Coastal long-term processes, tidal characteristics and climate change

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Abstract

Climate change will change coastal long-term processes. For the waterways in the southern North Sea we discuss this changes by the use of two different ways. At first we analyse the long-term changes of the sea level rise. Secondly, we go into the detail of a so called “model chain”. The model chain is the synonym for the regionalisation from global climate models toward the coastline. To decompose the processes we use a multi-scale analysis by the means of a wavelet-transform. The recent water level is to understand as the superposition of several processes with different periods on (multi-)decadal scales. If we consider the superposition of the processes an acceleration of the sea level rise is not likely. The model chain reproduces several of the processes, which are observed. However, not all periods can be detected. So we conclude that the model chain must used with care. The test of long-term coastal hydrodynamic model as the last step of the chain shows sufficient results. The artificial addition of the missing processes into the model chain must be discussed. It is an open question if the model chain can reproduce an increase of long-term variability sufficiently well

Keywords: sea level rise, regional climate models, coastal hydrologic processes, multi-scale analysis

1 Background: Global Climate Change and regional impact

It is widely accepted, that climate-related sea level rise (SLR) influences the long-term coastal processes. In this context the term “climate mean” is defined as the characteristic frequency distribution of local conditions and processes for a sufficient period of time. This period reflects the probability density of states and processes of the typical conditions in the region. The Mean Sea Level (MSL) as climatologically value of the sea level is defined as “the average height of the surface of the sea at a tide station for all stages of the tide over a 19-year period” (IHO, 1994). For the presentation of the SLR (SLR) often the secular rise (100 years) is a common used period. An almost linear secular rise of about 1-2 mm per year (Wahl et al., 2010, Wahl et al., 2011, Hein et al. 2011) has already been observed in the southern German Bright (Figure 1). A future acceleration of global SLR is expected (IPCC, 2007). However, besides linear secular trends, nothing seems to be proven with the SLR, yet processes seem not to be understood. For several regions of the world the trend of the sea level shows no significant acceleration, even deceleration has been calculated (Housten and Dean, 2011). Other studies found evidence for acceleration on century time scales (Woodworth et al, 2009). So it is essential to provide detailed studies for each region to improve knowledge about future SLR and its impact. Sensitivity studies (e.g. Mai et al., 2004a, b) show a variation of tidal water levels, of significant wave heights and also the morphology at the North Sea coast as the result of climate change. One predominant process, influencing most other parameters is the change of tidal characteristics. Coastal long-term processes (CLP) superpose the climate signal (Woodworth et al, 2009). Their study show acceleration on decanal periods and suggest connections to long-term changes of the atmosphere and ocean circulation changes.

It remains to be proven how these CLP influence the regional tidal characteristics. Our study investigates into these long-term processes by two approaches: The first method, to draw

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conclusions for the future changes of the tidal characteristics, is to examine historic gauging data, in order to deriving the recent rise of sea level. However, an extrapolation of SLR is difficult, because of its non-linearity. The second method is the use of a so called “Model Chain” (MC), to transfer the results of global climate models into results for coastal areas. It is yet to shown whether these MCs, which still base on very rough global climate models, are applicable for regionalization at all.

2 Methods and Data

To estimate the historic SLR, 8 tide gauges provided by the Waterways and Shipping Administration of the Federal Government of Germany (Emden Neue Seeschleuse, Norderney, Helgoland, Cuxhaven, Lt. Alte Weser, Wilhelmshaven, Bremerhaven and Husum), which are located in the southern German Bright (figure 1), are combined to one theoretical mean gauge. They are representative for the coastal region both due to their spatial extend and due to their distance to the coast-line. The data set is of a never before reached accuracy, because several new technical approaches for quality management and averaging are used to estimate the mean climatologically curve of SLR in this region. The data set is quality controlled and corrected for local datum shifts (Sudau and Weiß, 2010; Hein et al., 2010a). We use a fuzzy logic approach to extend the shorter time series of some gauges towards secular and even towards longer periods. The k-value approach by Lassen und Seifert (1991) and a low pass filtering with the Singular Spectrum Analysis is used to calculate the MSL. Moreover, land-subsidence is included by recognizing both, geodetic (Wanninger, 2009) and hydrologic data sets. One mayor uncertainty of the geodetic dataset is defined by the general bearing of the network, rather than by the point to point observation uncertainty of the geodetic methods. With this assumption it is possible to combine the sinking rates from long-term trends of the different tide gauge observations and the geodetic observations with a least squares fit. A more detailed description of the method is to be found in the study of Hein et al. (2011).

The modal chain used in the research program KLIWAS (Mai et al. 2009) of the German Federal Ministry of Transport, Building and Urban Development, by the Federal Institute of Hydrology together with several partners is given in Figure 2. The MC allows scaling the scenario down towards long-term simulations of the German North Sea estuaries. The MC starts with different emission scenarios. These are used to run various global climate models, to derive atmospheric and oceanographic parameter on a global scale. Secondly, it is necessary to transform the results of global climate models with regional downscaling into results for the region. This is usually done with the uncoupled models of ocean and atmosphere. In KLIWAS we also test coupled models on the regional scale. The last step is to scale the regional climate models down towards the certain stretch of the coastline. So we applied numerical hydrological models for the estuaries. Because the whole MC is used to simulate climate-relevant periods, we used simple and fast models, which are still in the position to reproduce baroclinic frontal processes (Hein, 2007). Within the MC the lacks of tidal information in most of the climate models is one challenge for the simulation of coastal the processes. We use additional global models of tides. It must be ensured for the sea-state, that the influence is considered, which is caused by the changing characteristics of future tides (Hein, 2010b). The MC is tested by hind-casting the recent climate and by comparing these results with the tide gauge measurements. Then the future long-term processes are compared with the recent conditions.

Two pathways of the model chain are tested. The first is the hind-cast which is based on the HAMSOM North Sea model published by Pohlmann (2006). The hind-cast covers the period of 1948 to 2007. The validation of the model by means of observed sea surface temperature data and of temperature data from a hydrographical transect demonstrates that the model is able to reproduce the observations of temperature reasonably well, nearer inspections of the sea level was not done. The second pathway based on the same HAMSOM North Sea model, but instead of the atmospheric hind-cast this model is driven by a regional climate model (REMO). The regional climate model was forced by ECHAM5 / MPIOM (figure 2).

To find the long-term processes which are present in both, observed and modeled data, we decompose the time series into the frequency space by the means of a wavelet transform (WT). The WT allows us to determine dominate modes of the fluctuation in the series as well as such modes which vary in time. For assistance of the reader we briefly introduce into the concept of wavelet transformation and refer to Torrence and Compo (1998) for those, who delve into the thematic.

The WT starts simply with ζ_t, which is an equidistant time varying water level and the following equation:

$$\psi_0(\eta) = \pi^{-0.25} e^{i\theta\eta} e^{-\eta^2/2} \tag{1}$$

This is the so called “Morlet-wavelet”, which depends on dimensionless time η and non-dimensional frequency θ. We use the typical Morlet-wavelet with $\theta = 6$, which results in about three oscillations inside the wavelet envelope and frequency = 1.03s, so the Wavelet scale is approximately equal to the Fourier period. The wavelet transform itself is defined with the following equation:

$$W(\tau, s) = \sum_{n=0}^{N-1} \zeta_{i'} \left[\psi_0\left(\frac{(t-\tau)}{s} \right) \right]^*_{\tau,s} \tag{2}$$

N the length of the time-series, s is the position in the frequency space and τ the position in time the star (*) indicates that the complex conjugate is used. This allows us to decompose the one-dimensional time-series of water levels into a two-dimensional time-series with respect to the time varying water level on different time scales.

3 Recent coastal long-term processes of the sea level rise

We start our investigations with the observed long-term variability of the SLR. Figure 3 shows the long-term fluctuation of the SLR, after the filtering process. The figure shows that the values shift periodically with time between approximately 0 cm a^{-1} and 0.3 cm a^{-1}. In the last years the rise is strongest but not in an uncommon range. In the period between 1960 and 1980 the sea level decreased. The orange line shows the approximation with a sum of sine functions, which seems to reproduce the variations in the SLR. In general acceleration is not to be found.

Figure 4 presents the wavelet spectra of the sea level. This allows us to detect long-term processes. First, greatest variability is to find on that scales, which are representative for typical atmospheric timescales of months to several years. We can conclude that sea level periods shorter than one year seem to be dominated by white noise processes, which may related to quasi random storm events. The SLR is positively correlated with the changes of the NAO on time-scales of 4 to 7 years (≈ 40 - 80 months). Variability on periods in the range of the Nodaltide (223 month) is indicated since 1930 and before 1900. Moreover periods of 30 to 40 years (≈ 400 months), are important and their amplitude increases with time. Theoretically, this is possible with the change of processes of self-oscillation of the basin; both North Sea and North Atlantic could have changed their characteristics. Self oscillation is related to the depth (sea level) of the basin, so the changes of the long-term processes related to the self-oscillation is likely. Additionally, periods of approximately 70 to 80 years (≈ 900 months) are present (however, not shown in figure 4). In general the scales of variability agree with actual studies of the North Atlantic, e.g. Medhaug and Furevik (2011) discuss this multi-decadal variability. Woodworth et al. (2010) presented, that on the regional scale we always must consider changes in the current system, because they can significantly influence the long-term trend.

4 Analysis of the model chain

The results of the WT of both, MC and observations are compared. However, instead of considering the known uncertainty of the MC we rather turn the question around and ask whether we found even useful, actionable information in the MC. The analysis of the MC shows that there is only small influence originating form the emissions scenarios on SLR. So we start with the output from the regional models, which provide important boundary information for coastal models. Figure 5 shows a) WT from historic observations in the period 1948 – 2007, which is the period of the North Sea model hind-cast (b). Generally, the hind-cast can reproduce the mayor variability of the observations. However, in detail there are some differences. The increase of variability, which is indicated on a scale of 100 month, is not simulated by the model. The important scale of 400 month is also not well reproduced by the model. It is to discuss, if periods of hind-casts are too short to indicate climate change signals. However, the period of approx 60 years is typical for hind-casts, which means that this seems a general problem of climate hind-casts.

Figure 5 c shows results from the regionalization of the climate model for the period of the hind-cast. Surprisingly, the variability itself is better represented by the climate model. But, the periods are shifted with time. For example, this means that we observed an increase of SLR in the last 10 years but the climate model reproduced a decrease. However, if we use the multi-scale analysis we can address this fact and may consider the shift in our analysis. Against the hind-cast results the increase of variability (100 month) is indicated, but not as strong as in the observations. Further analysis of the MC shows that global climate models provide realistic simulations only for a number of key aspects of natural internal variability, which we observed by measurements. We agree with several other studies (e.g. Chase et al. 2011, Hawkins and Sutton, 2009, Keenlyside, 2008) which analyze climate models for several different parameters: Climate-models are not useful for day-to-day or year-to-year predictions. For many, but not for all regions, the reproduction of the regional long-term climate is well done by the climate models. For many aspects this is true for the SLR in the southern German Bright. The modes of variability (e.g. North Atlantic Oscillation) and the displacements of these modes, which have been shown by observations, are poorly represented in most climate models.

Figure 5c show what happens in the future – by the means of the model. In general, the variability remains in the same range. In the scale-range of 100 to 200 month the variability is increased in comparison to recent years. If we consider that the increase of variability during the reference period is below that of the observations we suggest an underestimation of these increase of variability. The wavelet analysis shows that the modes are represented in the regional climate models but they are shifted in time. However, this natural internal variability is the major factor of uncertainty in the observed SLR in the southern North Sea (Hein, 2010a). On the regional scale (North Sea), some tests of coupled regional models done by Schrum (2001) indicate that the results of global models as driver of regional models are inadequate to reproduce the regional sea level in a deterministic way – independent if the models are coupled or not. Future work of simulations of longer-terms with coupled models must be done.

Figure 6 shows first results from the last step of the model chain. The applicability of long-term simulation of coastal and estuarine regions is tested by the implementation of a coarse resolution HAMSOM model, which is optimized for coastal purposes. A short validation is done by Hein (2010b). The figure shows the year-to-year variability of four winter periods and indicates that the strength of the year-to-year variability lies in the range of the climate signal. It remains to optimize boundary conditions which originate from the MC. We must discuss bias-corrections as well as the additionally inclusion of processes, which are not adequately solved by climate models. However, the long-tem coastal models provide a new insight into the impact of climate change as well as the impact of the long-term processes on the tidal characteristics.

5 Conclusion

We analyze long-term processes and their statistics form both observations and simulations. The rate of the SLR varies even on the long-term systematically with amplitude, stronger than the signal of climate change. Against the calculations for the rate of global SLR (Church and White, 2006, Woodworth et al, 2009) a significant acceleration is not detectable, but a superposition of several processes. The results of our MC are therefore analyzed by the means of a multi-scale analysis. Our study shows that, due to the large uncertainties in the MC, it is necessary to extract exactly, what “information" still exist at the end of the MC. Additionally, it should be noted, that the description of several physical long-term processes in the MC suffers.

Future investigation should test to add missing processes synthetically into the results of the climate models. Despite all uncertainties of climate models the increase of the strength of the long-term processes is indicated. The change of physical long-term processes causes non-stationary of the statistics. By the use of hydrodynamic models we show that the year-to-year variability is as strong as the climate signal. Future studies must investigate also in long-term simulations of the estuaries to analyze the impacts of the deducted increase of variability on the tidal characteristics.

6 Tables and Figures

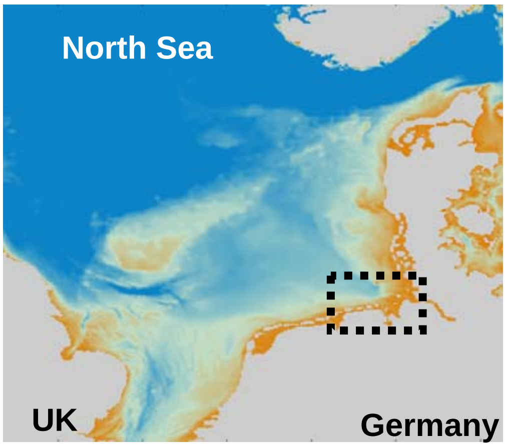

Figure 1: Map of the North Sea. The investigation area is located in the dashed box.

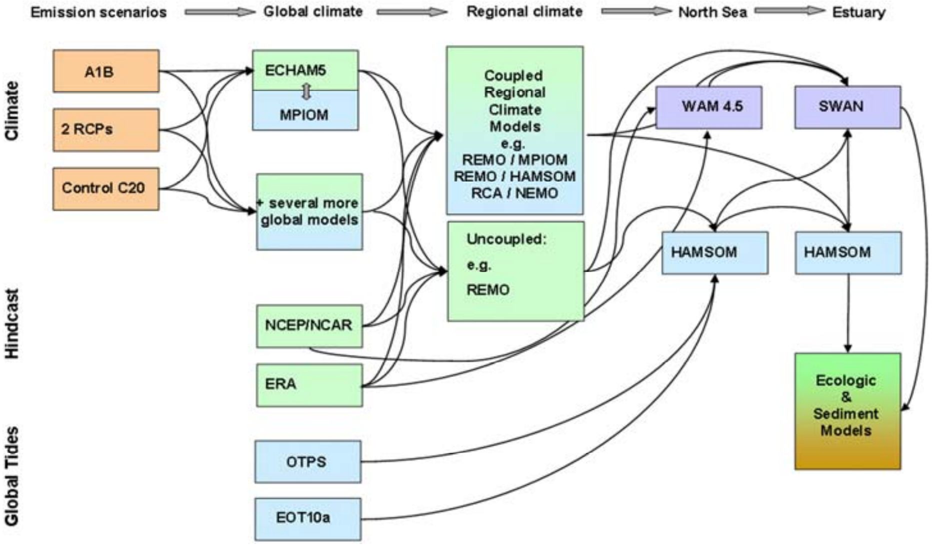

Figure 2: Model-chain from emission scenarios towards the coastal processes.

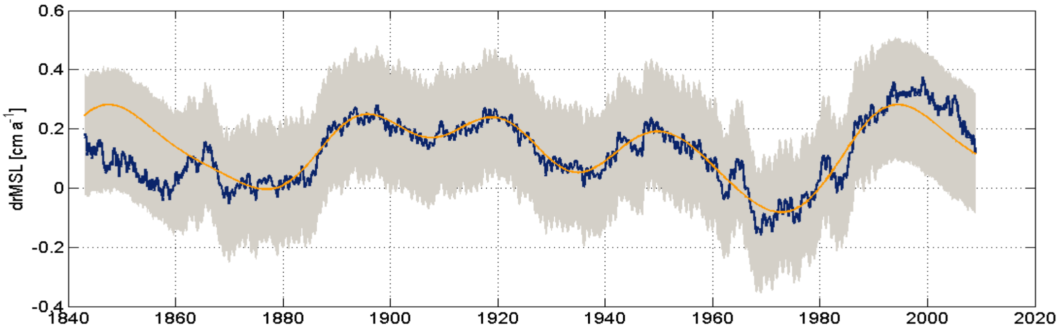

Figure 3: Rate of sea level rise in the southern German Bright.

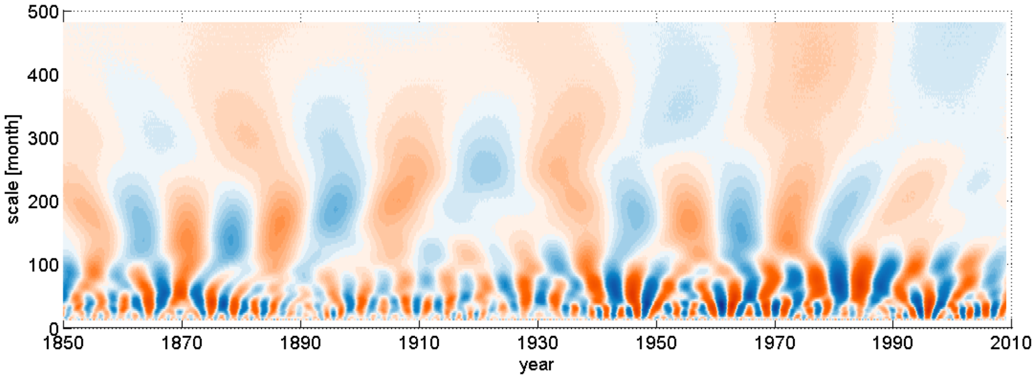

Figure 4: Wavelet transform of the rate of sea level variability. Blue areas indicate rise, red areas, fall of the sea level.

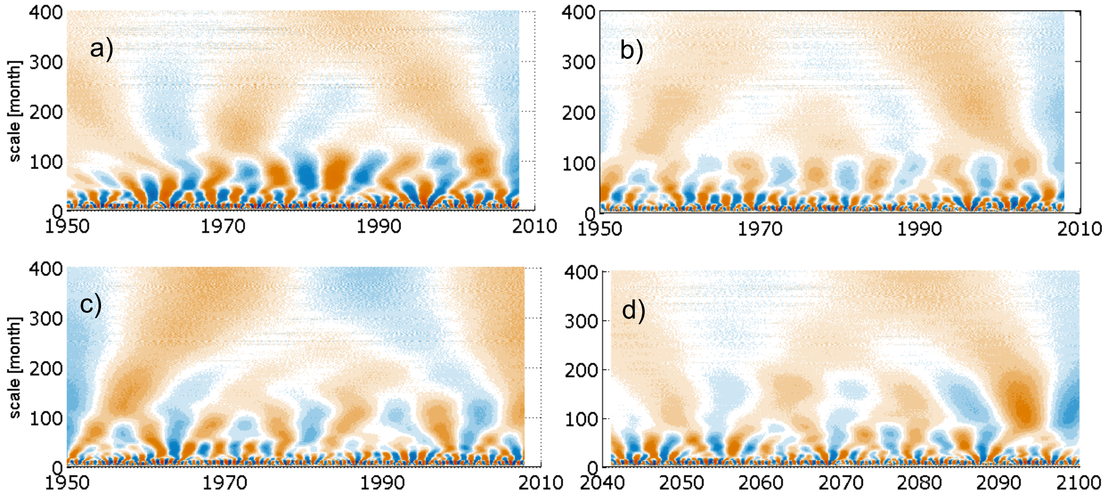

Figure 5: Wavelet transform of the rate of sea level variability. a) Observations, b) Hind-cast, c) climate model reference cast, d) climate model future.

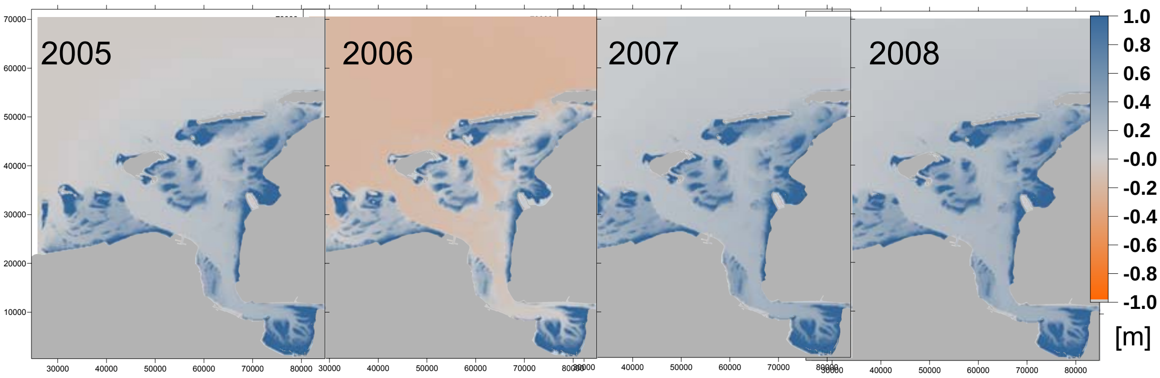

Figure 6: Example of the last step of the MC. Test-run of the coastal numerical model. The result of the mean winter sea level of four years is shown.

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