference simulation and the run with 0.8 m MSLR the dissipation rate in the shallow part is by a factor of approx. 1.8 higher.

Furthermore Table 4 includes also wet areas and dissipation rates of the simulation with 10 m MSLR. The gain of wet area from 0.8 m MSLR to 10 m MSLR is less than the gain of wet area from the reference run (no MSLR) to the run with 0.8 MSLR. Dissipation rate in the model run with 10 m MSLR decreases in comparison to MSLR of 0.8 m. In the shallow part of the German Bight up to the 20 m depth line it also decreases in comparison to the reference simulation. Generally, mean current velocities decrease in the channels in the model run with 10 m (Figure 13). This coincides with the smaller values of dissipation rate.

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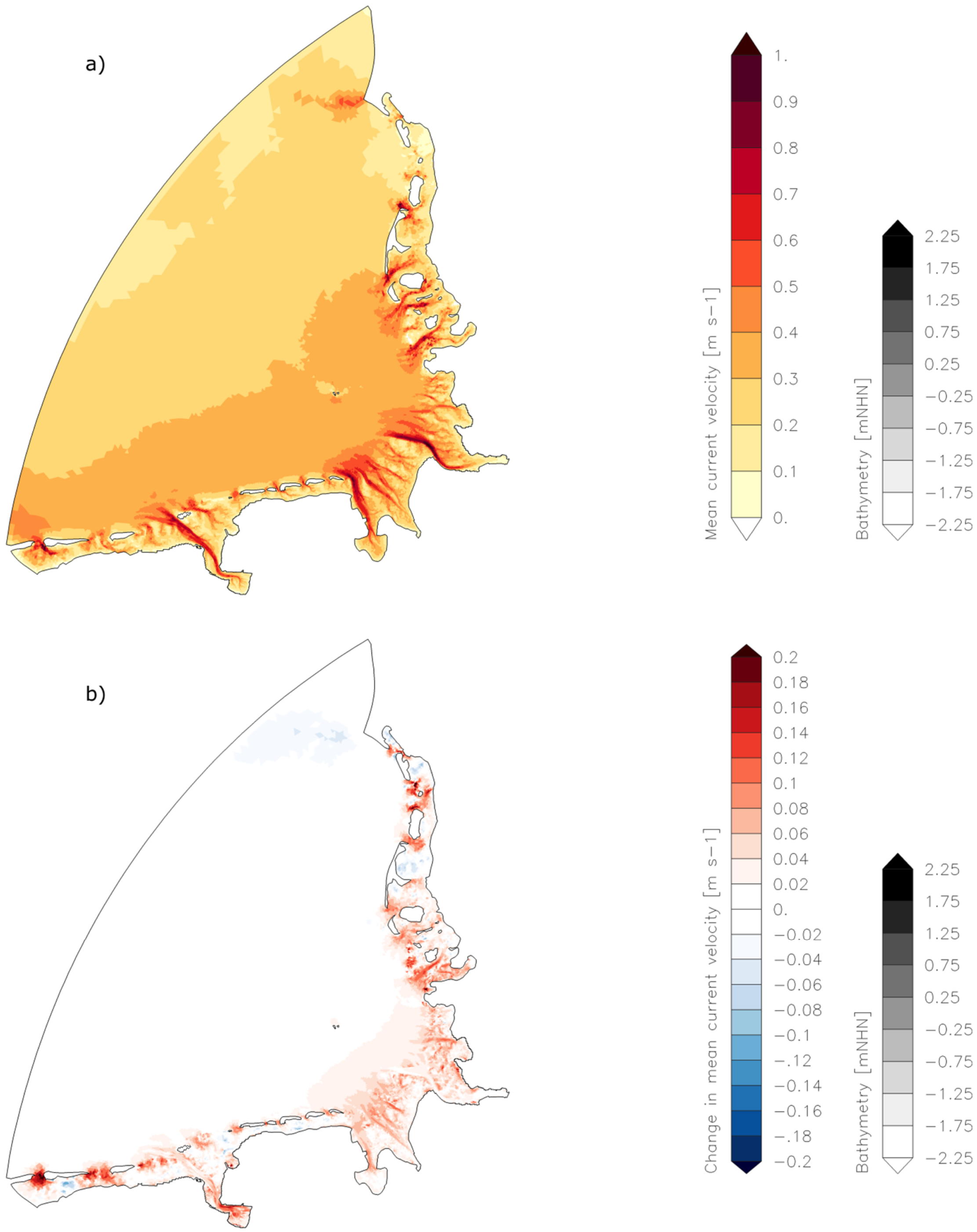

Figure 11: a) Mean current velocity without MSLR in the high resolution bathymetry (GBM_ref_CS1); b) Change in mean current velocity in the high resolution bathymetry due to MSLR of 0.8 m (increase in red, decrease in blue) (GBM_80_CS1 - GBM_ref_CS1).

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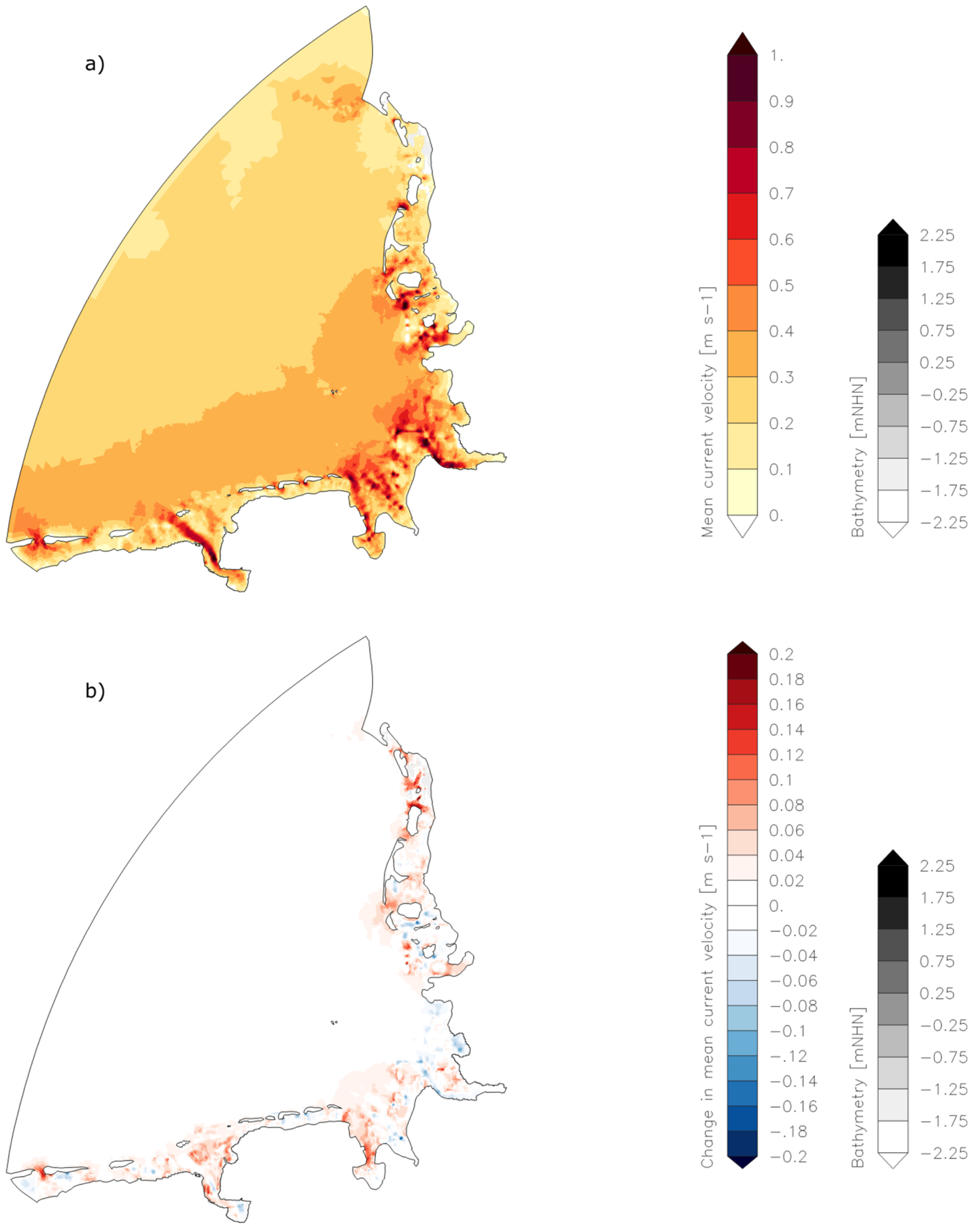

Figure 12: a) Mean current velocity without MSLR in the coarser bathymetry (GBM_ref_CS2); b) Change in mean current velocity in the coarser bathymetry due to MSLR of 0.8 m (increase in red, decrease in blue) (GBM_80_CS2 - GBM_ref_CS2).

https://doi.org/10.5194/os-2019-84
Preprint. Discussion started: 18 July 2019

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Table 4: Mean flooded area at tidal high water (wet area) in the shallow part of the German Bight up to the 20 m depth line, dissipation rate ϵ_S averaged in the shallow part of the German Bight up to the 20 m depth line and dissipation rate ϵ_G averaged over the entire model domain excluding the estuaries (global).

	wet area [10^9 m^2]	dissipation rate [10^{-3} W/m^2]		
	shallow part	shallow part ϵ_S	global ϵ_G	ϵ_S / ϵ_G
GBM_ref	15.88	2.8	1.6	1.75
GBM_80	16.11	3.4	1.9	1.79
GBM_1000	16.21	2.5	1.8	1.39

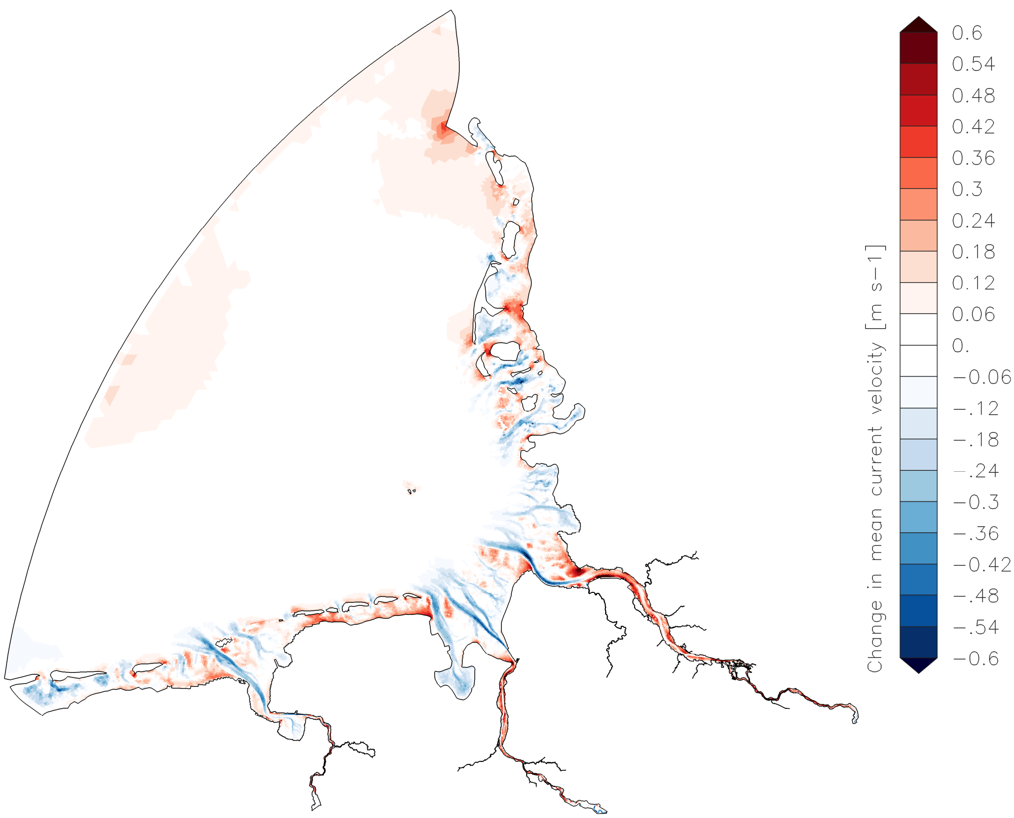

Figure 13: Change in mean current velocity due to MSLR of 10 m (increase in red, decrease in blue) (GBM_1000-GBM_ref).

https://doi.org/10.5194/os-2019-84
Preprint. Discussion started: 18 July 2019

4 Discussion

In this study we compare the response of two different kinds of models to mean sea level rise (MSLR) in the German Bight. The coarser shelf model DCSMv6FM and the finer German Bight Model respond to a MSLR of 0.8 m in different ways. The response to a MSLR of 10 m is more comparable in both models. To identify the reasons for the different response to 0.8 m MSLR we adjust the German Bight Model in two steps in order to more closely resemble the shelf model. In the first step the estuaries are excluded from the model domain. While the reduced tidal oscillation volume explains the locally increased M2 amplitude, it does not explain the different responses of the two models seen on a larger scale. In the second step the coarse bathymetry of the shelf model is mapped onto the fine model grid of the German Bight model. With this step the German Bight model responds in a similar way to a MSLR of 0.8 m as the shelf model DCSMv6FM. Thus it is mainly the different resolution of the bathymetry used in the two models, which leads to the different responses to 0.8 m MSLR.

Pelling et al. (2013) explain the different response to MSLR of two shelf models by different dissipation behaviour due to newly flooded cells outside the former model boundary in one of the two models. The boundaries of the Shelf Model DCSMv6FM and of the German Bight Model are defined in the way that dikes cannot be overflowed, i.e. no new cells can be flooded behind dikes. However, owing to the drying and flooding algorithm implemented, the models are able to flood new cells in the dike foreland when mean sea level rises. Following the argumentation of Pelling et al. (2013), one explanation for the different response to 0.8 m MSLR in the finer German Bight Model and the coarser shelf model DCSMv6FM could be that less new area is flooded in the shelf model when mean sea level rises and thus less highly dissipative area exists in the shelf model. In this way the larger dissipative areas in the fine model would be an explanation for the weaker increase and in some regions decrease of the M2 amplitude in the fine model. The analysis of wet areas (Table 3) in the different case studies, however, does not support this explanation. The changes in wet area due to a MSLR of 0.8 m in the model with fine bathymetry (case study 1) and the model with coarse bathymetry (case study 2) do not differ much. Nevertheless, the change of dissipation rates due to MSLR of 0.8 m is different in the model runs with fine or coarse bathymetry. In the fine bathymetry model dissipation rate averaged over the region of the Wadden Sea including the shallow part up to the 20 m depth line increases, whereas it almost stays constant in the coarse bathymetry model. The larger increase in dissipation rate in the fine bathymetry model results mainly from overall increased current velocities. In the coarse bathymetry model this increase in current velocities cannot be seen in the same characteristic. The coarse bathymetry contains artificial shoals and barriers. Many channels in the Wadden Sea do not allow a continuous flow of water. This leads to the differences in mean current velocity and its response to MSLR in the coarse model.

These results suggest that a sufficiently fine resolution of shallow regions such as the Wadden Sea is needed in hydrodynamic models for the most accurate representation of tidal dynamics and its response to MSLR possible. In this respect, shelf models as used by Ward et al. (2012) and Pickering et al. (2012) are only with limits suited to draw conclusions for the tidal response to MSLR in shallow areas such as the German Bight. With a MSLR of 10 m the impact of the resolution of bathymetry on tidal dynamics in the German Bight, however, diminishes.

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The increase in mean current velocities at 0.8 m MSLR can be explained by an increased ratio of flood volume to cross-sectional areas of the tidal inlets (Wachler et al., in prep.). The mean sea level rise induced change in ratio of flood volume and the cross sectional area of the inlets depend on the geometry of the tidal basin, e.g. on the ratio between the area of intertidal flats and channels. The tidal basins in the Wadden Sea of the German Bight are characterised by a large flat area relative to the area of the channel (Ferk, 1995, Spiegel, 1997). Due to these geometric characteristics, with rising mean sea level the flood volume increases more than the cross section of the tidal inlet resulting in higher current velocities in the tidal inlet system.

In contrast, in the simulation with 10 m MSLR mean current velocities decrease in the channels. We suppose that the decrease of mean current velocities is due to the much higher increase of water levels compared to the scenario with 0.8 m MSLR. The water extends up to the models boundary and can only accumulate vertically but cannot overflow new areas. Wetting and drying do not take place any longer. Unlike in the case of 0.8 m MSLR the cross-sectional areas of the tidal inlets increase considerably more such that the ratio between flood volume and the cross section of the tidal inlet decreases.

Since dikes cannot be overflowed in both numerical models used, note that, especially the simulations with 10 m MSLR do not represent how the system would react in the real world, in which dikes are usually not high enough to retain such high water levels. These simulations are mostly included to gain a better understanding of the systems response to increased water levels caused by mean sea level rise. Another remark concerning the point of matching reality relates to the assumption of unchanged bathymetries in the case of mean sea level rise. Due to mean sea level rise, e.g., a vertical growth of tidal flats is expected (Hofstede, 2002, van Maanen et al., 2013). For a study considering changes of the Wadden Sea bathymetry in combination with mean sea level rise see Wachler et al. (in prep.).

5 Conclusions

Especially in flat coastal areas such as the Wadden Sea in the German Bight the representation of the bathymetry plays a crucial role for the estimation of changed tidal dynamics in response to mean sea level rise in the order of about 1 m. The dissipation rate in the region of the Wadden Sea is considerably higher than in deeper areas. Thus these flat areas must be sufficiently resolved. For higher mean sea level rise scenarios (10 m) the resolution of the bathymetry is less important.

Depending on the research question and the focused area, it is important to select the model setup in such a way that all relevant processes are sufficiently taken into account. For investigating the response of the North Sea the usage of a shelf model with lower resolution might be sufficient. However, to draw conclusions for coastal stations it is necessary to use numerical models that resolve coastal bathymetry and the shoreline (e.g. including estuaries) as best as possible.

6 Data availability

Data and results in this article resulting from numerical simulations are available upon request from the corresponding author.

7 Author contribution

Caroline Rasquin worked on the simulations, analyses and figures. Rita Seiffert and Benno Wachler participated in the analyses and the interpretation of the results. Caroline Rasquin and Rita Seiffert wrote the manuscript with contributions from Benno Wachler. Norbert Winkel was involved as a scientific expert, supervised the study and gave input for writing and revision of the paper.

8 Competing interests

The authors declare that they have no conflict of interest.

9 Acknowledgements

This work has been carried out within the framework of the Network of Experts financed by the German Federal Ministry of Transport and Digital Infrastructure. We thank all our co-workers at the Federal Waterways Engineering and Research Institute in Hamburg for their continuous support. Special thanks go to Günther Lang, Frank Kösters, Julia Benndorf and Elisabeth Rudolph for inspiring discussions.

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