Zorndt, Anna

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Sources of Uncertainty in Climate Impact Modeling at the Example of a 3D Hydrodynamic Model of the Weser Estuary

A.C. Zorndt
Franzius-Institute for Hydraulic, Estuarine and Coastal Engineering, Hannover, Germany

ABSTRACT: As it takes decades to plan and build new constructions, early planning decisions which take into account the impact of climate change have to be made under uncertainty. Thus, the explicit investigation of the level of uncertainty in climate impact research is becoming increasingly important. The work presented here is part of a climate impact research cooperation funded by the German State of Lower Saxony. Its aim is to study the impact of climate change on a regional basis, with a focus on the impact on hydrodynamic conditions and salinities of the Weser Estuary. The impact model is a 3D baroclinic circulation model. This contribution focuses on sources of uncertainty in the investigation of climate change impact.

Keywords: Climate change impact, 3D hydrodynamic model, Estuary, Weser, Uncertainty

1 INTRODUCTION

1.1 *Motivation*

The change in global climate in the 21st century, as predicted by the Intergovernmental Panel on Climate Change (IPCC), will affect coasts through mean sea level rise (MSLR), changes in the storm surge climate and the river runoff. In order to keep the coastal protection system at the present level of safety, research on the impact of climate change on the coastal systems has become increasingly important. However, today's knowledge is still limited and the projections are made with a certain amount of uncertainty. As planning times can be in the order of decades, early planning decisions have to be made despite limitations in the projections, as illustrated by Lowe et al. (2009, see Figure 1).

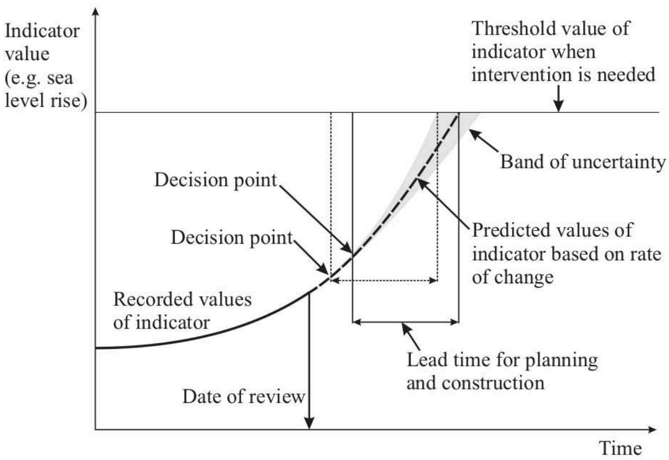


Figure 1. Decision making with an uncertain future (Lowe et al., 2009).

Thus, the explicit investigation of the level of uncertainty in climate impact research is becoming increasingly important. Some recent impact studies have discussed aspects of this (cmp. Sterl et al., 2009 or Lewis et al. 2011).

1.2 *Sources of Uncertainty*

In the fifth assessment report (AR5) of the IPCC (2013), suggestions are made on how to communicate the level of confidence on the results in climate modeling or impact studies. Sources of uncertainty are categorized into scenario uncertainty, model uncertainty, boundary condition uncertainty and uncertainty caused by natural internal variability.

Natural variability induced uncertainty arises when the reference period does not reflect the whole variability of the system. In climate modeling, it is also called initial condition uncertainty and is the fluctuation which shows if no radiative forcing is present (IPCC, 2013, p. 138). It is dealt with by using different GCM runs with different initial conditions. An excellent example for an impact study is given by Sterl et al. (2009) who used 17 GCM initializations to investigate the impact of climate change on high return intervals for storm surge height under a climate change scenario.

Model uncertainty stems from a model's limited ability to account for all significant processes in the investigated system (IPCC, 2013, p. 138). It can be divided into structural and parametric uncertainty. The first is induced by the model formulations, while the latter is induced by the model parameters. According to the AR5 (IPCC, 2013, p. 750), parametric uncertainty may increase when models are extensively tuned for better representation of certain aspects in the model.

Scenario uncertainty is defined by the IPCC as due to "limited understanding on future emissions" etc (p. 138). It is dealt with by using commonly agreed scenarios. Since the AR5, those are the representative concentration pathways (RCPs) which replace the SRES scenarios. An overview on MSLR values for different RCP is presented in Figure 2.

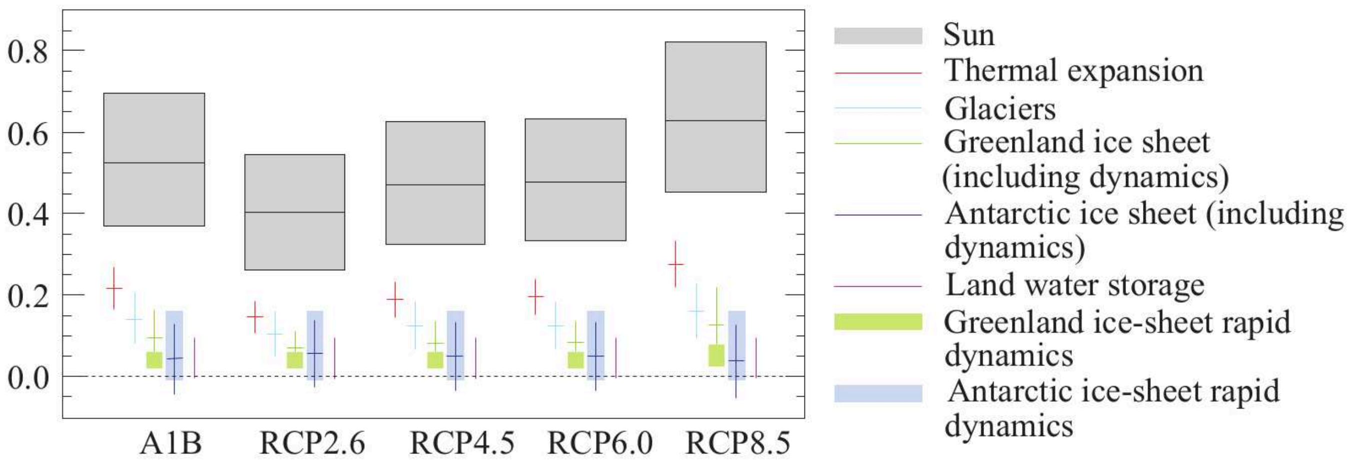


Figure 2. Mean sea level rise [m] and its contributions projected for 2081-2100 relative to 1986-2005, indicating median and likely values (redrawn after IPCC, 2013, p.1180).

1.3 *Application to an estuary impact study*

In this study, the categorization suggested by the IPCC (2013) is applied to an impact study in an estuary. Here, the challenge is that no transient simulations for reference and scenario climate can be carried out. Instead, the simulations are limited to time slices from the reference period which are repeated under scenario boundary conditions. This approach has been chosen by prior impact studies on the Weser estuary (i. e. Grabemann et al., 2001). This is firstly due to the numerical limitations of the impact model (long simulation times for 3D baroclinic processes). Secondly, there is often limited transient information on the boundary conditions. The time slice approach therefore has a different set-up and experimental design than a classical climate impact study as for example conducted by Gaslikova et al. (2013). The objective of this contribution is to investigate uncertainties for a climate impact study using a time slice approach.

2 BACKGROUND AND METHODS

2.1 *Research framework*

The purpose of the research is to investigate impacts of climate change on hydrodynamic conditions and salinities in the Weser estuary, Germany. The work was carried out within the joint project framework of the KLIFF project funded by the German State of Lower Saxony[1]. In Zorndt et al. (2012), short time effects of past and scenario storm surges on the salt distribution are studied. Results and discussions of a mean sea level rise (MSLR) scenario are described in Zorndt and Schlurmann (2014a, 2014b). The contributions focus on RCP8.5, assuming a continued rise in greenhouse gas emissions. From the range of likely GMSLR values given for this scenario, the median of 74 cm is chosen.

This contribution builds on the aforementioned articles and focuses on the underlying uncertainties of the impact modeling approach in regard to the scenario which is described there.

2.2 *Study area*

The Weser estuary has an area of around 2,000 km^2 (Figure 3, right). It is connected to the open ocean via the shelf sea North Sea (Figure 3, mid). The thalweg has a length of about 120 km. It reaches from the tidal weir upstream, located in the city of Bremen, up to the German Bight where seawater salinity prevails. The hinterland is low-lying and many inhabitants are living in areas located below the mean tidal high water. Therefore, a comprehensive coastal protection system with a main dike line of approximately 250 m length is in place today. It protects the hinterland from regular flooding due to storm surges and river floods from the watersheds.

Figure 3. Study area Weser estuary (right) located at the German North Sea coast (mid).

The Weser has a tidal range of 2.8 m in the outer estuary which increases to a value of 4.2 m at the weir due to the strong convergence of the estuary. The average runoff from the watershed mounts to 325 m^{3}s^{-1} with extremes of 74 m^{3}s^{-1} and 2190 m^{3}s^{-1} for the years 1990 to 2010.

2.3 *Model*

To simulate climate change responses of the Weser estuary, a baroclinic circulation modeling tool is applied. The main modeling challenges of the area are the vast proportion of intertidal flats in the outer estuary, which make up a proportion of around 30 % of the model domain, and the contrasting spatial scales which range between the orders of meters in the upstream harbors and hundreds of meters in the vast tidal flats. The modeling tool SELFE (Zhang and Baptista, 2008) was chosen which solves the Reynolds averaged Navier-Stokes equations with shallow water assumption and Boussinesq approximation, following a semi-implicit Eulerian-Lagrangian finite-element approach.

[1] KLIFF web presence: www.kliff-niedersachsen.de (last-checked: 2014-06-30). This research is part of work package TP5.2 which is a part of A-KÜST (FT7)

The model domain is the area described in Section 2.2. It includes relevant tributaries such as Wümme and Hamme and the Jade estuary. An unstructured model of the area was developed which contains 191,111 vertices and 372,708 elements. The vertical is discretized with 25 terrain- and solution following s-layers. The model was calibrated against measurements along the estuary. Different events were used to validate the model, for example the river flood from 2003 which lead to the maximum runoff of 2190 m^3s^{-1} (Sec. 2.2). A comprehensive assessment considering the Murphy skill score showed that the model is capable of reproducing measured values with very good model skill.

3 ESTIMATIONS OF UNCERTAINTY

3.1 *Time slice approach*

As described in Sec. 1, this study is limited to simulations of time slices. This potentially increases natural variability uncertainty. Here, a simple quantification of the uncertainty due to internal variability in a time slice approach is presented.

The time slices are chosen in a way to reflect as much of the natural variability of the reference state as possible. This is done by modeling past events with boundary conditions generated from measurements. An alternative is to construct synthetic events representing special situations such as long durations of high or low river runoff which would not occur in nature. This approach allows more detailed analysis of single scenarios and better control of confounding factors in the boundary conditions. However, the idea here is to incorporate as much of the natural variability of the system as possible. For this reason, past events are chosen rather than synthetic events.

The choice is based on an analysis of the present state (Figure 4). The simulations include a period of average runoff (MQ), a period of a typical summer low (MLQ), two winter river runoff (FL1, FL2) and two storm events (S1, S2). The latter are chosen to combine more frequently occurring events with events with higher return values.

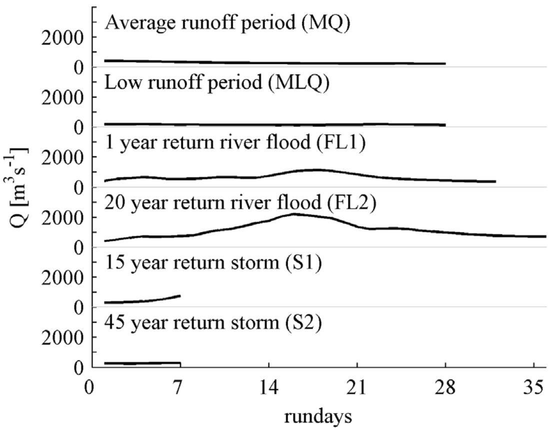


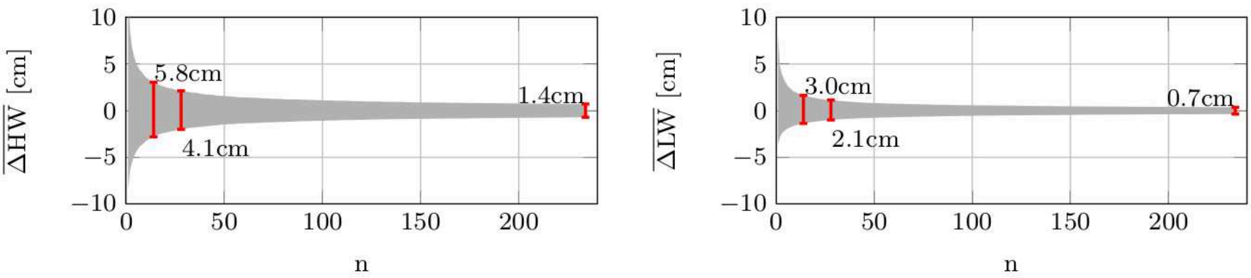
Figure 4. Experimental design, simulations carried out for describing the present state.

The following quantification of uncertainty due to internal variability is location-specific and scenario-specific (the underlying scenario of MSLR is described in Zorndt and Schlurmann, 2014a, 2014b).

Reference (REF) and scenario simulations of the MSLR scenario (SC) are carried out. The tides of both simulated time series are matched and the tidal characteristics (TCs) of each tide and of both reference and scenario are evaluated, as described in Zorndt and Schlurmann (2014b). This leads to a total number of N TCs for both REF and SC. Differences in the tidal characteristics are calculated leading to N ΔTCs. The following approach is used to calculate averages ($\overline{\Delta TC}$) which are based different numbers of randomly selected ΔTCs. Both steps are automatically repeated R=10,000 times:

1. An array $\mathbf{A}_r$ of N uniformly distributed random integers in the range of 1:N is generated.
2. N $\overline{\Delta TC}$ are computed based on increasing number of ΔTCs. In the first sample n=1, only the first entry in $\mathbf{A}_r$ is used for the average. In the second sample n=2, the first two entries in $\mathbf{A}_r$ are used and so forth.

This leads to a matrix **M** with NxR samples of averaged differences of tidal characteristics $\overline{\Delta TC}$. For each of the N sets of R $\overline{\Delta TC}$, the 2.5 and 97.5 % percentiles are calculated ($p^{2.5}{}_n$, $p^{97.5}{}_n$). For the Nth set, the average is calculated (m_N) and subtracted from all percentile values $p^{2.5}{}_n$, $p^{97.5}{}_n$. The results are presented in Figure 5 at the example of high water (HW) and low water (LW) at the station Rechtenfleth (REC) which is located in the inner estuary. The gray areas show the 95% confidence intervals. They can be interpreted as the uncertainty which remains due to the internal variability.



(a) tidal high water (HW) (b) tidal low water (LW)

Figure 5. Uncertainty by internal variability at the examples of tidal high water (HW, a) and tidal low water (LW, b) at the inner estuary station REC. Uncertainty is shown by the 95 % confidence intervals derived from a random averaging process depending on the number of tides N used to compute averaged differences between scenario and reference.

Results show that the bandwidth of differences between scenario and reference decreases with increasing number of evaluated tidal characteristics n. If the average is based on only one spring-neap cycle with 28 tides, which is a common practice in tidal environments, the bandwidth in this example amounts to 4.1 cm for tidal high water and 2.1 cm for tidal low water. When more tides are incorporated, the bandwidth decreases. For the total number of N = 224 investigated tides here, it does not reach zero but converges to 1.4 cm for high and 0.7 cm for low water. The same has been tested for other stations and different tidal characteristics of salinity and the same convergence can be observed.

To summarize, the simple randomized averaging process can help to quantify the uncertainty due to internal variability of the system. The simulations chosen for the reference state here reduce the internal variability uncertainty if compared to an investigation based on only one spring-neap cycle.

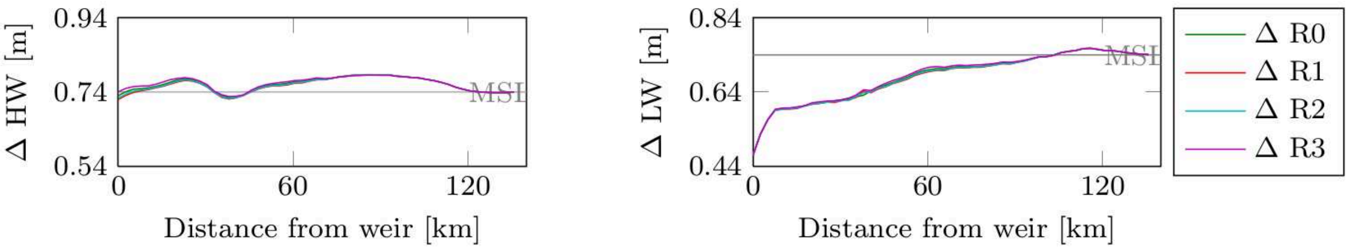
3.2 *Bathymetry and Roughness*

3.2.1 *Parametric model uncertainty*

In the present state, both roughness and bathymetry are physical values and can be determined from observations. However, in practice there is usually limited knowledge on the real values. Also, both parameters are often used to tune the results in numerical modeling (cf. Zijl et al., 2013). In this case, the scenario may have a different effect due to interactions between bathymetry/roughness tuning and scenario effects. According to the definition presented in Section 1.2, his would increase parametric model uncertainty. In this study, the bathymetry was very well resolved and only roughness was used as a calibration parameter.

Roughness is therefore investigated as a source of parametric model uncertainty. This can be done by testing if the derived differences in tidal characteristics between scenario and reference are the same under different roughness distributions. To derive alternative roughness distributions, the roughness length z_0 in the area between 50 and 100 km from tidal weir was increased by +0.1 mm (R1), +0.2 mm (R2) and -0.1 mm (R3) relative to the final model roughness distribution (R0).

The results are depicted in Figure 6 and underline that the differences ΔTC between the sets of simulations (R0 – R3) are small compared to the absolute differences. Due to the small sample size of four sets of simulations, no confidence interval can be calculated. The ranges between highest and lowest differences are therefore considered as a rough estimate of the uncertainty. They are location-dependant as can be seen in Figure 6. Maxima are 2 cm for HW and 1 cm for LW.



(a) Tidal high water HW (b) Tidal low water LW

Figure 6. Changes in tidal characteristics along the main river channel for different model roughness distributions for the MSLR scenario.

3.2.2 *Boundary condition uncertainty*

Another source of uncertainty lies in neglected physical processes. One relevant neglected process in this study is morphodynamic change. The outer estuary is a highly dynamic area with tidal currents being the main driver of the long-term morphologic changes (Kösters and Winter, 2014). Also, those changes go along with altered sedimentation patterns and thus different physical roughness. To neglect those processes increases structural model uncertainty. However, as long-term morphodynamic modeling of domains of this size is still a challenge, incorporating those processes was not considered meaningful in this context of this study. Alternatively, morphodynamic changes can be considered as additional scenarios (cf. Grabemann et al., 2004). However, it is difficult to determine meaningful scenarios with changed bathymetry or roughness to which a confidence can be assigned. Therefore, the influence of a simple roughness distribution change is tested here upon its influence on the scenario impact. This is here regarded as an aspect of boundary condition uncertainty. Due to the complex set-up, alternative bathymetries are not tested.

The test is conducted in analogy to the assessment of roughness as a source of parametric model uncertainty in Section 3.2.1. This is done by testing if the derived differences in tidal characteristics between scenario simulations with roughness values R0, R1, R2 and R3 and the reference simulation with roughness R0 are the same. Again, the ranges between highest and lowest differences are considered as an estimate of the uncertainty. The maximum differences are 6 cm for HW and 9 cm for LW.

4 DISCUSSION OF NON QUANTIFIED SOURCES UNCERTAINTY

4.1 *Climate change impact in adjacent systems*

As mentioned earlier, the challenge in impact studies in estuaries is that climate change impacts indirectly by influencing neighboring systems. This is problematic as the impact study highly depends on impact studies in the adjacent systems. In case of the Weser, those are the North Sea and the watersheds. Studies in those systems may inherit different degrees of uncertainty which are passed on to the impact model via the derived boundary conditions of the scenario.

In case of the Weser estuary, a comprehensive literature study on possible impacts showed that the main driver of climate change is the mean sea level rise. Changes of storm climate or runoff play a less important role (see Zorndt and Schlurmann, 2014a). The MSLR value which is used (see Sec. 1.2) can be assigned a “medium confidence” for RCP8.5 (IPCC, 2013) on the global scale. As discussed in Zorndt and Schlurmann (2014b), the confidence in the scenario decreases when the GMSLR is superposed as a constant on the boundary condition of the Weser. This is because the GMSLR will not be distributed evenly on the globe and because it may lead to changing tidal dynamics (TDs) in the North Sea. This can be regarded as scenario uncertainty if the SLR at the North Sea boundary is considered the “scenario” but also as boundary condition uncertainty if the IPCC definition is strictly adopted.

Simulations with a North Sea tidal model were carried out in this framework to assess in which way the GMSLR might deform the tides in the German Bight. Results and discussions are presented in Zorndt and Schlurmann (2014a). The conclusion is that accounting for TD changes in the German Bight boundary conditions of the Weser model may inherit an equal amount of uncertainty as not doing it. A quantification of this uncertainty is an important topic and has not been addressed yet.

4.2 *Sea water salinity*

Similar to roughness, salinity may be a source of both parametric model and boundary condition uncertainty. The salinity at the open boundary in the German Bight is set to a constant value of 31.6 psu. This value is based on salinity stations close to the boundary and ferry box data from ferries regularly passing the open boundary. This is a simplification as factors such as the Weser runoff, the Elbe runoff plume and meteorological events influence the salinity.

5 SUMMARY

This contribution focuses on sources of uncertainty in a climate impact study of an estuary. There are two main challenges in such impact studies. First, only time slices can be considered in many cases due to limited transient boundary conditions and numerical capacity. Secondly, the main driver of climate impact is often not the meteorological changes but impacts in adjacent systems. Those are important differences to classical climate impact studies and may increase the uncertainty linked to the projections. Nevertheless, projections are necessary as politicians and decision makers plan ahead for preparing for future challenges and therefore need regional assessments of climate impact. To enhance the reliability of impact studies, this contribution aims toward a more comprehensive assessment of sources of uncertainty in impact studies.

At the example of the Weser estuary, a climate impact study was conducted (focusing on hydrodynamic conditions and salinity). Uncertainty due to model parameters, structural limitations of the model, boundary conditions, the scenario uncertainty and internal variability were discussed.

A way for quantifying uncertainty due to internal variability was suggested. It is specific to the chosen scenario and the simulations chosen to represent the current state. The boundary condition and parametric model uncertainty due to roughness were tested by comparing the outcomes of different combinations of several roughness distributions. The results show that the uncertainty due to roughness as a model parameter is very small. The uncertainty due to internal variability is in the same magnitude as the uncertainty due to roughness as a boundary condition. Summing up all maximum bandwidths of the three investigated sources of uncertainty leads to values well below 10 cm for the impact of a MSLR scenario (RCP8.5, 74 cm) on the change of tidal high water. This is small compared to the likely range of MSLR in RCP8.5 (52 cm – 98 cm).

Despite the limited number of aspects which are quantified, the analysis shows that the uncertainty which stems from the impact model and the chosen parameters in this study may be negligible. The uncertainty due to internal variability (How well is the reference state represented in the simulations?) is more important and should be considered more explicitly in the future. The highest uncertainty still lies in the boundary conditions which mainly depend on impacts from adjacent systems. Future challenges are to improve our understanding of MSLR impact on the North Sea and to investigate impacts of MSLR on morphology in the German Bight.

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