Ocean Dynamics (2013) 63:209–224
DOI 10.1007/s10236-013-0598-0

Characteristics of intra-, inter-annual and decadal sea-level variability and the role of meteorological forcing: the long record of Cuxhaven

Sönke Dangendorf · Christoph Mudersbach · Thomas Wahl · Jürgen Jensen

Received: 24 August 2012 / Accepted: 15 January 2013 / Published online: 2 February 2013

Abstract This paper addresses the role of meteorological forcing on mean sea level (MSL) variability at the tide gauge of Cuxhaven over a period from 1871 to 2008. It is found that seasonal sea level differs significantly from annual means in both variability and trends. The causes for the observed differences are investigated by comparing to changes in wind stress, sea level pressure and precipitation. Stepwise regression is used to estimate the contribution of the different forcing factors to sea level variability. The model validation and sensitivity analyses showed that a robust and timely independent estimation of regression coefficients becomes possible if at least 60 to 80 years of data are available. Depending on the season, the models are able to explain between 54 % (spring, April to June) and 90 % (winter, January to March) of the observed variability. Most parts of the observed variability are attributed to changes in zonal wind stress, whereby the contribution of sea level pressure, precipitation and meridional wind stress is rather small but still significant. On decadal timescales, the explanatory power of local meteorological forcing is considerable weaker, suggesting that the remaining variability is attributed to remote forcing over the North Atlantic. Although meteorological forcing contributes to linear trends in some sub-periods of seasonal time series, the annual long-term trend is less affected. However, the uncertainties of trend estimation can be considerably reduced, when removing the meteorological influences. A standard error smaller than 0.5 mm/year requires 55 years of data when using observed MSL at Cuxhaven tide gauge. In contrast, a similar standard error in the meteorologically corrected residuals is reached after 32 years.

Keywords Mean sea level variability · German Bight · Meteorological forcing · Sea level rise

Responsible Editor: Birgit Andrea Klein

S. Dangendorf (✉) · C. Mudersbach · T. Wahl · J. Jensen
Research Institute for Water and Environment (fwu), University of Siegen, Paul-Bonatz-Str. 9-11, 57076 Siegen, Germany
e-mail: soenke.dangendorf@uni-siegen.de
URL: http://www.uni-siegen.de/fb10/fwu/

T. Wahl
Institute of Advanced Studies, Research Group of Civil Security, University of Siegen, Unteres Schloss 2, 57072 Siegen, Germany

1 Introduction

In the last few decades, there has been a great effort to understand the characteristics of long-term global sea level rise (SLR) (Douglas 1991; Woodworth 1990; Church and White 2006; Church and White 2011). The importance of such studies is rooted in the high impacts, which are related to possible future sea level rise. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007) suggested a global mean sea level (MSL) rise of up to 60 cm by 2100 as a result of global ocean warming, glacier melting and the balance between melting, snowfall and the regular outflow from glaciers from ice sheets (potential accelerated ice-sheet melting, which could add another 20 cm of SLR, is not included in these projections). Such an increase would have considerable consequences for the flood risk in coastal areas, as the MSL is the reference frame for storm surges. However, studies dealing with future SLR base on the knowledge of the physics behind past sea level changes. Hence, a detailed understanding of observed sea level in the past is a fundamental step before doing studies focusing on future SLR.

Sea level has been observed since the eighteenth century with the longest records based on tide gauge measurements at coastlines. Since 1992, there has been a quasi-global coverage of sea level observations with the introduction of satellite measurements. Both measurement methods have different advantages and disadvantages. Tide gauge measurements, for example, are available since the eighteenth century and consequently provide a good insight into the history of sea level. The disadvantage of tide gauges is that they give a measure of relative sea level change, i.e. the observations include both sea level changes and vertical land movements. These relative measurements are important for coastal planners, as for coastal zone management, the relative sea level change is the proper magnitude, but disregarding the vertical land movements can compromise estimates of global SLR. Furthermore, the heterogeneous distribution of tide gauges around the world biases the estimation of global SLR (Merrifield et al. 2009). Satellite altimetry, however, allows the observation of absolute sea level in a precise reference frame with quasi-global coverage, but as satellite altimetry observations are only available since 1992, the data sets are not yet usable for the estimation of long-term trends. Additionally, satellite measurements are not reliable for coastal areas. Hence, for understanding past sea level changes, both data types have to be combined. While tide gauge observations point to a significant increase in global MSL (GMSL) of ~17 cm throughout the twentieth century, a closer look on the development shows that this rise is far from linear with considerable inter-annual and decadal fluctuations, which are linked to climate patterns (Bindoff et al. 2007). Additionally, satellite altimetry reveals a high spatial heterogeneity of sea level changes around the world with regions of increase and regions of decrease (Milne et al. 2009). This fact clarifies the particular importance of understanding past sea level changes and variability. The large deviations in regional SLR show that regional MSL variability, rather than the global mean, is the main concern for risk assessments.

Generally, fluctuations in the sea surface height (SSH) are caused by changes in the steric components, i.e. changes due to variations in water temperature or salinity. Likewise, meteorological forces drive regional sea level through the effects of wind and sea level pressure (SLP). While wind pushes sea level towards or away from the coastline, SLP influences the SSH through the inverse barometric effect (IBE), i.e. hydro-static de-/compression. In some areas, river runoff or climatic effects are other prominent forcing factors of SSH variability (Tsimplis and Woodworth 1994). Apart from these direct forcing factors, it should be noted that sea level is affected by long-period tides such as the nodal cycle (e.g. Jensen 1985, Haigh et al. 2011). These cycles have to be taken into account, especially if the trend development or acceleration/deceleration characteristics are investigated (Baart et al. 2012).

Many studies have tried to identify the climatic factors that drive sea level variability (Tsimplis and Josey 2001; Wakelin et al. 2003; Woolf et al. 2003; Yan et al. 2004; Tsimplis et al. 2005; Jevrejeva et al. 2005; Woodworth et al. 2010; Dangendorf et al. 2012). In the North Atlantic region, the leading atmospheric mode is the North Atlantic Oscillation (NAO) during wintertime. The NAO index is defined as the standardised difference of the two leading atmospheric pressure fields, the Azores High and the Icelandic Low. Since the NAO dominates the winter climate over Northern Europe (Hurrell 1995), there is a clear link between sea level and the NAO index. Especially during the last decades, MSL along the European coasts correlates well with the NAO (Yan et al. 2004; Jevrejeva et al. 2006). The problem with the NAO is that it is just presented as an index. Therefore, it does not affect sea level directly. It rather represents a proxy affecting different related parameters, such as wind, sea level pressure or precipitation (Suursaar and Sooäär 2007).

The main objective of this study is to examine the effects of such NAO-related processes on MSL variability in the Cuxhaven record. The tide gauge of Cuxhaven is located in the mouth of the Elbe estuary in the southeastern part of the shallow North Sea. The record is of particular interest for sea level studies, as it is one of the longest records available worldwide. Starting in 1843, the tide gauge has recorded over 160 years of sea level changes up to date. In the last decades, the tide gauge has been the subject of several sea level studies (Jensen et al. 1993; Tsimplis et al. 2005; Jevrejeva et al. 2006; Jensen and Mudersbach 2007; Wahl et al. 2010, 2011; Albrecht et al. 2011; Albrecht and Weisse 2012; Dangendorf et al. 2012). While earlier studies (Jensen et al. 1993; Jensen and Mudersbach 2007) deal with the mean high and mean low water levels, Wahl et al. (2010, 2011) reconstructed monthly MSL time series using the *k*-factor approach, a method which allows the combination of low- and high-frequency data for the reconstruction of MSL time series.

It is well known that the major forcing factor of MSL variability in the German Bight is wind (Wakelin et al. 2003), but its full contribution is only known by the output of hydro-dynamical models providing data only for the past 50 years. Since the NOAA provides long-term gridded climatic reanalysis datasets back to the nineteenth century (Compo et al. 2011), the comparison of different related parameters with regional sea level over longer timescales becomes possible. In this study, we try to estimate the contribution of wind stress, sea level pressure and precipitation on sea level variability in the German Bight, exemplarily shown for the tide gauge of Cuxhaven. These investigations have several implications for the aspects of coastal planning and management. First, an improved knowledge about past sea level changes allows for a better look into the near future. Here, the near future refers to time spans of 30 to 50 years, which are interesting for coastal planning purposes. Second, the large variability, which is regionally present in a lot of sea level time series, complicates a reliable estimation of long-term trends. Under the assumption that we can consistently estimate the amount of non-tidal variability in sea level data, the estimation of long-term trends should become more precise. Several authors (Douglas 1991; Tsimplis and Spencer 1997; Woodworth 1990; Woodworth 1991; Haigh et al. 2009) pointed out that periods of 30 or 50 years are necessary, to get a stable trend estimate with an adequate standard error. Locally or regionally the available data often do not fulfill these requirements. A good example in this context is the area of the Halligen, which is located northeastwards from Cuxhaven. The Halligen are small islands with high cultural importance (UNESCO World Cultural Heritage Site), but they are highly impacted by climatic change (Arns et al. 2011). Therefore, local MSL studies are required for an integrated risk assessment. The available data in this area are sparse and do not provide such long periods; however, an improved understanding of the driving mechanisms could help for local coastal planning. Finally, since decades, sea level scientists and coastal planners attempt to answer the questions whether acceleration in SLR can be detected. Rahmstorf et al. (2012) pointed out that the large amount of non-tidal variability hampers the detection of acceleration patterns in SLR. For global reconstructions in which the variability is smaller through the applied methods (Church et al. 2004; Church and White 2006, 2011), a potential acceleration will be easier to detect than in a local record. Especially on regional scales, the variability therefore needs to be minimised to get more information about the shape of the long-term trend. MSL time series in the German Bight, such as the Cuxhaven record, are characterised by a large intra-, inter-annual and decadal variability Wahl et al. under review. Hence, the explanation of this variability is an important step for the above-mentioned issues.

The paper is structured as follows. In "Section 2", we describe the data and methods used for the different investigations. The corresponding results are presented and discussed in "Section 3", while "Section 4" contains the conclusion.

2 Data and methods

Monthly MSL data from the tide gauge of Cuxhaven are used in this study (Fig. 1). The raw data have been provided by the Federal German Waterways and Shipping Administration (WSv). Observations at the tide gauge are available since 1843. These observations are restricted to the tidal high (HW) and low water levels (LW) handwritten in log books. In 1899, the measurement technique had changed, making it possible to observe the full tidal curve on tidal charts. Extensive digitisation works provided hourly sea level data from 1918 to the present. Since the mid-1990s, tide gauge observations are directly and digitally archived with a 1-min resolution. While monthly or annual MSL back to 1918 can be calculated from high-resolution data (at least hourly resolution), before that time Wahl et al. (2010, 2011) applied a technique to reconstruct MSL values on the basis of LW and HW back to 1843. Here, we use the reconstruction for a deeper analysis of observed changes during a period from 1871 to 2008 (a time span for which climate reanalysis data exists). The data set has been checked for errors and corrected for local datum shifts, as reported in IKÜS (2008).

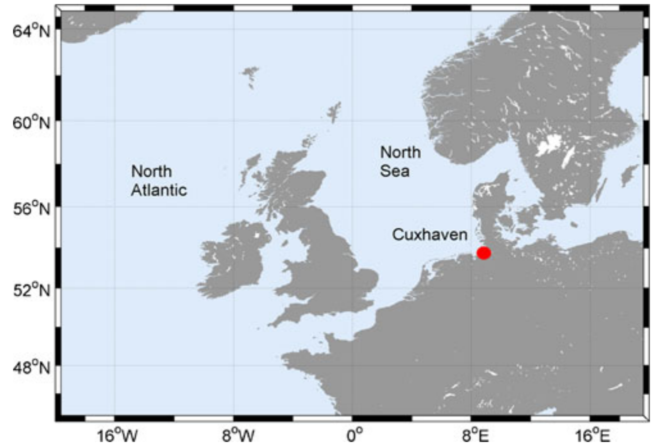

Fig. 1 Investigation area and location of the Cuxhaven tide gauge

The main aim of this study includes investigating climatic and meteorological induced variations of MSL, which are related to the large-scale atmospheric circulation pattern (NAO). Monthly data sets were extracted from the twentieth-century (20CR) reanalysis data on a 2×2 grid for the larger European and North Atlantic area, provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA (http://www.esrl.noaa.gov/psd/data/20thC_Rean/). For the present investigation, we extracted SLP, zonal (WSu) and meridional (WSv) wind stress and precipitation (P) data covering a period from 1871 to 2008. The data are based on ensemble model simulation with data assimilation. SLP and sea surface temperature observations are used as boundary conditions. Since especially for earlier periods the observations are sparse and spatially uneven distributed, the uncertainties of the data are larger before 1950 than afterwards. Krüger et al. (2012) pointed to some discrepancies between the long-term trends of storminess proxies from 20CR reanalysis data and observations. However, since our main focus is on investigating variability patterns, our results should be independent from these discussions. Furthermore, the correlations have been tested to be stationary high during the whole investigated period.

Before investigating the various time series, the seasonal cycle has been removed by subtracting the long-term monthly average from every monthly subseries. If not stated otherwise, we further corrected the time series for their observed linear long-term trend, as our main motivation aims at an investigation of intra- and inter-annual variabilities. To analyze the relationship between the different forcing factors and sea level, in a first-step correlation coefficients between MSL in Cuxhaven and gridded meteorological time series covering the larger Northern European and the North Sea area are computed. The correlation between two different time series can be computed with

$$r = \frac{\sum xy}{\sqrt{x^2 \sum y^2}} \tag{1}$$

The significance of the correlation can be estimated using

$$T = |r|\sqrt{\frac{n-2}{1-r^2}} \tag{2}$$

and comparing *T* with critical values from the *t* distribution with $n-2$ degrees of freedom (von Storch and Zwiers 1999). The resulting correlations between the different time series are presented as contour lines of similar correlations on geographic maps. This allows us to find the coherencies over the larger continental area.

If there is a significant relationship between two or more parameters, the contribution can be estimated within linear or multiple regression models. Since the different MSL contributors vary considerably throughout the whole year, the regression models are built up on seasonal time scales. For that purpose, the following definitions are used: The winter season is defined as the seasonal mean from January to March; spring season means the average from April to June; summer indicates the months between July and September, while October to December are summarised as the autumn season. We use the above-mentioned meteorological parameters to explain the MSL variability in Cuxhaven. The following model has been fitted to the time series, to estimate the effects of meteorological forcing. The multiple regression model for observed MSL is given by the equation

$$\eta = a_0 + a_1\mathrm{Wsu} + \mathrm{a_2Wsv} + \mathrm{a_3SLP} + \mathrm{a_4P} + \varepsilon \tag{3}$$

where the variables *Wsu*, *Wsv*, *SLP* and *P* are the zonal and meridional wind stress, sea level pressure and precipitation, respectively. The coefficient a_0 is constant and ε represents the random error. The explained variance of the multiple regression models (i.e. they include all meteorological parameters) can then be estimated by

$$\mathrm{VAR_{exp}} = \left[1 - \frac{(\mathrm{var}(\eta) - \mathrm{var}(\eta_{\mathrm{Wsu}} + \eta_{\mathrm{Wsv}} + \eta_{\mathrm{SLP}} + \eta_{\mathrm{P}}))}{\mathrm{var}(\eta)}\right] \times 100 \tag{4}$$

while the variances explained by each contributing factor are

$$\mathrm{VAR_{exp,i}} = \left[1 - \frac{(\mathrm{var}(\eta) - \mathrm{var}(\eta_{\mathrm{i}}))}{\mathrm{var}(\eta)}\right] \times 100 \tag{5}$$

The range of $\mathrm{VAR_{exp}}$ lies between 0 and 100 % and describes how much of the observed variability can be explained by the prediction. A value of zero means no correlation between both curves, whereas a value of 100 % means that the observed variability is equal to the predicted one. It should be noted that all the different predictors are driven by the NAO, which means that they should not be independent from each other. Hence, the sum of the explained variances of the linear regressions will not be the same as the explained variances by the multiple regression models:

$$\mathrm{VAR_{exp}} \neq \sum_{1}^{\mathrm{n}} \mathrm{VAR_{exp,i}} \tag{6}$$

For the identification of the different predictors, we use stepwise regression with forward selection. A stepwise regression means that we include the different meteorological contributing factors step by step into the regression model, if their relation is statistically significant and if they explain a significant part of the observed variances. This approach allows us to find a model consisting of preferably few predictors that explains as much variability as possible. The procedure can be summarised as follows:

1. Including the predictor with the largest bivariate correlation,
2. Including the predictor that explains the most significant part of the variability after removing the influence of the first predictor,
3. Including the predictor that explains the most significant part of the variability after removing the influence of the first and second predictor, and
4. The regression model is finished if no more predictors are able to give a significant contribution to the explained variability.

The significance of the regression models can be tested with *t*-statistics or *f*-statistics which can be found in standard mathematical literature. As a further quality control for the accuracy of the regression models, we compute the root-mean-square error (RMSE):

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{\mathrm{i}=1}^{\mathrm{n}} \left(\mu_{\mathrm{i}} - \left(\eta_{\mathrm{Wsu,i}} + \eta_{\mathrm{Wsv,i}} + \eta_{\mathrm{SLP,i}} + \eta_{\mathrm{P,i}}\right)\right)^2}{\mathrm{n}}} \tag{7}$$

where *n* is the sample size. The RMSE is a measure for the resulting differences between observed and predicted MSL. In contrast to the explained variability, the RMSE gives a direct measure of the resulting size of the residuals.

All regression coefficients are estimated with de-trended data sets. However, to allow a discussion of seasonal trends, we apply the estimated regression coefficients to the nondetrended meteorological time series (Huenicke et al. 2008). Linear trends are estimated by using the ordinary least-squares fit. The confidence intervals are described by the standard error (SE) of the regression residuals. It is assumed that the regression residuals are normally distributed, which is critical because of serial correlation in the sea level time series. Hence, the estimated confidence bounds are generally too optimistic. Nevertheless, in order to make sure that our results are comparable to earlier studies (especially when estimating the required data lengths to obtain certain SEs, see, e.g. Douglas 1991), we ignore the autocorrelation term.

3 Results and discussion

3.1 Observed seasonal MSL variations

The findings of Dangendorf et al. (2012) indicate significant dissimilarities between seasonal and annual MSL trends in the southeastern North Sea during the second part of the twentieth century. This heterogeneous development can be confirmed by the present investigations. To compare seasonal with annual MSL trends over the whole period from 1871 to 2008, moving trends are computed using a 30-year moving window (Fig. 2). For each window, the linear trend together with its SE is calculated for the annual MSL values as well as for seasonal means. The results of the moving trend analysis are summarised in Fig. 2. The blue lines represent the linear trend estimates of annual averages, while seasonal trend estimates are shown in red. The associated SEs are shown as 1σ confidence bounds with the transparent colored areas. At times, especially during the winter and autumn season, the seasonal trends differ significantly from the annual means. For example before 1900, seasonal deviations from the annual mean of up to ~5 mm/year can be found during winter seasons.

Until 1900, the winter trends, especially, exceed the trends of annual means considerably, whereby afterwards annual trends exceed winter trends over a period of ~20 years. From ~1920 on, the winter trends scatter around the annual MSL trends until the 1970s. Afterwards, considerably larger trends in the winter season have been detected. The differences as well as the inter-annual variability are in the spring and summer seasons considerably smaller, which is due to the fact that the atmospheric induced variability is largest in the winter and autumn months (Tsimplis et al. 2005; Dangendorf et al. 2012). However, the larger trends during the winter season in the second half of the twentieth century are also striking. Largest trend rates with values up to ~10 mm/year are observed in the winter season of the mid-1980s, a phase in which the atmospheric variability represented by the NAO index reached a local maximum (Hurrell 1995; Tsimplis and Josey 2001). The high variability during that time expresses itself in larger-than-normal SEs. Therefore, it can be suggested that a combination of different physical processes, which are related to the NAO, are responsible for the anomalous large variations between the different seasons.

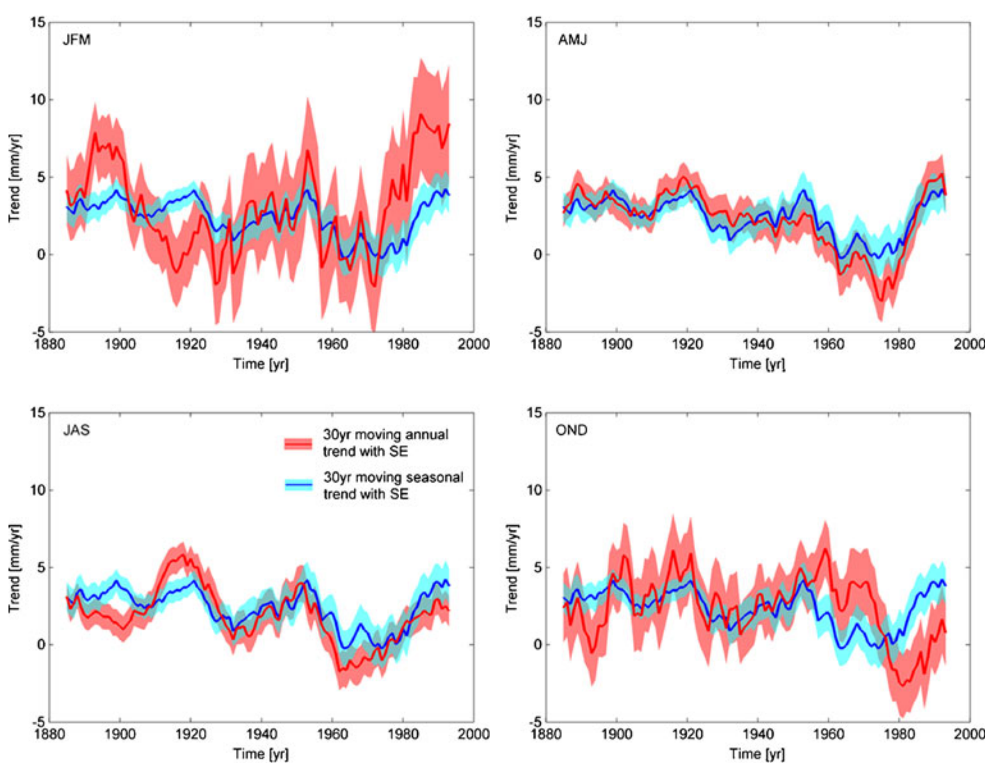

Fig. 2 30-year moving trend of seasonal (*red*) and annual (*blue*) MSL with their related 1σ SE (*shaded areas*)

3.2 Meteorological forcing of seasonal MSL

3.2.1 Correlation analysis

To examine these processes more precisely, meteorological time series of different related parameters are evaluated. Figure 3 shows correlation maps between monthly MSL in Cuxhaven and gridded climate data. The MSL time series is correlated to every gridpoint time series of SLP, wind stress and precipitation. First, the results of the correlation analysis between SLP and MSL (Fig. 3a) show that the relationship at the nearest grid point to the tide gauge is rather weak with values around ~−0.3, meaning that the MSL variability in Cuxhaven is not directly linked with the SLP variability over the southeastern German Bight. Therefore, the IBE by the classical approach is not the main forcing factor influencing MSL in Cuxhaven. In theory, for an infinite ocean, the response of sea level to SLP changes can be well described by a linear relationship. A hydrostatic reduction of ~1 mb in atmospheric pressure causes a stationary rise of 1 cm in sea level (Pugh 2004). The North Sea basin, however, has open boundary conditions, which complicates a clear description of that process. Interestingly, a linear relationship can be observed between MSL in Cuxhaven and the SLP field over Scandinavia with correlations over −0.8. A smaller but still significant correlation is further found between the SLP fields over the Iberian Peninsula. This relationship between MSL and both pressure fields shows similarities to the NAO, but it is even stronger. The spatial SLP pattern describes large parts of the observed variability in the German Bight (~70–80 % of the observed variance; not shown). The physical process behind that strong connection can be explained by the typical tracks of low pressure systems in the North Sea (Heyen et al. 1996; Ullmann and Monbaliu 2010). Usually, the low-pressure systems move from southern Greenland over the North Sea to Scandinavia. The strongest winds, which push the water masses into the German Bight, are observed at the rear of those low-pressure systems over Scandinavia. Thus, distinctive anomalies in both SLP fields can be associated with strong westerly winds in the North Sea and therefore influencing the MSL variability in the German Bight.

This assumption can be confirmed by the correlation between MSL in Cuxhaven and zonal/meridional wind stress over the North Sea area (Fig. 3c, d). Strongest correlations are found with zonal wind stress reaching values up to ~0.9. For meridional wind stress, the relationship is considerably weaker but still significant at the 95 % significance level (*t*test statistics). A further important correlation has been found

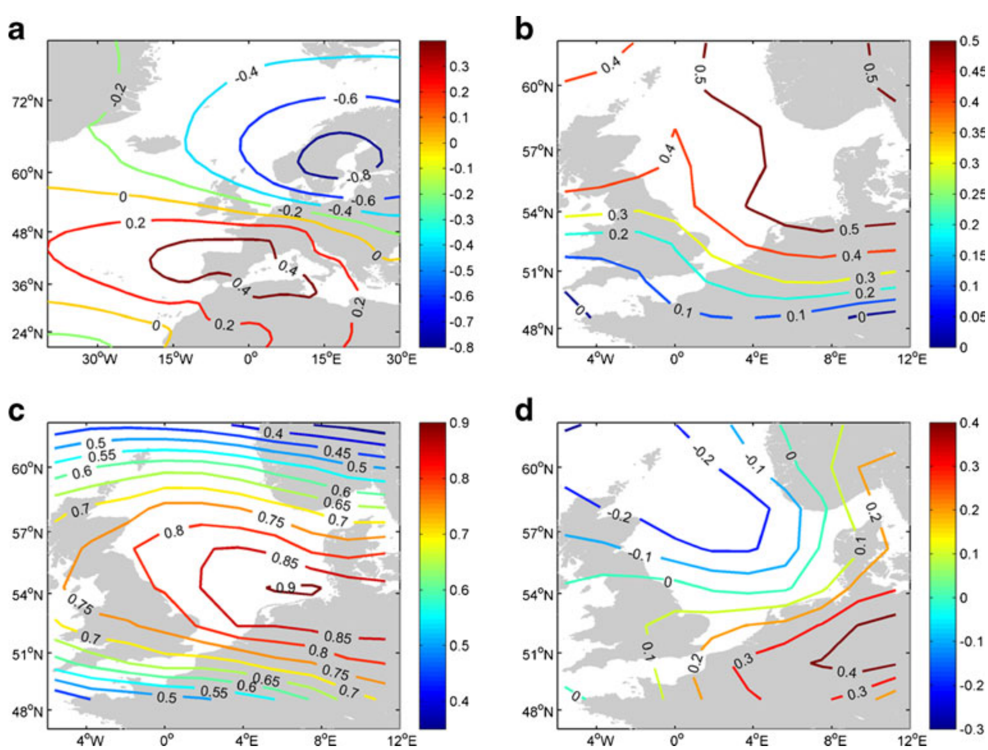

Fig. 3 Correlation maps between MSL anomalies measured in Cuxhaven and gridded climate data for **a** SLP, **b** precipitation, **c** zonal wind stress and **d** meridional wind stress

between MSL variability and precipitation. Figure 3b shows a significant coherence between both parameters at the nearest grid points to the tide gauge of Cuxhaven. Precipitation can be connected with sea level through a couple of different processes. The salinity (and therefore the halosteric height) in near-coastal areas is correlated with the difference between evaporation and precipitation and river runoff. Large variations in the salinity content can lead to volume changes associated with variations in the SSH (Schott 1966; Barbosa et al. 2004; Huenicke et al. 2008).

The correlation between the different forcing factors further shows considerable seasonal differences in all parameters (Table 1). The largest similarities are found between zonal wind stress and MSL through all the different seasons with largest values in winter of up to 0.93 and smallest values in spring (0.71). The second strongest relationship is observed between MSL and precipitation, followed by SLP and the meridional wind stress. While the seasonal correlation of zonal wind stress and precipitation has a maximum in winter, the largest correlation coefficients for SLP and meridional wind stress are found in the summer season. However, the correlation analysis points to a common influence of all selected parameters on MSL measured in Cuxhaven. Since all these parameters are directly linked to the NAO, co-variability between the different parameters can be suggested. This is confirmed by the cross-correlations between the different forcing factors (Table 1). Therefore, in the following, a stepwise regression is applied to the datasets. For the regression models, we use the meteorological time series from the nearest grid point to Cuxhaven with the coordinates 7.5000°E and 54.2846°N.

3.2.2 Regression analysis

The results of the multiple regressions are presented in Figs. 4 and 5a, b. While Fig. 4 displays the relationship between observed and predicted MSL, Fig. 5a, b represents the regression results as explained variances and the RMSE. The blue lines in Fig. 4 indicate the de-trended seasonal MSL, whereby the meteorologically reconstructed MSL is shown by the black lines. From that figure, it can be seen that the largest variability in seasonal MSL is observed during autumn and winter with standard deviations of 10 and 13 cm, respectively. Throughout the spring and summer seasons, the standard deviations are considerably lower with values around 5 cm. Hence, the amount of non-tidal variability, which can be explained through these seasons, is much lower than in winter and autumn. This is also reflected in the explained variances for the different seasons (Fig. 5a). During autumn and winter ~83 and ~90 % of the observed variability can be explained, while through the spring and summer seasons the contribution of meteorological forcing on MSL variability weakens considerably to values of ~54 and ~57 %. For the autumn and winter seasons, the predicted MSL is able to explain most of the observed peaks. Even the largest peaks such as the maximum and minimum values in the winter seasons of 1990 and 1996 are well reproduced by the model. During spring and summer seasons, the performance of the model is weaker, and several peaks are not well reproduced. For example, there is a remarkable minimum value observed in the spring season of 1978. The predictors used in the model cannot fully explain that minimum. The RMSE between observed and reconstructed MSL is, however, largest in winter and smallest in summer season, but the seasonal differences are considerably smaller than the observed standard deviations, indicating that the model is able to reproduce a major part of meteorological induced variability.

The contributors to MSL variability vary considerably through the different seasons. The largest amount is given by zonal wind stress across all seasons. In the winter, seasonal zonal wind stress alone is able to explain ~87 % of the

Table 1 Correlation coefficients between seasonal MSL observed in Cuxhaven and different meteorological forcing factors from the next grid point over the period from 1871 to 2008

	Winter					Spring				
	MSL	Wsu	Wsv	SLP	P	MSL	Wsu	Wsv	SLP	P
MSL	1.00	**0.92**	**0.29**	−0.10	**0.59**	1.00	**0.67**	**0.18**	**−0.22**	**0.40**
Wsu	–	1.00	**0.37**	0.07	**0.51**	–	1.00	**0.22**	−0.02	**0.31**
Wsv	–	–	1.00	−0.02	**0.30**	–	–	1.00	**−0.22**	**0.41**
SLP	–	–	–	1.00	**−0.60**	–	–	–	1.00	**−0.59**
P	–	–	–	–	1.00	–	–	–	–	1.00
	Summer					Autumn				
MSL	1.00	**0.73**	**0.45**	**−0.47**	**0.50**	1.00	**0.85**	−0.06	**−0.23**	**0.50**
Wsu	–	1.00	**0.54**	**−0.41**	**0.42**	–	1.00	0.12	−0.08	**0.41**
Wsv	–	–	1.00	**−0.43**	**0.46**	–	–	1.00	−0.11	0.12
SLP	–	–	–	1.00	**−0.82**	–	–	–	1.00	**−0.73**
P	–	–	–	–	1.00	–	–	–	–	1.00

Correlations which are statistically significant on the 95 %-significance level are marked bold

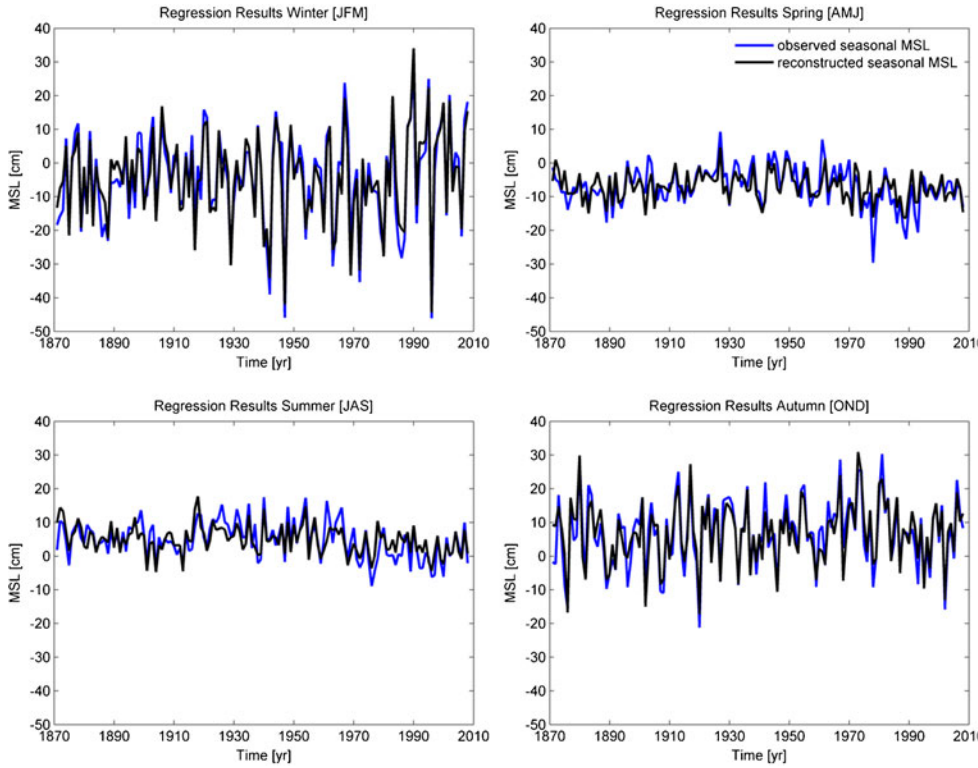

Fig. 4 Observed (*blue*) and reconstructed (*black*) seasonal MSL at the tide gauge of Cuxhaven

observed variability. This value weakens through spring and summer seasons with values of ~50 and ~54 % and then rises up again to a value of ~78 % in autumn. A further significant contribution to MSL variability in winter is given by SLP. Adding SLP to the sea level equation increases the performance of the regression model to an explained variance of ~90 %, whereby the contribution of SLP explains ~2.8 % of the non-tidal variability. Precipitation is a

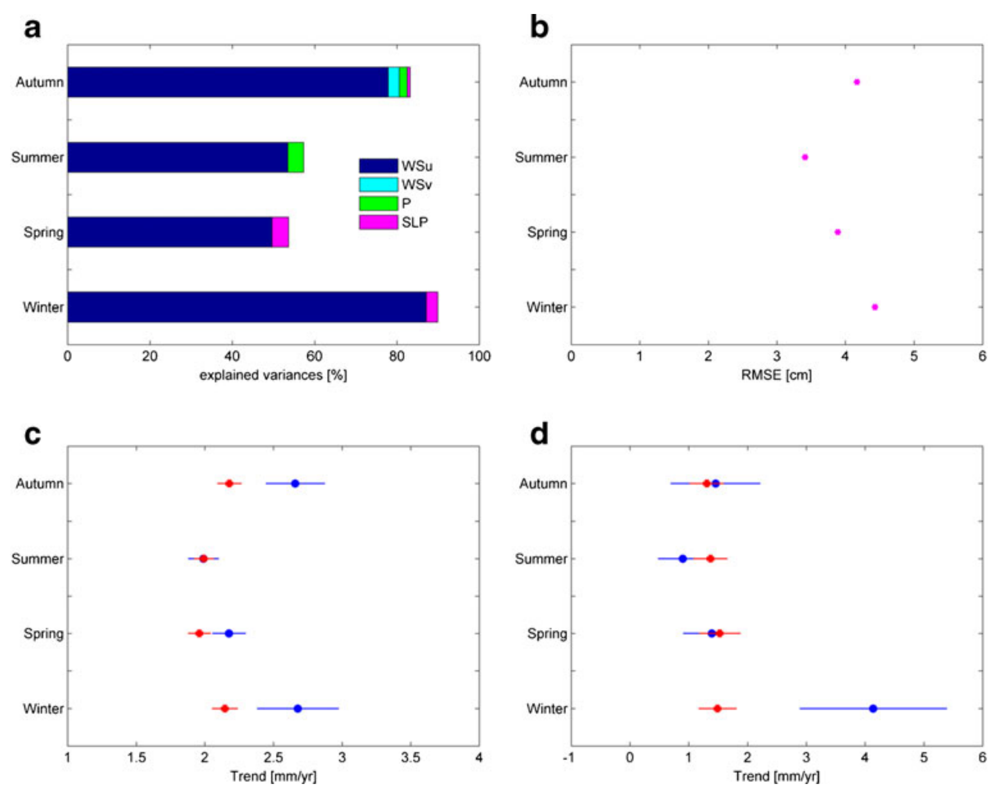

Fig. 5 Results of the seasonal stepwise regression; **a** explained variances by the regression models for the period from 1871 to 2008. The different contributors are shown in different *colored bars*. The sum of all bars represents the explained variances by the full model, i.e. including all contributors. **b** RMSE between observed and reconstructed MSL. **c** observed (*blue*) and meteorologically corrected (*red*) MSL trends ±2σ SE for the period 1871 to 2008. **d** observed (*blue*) and meteorologically corrected (*red*) MSL trends ±2σ SE for the period 1951 to 2008

significant forcing factor in summer and autumn. Throughout the summer and autumn seasons, precipitation is able to explain another 3.8 and 1.9 % of variations in MSL. In autumn, nevertheless, meridional wind stress also explains a significant part of seasonal MSL with a value of 2.7 %.

As stated above, considerable differences between seasonal and annual trend development have been detected throughout the nineteenth and twentieth centuries. Hence, we prove the impacts of meteorological forcing on seasonal MSL trends. Since the second half of the twentieth century is a period of anomalous large atmospheric variability, a sub-period from 1951 to 2008 is also investigated. The trends for every seasonal subseries are estimated first for the observed time series and second for the residuals after correcting the time series for meteorological forcing. Note that trends are assumed to be significantly different from each other if their 1σ SEs do not intersect, i.e. the minimum confidence bound of the larger trend is larger than the maximum confidence bound of the smaller trend. The results are shown in Fig. 5c for the whole period from 1871 to 2008 and in Fig. 5d for the shorter period from 1951 to 2008. The linear trend estimates of the observed seasonal subseries are shown as blue dots with their related 1σ SEs as blue lines, while the trend estimates after the meteorological correction are presented in a similar manner in red color. For the longer period from 1871 to 2008, the trends are as follows: For the winter season, a trend of 2.7± 0.3 mm/year has been observed. During spring and summer seasons, the trends are significantly smaller with values of 2.2±0.1 and 2.0±0.1 mm/year. In autumn, the seasonal MSL trend is approximately the same as in winter season (2.7±0.2 mm/year). The differences between autumn/winter and spring/summer trends can be explained by meteorological forcing to some extent. After removing meteorological forcing from the observed data, the seasonal trends are reduced to values of 2.1±0.1 mm/year (winter), 2.0± 0.1 mm/year (spring), 2.0±0.1 mm/year (summer) and 2.2± 0.1 mm/year (autumn). Hence, the seasonal trend distribution becomes more homogeneous. Furthermore, the seasonal differences in the SE are mostly removed. For the shorter period from 1951 to 2008, a similar but considerable larger phenomenon has been found. While the trends in spring, summer and autumn are approximately the same (1.4±0.5, 0.9±0.4, 1.5± 0.8 mm/year), the winter trend exceeds the remaining trends significantly with a value of 4.1±1.3 mm/year. The SEs show considerable dissimilarities as well. After removing the meteorological influences from the seasonal MSL time series, the trend distribution as well as the SEs become more homogeneous with values of 1.5±0.3 mm/year (winter), 1.5± 0.4 mm/year (spring), 1.4±0.3 mm/year (summer) and 1.3± 0.3 mm/year (autumn). Hence, meteorological forcing is identified to be the main driving factor for the large deviations in seasonal trends in the second part of the twentieth century.

3.2.3 Model validation

If one variable in the climate system should be described through one or more other variables within a regression model, the quality of the model depends on different factors. Climate is a highly variable system showing large changes on different time scales. Observed relationships between different climatic or non-climatic variables need not to be stationary in time. Since observations, such as tide gauge records or meteorological measurements, have a heuristic character, i.e. they only extract a narrow window from a more complex system, it is rather uncertain whether the observed relationship will hold in the future. Hence, there are two major questions that need to be addressed here within the process of model validation. (1) Are the observed seasonal relationships between MSL and the different meteorological parameters constant over time? (2) How many years of data are required to explain most of the observed MSL variability?

To investigate these questions in detail, the following procedure has been applied. First, we choose a window consisting of 20 observations. The data within that window are used to estimate a seasonal regression model. This model is then applied to predict the whole observation period from 1871 to 2008. To measure the quality of the prediction, the regression coefficients as well as the explained variances between prediction and observation are extracted. The window is moved over the whole period to prove whether the used window size plays an important role for the model quality. That means that the first prediction is based on the first 20 years of the observation from 1871 to 1890, the second on the 20 years from 1872 to 1891 and so on, until the last prediction is based on the last 20 years. This procedure has been repeated for 101 different window sizes varying between 20 and 120 years. Finally, for every window size, different numbers of predictions exist, whereas the number of predictions decreases as the window size increases. Therefore, the number of predictions varies for the 101 window sizes. To measure whether the models estimated within the different time windows are comparable to the models for the whole investigation period, we compute the related 95 % confidence bounds and apply the following definition: With a window size x, a trustworthy regression model can be estimated, if the related regression coefficients are within the confidence bounds of the whole investigation period.

The results of the cross-validation are shown for in Fig. 6. Since zonal wind stress is the main forcing factor influencing sea level variability across all seasons, the validation is only shown and discussed for the regression coefficients of zonal wind stress. The validation results of the regression coefficients of the remaining contributors have been found to be similar to those of zonal wind stress. The regression coefficients for the whole period vary from season to season between 189.7 during summer season and 265.3 during

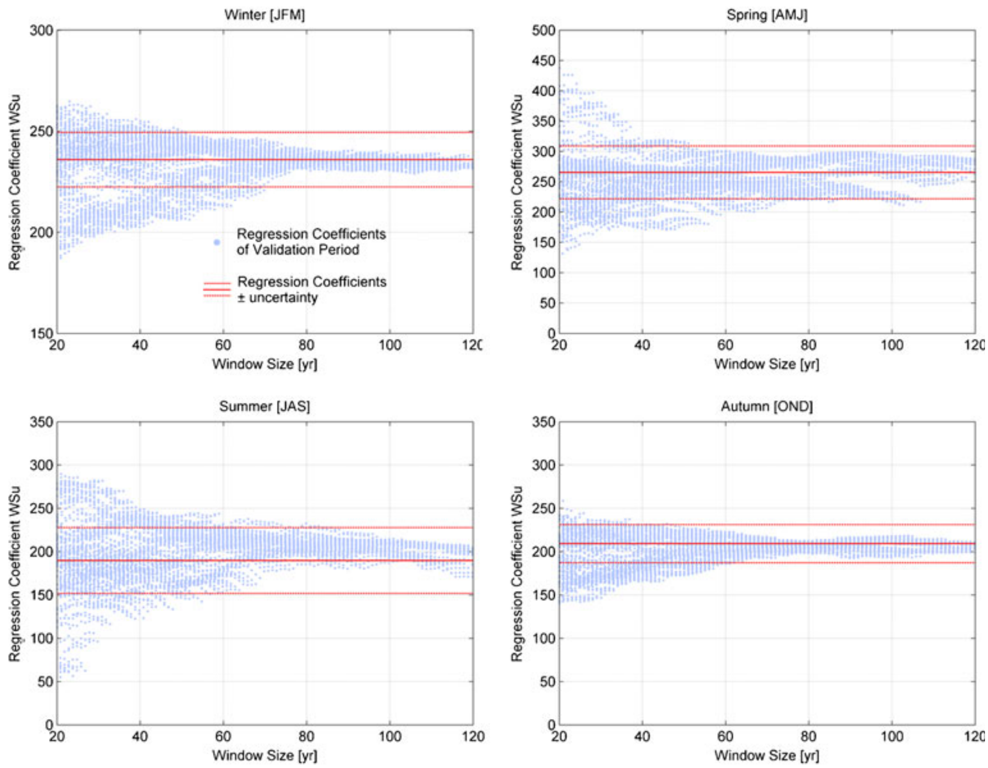

Fig. 6 Results of model validation. The *blue dots* indicate the regression coefficients of zonal wind stress (in Newton per square meter) by the different time-dependent simulations. The *red line* shows the regression coefficient estimated for the whole observation period (1871–2008), while the *red dotted lines* represent its 95 % confidence bounds

spring season (for wind stress in Newton per square meter). The regression coefficients estimated within the different time-dependent windows also vary considerably, but for the four seasons the time and window size-dependent regression coefficients generally show a similar shape. For small window sizes, the estimates of the regression coefficients show substantial deviations from the mean with a large number of models estimating regression coefficients outside the confidence bounds. With an increasing window size, these deviations decrease. For all selected seasons, the regression coefficients are getting stable (i.e. they are within the confidence bounds) after approximately 60 to 80 years. Only in spring does a small band of estimates exceed the confidence bounds for longer time periods. We cannot explain these deviations at the moment. Since these negative deviations are mainly caused by windows including values for the earliest periods, data inaccuracies could be a possible explanation. However, since the general shape is similar to those in the remaining seasons, we do not further discuss these deviations. We also analysed the explained variances in a similar manner as the regression coefficients and found in general a similar shape, i.e. the explained variances estimated within the process of model validation are getting comparable to the variances explained within the whole investigation period after approximately 60 to 80 years.

These results reflect the dependence of the regression models from the used window length and time period. The band of regression coefficients and the explained variances are both getting stable for similar window sizes of 60 to 80 years. Therefore, we suggest that models estimated with window sizes larger than approximately 60 to 80 years give a trustworthy estimate for the relationship between meteorological forcing and sea level variability measured at the Cuxhaven tide gauge.

3.2.4 Meteorologically corrected MSL variations

To determine the general influence of meteorological forcing on seasonal MSL trends, seasonal and annual 30-year moving trends are computed for the residuals after correcting seasonal MSL for meteorological influences and reconstructing the annual means. The results are presented in Fig. 7. In comparison to Fig. 2 (same results without corrections), the dissimilarities between seasonal and annual moving MSL trends are reduced considerably. Especially for the seasons of spring, summer and autumn, the differences are rather negligible. The large deviations of winter MSL in the second half of the twentieth century are removed completely. Sensitivity analysis (not shown) suggests zonal wind stress as the main forcing factor for the large gradient in seasonal trends, which has been detected by Dangendorf et al. (2012). Before the 1950s, for the winter season, some differences remain, especially between the 1910s and the end of the 1950s. On the one hand, these differences may indicate other forcing factors influencing seasonal MSL during that period of time; otherwise uncertainties and inaccuracies of the statistical model or the used data sets may be possible explanations. Despite these uncertainties, the

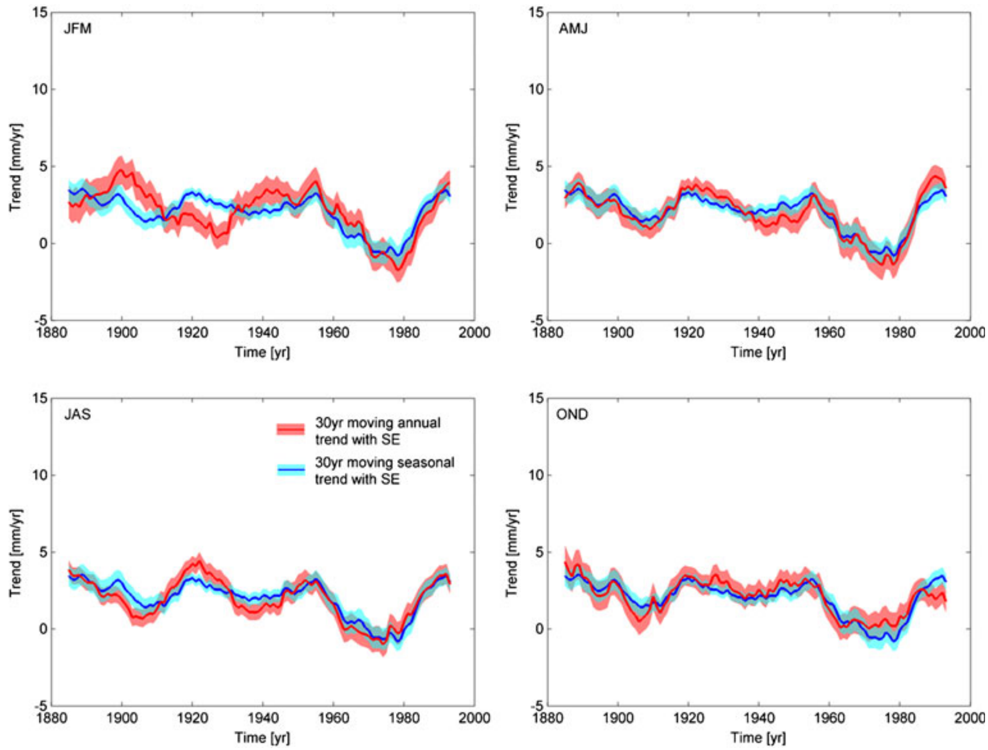

Fig. 7 30-year moving trend of seasonal (*red*) and annual (*blue*) meteorologically corrected MSL with their related 1σ SE (*shaded areas*)

general shape of annual moving MSL trends is better described by meteorologically corrected seasonal MSL than with the original MSL, which implies that meteorological forcing is able to explain large parts of the intra- and inter-annual variability and significant parts of seasonal trends in some sub-periods.

4 Meteorological forcing on inter-annual and decadal time scales

The seasonal MSL time series used here can be averaged to annual means to investigate the inter-annual long-term development. The observed annual MSL time series and the annual residuals after removing the meteorologically predicted MSL are presented in Fig. 8a. The observed annual MSL time series (blue) has a linear long-term trend of 2.4± 0.1 mm/year over the period from 1871 to 2008, and it is characterised by a large inter-annual and decadal variability. This variability as well as the linear long-term trend are reduced in the meteorologically corrected MSL time series (black line with red dots) showing a long-term trend of 2.1± 0.1 mm/year. In the last decades, one of the most discussed questions in sea level science is whether acceleration due to anthropogenic climate change has taken place in the recent past (Woodworth et al. 2008, 2009, 2011). Generally, there are two approaches which have been used to analyse the evidence of increase in the rate SLR. Some authors try to fit quadratic trends to the MSL observations and prove the evidence of acceleration with the quadratic coefficient, while others use moving linear trends. For example Wahl et al. (2011) fitted 30- to 40-year moving trends to time series from records in the German Bight. Hence, we apply this method to the annual MSL values before and after removing meteorological forcing from the annual data. The rates of observed MSL rise vary considerably between ~0 and ~4 mm/year. There are four noticeable periods during that time span: The high rates at the end of the nineteenth and the middle of the twentieth century, the low rates during the 1960s and 1970s and the high rates afterwards. In agreement with the finding of Wahl et al. (2011), the largest rates of rise have been observed during the last three decades. Starting from the low point in the 1970s, the rates increase to an absolute maximum of over 4 mm/year in the last overlapping periods. Even if it is the highest rate measured during the observation period, comparable values have been observed at the end of the nineteenth and the middle of the twentieth century. The meteorologically corrected residuals show in general a similar decadal variability in the rates of rise. Some periods can partially be explained by meteorological influences. For example, at the beginning of the twentieth century, up to 1.4 mm/year of the observed MSL trend can be explained by the regression models. From the second half of the twentieth century to present, a nearly constant part of 1 mm/year is traced to meteorological forcing, mainly occurring during winter season. However,

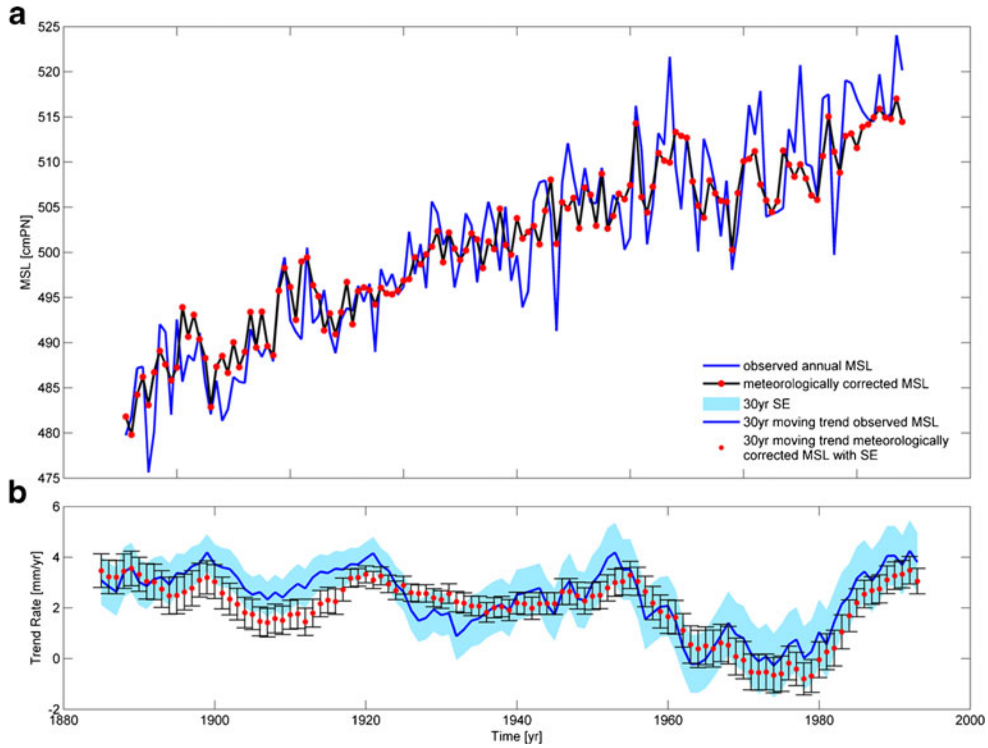

Fig. 8 **a** Observed (*blue*) and meteorologically corrected (*black line, red dots*) annual MSL in Cuxhaven. **b** 30-year moving trends ±1σ SE for observed (*blue, light blue*) and meteorologically corrected (*black, red*) MSL

even if some sub-periods are driven by atmospheric trends or variability, the general shape of the curve remains unchanged. Hence, meteorological forcing plays an important role when explaining MSL variability on intra-, inter-annual and decadal time scales in the German Bight, but long-term trends are less affected.

In the residual annual MSL time series, large parts of decadal variability remain unexplained by local meteorological forcing. Hence, the question arises, which other parameters or processes could explain these variations? There is a possibility that pressure differences over the subtropical gyre of the North Atlantic Ocean may lead to sea level variations at the coastlines through the propagation of Rossby waves (Kolker and Hameed 2007; Miller and Douglas 2007). Miller and Douglas (2007) suggested that a spin down of the North Atlantic gyre could explain the higher SLR in the twentieth century observed at tide gauges along North Atlantic coastlines. In contrast, more recent studies show that longshore components of windstress and wave propagation along the boundary of the North Atlantic Ocean rather than changes in the North Atlantic gyre are the main contributors to decadal coastal sea level variability (Sturges and Douglas 2011; Calafat et al. 2012). Calafat et al. (2012) found remarkable similarities between longshore wind stress integrated from the equator northwards and different tide gauges along the eastern North Atlantic and Mediterreanean and the outputs of a baroclinic model. Since this phenomenon shows an increasing influence at northwards latitudes, the influence on North Sea MSL should also be investigated in future.

5 The effect of SE reduction

An important question for the aspects of coastal planning is whether the models applied in this study may help to get more stable trend estimates for past MSL. The stability of the trend estimates is directly linked with the non-tidal variability and the length of the time series. Hence, especially in regions with large non-tidal variability, long and high-quality measurements are needed. As mentioned before, in some areas, the data availability is restricted to a few decades. For these areas, it is of particular interest whether it is possible to accurately predict SLR. It is well known that large inter-annual variability influences the SE, which is related to the trend estimate. It has been demonstrated by several authors in different parts of the world that periods of 50 or 30 years are required to get a SE in the order of 0.5 and 0.3 mm/year, respectively (Douglas 1991; Tsimplis and Spencer 1997; Woodworth 1990, 1991; Haigh et al. 2009). For the German Bight, by contrast, longer periods are needed to get a comparable accuracy in estimating trends (Wahl et al. under review). They explained that phenomenon with larger variability of MSL in this region. Hence, the SE of the meteorologically corrected time series should become smaller in comparison to the original time series.

A number of authors have tried to reduce the variability (and therefore the SE of trend estimates) from atmospheric or oceanographic forcing by subtracting an index time series (a time series built on the basis of empirical orthogonal functions or area weighted averages representing a larger geographical area; "master station" method) or a time series of a single station representing the typical variability in the study area (Woodworth 1987, 1991; Haigh et al. 2009). This procedure works well in reducing the uncertainties related to trend estimates, but it does not help to explain the causes of the observed variability. The regression models used in this study aim to identify and explain the physical processes behind the atmospheric forcing. Understanding the processes driving regional sea level variability may help to identify the causes of differences between single tide gauge locations.

We follow the method described in the above-mentioned studies and compute linear trends and their corresponding SEs with different time windows. Starting at the end of the Cuxhaven record, linear trends and SEs are computed first for a period of 19 years, followed by a period of 20 years and so on. This procedure is done for the observed MSL time series as well as for the meteorologically corrected one and the residual time series after subtracting the de-trended index time series from Wahl et al. (2011) from the Cuxhaven record. The results are shown in Fig. 9. In contrast to other stations around the world, a SE of 0.5 mm/year requires a window size of at least 55 years. That is 25 years longer compared with other tide gauges around the world (for example, Newlyn, which is located at the southwestern boundary of the English Channel). After removing the influences of meteorological forcing, this window can be reduced significantly. For the meteorologically corrected residuals, the SE is smaller than 0.5 mm/year after 32 years. The effect is nearly the same when using the 'master station' method for reducing the regional variability. Hence, the multiple regression models are able to explain the largest parts of the inter-annual variability. This is an important finding for two reasons. First, tide gauges with shorter records in the area of the German Bight can be used to estimate sea level changes with similar confidence to the long record of Cuxhaven. Second, the reduced variability enables for an earlier detection of acceleration or deceleration behavior of MSL rise, which is one of the most important questions in climate science and coastal planning requirements.

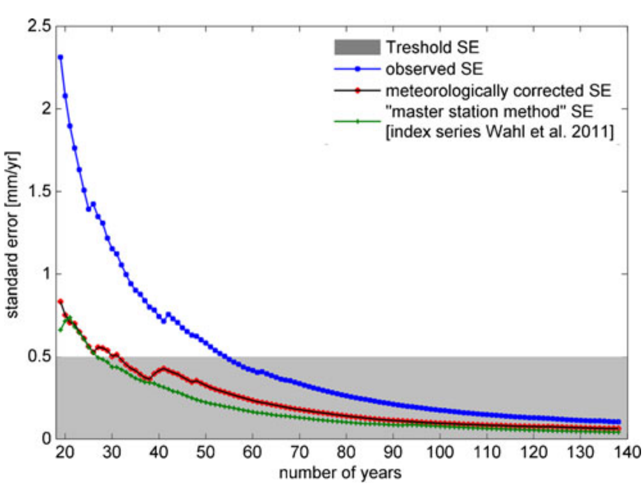

Fig. 9 SE of the observed (*blue*), meteorologically corrected (*black, red dots*) and index corrected (*green*) annual MSL trend calculated with changing numbers of years

6 Conclusion

This paper presents a case study of intra-, inter-annual and decadal variability and the role of meteorological forcing factors at the tide gauge record of Cuxhaven. It has been shown that there are considerable seasonal differences driven by meteorological forces. Stepwise regression has been applied to estimate the contribution of different meteorological forcing factors. Although there exist some barotropic models in the North Sea region (Tsimplis et al. 2005; Woodworth et al. 2007) that can be used for estimating the atmospheric contribution, these models are currently restricted to the period of available NCEP/NCAR data (i.e. from 1948 on) and a constant bathymetry. Hence, statistical models are additionally important to study changes on longer time scales. Depending on the investigated season, the models explain between 54 (summer) and 90 % (winter) of the observed non-tidal variability during a period from 1871 to 2008. The variability is dominated by zonal wind stress through all seasons, while the contribution of precipitation, SLP and meridional wind stress is rather small, but in some seasons it is still significant. The models are able to give a robust estimate of the local atmospheric contribution to MSL variability, if 60 to 80 years of data or more are used to build the regression models. It is further supposed that major parts of the remaining variability should be related to transregional forcings, such as postulated by Sturges and Douglas (2011) and Calafat et al. (2012) for tide gauges located at the eastern boundary of the North Atlantic basin. Additionally, it has been shown that the large derivations of winter MSL in the second half of the twentieth century are the result of changing pressure conditions over the North Atlantic, associated with an increase in the local zonal wind conditions. However, even if meteorological forcing is partially able to explain considerable parts of the trend in some subperiods, the long-term trend is less affected. This is consistent with the findings of Albrecht and Weisse (2012).

The dominant influence of zonal wind stress expresses itself in strong correlations with SLP anomalies over Scandinavia and the Iberian Peninsula. Although this pattern shows remarkable similarities to the NAO, it is able to explain a larger part of the non-tidal variability in the German Bight.

While the NAO explains between 30 and 35 % of the observed variability during winter season (Jevrejeva et al. 2005; Dangendorf et al. 2012), the more eastward gradient enables us to reconstruct between 70 and 80 % of the variability of monthly MSL anomalies. Sea level pressure is well reproduced by climate models (Weisse and von Storch 2009). Hence, it can be suggested that the SLP fields over Scandinavia and the Iberian Peninsula indicate a larger potential for estimating future sea level variability and the related flood risk of near coastal areas. This is a scientific topic that has to be investigated in the near future.

While studies related to GMSL are important to understand the climatic system of the Earth, for the aspects of coastal planning, regional or local MSL studies are required (Nicholls and Cazenave 2010). RMSL may differ significantly from the global mean (Wahl et al. 2010; Sallenger et al. 2012). Hence, the identification of forcing factors affecting regional MSL variability is a crucial step for estimating possible future states of SLR (Tsimplis et al. 2006; Dangendorf et al. 2012). The first steps in estimating future regional MSL are done (Katsmann et al. 2011; Slangen et al. 2011), but these projections are restricted to the regional response of ice melting, ocean mass changes and glacial isostatic adjustment. The consequences of atmospheric forcings are not considered. With the knowledge of the link between atmospheric forcing and MSL, the additional effects could be integrated into these scenarios for the different regions. Hence, future studies should combine these results to establish scenarios including both possible trends (with considerable uncertainties) and variability.

Furthermore, we show some practical applications of the regression models for the aspects of estimating SLR. Due to the reduction of the non-tidal variability, the related SE can be reduced significantly, which allows for a better evaluation of SLR patterns. With the application of the regression models, a similar variability reduction is reached as with the master station method used by Woodworth et al. (2009) and Haigh et al. (2010). This is important for the aspects of coastal planning. Rahmstorf et al. (2012) pointed to the uncertainties related to the search of acceleration patterns in SLR under the presence of larger inter-annual and decadal variability. Since the southeastern North Sea is an area of particular large variability, it should be established whether potential accelerations of sea level can be detected earlier after the removal of meteorologically induced variability. This will be investigated in a future study. The results presented in this study should be further applied to more tide gauges around the North Sea basin to analyse the regional differences in meteorological forcing. Additionally, future studies should address the comparison of the results of the regression models with the output of barotropic models.

Acknowledgements This study is based on investigations, which have been partially made in the framework of the KLIWAS research project. Therefore, we highly acknowledge Anette Ganske, Hartmut Heinrich, Sylvin Müller Navarra, Birgit Klein and Jens Möller from the BSH and Gudrun Rosenhagen, Birger Tinz and Katharina Bülow from the German Weather Service (DWD) for the fruitful discussions and the funding of the project. We are thankful to two anonymous reviewers who helped to improve an earlier version of the manuscript. We are further grateful to the Waterways and Shipping Administration of the Federal Government for providing us the tide gauge data.

References

Albrecht F, Weisse R (2012) Pressure effects on past regional sea level trends and variability in the German Bight. Ocean Dyn 62:1169–1186. doi:10.1007/s10236-012-0557-1

Albrecht F, Wahl T, Jensen J, Weisse R (2011) Determining sea level change in the German Bight. Ocean Dyn 61:2037–2050. doi:10.1007/s10236-011-0462-z

Arns A, van Eynatten H, Häußling R, van Riesen D, Schüttrumpf H, Jensen J (2011) Developing sustainable coastal protection- and management strategies for Schleswig-Holstein's Halligen Considering Climate Changes (ZukunftHallig), 5th International Short Conference on Applied Coastal Research, Aachen, 2011

Baart F, van Gelder PHAJM, de Ronde J, van Koningsveld M, Wouters B (2012) The effect of the 18.6-year lunar nodal cycle on regional sea level rise estimates. J Coast Res 28:511–516. doi:10.2112/JCOASTRES-D-11-00169.1

Barbosa SM, Fernandez MJ, Silva ME (2004) Nonlinear sea level trends from European tide gauge records. Ann Geoph 22:1465–1472

Bindoff NL, Willebrand J, Artale V et al (2007) Observations: oceanic climate change and sea level. In: Climate change 2007. In: Solomon S, Qin D, Manning M et al (eds) The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Calafat FM, Chambers DP, Tsimplis MN (2012) Mechanisms of decadal sea level variability in the eastern North Atlantic and the Mediterranean Sea. J Geophys Res 117:C09022:10.1029/2012JC008285

Church JA, White NJ, Coleman R, Lambeck K, Mitrovica JX (2004) Estimates of the regional distribution of sea-level rise over the 1950 to 2000 period. J Clim 17:2609–2625

Church JA, White NJ (2006) A 20th century acceleration in global sea-level rise. Geophys Res Lett 33:L10602. doi:10.1029/2005GL024826

Church JA, White NJ (2011) Sea-level rise from the late 19th to the early 21st century. Surv Geophys. doi:10.1007/s10712-011-9119-1

Compo GP, Whitaker JS, Sardeshmukh PD et al (2011) Review article—the twentieth century reanalysis project. Quarter Journal of the Royal Meterological Society 137:1–28

Dangendorf S, Wahl T, Hein H, Jensen J, Mai S, Mudersbach C (2012) Mean sea level variability and influence of the North Atlantic oscillation on long-term trends in the German Bight. Water 4:170–195. doi:10.3390/w4010170, ISSN 2073-4441

Douglas BC (1991) Global sea level rise. J Geophys Res 96(C4):6981–6992. doi:10.1029/91JC00064

Haigh ID, Nicholls RJ, Wells NC (2009) Mean sea-level trends around the English Channel over the 20th century and their wider context. Cont Shelf Res 29(17):2083–2098

Haigh ID, Nicholls RJ, Wells NC (2010) Assessing changes in extreme sea levels: application to the English Channel, 1900–2006. Cont Shelf Res 9:1042–1055. doi:10.1016/j.csr.2010.02.002

Haigh ID, Elliot M, Pattiaratchi C (2011) Global Influences of the 18.61 year nodal cycle and 8.85 year cycle of lunar perigee on high tidal levels. J Geophys Res 116:C06025. doi:10.1029/2010JC006645

Heyen H, Zorita E, von Storch H (1996) Statistical downscaling of monthly mean North Atlantic air-pressure to sea level anomalies in the Baltic Sea. Tellus A 48:312–323

Huenicke B, Luterbacher J, Pauling A, Zorita E (2008) Regional differences in winter sea level variations in the Baltic Sea for the past 200 years. Tellus A 60:384–393

Hurrell JW (1995) Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. Science 269:676–679

IKÜS (2008) Aufbau eines integrierten Höhenüberwachungssystems in Küstenregionen durch Kombination höhenrelevanter Sensorik (final report). Online available from: http://tudresden.de/die_tu_dresden/fakultaeten/fakultaet_forst_geo_und_hydrowissenschaften/fachrichtung_geowissenschaften/gi/gg/veroeffentlichungen/BMBF03KIS055-58.pdf

IPCC (2007) Climate Change. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, p 996

Jensen J (1985) Über instationäre Entwicklungen der Wasserstände an der deutschen Nordseeküste. Mitteilungen Leichtweiß-Institut der TU Braunschweig 88:151–319 (in German)

Jensen J, Hofstede J, Kunz H, De Ronde J, Heinen P, Siefert W (1993) Long term water level observations and variations. Coastal Zone '93, special volume "Coastlines of the Southern North Sea"

Jensen J, Mudersbach C (2007) Zeitliche Änderungen in den Wasserstandszeitreihen an den deutschen Küsten. In: Glaser R, Schenk W, Voigt J, Wießner R, Zepp H, Wardenga U (eds) Berichte zu Deutschen Landeskunde, Themenheft: Küstenszenarien, vol 2, 81st edn. Selbstverlag Deutsche Akademie für Landeskunde E.V, Leipzig, Germany, pp 99–112, in German

Jevrejeva S, Moore JC, Woodworth PL, Grinsted A (2005) Influence of large-scale atmospheric circulation on European sea level: results based on the wavelet transform method. Tellus A 57:183–193

Jevrejeva S, Grinsted A, Moore JC, Holgate S (2006) Nonlinear trends and multiyear cycles in sea level records. J Geophys Res 111: C09012. doi:10.1029/2005JC003229

Katsman CA, Sterl A, Beersma JJ et al (2011) Exploring high-end scenarios for local sea level rise to develop flood protection strategies for a low-lying delta—The Netherlands as an example. Clim Chang. doi:10.1007/s10584-011-0037-5

Kolker AS, Hameed S (2007) Meteorogically driven trends in sea level rise. Geophys Res Lett 34. doi:10.1029/2007GL031814

Krüger O, Schenk F, Feser F, Weisse R (2012) Inconsistencies between long-term trends in storminess derived from the 20CR reanalysis and observations. J Clim. doi:10.1175/JCLI-D-12-00309.1

Merrifield MA, Merrifield SA, Mitchum GT (2009) An anomalous recent acceleration of global sea level rise. J Clim 22:5772–5781. doi:10.1175/2009JCLI2985.1

Miller L, Douglas BC (2007) Gyre-scale atmospheric pressure variations and their relation to 19th and 20th century sea level rise. Geophys Res Lett 34:L16602. doi:10.1029/2007GL030862

Milne GA, Gehrels WR, Hughes CW, Tamisiea ME (2009) Identifying the causes of sea-level change. Nat Geosci 2:471–478. doi:10.1038/ngeo544

Nicholls RJ, Cazenave A (2010) Sea-level rise and its impact on coastal zones. Science 328:1517–1520

Pugh D (2004) Changing sea levels: Effects of tide, weather and climate, 1st edn. Cambridge University Press, Cambridge, UK

Rahmstorf S, Perrette M, Vermeer M (2012) Testing the robustness of semi-empirical sea level projections. Clim Dyn 39:861–875

Sallenger AH, Doran KS, Howd PA (2012) Hotspot of accelerated sea-level rise on the Atlantic coast of North America. Nature Clim Change. doi:10.1038/nclimate1597

Schott F (1966) Der Oberflächensalzgehalt in der Nordsee. Dt. Hydrogr. Zt. (suppl. A9), pp. 1–58

Slangen ABA, Katsman CA, van de Wal RSW, Vermeersen LLA, Riva REM (2011) Towards regional projections of twenty-first century sea-level change based on IPCC SRES scenarios. Clim Dyn 38:1191–1209. doi:10.1007/s00382-011-1057-6

Sturges W, Douglas BC (2011) Wind effects on estimates of sea level rise. J Geophys Res 116:C06008. doi:10.1029/2010JC006492

Suursaar Ü, Sooäär J (2007) Decadal variations in mean and extreme sea level values along the Estonian coast of the Baltic Sea. Tellus A 59:249–260

Tsimplis MN, Woodworth PL (1994) The global distribution of the seasonal sea level cycle calculated from coastal tide gauge data. J Geophys Res 99(C8):16,031–16,039. doi:10.1029/94JC01115

Tsimplis MN, Spencer NE (1997) Collection and analysis of monthly mean sea level data in the Mediterranean and Black Sea. J Coast Res 13:534–544

Tsimplis MN, Josey SA (2001) Forcing of the Mediterranean Sea by atmospheric oscillations over the North Atlantic. Geophys Res Lett 28:803–806

Tsimplis MN, Woolf DK, Osborn TJ, Wakelin S, Wolf J, Flather R, Shaw AGP, Woodworth P, Challenor P, Blackman D, Pert F, Yan Z, Jerjeva S (2005) Towards a vulnerability assessment of the UK and northern European coasts: the role of regional climate variability. Philosophical transactions. Mathematical, Physical and Engineering Sciences (Series A 363:1329–1358. doi:10.1098/rsta.2005.1571

Tsimplis MN, Shaw AGP, Flather RA, Woolf DK (2006) The influence of the North Atlantic Oscillation on sea level around the northern European coasts reconsidered: the thermosteric effects. Philos Trans R Soc A 364:845–856

Ullmann A, Monbaliu J (2010) Changes in atmospheric circulation over the North Atlantic and sea surge variations along the Belgian coast during the twentieth century. Int J Clim 30:558–568. doi:10.1002/joc.1904

Von Storch HV, Zwiers FW (1999) Statistical analysis in climate research, 1st edn. Cambridge University Press, Cambridge, UK

Wahl T, Jensen J, Frank T (2010) On analysing sea level rise in the German Bight since 1844. Nat Hazards Earth Syst Sci 10:171–179. doi:10.5194/nhess-10-171-2010

Wahl T, Jensen J, Frank T, Haigh I (2011) Improved estimates of mean sea level changes in the German Bight over the last 166 years. Ocean Dyn 61:701–715. doi:10.1007/s10236-011-0383-x

Wahl T, Haigh ID, Woodworth PL, Albrecht F, Dillingh D, Jensen J, Nicholls RJ, Weisse R, Wöppelmann G (under review) Observed mean sea level changes around the North Sea coastlines from 1800 to present. Earth Science Reviews

Wakelin SL, Woodworth PL, Flather RA, Williams JA (2003) Sea level dependence on the NAO over the NW European Continental Shelf. Geophys Res Lett 30(7):1403. doi:10.1029/2003GL017041

Weisse R, von Storch H (2009) Marine climate and climate change: Storms, wind waves and storm surges, 1st edn Springer, Heidelberg, Germany

Woodworth PL (1987) Trends in U.K. mean sea level. Mar Geod 11:57–87

Woodworth PL (1990) A search for acceleration in records of European mean sea level. Int J Clim 10:129–143

Woodworth PL (1991) The permanent service for mean sea level and the global sea level observing system. J Coast Res 7(3):699–710

Woodworth PL, Flather RA, Williams JA, Wakelin SL, Jevrejeva S (2007) The dependence of UK extreme sea levels and storm surges on the North Atlantic Oscillation. Cont Shelf Res 27 (7):935–946

Woodworth P, White NJ, Jevrejeva S, Holgate SJ, Chuch JA, Gehrels WR (2008) Evidence for the accelerations of sea level on multi-decade and century time scales. Int J Climatol 29:777–789

Woodworth PL, White NJ, Jevrejeva S, Holgate SJ, Gehrels WR (2009) Evidence for the accelerations of sea level on multi-decade and century timescales. Int J Climatol 29(6):777–789. doi:10.1002/joc.1771

Woodworth PL, Pouvreau N, Wöppelmann G (2010) The gyre-scale circulation of the North Atlantic and sea level at Brest. Ocean Sci 6:185–190. doi:10.5194/os-6-185-2010

Woodworth PL, Menéndez M, Gehrels WR (2011) Evidence for century-timescale acceleration in mean sea levels and for recent changes in extreme sea levels. Surv Geophy 32:602–618. doi:10.1007/s10712-011-9112-8

Woolf DK, Shaw AGP, Tsimplis MN (2003) The influence of the North Atlantic Oscillation on sea level variability. The Global Atmosphere and Ocean System 9:145–167

Yan Z, Tsimplis MN, Woolf D (2004) Analysis of the relationship between the North Atlantic Oscillation and sea level changes in Northwest Europe. Int J Climatol 24:743–758