Conference Paper, Published Version

Hein, Hartmut; Mai, Stephan; Barjenbruch, Ulrich

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ICHE 2014, Hamburg - Lehfeldt & Kopmann (eds) - © 2014 Bundesanstalt für Wasserbau ISBN 978-3-939230-32-8

Long-term Changes of the Tidal Amplitudes and Phases in the Elbe Estuary

H. Hein, S. Mai & U. Barjenbruch
Federal Institute of Hydrology, Koblenz, Germany

ABSTRACT: During the last century the response of the oceans to tidal forces has changed significantly, changes of tidal amplitude and/or phase have taken place over large scales. Continuous long-term simulations of the Elbe estuary are discussed for present-day conditions as well as for future conditions. The simulations are conducted with a limited area model of the Elbe estuary, which is offline nested into a model of the North Sea. In the North Sea and the estuary currents and sea-levels are modelled by the hydro-numerical HAMburg Shelf Ocean Model (HAMSOM).
The results of the long-term modelling confirm the larger scale estimations. Physical inherent changes of tidal phases and amplitudes have been proved in the Elbe Estuary. With the rising sea level, the wave speeds and wave lengths increase. This can cause modifications of the reflections of the tides. Additionally energy dissipation by bottom friction is reduced. Both processes act together and result in the migration of complex patterns of non-linear changes in the tides with climate change.
Despite uncertainties associated with the SLR over the next century, modifications of the tides in coastal areas and estuaries implicate modifications of the coastal management by estimation of adapted design levels, in the availability of tidal renewable energy and dredging requirements.

Keywords: Sea Level Rise, Harmonic Analysis, Tidal Amplitudes, Tidal Phases, Numerical Modelling

1 INTRODUCTION

In coastal regions and estuaries physical processes influence many economic, ecologic processes and also security issues. Global climate change has high potential to influence both, the persistence and the transport pathways of water masses and its constituents in tidal waters and estuaries (Dietrich et al., 2013). Sensitivity studies (e.g. Mai et al., 2004) show the variation of tidal water levels, of significant wave heights and the morphology at the southern German Bight as the result of climate change. In the long term context of climate change, these physical processes are subject to changes, too (Hein et al., 2011b).

It is widely accepted, that the climate-related sea level rise (SLR) influences the long-term coastal processes. An almost linear secular rise of about 1-2 mm per year (e.g. Wahl et al., 2010, Hein et al. 2011c, Albrecht et al. 2012) has already been observed in the southern German Bight. The future acceleration of global SLR is expected (Solomon et al. (2007). Historic acceleration for the German Bight is not to be found significant (Hein et al. 2010).

The expected future changes of the global sea level in the 21st century are mainly determined by the steric expansion of the ocean due to global warming. Additionally increasing fresh water supply from melting of the two ice sheets over Greenland and the Antarctic and from inland deglaciation accelerates the SLR in the 21st century. However, the regional sea level rise must be determined by the regional distribution of globally added melt water masses due to gravitational effects and also by barotropic and baroclinic ocean dynamics due to changing density distributions (Mathis, 2013). In the Elbe estuary the glacial isostatic adjustment causes land subsidence in order of 5 cm to 10 cm (Hein et al., 2011c). For this model study, we use the approach from Mathis (2013), who implements the sea level rise at the lateral boundary of the North Sea model in form of a scenario.

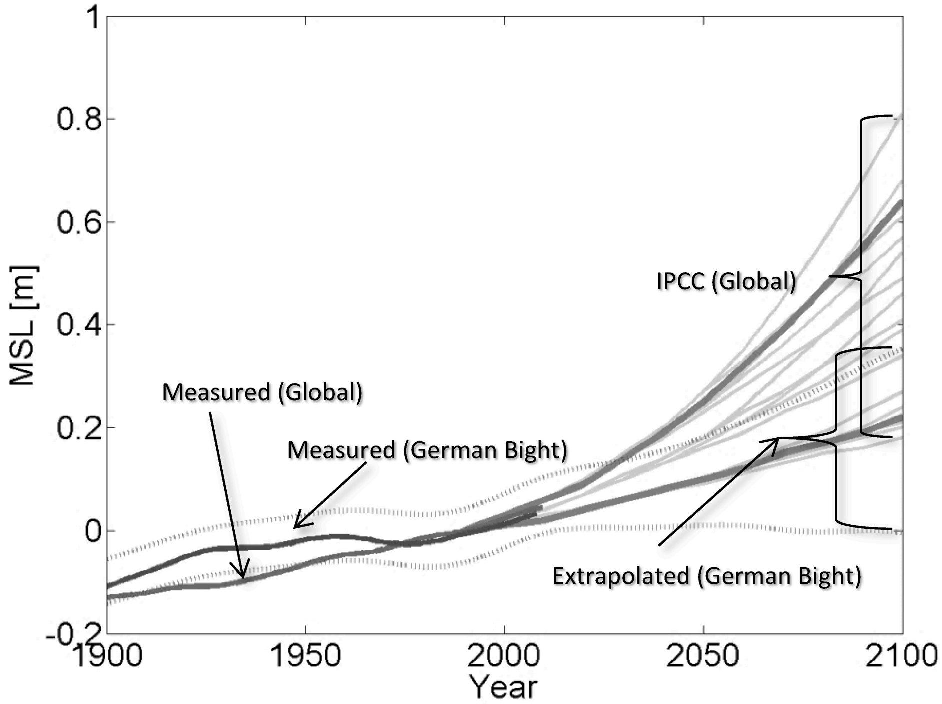

Figure 1. Sea level rise, measured and extrapolated (dashed line) for the German Bight, observed global sea level rise, IPCC estimations.

Figure 1 shows the global as well as the regional SLR. The SLR in the German Bight is estimated from tide gauge measurements. The dashed bandwidth images the extrapolation of the observed SLR (Hein et al., 2010, 2011c). The historic global SLR is estimated by observations (Church and White, 2011). The global future estimations are taken from the IPCC-report (Solomon, 2007).). Thicker lines highlight the A1B scenario. The regional sea levels rise is a bit less than the global SLR. The non-linear statistical extrapolation can only explain sea level rise of O(35 cm) up to the end of the century. However, the physical processes behind the future sea level rise are not included in the statistics.

Sea level is not level (Gehrels & Long, 2008). Variability of the SLR acts on almost all scales - in terms of both - time and space. Beneath the typical tidal scales, which are commonly semi-diurnal (M2) to 19th yearly (Nodaltide), several additional sales are representative for typical atmospheric timescales of months to several years (Dangensdorf et al., 2012). The SLR is positively correlated with the changes of the NAO on time-scales of 4 to 7 years (Hein et al., 2011b, Dangendorf et al., 2012). Variability on scales in the range of the Nodaltide is indicated since 1930 and before 1900; periods in order of 30 to 40 years are important, their amplitudes increase with time. Additionally, periods of approximately 60 to 80 years are present in the sea level of the German Bight (Hein et al., 2011b).

During the last century the response of the oceans to tidal forces has changed significantly, changes of tidal amplitude and/or phase have taken place over large scales (Müller et al., 2011). In the North Sea region the response of the M2 tide to sea level rise is predicted to be greatest in the southern German Bight, coming with a lot of non-linearity (Pickering et al. 2012). So, it is a legitimate question asking for changes of the tidal constituents at coastal sections or inside estuaries, e.g. the Elbe estuary.

The Elbe River is one of the largest rivers in Europe O(1000 km), the tidal influence in the estuary reaches O(150 km) inward from the centre of the German Bight to the weir in Geesthacht. The hydrological regime of the Elbe estuary is dominated by tides, mainly by the M2 tide and their overtides. The amplitude of the M2 tide in the Elbe estuary is about 1.5 meters. The amplitudes of the M2 overtides are one fourth of that. The S2 tide is also prominently detectable with amplitude of 0.3 meters.

2 METHODS

2.1 *Simulations*

The changes of the tides are derived by the use of long-term regionalized coupled numerical modeling of atmosphere and ocean (Hein et al. 2013); the so called model chain (MC) is used. The MC implemented in the research program KLIWAS of the German Federal Ministry of Transport, Building and Urban Development, by the Federal Institute of Hydrology together with several partners downscales one climate scenario towards long-term simulations of the German North Sea estuaries.

Time-series of water level and wind are derived from the global climate run A1B MPI-OM, which is regionalized to the North-Sea with the offline coupled models HAMSOM/Remo (Pohlmann, 2006; Mathis, 2013) with the use of an additional forcing from a global tide model. To simulate the circulation and the sea level, the hydro-numerical model HAMburg Shelf Ocean Model (HAMSOM) is used. HAMSOM was first set up in the mid-eighties by Backhaus (Backhaus, 1985). In general, it is a three-dimensional, prognostic-baroclinic, frontal- and eddy-resolving model with a free surface. The numerical scheme of HAMSOM is defined in z-coordinates on an Arakawa C-grid. The governing equations for shallow water combined with the hydrostatic assumptions are implemented.

The basic descriptions of the North Sea Model can be found in Pohlmann (2006) and citations therein. The model version for the Elbe estuary is optimized for the use in estuarine regimes (Hein et al. 2007; Hein et al., 2011a; Hein et al. 2013a) and recognizes also horizontal sub-grid processes, e.g. drying (Hein et al. 2012), friction, horizontal turbulence (Hein, 2008). The fast numerical schemes allow simulating hundreds of years - or the permutation of parameters, numerical algorithms, resolution and boundary conditions. The Elbe model has scalable resolutions between 80 m - 600 m in the horizontal and 4 m – 12 m in the vertical.

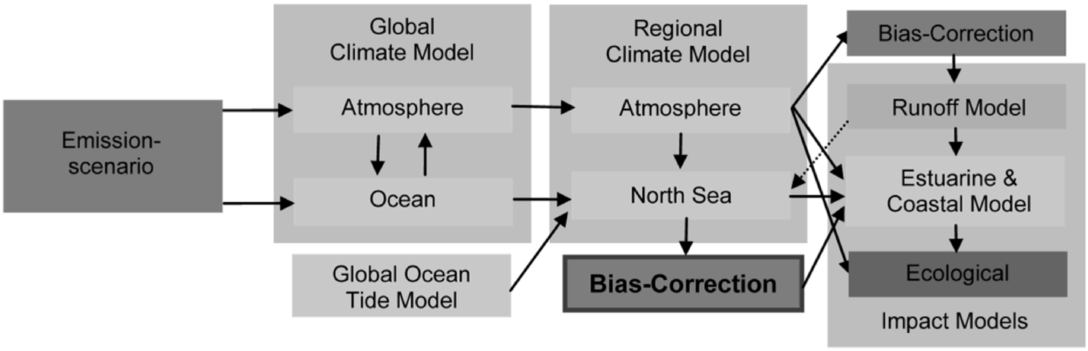

Figure 2. Model Chain in the coastal region of the research program KLIWAS.

The overall MC (Figure 2) starts with emission scenarios. These are used to run various global climate models, to derive atmospheric and oceanographic parameters on the global scale. It is necessary to transform the results of the global climate models with regional downscaling into results for the specific region. This is usually done with the uncoupled models of ocean and atmosphere. The last step is to scale down the regional climate models towards the certain stretch of the coastline. The lack of tidal information, in most of the global climate models is one challenge for simulations of coastal processes. The regional topography of the simulations is shown in Figure 3.

The long-term run is forced by a regional climate model (REMO). Future discharges are included from improved rainfall-runoff modelling of the catchment area of the Elbe River (Lingemann, 2012). The fundamental study of Mathis (2013) induce estimations of the different components of global sea level rise (SLR) and continually add them onto the sea surface elevation at the open boundaries of the North Sea model, which results in agreement with the IPCC upper limit. Therefor SLR can reach 55 cm until the end of the century (Figure 1). Additionally to the long-term run a parameter permutation experiment investigate into uncertainties. The model data are processed by spatially and temporal solved Harmonic Analysis.

The applicability of the regional circulation model was shown in several presentations (Hein et al., 2011a, Hein et al., 2012, Hein et al., 2013b). It turns out, that the local model, despite the low resolution transports the tidal wave to the port of Hamburg in an adequate manner. However, numerical models may be useful tools to get insight in the coastal processes of the system being modelled, but poor input data leads to uncertain model results (Spek, 2013).

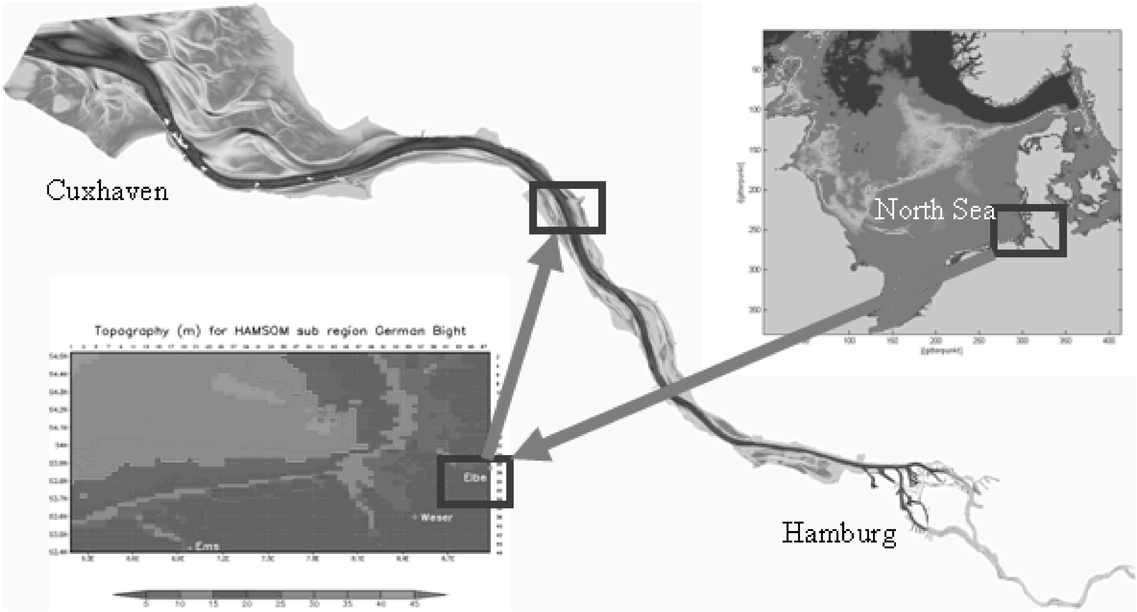

Figure 3. Regional topography used by the simulations.

2.2 *Harmonic Analysis of the model results*

The amplitude and phase for the sinusoids representing of each known constituent of the modelled time series of each kilometer in the estuary must be estimated. This can be done by solving a system of linear equations (Foreman& Henry, 1989).

$$z_i = A_0 + \sum_{j=1}^{M} A_j cos(\sigma_j t_i - \Phi_j) \quad (1)$$

In equation (1) Aj, σj and Φj are the amplitude, frequency and phase of tidal constituent j constructing the simulated water level zi. Equation (1) can be solved by introducing two new unknown Sj and Cj resulting in the linear formulation.

$$A_j cos(\sigma_j t_i - \Phi_j) = C_j cos(\sigma_j t_i) + S_j sin(\sigma_j t_i) \quad (2)$$

$$A_j = (C_j^2 + S_j^2)^{1/2} \; and \; \varphi_j = arctan\left(\frac{S_j}{C_j}\right)^{1/2} \quad (3)$$

Equation (2) can be simply solved by least squares or if the time series is short and noisy time with weighed solutions (robust fit). The following results are restricted to six of the main components, which are the M2, S2, M4, N2, K1, O1. If necessary the nodal tide is reduced by the use of polynomial filtering.

3 RESULTS AND DISCUSSION

3.1 *Changing tides at the mouth of the estuary*

The results of the long-term modelling confirm the larger scale estimations of Müller et al. (2011). Physical inherent changes of tidal phases and amplitudes have been proved at the mouth of Elbe Estuary. Figure 4 shows the long term changes of the 6 main components, which are normalized by their today mean and standard deviation. The importance of the Nodal cycle is noticeable. The increase of the amplitude of the M2-Tide due to SLR must be noted. But in contrast the M4-tide decreases, which indicates the reduction of overtides in the German Bight.

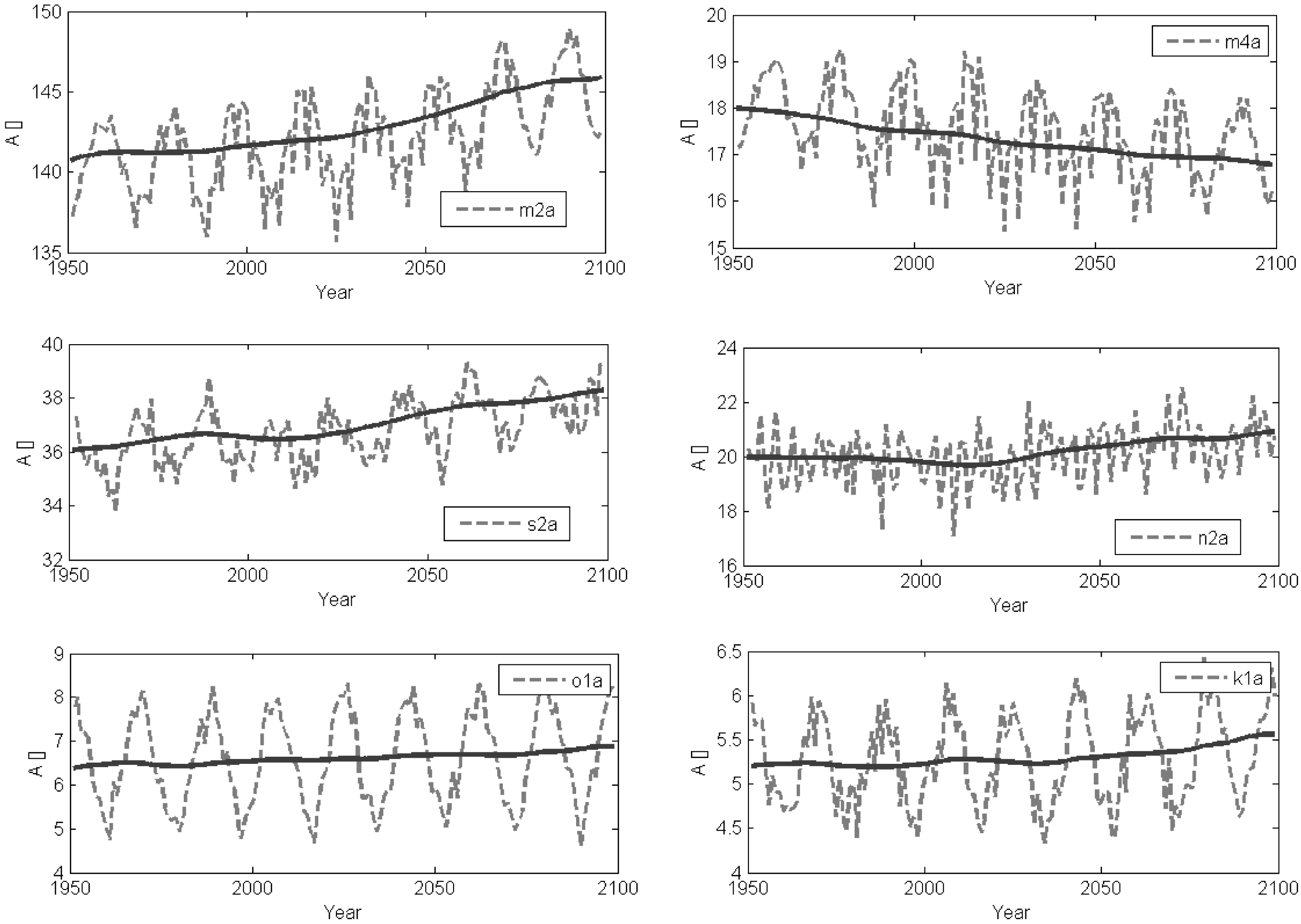

Figure 4. Changes of the amplitudes of six tidal main components.

3.2 *Changing tidal characteristics: Hamburg to the mouth of the estuary*

One step further is the long term modelling of the estuary and the analysis of the results. First of all Figure 5 shows the overall changes of the tidal characteristics, represented by the tidal high-water (THW), tidal low-water (TLW) and the tidal range (TR). Here, the uncertainties coming from the IPCC report are included. The lower area in the pictures represents the changes in the near future (2030 – 2049) relative to today's situations (1980 – 1999). The changes of the THW and TLW are in the magnitude of the change in the MSL. However, the combining effect of a bit faster rising THW and a decreased rise of the TLW let the tidal range rise with the SLR.

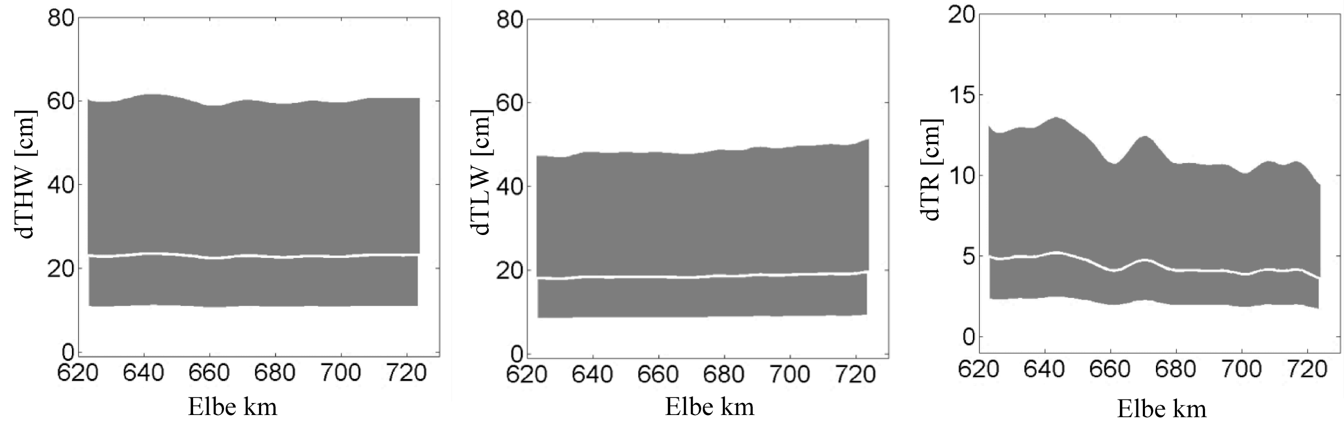

Figure 5. Changes of the tidal characteristics between Hamburg and Cuxhaven; a) THW, b) TLW, c) TR

The upper area in the pictures represents the changes in the far future (2080 – 2099) relative to today's situations (1980 – 1999). The situation is now clearer: the faster rising THW and the decreased rise of the TLW let the tidal range rise with the SLR. Also the effect of a stronger amplifying of the tides directed to the inside of the estuary is documented. Especially, taken the high-end scenario pronounced changes of the TR toward Hamburg are modelled. Noticeable is the non-linear changes of the TR along the estuary, it is worthwhile to look into these changes more closely by analysis of the tidal constituents.

3.3 *Changing tidal constituents: Hamburg to the mouth of the estuary*

Figure 6 illustrates how the change of the tidal constituent along the estuary has to be expected in the high end scenario until the end of the century. For five of the components the amplification of the tidal amplitudes continues in the estuary, but with decreasing tendency in upstream direction until the port of Hamburg, where a strong amplifying peek establishes. In contrast to the other constituents the patterns of the changes of the first M2 overtide (the M4) is different. Here the amplitude is lower at the mouth and in the outer part of the estuary, but increases downstream the port of Hamburg. This is documented in the amplitudes as well as in the shift of the tidal phases.

With SLR, the wave speed and wave length increase, causing changes in the reflections of the tides.

The following changes in the self-oscillations are documented in the simulation (Figure 6). Caused by the SLR the tidal flats are longer flooded. Therefor in cross-sections energy dissipation by bottom friction is less important. The overall longer flooding of the tidal flats decreases the effective mean depth of the estuary and also causes the reduction of the funneling effect. All mechanisms in combination result in the migration of complex patterns of non-linear changes in the tides with SLR (Pickering et al. 2012).

4 CONCLUSIONS

Global climate change in form of SLR has high potential to influence the physical processes in estuaries. For the Elbe estuary nonlinear effect of the rise of the sea level induce changes of the tidal constituents in the German Bight. These changes of the tidal constituents continue well into the estuary, which results in the shift of the spatial distributions of the tides. In future the tides amplify stronger than today in the upstream direction. The reflections of the tidal wave in the estuary will differ in contrast to today's situation. Despite uncertainties associated with the SLR over the next century, modifications of the tides in coastal areas and estuaries implicate modifications of the coastal management by estimation of adapted design levels, in the availability of tidal renewable energy and dredging requirements (Pickering et al. 2012). In particular this also applies to the Elbe estuary.

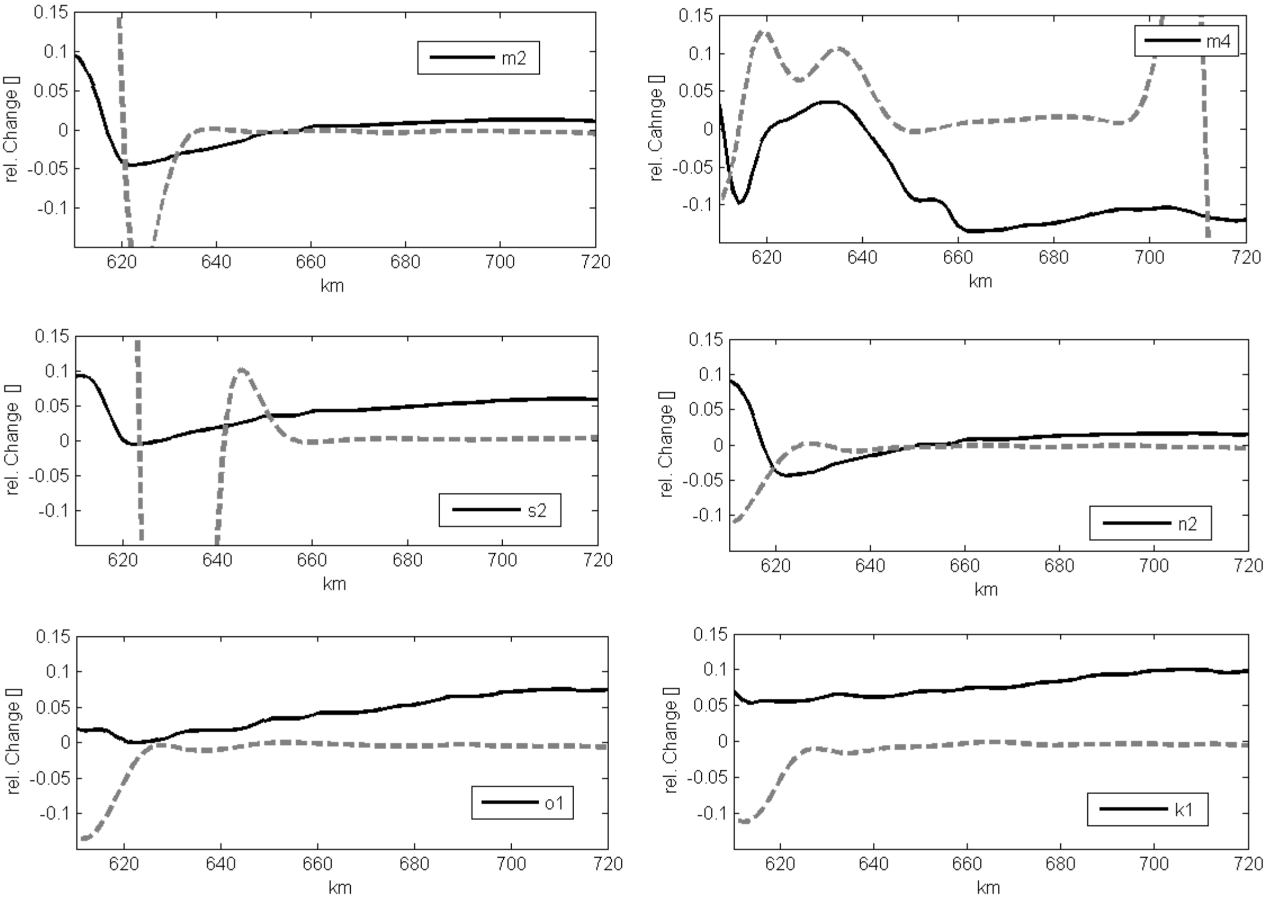

Figure 6. Relative changes of the tidal constituent between Hamburg and Cuxhaven in the far future (2080- 2099).

NOTATION

A_j,	amplitude of tidal constituent j
σ_j	frequency of tidal constituent j
Φ_j ,	phase of tidal constituent
THW	Tidal High Water
TNW	Tidal Low Water
TR	Tidal Range
M2, S2, M4, N2, K1, O1	tidal constituent

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