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Improved estimates of mean sea level changes in the German Bight over the last 166 years

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Abstract In this paper, mean sea level changes in the German Bight, the south-eastern part of the North Sea, are analysed. Records from 13 tide gauges covering the entire German North Sea coastline and the period from 1843 to 2008 have been used to derive high quality relative mean sea level time series. Changes in mean sea level are assessed using non-linear smoothing techniques and linear trend estimations for different time spans. Time series from individual tide gauges are analysed and then 'virtual station' time series are constructed (by combining the individual records) which are representative of the German Bight and the southern and eastern regions of the Bight. An accelerated sea level rise is detected for a period at the end of the nineteenth century and for another one covering the last decades. The results show that there are regional differences in sea level changes along the coastline. Higher rates of relative sea level rise are detected for the eastern part of the German Bight in comparison to the southern part. This is most likely due to different rates of vertical land movement. In addition, different temporal behaviour of sea level change is found in the German Bight compared to wider regional and global changes, highlighting the urgent need to derive reliable regional sea level projections for coastal planning strategies.

Keywords North Sea · German Bight · Regional mean sea level changes · Tide gauge data · Vertical land movements

1 Introduction

Changing sea levels are one of the major concerns we have to deal with in times of a warming climate. Many authors have recently studied observed global and regional sea level changes based on tide gauge or altimetry datasets (e.g. Church and White 2006; Cazenave et al. 2008; Church et al. 2008; Domingues et al. 2008; Haigh et al. 2009; Wahl et al. 2010; Woodworth et al. 2008 and 2009a, b; Wöppelmann et al. 2008, 2009) and possible future global sea level changes have been assessed using climate models (summarised in Meehl et al. 2007) or semi-empirical models (Rahmstorf 2007; Vermeer and Rahmstorf 2009; Grinsted et al. 2010; Jevrejeva et al. 2010). The results from these studies, which analyse sea level changes on different spatial scales with different methods, clearly point to the existence of considerable regional variability in rates of sea level change (e.g. Church et al. 2004, 2008; Mitrovica et al. 2001, 2009). This arises due to an uneven distribution of meltwater from ice sheets and glaciers, gravitational effects, non-uniform thermal expansion and salinity changes. As Miller and Douglas (2007) and Woodworth et al. (2010) reported, gyre-scale atmospheric pressure variations may also contribute to different regional behaviour of sea level changes.

As there has been considerable spatial variation in sea level changes in the past, it is very reasonable to assume that future changes in sea level will also exhibit strong spatial variability. Currently, global sea level projections

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from the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (Meehl et al. 2007) are used for most coastal planning purposes, and regional differences from the global mean changes are ignored. To overcome this inadequacy, reliable regional sea level projections are urgently needed. Thus, studies of regional sea level have become all the more important in recent years.

In a recent study, Wahl et al. (2010) used sophisticated techniques to analyses sea level rise at two stations (Cuxhaven and Helgoland) in the German Bight (Fig. 1). The overall aim of this present study is to apply these analyses techniques to a larger tide gauge dataset (13 sites) in the same region. The main objectives of the paper are to: (1) determine more accurately than before rates of relative mean sea level (RMSL) changes at single tide gauge sites in the German Bight, (2) examine whether there are differences in RMSL changes along the German coastline, (3) compare the changes in sea level observed in the German Bight with behaviour on a wider regional and global scale, and finally (4) to provide simple estimates of rates of vertical land movement based on the generated RMSL time series. It is hoped that the results from this study (and others) will contribute to the validation of regional models used for the estimation of future sea level rise projections.

The structure of the paper is as follows: In Section 2, the tide gauge datasets and the investigation area are described. The methodology used to generate and analyse the high quality RMSL time series is also outlined. The results are described in Section 3. The key findings are discussed in Section 4 and the conclusions are given in Section 5.

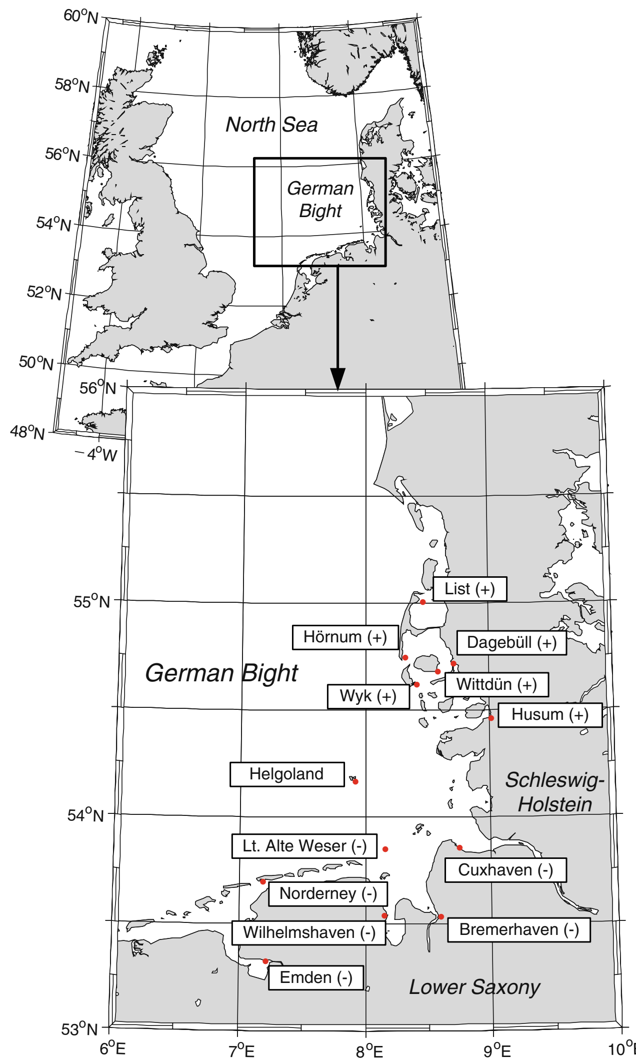


Fig. 1 Investigation area and locations of the considered tide gauges along the German North Sea coastline. Gauges marked with (+) are used to create a virtual station time series for the eastern part of the German Bight and gauges marked with (−) are used to create a virtual station for the southern part

2 Data and methods

Figure 1 shows the investigation area in the southeastern North Sea. Originally 18 tide gauges were selected for the study, each with records of at least 50 years in duration. Fifty years has been identified as a sufficient length for long-term trend analyses (Douglas 1991; Pugh 2004), although the underlying variability still has to be taken into account. The effect of the length on the resulting long-term trend and the related standard error has recently been assessed by Haigh et al. (2009) for the UK. Of the initial 18 sites, five were not considered further due to impacts from: inland drainage (tide gauges of Schlüttsiel and Bensersiel), barrages (tide gauge of Tönning), significant coastal engineering measures (tide gauge of Büsum), and suspicious data (tide gauge of Borkum). The final 13 sites chosen for analysis are shown in Fig. 1 and are almost evenly distributed along the German North Sea coastline.

Figure 2 shows the lengths of data available at each of the study sites and distinguishes between the two different sources of data available. The older data mainly consists of time series of high and low waters, which can be averaged over a year to give an estimate of mean tide level (MTL). The second source of data is high frequency (at least hourly values) sea level measurements, which can be averaged over a year to give an estimate of mean sea level (MSL). High frequency datasets are available since the late 1990s for most of the considered tide gauges. Longer high frequency datasets are available for Helgoland, Cuxhaven and Wilhelmshaven. To partially resolve the shortcoming of missing high frequency data from the past, selected data from the tide gauges of Hörnum (1951, 1965, 1976, 1987) and Wyk (1951, 1952) have recently been digitised by the Agency of Roads, Bridges and Water in Hamburg and the Ministry of Agriculture, Environment and Rural Areas in Schleswig–Holstein, respectively. Most tide gauges provide

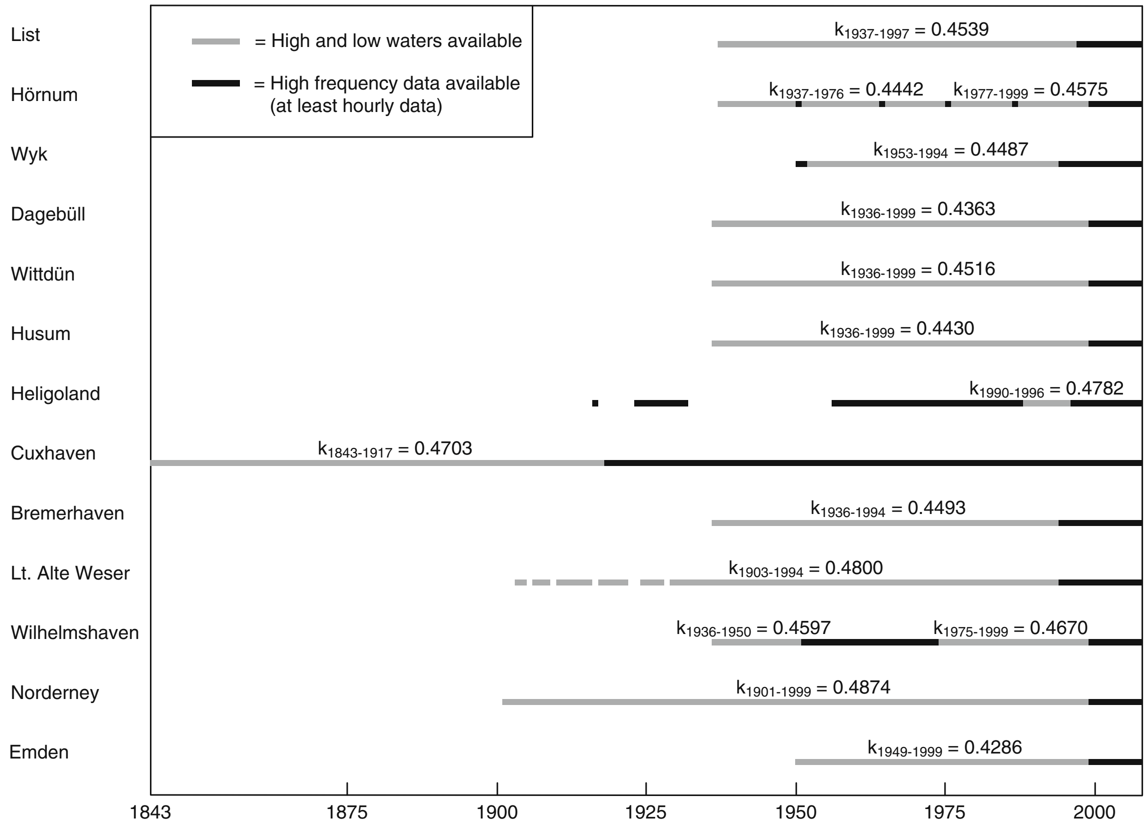


Fig. 2 Duration of the sea level data sets and the *k* factors calculated for different time periods, which have been used to transfer the MTL data, derived from tidal high and low waters, to MSL data

data from 1936/1937 onwards. The Cuxhaven tide gauge provides the longest record (starting in 1843), followed by Norderney (starting in 1901) and Lt. Alte Weser (starting in 1903). All considered data sets were checked for errors and corrected for local datum shifts, as reported in IKÜS (2008). No inverse barometer correction was applied.

In regions such as the southern North Sea, strong shallow water effects deform the tide resulting in large (>20 cm) differences between MTL and MSL. Hence, this has to be considered when generating and analysing mean sea level time series. Not accounting for the difference between MTL and MSL would lead to erroneous trend estimates. To transfer MTL to MSL, we use the *k* factor method, described in detail in Wahl et al. (2010) (hereinafter: W10). *k* Factors are reference values for the observed differences between MTL and MSL, and have been calculated for all tide gauges as follows:

$$k(t) = \frac{(\mathrm{MHW}(t) - \mathrm{MSL}(t))}{\mathrm{MTR}(t)} \qquad (1)$$

where: $k(t)$ is the monthly *k* factor time series calculated for time periods with high frequency data; MHW(t) is the monthly mean tidal high water time series; and MTR(t) is the monthly mean tidal range time series. A symmetric tide has a *k* factor of 0.5. The smaller the calculated *k* factor, the stronger the asymmetry of the tide and the larger the deviation between MTL and MSL. Before the mean *k* factors can be used to combine the long MTL time series with the (for most gauges) shorter MSL time series they have to be tested for stationarity (i.e. the time series have to be free of trends, shifts and periodicity) (e.g. Mudersbach and Jensen 2010). In addition to the approach described in W10, we also applied a Mann–Kendall test (Mann 1945) to look for significant trends in the monthly *k* factor time series. Figure 2 shows the calculated mean *k* factors for the considered tide gauges. For some gauges (i.e. Wilhelmshaven and Hörnum), non-stationary behaviour of the *k* factors has been detected and different *k* factors for different time periods have been considered. The tide gauge of Emden shows the lowest mean *k* factor of 0.4286, which, considering a mean tidal range of 323 cm at this site, equates to a difference between MTL and MSL of about 23 cm. The highest *k* factor of 0.4874 is derived for the tide gauge of Norderney and equates to a difference between MTL and MSL of only 3 cm (considering a mean tidal range of 244 cm at this site).

The *k* factor-corrected RMSL time series, for each of the 13 study sites, are the dataset analysed in the remainder of the paper. The methods used to analyse these time series are the same as those applied by W10 and hence are only briefly described below.

To detect non-linear changes in sea level a non-linear smoothing technique (here, singular system analysis (SSA) with an embedding dimension of 15 years) is applied to the RMSL time series at each site. This is done in combination with Monte Carlo autoregressive padding (MCAP), an advanced approach to assess the uncertainties when continuing the smoothing to the ends of the available time series. By identifying the SSA reconstruction that gives the smallest mean squared error (MSE) against the observations, we achieve a very data adaptive smoothing of the available time series. The rates of sea level rise (SLR) are estimated as the first differences of the SSA reconstructions providing the best fit. These methods allow for the detection of inflection points and periods of high or low (or even negative) rates of SLR. To analyse the longer-term changes, linear trends from single time series are estimated for a range of different periods. These periods were chosen based on the length of the available time series and the results from the non-linear smoothing.

Following the analysis of individual sites, so-called 'virtual stations' are constructed by averaging the observed rates of SLR per year (i.e. the first differences of the annual MSL time series) from a specified number of tide gauges. The resulting time series are integrated backwards by adding up the previously calculated averaged rates of SLR. These time series are also assessed using the non-linear smoothing and linear trend methods described above. The derived virtual station for the entire German Bight is contrasted to the northeast Atlantic and global sea level reconstruction of Jevrejeva et al. (2006). The northeast Atlantic reconstruction was obtained from Svetlana Jevrejeva and the global reconstruction was downloaded from the website of the Permanent Service for Mean Sea Level. Rates of SLR calculated from each of the three time series are compared and correlation coefficients are calculated for running 20-year periods.

Finally, a simple method (following the approach of Haigh et al. 2009) is used to provide an estimate of rates of vertical land movement at the 13 study sites. Woodworth et al. (2009a, b) estimated that the rate of SLR solely from oceanographic processes (i.e. no vertical land movements) around the UK was 1.4 mm/a for the period from 1901 to 2006. Given the regional connection between the two study areas (UK and German Bight), we assume that similar long-term sea level changes took place over the last century in the German Bight (based on the results of this study, this appears appropriate, but we recognise the simplicity of the approach). Thus, the linear trends derived for stations providing data for the period from 1901 to 2006 are subtracted from 1.4 mm/a to give an estimate of vertical land movement at these sites. The tide gauges providing long records are then used as 'reference stations' to give estimates of vertical land movement for the other tide gauges considered in the present study. In addition, estimates of vertical land movement from a glacial isostatic adjustment (GIA) model and from geological studies are also presented for comparison purposes.

3 Results

3.1 RMSL changes along the German North Sea coastline

Figure 3 shows the results from the non-linear smoothing of the considered tide gauge records. The uncertainties increase near the ends of the time series due to the padding (i.e. extrapolating the time series before smoothing, see W10). The shaded bands represent the results from a large number of SSA reconstructions from which the one providing the best fit (i.e. the smallest MSE) compared to the observations is highlighted in the plot. The underlying annual MSL time series are in good agreement, showing noticeable high or low values for the same years, which indicates high data quality and regional coherence. Most of the smoothed time series point to an accelerated SLR over the last few decades, with a starting point in the 1970s. For most of the shorter records, the estimated recent rates of SLR are the highest ones observed. However, longer records (i.e. Cuxhaven and Norderney) show similar rates in the past, indicating that the recent high rates of rise are not as yet particularly unusual. The findings are confirmed by calculating linear trends for different common time periods, as shown in Table 1. All stated errors are 1-σ standard errors (equivalent to 68% confidence levels). Higher trends (3.6 mm/a on average) are estimated for the time period from 1971 to 2008, compared to the periods from 1951 to 2008 and 1937 to 2008 (2.0 and 2.1 mm/a on average). However, standard errors for the shortest time period are relatively large (in the order of 0.8 mm/a). The long records show slightly higher rates again, when longer time periods (1901–2008, 1843–2008) are considered. For the period 1951–2008, for which data are available from all gauges, the trends vary between 1.0 mm/a (Bremerhaven) and 2.8 mm/a (Norderney). Standard errors are in the order of 0.4 mm/a. The tide gauge of Norderney is most influenced by the local datum corrections reported in IKÜS (2008). In previous studies, these datum corrections were not accounted for (e.g. Jensen and Mudersbach 2007). Thus, the trends presented here for Norderney might differ from those reported in earlier studies. The estimated long-term trend (1843–2008) for the Cuxhaven station is 2.3 mm/a. Trends found for the period starting in 1971, which has been identified as the starting point of the recent SLR acceleration, are mostly greater than 3.5 mm/a.

It has been recognised that standard errors can be reduced by applying 'master station' methods (e.g. Woodworth et al.

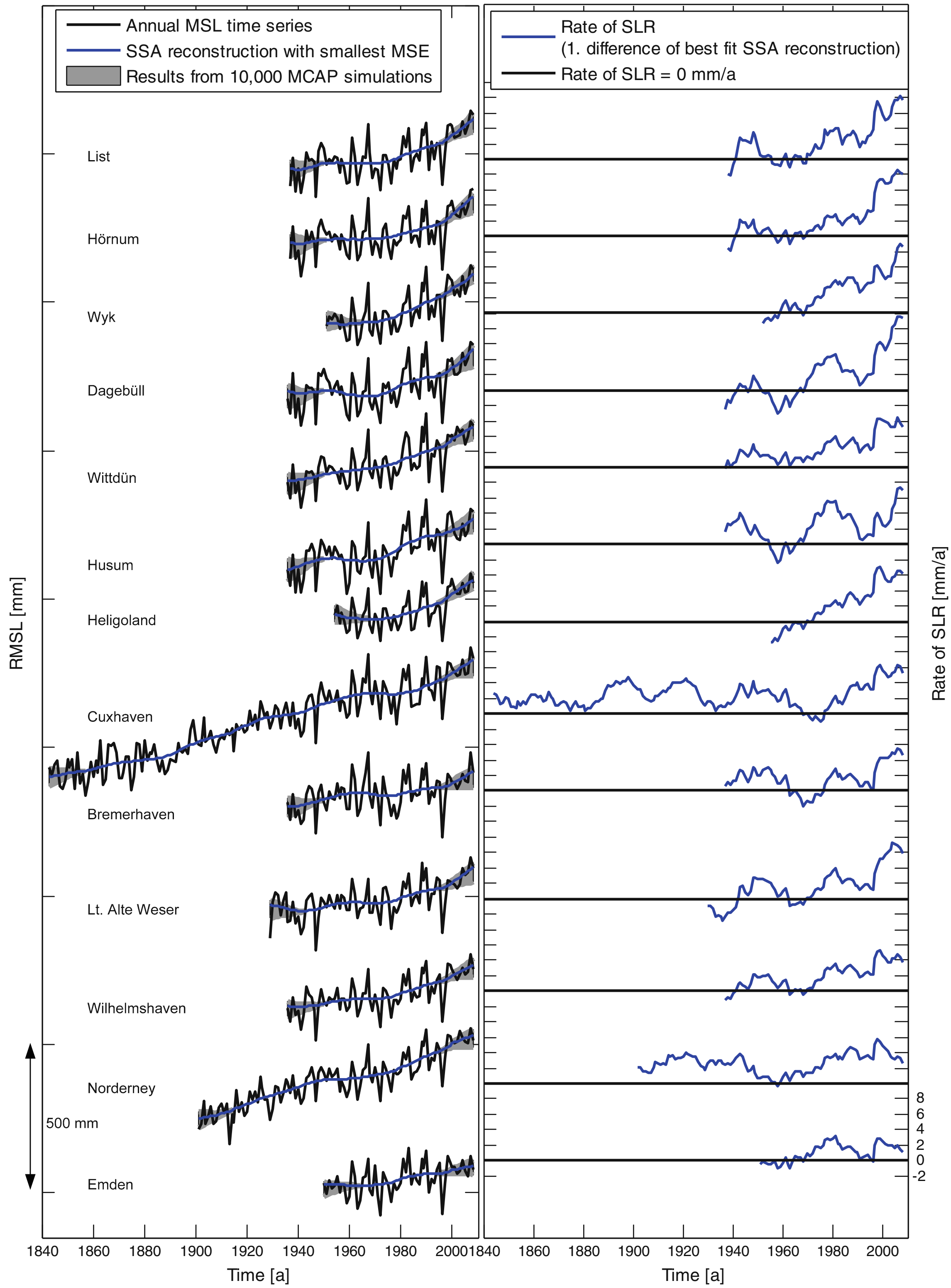


Fig. 3 Mean sea level time series for the considered tide gauges and non-linear smoothing applying SSA with an embedding dimension of 15 years in combination with 10,000 MCAP simulations (*left*) and rates of SLR estimated as the first differences from the SSA reconstruction providing the best fit (*right*); all time series have been plotted with arbitrary offsets for presentation purposes

Table 1 Linear trends with 1-σ standard errors and correlation coefficients (values in parentheses) for common time periods for single time series and virtual station time series

Tide gauge	Linear trends of RMSL for different time spans ± 1-σ standard errors [mm/a] (correlation with 'virtual station'–German Bight)				
	1843–2008	1901–2008	1937–2008	1951–2008	1971–2008
List (+)	–	–	2.0±0.3 (0.98)	2.4±0.4 (0.98)	4.2±0.8 (0.98)
Hörnum (+)	–	–	1.8±0.3 (0.98)	2.1±0.4 (0.98)	3.7±0.8 (0.98)
Wyk (+)	–	–	–	2.8±0.5 (0.98)	4.6±0.8 (0.97)
Dagebüll (+)	–	–	1.7±0.4 (0.95)	2.2±0.5 (0.96)	3.7±0.9 (0.97)
Wittdün (+)	–	–	2.4±0.3 (0.97)	2.6±0.4 (0.97)	3.9±0.8 (0.97)
Husum (+)	–	–	2.2±0.3 (0.96)	2.5±0.5 (0.96)	3.6±0.9 (0.97)
Helgoland		–	–	2.1±0.4[a] (0.96)	3.5±0.7 (0.96)
Cuxhaven (−)	2.3±0.1 (0.99)	2.2±0.2 (0.96)	2.1±0.3 (0.95)	2.0±0.4 (0.94)	3.6±0.8 (0.94)
Bremerhaven (−)	–	–	1.2±0.3 (0.92)	1.0±0.5 (0.90)	2.5±0.8 (0.94)
LT Alte Weser (−)	–	1.9±0.2[a] (0.88)	1.7±0.3 (0.95)	1.7±0.4 (0.95)	3.1±0.8 (0.96)
Wilhelmshaven (−)	–	–	1.9±0.3 (0.98)	2.0±0.4 (0.99)	3.4±0.7 (0.99)
Norderney (−)	–	2.4±0.1 (0.95)	2.4±0.3 (0.96)	2.8±0.4 (0.95)	4.2±0.6 (0.96)
Emden (−)	–	–	–	1.3±0.4 (0.94)	2.1±0.7 (0.94)
'virtual Station' (eastern German Bight)	–	–	2.2±0.3 (0.99)	2.5±0.4 (0.99)	4.1±0.8 (1.00)
'virtual Station' (southern German Bight)	2.0±0.1 (1.00)	1.7±0.1 (0.99)	1.8±0.3 (0.99)	1.8±0.4 (0.99)	3.2±0.7 (0.99)
'virtual Station' (German Bight)	2.0±0.1	1.7±0.1	2.0±0.3	2.1±0.4	3.6±0.7

[a] Some years of the considered time period are missing, but at least 93% are available (see also Fig. 2)

2009a, b; Haigh et al. 2009), lowering the variability (e.g. by subtracting a sea level index describing the coherent part of sea level variability of the considered time series). We have tested this approach with the datasets from the German Bight using the de-trended virtual station for the entire German Bight (see Section 3.2) as 'master station'. This leads to an error reduction of up to 75% for the period from 1937 to 2008. However, the estimated trends do not change significantly.

In general, higher RMSL trends are observed for the tide gauges in the eastern part of the German Bight (federal state of Schleswig–Holstein) compared to those located in the southern part (federal state of Lower Saxony). Significant differences (at 95% confidence level) between the two groups of gauges (in Table 1: List to Husum, marked with (+); Cuxhaven to Emden, marked with (−)) are found for the periods from 1951 to 2008 and 1971 to 2008.

3.2 Temporal changes of RMSL from virtual stations

In this section, we analyse virtual stations for the entire German Bight and southern and eastern parts of it. As outlined in Section 2, virtual stations are constructed by first differentiating the single time series, before averaging the resulting rates of sea level change between adjacent years. Figure 4 (top) shows the results of this computational step (all 13 RMSL time series are considered). The resulting time series highlights the strong short-term variability in sea level changes along the German North Sea coastline. The absolute maximum difference between two adjacent years of observations is of the order of 150 mm and is about 50 mm on average. The absolute maximum first difference found from the monthly RMSL time series (not shown here, but in W10 for selected tide gauges) is of the order of 770 mm and is about 140 mm on average. Church et al. (2004) and Church and White (2006) assumed that differences of more than 250 mm between adjacent monthly values were related to local datum shifts and the time series were broken into separate sections. Defining such limits is necessary when doing global studies of a large number of records from tide gauges along different coastlines. However, the presented results indicate importantly that changes in the order of 250 mm (first of all due to meteorological forcing) between 2 months are not unusual for MSL time series from the German North Sea area. This of course also complicates the estimation of long-term changes from short time series (e.g. <30 years).

Figure 4 (middle) shows the standard deviations for the particular years above the average. As the Cuxhaven station is the only one providing data for the nineteenth century, the virtual station is the same as the Cuxhaven time series for this period and the standard deviation is zero. Some outliers occur at the beginning the twentieth century. This is because the Norderney time series shows different changes

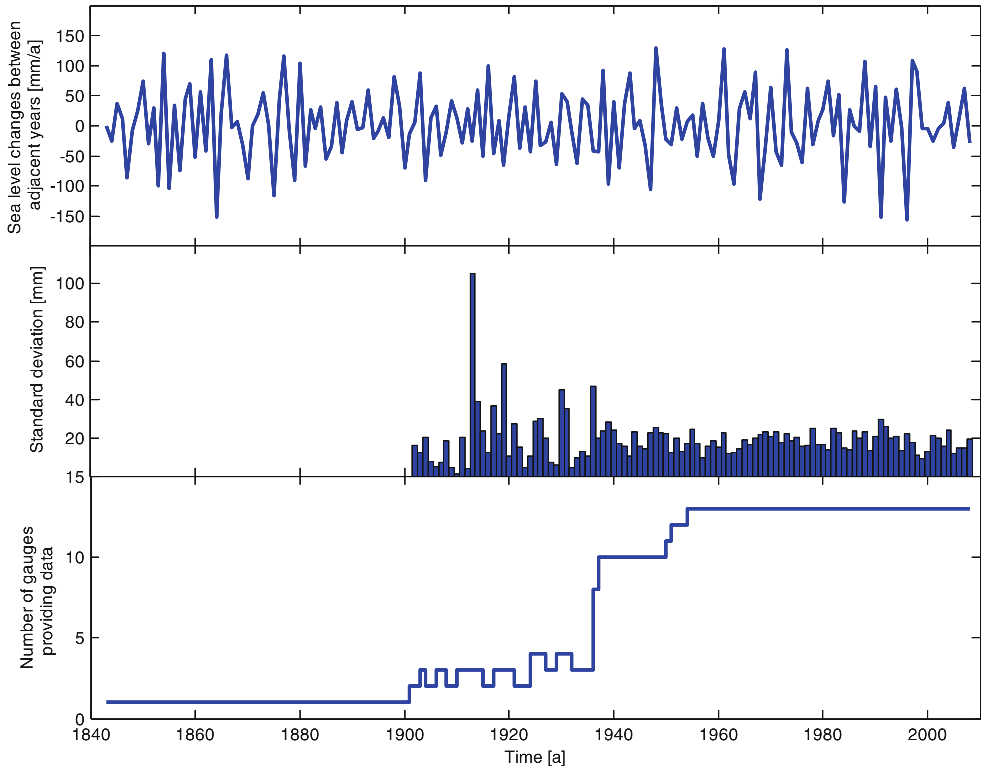


Fig. 4 Averaged rates of SLR between adjacent years (*top*), standard deviation about the average (*middle*) and number of tide gauges providing data for any given year (*bottom*)

compared to the Cuxhaven and the Lt. Alte Weser records. As stated in Section 3.1, the Norderney record has been corrected for a number of datum shifts reported in IKÜS (2008), which occurred after 1937. The different behaviour in comparison to Cuxhaven and Lt. Alte Weser at the beginning of the twentieth century might indicate that other datum shifts occurred before 1937, but no detailed information on datum changes is available before 1937. This warrants further investigation and a more detailed data archaeology exercise. The standard deviations remain constant, in the order of about 20 mm, from the end of the 1930s onwards, indicating higher data quality for this period. Since the 1930s, the maintenance of the tide gauge equipment has improved and more precise levelling has been undertaken. Figure 4 (bottom) shows the number of records averaged to create the virtual time series. Only the Cuxhaven tide gauge provides data for the period before 1900 (and two to four gauges from then on until the mid 1930s), which increases the uncertainties for this time period(s). Other methods of determining virtual stations (e.g. empirical orthogonal function (EOF) analyses) are not discussed in this paper, but are examined in a related paper by Albrecht et al. (2011).

The time series shown in Fig. 4 (top) is integrated backwards to achieve a time series representative of RMSL changes for the entire German Bight (Fig. 5). The influence of vertical land movements has not been removed before constructing the virtual station time series. Hence, it is affected by the spatial differences in vertical land motions and therefore should be seen as representing the average RMSL changes in the German Bight.

The values in parentheses in Table 1 are correlation coefficients for different time spans, calculated for the single time series and the virtual station for the entire German Bight. The considered time series are highly correlated, with coefficients mostly greater than 0.95. Tide gauges covering the eastern part show slightly better correlation with the virtual station than those covering the southern part. The latter is confirmed by EOF analyses conducted by Albrecht et al. (2011).

The non-linear smoothing techniques have been applied to the virtual station time series and the results are shown in Fig. 5. Consistent with the results from the individual stations, an acceleration of SLR took place at the end of the nineteenth century, followed by a deceleration. SLR started to accelerate again around the 1970s with a post-1990 intensification, leading to high recent rates in the order of 4–5 mm/a. These findings are similar to those reported in W10, based on the results from analysing only two tide gauges (Cuxhaven and Helgoland).

Linear trends calculated using the virtual station for the entire German Bight are presented in Table 1 and are in the order of 2 mm/a for the majority of the considered time spans. The trend estimated for the period from 1971 to 2008 is 3.6±0.7 mm/a and increases to 7.3±2.7 mm/a for the shorter period from 1993 to 2008. In comparison, the global trend estimated using altimetry data for the latter period is 3.5±0.4 mm/a (Mitchum et al. 2010).

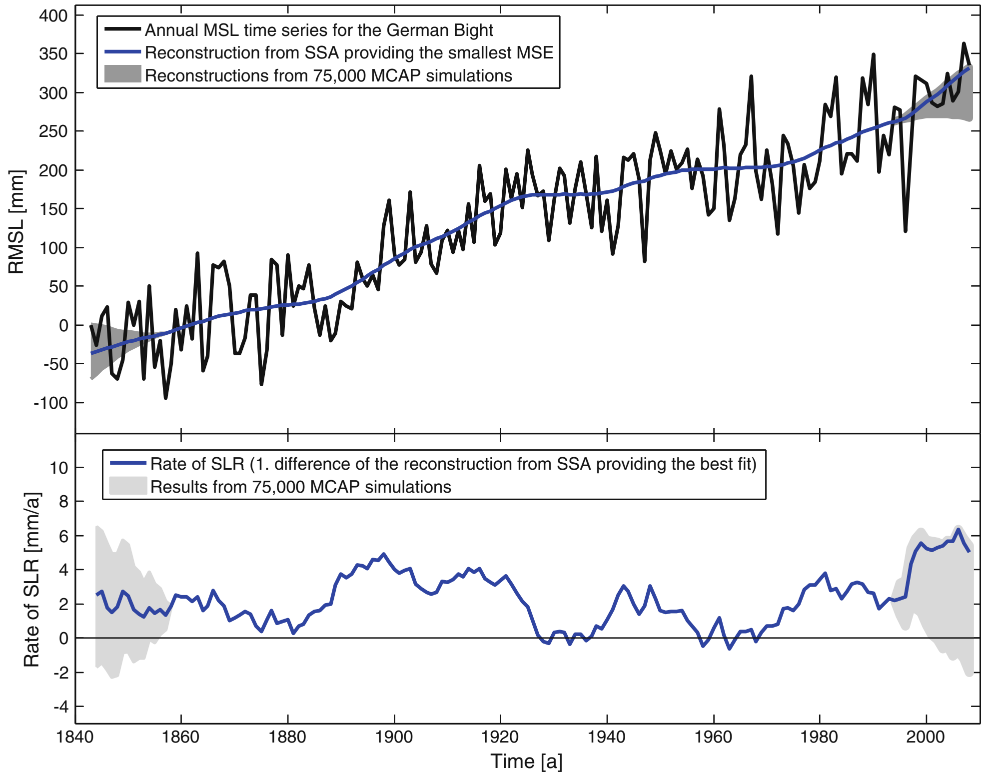


Fig. 5 Virtual station time series for the entire German Bight and results from non-linear smoothing applying SSA in combination with MCAP

Although the estimated trend for the German Bight is reduced when vertical land movements in the order of 0.5 to 1.0 mm/a are accounted for (see Section 3.4), the results indicate a more rapid SLR over the last one and a half decade in the German Bight area compared to the observed global changes.

Figure 6 shows linear trends calculated for different time spans from the virtual station for the entire German Bight. Trends are calculated for all overlapping 20-, 30-, 40- and 50-year periods and 1-σ standard errors are presented. The trend values are plotted at the final year of the time window considered for the trend calculation.

A window length of 20 years appears to be too short to meaningful assess the underlying high variability present in the RMSL time series. The results for 30-, 40- and 50-year time spans confirm the existence of two periods of SLR acceleration (end of the nineteenth century and recent decades). Similar inflections at the end of the nineteenth century can be observed from other long European sea level records (e.g. Liverpool and Brest). Miller and Douglas (2007) and Woodworth et al. (2010) argue that these are related to gyre-scale atmospheric pressure variations.

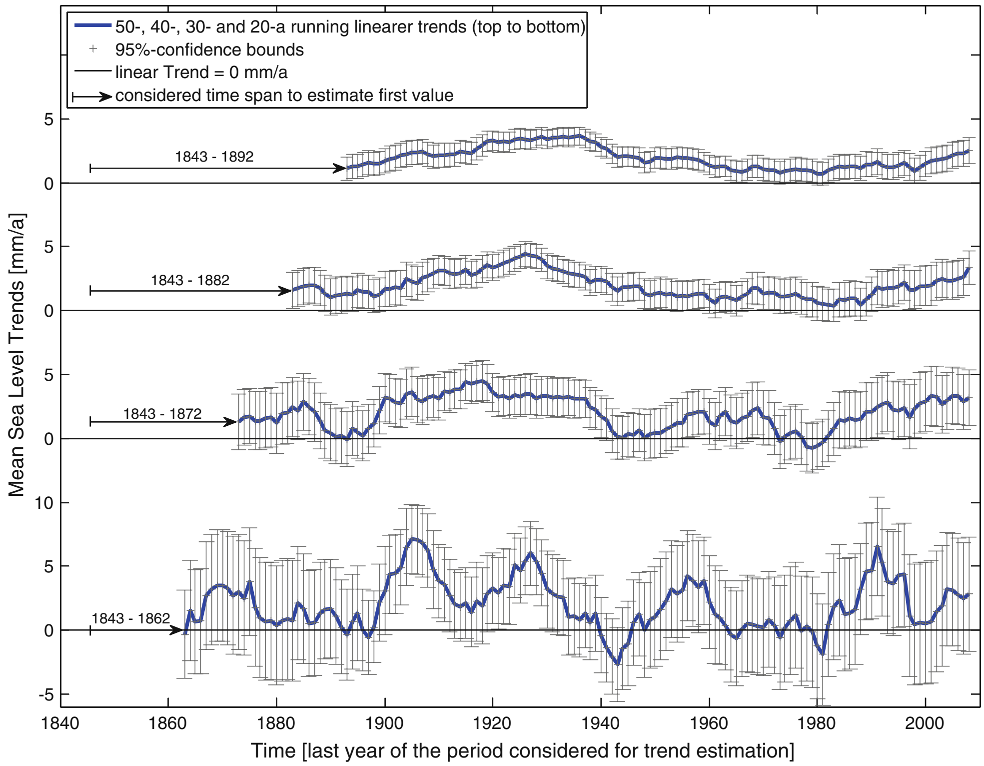
As higher rates of SLR are found for the tide gauges covering the eastern part of the German Bight compared with those covering the southern part, two further virtual stations are created. A virtual station is determined for the eastern German Bight based on the time series from the tide gauges of List, Hörnum, Wyk, Dagebüll, Wittdün and Husum (marked with (+) in Fig. 1 and Table 1) and a virtual station for the southern German Bight is created from the tide gauges of Cuxhaven, Bremerhaven, Lt. Alte Weser, Wilhelmshaven, Norderney and Emden (marked with (−) in Fig. 1 and Table 1). The offshore tide gauge of Helgoland is omitted at this stage. Again, non-linear smoothing is applied to these time series and linear trends are calculated.

The non-linear smoothing of the two virtual stations is shown in Fig. 7. The estimated linear trends for different time periods and the related correlation coefficients with the virtual station for the entire German Bight are listed in Table 1. As found from analysing the time series of individual gauges, the virtual station for the eastern German Bight shows higher rates of relative SLR than the virtual station for the southern German Bight. The post-1970 acceleration with an intensification from the 1990s onwards is confirmed by both time series and the recent rates found from non-linear smoothing are in the order of 4–6 mm/a for the southern part of the German Bight and 7–8 mm/a for the eastern part.

3.3 Sea level changes on regional, trans-regional and global scales

In this section, we compare the coherent temporal changes evident in sea level in the German Bight to those observed over a wider regional and global scale. Figure 8 (top) shows

Fig. 6 Running linear trends of the virtual station of the entire German Bight for different time spans (50-, 40-, 30- and 20 years, from top to bottom)



the estimated rates of SLR for the German Bight virtual station and Global and northeast Atlantic reconstructions. For consistency, in this part of the analysis, the time series of the tide gauges from the German Bight were corrected for GIA (Peltier 2004), as has been done by Jevrejeva et al. (2006). The time period from 1843 to 2001 is considered, as this is the period covered by the reconstructions.

Figure 8 (middle) shows the estimated rates of SLR by calculating the differences between the pairs: German Bight–Global; and German Bight–northeast Atlantic. The results from the comparison with the global reconstruction are similar to those presented in W10. Considerably higher rates of SLR are found from the reconstruction for the German Bight for the period covering several decades around 1900 and from the global reconstruction for a period around the 1940s. The reconstruction for the northeast Atlantic agrees slightly better with the reconstruction for the German Bight, especially for a period around the 1950s.

Figure 8 (bottom) shows running 20-year correlation coefficients between the annual MSL time series for the pairs: German Bight–Global; and German Bight–northeast Atlantic. The 95% significance levels (from *t* test statistics) are also displayed and highlight that most of the estimated correlation coefficients for the pair German Bight–Global are insignificant (66% of the estimated coefficients for 20-year periods). In contrast, 83% of the 20-year correlation coefficients estimated for the pair German Bight–northeast Atlantic is found to be significant.

3.4 Vertical land movements

Up to this point, we have mostly dealt with relative mean sea level changes, which unquestionably is the most important parameter to be considered for coastal planning purposes. However, for a better understanding of the underlying processes, a separation of the isostatic and the eustatic component is important. Vertical land movements can arise from a range of processes (e.g. Woodworth 2006). Regional land movements can be caused by GIA, a rebound effect resulting from the deglaciation after the last ice age (e.g. Shennan and Horton 2002; Teferle et al. 2006). Locally, other effects such as sediment compaction, extraction of ground water and other natural resources, collision of tectonic plates, sediment loading or subsurface faulting (e.g. McKee Smith et al. 2010) may also contribute to land subsidence or uplift.

As stated in Section 2, the current best estimate for twentieth century SLR around the UK solely from oceanographic processes (vertical land movements removed by considering results from geological and geodetic studies) is 1.4±0.2 mm/a, derived by Woodworth et al. (2009a, b) from analysing tide gauge data from 1901 to 2006 (with most of the long records coming from tide gauges located along the UK east coast). Considering both, the results presented above (which show similar sea level characteristics between the German Bight and the northeast Atlantic (Section 3.3)) and the close regional connection between the investigation areas, we assume that similar long-term sea level changes took place over the last century in the

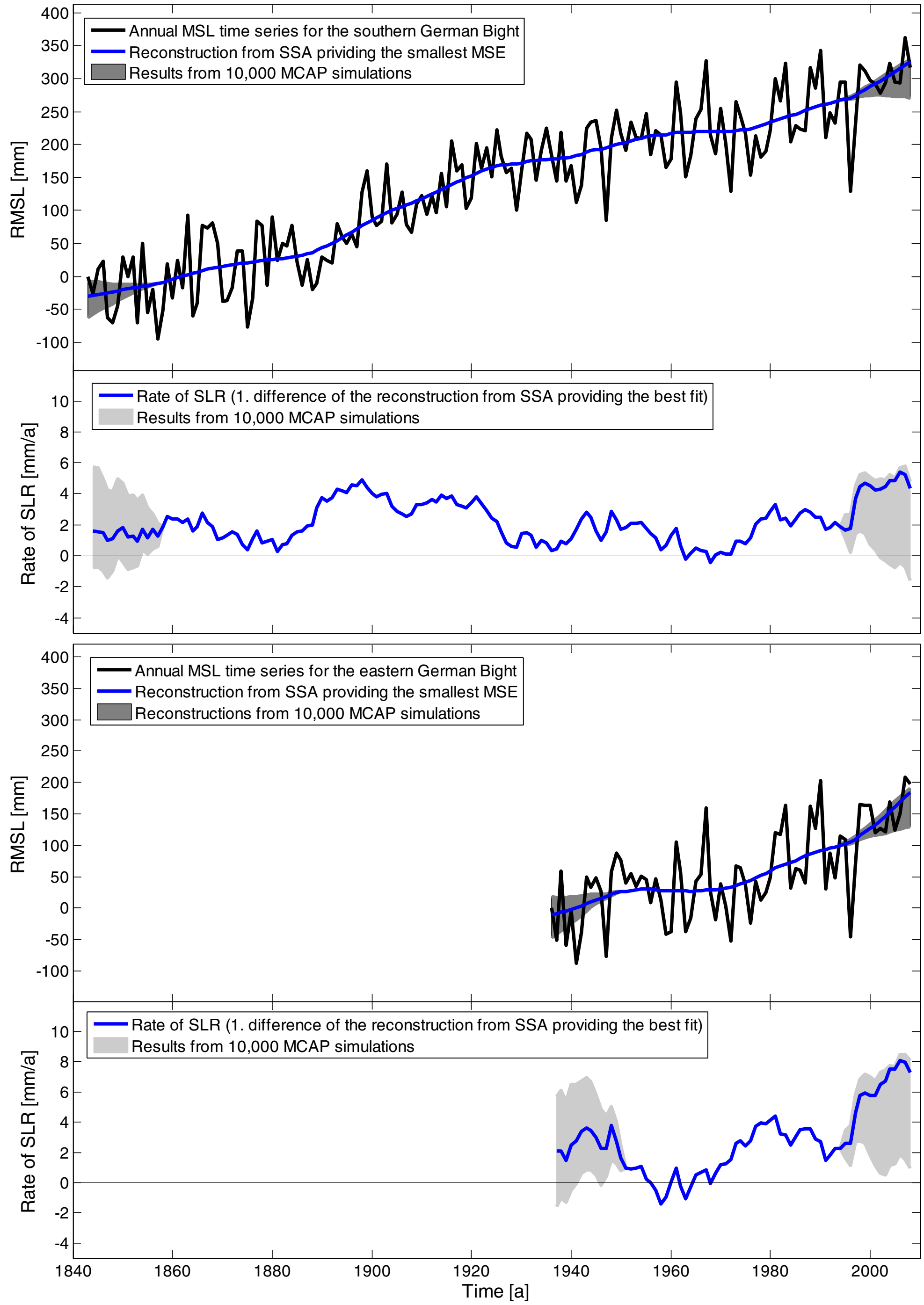


Fig. 7 Virtual station time series for the southern German Bight (*top*) and the eastern German Bight (*bottom*) and the non-linear smoothing applying SSA in combination with MCAP

German Bight and around the UK. Other effects like atmospheric pressure variations and winds in the North Sea area are not taken into account, as there is no indication in literature that they led to significant differences between the long-term sea level trends (>100 years) in the two nearby investigation areas. Thus, the estimated RMSL trends of the tide gauges Cuxhaven, Lt. Alte Weser and Norderney (calculated for the period from 1901 to 2006) are subtracted from 1.4 mm/a. This, initially, gives estimates of rates of vertical land movement for the three tide gauges providing the longest records (−0.7±0.2 mm/a for Cuxhaven, −0.5±0.1 mm/a for Lt. Alte Weser, and −0.9±0.2 mm/a for Norderney; negative values denote land subsidence). For error estimation, the uncertainty of 0.2 mm/a stated by Woodworth et al. (2009a, b) for the oceanographic component is ignored, following Haigh et al. (2009). Hence, this assumes that all the uncertainty in the estimated RMSL trends is associated with vertical land movements. Therefore, the stated errors are 1-σ standard errors from estimating the linear trends for the

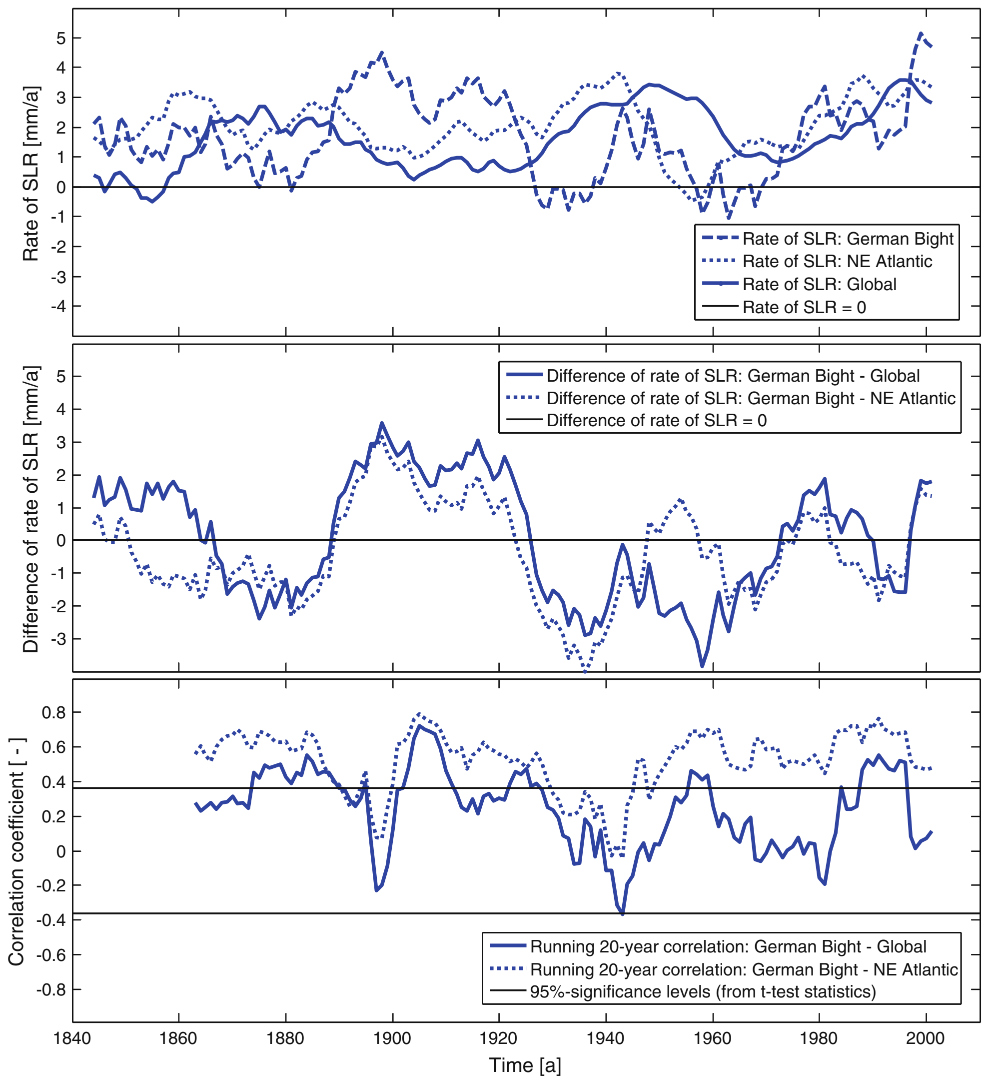


Fig. 8 Rates of SLR estimated for the German Bight virtual station, the global reconstruction and the northeast Atlantic reconstruction (*top*); Differences of rates of SLR between the pairs German Bight–Global and German Bight–northeast Atlantic (*middle*); 20-year running correlation coefficients between the annual MSL time series for the pairs German Bight–Global and German Bight–northeast Atlantic (*bottom*; each correlation coefficient is displayed for the last year of the considered 20-year period)

considered time span (1901–2006). The rate we estimated for Cuxhaven is comparable with the rate of −0.68±0.08 mm/a found by Shennan (1987) from geological studies, which suggests our simple method of estimating vertical land movements is appropriate (see also Führböter and Jensen 1985). Augath (1993) estimated a vertical velocity of −0.5 to −0.7 mm/a for the Langeoog area (located about 75 km westerly of Cuxhaven (see also Bungenstock and Schäfer 2009)), which is again consistent with our simple estimate.

For the following calculations, we proceed on the assumption that vertical trends describe ongoing long-term processes (e.g. Schöne et al. 2009; Woodworth et al. 2009b). Hence, all RMSL trends of the three long records reported in Table 1 can be corrected for vertical land movements considering the rates estimated above. Afterwards, the tide gauges Cuxhaven, Lt. Alte Weser and Norderney serve as ‘reference stations’ to derive estimates of vertical land movement for other stations. Therefore, the averaged corrected trends (influence of vertical land movements removed) from the ‘reference stations’ for a particular time period are compared to the RMSL trends of other stations for the same period.

As an example, the corrected trends for the period from 1937 to 2008 are 1.4±0.3 mm/a for Cuxhaven, 1.3±0.3 mm/a for Lt. Alte Weser and 1.4±0.3 mm/a for Norderney (for the considered period 1937–2008 the trends are the same or similar to the 1.4 mm/a reported by Woodworth et al. (2009a, b) for the period 1900–2006; this is not the case for other periods considered in the study, e.g. 1951–2008). The average value is 1.4 mm/a (standard error is already included in the estimated rates of vertical land movement for the ‘reference stations’, see below). To achieve an estimate of vertical land movement for the tide gauge of List, the RMSL trend of 2.0±0.3 mm/a for the period 1937–2008 reported in Table 1 is subtracted from the average value of 1.4 mm/a. Thus, the rate of vertical land movement for List is estimated to be −0.6±0.5 mm/a. Following this approach, the standard errors from calculating different linear trends accumulate. The quoted error of 0.5 mm/a for the tide gauge of List is derived by adding the mean standard error of 0.2 mm/a resulting from calculating the vertical land movement rates for the 'reference stations' to the standard error of 0.3 mm/a stated in Table 1 for the tide gauge of List for the period 1937–2008.

The results for all gauges are shown in Fig. 9, indicating higher rates of subsidence for the eastern part of the German Bight, as expected considering the results described in Sections 3.1 and 3.2, where higher trends in RMSL have been detected for this area. Based on the results, uplift appears to be occurring at the gauges of Bremerhaven and Emden. In the case of Emden this is surprising, as we expected that land subsidence would be evident at this site due to the withdrawal of gas in the vicinity of the area (IKÜS 2008).

Rates of vertical land movement from the GIA model of Peltier (2004; which were downloaded from the website of the Permanent Service for Mean Sea Level) are also included in Fig. 9 for comparison (no error estimates are available for the GIA values). Discrepancies between the rates derived from GIA modelling and from tide gauges vary from site-to-site. This illustrates that correcting sea level records for GIA is only a good approximation for some gauges, but a very poor one for other gauges (i.e. those where local effects lead to additional subsidence or uplift).

4 Discussion

The results of this study indicate that the available sea level records from the German Bight area are of good quality. Long records (>75 years) are available for most of the considered tide gauges. However, no observations are available prior to 1936 for the eastern part of the German Bight (see Fig. 2). Most of the tide gauges in this area were installed before 1936, but the data prior to 1936 has not yet been digitised (i.e. it exists in the form of analogue tidal charts or paper lists of tidal high and low waters). Further digitisation exercises are necessary, making the analogue data available for sea level analyses, such as the ones presented in this paper. Due to the high correlation between the individual time series and the virtual station (see Table 1), we recommend that the focus be on significantly extending one or two records, rather than partially extending the records for several gauges. EOF analyses may help to identify specific gauges, or combinations of gauges, which provide most reliable information about the decadal sea level variability in the region (Albrecht et al. 2011). The estimated correlation coefficients in Table 1 indicate that the tide gauges of List or Hörnum (showing correlation coefficients of 0.98 for all considered time spans) might be most appropriate/representative to provide useful information about the average sea level changes along the coastline of Schleswig–Holstein from the end of the nineteenth or beginning of the twentieth century. The tide gauges of Husum and Dagebüll may provide even longer data sets, as they have been installed in 1867 and 1873, respectively.

The analysis of the individual station time series, as well as the assessment of the virtual stations, reveals two periods of accelerated SLR (commencing at the end of the nineteenth century and from the 1970s on with a post-1990 intensification). Woodworth et al. (2009b) searched for sea level accelerations in selected sea level records

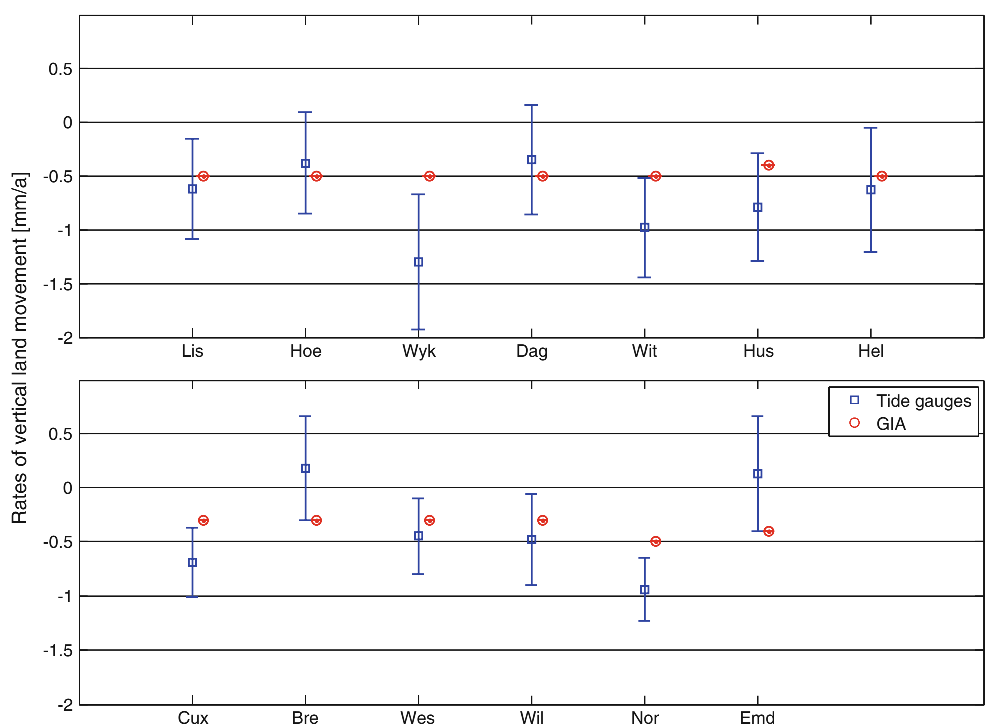


Fig. 9 Rates of vertical land movement for the considered tide gauges from estimates based on the RMSL time series (*blue*) and from a GIA model (*red*)

around the world and different regional and global sea level reconstructions. They found evidence for a positive acceleration in 1920/1930 and a negative acceleration (or deceleration) in 1960. They also report that these findings are not consistent for all regions (i.e. the 1920/1930 acceleration is absent for most of the considered European records, whereas the 1960 deceleration is evident). This is partly consistent with the findings reported in the present study. As the comparison in Fig. 8 (top) shows, the 1920/1930 acceleration is not evident in the German Bight virtual station, whereas the post 1960 deceleration is present to some extent. The recent acceleration (which started in the 1970s) evident in the German Bight is not reported by Woodworth et al. (2009b) for the European tide gauges.

Woodworth et al. (2009b) argued that the temporal behaviour in sea level records is consistent with the behaviour of other climate-related parameters (temperature, volcanic eruptions etc.), but that it is not possible yet to reliably capture such features by numerical modelling. This emphasises the need to extend the available sea level data sets (spatial distribution and length). Updating the analyses undertaken in our study at regular intervals (i.e. every 5–10 years) will be necessary to examine whether another deceleration will take place in the near future or whether the recent acceleration denotes the beginning of an anthropogenically influenced SLR in the German Bight area.

The differences found from comparing the virtual station time series for the German Bight with a global sea level reconstruction (Jevrejeva et al. 2006) raises the question whether global sea level rise projections (as published by the IPCC) are appropriate for regional coastal management assessments. This and the better agreement between the virtual stations for the German Bight and the northeast Atlantic region highlights the necessity to derive reliable regional SLR scenarios. Further analyses, to compare the sea level reconstruction for the German Bight with some global, trans-regional or other regional sea level reconstructions in detail, are likely to be useful. Furthermore, the consideration of additional climate related parameters may improve our understanding of the underlying processes which contribute to temporal and spatial changes in sea level around the German Bight. The influence of atmospheric pressure variations and wind forcing is not considered in the present study, but may contribute to a reduction of the variability of the RMSL time series. Woodworth et al. (2009a, b) found that the 'inverse barometer' accounts for one third of the variability observed from UK mean sea level time series, whereas larger-scale atmospheric or ocean processes (such as gyre-scale circulation) are also important. Investigating the correlation between the virtual station of the German Bight and the North Atlantic oscillation (e.g. Hurrell 1995) could help to explain the observed behaviour to some degree. A comparison with variations in surface temperature, salinity, or river runoff would also be useful.

Higher RMSL trends are observed for the tide gauges in the eastern part of the German Bight (federal state of Schleswig–Holstein) compared to those located in the southern part (federal state of Lower Saxony). This information is essential for coastal planners, as long-term relative sea level changes are an important factor when defining future design water levels for coastal protection measures. The regional differences are most likely due to different rates of vertical land movement, although other effects (e.g. atmospheric pressure variations) may also contribute to a minor degree.

A simple method is used to provide an estimate of rates of vertical land movement at the 13 study sites. Increasingly, direct measurements of vertical land movement are being made at tide gauge sites around the world using the Continuous Global Position System (CGPS; e.g. Wöppelmann et al. 2007, 2009; Schöne et al. 2009). Currently, no reliable estimates of vertical land movement from CGPS are available for the German North sea coastline. This is because most of the CGPS sensors have been installed over the last few years and do not yet provide long enough time series to determine rates to an appropriate level of accuracy. However, more reliable information will be available in the near future, as the record lengths increase.

5 Conclusions

This paper examines changes in relative mean sea level in the German Bight over the last 166 years. Time series from 13 tide gauges covering the entire German North Sea coastline are analysed. Non-linear smoothing techniques are applied to identify the underlying decadal and longer-term variability, which includes the identification of periods with high or low rates of sea level rise. It was found that an acceleration of sea level rise commenced at the end of the nineteenth century followed by a deceleration. Another acceleration with its starting point in the 1970s and intensification from the 1990s has been identified, but the high rates of sea level rise during this period are comparable with rates at other times during the last 166 years. Higher rates of sea level rise are detected for tide gauges covering the eastern part of the German Bight than for those covering the southern part, which is an important finding for coastal planning purposes. The comparison of a virtual station time series for the German Bight with a global sea level reconstruction reveals different temporal behaviour of sea level changes, but reasonable agreement is found between the German Bight virtual station and the northeast Atlantic reconstruction.

Rates of vertical land movement are estimated from the sea level records using a simple approach and are compared with geological data and modelled GIA estimates. Higher rates of vertical land movement are found for the eastern part of the German Bight. This is to some extent supported by the GIA model results. The comparison between the rates estimated from the sea level records and those predicted by the GIA model, illustrate that the single consideration of GIA to correct tide gauge data for vertical land movements can only serve as an approximation. In the future, precise vertical land movement rates are expected to be derived from longer CGPS time series allowing more reliable trend estimates.

To conclude, the presented results indicate the importance of regional sea level studies based on long and high quality sea level observations and we recommend that further digitisation and data archaeology exercises are undertaken. Increasing the length of sea level records that are currently available will allow for more thorough analyses of the underlying physical processes and lead to more reliable results. The latter is essential to improve the accuracy of regional sea level rise projections to be considered in coastal management strategies.

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