Project: **1019**
Project title: **SeaStorm**
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Working report (period 2018-01-01 – 2018-10-30)

To investigate the long-term variability of extreme storm floods and their associated forcing mechanisms we employ the regionally coupled atmosphere-ocean model REMO-MPIOM (Mikolajewicz et al., 2005, Sein et al., 2015) to dynamically downscale the climate variations from the Last Millennium simulation from MPI-ESM-P using a coupling time-step of one hour.

During the last term, the downscaling simulation has been completed for the years 1000-2000 providing hourly sea level fields. Results from the analysis of this data is shown in the following.

Model validation

Comparison of the simulated extreme sea levels (ESL) with observations from the tide gauge record in the German Bight (data from AMSeL project, see Jensen et al., 2011) shows that the model reproduces observed storm surge statistics, both in terms of magnitude above mean high waters (see return value plot in Fig. 1) as well as seasonality (not shown). Further, the underlying processes on a daily scale with fast moving cyclones from predominantly westerly directions are well-captured. Yet, the large model spread for high return periods (simulated 100 year return values vary by more than 1 meter) indicates that the statistics of the high-end extremes exhibit considerable variability on centennial scales and stresses the uncertainty related to estimating extreme storm surges from a limited sample size, especially for future extremes.

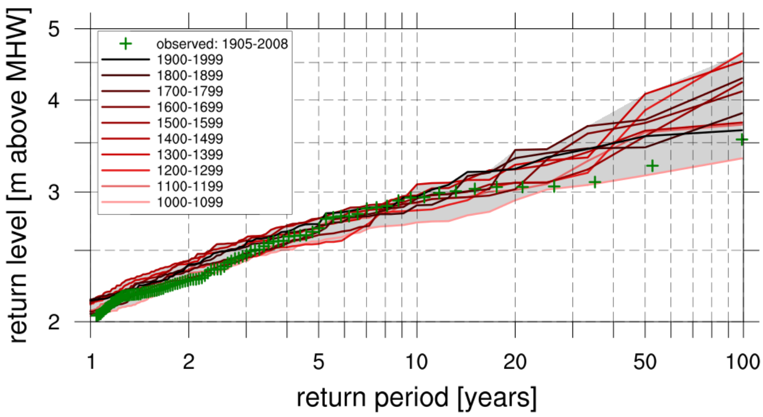

Figure 1: *Return value plot of modelled ESL at Cuxhaven [m over MHW] (colored lines representing 100-year long chunks of the full 1000 years) against observations from tide gauges (green crosses).*

Extreme storm flood variability

The variability of extreme sea levels has been investigated based on annual maximum sea levels. Since storm floods primarily occur in winter, annual statistics are computed for July-June. To account for the independence of consecutive extremes, we prescribe a minimum separation distance of 72 hours between extremes.

The resulting time series of ESL over the last 1000 years is shown in Fig. 2, together with the background sea level (BSL) in terms of the winter median and the frequency of storm floods as events binned per decade, following the storm surge definition after the Federal Maritime and Hydrographic Agency (BSH). ESL do not exhibit any long-term trend and extreme storm floods have occurred during the entire last Millennium, independent of long-term externally forced temperature variations (e.g. the Maunder Minimum). Yet, ESL exhibit large interannual variations (stddev = 0.5 m) and pronounced variability on multiple timescales.

As the histogram in Fig. 2 indicates, years with one particularly *extreme storm surge* do not necessarily coincide with a greater occurrence of more moderate storm floods, and elevated BSL and the modulations between ESL and BSL are not always coherent: The correlation between BSL and ESL is low and highly variable over time (not shown), with longer periods of insignificant correlation between the two. This suggests that ESL and BSL variations are decoupled over large parts of the last millennium.

This is related to the different variability spectra between ESL and BSL. Spectral analysis shows that ESL exhibit white power spectra and do not show preferred modes of variability (Fig. 3a). The large variability at high frequencies and the flat power spectrum stress the influence of the atmosphere; in contrast, BSL in terms of annual median sea level (Fig. 3b, separately shown for both winter and summer) exhibits a red spectrum with more power on multidecadal and centennial timescales, stressing the influence of the ocean which carries the "memory" of the system. In summer, when the wind effect on the water surface is lower, the high-frequency variability is reduced and thus lower frequencies are dominating the power spectrum. The large but white variations of ESL together with the independence of BSL variations stress the uncertainty in estimating ESL changes, esp. for the typically short instrumental records.

A second downscaling of the last 500 years using the same global GCM simulation has shown that the temporal variations remain unchanged (Fig. 4); that is, ESL variability is not related to the downscaling, but rather to the parent GCM simulation, i.e. either its internal variability or external forcing. Only the absolute magnitude of single events differs by up to 1 m in both downscalings. How internal variability of the parent GCM simulation and external forcing compare shall be investigated in the next allocation period.

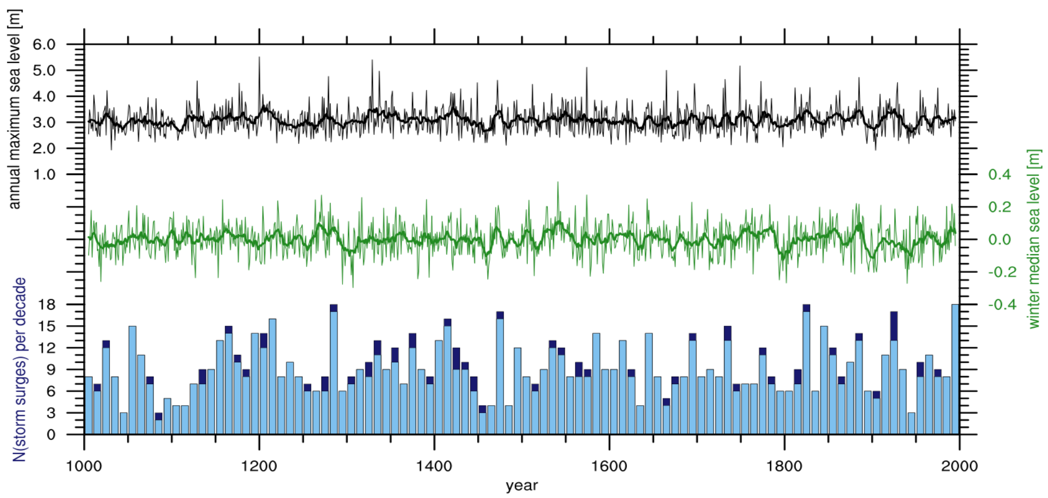

Figure 2: *Simulated ESL (black), winter median sea level (green) as well as number of heavy (blue bins) and extreme (dark blue bins) storm surges per decade at Cuxhaven. Thick lines correspond to the 11-yr running mean.*

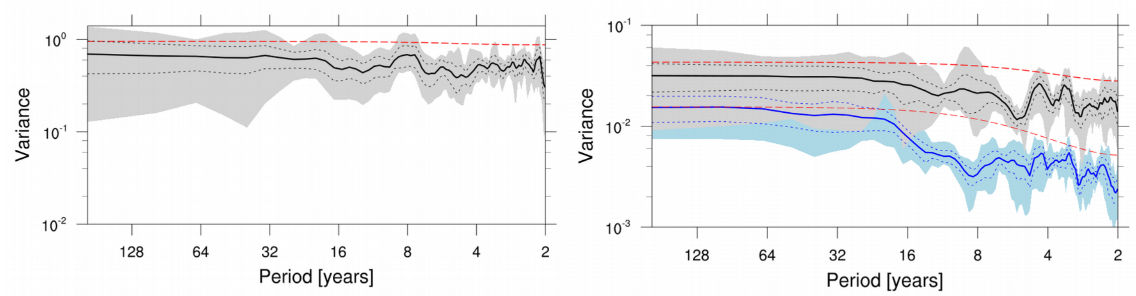

Figure 3: *Power spectrum of (left) annual maximum sea level and (right) annual winter (black) and summer median (blue) sea level (right) at Cuxhaven. Thick lines (shading) correspond to the average (range) over 9 overlapping 200-yr periods of the full time series; red lines indicate the 95% confidence bounds using a theoretical Markov spectrum.*

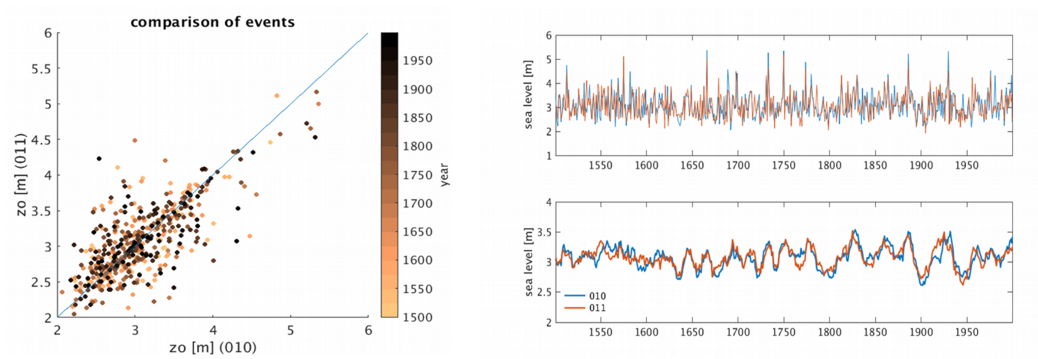

Figure 4: *Comparison of the two downscalings '010' and '011' from the global simulation 'past1000r2'*

Relation to large-scale climate variability

In order to investigate large-scale climate patterns associated with enhanced storm surge activity, we relate periods where the extreme sea level time series exceeds its mean plus 1.5 times its standard deviation with gridded winter sea level pressure (SLP) as an indicator of multi-decadal climate variability and compare them to those related to enhanced background sea level.

The SLP constellation associated with anomalously high BSL (not shown) with a more meridional dipole axis resembles the positive NAO (correlation of r=0.5 for BSL). Such link between NAO and North Sea BSL variations has also been described using observations (e.g. Wakelin et al., 2003, Dangendorf et al., 2014a). In contrast, the SLP pattern favoring high ESL (Fig. 5a) differs from the NAO and shows a dipole over the northeast Atlantic, with centers of action over northeastern Scandinavia and the Gulf of Biscay. This dipole leads to a more northwesterly wind component and less zonal geostrophic flow. The SLP pattern resembles the one found by Dangendorf et al. (2014b) for cross correlations of SLP and daily surges at Cuxhaven and might point to an influence the Scandinavian Pattern in its negative phase (SCA-) onto the NAO centers of action, such as described by Chafik et al. (2017).

Using this dipole's two centers of action (Biscay – Northeast Scandinavia) to define a SLP index based on the normalized SLP difference between those points and regressing the time series of this index onto gridded annual maximum sea level shows highest values in the center of the German Bight as well as in the southern Baltic Sea (see Fig. 5b). This suggests coherent ESL variations along eastern North Sea and Baltic Sea through common forcing. A wavelet coherence analysis between this tailored index and ESL at Cuxhaven shows that this relationship mainly acts on multidecadal to centennial timescales (not shown).

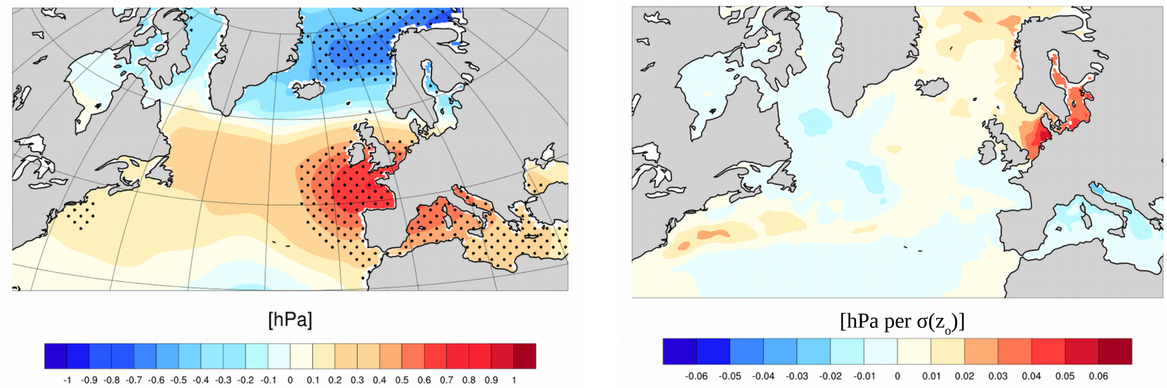

Figure 5: Left: *Positive composites of winter SLP anomaly on ESL at Cuxhaven. Stippling marks areas significant at the 5% confidence level.* ***Right:*** *Pointwise regression of tailored SLP index onto annual maximum sea level.*

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