Reply to reviewer 1:

P1 Line 23: The first sentence feels clumsy – consider omitting (you explain in more detail later on anyway) or at least add a reference for this (quite bold) statement

We have omitted this sentence.

P1 Lines 23 – 28: what is the point you are trying to make by mentioning the acceleration in MSLR? Maybe it would be more helpful to look at total increases in SLR? This is what really will affect coastal areas. Are there more recent references?

We mention especially the past acceleration of SLR, because the numbers illustrate in a striking way that changes are already going on. We revised this introductory text passage. We included numbers for total future increases in mean sea level rise and refer to the recently published IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC 2019, 2019).

P1 Line 28-29: worth including a reference and eluding to the reasons for this.

We added references and modified the text passage in order to better explain the connections.

P1 Line 28: highlight why changes in the tides are important – water level variations, extreme water levels, species distributions, changing currents, etc

We revised this part of the manuscript.

P1 Line 29 – P2 Line 7: are the changes you mention here due to changing tides or changing sea level? If the latter then they feel slightly out of context.

We are referring to changes in tidal dynamics but these changes are directly related to changes in mean sea level. We modified the text passage to explain this more clearly.

P2 Line 25: what sort of shelf models are you referring to here? Tide models? OGCMs?

The shelf models meant are tide models. In the manuscript we included examples to clarify this aspect.

P3 Shelf Model description(s): Given that your work is all about tides it would be helpful to include more information on the calculations of the tides in the model. How is bed roughness dealt with? Internal tides? Is this a 2D or 3D model? What happens at the open boundaries?

The DSCMv6FM is a 2D model based on the shallow water equations that includes tide generating forces. Surge calculation is based on the inverse barotropic correction. At the open boundary 22 tidal constituents are used from GOT00.2 (Q1, O1, P1, K1, N2, M2, S2, K2, 2Q1, σ1, ρ1, χ1, π1, ϕ1, θ1, 2N2, μ2, ν2, l2, L2 and T2) and 16 partial tides from FES2012 (Ssa, Mm, Mf, Msf, Mfm, S1, J1, M3, MNS2, R2, M4, MN4, MS4, S4, M6 and M8). Thus tides are produced/affected by two mechanisms, by astronomical factors (gravitational attraction between Earth, moon and sun, rotation of the Earth-moon and Earth-sun systems) and by nonlinear processes (e.g. friction due to bed roughness) that affect the tidal constituents when propagating across the model domain.
The DCSMv6FM uses a spatially varying bed roughness. We modified the text passage to complete the model description.

P3 Line 19: are you really using GOT00.2? The latest version is GOT4.7

Yes, we are using GOT00.2. We believe that the data set is sufficient for our purpose, since this study is a case study and we are running both models with the same forcing. Thank you for the remark. We plan to update these data for future studies.

P4 Line 5: why would you want sediments in your model?

Since the numerical model UnTRIM² is principally able to compute the transport of suspended sediment, with this sentence we want to make clear, that for this study we have this process not included. In our study the focus lies on the response of tidal dynamics to sea level rise. The transport of suspended sediment is computationally intensive and not of primary relevance to tidal dynamics. To clarify this point, we included a short explanation.

P4 Line 7: What parameters are used in the subgridscale option? How does this feed into the shallow water equations? Do both models have this option? How does turning this option on and off affect the results?

Subgrid allows using coarser computational grids with high resolution data for bathymetry at subgrid level. The advantage of this technique is that large time steps can be used in the simulation due to the coarser computational grid. The algorithm that correctly represents the precise mass balance in regions where wetting and drying occurs and was derived by Casulli (2008) and Casulli and Stelling (2011). The computational grids are allowed to be wet, partially wet or dry. This implies that no drying threshold is needed. With the subgrid option the accuracy of the simulation results can be improved when using the same classical computational grid. Comparable results to simulations with a classical grid are obtained with using a coarser computational grid but with the subgrid technique. (Sehili et al., 2014)
For further information on the implementation of this method in the shallow water equation we refer to equation (7) in Sehili et al. (2014).
The DCSMv6FM uses the new flexible mesh capacities D-Flow-FM. The flexible mesh technique is another designation for the classical unstructured grid concept and thus, in contrast to the German Bight Model, does not include subgrid information.
We included the information on the subgrid option in the model description of the German Bight Model and clarified that DCSMv6FM does not use subgrid information.

Table 1: It would helpful to include a root mean square error here as this gives an additional measure of the absolute model error rather than the relative error you get with the bias.

We added the rmse and the bias of the M2 amplitude at all stations in the table 1.

P6 Line 7: explain RMSE*?

RMSE is the root-mean-squared-error normalised with the standard deviation.*
We added this in the manuscript.

P6: Given that you mainly discuss changes in M2 amplitude later on, it would be helpful to include an evaluation of the model performance in simulating the tides against the amplitudes at the stations and possibly also against a product such as TPXO or FES. This is probably more important than including an analysis of the water levels as it is not clear through which processes the water level errors arise (i.e. your model could perform very well at simulating tides but not for storms or vice versa).

We chose a validation period in which wind velocities are small. Thus water levels are not influenced by storm surges. For this reason we believe that if the model simulates water level well it also simulates the tidal constituents

(such as M2 amplitude) well. To complete the picture we, however, added the bias for the M2 amplitude between the measurements and the models at the stations in table 1.
In our opinion products such as FES or TPXO are not suited for validation purpose in our case. They are designed to model tides in the deep oceans. The bias increases on the shelf and especially at the coast where shallow water tides dominate. The error of these models on the coast is larger than the error we see in our validation. (https://www.aviso.altimetry.fr/en/data/products/auxiliary-products/global-tide-fes/description-fes2014.html)

P7 line 12 – 13: This statement is not clear to me – why do you add SLR at the open boundary rather than over the whole domain? Is this the case for both models?
Can you explain in more detail how the model deals with flooding areas, i.e. the wetting and drying scheme? How does that work at low water and sea level rise? Surely, with SLR more normally dry areas are flooded and more energy is lost there?

Water levels within the model domain are dominated by the forcing at the open boundary. Adding the mean sea level rise at the open boundary is a simple way to introduce sea level rise into the model domain. It would be more straightforward to add mean sea level also to the whole domain at the initial time step of the simulation period. However, the water signal introduced at the open boundary travels within a few days across the whole model domain. We chose the initialisation time of both models to be sufficiently long that a dynamical equilibrium is reached before analysing the data.
At the open boundary of the DCSMv6FM the mean sea level rise is added as a constant factor in the formula that calculates the tide using several harmonic constants (Zijl et al. (2013) eq. 1). At the open boundary of the German Bight Model water levels are used from DCSMv6FM which already include the effects of mean sea level rise on the shelf. At the corresponding text position in the manuscript we added this information.

Most numerical models control wetting and drying using thresholds for a minimum water depth. The models set the flow velocity to zero and take points out of the computational domain when a certain drying threshold is reached. Those points are "reactivated" when the water depth increases over the flooding threshold. The algorithm used in UnTRIM² is directly derived from the governing differential equation and is a substantial part of the numerical method. It guarantees mass conservation and allows any computational cell to be wet, partially wet or dry which is detected by having precisely zero water depth. No drying threshold is needed. For further information concerning the wetting and drying algorithm we recommend (Casulli, 2008) and the literature within. We have added the additional literature in the manuscript.

In principle rising mean sea level leads to a flooding of former dry area and thus more energy is dissipated on these areas. But it depends on the profile of the flooded area. If it is a steep profile then it could be that in the sum more or less the same amount of energy dissipates with or without MSLR, because the water depth increases (and dissipation decreases) in areas that were already flooded without mean sea level rise. When having a flat profile the area on which dissipation takes place increases more relative to the decrease of dissipation caused by deeper water levels. Thus no general statement is possible.

P7 Simulations: How do you deal with open boundary tidal forcing with sea level rise? Harker et al. (2019) show that using present day tides at the model open boundaries leads to large changes in tidal responses on the Australian Shelf – can you comment on this for your work? Similarly, global studies such as Mawdsley et al. (2015) show global changes in water levels. Work by Wilmes et al. (2017) show global tidal responses to large-scale sea level changes on the levels of your 10 m simulation.
Do you allow for flooding in the large SLR scenario? What coastal defences do you assume?

Thank you for this remark. Sea level rise will affect global tides. We, however, assume that the tidal constituents will not change at the open boundary of the shelf model DCSMv6FM. We add mean sea level rise as a constant value to the boundary conditions. For our study this is a reasonable assumption since it is designed as a conceptual

study investigating the interaction between sea level rise and the representation of the bathymetry in the coastal zone. Our study does not characterise the future development of the tides. We clarified this point in the discussion. Besides the uncertainty due to the assumption that the tidal constituents do not change at the boundary condition there are other uncertainties we did not account for. As mentioned in the paper one of the largest uncertainties is how the bathymetry near the coast will change due to MSLR. Due to mean sea level rise, e.g., a vertical growth of tidal flats is expected. Such changes in coastal bathymetry will affect tidal dynamics in the German Bight.
The wetting and drying algorithm is in principle still working when simulating large sea level rises. However, in the scenario with MSLR 10 m the model is flooded at all times, since the water cannot escape. The model domains of the models have a fixed vertical wall which is so high that it is not possible to flood the hinterland.

Figure 4: Why does Emden have such a large error?

Emden is located in the inner estuary of the Ems. Therefore it is a station which is principally harder to calculate in high accuracy. Especially with a model which has a relatively coarse resolution. We added the explanation also in the manuscript.

Figure 3: what are the units? Explain mNHN in the caption

mNHN denotes metres above the German datum which is a good approximation of mean sea level We added an explanation in the caption.

P10 Line 3: How do you calculate tidal amplitudes?

Tidal amplitudes are estimated by a harmonic analysis of tides (Pansch, 1988), which is based on a Fourier decomposition of the water level time series into harmonic functions of prescribed tidal constituents. We added this explanation in the paper.

P10 line 4-5: omit sentence

Changed in the manuscript

Figure 6. Which model performs better at the present-day tides?

It is hard to decide which model performs better at present-day tides only from the picture since there is no spatial dataset of measurements. Both results seem plausible.
The comparison to measurements at individual gauges shows that both models calculate the tidal dynamics sufficiently accurate and the results of both models are in the same order of magnitude (see table 1). The DCSMv6FM performs slightly better in comparison which is probably a result of the calibration method (see 2.1). For the present day this calibration method provides good results but the question arises if this is also the case for future projections.

P19 lines 4-5: '"The response to a MSLR of 10 m is more comparable in both models" – the differences between the two model setups are probably on a similar magnitude or larger as for the 0.8m SLR scenario, however, they are masked by the larger-scale differences occurring on the whole shelf area (whereas for a 0.8 m SLR the shelf-scale changes are much smaller). I would, however, argue that there are pretty big differences between Figure 6 e and f, especially around the islands in the southern part of the domain where the difference amounts to over 1 m in amplitude.

Thank you very much for this comment. This is a very important aspect. You are right. We plotted the differences between Figure 6f and e and also between Figure 6d and c (supplement Figure S1). The differences in the region offshore of the North Frisian Wadden Sea are smaller but in a similar order of magnitude as in the case of MSLR

0.8 m. In the South the differences have opposite sign. That means, in contrast to MSLR 0.8 m, the response to MSLR 10 m in the shelf model is smaller than in the German Bight model.
We modified the section 3.1 accordingly.

P19 lines 32-33: I'm not sure I agree – see comment above. The differences locally are pretty significant. Your large-scale, regional or shelf-wide responses are similar, but then arguably they are also similar (i.e. not very much happens) for small sea level increase.

Following the argumentation of your comment above, we modified this statement.

P20 line 24: "For higher mean sea level rise scenarios (10 m) the resolution of the bathymetry is less important" see comments above. I would conclude that, if looking at complex coastal areas such as the German Bight, highly resolved nearshore bathymetry is important for assessing the impact of sea level changes in these complex areas as the local responses can differ from the regional, offshore tidal changes. This is the case whether the forcing is large or small.

After explicitly comparing the differences of the responses (see above) we agree. We deleted the statement in the conclusion. Thank you again for your careful reading and your remarks on this aspect.

3 Technical comments
P2 Line 21: "1m" – space needed; also check remainder of the document
Changed in the manuscript

P2 Line 23: defence -> defences
Changed in the manuscript

P2 Line 28: After "Thus" add a comma
Changed in the manuscript

P10 Lines 3 – 4: 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.
-> Figure 6 shows the M2 amplitude and its changes in response to mean sea level rise in the region of the German Bight for both numerical models.
Changed in the manuscript

Table 2: You have quite a lot of different cases – remembering what case study 1 referred to later on in the manuscript is hard – why not label them something intuitive like GBM_ref_CS1 -> GBM_ref_NE and GBM_80_CS2 -> GBM_80_NE_CB
Changed in the manuscript

Figures 7 onwards: rather than having lots of single plot figures it would be better to condense your individual images into one or two figures with more subplots like you have done in Figure 6.
Changed in the manuscript

P13 lines 8 - 9: Similar to the shelf model the M2 amplitude increases in this case study in the German Bight. -> The M2 amplitude increases in the German Bight in this case study are now similar to the shelf model changes.
Changed in the manuscript

References

Casulli, V.: A high-resolution wetting and drying algorithm for free-surface hydrodynamics, Int. J. Numer. Meth. Fluids, 60, 391–408, https://doi.org/10.1002/fld.1896, 2008.

Casulli, V. and Stelling, G. S.: Semi-implicit subgrid modelling of three-dimensional free-surface flows, Int. J. Numer. Meth. Fluids, 67, 441–449, https://doi.org/10.1002/fld.2361, 2011.

IPCC 2019: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, in press, 2019.

Pansch, E.: Harmonische Analyse von Gezeiten- und Gezeitenstrombeobachtungen im Deutschen Hydrographischen Institut, Deutsches Hydrographisches Institut, Hamburg, Wissenschaftlich-Technische Berichte 1988-1, 2350, 1988.

Sehili, A., Lang, G., and Lippert, C.: High-resolution subgrid models: Background, grid generation, and implementation, Ocean Dynamics, 64, 519–535, https://doi.org/10.1007/s10236-014-0693-x, 2014.

Zijl, F., Verlaan, M., and Gerritsen, H.: Improved water-level forecasting for the Northwest European Shelf and North Sea through direct modelling of tide, surge and non-linear interaction, Ocean Dynamics, 63, 823–847, https://doi.org/10.1007/s10236-013-0624-2, 2013.

Reply to reviewer 2:

1. Methods and model description. The studies relies on two models. In the description of the models (sections 2.1 and 2.2), it seems that the simulations are done taking into account meteorological forcing, offshore salinity and river discharge. No information is provided on these conditions. In addition, if the regional model accounts for the salinity on its offshore boundary, we can guess that the river salinity is also accounted for.
Nothing is said, no value is given. Thus, the manuscript really required improvement on the description of the simulations (input conditions) and justification. Indeed, for the purpose of the study, why using 3D baroclinic simulations rather than 2DH simulations? Nothing is said.

Thank you for your careful reading. We added the missing information on the boundary and initial conditions in the model descriptions.
3D baroclinic simulations allow taking into account stratification and variations in density which have a major influence on salt intrusion and distribution. We decided to include salt in the model since it is an important parameter for modelling tidal dynamics especially in the estuaries and near the mouths of the estuaries.

2. Validation. First, the manuscript should provide the validation period over which they validate the tide. Second, even if they do not state it, the authors assume indirectly that the regional model (at high resolution) is better than the shelf model (at low resolution) to reproduce tide changes induced by sea-level rise. To support this assumption, a comparison of observed past tide change trends (using for instance literature results on tide gauges located in the study area) and results obtained simulating an additional and more moderate sea level rise scenario of e.g. 0.2 or 0.3 m, would be useful, with all the limits that such comparison has (additional mechanisms can contribute also modify the tide). But, as in Schindelegger et al. (2018), this would reinforce the paper.

We added the validation periods in section 2.3 Model validation..
One of the main statements of the paper is that the shelf model (DCSMv6FM) and the regional model (GBM) show different responses to MSLR and that these different responses can be attributed to the different resolution of bathymetric information included in the models. Thus at least one of the two models does not simulate the correct response to MSLR. However, both models are likely incorrect. Especially, due to several uncertainties (e.g. missing morphodynamic processes) both model simulations are not able to predict the future response of the tidal dynamics to MSLR. Nevertheless, you are right, we assume that the regional model (with high resolution) simulates the response to MSLR more correctly than the shelf model (with low resolution) under the given boundary conditions (morphostatic simulations, high dikes at their current position). The assumption, that the regional model is more reliable, is based on the fact that physical processes are represented more accurately in the regional model (see e.g. Figures on current speed). We clearified this aspect at the end of the discussion section.
A comparison of observed past tide change trends and model results with a moderate sea level rise scenario is difficult. In contrast to the model results observed past tide change trends include several factors that are not incorporated in the model simulations. Such factors are natural and anthropogenic morphodynamic changes as well as engineering measures (e.g. construction of embankments, construction of flood barriers). These factors, however, influence especially tide gauges closely located at the coast. Other challenges are vertical land motion and the natural variability caused by the meteorology in oberservational data. Also Schindelegger et al. (2018) found that the comparison of oberservational data and model results on the European Shelf is complicated by factors (e.g. dredging) not incorporated in the model simulations.
In general, the comparison of model results with observed past tide change trends is an important basis for reliable future projections. In the light of the uncertainties mentioned we do not attempt to make future projections in this study. However, the comparison of model results with observed past tide change trends in the German Bight is a challenging and important research question that should be pursued in further studies.

3. Sensitivity of the tide changes to the bathymetric resolution. The manuscript would strongly benefit from a real sensitivity study of the tide changes to the bathymetric resolution, by investigating different bathymetric resolutions with the regional model, and not only the one corresponding to the shelf model. This would allow identifying if there is a bathymetric resolution below which there is no further improvement. Such result would allow the authors to make recommendations for the German Bight, and would strongly increase the impact of the work.

Thank you very much for this comment. We completely agree that an advanced sensitivity study would support further understanding of this topic.
However, due to the unstructured computational grid that has different resolutions in different regions, the generation of computational grids with different resolutions is complex and not straightforward. Furthermore, the subgrid technology used in the regional German Bight model plays a crucial role. It allows to specify bathymetric details at a much higher resolution compared to the computational grid. With the subgrid option the accuracy of the simulation results can be improved when using the same classical computational grid. As shown in Sehili et al. (2014) different resolutions of the computational grid (within a certain range) do not influence the simulated results when using the subgrid option. Thus we suppose that a different resolution of the computational grid would not change the basic results. A sensitivity study investigating different grid resolutions and the role of bathymetric subgrid information, however, is an interesting research question for further studies.
We added this idea and some thoughts on subgrid in the discussion section. In the model description of the German Bight Model more information on subgrid is given.

"On-line" Remarks

P1-Line 27: "flat" -> in most of the paper, the authors use "flat". I think that "low lying" is more relevant

We have changed it in this context. Later on we aim for the profile which is better described with "flat" in the Wadden Sea.

P1-Line 27: add a reference to figure 1 and figure 2 (German Bight).

Changed in the manuscript

P1-Line 29: "estuaries." -> reference?

We added a reference in the manuscript.

P1-Line 29 -> P2, line 5: would better fit in the discussion section? Or remove it?

This text passage is part of the motivation why it is important to investigate how mean sea level rise influences tidal dynamics in the German Bight. We revised this part of the manuscript and hope that this intention is now clearer and that it now fits better to the rest of the introduction.

Figure 4: hard to see the green star and blue points ! make a zoom for _RMSE=0 to 0.5

Figure added in the manuscript

P15, line 5: make clear what is the mean current velocity. Is it the M2 - depth averaged current velocity? Is it the M2 depth averaged current velocity averaged over a given period (and is so, which period?)

It is the depth averaged mean current speed analysed over a spring-neap-cycle in July 2010. We added this information in the manuscript.

References

Casulli, V.: A high-resolution wetting and drying algorithm for free-surface hydrodynamics, Int. J. Numer. Meth. Fluids, 60, 391–408, https://doi.org/10.1002/fld.1896, 2008.

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Schindelegger, M., Green, J. A. M., Wilmes, S.-B., and Haigh, I. D.: Can We Model the Effect of Observed Sea Level Rise on Tides?, J. Geophys. Res. Oceans, 123, 4593–4609, https://doi.org/10.1029/2018JC013959, 2018.

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Reply to reviewer 3:

1. In the Introduction the sentence, “The German Bight located in the south-east of the North Sea with its flat coastal areas could be especially vulnerable” appeared a bit surprisingly. The authors started with a global perspective and I wondered why the German Bight was the area of choice. In addition, why is the German Bight especially vulnerable compared to other flat and low-lying coasts?

> *We changed this part of the introduction. We focus on the German Bight as one example for low-lying coastal areas. The low-lying coast of the German Bight is not more vulnerable than other coasts with the same conditions like the Dutch coast. This part of the introduction shall say that the flat German coast with the Wadden Sea is more vulnerable than a steep rocky coastline like the east coast of Great Britain.*

2. As the authors motivated their study by differences in the response of global models, can the conclusions from the German Bight be generalized?

> *Our motivation for this study is to show that depending on the model setup and especially the resolution of the bathymetry different responses to the same mean sea level rise can be estimated. This is especially effective in shallow coastal waters where the small-scale topographic structure has a great influence. Thus we would say that the conclusions could be transferred to other regions which show a comparable tidal regime and similar topographical characteristics like e.g. flat intertidal areas but could not be generalised without restrictions.*

3. Model set-up and experiments need some more explanation, in particular

a. Why did the authors choose to include meteorological forcing and not just used a tide-only simulation, in particular as they said they choose the summer to “ensure that the results are not influenced by storm surges or extraordinary high river discharge” (page 7).

Tide-only simulations would have been also a good option. In the first place we decided to include meteorological forcing to be more realistic. Since we choose a summer period for our analyses, in which wind speeds are small, the meteorological forcing does not influence the results. Thus it is not critical whether we include meteorological forcing. We added a short explanation in the manuscript.

b. The salinity boundary condition (page 5) needs some explanation as I expect that readers are not necessarily aware of what was done in the referenced project.

We added additional information about the salinity boundary condition in the manuscript.
The aim of the project AufMod was to develop a model-based tool to analyse long-term sediment transport and morphological processes. During this project a numerical model of the North Sea was set up. The used salinity boundary condition is a result of a reference simulation carried out during AufMod.

c. A source for the river discharge data and their time resolution should be provided.

The data for the river discharge is provided by the Water and Shipping Authorities and the "Gewässerkundliches Jahrbuch" which are published by the Hamburg Port Authority for the Elbe and the NLWKN for Ems and Weser. The time resolution of the data is one day. We added this information in the manuscript.

4. Figure 6 and following: The gray color bar should be explained in the caption. I was not able to clearly identify gray areas in the Figures.

We removed the grey colour bar in the figures where it isn't necessary. The grey colour which indicates dry areas is now explained in the caption.

5. Page 19, line 29: What exactly is "sufficiently fine"? There are probably substantial changes in bathymetry over time as well. What would the authors then consider a "sufficiently fine" resolution?

You are right; the formulation "sufficiently fine" is not a very clear choice. The answer to the question what we would consider as a "sufficiently fine" resolution cannot be given easily. It depends on the concrete research question. In particular, for questions related to locations close to the coast the model bathymetry should incorporate the main characteristics of the Wadden Sea. To give a proper answer further research is needed. One way to explore which resolution is needed could be a sensitivity study, in which the resolution is systematically varied as suggested by reviewer #2. We added this aspect in the discussion at the corresponding text position.

Reply to editor:

p1, line 8 (and other places) - is the German Bight really in the SE of the North Sea rather than the east.

In our comprehension the German Bight is located rather in the south-east of the North Sea than in the east. That is certainly a matter of opinion. Also other authors describe the location of the German Bight in the south-east (e.g. Wahl et al., 2011; Albrecht and Weisse, 2012).

figures 1 and 2. These have several errors. Fig 1 has degrees longitude and latitude swapped. But anyway they should read North Latitude (deg) and East Longitude (deg). In figure 1 deep water bathymetry, shown by dark blue, is a negative number whereas in Figure 2 it is a positive number. In Figure 2 it is hard to read the black names.

We corrected the figures and updated them in the manuscript.

Explain somewhere that NHN is the German datum which is a good approximation of MSL.

An explanation is now given on page 6.

Table 1. replace commas in the numbers with dots which is more normal internationally.

Changed in the manuscript.

Figure 3. define MEZ in terms of UT
It is not necessary to have 00:00 in the times.

Changed in the manuscript.

Figure 3. Why is there a slightly different set of 7 stations used for the 2 models (because of the grids presumably). explain better. It is not easy to spot the grouping of blue A,B etc. when printed - I had to blow up the pdf to see that. Anyway Target-Diagram would be better as 'Target Diagram' and things would be clearer if the maximum radius was 0.6.

The seven stations that we show in the diagram are the same spots in each model. The only difference is the order of the stations in the legend. I am afraid we could not change the order because it is hardcoded in the analysis and the plotting program.
We zoomed in so hopefully the locations can be better seen now.

p8, 5 and elsewhere - oscillation volume sounds odd to me although I am struggling to think of something else. perhaps have this sentence read: Therefore, the only difference between models concerns the volume of water exchanged through the tidal cycle, which we call the oscillation volume.

We agree with you that "oscillation volume" (page 8, line 5) may lead to misunderstandings.
The removed estuaries shorten the length of the estuary and inhibit the tidal wave from propagating further. The wave is reflected much earlier and therefore the oscillation behaviour changes in the corresponding areas.
In this context we don't mean the tidal prism thus the water volume that is exchanged through every tidal cycle. We mean the varied volume of the tidal basin itself. To make this clear we changed the manuscript.

Figure 5. why does this have a different colour scale to Figure 2? It covers almost the same area.

In figure 2 and also in figure 1 we show the whole model domain and the used colours should give information about the present depths. In figure 5 we use a different colour scale which looks more realistically. This colour scale gives the viewer a better idea of the tidal flats, the channels and the complex structure of the Wadden Sea (right hand side). The simplifications resulting from the coarser topography (left hand side) can then be better estimated.

section 2.5 header. Please do not be so cryptic. Perhaps Analysis of Model Simulations. section 3 Model results

Changed in the manuscript.

p10, 26 - this is not surprising as the volume of water in the estuaries is small.

We agree, but we were not sure before we conducted this study.

Figure 6 and others. What is the second b/w scale for? Is that because of the wet/dry areas or what? Anyway it is not explained in the captions. It seems to me it could be just left off.

We removed the grey colour bar in the figures where it isn't necessary. The grey colour which indicates dry areas is now explained in the caption.

The paper does not discuss changes in phase lags, only amplitudes. Nothing to say about them?

In our paper we focus on the amplitude of M2. For completeness, we added in the results section and in the supplement some information on the changes in the phase of M2.
Based on figure 6, figure S2 shows the phase of M2 in both models in the reference case and the respective changes by a rise of mean sea level of 0.8 m and 10 m. In both models the celerity of the tidal wave increases due to mean sea level rise. In the simulations with mean sea level of 10 m this increase is stronger than in the simulations with mean sea level of 0.8 m. This seems plausible since water depth increases.

p15 current velocity should be current speed (velocity is a vector)

We agree with you that current speed is the correct term. We changed the manuscript at the according positions.

Figure 11 and 12 (a) remove the white arrow. You can't have a negative speed.

Changed in the manuscript.

Somewhere I noted R2 pointing to the recent Schindelegger et al. (2018) paper regarding model validation, and I was reminded of the Harker et al. (2019) paper in Ocean Science concerning the important aspect of whether model tides are allowed to change on an open boundary when MSL changes, and that should be made clear in the present paper.

Thank you for this hint.
Contrary to the considerations from Harker et al. (2019) we assume that the tides will not change at the open boundary of the DCSMv6FM due to mean sea level rise since we are performing a case study. But nevertheless changes in tides on the European shelf due to shallow water effects are taken into account in the study since the boundary values of the German Bight Model are derived from the DCSMv6FM.
We added this additional information in the manuscript to make this more explicit.

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

Caroline Rasquin[1], Rita Seiffert[1], Benno Wachler[1], Norbert Winkel[1]

[1]Federal Waterways Engineering and Research Institute, Wedeler Landstraße 157, 22559 Hamburg

Correspondence to: Caroline Rasquin (caroline.rasquin@baw.de)

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 low-lying ~~flat~~ coastal areas, ~~especially~~ the German Bight (located in the south-east of the North Sea) will be especially 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 t~~The shelf model and the German Bight Model react in different ways. In the simulations with a mean sea level rise of 0.8 m ~~shelf model~~ the M2 amplitude in the shelf model 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 the simulations with a mean sea level rise of 10 m the M2 amplitude increases in both models, the patterns, however, differ, too. 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

During the 20th century and the beginning of the 21th century an increase and acceleration in global mean sea level rise (MSLR) has been observed. The global mean sea level rose between 1901 and 1990 by 0.14 mm/year. Between 1993 and 2015 this value more than doubled with a rate of 3.2 mm/year. Future predictions show a MSLR of 0.55-1.40 m in 2100 (17.-83. % percentile) in the scenario RCP8.5. This increase could exceed to several meters during the 22th century (IPCC

2019, 2019). ~~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.

Our study focusses on the German Bight which is~~The German Bight~~ located in the south-east of the North Sea (see Figure 1 and Figure 2). This part of the North Sea is characterised by ~~with its~~ low-lying~~flat~~ coastal areas, which are in contrast to steep coastlines ~~could be~~ especially vulnerable in a changed climate. ~~Mean sea level rise~~ MSLR will not only influence mean water levels in itself, and so be important with regard to coastal protection or storm surges ~~(i.e. coastal protection)~~, ~~it~~ but also ~~changes~~ tidal dynamics (e.g. the magnitude of different tidal constituents and current velocities) in the North Sea (Ward et al., 2012; Pickering et al., 2012; Wachler et al., submitted) and its adjacent estuaries (Seiffert and Hesser, 2014; Plüß, 2004). Changes in the tidal dynamics have a number of consequences for the Wadden Sea and the estuaries. Altered sediment transport due to a changed ratio of flood to ebb current velocity lead to sea level rise-induced morphological changes in the Wadden Sea (Dissanayake et al., 2012; Becherer et al., 2018). Due to MSLR the turbidity zone in the estuaries, which depends on the discharge as well as on the tidal conditions, will shift upstream (Kappenberg and Fanger, 2007; Seiffert et al., 2014). Furthermore, salt intrusion into the estuaries will be affected (Seiffert and Hesser, 2014). Thus, future challenges related to MSLR~~mean sea level rise~~ include not only coastal protection issues, but also other aspects such as sediment management in ~~the~~ estuaries functioning as access waterways to ports. Some of the largest ports in Europe like Rotterdam, Hamburg and Antwerp are located ~~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 MSLR ~~mean sea level rise~~ changes tidal dynamics.

Several previous studies have investigated the impact of MSLR ~~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~~ came to contradictory results. Ward et al. (2012) analysed a ~~mean sea level rise~~ ~~(~~MSLR~~)~~ of 2 m with the shelf model KUTM and obtained a decrease of M2 amplitude in the German Bight whereas Pickering et al. (2012) ~~find~~ found 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 counteracts ~~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 along the Dutch and German coast ~~and the East Frisian Wadden Sea~~. In the model with a fixed boundary, more energy remains in the M2 tide with MSLR due to the lack of additional dissipative area, leading to an increase of M2 amplitude with mean sea level rise. A~~nother~~ study by Pelling and Green (2014)with similar model setups using smaller levels of MSLR (up to 1 m) ~~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 defences are needed to estimate changes~~d~~ in tidal dynamics due to MSLR. Not only the adequate representation of flood defence but also the correct representation of topographical details in ~~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 such as DCSM or KUTM 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~~ such as missing ~~oscillation~~ volume in the tidal basins of the estuaries or inadequately resolved topographical structures might yield~~lead~~ to misleading results. The aim of our study is to investigate whether the response of tidal dynamics in the German Bight ~~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 with regard to bathymetric features and the coastline (~~and different~~ model domain~~s~~).

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 (Zijl, 2014) is a 2D-hydrodynamical model based on the shallow water equation. It is a further development of the structured Dutch Continental Shelf Model DCSMv6 (Zijl et al., 2013; Zijl et al., 2015) using the new flexible mesh capacities ~~technology~~ D-Flow FM (Kernkamp et al., 2011) ~~(Donchyts et al., 2014)~~. The flexible mesh technique is another designation for the classical unstructured grid concept and thus, in contrast to the German Bight Model, does not include subgrid information.

The model domain covers the northwest European shelf (Figure 1). In the North Sea the resolution of the model grid is 1.5´ in the east-west direction. The resolution in the 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, 2002)~~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. For further information on the calibration of the DCSMv6 we refer to Zijl et al. (2013).

The model includes tide generating forces. At the seaward open boundary t~~T~~he model is forced by ~~astronomical~~ tidal~~es~~ constituents ~~(22 constituents)~~. The amplitudes and phases of the main diurnal und semi-diurnal constituents (22) are derived by interpolation from the dataset generated by the GOT00.2 global ocean tide model (Ray, 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. A~~s a~~tmospheric forcing (wind at 10 m and atmospheric surface pressure) is included by use of ~~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.

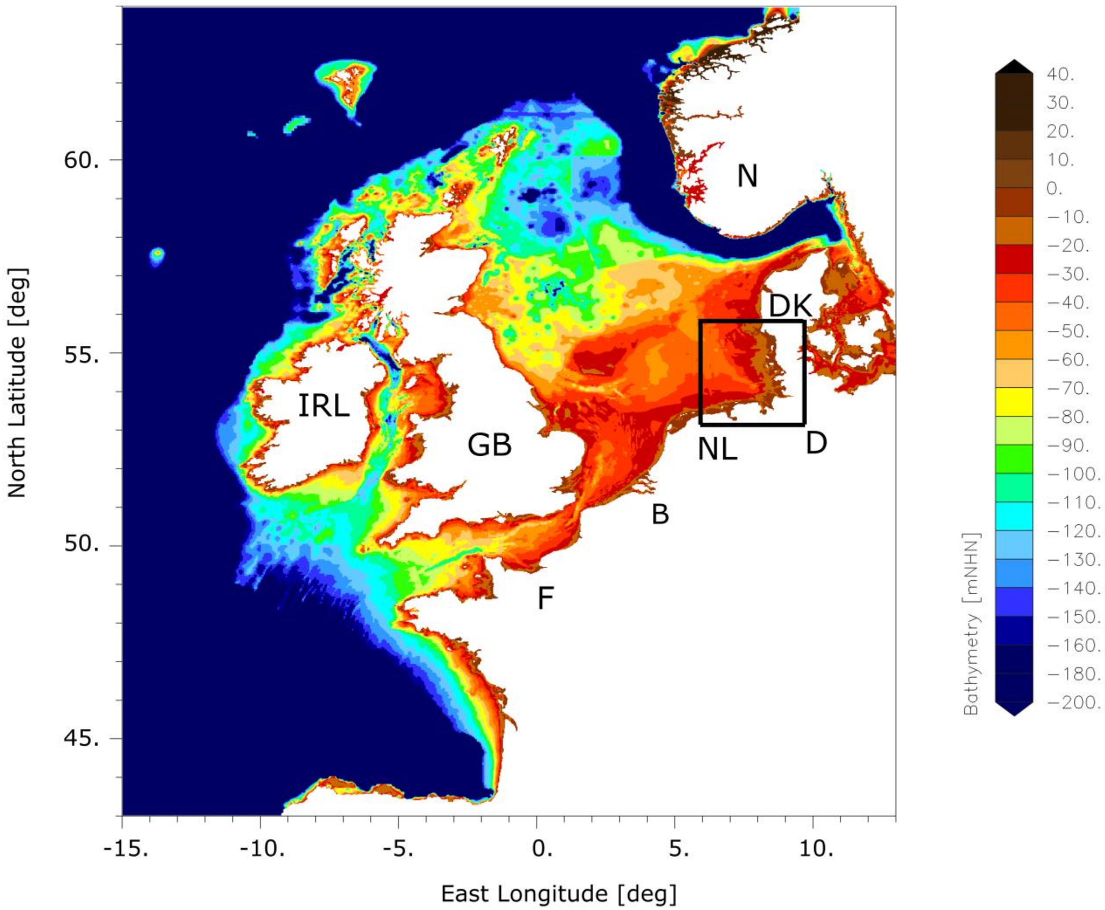

Figure 1: Model domain of the DCSMv6FM. The black box marks the German Bight.

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 as it is computationally intensive and not of primary relevance to tidal dynamics. To account for baroclinic processes the simulations are carried out in 3D. An~~One~~ advantage of the UnTRIM²-method compared to its predecessor UnTRIM is the subgrid option. This option allows to describe the bathymetry at a higher resolution compared to the computational grid (Sehili et al., 2014). The algorithm, which was derived by Casulli (2008) and Casulli and Stelling (2011), represents correctly the precise mass balance in regions where wetting and drying occurs. The computational grids are permitted to be wet, partially wet or dry. This implies that no drying threshold is needed (Sehili et al., 2014). ~~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 a resolution ~~n 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 well in the model (Sehili et al., 2014).

At the open seaward boundary ~~to the North Sea~~ water level is derived from DCSMv6FM. In this way shallow water effects generated on ~~caused by~~ the shelf are included ~~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). The aim of the project AufMod was to develop a model-based tool to analyse long-term sediment transport and morphological processes. During this project a numerical model of the North Sea was developed. The used salinity boundary condition is a result of a reference simulation carried out in this project.

At the upstream boundaries of the estuaries measured river discharge and a constant salinity is applied. The river discharge is provided by the Water and Shipping Authorities, the Hamburg Port Authority and the NLWKN (Hamburg Port Authority; Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz, 2013) with a temporal resolution of 1 day. The initial data for salinity for the estuaries are provided by the preceding project KLIWAS ~~–~~(Seiffert et al., 2014). They reach from 0.4 PSU near the upstream boundaries to 33 PSU in the mouths of the estuaries. In the outer German Bight a value of 33 PSU is assumed. For the initial conditions of the water level a constant value of 0 mNHN[1] is set. A sufficient long initialisation time ensures that the model reaches a dynamical equilibrium before the simulations start. A~~s a~~tmospheric forcing (wind at 10 m and atmospheric surface pressure) is included by use of the same reanalysis data as for the shelf model DCSM6vFM (COSMO-REA6 from ~~(~~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).

[1] The unit mNHN denotes metres above the German datum which is a good approximation of mean sea level.

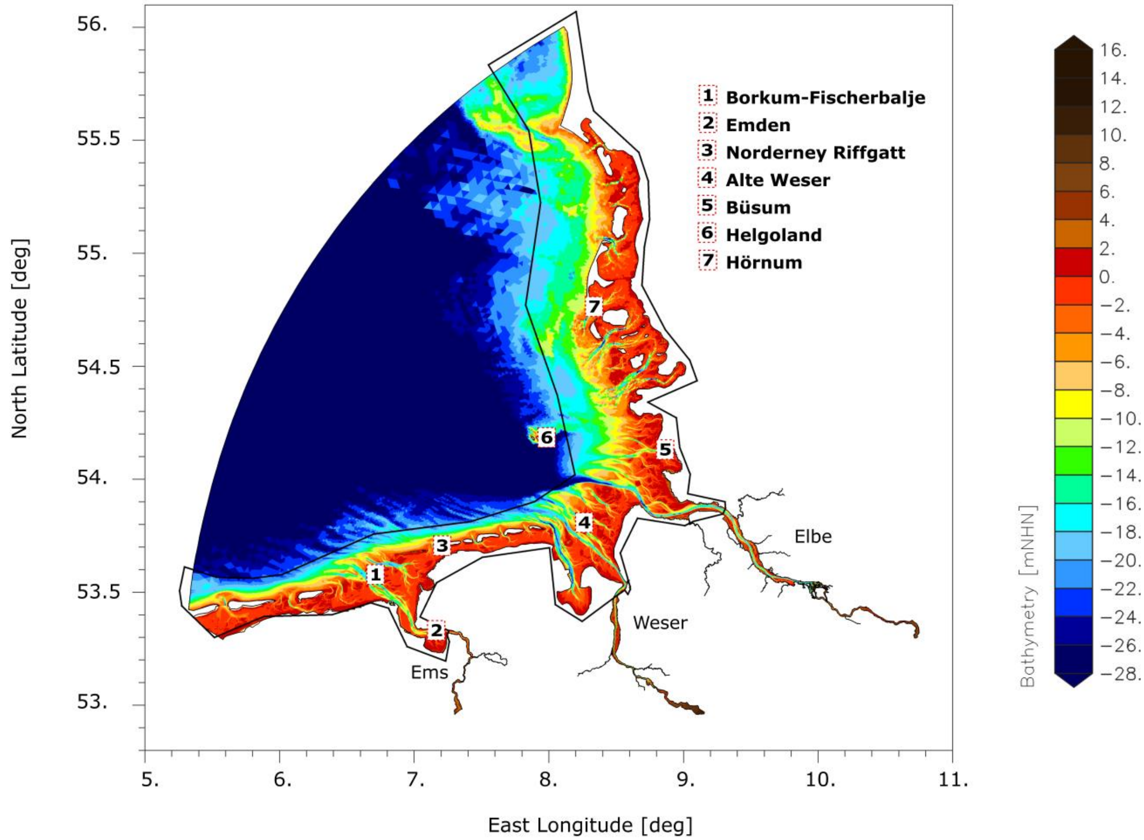

Figure 2: Model domain of the German Bight Model. The ~~A~~area within black polygon is used for spatial averag~~es~~ing as described in section 3.4.

2.3 Model validation

In the bias (mean deviation between measurement and model) and the root mean square error of the two models compared to measurements for tidal high water, tidal low water, ~~and~~ tidal mean water and the M2 amplitude are listed ~~at~~ for different stations ~~along~~ in the German Bight. The stations are marked in Figure 2. The validation period for tidal high water, tidal low water and tidal mean water is a spring-neap-cycle in July 2010 (06.07.2010 – 21.07.2010). For the validation of the M2 amplitude three months are used (03.06.2010 – 01.09.2010). A period of three months comprises the cycle of most relevant tidal constituents in the North Sea. The comparison shows that both models are able to represent basic characteristics of the tidal dynamics. In general, tidal high water is simulated ~~in~~ to higher accuracy than tidal low water. The comparable shape of the water level curves between the two models, and measurements can be seen by the exa~~e~~mple~~arily~~ in Figure 3 for~~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 stations~~spots~~ are located ~~along~~ in 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 model's accuracy. The modelled water levels at the displayed stations are for both models almost all within the inner circle within a range of -0.25 to 0.25 which resembles a RMSE* (Root-Mean-Square-Error normalized with the standard deviation) of 0.25. The only point with a larger RMSE*is the station Emden simulated by DCSMv6FM. Since Emden is located in the inner estuary of the Ems (Figure 2), the water levels are difficult to compute with the shelf model that has a relatively coarse resolution.

~~**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~~

Table 1: Bias and root mean square error for four tidal parameters (tidal high water, tidal low water, tidal mean water and M2 amplitude) at different stations in the German Bight for the German Bight Model and the DCSMv6FM (stations marked in Figure 2).

		Thw		**Tlw**		**Tmw**		**M2**
		Bias	**RMSE**	**Bias**	**RMSE**	**Bias**	**RMSE**	**Bias**
Borkum Fischerbalje	**GBM**	-0.02	0.05	0.23	0.24	0.06	0.07	-0.07
	DCSMv6FM	-0.02	0.06	0.18	0.19	0.05	0.07	-0.07
Norderney Riffgat	**GBM**	-0.04	0.06	0.32	0.32	0.10	0.11	-0.09
	DCSMv6FM	-0.05	0.07	0.23	0.23	0.09	0.09	-0.04
Alte Weser	**GBM**	-0.10	0.12	0.28	0.28	0.08	0.09	-0.09
	DCSMv6FM	-0.07	0.09	0.22	0.23	0.06	0.08	-0.04
Helgoland	**GBM**	-0.13	0.14	0.31	0.31	0.07	0.08	-0.12
	DCSMv6FM	-0.22	0.11	0.25	0.22	0.06	0.08	-0.07
Hörnum	**GBM**	-0.12	0.12	0.20	0.20	0.06	0.07	-0.11
	DCSMv6FM	0.10	0.05	0.00	0.07	-0.01	0.04	0.01

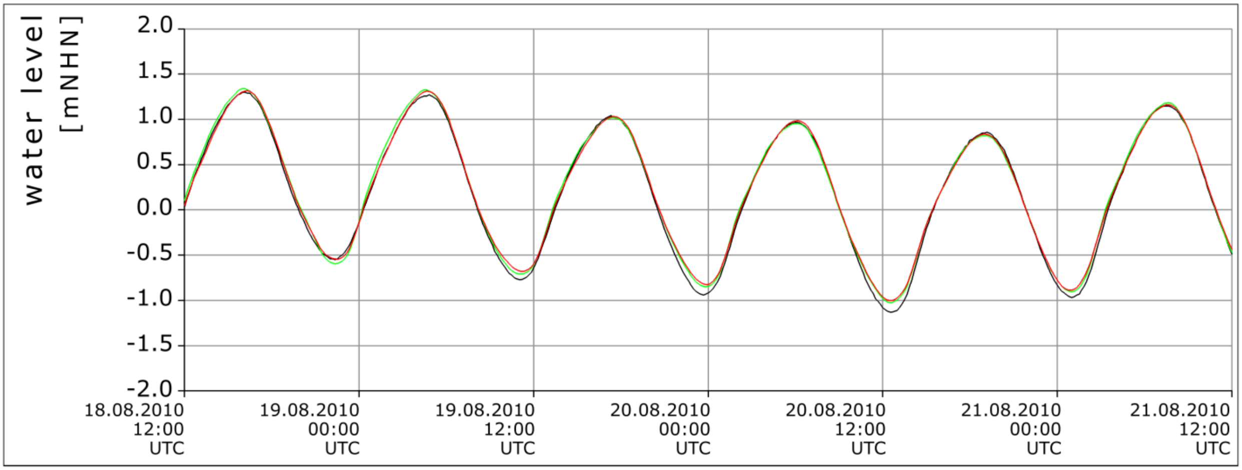

Figure 3: Water level relative to mNHN (metres above the German datum) at the station "Borkum Fischerbalje" (see Figure 2): Black: Measured data, red: Simulated data with the German Bight Model, green: Simulated data with the DCSMv6FM.

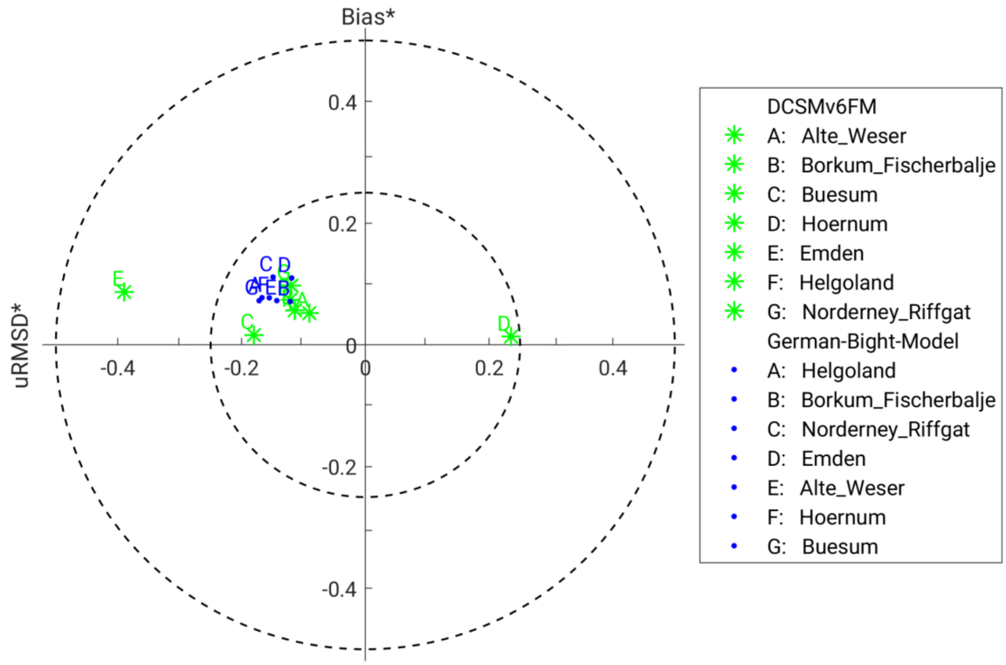

Figure 4: “Target ~~-~~Diagram” for the comparison of the German Bight Model and the DCSMv6FM with measured water levels at seven stations ~~locations~~ along the German Bight (stations marked in Figure 2). Note, although the order of the stations in the legend is different, for both models the same stations are shown.

2.4 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 period~~s~~ ensures that the results are not influenced by storm surges or extraordinary high river discharge. Note, since wind speeds are generally small in the summer period tide-only simulations would give similar results. 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 assessment report (Stocker et al., 2013). To gain a better understanding of the system's 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. We assume that the tides will not change at the open boundary of the DCSMv6FM due to MSLR. This is a reasonable assumption since the study is designed as a conceptual study investigating the interaction between sea level rise and the representation of the bathymetry in the coastal zone. It does not primarily characterise the future development of the tides, which may be altered by rising sea levels (e.g. Harker et al., 2019). The German Bight Model is forced by water level times series extracted from DCSMv6FM that already include the effects of MSLR on the shelf. Sufficient long initialisation times in both models ensure that the model reaches a dynamical equilibrium.

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~~NE and GBM_80_~~CS1~~NE) and the corresponding reference run (GBM_ref_noQ) no river discharge is included (Table 2). Thus the only difference is the varied length of the estuaries that means the volumes of the tidal basins are changed. ~~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).

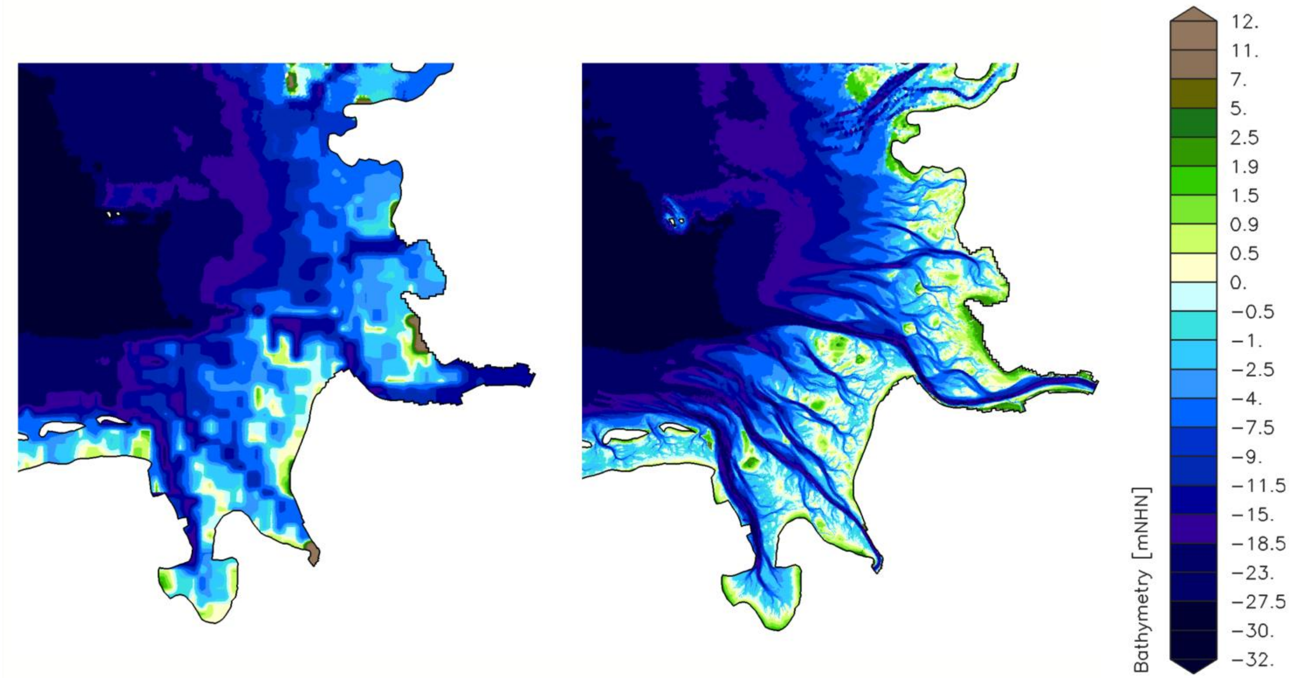

Figure 5: Bathymetry in the German Bight, left: coarse model bathymetry on the high resolution grid, right: the original highly resolved bathymetry of the GBM.

Table 2~~2~~: Overview of model simulations ~~carried out~~undertaken.

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~~NE	German Bight Model, no estuaries	-
GBM_80_~~CS1~~NE	German Bight Model, no estuaries	0.8 m
GBM_ref_~~CS2~~NE_CB	German Bight Model, no estuaries, coarse bathymetry	-
GBM_80_~~CS2~~NE_CB	German Bight Model, no estuaries, coarse bathymetry	0.8 m

2.5 Analysis of model simulations

The analyses of the numerical model simulations shown in this paper concentrate on the M2 amplitude, mean current velocities and variations in~~,~~ 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 of tides (Pansch, 1988), which is based on a Fourier decomposition of the water level time series into harmonic functions of prescribed tidal constituents. The harmonic analysis of tides is applied over the simulation period (3 June – 1 September). The results ~~of~~ from 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~~,~~ and 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).

3 Model ~~R~~results

3.1 M2 amplitude

Figure 6 shows ~~for both numerical models~~ the M2 amplitude and its changes in response to MSLR ~~mean sea level rise~~ in the region of the German Bight for both numerical models. ~~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 MSLR~~mean sea level rise~~ scenarios. The German Bight Model shows a different response for the MSLR of 0.8 m. ~~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 within~~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). For the scenario with a MSLR of 10 m the German Bight Model shows like the shelf model an increase of the M2 amplitude in the entire German Bight. A closer comparison of the responses of both models to the MSLR of 10 m reveals that the differences (compare Figure 6f and Figure 6e, see supplement Figure S1b) in the region offshore of the North Frisian Wadden Sea are smaller, but in a comparable order of magnitude as in the case of MSLR 0.8 m (compare Figure 6d and

Figure 6c, see supplement Figure S1a). For completeness, changes in the phase of M2 indicate that the tidal wave propagates faster in the simulations with MSLR due to the increased water depths (see supplement Figure S2).

To explore the reasons for the observed differences between the shelf model and the German Bight Model two case studies are conducted and investigated for a MSLR of 0.8 m. ~~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 volume of the tidal basins Elbe, Weser and Ems is different in 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~~ positions where the DCSMv6FM ends in the estuaries. Figure 7a 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 7b. 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 of the tidal basins 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.

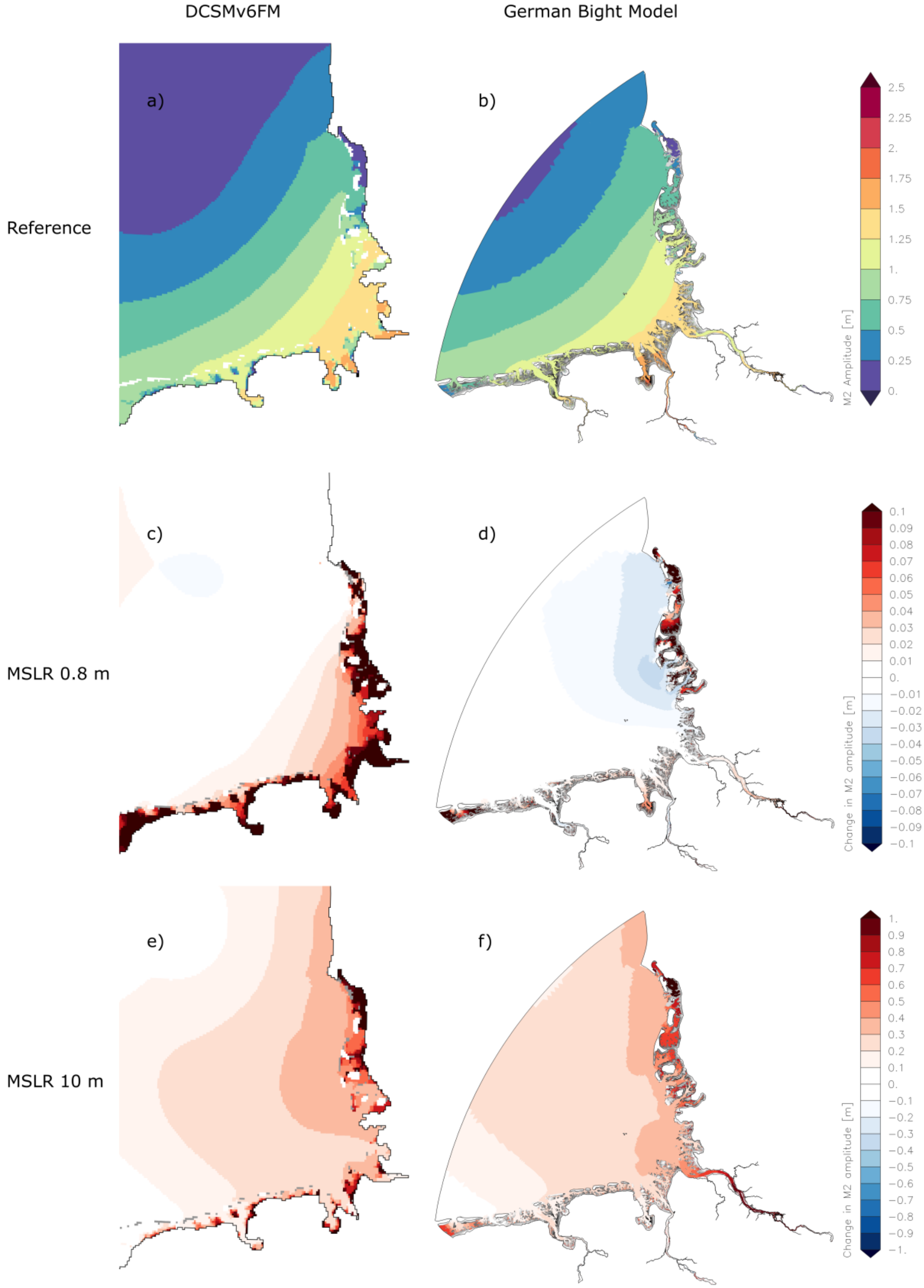

Figure 6: M2 amplitude and response of M2 amplitude to MSLR (increase in red, decrease in blue, dry areas in grey), left: DCSMv6FM (a, c, e), right: German Bight Model (b, d, f); first row: Reference; second row: MSLR of 0.8 m; third row; MSLR of

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.

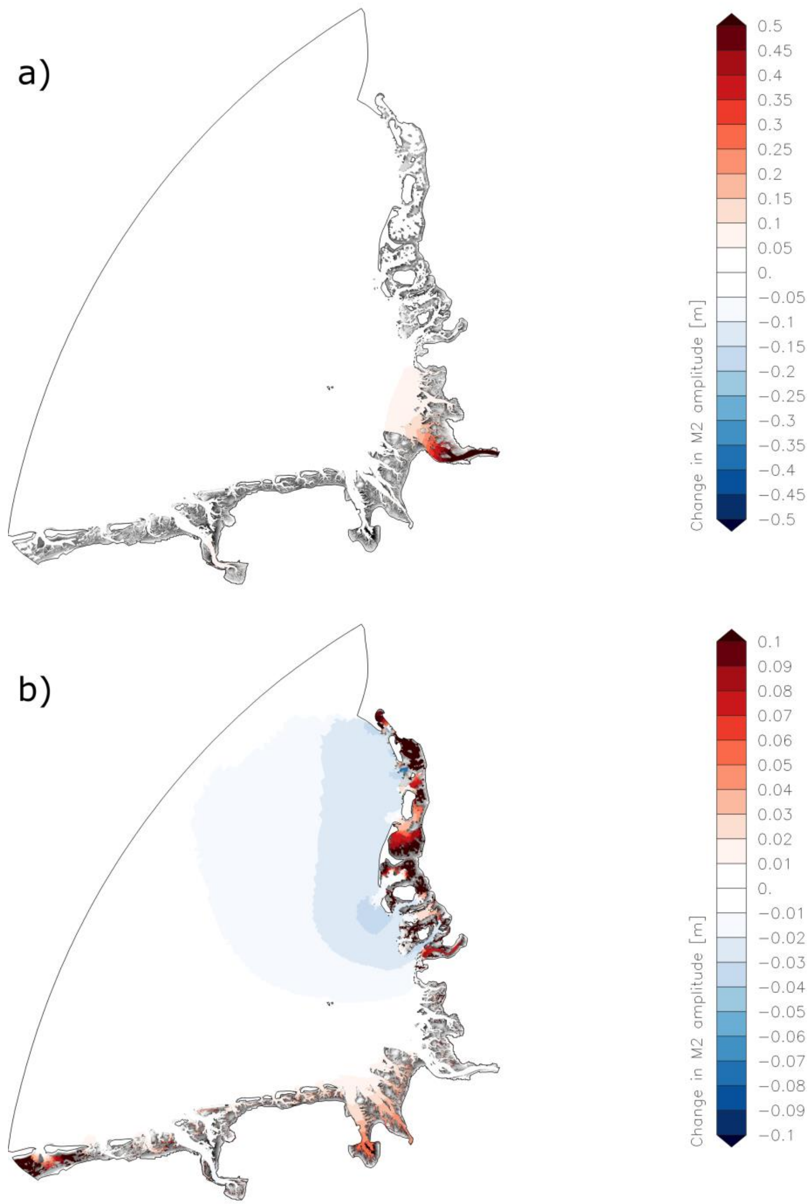

Figure 7: a) Changes in M2 amplitude due to the removed estuaries (increase in red, decrease in blue, dry areas in grey) (GBM_ref_~~CS1~~NE – GBM_ref_noQ). b) Changes in M2 amplitude due to MSLR 0.8 m in the German Bight Model without the estuaries (increase in red, decrease in blue) (GBM_80_~~CS1~~NE - GBM_ref_~~CS1~~NE).

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 8a 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~~Figure 8b. The increase of M2 amplitude in the German Bight in this case study is now comparable to the shelf model response. ~~Similar to the shelf model the M2 amplitude increases in this case study in the German Bight.~~ Therefore, most of the changes in the shelf model induced by the MSLR of 0.8 m (Figure 6c) must be due to the coarse bathymetry.

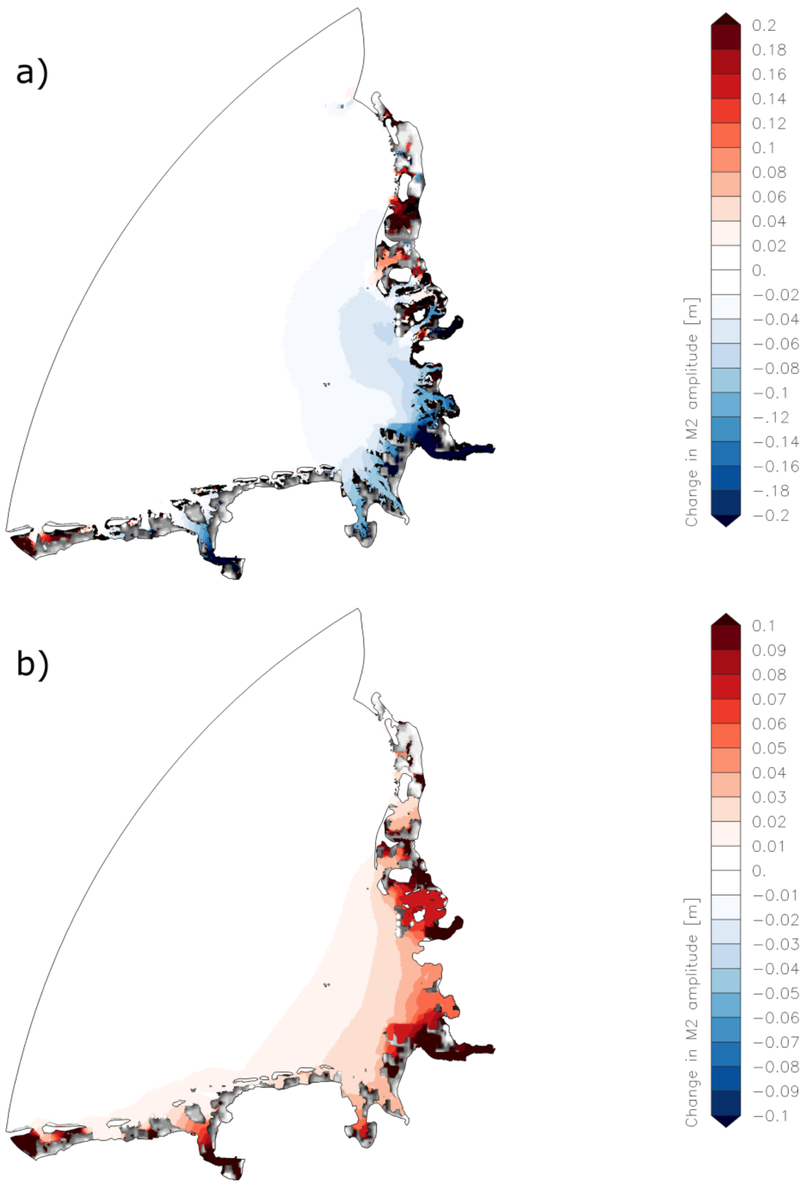

Figure 8: a) Changes in M2 amplitude due to the coarser bathymetry (increase in red, decrease in blue, dry areas in grey) (GBM_ref_NE_CB – GBM_ref_NE). b) Changes in M2 amplitude due to MSLR 0.8 m in the German Bight Model with coarse bathymetry (increase in red, decrease in blue) (GBM_80_NE_CB – GBM_ref_NE_CB).

3.4 Wet areas, dissipation rate and current velocities

To further investigate the reasons for the similarity of the ~~similar~~ response to 0.8 m MSLR 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 the main differences to be 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~~out as far as 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 resolution~~s~~ of bathymetry is considered.

The numbers in Table 3 show that wet areas ~~enlarge~~ increase due to MSLR~~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~~between the 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).

Table 3~~3~~: Mean flooded area at tidal high water (wet area) in the shallow part of the German Bight ~~up~~ out to ~~the~~ 20 m depth ~~line~~ and dissipation rate averaged over that region (see Figure 2).

	wet area [10^9 m^2]	dissipation rate [10^{-3} W/m^2]
GBM_ref_~~CS1~~NE	15.90	2.9
GBM_80_~~CS1~~NE - GBM_ref_~~CS1~~NE	0.22	0.6
GBM_ref_~~CS2~~NE_CB	15.91	3.0
GBM_80_~~CS2~~NE_CB - GBM_ref_~~CS2~~NE_CB	0.24	0.2

Figure 9a) and c) show~~s~~ the mean current ~~velocity~~speed (depth averaged and analysed over a spring-neap-cycle in July 2010) in the reference case ~~(a)~~ and the change of mean current ~~velocity~~speed due to MSLR of 0.8 m in case study 1 (fine bathymetry with removed estuaries) ~~(b)~~. Figure 9 shows the same for case study 2 (coarse bathymetry with removed estuaries). In the fine bathymetry~~case study 1~~ the mean current ~~velocity~~speed increases due to mean sea level rise in coastal areas, especially in the tidal channels, almost everywhere in the German Bight. In the coarse bathymetry~~case study 2~~ the change of mean current ~~velocity~~speed has a different pattern. In general the course of the channels is less distinctively represented and increases in mean current ~~velocity~~speed are not as pronounced as in the fine bathymetry~~case study 1~~. These results ~~coincide~~ are consistent with the smaller increase of dissipation rate in the coarse bathymetry~~case study 2~~ compared to the case of the fine bathymetry~~study 1~~, since dissipation rate strongly depends on ~~velocity~~speed.

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~~ out 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 higher by a factor of approximatively~~.~~ 1.8 ~~higher~~.

Furthermore Table 4 includes also wet areas and dissipation rates of the simulation with 10 m MSLR. The ~~gain~~ increase of wet area from 0.8 m MSLR to 10 m MSLR is less than the ~~gain~~ increase 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~~ out 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 10). This ~~coincides~~ is consistent with the smaller values of dissipation rate.

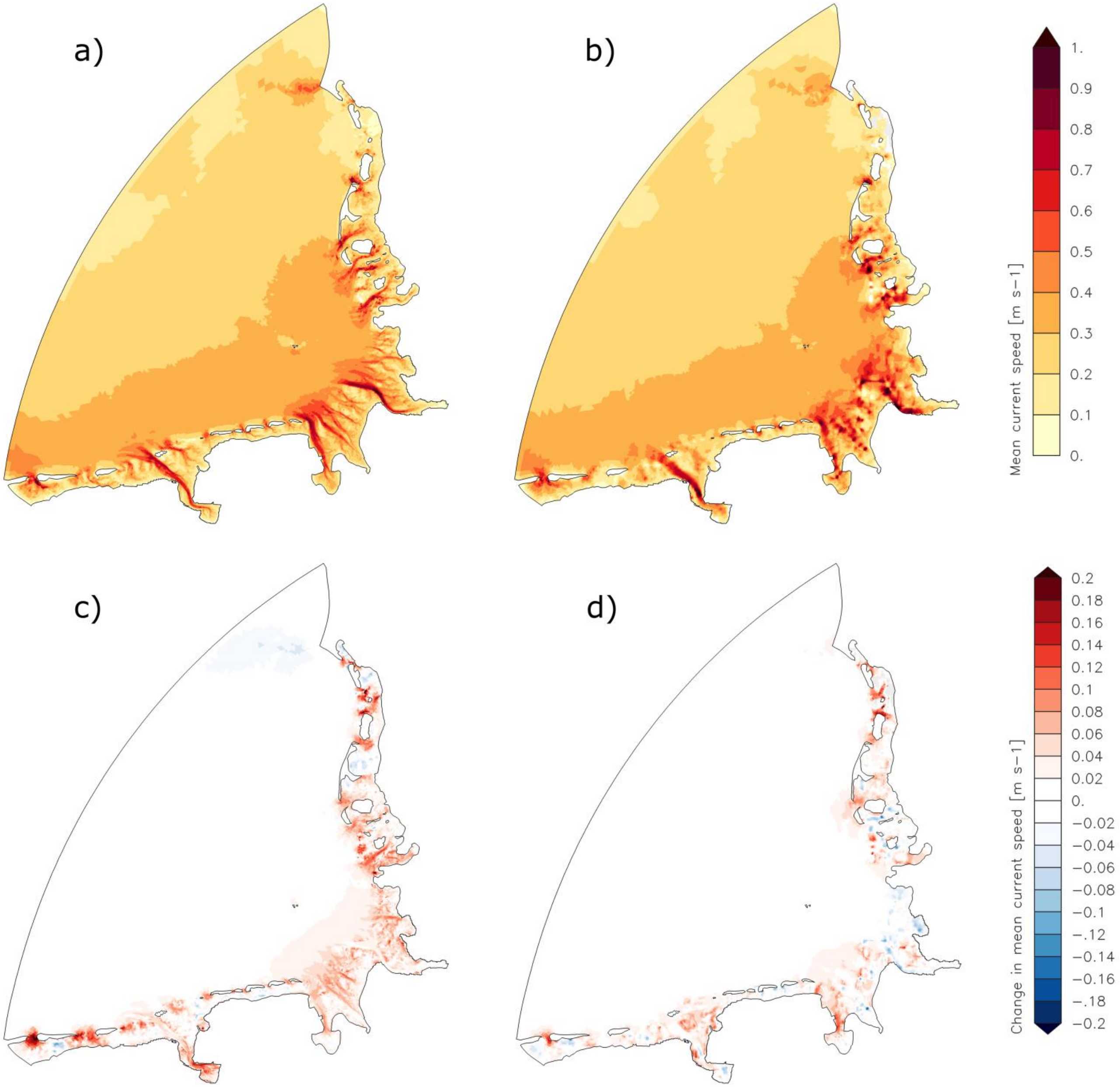

Figure 9: a) Total mean current speed (depth averaged and analysed over a spring-neap-cycle in July 2010) without MSLR in the high resolution bathymetry (GBM_ref_NE) and b) in the coarser bathymetry (GBM_ref_NE_CB); c) Change in total mean current speed in the high resolution bathymetry (GBM_80_NE - GBM_ref_NE) and d) in the coarser bathymetry due to MSLR of 0.8 m (GBM_80_NE_CB - GBM_ref_NE_CB).

Table 44: Mean flooded area at tidal high water (wet area) in the shallow part of the German Bight ~~up~~ out to ~~the~~ 20 m depth ~~line~~, dissipation rate ϵ_S averaged in the shallow part of the German Bight ~~up~~ out 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_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

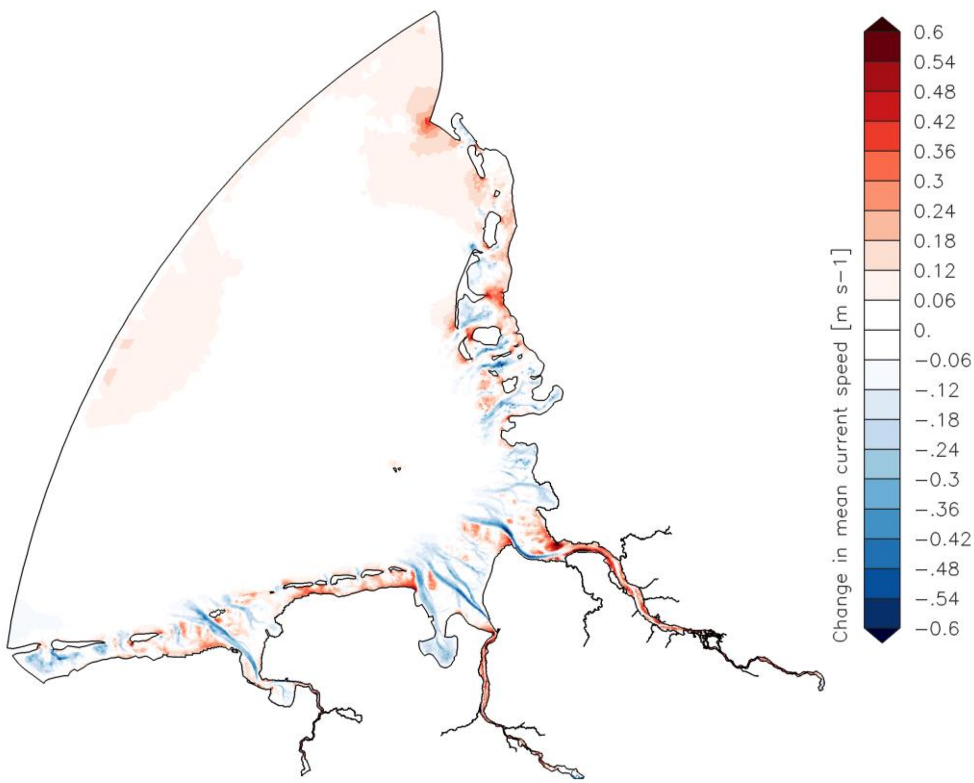

Figure 10: Change in total mean current ~~velocity~~speed (depth averaged and analysed over a spring-neap-cycle in July 2010) due to MSLR of 10 m (increase in red, decrease in blue) (GBM_1000-GBM_ref).

4 Discussion

In this study we compare the response of two different kinds of models to mean sea level rises ~~(MSLR)~~of 0.8 m and 10 m in the German Bight. The coarser shelf model DCSMv6FM and the finer German Bight Model respond in different ways to mean sea level rise~~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 responses~~ to 0.8 m MSLR~~ we adjust the German Bight Model in two steps in order to more closely resemble the shelf model and repeat the simulations with MSLR of 0.8 m. In the first step the estuaries are excluded from the model domain. While the reduced volume of the tidal basins due to the shortened estuaries ~~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) explained the different response to MSLR of two shelf models by means of 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~~significantly. 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~~ out 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~~speeds. In the coarse bathymetry model this increase in current ~~velocities~~ speeds cannot be seen in the same characteristic. The coarse bathymetry contains many artificial shoals and barriers. In this case, ~~M~~many channels in the Wadden Sea do not allow a continuous flow of water. This leads to the differences in mean current ~~velocity~~speed 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 within 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.~~ One question that needs further research is how fine the bathymetric resolution should be to estimate the response of tidal dynamic to MSLR correctly. A sensitivity study varying the resolution of the computational grid systematically could provide further insight into this open question. The subgrid technology used in the regional German Bight Model, however, already allows to specify bathymetric details at a very high resolution. As shown in Sehili et al. (2014) different resolutions of the computational grid (within a certain range) do not influence the simulated results when using subgrid. Their conclusion is that a relatively coarse resolved computational grid yields similar results to a finer resolved computational grid when using the same very fine resolved subgrid information. Thus we suppose that a different resolution of the computational grid would not change the basic results. To confirm this supposition further studies on the role of bathymetric subgrid information in combination with MSLR are needed.

The increase in mean current ~~velocities~~ speed 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., submitted). The MSLR~~mean sea level rise~~ induced change in ratio of flood volume to ~~and the~~tidal inlet cross sectional area ~~of the inlets~~ depends 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 intertidal 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~~ speeds in the tidal inlet system.

In contrast, in the simulation with 10 m MSLR mean current ~~velocities~~ speed decreases in the channels. We suppose that the decrease of mean current ~~velocities~~ speeds 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 model's 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 tidal inlet cross sectional area ~~of the tidal inlet~~ decreases.

In the following a few aspects are discussed to which degree the model simulations described in this study are applicable to estimate the tidal response to MSLR in future reality. In this study we add MSLR as a constant value to present day boundary conditions. Thus changes in the response of global tides to MSLR are not included. Harker et al. (2019) find that for the Australian Shelf the differences between considering the change of global tides to MSLR and using present day tides are not negligible. For the German Bight it is not clear how large this difference would be. Further studies are needed. 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 MSLR~~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 MSLR~~mean sea level rise~~ see Wachler et al. (submitted). Furthermore, s~~S~~ince 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. (submitted).~~ Due to these constrains both models, the shelf model and the regional model, do not simulate the correct response to MSLR in future reality. Nevertheless, we assume that the regional model (with high resolution) is able to simulate the response to MSLR more correctly under the given boundary conditions (e.g. morphostatic bathymetry) than the shelf model. This assumption, that the regional model is more reliable, is based on the fact that physical processes are represented more accurately in the regional model (see e.g. Figures on current speeds).

5 Conclusions

~~Especially i~~In flat coastal areas such as the Wadden Sea in the German Bight where the small-scale topographic structure has a great influence, the representation of the bathymetry plays a crucial role for the estimation of changing~~ed~~ 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~~ shallow 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~~ well 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. We also thank three anonymous reviewers and the editor Philip Woodworth for their careful reading and many valuable comments to improve the manuscript.

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