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A Consistent Return Level Assessment Considering Present Day and Future Mean Sea Level Conditions

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Die Küste, 81 (2014), 525-539

A Consistent Return Level Assessment Considering Present Day and Future Mean Sea Level Conditions

Arne Arns, Jürgen Jensen and Thomas Wahl

Summary

This paper presents the result from combining statistical and numerical models to assess return levels and return periods of extreme water levels under current and possible future mean sea level conditions. As water level records are limited in some parts of the study area, the proposed method is based on a numerical multi-decadal model hindcast of water levels for the whole of the North Sea. Predicted water levels from the hindcast are bias-corrected using the information from the available tide gauge records. These bias-corrected water levels are then used to calculate return water levels for the entire coastline of Schleswig-Holstein. Additionally, the impact of sea level rise on extreme water levels is investigated using the same numerical model and conducting a second hindcast that considers the same atmospheric forcing but adding +0.54 m to the MSL to explore the effects of SLR on storm surges in the investigation area. At most locations, the second model run leads to changes in the storm surge and return water levels that are significantly different from the changes in MSL alone.

Keywords

storm surges, numerical modelling, statistical assessment, sea level rise, return levels

Zusammenfassung

Dieser Beitrag zeigt die Kopplung statistischer und numerischer Modelle zur Ermittlung der Höhen und Häufigkeiten extremer Wasserstände. Die Untersuchungen erfolgten am Beispiel der Schleswig-Holsteinischen Nordseeküste. Da die zur Verfügung stehenden Wasserstandsaufzeichnungen in einigen lokalen Bereichen des Untersuchungsgebietes limitiert sind, wurden die benötigten Wasserstandsinformationen mit Hilfe eines hydrodynamisch-numerischen Modells generiert. Die modellgenerierten Wasserstände wurden mit den Wasserstandsinformationen an den vorhandenen Pegelstandorten Bias korrigiert. Die Bias korrigierten Modellwasserstände wurden anschließend für die statistische Ermittlung extremer Wasserstände entlang der gesamten Küstenlinie Schleswig-Holsteins verwendet. In einem weiteren Modelllauf wurde der Einfluss eines möglichen Meeresspiegelanstiegs von 0,54 m auf Extremwasserstände untersucht. In den meisten Bereichen zeigt dieses Szenario einen Anstieg in den Extremwasserständen, der signifikant über den Anstieg des mittleren Meeresspiegels hinaus geht.

Schlagwörter

Sturmfluten, numerische Modellierung, statistische Analysen, Meeresspiegelanstieg, Wiederkehrintervalle

Contents

1 Introduction

Storm surges are among the most hazardous geophysical risks in coastal regions and are often associated with significant losses of life and property (VON STORCH 2012). The North Sea, and the German coastline in particular, has a long history of severe storm surges. For example, a large storm occurred in the German Bight in 1962 and more than 300 people lost their lives (BÜTOW 1963; VON STORCH and WOTH 2006). It is thus essential that the flood risk is accurately evaluated and defences are upgraded where necessary (COLES and TAWN 2005; HAIGH et al. 2010a).

The design of coastal defences is often based on some form of statistical models (DIXON and TAWN 1994). These models are mostly based on extreme value statistics, a special discipline in probability theory that deals with rare events, such as coastal floods (COLES 2001). Over the last five decades, several different extreme value analysis (EVA) methods for estimating the heights (i.e. return levels) and occurrence probabilities (i.e. return periods) of extreme water levels have been developed (see HAIGH et al. 2010a for an overview). There is, however, currently no universally accepted method available. Instead, different methods have been applied on transnational but also on national scales resulting in a heterogeneous level of protection. Therefore, it is difficult to assess the level of protection offered by defences across the different states. To provide coastal protection of consistent standard, design levels need to be consistently calculated based on an objectively defined model setup.

Furthermore, an accurate assessment of return water levels using traditional extreme value analysis methods requires records of sufficient length (> 30 years; HAIGH et al. 2010a), indicating one of the largest pitfalls of extreme value models, as the availability of measured water levels is limited in many regions. In the German Bight, multi-decadal records of high and low waters exist at several sites, but for some regions (e.g. at some small islands in the German Wadden Sea) no or only very short and incomplete time series exist. In practical applications it is often assumed that at-site (i.e. using local water level records from a tide gauge station) estimates can be transferred to un-gauged surroundings. Nevertheless, water levels in the German Bight can differ significantly between stations as they are strongly influenced by shallow water effects and the complex topography of the coastline (see e.g. JENSEN and MÜLLER-NAVARRA 2008). Simply transferring information about the likelihood of extreme water level events from gauged to surrounding un-gauged sites is thus highly debatable and can cause erroneous return level estimates. Thus, more elaborate procedures to adequately transfer water level information are required

The return water level assessment is not only uncertain regarding the heterogeneous assessment procedures or the limited water level information but also with respect to possible future projections related to climate change. Recent analyses highlight that global MSL rose by 3.2 mm/year from 1971 to 2010. As consequence from an increased ocean warming and the increased loss of mass from glaciers and ice sheets, future rates of sea level rise (SLR) are expected to very likely exceed those observed during 1971 to 2010 (IPPC 2013). Until now, most coastal protection strategies assumed that changes in extreme water levels during the 21st century will be dominated by changes in MSL and design water levels were raised by exactly the same amount of the projected SLR (SMITH et al. 2010). These results are limited to the assumption of a similar long-term behaviour between mean and extreme water levels. For the German Bight, however, MUDERSBACH et al. (2013) showed that trends in extreme high water levels differed significantly from those in MSL from the mid-1950s to approximately 1990, indicating the presence of non-linear interactions between the different sea level components (i.e. MSL, tide, surge). This is contrary to most other locations around the world, where observed changes of extremes were found to be equal to those of the MSL. In order to plan adequate adaptation strategies to cope with climate change challenges it is thus essential that reliable projections of extreme water level changes become available.

2 Data and study area

The methodologies and results presented hereafter were developed in the '*ZukunftHallig*' research project investigating the future development of the North Frisian Halligen. The Halligen are small low lying islands located off the coastline of Schleswig-Holstein (the most northern federal state) in Germany (see the blue shaded areas in Fig. 1b). The Halligen are surrounded by the North Frisian Wadden Sea which was added to UNESCO´s World Heritage List in 2009.

For the analyses a number of tide gauges along the coastlines of the United Kingdom (UK), the Netherlands (NL), France (FRA) and Germany (GER) (see Tab. 1) are used and their locations are shown in Fig. 1. All water level records are referred to the German reference datum 'Normalhöhennull' (NHN). To calibrate a numerical model, high resolution tide gauge data from the inner North Sea were used, covering the British East Coast, the English Channel, the Dutch coastline and the German Bight. The calibration was performed using the storm surge event of November 1st, 2006. For the bias-correction of the model output, high water levels for the period from 1970 to 2009 from all German Bight tide gauges except Pellworm Harbour were used; the water level record of Pellworm Harbour was used for validation purposes.

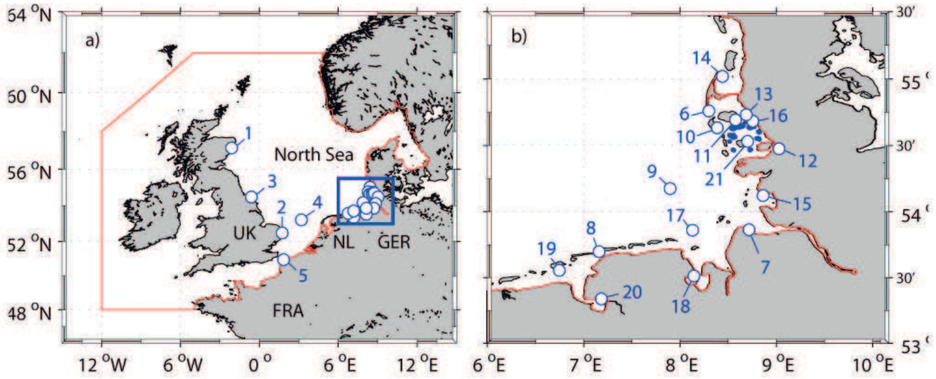

Figure 1: Study area with a) tide gauges in the entire model domain and b) tide gauges in the German Bight.

Table 1: Tide gauges used to calibrate, correct and validate the model output. The (*) indicates that tidal high and low waters are available; at all other stations, high resolution values (1-minute) were used. The marker (✓) indicates in which computational step the data was used.

#	tide gauge location (label)	country	years	availability [%]	cal.	cor.	val.
1	Aberdeen (ABE)	UK	2006	100	✓	-	-
2	Lowestoft (LOW)	UK	2006	100	✓	-	-
3	Whitby (WHI)	UK	2006	100	✓	-	-
4	K 13a Platform (K13)	NL	2006	100	✓	-	-
5	Calais (CAL)	FRA	2006	89.6	✓	-	-
6	Hörnum (HOR)	GER	2006 1970-2009	98.9 100*	✓ -	- ✓	✓
7	Cuxhaven (CUX)	GER	1970-2009	100*	✓	✓	✓
8	Norderney (NOR)	GER	1970-2009	100*	✓	✓	✓
9	Helgoland (HEL)	GER	1970-2009	100*	-	✓	✓
10	Wittdün (WIT)	GER	1970-2009	100*	-	✓	✓
11	Wyk (WYK)	GER	1970-2009	100*	-	✓	✓
12	Husum (HUS)	GER	1970-2009	100*	-	✓	✓
13	Dagebüll (DAG)	GER	1970-2009	100*	-	✓	✓
14	List (LIS)	GER	1970-2009	100*	-	✓	✓
15	Büsum (BUS)	GER	1970-2009	100*	-	✓	✓
16	Schlüttsiel (SCH)	GER	1970-2009	100*	-	✓	✓
17	LT Alte Weser (LTA)	GER	1970-2009	100*	-	✓	✓
18	Wilhelmshaven (WIL)	GER	1970-2009	100*	-	✓	✓
19	Borkum FB (BOR)	GER	1970-2009	100*	-	✓	✓
20	Emden (EMD)	GER	1970-2009	100*	-	✓	✓
21	Pellworm Hafen (PEL)	GER	1970-2009	100*	-	-	✓

3 Return level assessment

A recent assessment on the general performance of the two main direct extreme value analysis methods (i.e. the block maxima (BM) method and the peaks over threshold (POT) method) and their applicability to water level records in the German Bight was conducted in a companion study by ARNS et al. (2013). The return level and return period assessment in this paper is based on these recommendations. Results from that study showed that the POT method generally yields better results than the BM method if the model set-up is carefully chosen. The POT method is based on the assumption that the sample (i.e. all values above a threshold) is characterized by the generalized Pareto distribution (GPD). The POT sample is created choosing all values of a record that exceed a predefined threshold. The threshold selection is often subjective and this can potentially lead to different outcomes, especially when comparing the results from many sites along a coastline. In analyzing different threshold selection criteria, ARNS et al. (2013) showed that the 99.7th percentile leads to stable and consistent results in the German Bight. Furthermore, it was shown that the storm surge of 1976 has to be included in the statistical analyses; this event was the highest one ever recorded in large parts of the German Bight. The approach recommended by ARNS et al. (2013) for estimating return levels in the German Bight with minimal subjectivity comprises the following steps:

- Use a high water peak time series starting in 1976 or earlier as input data.
- Create a stationary dataset using a 1-year moving average trend correction of the high water peaks.
- Create a sample from all 99.7th percentile threshold exceedances of the high water peaks.
- Use the extremal index for declustering.
- Fit the GPD to the extreme value sample.
- Use the maximum likelihood estimation (MLE) for parameter estimation (see. e.g. SMITH 1986; HOSKING and WALLIS 1987).

4 Methods

4.1 Numerical model setup

To generate continuous water levels for the entire German Bight, a 40-year hindcast for the period from 1970 to 2009 was conducted with a process-based hydrodynamic numerical model. A two-dimensional, depth-averaged barotropic tide-surge model of the entire North Sea has been configured using the Danish Hydraulic Institute's (DHI) Mike21 FM (flexible mesh) model suite. The software is based on the numerical solution of the incompressible Reynolds averaged Navier-Stokes equations; the spatial discretization is achieved using a flexible mesh. The model was configured within a coastline provided by the National Oceanic and Atmospheric Administration (NOAA) with a resolution of 1:250.000 km (http://www.ngdc.noaa.gov/mgg_coastline/). The resolution of the coastline was resampled to 30 km along the open boundaries, increasing to 10 km in the northern- and southern-most parts of the European mainland coastline. In between these locations (Scandinavia, the Netherlands, Belgium, France), the resolution was successively resampled until reaching a maximum resolution of 1 km in the German Bight.

The bathymetric data, interpolated onto the model grid (see Fig. 2), was obtained from various sources. In the northern part of the German Bight, high resolution (~ 15 m) survey maps of the Wadden area provided by the Schleswig-Holstein Agency for Coastal Defence, National parks and Marine Conservation (LKN-SH) were used. In this particular area, the Halligen are located. To account for influences on currents resulting from these small islands, a Digital Elevation Model (DEM) covering all of the ten existing Halligen was integrated into the model. The DEM was also provided by the LKN-SH. In the remaining parts of the German Bight, a bathymetric dataset with a resolution of 1 nautical mile provided by the Federal Maritime and Hydrographic Agency (BSH) was interpolated onto the grid. Apart from the German Bight, the General Bathymetric Chart of the Oceans (GEBCO) data provided by the British Oceanographic Data Centre (BODC) with global coverage and a resolution of 0.5° was used. All datasets were corrected to the German reference datum NHN.

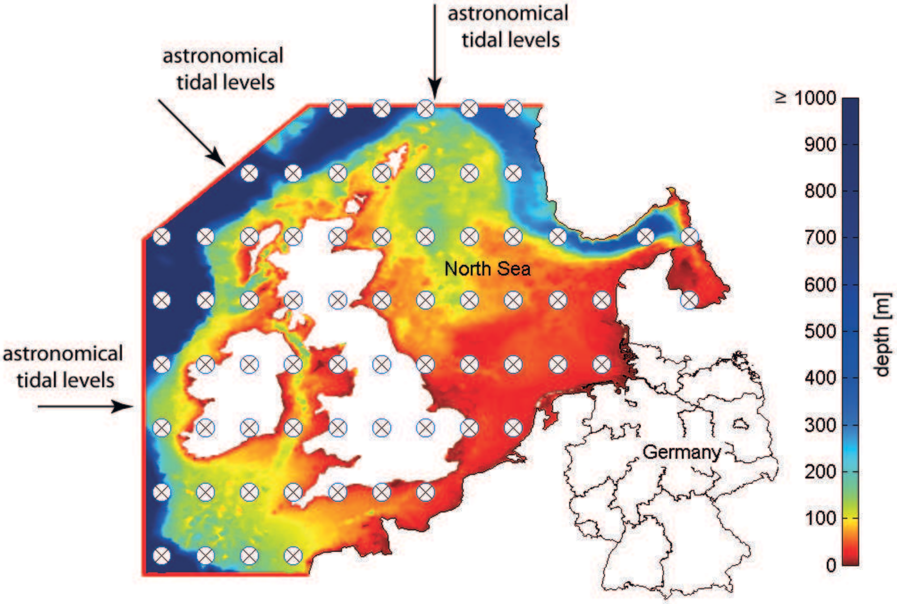

Figure 2: Model domain (outer boundary), bathymetry (according to the legend) and locations of atmospheric (crosses) and tidal (red line) boundary conditions.

At the open boundaries, the model was driven by astronomical tidal levels (see Fig. 2). These were derived from a global tide model provided by MIKE21 (DHI), including the eight primary harmonic constituents (K_1, O_1, P_1, Q_1, M_2, S_2, N_2 und K_2, see e.g. ANDERSEN 1995). Additionally, the Mean Sea Level (MSL) was considered using an index-time series for the entire North Sea from WAHL et al. (2013); the time series was derived using data from 30 tide gauges located around the North Sea basin. As each year of the considered 40- year hindcast was run separately, the MSL at the open boundaries was adjusted according to the annual average MSL values from the index time series.

The surge component was generated by forcing the model with mean sea level pressure fields and u and v components of 10 m wind fields provided by the Cooperative Institute for Research in Environmental Sciences (CIRES) 20th Century Project (COMPO et al. 2011) of the Earth System Research Laboratory, US National Oceanic & Atmospheric Administration (NOAA). These fields are available with a spatial resolution of 2° and a temporal resolution of 6 hours (3 hours in the forecast).

The model was run for each year with a two day warm up period (using longer warm up periods did not show any changes) and results were stored at an interval of 10 minutes for every model grid point. A calibration was performed by using a stepwise variation of the bed resistance and comparing the simulated and observed water levels. For this purpose, the storm surge of the 1st November 2006 was used. Simplified, constant Manning's n-values were used spatially across the entire model domain. The evaluation of the models performance was conducted using the *Coefficient of determination (r^2),* the *Index of agreement (d)* and the *Root Mean Squared Error (RMSE)* (see KRAUSE et al. 2005 for a description of different efficiency criteria). The calibration results are shown in Tab. 2, highlighting that the overall agreement was highest along the UK coastline. Slightly higher differences occurred in the German Bight and are most probably attributed to using one representative bed resistance instead of defining regions of different resistances as well as from shallow water effects that occur in this region and which are possibly not captured properly by the model.

Table 2: Efficiency criteria based on the models best fit.

Criteria	ABE	WHI	LOW	CAL	K13	HÖR	CUX	NOR
r^2 [-]	0.97	0.95	0.86	0.94	0.85	0.91	0.88	0.89
d [-]	0.99	0.99	0.96	0.98	0.96	0.98	0.96	0.97
RMSE [cm]	13.26	19.76	17.25	33.20	14.61	16.64	31.08	21.92

4.2 Bias-correction

The calibration exercise allowed us to minimize the differences between the observed and the modelled water levels (bias) at individual stations but there are still some differences present. The possible sources of such differences are multifarious including the parameterization that is conducted in the model set-up, allowing for a range of different strategies. Furthermore, all water level observations are prone to natural and anthropogenic influences that cannot entirely be captured by a numerical model. For instance, the wind fields that were used have a temporal resolution of 3 hours and a spatial resolution of 2°; for simulating storm surges, this might be too coarse in order to capture all local meteorological effects. The bias can also be attributed to input deficiencies e.g. resolution or scaling effects. With regards to extreme value analyses, this bias can produce large discrepancies in return water level estimates, particularly at higher return periods.

Thus, the modelled water levels are corrected prior to performing the extreme value analysis. The bias correction can be assumed as a function to transfer the modelled variable into a corrected variable (PIANI et al. 2010). This function is created by describing the differences between a pair of variables (e.g. observed and modelled water levels at a tide gauge station) with a parametric or a non-parametric fit (MUDELSEE et al. 2010). In this paper, we use a bias correction method (for more details see ARNS et al. 2013 and ARNS et al., in review) to derive reliable water level data covering the entire German Bight and the period 1970 to 2009, i.e. a period where many tide gauge records exists. A non-parametric transfer function for each individual year of the 40-year hindcast is used.

The bias correction is based on three computational steps. Firstly, high water levels of observed x_o and modelled water levels x_m are computed and sorted in ascending order. Secondly, the differences (bias) between the cumulative distribution functions (CDF) of observed $Q\left(x_{o,js}\right)$ and modelled $Q\left(x_{m,js}\right)$ high waters at tide gauge station s and for year j are calculated as follows:

$$B_{c,js} = Q\left(x_{o,js}\right) - Q\left(x_{m,js}\right) \tag{1}$$

The differences ($B_{c,js}$) are added to the distributions of the modelled high waters $Q\left(x_{m,js}\right)$ in order to eliminate the bias at each individual station; the resulting values correspond to the high waters derived from tide gauge records:

$$Q\left(x_{o,js}\right) = B_{c,js} + Q\left(x_{m,js}\right) \tag{2}$$

This procedure can be used to eliminate the bias at each gauged station and for each period where observational data is available. Fig. 3b exemplarily shows the distributions of observed (black line) and modelled (red line) high waters using the Hörnum tide gauge station as a case study. The bias, i.e. difference between the two distributions according to Equation (1), is shown as blue line. Any bias having a probability between 0 and 1 yields a value to correct the modelled data. For instance, the correction for Q(x = 0.2) amounts to Δh = 4.95 cm.

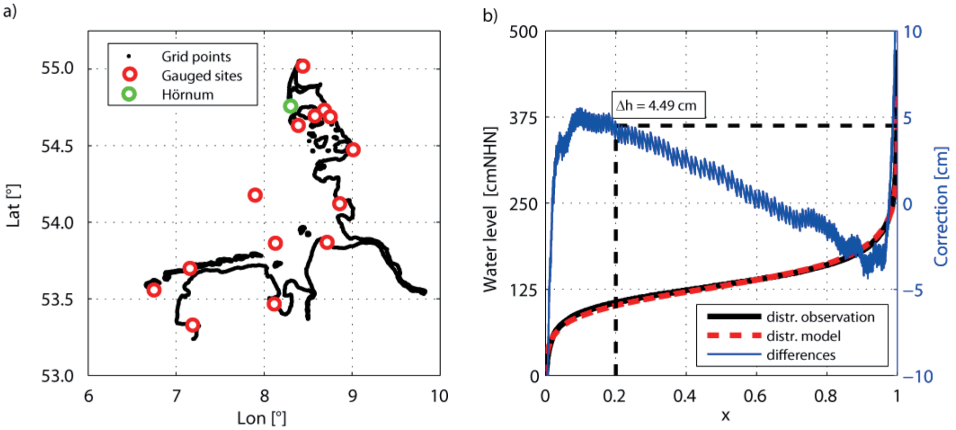

Figure 3: Example of performing the bias-correction (adapted from Arns et al. 2013) with: a) showing all grid-points (black) and tide gauges (red) of the model along the coast; b) the distributions of observed (black) and modelled (red) high waters for Hörnum tide gauge.

Fig. 3a shows all grid-points (black dots) of the model along the coast for which water level time series are available from the 40-year hindcast tide gauge locations are shown as red circles. This figure indicates that the model also generates water levels between the gauged sites highlighting that the bias-correction needs to be transferred to these locations. In the third stage, the bias-correction is thus interpolated from all 15 tide gauge stations envisaged for correction purposes (see the correction (cor.) column in Tab. 1) to the locations between the gauged sites. The interpolation is performed for each year individually using the *Inverse Distance Weighted* (IDW) method (e.g. McMillan et al. 2011).

4.3 Validation

For validation purposes, the methodology described above is applied to 15 validation sites that are listed in Tab. 1 (see the validation (val.) column). From this list, Pellworm Harbour is the only tide gauge station that has not been used for the correction. Instead it has been removed from the pool of tide gauge records considered for correction purposes, so that the modelled water levels of Pellworm Harbour are adjusted using the bias-correction that has been interpolated from neighbouring stations. The overall performance of the methodology is assessed using the same efficiency criteria as in Sect. 4.2. In Fig. 4, the red dots show the comparison of observed and modelled water levels at individual stations; the blue dots show the comparisons of observed vs. modelled and bias-corrected water levels. As expected, the bias-correction increases the *coefficient of determination* r^2 at all stations (including Pellworm Harbour), reaching values of $r^2 \approx 1$ [-] (Fig. 4a). Fig. 4b shows a similar effect for the *index of agreement d*. At all stations, the *d* is improved to $d \approx 1$ [-]; the improvement at Wittdün, Wyk and Dagebüll is small, as the *index of agreement* was already high at these stations before the bias-correction was applied. In summary, the validation shows that high water levels derived from numerical model simulations are very well represented when the bias-correction is applied. A more sophisticated verification can be found in ARNS et al. (2013), concluding that the above presented bias-correction is suitable to be used with modelled water levels in the German Bight, which are envisaged to serve as input for extreme value analyses, especially in un-gauged areas.

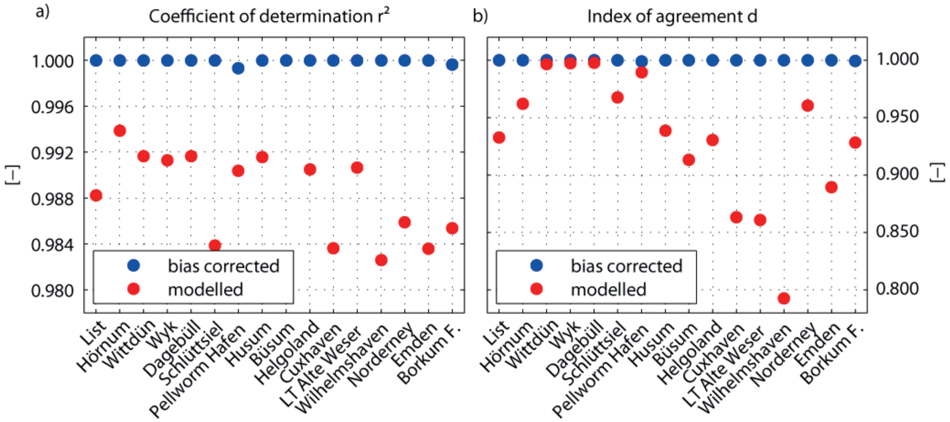

Figure 4: Compilation of efficiency criteria applied to 16 stations (taken from ARNS et al. 2013).

4.4 SLR run

A scenario run was conducted to examine how SLR might affect extreme water levels in the future, hereafter referred to as SLR scenario run. Regional MSL projections have recently been published in the AR5, but the model resolution is still relatively coarse for marginal seas such as the North Sea. To account for changes in MSL the global projections given in the AR5 are used, reporting that SLR will very likely exceed the observed rates during 1971 and 2010 due to increased ocean warming and increased loss of mass from glaciers and ice sheets. Based on climate projections in combination with process-based models they state that global MSL rise for 2081–2100 relative to 1986–2005 will likely be in the range of 0.26 to 0.82 m including uncertainties. This range covers four different Representative Concentration Pathways (RCPs) allowing for possible future climates, each of which is considered possible depending on how much greenhouse gas is emitted in the upcoming decades. For the SLR scenario the average of all four RCPs is used with z = 0.5 m and it is assumed that this is the global MSL rise by 2100.

Additionally, vertical land movements in the German Bight are considered as derived from the glacial isostatic adjustment (GIA) model of PELTIER (2004) which were downloaded from the website of the Permanent Service for Mean Sea Level. In the study region, GIA amounts to ~0.44 mm/year on average (closest point to the study region: Lon. 8; Lat. 54.4). Assuming that vertical trends describe ongoing (at least until 2100) long-term processes, SLR projection and GIA influence can be summed up to a relative mean seal level (RMSL) rise scenario of +0.54 m. This projection is assumed to be valid for the entire study region.

Currently, changes in atmospheric circulation and storminess are controversially discussed (see e.g. WEISSE and VON STORCH 2009 and references therein). In the light of these competing results, the SLR scenario used here assumes that wind conditions (speed and directions) do not change. Instead, the SLR scenario runs are conducted using the same meteorological forcing from 1970 to 2009, i.e. the SLR scenario run considers all boundary conditions to remain as described in Sect. 4.1 but assuming the MSL to have increased by an additional +0.54 m. This increase is added to the observed MSL between 1970 and 2009. Hence, the effects of SLR on storm surge water levels can directly be compared. It is noted that changes in storminess may additionally increase future storm surge water levels in the German Bight (WOTH et al. 2006).

5 Results

5.1 Present day return levels

Following the bias correction stage, extreme value analyses were conducted for the whole North Sea coastline of Schleswig-Holstein (north-eastern German Bight). For this stretch of coastline, the model provides water level time series at about 900 coastal grid points that are located approximately every kilometre (i.e. the mean distance). All return water levels are estimated using the approach recommended in Sect. 3 (see ARNS et al. 2013 for details). Fig. 5 schematically shows present day water levels with a return period of 200 years for the entire coastline of Schleswig-Holstein including the un-gauged islands and Halligen areas. This information can be used as a basis for the design of protection measures and is also useful for risk analyses in un-gauged regions like the Halligen.

5.2 Changes in return periods in the SLR scenario

This section investigates changes in return periods of extreme water levels due to a SLR of 0.54 m along the entire coastline of Schleswig-Holstein (a federal state in Germany). Fig. 6 shows the samples and the theoretical distributions of a) the control run, b) the control run simply superimposed by the considered SLR, and c) the SLR scenario run, explaining how changes in return periods were assessed. Furthermore, this figure highlights that future extreme water levels could be notably larger than expected from SLR alone (for more details see ARNS et al., in review).

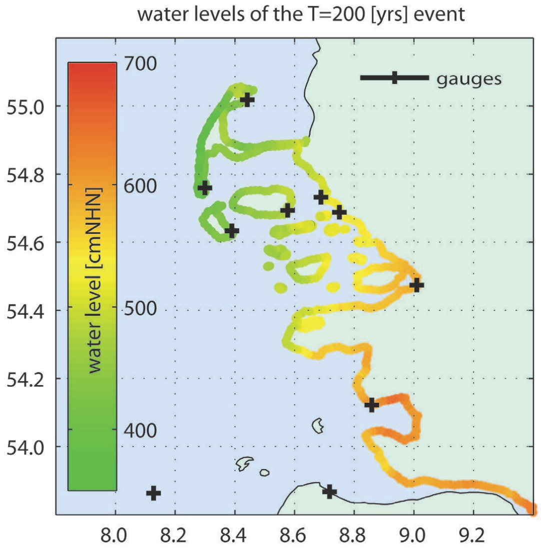

Figure 5: Return water levels along the coastline of Schleswig-Holstein.

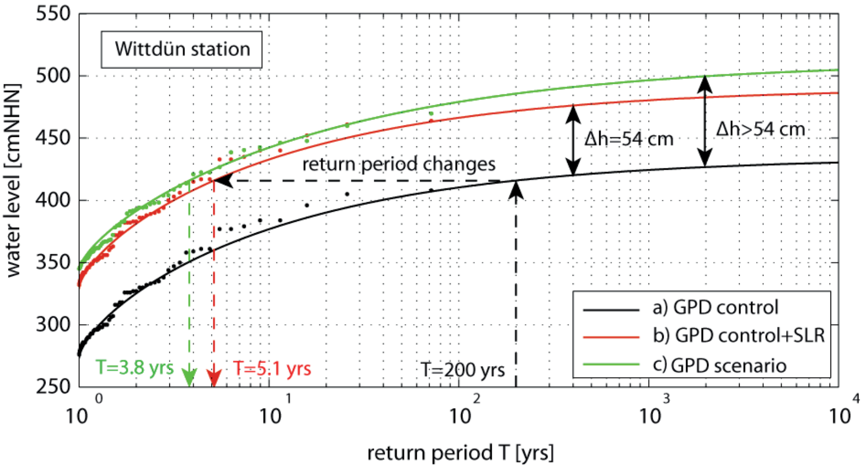

Figure 6: Present day return water levels at tide gauge Wittdün (a) and the effect of SLR when using the MSL-Offset method (b) or the numerical model simulations (c).

Fig. 7 shows the return periods from the SLR scenario run calculated on basis of the current state 200 year return levels for the entire coastline of Schleswig-Holstein. The figure indicates that water levels that currently have a return period of 200 years considerably reduce to return periods of down to 3 years in the SLR scenario. The figure further highlights the spatially inconsistent feedback showing the largest return period changes in the most westerly parts (e.g. the larger islands), but partly also along the mainland coastline.

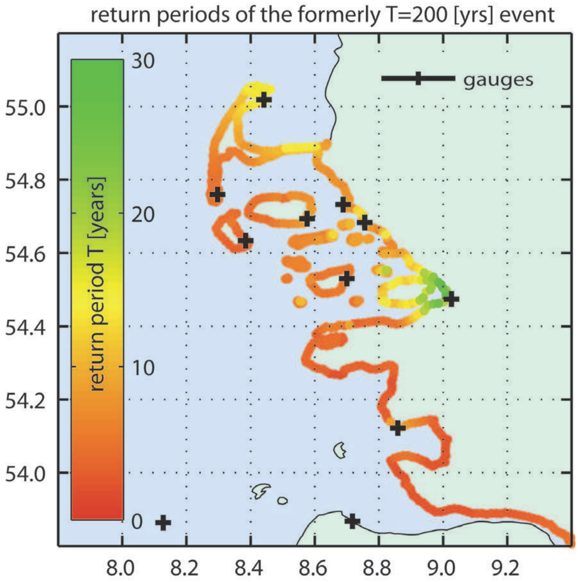

Figure 7: New return periods as a result of the SLR scenario run; the return periods are referred to the water levels of the former 200-years water levels.

6 Summary and discussion

This study uses a combination of numerical and statistical methods to estimate present day return water levels at sites where only little or even no measured water level data is available. A similar method has recently been applied along different stretches of coastlines around the globe (see e.g. HAIGH et al. 2013). This approach was adopted and modified to satisfy the characteristics along the entire coastline of Schleswig-Holstein in northern Germany. It is shown that water levels derived from a hydrodynamic model can be used to calculate reliable return water levels. Regions with no or only few tide gauge stations can especially benefit from this approach. However, a precondition is to adequately correct the bias that is generated with the numerical simulations. The bias-correction is performed first at each individual station where water level observations exist. Then the correction is transferred to the neighbouring sites points using an *Inverse Distance Weighting* interpolation method. As a result, regionalized return water levels at ungauged sites are obtained, that account for locally confined coastal attributes. An assessment showed that return water levels that are estimated using the approach presented in this paper are highly consistent with the return water levels from at-site analyses.

To account for possible future changes we also investigated the impact of a 0.54 m SLR on future extreme water levels along the coastline of Schleswig-Holstein (a federal state in Germany). The study shows that future extreme water levels could be significantly larger than expected from SLR alone. These differences are mainly caused by changes in shallow water and frictional effects, altering the tidal component of the total water levels (for more details see ARNS et al., in review). Furthermore it is shown that return levels of extreme water levels will considerably reduce, i.e. a water level of given return period occurs more frequently in future as e.g. the 200 year return level, which will be 3 year return level in the SLR scenario.

A combination of individual parts of this paper can be used to objectively and reliably estimate regional to local return levels for current and future SLR conditions. These methodologies enable to estimate return levels for an entire coastline helping to obtain water level information in un-gauged areas. The results can be used for the design of coastal defences or for risk analyses.

7 References

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