Simulated future tides and sea state in the Elbe estuary

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Abstract

Long-term simulations of the tides and the sea state in the Elbe estuary are discussed for expected future conditions in relation to present-day conditions and multi-scale variability. Simulations of the tides (1950 – 2100) are conducted with a three-dimensional limited area model of the Elbe estuary, which is offline nested into a baroclinic circulation model of the North Sea. For determining the sea state a statistical approach links the statistics of the water level, the wind speed and direction to the statistics of wave parameters, like significant wave height, wave period and wave direction. The statistical transfer uses results of numerical simulations of wave propagation.

For one typical point in the river mouth monthly maxima, yearly maxima, 19 yearly maxima and the maxima of 100 years are calculated for tidal water levels as well as for significant wave heights. They are statistically analysed afterwards. Two modern methods [detrended fluctuation analysis (DFA) and wavelet analysis (WA) are applied to estimate the temporal correlations of the numerical long term simulations, for both monthly means and maxima.

Process based downscaling of a global climate model into an estuary is a quite well functional method to estimate future changes of mean conditions and maxima – if an uncertainty analysis of the results is done. Non-stationary and multi-decadal hydrodynamic responses of estuaries to climate change can be estimated. A critical challenge in supporting adaptation is the linkage between vulnerability research and coastal management decisions with respect to multi-scale variability.

1 INTRODUCTION

In coastal regions and estuaries physical processes influence many economic, ecologic processes and also security issues. Global climate change has a 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 North Sea coast 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). In order to get the impression of the future changes and the probability of their occurrence, physically consistent long term simulations are needed to describe how wind waves and currents interact and control processes like erosion, sedimentation and biological production.

It is widely accepted, that the 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, which is in this study the mouth of the river Elbe. An almost linear secular rise of about 1-2 mm per year (e.g. Wahl *et al.*, 2010; Hein *et al.,* 2011c) has already been observed in the southern German Bight. The future acceleration of global SLR is expected (IPCC, 2007), historic acceleration for the German Bight is not to be found significant (Hein *et al.*, 2010).

Variability of the SLR is acts on almost all scales. Several of the sales are representative for typical atmospheric timescales of months to several years (Dangensdorf, 2013). The SLR is positively correlated with the changes of the NAO on time-scales of 4 to 7 years (Hein, 2011b; Dangendorf, 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).

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 out boundary of the North Sea model in form of a scenario. Based on this scenario this study estimates monthly maxima, yearly maxima and the maxima of 19 years. Both, tidal water levels and significant wave heights are calculated and statistically analysed.

Tide and wave climate forecasting is one major issue for coastal management. For sedimentation processes often not the mean states the important ones, but the maxima are in the focus of research - simply related to the quadratic law in the calculation of shear stresses. From former studies (Mudersbach *et al.*, 2013; Weisse *et al.*, 2011) it is known that the storm surges and also wave heights in the German Bight vary on long time scales but they show no significant trend. It is expected that extreme sea levels increase primarily as a result of mean sea level changes or as a result of increasing of the tidal amplitudes.

2 APPROACH

2.1 Simulations

The changes in the statistical maxima of water levels and wave parameter, like monthly maximum high water and monthly maximum significant wave height (Hs) 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.

The overall MC 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 the regional climate models down 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 are shown in Figure 1.

The second missing parameter in global climate models is the SLR. This stands in contrast to the importance of the SLR for the future change of the regional tidal system. Since often climate models are volume-conserving, they cannot account for SLR due to thermal expansion. Sea level changes due to increasing fresh water supply from melting off the ice are neglected, too. For the HAMSOM simulations Mathis (2013) induce estimations of the different components of global sea level rise and continually add them onto the sea surface elevation at the open boundaries. Corresponding to the upper limit of the IPCC bandwidth, in this study SLR of about 50 cm from the period 1990-1999 to 2090-2099 is added at the North Sea boundary.

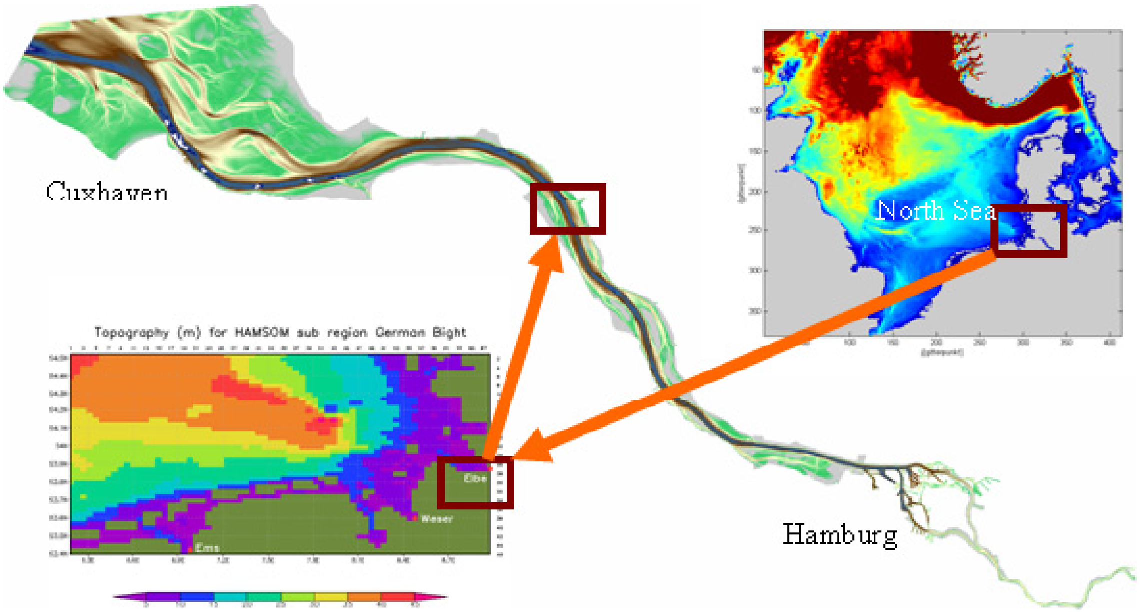

Figure 1: Regional topography used by the simulations

Time-series of water level and wind are derived from the global climate run A1B MPI-OM, which is regionalised to the North-Sea with the offline coupled models HAMSOM/Remo (Pohlmann, 2006) 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 equations can be found in Pohlmann (1996).

The simulation of the estuarine circulation yield several numeric requirements to the model (Hein *et al.*, 2007). Therefore, high-order formulations are used for the momentum equation and the transport equation. The importance of diffusion processes on (de-) stratification in estuaries is considered by sub-grid stochastic simulations: The vertical turbulent viscosity is calculated by a Kochergin-Pohlmann-Scheme (Pohlmann, 1996). The horizontal sub-grid processes are estimated by a Smagorinsky-Scheme (Hein, 2008).

The applicability of the regional circulation model was shown in several studies (Hein *et al.*, 2011a; Hein *et al.*, 2012; Hein *et al.*, 2013). It turns out, that the local model, despite the low resoltution 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). Especially by the use of a climate MC additional stochastic analysis should be used.

To estimate the significant wave hight (Hs) the results of the long term hydrodynamic models are combined with short-term numerical modelling of waves. A flow chart of the calculation scheme for Hs (Mai *et al.*, 2008) is given in Figure 2. For the short-term calculations of wave parameters as a function of water level, wind speed and direction the numerical model SWAN (Booij *et al.*, 1999) is used. The calculations were carried out on a curvilinear computational grid of the topography of the year 2006 with a resolution of approx. 20 m along the river and approx. 2 m across the river (Berkhahn & Mai, 2004).

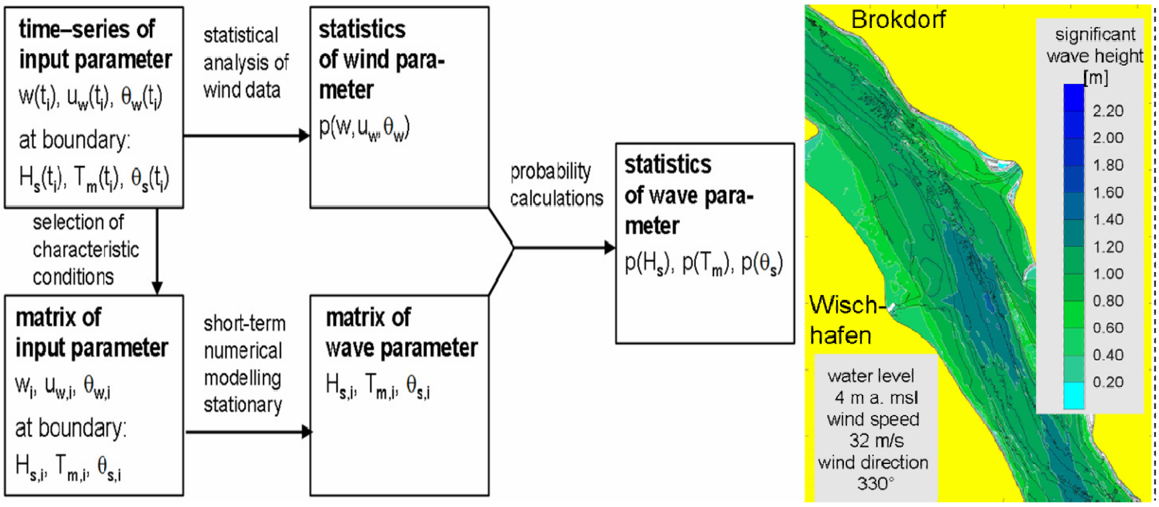

Figure 2: Calculation scheme combining time-series of water level and wind with wave parameters

The wave field is calculated for 840 combinations of different boundary conditions, i.e. water levels and winds. The set of wave simulations is used to derive transfer functions from water level and wind to wave parameters (Figure 3). Between the discrete values the spline interpolation is used. On the right hand side of Figure 3 a typical wave field in the study area can be seen.

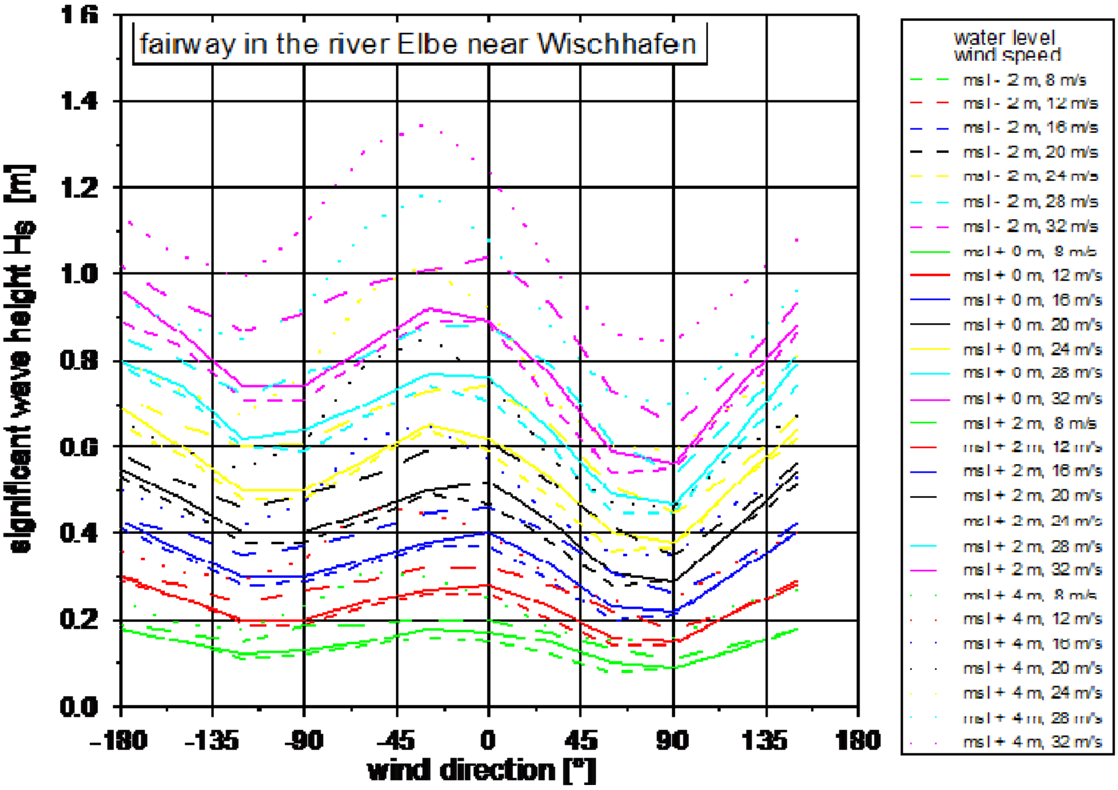

Figure 3: Transfer functions for wave height

2.2 Analysis tools

Hurst (1951) analysis of hydrological data indicates that the fluctuations in hydrology are self-similar over a wide range of time scales, with no single characteristic scale. This should be the same with mean *coastal* hydrological parameters like sea level and sea state. As one conclusion of the Hurst's work can be drawn, that it is general difficult to distinguish trends from long-term correlations. Stationary long-term correlated time series feature persistent behaviour, which may cause the detection of erroneous trends. In the last years, several methods such as detrended fluctuation analysis (DFA, Peng *et al.*, 1994) and wavelet analysis (WA, Torrence & Compo, 1998) have been developed. They are able to determine long-term correlations in the presence of trends.

3 RESULTS AND DISCUSSION

3.1 Monthly, yearly and 19 yearly and 100 yearly Maxima

Figure 4a shows the monthly, yearly, 19 yearly and 100 yearly maxima of the long term simulations in relation to the monthly, yearly and 19 yearly mean sea level. In the mean values the added sea level rise can be seen. The rate of the rise of the maxima differs not significantly from that of the means. The variability of the maximum values is statistically reasonable higher than that of the mean values. Long-term statistical maxima (19 year maxima and 100 year maxima) of the sea level are triggered by single (storm) events. Therefore, no future changes can be predicted by the means of one member of a MC. This means that it can be expected that the SLR published by the IPCC related to the A2B Scenario cannot significantly influence statistical maxima. The relation of the SLR to the powerfulness of one single storm event is low. However, the monthly and yearly maxima underlie a slightly higher mean rise than the mean sea level. This result is important information regarding sedimentation processes or ecologic proposes because these short time maxima may be relevant for these processes.

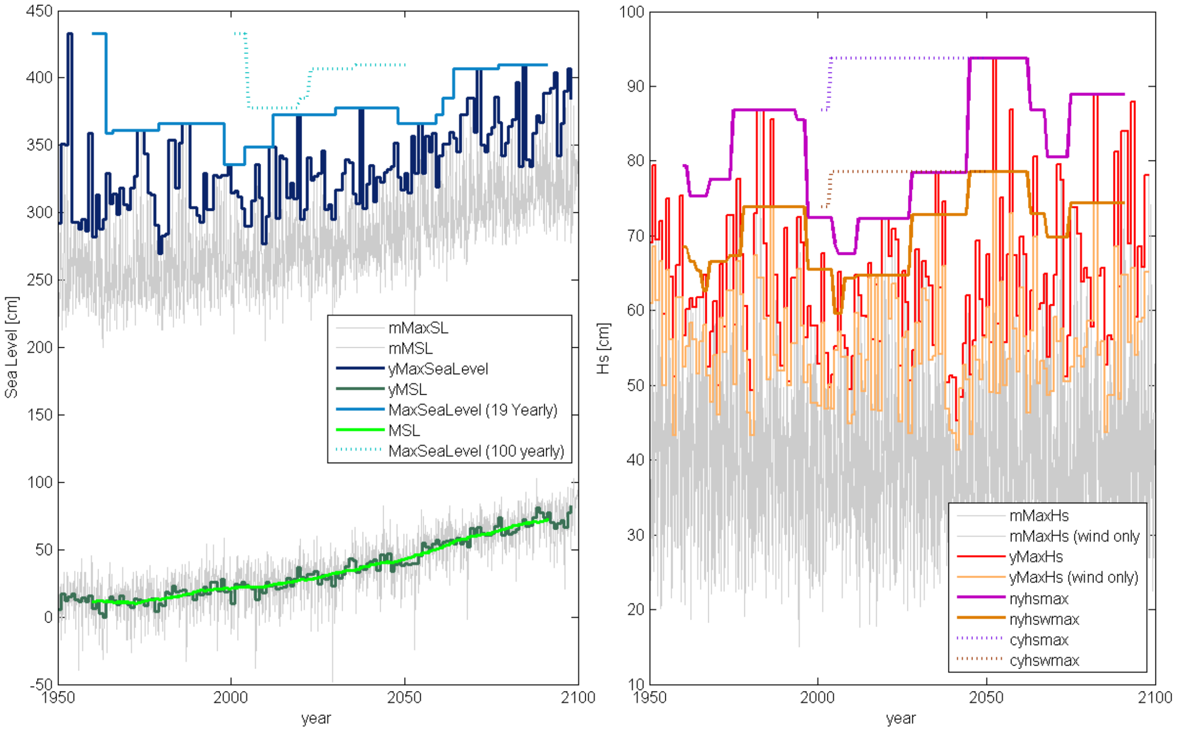

Figure 4: Monthly, yearly, 19 yearly and 100 yearly maxima and mean of sea level (left) and significant wave heights (right)

Figure 4b shows the monthly, yearly and 19 yearly maxima of the long term simulations of the significant wave height (Hs). Two simulations are compared, one including sea level data, the second with a constant sea level with time. If the sea level is included the maxima are slightly higher for all time scales. A clear trend is not to be seen in the monthly mean, nor in the yearly and nor in the 100 yearly maxima. If the difference between the two simulations is taken into account, it seems that as a result of the SLR the 19 yearly maximum increases with time. However, the clear stochastically statement suffers, due to the use of one member of a MC.

3.2 Persistence of Monthly sea levels

By use of the DFA we calculated the Hurst coefficient with the value 1.05 for the monthly mean sea level and 0.88 for the monthly maximum sea level. However, monotonic trends tend to result in an over-estimation of the Hurst exponent and uncorrelated data superimposed on a long-term trend will exhibit autocorrelation (Bhatthacharya *et al.*, 1983). Our time series form the simulations underlie the before given trend in the mean sea level. Therefore we calculated the Hurst coefficient again, based on detrended time series. We calculated the Hurst coefficient for the detrended time series with the value 0.85 for the monthly mean sea level and 0.75 for the monthly maximum sea level.

In detail figure 5 demonstrates that there is a relatively higher intra yearly Hurst coefficient, which indicates the seasonal cycle. The coefficient changes more to white noise in the short term variability of 1 to 4 years. On longer scales the persistence turning more to pink noise which can typically be estimated on such time scales for atmospheric-oceanographic components (Fernández *et al.*, 2003). The results of the detrending of the time series are mostly visible on the longer scales.

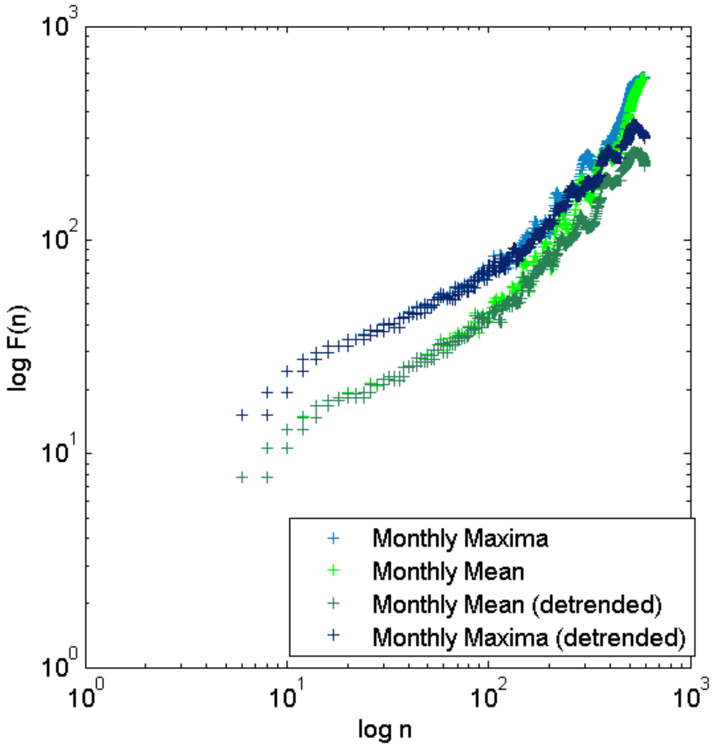

Figure 5: DFA from the monthly mean and maximum sea level

The calculated mean values for the Hurst coefficient are typical for hydrological regimes, which variability is suggested to be somewhere between white noise and pink (1/f) noise. For example Sakalauskienė (2003) calculated for the Nemunas river (Lithuania) the value of 0.67 for the Hurst coefficient. It might be surprising that also the monthly maxima underlie long term persistence. However, Lye & Lin (1994) also estimated the persistence in the yearly maxima of several Canadian rivers.

Our literature research indicates that in coastal sciences the calculation of persistence is not common. However, our result indicates that coastal time-series of sea level are dominate by long term multi-scale variability which complicates the trend estimation and hinders us estimating the acceleration of the SLR.

3.3 Persistence of Monthly significant wave heights

By use of the DFA we calculated the Hurst coefficient with the value 0.4 for the monthly mean Hs and 0.47 for the monthly maximum Hs if considering the sea level variations. For the simulated Hs forced by wind only the DFA results in a Hurst coefficient of 0.4 for the monthly mean Hs and 0.46

for the monthly maximum Hs. Hence the persistence remains the same, which demonstrate that the sea level does not influence the persistence of Hs on a significant level. The results indicate that the significant wave heights are dominated by white noise processes.

In detail, it can be see in Figure 6 that only on intra-annual scales, increased Hurst coefficients are to be found, which indicate the seasonal cycle. Persistence on higher time scales could not be seen. However, our model chain is forced by a global climate model. Bakker & van den Hurk (2012) analyzed the sea level pressure in the North Atlantic region. They estimate a Hurst coefficient in the Range of 0.58 to 0.74 from observations and almost white noise from climate models. So it may be concluded that there should also persistence in the significant wave heights if the estimations base on observations.

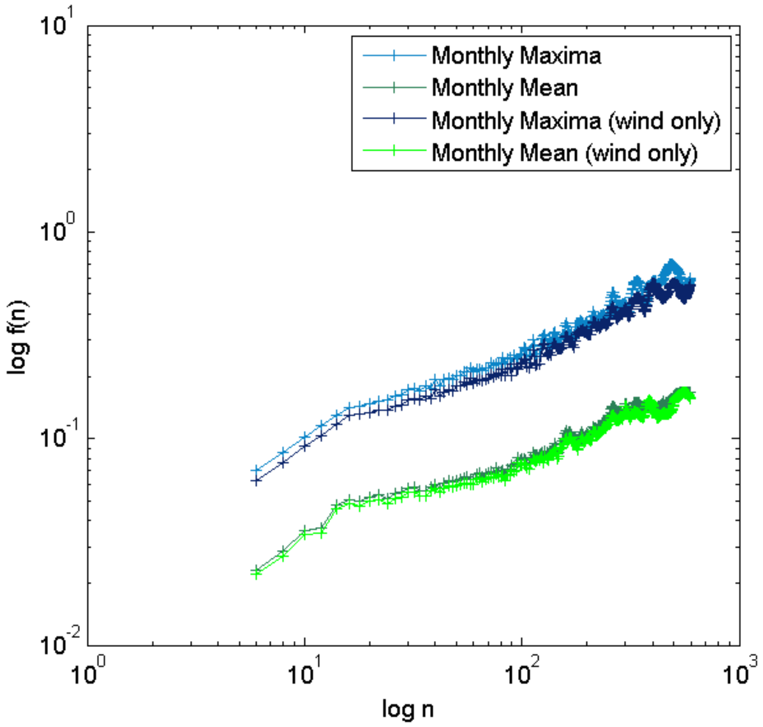

Figure 6: DFA from the monthly mean and maximum sea significant wave heights

3.4 Wavelet Power

By the use of a wavelet transform we estimate the important fluctuations in the simulations of sea level and significant wave heights. Figure 7 shows the result of the estimated wavelet power (WP) for each scale and parameter. The results from the DFA analysis are confirmed, in such way that the WP of Hs is decreasing with increasing scale, while the WP of the monthly maximum sea level is constant and the WP of the monthly mean sea level increases with scale. The difference between Hs calculated with and without sea level is weak.

The importance of the yearly cycle (1) is indicated. The second peak (2) is in the range of 3, while the third (3) has a lengths of 9 years, both maxima together represent something like the NAO cycle in the simulation. The 4th peak can only be seen in Hs but not in the sea level, the length of the scale is about 20 years. On hint to the scale can be found in Escudier *et al*. (2013). They deduced the mode of 20 years in coupled ocean-sea ice-atmosphere variability mode in the North Atlantic in a Global Climate Model. It is difficult to find a reason that the sea levels underlie no peak in this scale. The only reason one might find is a change in wind direction, further studies might go into detail.

The last pronounced peak in wavelet analysis can be observed in the sea level time series only and has a period of 30 years. It may be the response of the lateral boundary forcing of the North Sea to the multidecadal oscillation of the Atlantic Meridional Overturning Circulation (AMOC) reproduced by the Global Climate model. In a sensitive study using such kind of a model Huang *et al.* (2012) significant fluctuations were also found on that scale in the AMOC.

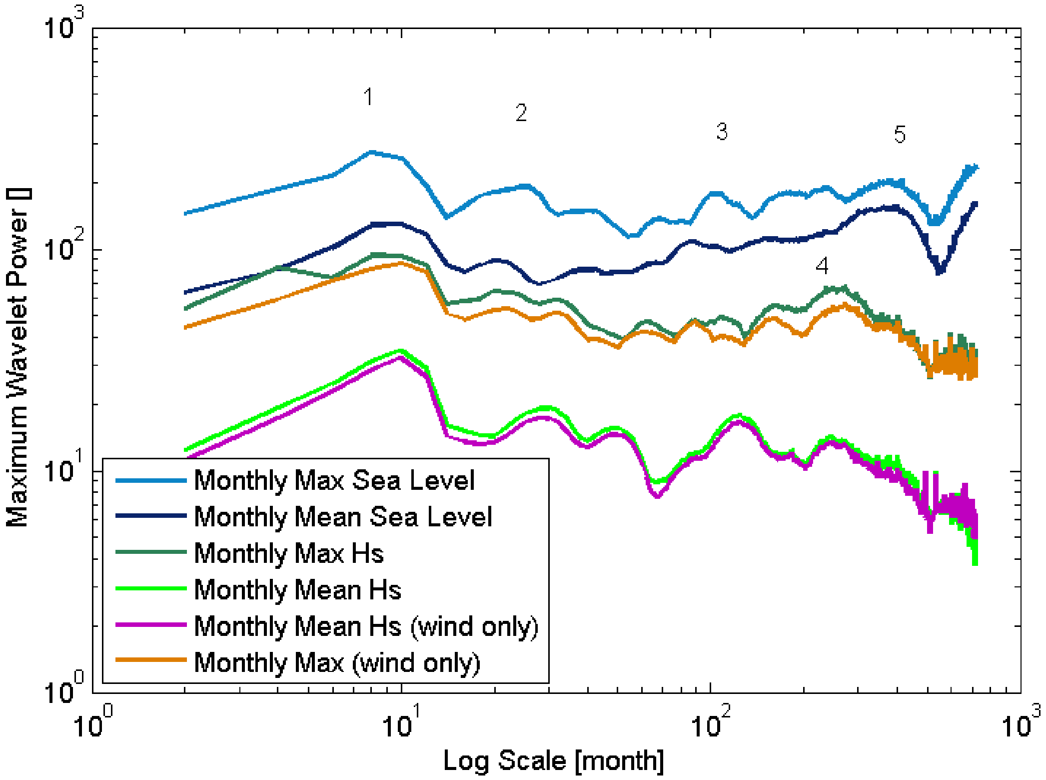

Figure 7: Wavelet Power from the monthly mean and maximum sea significant wave heights

4 CONCLUSION

Result from the so called model chain used in the KLIWAS framework are presented and analysed. Our study calculates the persistence of these downscaled climate models. The persistence found in sea level simulations is in the same order like it is known from river hydrology. The differences between the sea level simulations and the wave simulation is mainly due to long term memory which can be found in the sea level data. The typical explanation might be the slow response of the ocean to a fast atmosphere. On longer scales the persistence is not explained by atmospheric forcing. One conclusion could be drawn that stochastic analysis using the sea level – atmospheric relations must fail to reproduce the multi decadal variability.

For the sea level multi-decadal variability must be taken into account if trends in sea level are the subject of interest. For sea level maxima on longer (19 and 100 yearly) scales no trend or systematic change could be found with the technics used in this study. They are triggered by suggested random single events. For the significant wave height already the monthly mean and monthly maxima are just white noise. Therefore the long term predictability of this parameter is questionable. However, it is know that global climate models tend to underestimate the atmospheric persistence.

Process based downscaling of a global climate model into an estuary is a quite well functional method to estimate future changes of mean conditions and maxima – if an uncertainty analysis of the results is done. Non-stationary and multi-decadal hydrodynamic behaviour of an estuary to climate change are inherent uncertainties. A critical challenge in supporting adaptation is the linkage between vulnerability research and coastal management decisions with respect to this multi-scale variability.

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