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Determining Sea Level Change in the German Bight

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Abstract

Regional mean sea level changes in the German Bight are considered. Index time series derived from 15 tide gauge records are analysed. Two different methods for constructing the index time series are used. The first method uses arithmetic means based on all available data for each time step. The second method uses empirical orthogonal functions. Both methods produce rather similar results for the time period 1924-2008. For this period we estimate that regional mean sea level increased at rates between 1.64mm/yr and 1.74mm/yr with a 90%-confidence range of 0.28mm/yr in each case. Before 1924 only data from a few tide gauges are available with the longest record in Cuxhaven ranging back till 1843. Data from these tide gauges, in particular from Cuxhaven, thus receive increasingly more weight when earlier years are considered. It is therefore analysed to what extent data from Cuxhaven are representative for the regional sea level changes in the German Bight. While this can not be clarified before 1924 it is found that this is not the case from 1924 onwards when changes in Cuxhaven can be compared to that derived from a larger data set. Furthermore, decadal variability was found to be substantial with relatively high values towards the end of the analysis period. However, these values are not unusual when compared to earlier periods.

Keywords: regional mean sea level changes, German Bight, reconstruction methods, data homogenization, accelerating sea level rise

1 Introduction

Changes in global mean sea level (GMSL) and a possibly accelerating GMSL rise within the last few decades are of great interest to both science and public. This is not surprising as an accelerating sea level rise would have considerable impacts on coastal regions, especially on densely populated low lying areas. Based on tide gauge data, GMSL increased over the 20th century at rate of about 1.7mm/yr (Bindoff et al. 2007). For the future, considerably higher rates are expected (Meehl et al. 2007). Since 1993 satellite data are available to complement the estimates derived from tide gauge data. Compared to the latter, satellite data have the advantage that they provide nearly global coverage and that they are not measured with respect to local references. However, there are only 17 years of satellite data available, strong statements about long-term sea level trends and the consistency between estimates derived from tide gauge and satellite data are difficult. The latter was analysed by Holgate and Woodworth (2004). They found a difference between open ocean and coastal global mean sea level and noticed that the trends derived from the latter coincide with those obtained from tide gauge data.

Church et al. (2004) used a combination of tide gauge and satellite data to construct an index time series for the GMSL. Subsequently they considered the question whether or not an accelerating rise during the more recent years could be detected (Church et al. 2006; 2007). From an analysis of 20-year moving trends they found that highest values occurred at the end of the record, indicating a possible acceleration in the rate of sea level rise. Jevrejeva et al. (2006, 2008) produced another estimate of a GMSL time series using only tide gauge data. They found a trend of 2.4mm/yr for the time period 1993 to 2000, which is smaller than the trend estimated from satellite data for the same period. They showed that similar rates of sea level rise could also be found earlier in the record. Long records from individual tide gauges have been analysed by several authors. Holgate (2007) analysed data from nine tide gauges and reported an average trend of 1.74mm/yr for the time period 1904 - 2003. Douglas (1997) analysed data from 24 tide gauges from the last about 100 years. The average length of the records was 83 years with a minimal length of 60 years. Based on this data set Douglas (1997) reported an average rate of sea level rise of 1.8mm/yr.

Sea level is not likely to rise uniformly over the globe, but regional deviations are expected. For Europe, Wöppelmann (2006) studied tide gauge data from Brest, France, which represents one of the longest records worldwide. By dividing the record into three time periods he documented changes in the linear trends, in particular -0.9 ± 0.15mm/yr for 1807-1890, 1.3 ± 0.15mm/yr for 1890-1980 and 3.0 ± 0.5mm/yr for 1980-2004. Other regional studies comprise for example, Woodworth (1987) and Woodworth et al. (1999, 2009) who analysed sea level changes along the British coast or Peltier (1996) and Davis and Mitrovica (1996) who analysed tide gauge data from North America.

In this paper we focus on regional mean sea level (RMSL) changes in the North Sea and more precisely in the German Bight. Up to now, mean sea level (MSL) changes in the German Bight have received only little attention and most existing work is related to analysis of changes in tidal high and low waters as well as in tidal ranges (e.g., Jensen et al. 1992; Lassen 1995; Jensen and Mudersbach 2007). More recently, attempts to analyse changes in MSL were also provided either using data from one tide gauge only (Wahl et al. 2008) or by constructing an index time series by using an arithmetic mean over data from different tide gauges (Wahl et al. 2010, 2011). In this paper, our objectives are 1) to construct an index time series for the RMSL using two different approaches (one of which is the arithmetic mean approach used by Wahl et al. 2011), and 2) to analyse the extent to which both approaches reveal similarities and differences regarding changes in RMSL in the German Bight.

In section 2 we first introduce the two approaches and the data used for the analysis. Subsequently, the index time series obtained are compared in section 3.1. As data from Cuxhaven (the longest record available) receive increasingly more weight in the analysis for earlier years also the extent to which the record from Cuxhaven can be considered to represent the average conditions for the German Bight is investigated. In section 3.2 we analyse the effect data homogenisation may have had on our results. This is done by applying the same approach to both - the non-homogenised data and the homogenised data and by comparing the results of the analyses. Regional differences in RMSL changes within the German Bight are considered in section 3.3. In particular, we separate between Lower Saxony and Schleswig-Holstein, two regions along German coast line. In section 3.4 the question on whether or not an acceleration in the rate of sea level rise over the more recent years was observed in the German Bight is addressed. This is done by analysing decadal trends and comparing the results obtained from the different methods and from interpretation of the sea level data in Cuxhaven. In general, all linear trends presented in this paper are computed with least square fits.

2 Data and Methods

We use homogenised annual mean sea level data 1843 - 2008 from 15 tide gauges (Fig. 1) in the German Bight as provided by the AMSeL[1] project (Wahl et al 2010; Wahl et al. 2011). The methodology used to derive these data is described in detail in Wahl et al. (2010, 2011). Essentially all data sets were quality checked and corrected for local datum shifts as described in IKÜS (2008) and Wanninger et al. (2010). Both high resolution (at least hourly) and low resolution (high and low waters) data were used to construct MSL values. For the low resolution data, mean tide level (MTL) obtained by averaging subsequent high and low waters were used to derive MSL values using the k-factor method (Wahl et al. 2010). Dimensionless k-factors basically represent the local differences between MTL and MSL and are estimated locally from periods where both high and low resolution data are available. K-factors are then used to derive MSL as a function of MTL for periods where only low frequency data are available. From these data, following the guidelines of the Permanent Service for Mean Sea Level (PSMSL), monthly MSL values were estimated when at least 15 days of data were available for the particular month.

[1]Mean Sea Level and Tidal Analysis at the German North Sea Coastline

Subsequently, annual values are determined whenever 11 or more monthly values were available. Note that in this study two additional tide gauges, Büsum and Borkum are used, that were not considered in Wahl et al. (2011) due to suspicious data, but which were retained in one of the approaches used in this paper (the EOF-approach, see section 3.1). A comparison of the results with and without the data of Büsum and Borkum shows that these in-homogeneities are filtered out by this approach (not shown).

We will follow two approaches to derive an index time series for RMSL. We will then compare the results from these two approaches when applied to the same data. The first approach (henceforth denoted as mean approach) starts with computing the annual linear trends from all time series considered. Afterwards, the rates of sea level change between adjacent years from tide gauges providing data for the particular time step are averaged. By adding up the averaged rates, one yields a RMSL time series comprising a defined number of single tide gauges. For details on this procedure see also Holgate (2004), Church et al. (2004, 2006) or Wahl et al. (2011). The second approach is based on an empirical orthogonal function (EOF) analysis (henceforth denoted as EOF-approach) of annual MSL data. We expect the first EOF to represent the large scale changes common for all tide gauges and refer to the first principal component as the RMSL derived from the EOF-approach. We further assume that any small scale changes such as those caused by local construction works will only cause locally confined variations which should manifest in higher EOFs only. This way, the EOF-analysis acts as a filter for the small scale fluctuations by rotating the coordinate system from the standard basis such that the first vector of the new basis points into the direction of the highest variance of the analysed data.

In more detail, let us denote the number of tide gauges with $i = 1, \ldots, 15$. Let then $\{x(t,i)\}_{t=1,\ldots,k,i=1,\ldots,15} \in \mathbb{R}^{k\times 15}$ be the matrix with our data with $k \in \mathbb{N}$ the number of time steps. Each entry $x(t_0, i_0)$ equals the MSL at tide gauge i_0 and time t_0. Then $\{x(t_0,i)\}_{t_0:const,i=1,\ldots,15}$ is the MSL at a specific time t_0 for all tide gauges represented in the standard basis of $\mathbb{R}^{15}$. We now write the $\{x(t_0,i)\}_{t_0:const,i=1,\ldots,15} \in \mathbb{R}^{15}$ with new basis vectors $e_j \in \mathbb{R}^{15}$, $j \in \mathbb{N}$ and associated coefficients (principal components) $a_j(t_0) \in \mathbb{R}^{15}$, such that

$$x(t_0,i) = \sum_{j=1}^{15} a_j(t_0)e_j(i),$$

for each $t_0 \in \{1,\ldots,k\}$. Within this representation we choose the first basis vector $e_1 \in \mathbb{R}^{15}$ such that it points into the direction of the highest variance of our data. If we now consider the corresponding time series of coefficients (first principal component) $a_1(t)$ with $t = 1,\ldots,k$ we describe the variability in time along a common (mostly uniform) spatial pattern. We thus denote this time series as RMSL. A detailed description of the EOF-analysis can be found in von Storch and Zwiers (1998).

The representativeness of our RMSL time series for the larger area strongly depends on the explained variance of the first EOF, which is equal to the fraction of the largest eigenvalue of the covariance matrix C of $\{x(t,i)\}_{t=1,\ldots,k,i=1,\ldots,15}$ and the total variance, that is the sum of all

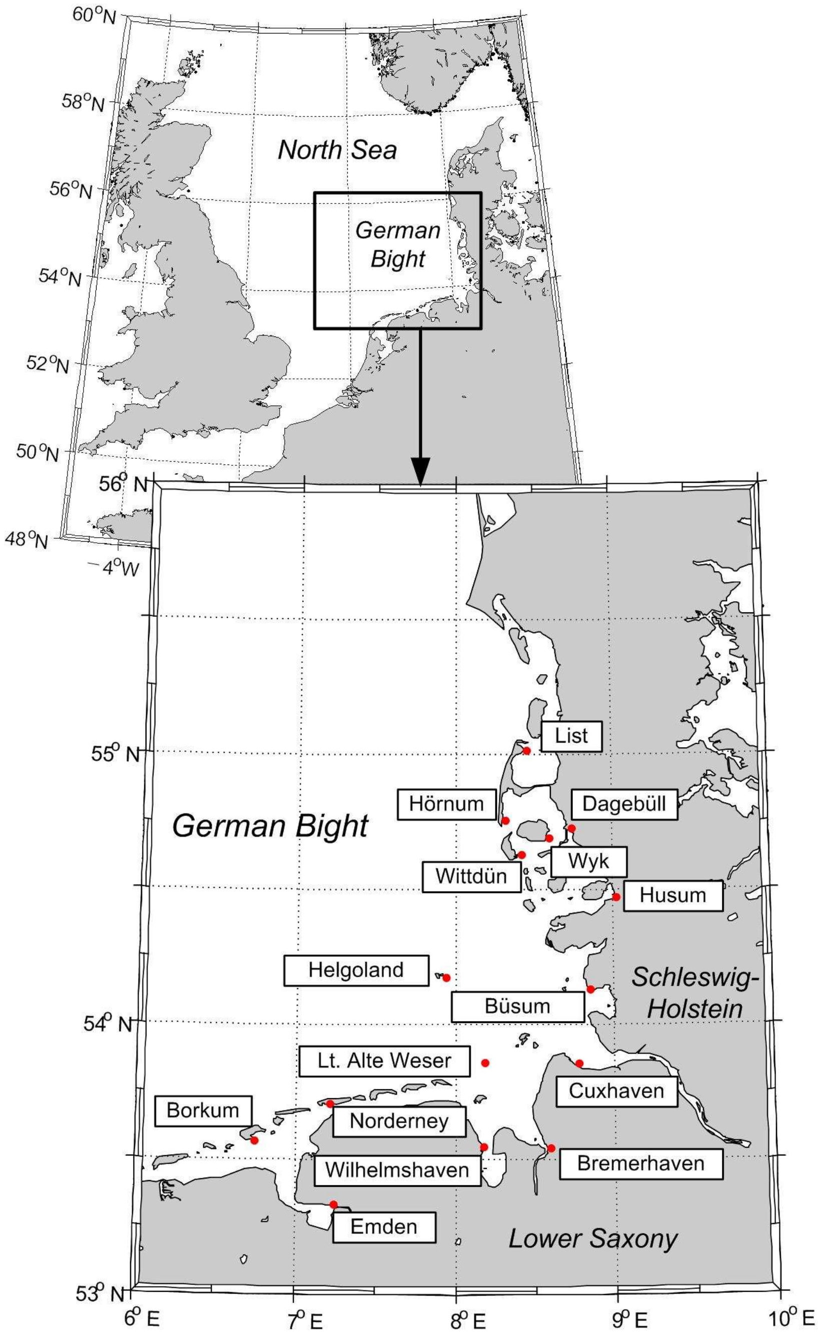

Fig. 1 Investigation area and locations of the considered tide gauges in the German Bight.

eigenvalues of C (von Storch and Zwiers 1998). As for our case all reasonable reconstructions have explained variances of more than 90% (see section 3.1) we conclude that the principal component time series from the first EOF represents a reasonable approximation of the RMSL.

3 Results

3.1 Comparison of Different Methods to Estimate Regional Mean Sea Level

In section 2, two different methods to construct artificial index time series for the RMSL were introduced. Fig. 2 shows the results from the two approaches when applied to the same data from the German Bight. Both time series share strong similarities (Table 1) with comparable inter-annual fluctuations but also similar long term trends (Table 2). Fig. 3 shows the corresponding spatial pattern from the EOF-approach. It explains about 90% of the total variance and is positive everywhere with larger amplitudes for the tide gauges along the Schleswig Holstein coast (HUS, WTD, WYK, DAG, HOE, LIS) and smaller values along the coast of Lower Saxony (BOR, EMD, NDN, WHV, BHV, LAW). We thus conclude that the first principal component represents a good approximation of the common sea level variability signal at these gauges and can be used as an index for RMSL in the German Bight.

Methodically, the main difference between the two approaches is that in the mean approach arithmetic means from a number of records are computed, the availability of which may vary in the course of time, while in the EOF-approach the covariance structure of the data is exploited. By design, the EOF-approach returns (in the first EOF) a common signal present at all tide gauges. We assume that signals present at a few or only one gauge are thus effectively filtered out. To support this hypothesis, the following simple test was performed: We introduced an artificial in-homogeneity (signal) in the data of Bremerhaven by adding an artificial offset of 0.06m from 1972 onwards. This offset corresponds to one standard deviation of the Bremerhaven time series itself. We then repeated the EOF-analysis and compared the RMSL time series with that obtained from the undisturbed data set. It is found that the first EOFs from both computations have comparable explained variances of about 90% and that both RMSL time series are nearly identical with a correlation coefficient of more than 0.99. For higher EOFs differences in both the patterns and the corresponding time series become increasingly larger (not shown) supporting our assumption that the EOF-approach effectively filters out local signals.

Another aspect to consider is the impact of data gaps on the results of the two approaches. The two approaches react differently on missing values. While in the mean approach only the period is affected in which the missing values occur, in the EOF-approach the whole analysis period is affected. The degree to which this occurs depends on the extent of the data gaps. Since the effect cannot be quantified in general, again two simple sensitivity experiments were performed: First we chose 11 tide gauges without any data gaps within the period 1937 - 2007 and performed an EOF-analysis. This analysis later served as a reference “truth”. Subsequently, artificial gaps with missing data between 13 to 25 years were introduced into these time series, mimicking the real situation for the complete data set. We again performed an EOF-analysis with these reduced data and compared the results to the reference "truth". The missing data is treated as follows. The EOFs and principal components are computed as the eigenvectors and eigenvalues of the covariance matrix. Whenever there is a missing value at a location, this station is left out for that year in the computation of the covariance matrix. In all tests the resulting time series were found to be rather similar to that from the reference truth sharing correlation coefficients of more than 0.99 and linear trends that differ by less than 0.1mm/yr.

The second test is to compare the results from the reference truth with those obtained from analysing the full data set, including all 15 tide gauges. As in the first test the resulting time series are nearly identical with correlation coefficient of more that 0.99. Additionally, the patterns of the EOFs which occur in both analyses are almost the same. In both tests the explained variance of the first EOF is more than 90%. In summary these analyses suggest, that the number of missing values in the data do not have significant impact on the results from the EOF-approach. We conclude that the EOF-approach represents a robust method to derive estimates of RMSL from a sufficiently large number of tide gauges. Further tests show that this situation is given back to 1924. That is why in the following we use the EOF-approach to provide an estimate of RMSL for 1924 - 2008.

	1936 - 2008	1924 - 2008	1843 - 2008
mean approach - EOF-approach	0.999	0.996	-
mean approach - Cuxhaven	0.92	0.92	0.93
Cuxhaven - EOF-approach	0.92	0.92	-

Tab. 1 Correlation coefficients between different RMSL estimates and sea level in Cuxhaven for different time periods.

Method	1936 - 2008	1924 - 2008	1843 - 2008
mean approach 1843 - 2008	1.94mm/yr±0.36mm/yr	1.64mm/yr±0.28mm/yr	2.01mm/yr±0.1mm/yr
EOF-approach 1924 - 2008	1.95mm/yr±0.36mm/yr	1.74mm/yr±0.28mm/yr	-
Cuxhaven 1843 - 2008	2.07mm/yr±0.4mm/yr	1.93mm/yr±0.3mm/yr	2.28mm/yr±0.1mm/yr

Tab. 2 Linear trends derived from different RMSL estimates and sea level in Cuxhaven for different time periods. Additionally 90%-confidence intervals are shown.

An important question remaining is whether it is reasonable to further go back in time. There are only few tide gauges available before 1924 with all of them located in Lower Saxony and there is only Cuxhaven remaining when the period is extended beyond 1900. Since the time series of the mean and the EOF-approach match very well in the common time period the question arises whether we can have confidence in the results of the mean approach for the years before, or in other words whether the sea level changes in Cuxhaven are representative for the

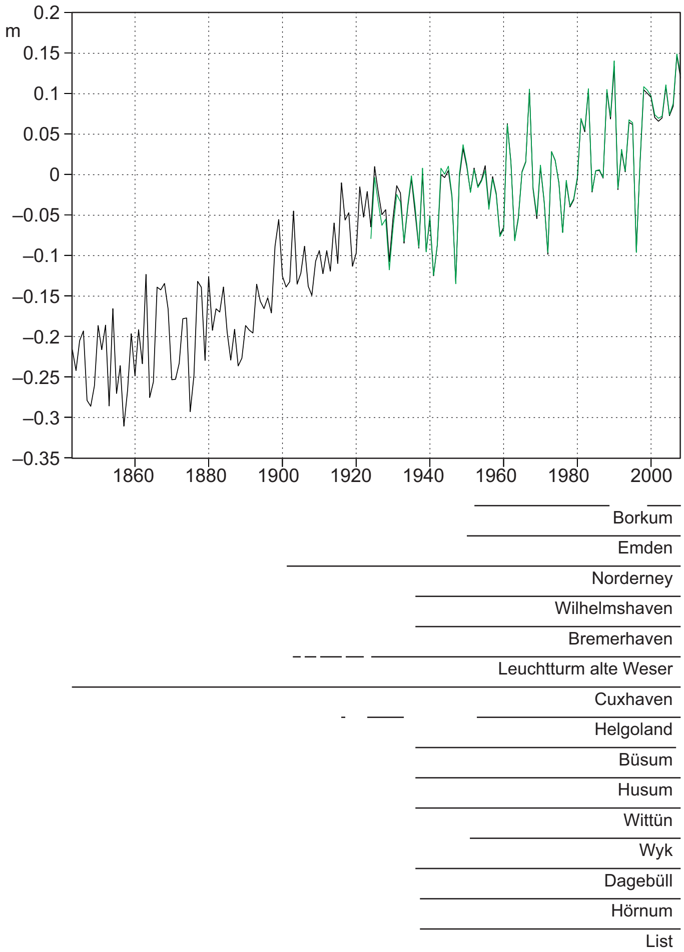

Fig. 2 RMSL in the German Bight as estimated from two different approaches: mean approach 1843-2008 (black); EOF-approach 1924-2008 (green); data availability at the tide gauges used for the analysis (bottom).

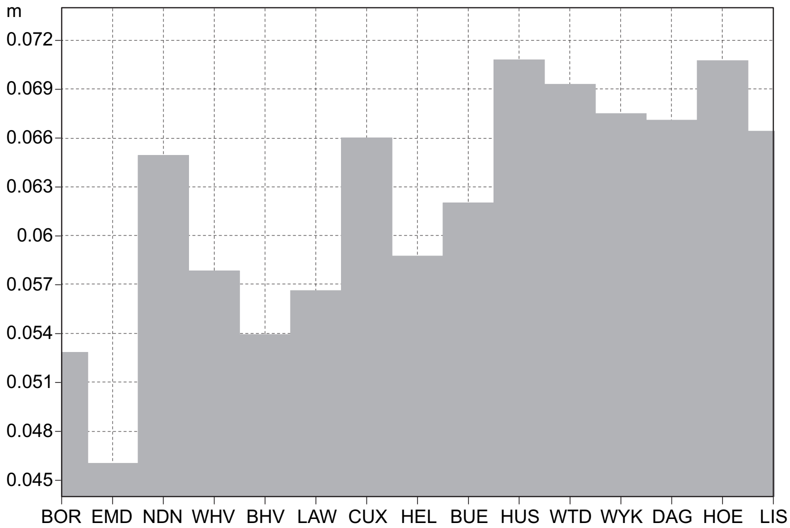

Fig. 3 Pattern of the first EOF in the EOF-approach 1924 - 2008. Three letter codes indicate tide-gauges, from left to right: Borkum, Emden, Norderney, Wilhelmshaven, Bremerhaven, Lighthouse Alte Weser, Cuxhaven, Helgoland, Büsum, Husum, Wittdün, Wyk, Dagebüll, Hörnum and List.

German Bight at least before 1924.

Table 1 shows that sea level variations in Cuxhaven and those derived from the two RMSL estimates are highly correlated. However, linear trends differ considerably with the linear trends in Cuxhaven exceeding those derived from the RMSL estimates by up to 17% (Table 2). While confidence intervals are mostly overlapping, this is not the case for the longest period 1843 - 2008, suggesting that sea level changes in Cuxhaven do not represent a good proxy for estimating long term changes at the regional scale. To consider this in more detail, decadal sea level changes were computed and analysed. Fig. 4 and Fig. 5 show 20- and 37-year trends of RMSL from both approaches and directly from data at Cuxhaven with the starting point of each 20/37-year segment incremented by one year. Note that 20-year trends were selected to maximize inter comparability with results in the literature while 37-year trends are considered as this corresponds to twice the nodal cycle and is a commonly used period in coastal engineering analyses in Germany (e.g. Jensen et al. 1992; Jensen and Mudersbach 2004, 2007). For the first 58 years the trends derived from the mean approach and those derived from the Cuxhaven data directly are indistinguishable. This is obvious as for this period data from Cuxhaven are the only data used in constructing the RMSL time series in the mean approach. From 1955 onwards the 20-year trends differ by up to 3.7mm/yr but with a few exceptions the estimates from Cuxhaven remain within the uncertainty range of the RMSL estimates. The situation is different, when 37-year trends are used (Fig 5). Here largest differences occur in the 1950s. They are up to 1.8mm/yr which is larger than the range indicated by the 90%-confidence intervals of the RMSL time series. The latter indicates that at least for these periods sea level variations at Cuxhaven do not represent a particularly well suited proxy for regional mean sea level variations in the German Bight.

A possible reason for these differences could be that the water levels at the Cuxhaven tide gauge are influenced by local construction works. Fig. 4 and Fig. 5 show, as a function of time, the different construction works that were carried out in the river Elbe. While Cuxhaven is located at the mouth of the river Elbe, effects on mean sea level in Cuxhaven were probably small, but may be still noticeable. The idea is supported by an analysis of the residuals between the RMSL from the EOF-approach and local sea level variations in Cuxhaven (Fig. 6). Provided local sea level variations in Cuxhaven are unaffected by local effects and represent the large scale signal in the German Bight we would expect these residuals to be small and oscillating around zero with no long-term trend or discontinuity. Fig. 6 shows that this is not the case. Moreover it is striking, that residuals are largest in periods where major construction work was carried out (Fig. 5). It is thus highly unlikely that local sea level variations represent a reasonable proxy for variations at the regional scale.

The reader may think of other influences such as local sea level dynamics at Cuxhaven to cause the differences. However, we do not consider this possibility as the main influence. We assume that changes in the sea level dynamics would not only have local influences at the tide gauge of Cuxhaven, but would effect the whole region and therefore the RMSL as well.

Using the EOF-approach RMSL can only reasonably be reconstructed back until 1924. Unfortunately, this coincides with the period after which most of the construction work in the river Elbe was implemented (Fig. 5). We are thus unable to make strong statements about the representativeness of the Cuxhaven data for the situation before 1924. Under the assumption that the construction works are the major cause for the deviations between RMSL and local sea levels in Cuxhaven, we can not exclude that the latter may provide a proxy for regional sea level changes before the construction works have implemented, i.e. before 1924 if we discount for the first deepening of the fairway around 1900. The extent to which data from Cuxhaven are representative for the regional conditions is important when RMSL variations for time periods before 1924 are reconstructed using the mean approach. This will become evident when possible accelerations in RMSL rise are considered (section 3.4).

3.2 Impact of Data Homogenisation

In section 3.1 we analysed results obtained from two different methods to construct index time series of RMSL applied to the same set of homogenised data derived from the AMSeL project (Wahl et al. 2011). We found that both approaches provided rather similar results. In the following we therefore only consider the EOF-approach. To elaborate on the effect the homogenisation

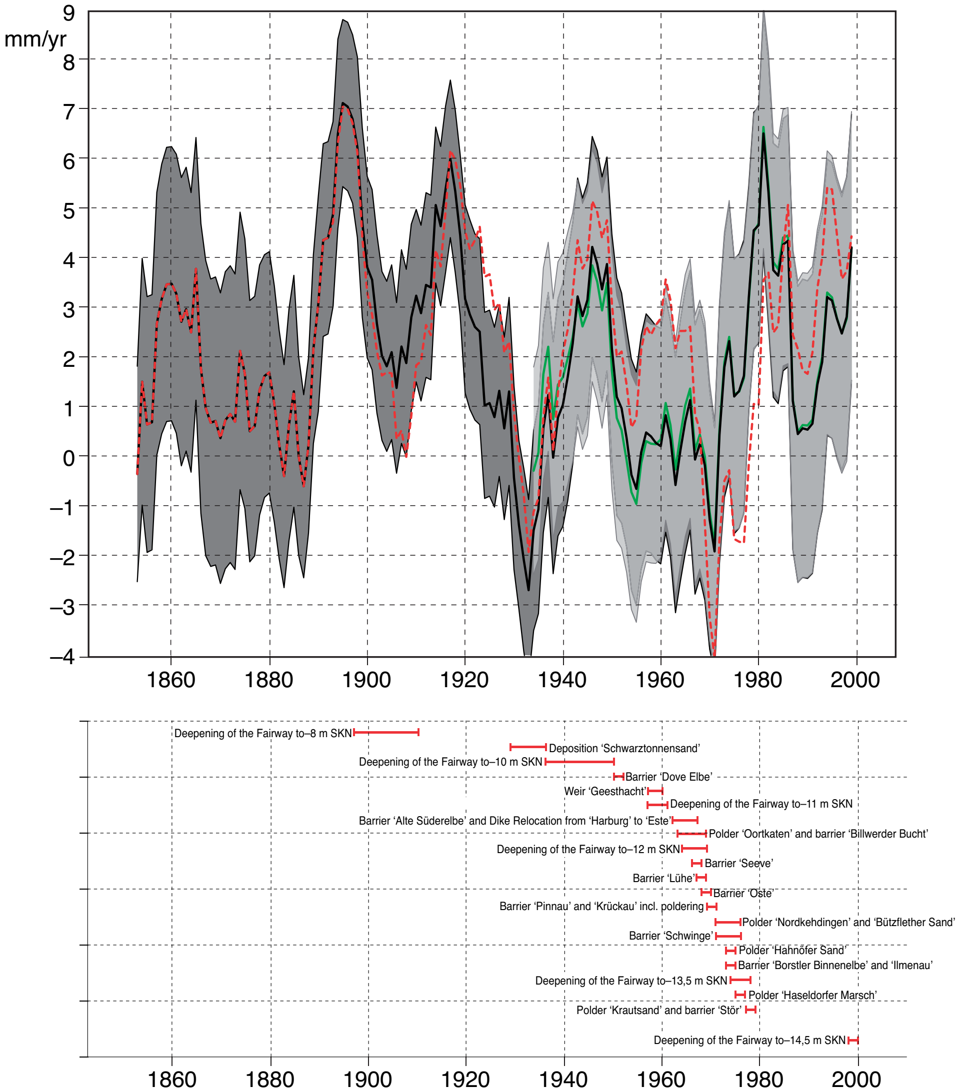

Fig. 4 20-year running trends of RMSL in the German Bight derived from the mean (black) and the EOF-approach (green) together with those derived from local sea level data in Cuxhaven (red). The 90%-confidence intervals for trends estimated from the RMSL time series are indicated in dark (mean approach) and light grey (EOF-approach). Trends are plotted relative to the centre of the 20-year time period considered. Also shown are periods in which major construction works were carried out in the river Elbe (bottom).

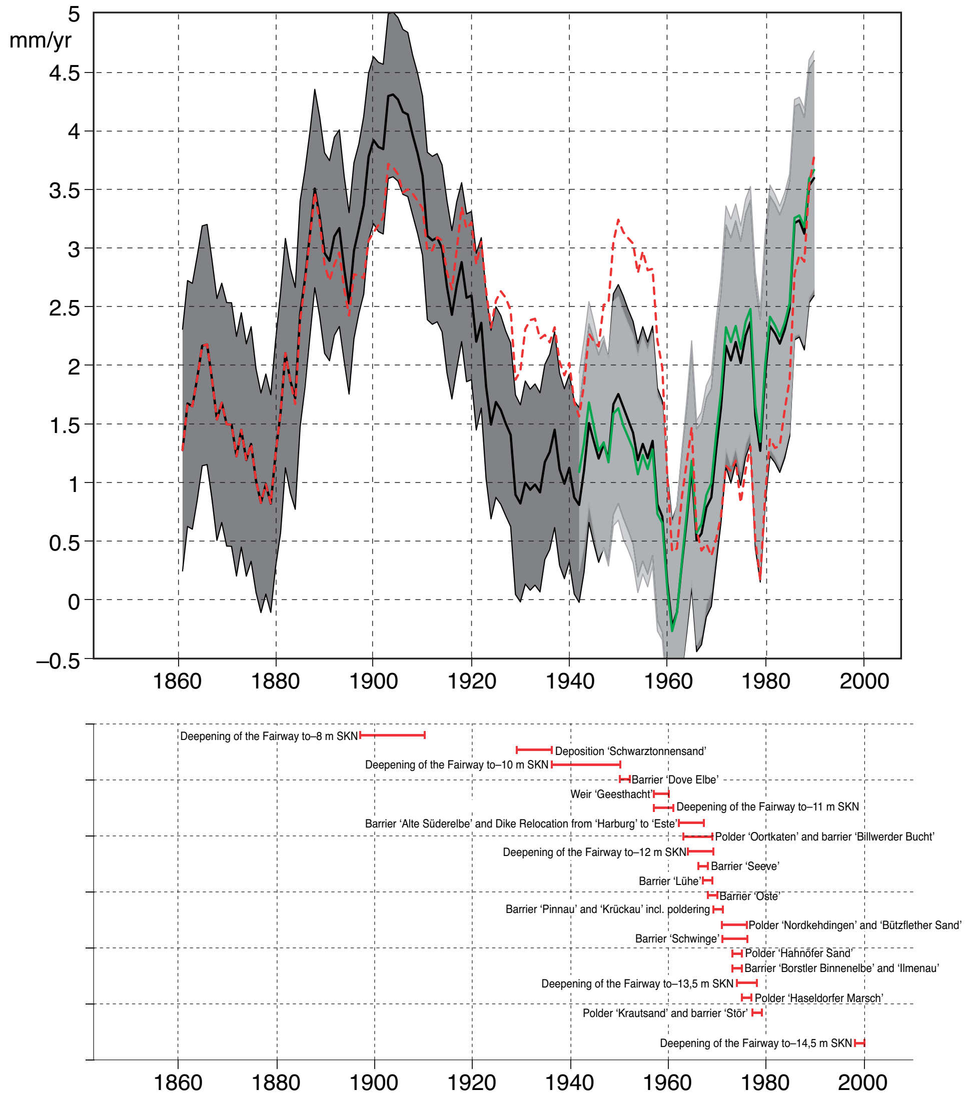

Fig. 5 37-year running trends of RMSL in the German Bight derived from the mean (black) and the EOF-approach (green) together with those derived from local sea level data in Cuxhaven (red). The 90%-confidence intervals for trends estimated from the RMSL time series are indicated in dark (mean approach) and light grey (EOF-approach). Trends are plotted relative to the centre of the 37-year time period considered. Also shown are periods in which major construction works were carried out in the river Elbe (bottom).

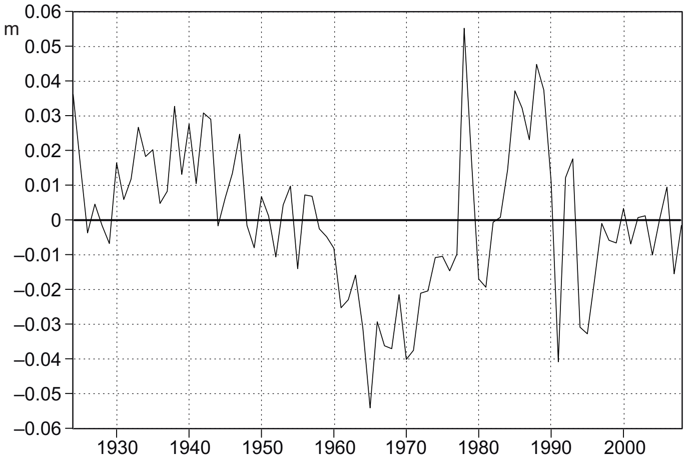

Fig. 6 Residuals 1924-2008 in m between RMSL derived from the EOF-approach and local sea level in Cuxhaven.

may have on our results, we applied the EOF-approach to the original data and the AMSeL data. What we denote here as original data are the data taken from the Gewässerkundliche Jahrbücher (in the following GJ) which are the official German journal in which hydrological values and statistics from gauges in German rivers, estuaries, and coastal areas are listed. Since the only digitized data of the GJ available to us are those from Emden (1901 - 2007), Norderney (1891 - 2006), Wilhelmshaven (1873 - 2007), Bremerhaven (1881 - 2007) and Cuxhaven (1843 - 2007)[2] which are all located in Lower Saxony (Fig. 1), the following analysis is done for Lower Saxony only. Moreover, note that the GJ only provides mean tidal high and low water. Local MSL are thus approximated by mean tide levels (MTL) which are the sum of subsequent high and low waters divided by two. In both data sets annual mean values are derived for the hydrological year, which is from November of the previous year until October of the current year. The periods considered are somewhat shorter for the AMSeL data set (Fig. 2) because the early years do not satisfy the necessary quality checks for homogenisation. We, however, retained those years for the analysis using the GJ data.

To assess the influence the homogenisation had on the estimates of the RMSL, an EOF-analysis for both data sets was performed. Fig. 7 shows the two RMSL time series obtained and their differences. For the common time period (1937 - 2006), both RMSL time series share a correlation coefficient of 0.99 and the linear trends are 1.6mm/yr and 1.53mm/yr for the homogenised and the original data respectively. In both cases the 90%-confidence range

[2]Note that in the Cuxhaven data a linear trend was added from the year 1855 to the year 1900 (Jensen (1984)) to account for vertical land movements. This trend was removed before analysing the data in order to get the relative MSL time series comparable to the other tide gauges.

is 0.4mm/yr. Analysis of the differences between both time series (Fig. 7) reveals, that they oscillate around zero until about 1970. From 1970 onwards large fluctuations begin to emerge and a positive trend is obvious towards the end of the analysis period. The later indicates a more substantial influence of the homogenisation towards the end of record. This becomes obvious if trends from 1978 - 2006 are considered. The latter is 1.62mm/yr and 2.27mm/yr in the original and the corrected data respectively. However, the 90%-confidence range has a value of 1.5mm/yr in both cases due to the relatively short time period.

There are a couple of reasons that can potentially explain the differences found. To some extend the differences are due to corrections for local datum shifts (IKÜS 2008; Wanninger et al. 2009) that have been applied when constructing MSL time series in the AMSeL-project to improve the overall data quality. Probably to a large extent, the differences result from the fact that we compare MTL time series (where MTL serves as a proxy) from the GJ with MSL time series from the AMSeL-project. In the German Bight shallow water effects play a dominant role and the tidal range has increased over the last century (Jensen und Mudersbach 2007). Especially for tide gauges like Emden and Bremerhaven, where the tide curves are strongly deformed, differences in the MTL trends and MSL trends can be expected. As we are interested in the decadal changes of the RMSL we again consider the 20- and the 37-year trends (Fig. 8). Here the 20-year trends calculated from the AMSeL data are above the trends derived from the original data for the periods before 1960 (1950 to 1969) and from 1981 (1971 to 1990) onwards. In-between it is the other way around. The maximum difference is about 1mm/yr for the period around 1986 (1976 to 1995). For the 37-year trends they higher when derived from the time series of the AMSeL data before the period around 1959 (1941 to 1977) and from 1977 (1959 to 1995) on. In-between it is again the other way around. The largest difference is 0.4mm/yr in the last period from 1970 to 2006 indicating that decadal variability obtained from both RMSL time series share rather strong similarities. In the following we thus only consider the homogenised data as they have a larger regional coverage.

3.3 Regional Mean Sea Level Changes in the German Bight

Fig 3 shows that tide gauges in Schleswig-Holstein and Lower Saxony have different weights in the construction of the RMSL time series. We therefore applied the EOF-approach separately to each region to obtain a separate estimate for each area. Here, the stations Borkum, Emden, Norderney, Wilhelmshaven, Bremerhaven, Lighthouse Alte Weser, and Cuxhaven from 1924 to 2008 were used to construct a RMSL time series for Lower Saxony, while Büsum, Husum, Wittdün, Wyk, Dagebüll, Hörnum, and List from 1936 to 2008 were used for Schleswig-Holstein. A similar sensitivity analysis as described in section 3.1 was performed to show that results are robust within the time periods considered. The results for Lower Saxony and Schleswig-Holstein are shown in Fig. 9. Both time series share high correlation coefficients with the RMSL for the entire German Bight (0.98 and 0.99 respectively) as well as between themselves (0.95). This indicates that all time series share strong similarities with respect to their variability. The

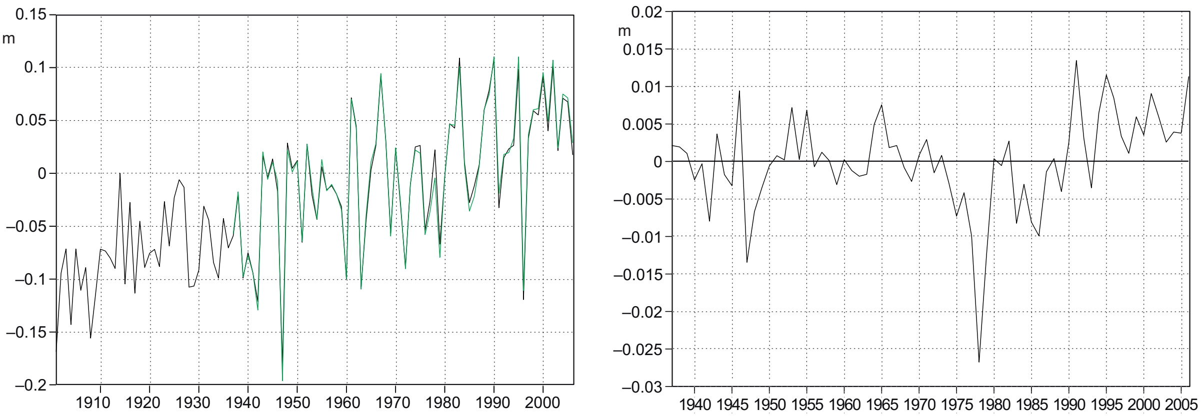

Fig. 7 Left: RMSL in m in Lower Saxony derived from the EOF-approach using data from Emden, Norderney, Bremerhaven, Wilhelmshaven and Cuxhaven; original (GJ) data 1901-2006 (black); data from the AMSeL project 1936 - 2006 (green). Right: differences in m between the RMSL derived from the AMSeL data and from original (GJ) data for the common time period 1937 - 2006.

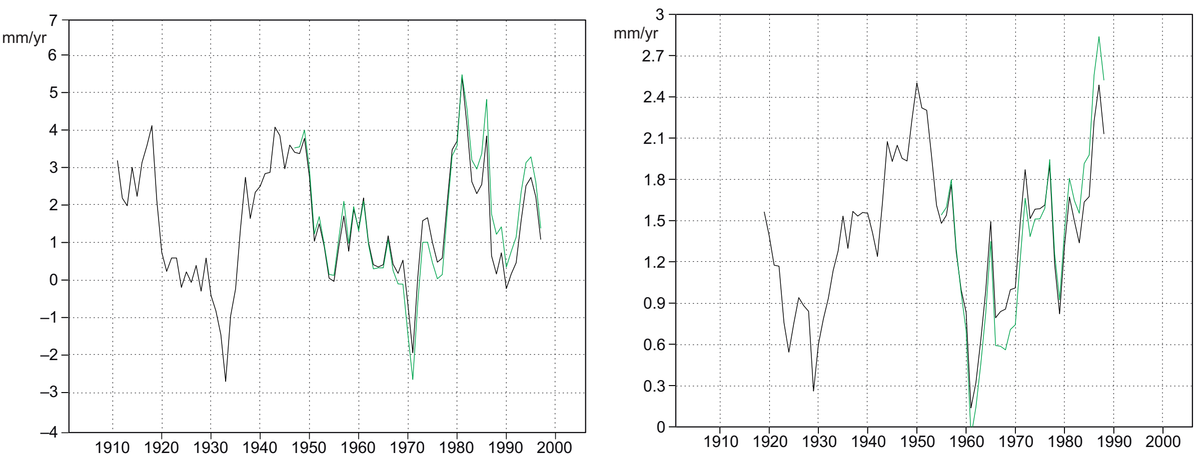

Fig. 8 20-year (left) and 37-year running trends (right) of the RMSL in Lower Saxony derived from the EOF-approach using data from Emden, Norderney, Bremerhaven, Wilhelmshaven and Cuxhaven; original (GJ) data (black); data from the AMSeL project (green).

linear trend for Lower Saxony has a value of 1.69 ± 0.3mm/yr for the period from 1936 to 2008, while for Schleswig-Holstein a somewhat higher value of 2.02 ± 0.4mm/yr is found for the same period. Though this difference is not statistically significant as the confidence intervals overlap, it is however noticeable and worth mentioning. For comparison, the linear trend for this period of the RMSL for the German Bight is 1.95 ± 0.4mm/yr. In each case the 90%-confidence range is given.

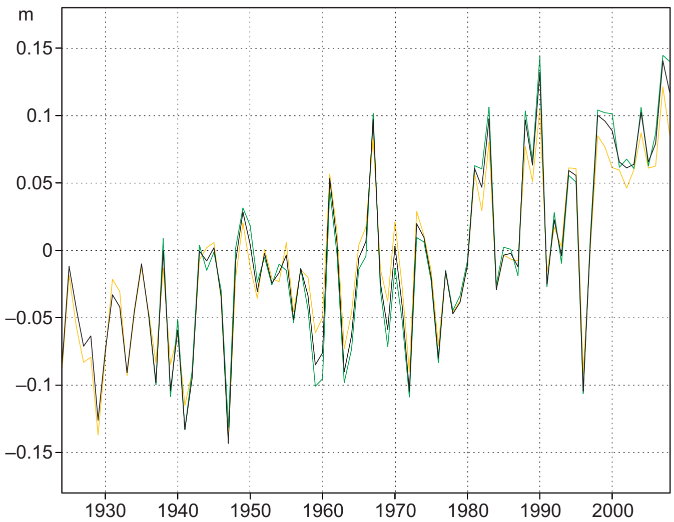

Fig. 9 RMSL in m for Lower Saxony (yellow), Schleswig-Hostein (green) and the German Bight (black) as derived from the EOF-approach.

In Fig. 10 the 20- and the 37-year running trends of Lower Saxony and Schleswig-Holstein are presented together with the trends of the German Bight and Cuxhaven. Also at these time scales considerable differences between RMSL changes in Schleswig-Holstein and Lower Saxony do occur. Differences are up to 2.7mm/yr and 1.4mm/yr in the 20-year and the 37-year trends respectively. Again, higher values are found for Schleswig-Holstein with the time series for Schleswig-Holstein being above or close to the upper bound of the 90%-confidence interval of the Lower Saxony time series from 1970 onwards. Thus regional differences in the trends and the pattern of the first EOF of the RMSL, which shows higher amplitudes in Schleswig-Holstein than in Lower Saxony (Fig 3) indicate a significant spatial variability in the MSL of the German Bight.

In Fig. 10 can be seen that the time series of Cuxhaven is within the 90%-range of the RMSL of Lower Saxony for most time periods. This indicates that Cuxhaven might be seen as a better proxy for the region of Lower Saxony than for the whole German Bight. Although, in the 20-year trends it is quite close to the border of the confidence interval for most time periods.

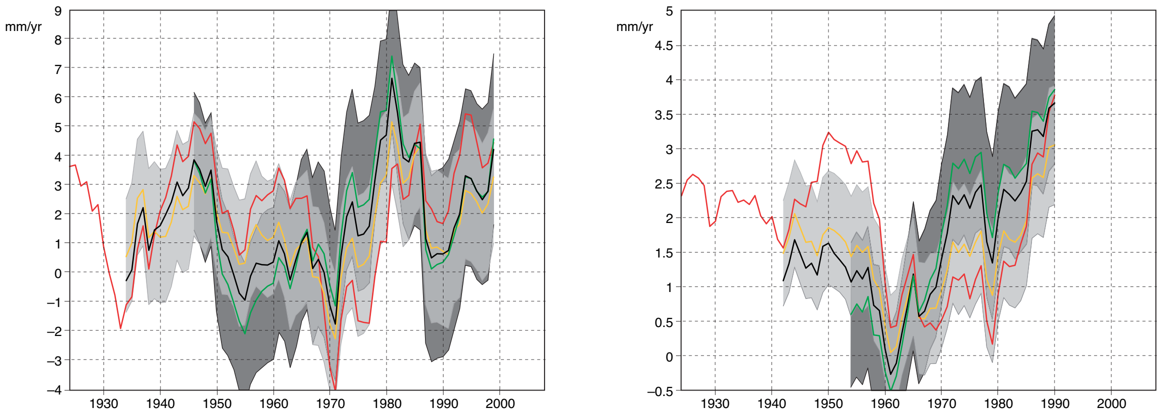

Fig. 10 20-year (left) and 37-year running trends (right) of RMSL in Lower Saxony (yellow), Schleswig-Hostein (green), and the German Bight (black) together with those derived from local sea level in Cuxhaven (red). The 90%-confidence intervals for trends estimated from the RMSL time series are indicated in dark (Schleswig-Holstein) and light grey (Lower Saxony).

3.4 Acceleration in Regional Mean Sea Level Rise

In this section we again consider the 20- and 37-year running trends in Fig. 4 and Fig. 5 but with another focus. We analyse the RMSL time series derived from both methods in relation to the question whether or not an accelerating rise within the most recent years can be inferred.

In section 3.1 we showed that both methods provide very similar RMSL time series for the common time period 1924 - 2008. Comparing the 20- and 37-year running trends correlation coefficients of 0.98 and 0.99 are obtained respectively. As explained in section 3.1 the RMSL time series derived from the mean and the EOF-approach differ at the very beginning because of the different behaviour of the methods in response to missing values. This can also be inferred from the 20-year trends Fig. 4 where the first three values of the trends differ by up to 1.2mm/yr, while thereafter differences are generally smaller than 0.5mm/yr. For the 37-year trends differences are generally smaller than 0.3mm/yr. While the RMSL time series derived from the mean approach becomes increasingly more uncertain for earlier years when less data are available, it is important for our analysis because it covers a much longer period than the time series derived from the EOF-approach. Using the RMSL time series from the mean approach as a benchmark gives us the chance to compare the most recent trends in RMSL with those observed before 1924. However, the increasing uncertainty should be taken into account.

Fig. 4 and Fig. 5 show that the 20- and the 37-year RMSL trends derived from both approaches are relatively high at the end of the analysis period and were more or less constantly rising within the last few years. The latter indicates an acceleration in sea level rise. However, closer inspection of the 20-year trends reveals that the present day rates of sea level rise are not unusual and that similar values already occurred earlier (e.g. around the 1980s). When 37-year trends are considered, the situation is somewhat different. If we only consider the common period covered by both approaches the most recent trends represent the highest on record. Only if additionally the information available from the mean approach for the earlier years is included, a similar conclusion as for the 20-year trends, namely that comparable trends have been observed already earlier, could be reached. The answer we can give to the question, on whether or not an accelerating rise in terms of 37-year trends could be observed in the RMSL record in the German Bight thus depends to a large degree on the reliability of the reconstruction using the mean approach for the earlier years in the available records.

Although sea level in Cuxhaven was found not be a good proxy for RMSL in the German Bight (section 3.1), an analysis of 20-year and 37-year trends is presented for completeness as Cuxhaven represents the longest record available. As for RMSL both the 20- and the 37-year trends are increasing towards the end of the analysis period reaching relatively high values in the most recent years. For the 20-year trends there are several peaks in the time series (1895,1917,1946,1986 and 1994) which show higher trends than within the most recent period around 1999 with a trend of 4.4mm/yr. The value of the 37-year trends within the last period centred around 1990 is 3.8mm/yr. There are two other high peaks in this curve. One is around 1950 with a trend of 3.2mm/yr and the other around 1903 with 3.7mm/yr. Both are somewhat smaller than the most recent trend, but differences are still small.

Summarizing we found that for all, the RMSL derived from two different approaches (Figs. 4, 5) and the original sea level data from Cuxhaven (Figs. 4, 5, 10), both 20-year and 37-year trends are increasing within the most recent years reaching relatively high values which are, however, mostly not unusual when compared to those derived for earlier periods.

4 Summary and Discussion

Two methods to derive an index time series for RMSL in the German Bight are presented and applied to a homogenised data set. Both methods produce very similar results and analysis of both RMSL time series provides very similar conclusions. Since the EOF-approach is supposed to filter out local disturbances at individual tide gauges (in-homogeneities such as e.g. due to construction works) our comparison shows that for the data used such effects only have minor impact on the results. Analysis of RMSL time series from both approaches suggest that RMSL has increased at rates between about 1.64mm/yr and 1.74mm/yr over the period 1924 - 2008. Analysis of decadal (20- and 37-year trends) additionally reveals considerable variability in the rates of sea level rise.

The length of the data records varies considerably between the different tide gauges (Fig 1). The longest record is available for Cuxhaven and this record gains increasingly more weight in one of the approaches (the mean approach) when fewer and fewer data from other tide gauges are available in earlier years. We thus considered the extent to which local sea level variations in Cuxhaven represent a reasonable proxy for the description of sea level variations at a larger scale. Comparing residuals and decadal trends we found that this is not case from 1924 onwards. However, some indications do exist that local construction works may be partly responsible for this result. The latter were carried out mostly from 1924 onwards, such that we could not exclude that Cuxhaven still may represent a good proxy before 1924. Unfortunately, we could not test this hypothesis for methodological reasons.

Nevertheless, the methodology introduced may be used to identify records from other tide gauges that may be better suited as proxies for RMSL in the German Bight. The latter may provide some aid in selecting tide gauges for further digitization, an extremely time consuming and costly endeavour that can not be carried out for all data.

The question on whether or not an acceleration in RMSL rise could be observed within the most recent years was addressed by analysing decadal, 20- and the 37-year trends, as a function of time. Both results obtained from using RMSL derived from the EOF and the mean approach show comparable rates (trends) for the time period covered jointly in both analyses with the most recent rates being relatively high. When 20-year trends are considered we found that these rates are, however, not unusual and that similar rates could also be identified earlier in the record. When 37-year trend are considered the situation is somewhat different. The time series derived from the EOF-approach is too short to infer a similar statement. Only when the longer record provided by the mean approach is considered we again find comparably high rates of sea level rise in earlier years. The answer we can give to the question on whether or not an accelerating sea level rise can be observed in the German Bight thus depends largely on whether or not sea level variations in Cuxhaven may serve as a proxy for regional variations before 1924. To the extent this is the case, we conclude that present rates of RMSL rise in the German Bight are relatively high, but are not unusual in the context of historical changes. The same conclusion concerning a possible acceleration in the recent past was drawn by Haigh et al. (2009) for the Northsea region of the English Channel.

We not only compared different methods to construct an index time series for RMSL, but also considered potential influences of the homogenisation of the data. By analysing 20- and 37-year trends of derived from RMSL constructed with the original data and with the revised (homogenised) data from the AMSeL-project we found that the influence was mostly small. However, within certain periods (1978 - 2006) trends may vary considerably with that derived from the homogenised time series exceeding that from the original data by as much as 0.62mm/yr. As the differences are small during most time periods and the homogenised data covers a larger area we decided to use the homogenisised data in order to represent the whole German Bight.

Since Church et al. (2006, 2007) analysed 20-year trends of the GMSL, a comparison of the decadal trends of the RMSL and the GMSL would be interesting. A comparison of GMSL and RMSL has been initiated in Wahl et al. (2008). Here, the correlation coefficient of the GMSL and the tide gauge Cuxhaven for the period 1870 to 2007 was computed to be 0.33. This low correlation coefficient is not surprising since the GMSL consists of up to 317 different locations compared to one single tide gauge. We now have a combination of 15 locations which still is a very low number compared to 317. However, a relationship on a decadal scale would be possible and worth analysing.

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