Regional Mean Sea Level Changes in the German Bight

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Abstract

Regional mean sea level changes of the German Bight are analysed. The time span considered ranges from the mid of the 19^{th} until the end of the 21^{st} century. Tide gauge data from 15 locations are used to analyse past regional mean sea level changes. From these data, a time series representing the regional mean sea level of the German Bight is reconstructed following two different approaches. From both approaches comparable long-term trends are obtained from 1924 onwards. For the period 1924 – 2008 these trends are 1.64 ± 0.28 mm/yr and 1.74 ± 0.28 mm/yr, respectively. Also inter-annual and decadal variability from both approaches is comparable from 1924 onwards. Results before 1924 largely depend on data from a few stations only, in particular from Cuxhaven which is longest record available dating back until 1843. Thus, it is analysed to what degree the tide gauge of Cuxhaven is representative for the German Bight. The test was made for the period from 1924 onwards where data from most tide gauges were available. It was found that data from Cuxhaven do not reflect the common signal from all tide gauges and thus Cuxhaven does not provide a good proxy for sea level changes in the German Bight. It is assumed that this is mainly a result from different construction works. However, it can not been excluded that Cuxhaven has been representative before 1924. Decadal trends are analysed to detect a possible acceleration in the mean sea level time series. The result shows that decadal trends in the most recent periods were relatively high. However, when compared with earlier periods they are not extraordinary high.

Subsequently, the impact of large-scale atmospheric pressure changes to the regional mean sea level is analysed. A statistical model between the regional mean sea level in the German Bight and the large-scale sea level pressure field over the North Atlantic is developed, using multiple linear regression. For the time period 1924 – 2001 it was found that the sea level pressure explains 58% of the inter-annual variability and 33% of the long-term trend. To capture large-scale mean sea level changes, not caused by corresponding changes in atmospheric pressure, the mean sea level of the North East Atlantic is introduced as a second variable in the regression. This improves both, the explained inter-annual variability (74%) and the explained long-term trend (87%). These results indicate that the sea level pressure accounts mainly for the inter-annual variability and the mean sea level of the North East Atlantic for the long-term

trend. However, cross-validation of the model shows that these results depend on the time period considered.

Finally, the derived statistical model is applied to atmospheric data from 78 climate change experiments of the 21^{st} century. This provides an estimate of that part of the regional mean sea level that is caused by corresponding long-term changes in sea level pressure. Using these data, on average an increase of 1.4 cm was projected, until the end of the 21^{st} century. When these projections are conditioned upon the considered climate scenarios, some differences within the scenarios can be seen with higher rates in SRES A1B and SRES A2 and smaller values in the commit and SRES B1 scenarios. However, the statistical uncertainties associated with theses estimates are large. When the sea level changes associated with atmospheric pressure changes are compared with those caused by other drivers towards the end of this century, the results presented here suggest that the sea level pressure field of the North Atlantic is not a major contributor to future regional mean sea level long-term trends in the 21^{st} century.

Zusammenfassung

In der vorliegenden Arbeit werden regionale Meeresspiegeländerungen in der Deutschen Bucht untersucht. Der betrachtete Zeitraum reicht von der Mitte des 19-ten Jahrhunderts bis zum Ende des 21-ten Jahrhunderts. Die Daten von 15 Pegeln werden untersucht und unter Verwendung von zwei unterschiedlichen Ansätzen wird eine Zeitreihe rekonstruiert, die den regionalen Meeresspiegel repräsentiert. Beide Ansätze zeigen für den Zeitraum 1924 – 2008 einen vergleichbaren Langzeittrend von 1.64 ± 0.28 mm/J bzw. 1.74 ± 0.28 mm/J. Auch jährliche und dekadische Schwankungen sind in diesem Zeitraum in beiden Ansätzen sehr ähnlich. Die Ergebnisse vor 1924 sind stark von den wenig vorhanden Daten abhängig, insbesondere von den Daten aus Cuxhaven, welches die längsten zur Verfügung stehenden Pegeldaten sind und bis 1843 zurückgehen. Es wird daher untersucht, in welchem Maße Cuxhaven repräsentativ für die Deutsche Bucht ist. Diese Analyse wurde für den Zeitraum ab 1924 durchgeführt, in dem Daten von den meisten Pegeln zur Verfügung stehen. Das Ergebnis zeigt, dass Cuxhaven das gemeinsame Signal der Pegel nicht wiedergibt und daher kein guter Proxy für Meeresspiegeländerungen der Deutschen Bucht ist. Es wird angenommen, dass dies vor allem an dem Durchführen verschiedener Baumaßnahmen liegt. Es kann allerdings nicht ausgeschlossen werden, dass Cuxhaven vor 1924 repräsentativ war. Mithilfe dekadischer Trends wird untersucht, ob in den letzten Jahren ein außergewöhnlich hoher Anstieg im regionalen Meeresspiegel zu beobachten ist. Im Ergebnis sieht man, dass die Trends in den letzten Dekaden relativ hoch waren, allerdings hat es vergleichbare Anstiegsraten bereits in früheren Perioden gegeben.

Anschließend wird untersucht, welchen Einfluss großskalige atmosphärische Druckänderungen auf den regionalen Meeresspiegel haben. Dazu wird eine multiple lineare Regression zwischen dem regionalen Meeresspiegel der Deutschen Bucht und dem großskaligem Luftdruckfeld über dem Nordatlantik durchgeführt. Die Regression zeigt, dass der Luftdruck 58% der jährlichen Schwankungen und 33% des Langzeittrends im Zeitraum 1924 – 2001 erklärt. Um weitere großskalige Meeresspiegeländerungen zu erfassen, die nicht mit entsprechenden Änderungen im Luftdruck einhergehen, wird der Meeresspiegel des Nord-Ost Atlantiks als eine zweite Variable in die Regression eingeführt. Dadurch werden sowohl die erklärte jährliche Variabilität (74%), als auch der erklärte Langzeittrend (87%) verbessert. Die Ergebnisse deuten darauf hin,

dass der Luftdruck hauptsächlich für die jährliche Variabilität und der Meeresspiegel des Nord-Ost Atlantiks für den Langzeittrend verantwortlich ist. Eine Kreuzvalidierung zeigt jedoch, dass die Ergebnisse vom betrachteten Zeitraum abhängig sind.

Schließlich wird das entwickelte statistische Modell auf Luftdruckdaten von 78 Klimaexperimenten für das 21-te Jahrhundert angewendet. Daraus ergibt sich eine Abschätzung für den Anteil des regionalen Meeresspiegels, der durch entsprechende Langzeitänderungen im Luftdruck hervorgerufen wird. Mit Hilfe dieser Daten wird ein mittlerer Anstieg von 1.4 cm bis zum Ende des 21-ten Jahrhunderts projiziert. Werden die Projektionen eingeteilt in die Klimaszenarien betrachtet, zeigen die einzelnen Szenarien Unterschiede, wobei SRES A1B und SRES A2 höhere Anstiegsraten zeigen und commit und SRES B2 niedrigere. Die statistischen Unsicherheiten dieser Ergebnisse sind allerdings sehr groß. Im Vergleich zu anderen Beiträgen zu regionalen Meeresspiegeländerungen, deuten die Ergebnisse dieser Arbeit daraufhin, dass der Luftdruck keinen Hauptbeitrag zum zukünftigen Langzeittrend des regionalen Meeresspiegels hat.

Contents

List of Papers

This thesis is based on the following peer-reviewed journal articles:

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

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

List of Abbreviations

AOGCM	atmosphere-ocean general circulation model
AR4	Fourth Assessment Report
commit	commitment climate change experiment
CMIP3	Coupled Model Intercomparison Project phase 3
EOF	empirical orthonormal function
GB	German Bight
GIA	glacial isostatic adjustment
GJ	gewässerkundliches Jahrbuch
GCM	general circulation model
GMSL	global mean sea level
IPCC	international panel on climate change
LGM	last glacial maximum
MSL	mean sea level
MTL	mean tide level
NAO	North Atlantic Oscillation
PSMSL	permanent service for mean sea level
PC	principal component
RMSL	regional mean sea level
SLP	sea level pressure
SRES	special report on emission scenarios
WCRP	World Climate Research Programme

1. Introduction

The oceans and their impact to coastal areas are an important issue in human life. Ever since coastal areas were settled, living at the coast was largely influenced by the impact from the sea. In Northern Europe people built their houses on dwelling mounds to defend flooding from storm surges. Only in the middle ages first dikes were built in this area in order to reduce the hazards rising from high water levels of the sea. Even nowadays, low-elevation zones are still vulnerable by the sea, especially in areas with insufficient coastal protection. Flooding of low lying coastal areas may have great socio-economic impacts, as the water may damage agricultural area, houses or other buildings. Nicholls and Cazenave (2010) reported that 10% of the world's population live in areas with less than 10 m elevation. Flooding results from extreme sea levels, that is an elevation in sea level that is much higher than the mean. An investigation of the development in frequency and intensity of extreme sea levels is important as changes would necessitate adjustments in coastal protection.

The observed sea level at a certain location can be divided in three different factors (Pugh, 1987). The first component is the meteorological surge, which describes the effect of large-scale meteorological conditions to sea level. To a great extent this part is determined by wind fields that are pushing the water towards the coasts or away from them. Another contribution to the meteorological surge is the *inverse barometric effect*. It describes the process that an increase (decrease) of the atmospheric pressure leads to an lower (higher) sea level. The second factor is the cycle of the astronomic tides. The tides are a superposition of the gravitational forces of the moon and the sun, acting on the water masses of the earth. These forces generate an oscillation which is lifting and lowering the sea level. The third factor is the *mean sea level* (MSL). The MSL can be regarded as the base line of the observed sea level, an increase of this basis would also increase the extremes. Adding up these three factors yield to the observed sea level. Changes in extreme sea levels may result from changes in any of these factors, e.g. a positive trend in MSL leads to higher extreme sea levels. The contribution from the factors to the overall changes depends on the considered location. Changes in the atmospheric pressure and wind may lead to a different track, frequency or intensity of storms, the influences to sea level are thus regionally different. The tide is a deterministic and predictable signal, however tidal patterns around the world differ and may also change. Different effects lead to a non-uniform distribution of MSL. For example, a regionally different heating of the ocean due to global warming leads to regionally different thermal expansion (Bindoff et al., 2007). The melting of land-ice leads to a greater volume of the entire water mass, however the spatial distribution of the additional water is far from uniform. Large ice masses have a strong gravity to the surrounding water. If these ice masses melt the changes in the gravity lead to a lower attraction in its environment and therefore MSL even shrinks close to the ice sheet. On the other hand the MSL rises higher than the global mean further away. (Mitrovica et al., 2001). Changes in the circulation of the ocean or the atmospheric pressure field may influence the sea surface height regionally (Gönnert et al., 2009). Many studies analysed the change in *global mean sea level* (GMSL) (e.g. Church et al., 2004; 2008; 2011; Hamlington et al., 2011; Holgate and Woodworth, 2004; Holgate, 2007; Jevrejeva et al., 2006; 2008). While such analyses are important for global climate change, they do not provide information at regional and local scales. In order to assess and to develop adequate adaptation strategies to rising sea levels, regional studies are urgently needed.

In this thesis focus is on regional sea level changes in the German Bight, the southeastern part of the North Sea (Fig. 1.1). The German Bight comprises a relatively shallow area with maximum water depths of about 50 m and coastal areas are generally characterised by low elevations above MSL (Fig. 1.2). Extreme sea levels have great impacts on the coastal zones and people living there. Changes in extreme sea levels in this area are mainly driven by changes in the meteorologicaly driven components and the MSL. However, long-term fluctuations and trends are also observed in the tidal pattern. The causes for these changes in the tidal pattern are not well understood until now (Weisse, 2011). Investigations of the meteorological surge in the German Bight show no systematic change of its induced sea level height. There is high variability in the occurrence and intensity of storm surges in the 20^{th} century. However, no systematic trend can be seen (Weisse, 2011).

An analysis of the *regional mean sea level* (RMSL) of the German Bight is the objective of this thesis. The overall aim of this work is to quantify and assess changes in the MSL of the German Bight. In the past, attempts of MSL analysis in the German Bight often considered changes tidal high, tidal low waters or tidal ranges (e.g. Jensen et al., 1992; Lassen, 1995; Jensen and Mudersbach, 2007), because no long high frequency sea level time series were available. For MSL analysis long-term sea level data measured on high frequency (at least hourly data) are needed. These measurements are often only available from the late 1990s on. Wahl et al. (2011) analysed 13 tide gauges of the German Bight and converted the much longer low frequency time series to MSL data. This data set allows new, more accurate analyses of the MSL of the German Bight. It is the basis for the MSL time series of the German Bight developed in Wahl et al. (2011). The authors constructed the time series by computing the arithmetic mean of the different locations for each year of the analysis period. This time series starts in the year 1843, as first tide gauge data were available in that time. However, only few data are available before the 1930s and for the first 58 years even the data of only one location (Cuxhaven) are accessible. Thus, further analysis on that time series and its representativeness for the German Bight is needed. Therefore, an alternative method for the reconstruction of a MSL time series is introduced in this thesis. In this approach the common signal of the sea level data of the different locations is used as the time series for the RMSL. Results from this approach are compared with that of Wahl et al. (2011) and analysed for similarities and differences in decadal variability and long-term trends. A focus of this work is the question to what extent Cuxhaven is representative for the German Bight. Therefore, a comparison of the decadal variability of the tide gauge of Cuxhaven and the MSL time series, for that time period where most tide gauge data are available, is conducted. Using results from both studies changes in MSL are quantified. The analysis of a possible acceleration in RMSL in the recent past is an important objective. This issue has to be investigated in order to be able to adapt to the expected changes - like raising the dikes.

Regional studies on MSL changes are important, because MSL regionally differs from the global mean. E.g. atmospheric pressure and wind act on the sea surface and regionally change its height. A change in the mean atmospheric pressure and wind pattern may thus also changes the RMSL. In this work, the influence of large-scale atmospheric pressure fields to the RMSL of the German Bight is considered. The atmospheric pressure itself regionally influences the sea surface height through the inverse barometric effect. Further, its gradient is directly related to the wind speed and wind direction. When the large-scale atmospheric pressure field changes, the wind climate also change. The North Sea is greatly influenced by the North Atlantic. Therefore the influence of the atmospheric pressure field over the North Atlantic to the RMSL of the German Bight is analysed. A characteristic pattern of the atmospheric pressure field of the North Atlantic is a dipole with a pressure low over Iceland and a pressure high over the Azores (or vice versa). The difference of the atmospheric pressure anomalies is called the *North Atlantic Oscillation* (NAO). The NAO accounts for a considerable fraction of the observable variance in MSL in Europe, therefore it is often used to explain annual or seasonal (mainly winter) variability of MSL in this area (e.g. Wakelin et al., 2003; Yan et al., 2004;

Jevrejeva et al., 2005, Dangendorf et al., 2012). This thesis uses the large-scale *sea level pressure* (SLP) field of the North Atlantic. The relation between this SLP-field and the RMSL is explored. An important issue is to assess the amount of the variability of the RMSL that can be explained by the SLP-field. This is done by developing a model, that describes the statistical relationship between the SLP-field and the RMSL. This relation is supposed to hold in future for potential climate projections. Further, it is analysed, which part of the long-term trend of the RMSL can be explained by the SLP-field and to what extent the statistical model is able to describe this.

Analysis on regional projections for MSL are relatively new and still in an developing process. In the few regional projections (e.g. Katsman et al., 2008; Lowe et al., 2009; Katsman et al., 2011, Slangen et al., 2011) the contribution of the different factors influencing the RMSL are added up to achieve a projected rise for the entire RMSL. In these projections so far the effect of a possible change in the large-scale atmospheric pressure field is not included. The aim of this study is to estimate and assess contributions from pressure effects on overall sea level variability and change. A statistical model, describing the relationship between the SLP-field and the RMSL is developed. Using this model, contributions from pressure changes on long-term sea level trends are determined and assessed for the 21^{st} century.

To summarise, the objectives of this thesis are the following:

(1) Reconstruction and comparison of time series for the RMSL of the German Bight in order to increase robustness of sea level trend estimates in the German Bight.

(2) Analysis of the influence of large-scale pressure effects to the variability and long-term trends of past RMSL of the German Bight.

(3) Analysis of the influence of large-scale pressure effects to the long-term trends of future RMSL of the German Bight.

The thesis is structured as follows. The objective of this first chapter is to give an overview and some background information about MSL. This includes a summary about current scientific knowledge concerning regional and global MSL studies in the 20^{th} century and about ongoing future projections for the 21^{st} century.

Chapter 2 represents a reprint of the publication "Determining sea level change in the German Bight" by Albrecht et al. (2011). The publication is a result of the work performed during this thesis and develops an approach to reconstruct a reliable MSL time series, which is subsequently applied to a homogenised tide gauge data set in the German Bight. This time series is then analysed for decadal and long-term changes. Chapter 3 is a reprint of a second publication that evolved from the work performed during this thesis. In the publication "Pressure effects on past regional mean sea level trends and variability in the German Bight" by Albrecht and Weisse (2012) a statistical model is developed, in order to analyse the impact of large-scale pressure effects of the North Atlantic to the RMSL of the German Bight. Both, the amount of the inter-annual variability and of the long-term trend that can be associated with pressure effects is analysed. In chapter 4 the statistical model developed in chapter 3 is applied to derive projections of potential future sea level changes arising from corresponding changes in large-scale atmospheric pressure fields. This is done by applying the statistical model to future projections of the SLP resulting from climate model data for the 21^{st} century. Eventually, in chapter 5, the results of this thesis are summarised and discussed.

1.1. Study Area: The German Bight

Todays coasts of the North Sea were formed after the last glacial period, about 20,000 years ago. The North Sea is located on the Northwest European shelf which was flooded when ice began to melt. In the North depths are up to 200 m and a maximal depth of more than 700 m is reached along the Norwegian

Trench. The Southern part of the North Sea has depths of up to 50 m and large parts of the coasts in the South and the East belong to the unique Wadden Sea area. (e.g. OSPAR Commission, 2000; Sündermann et al., 2002).

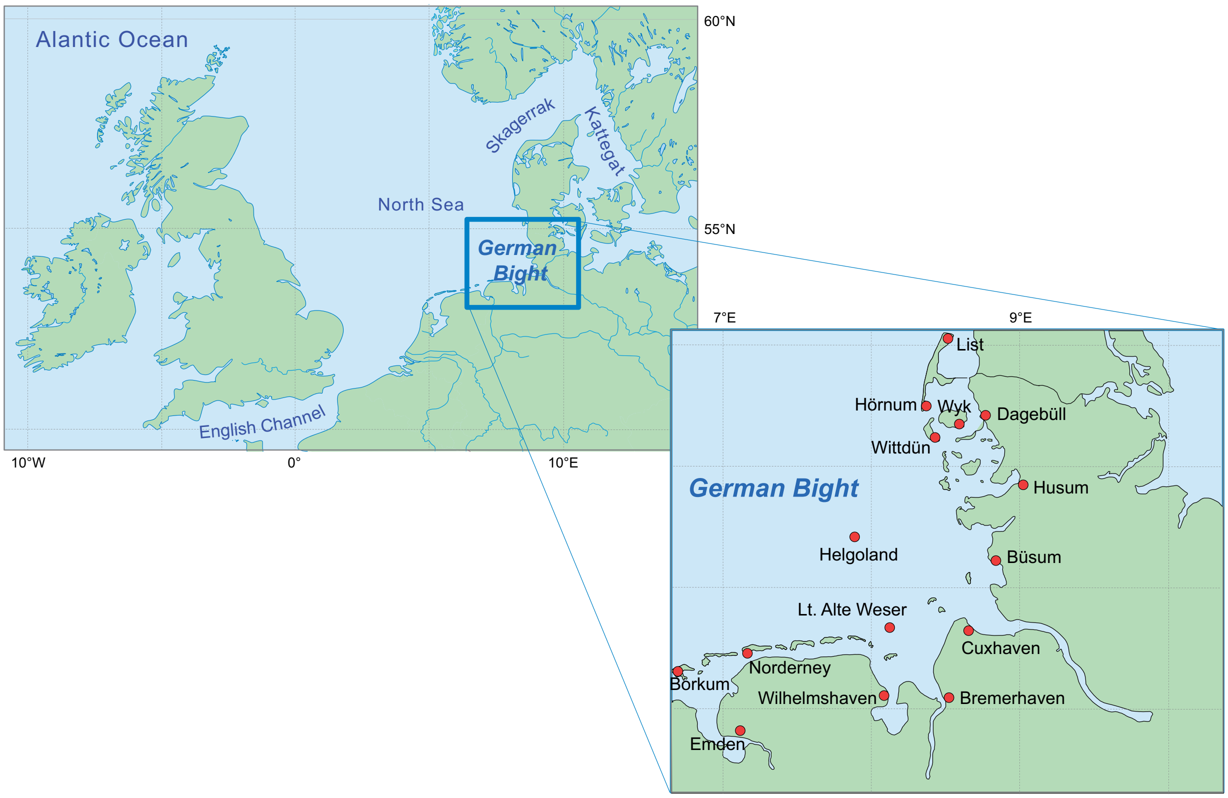

Figure 1.1. Study area and locations of the tide gauges considered (red dots) for the RMSL time series of the German Bight.

The area considered in this thesis is the German Bight (Fig. 1.1), which is the South Eastern part of the North Sea. The North Sea is a continental shelf sea of the Atlantic Ocean. It is surrounded by Great Britain, France, Belgium, the Netherlands, Germany, Denmark and Norway. The German Bight lies between the Dutch and the Danish coast (OSPAR Comission, 2000) and the coastal area is divided into two subareas. South West of the Elbe river lies the East Frisian coast, belonging to the federal state of Lower Saxony, including the East Frisian Islands. The area north of the Elbe river is the North Frisian coast, which belongs to the federal state of Schleswig-Holstein and includes the North Frisian Islands. Helgoland is the central island in the German Bight and officially belongs to Schleswig-Holstein. In contrast to the East and North

Frisian Islands, which lie close to the coast, Helgoland is located 46 km off the coastline (Fig. 1.1).

In the East - between Denmark and Norway - the Kattegat is a direct connection to the Baltic Sea. The Baltic Sea provides the largest part of fresh water input to the North Sea. This results from the rivers discharging into the Baltic Sea. Altogether, the river run-off from the Baltic Sea is about 470 km^3/yr. The main rivers of the North Sea - which are Elbe, Weser, Rhine, Meuse, Scheldt, Seine, Thames and Humber - serve as a second input for fresh water. The total amount of fresh water input from these rivers to the North Sea is $296 - 354\ km^3/yr$ (OSPAR Commission, 2000). In the North - between Great

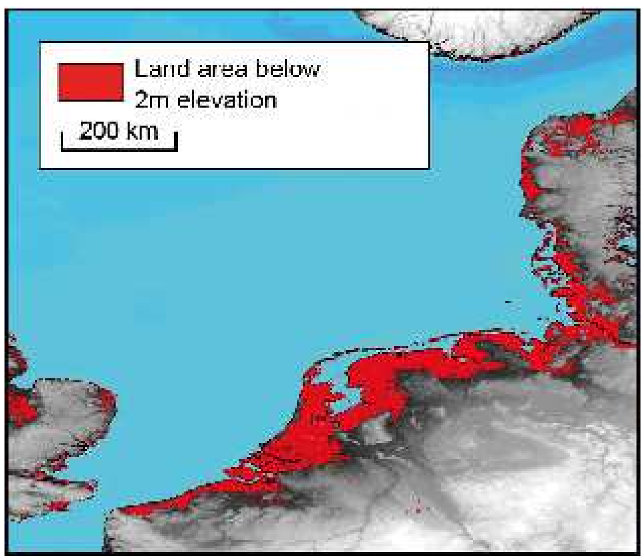

Figure 1.2. The North Sea area. Areas with an elevation of less than 2 m above sea level are marked in red. From Brooks et al. (2006, Fig. 2.2.7, extract of the original plot)

Britain and Norway - the North Sea has a wide opening to the Atlantic Ocean. The English Channel in the South West - between France and Great Britain - is another connection to the Atlantic.

The tides that can be observed in the North Sea are a result of the openings to the Atlantic Ocean. The water mass of the North Sea itself would be to small to produce such high tides. A theoretical approach to understand tides is the concept of the *equilibrium tide*. In this case, a hypothetical Earth with a global ocean is assumed. The celestial body which has most influence on the tides on Earth is the moon. If the motion of the Earth and the moon could be freezed and the ocean could come to *equilibrium* with the gravitational field, there would be two bulges of water: One in direction to the moon and the other one on the opposite side. These bulges result from the tidal force acting on the Earth. Adding the rotation of the Earth, each point of the Earth would have two high and two low waters per day. Analogue, the sun generates two such bulges of water. When the moon, the sun and the Earth are in line the tidal forces are reinforced and the water bulge is higher (*spring tide*). The water bulge is lower, when the moon, the sun and the earth form a right angle (*neap tide*). Detailed information about the equilibrium tide can be found in Pugh (1987). On the real Earth several effects disturb this theoretical concept. The Earth is not covered with water, but continents separate the oceans. Especially in coastal areas with shallow water the theoretical tidal pattern is disturbed, due to bottom friction. Therefore the tidal pattern differs regionally. In the German Bight the semi-diurnal tidal cycle prevails, that is there are two high and low waters of equal height per day. In the German Bight, the *tidal range*, which is the difference between tidal high and tidal low water is about 2 – 4 m, depending on the location (OSPAR Commission, 2000).

Similarly, the salinity and the temperature of the North Sea are to a large extent determined by Atlantic influences. The Atlantic Ocean has a mean salinity of more than 35, which is close to the salinity in the Northern and central North Sea. Because of the fresh water input of the rivers, the salinity is smaller in coastal areas of the North Sea (32 – 34.5). The influence of the Baltic Sea leads to a much smaller salinity of only 15 – 25 in the Kattegat surface water (OSPAR Commission, 2000). The temperature of the North Sea is strongly depending on the season. Weisse (2011) describe that the highest temperatures occur in August and the lowest in February. Coastal areas show most extreme values in both, summer and winter. This is mainly due to the reduced water depth. In these areas the water temperature achieves values between $0°C$ and $20°C$ (OSPAR Commission, 2000). Differences in temperature and salinity lead to density differences of water masses. Together with the circulation of the tides and the predominant wind pattern, these factors are responsible for the formation of currents. In the mean this results in a counter clockwise circulation in the North Sea. North West Europe is characterised by westerly winds, which enforce this circulation. However, strong easterly winds may occasionally turn this into a clockwise circulation (OSPAR Commission, 2000). The interaction of the tides and the meteorological surge, resulting from the wind and atmospheric pressure field determines the height of sea level at a location to a specific time. If severe storms occur together with spring tide, this may result in an extreme sea level. Coastal areas of the German Bight were often destroyed by storm surges. Within the last century, the most devastating storm surge occurred in February 1962. It especially affected the area around Hamburg. It took 340 lifes and destroyed many dikes and houses. Since then the coastal defense was systematically improved, but people are still threatened by a possible storm surge. The tidal cycle and the meteorological surge both change within hours, that is a storm surge is also an event of that time scale. A rise in the MSL means a higher base water level on which the tides and the meteorological surge act. This results in a higher risk for storm surges as the whole frequency distribution of water levels is shifted towards higher values.

1.2. Basic Terms and Definitions

This study is considering and analysing the MSL in the German Bight. Generally, the term MSL is referring to the arithmetic mean of at least hourly water levels at one location over a time period long enough that there is no tidal influence. Pugh (1987) writes:

"For geodetic surveys the mean sea level is frequently adopted being the average value of levels observed each hour over a period of at least a year, and preferable over about 19 years to average out cycles of 18.6 years in the tidal

amplitudes and phases, and to average out effects on the sea levels due to weather."

Similarly, the International Hydrographic Organization (IHO) defines the MSL in the Hydrographic Dictionary (1994) as

"the average height of the surface of the sea at a tide station for all stages of the tide over a 19-year period, usually determined from hourly height readings measured from a fixed predetermined reference level (chart datum)".

In both definitions averaging over a period of 19 years is mentioned. The reason for this is the so called *nodal tide*, which has a 18.6-year cycle. It results from a cyclic deviation in the rotational axis of the Earth. The period of this oscillation is 18.6-years. The different positions of the moon and the Earth to each other due to this oscillation ensues the nodal tide. Details about the nodal tide and tides in general can e.g. be found in Pugh (1987) and Godin (1972). As averaging over 19 years would shorten the available data enormously and the tidal range of the nodal tide is only a few centimeters often shorter periods are used for the analysis of long-term trends (e.g. Church and White, 2006, Jevrejeva et al., 2006, Holgate, 2007). This is also done in this work, as annual MSL data are considered. All tidal cycles that have smaller periods than one year are removed in this time series. However, that means the oscillation of the nodal tide is still in the data and may influence trend analysis. If e.g. a time period of 9 years is analysed, which happens to start at the minimum of the nodal cycle and the amplitude of the nodal tide is assumed to be 4 cm, the nodal tide contributes 0.89 cm/yr to the decadal trend of this period. If 102 years (5 and a half times the period of the nodal tide) under the same conditions are considered, the contribution of the nodal tide is only 0.08 cm/yr. In general, the influence of the nodal tide is smaller, the longer the analysed time period. However, especially on the decadal scale, this may lead to a misinterpretation of decadal variability. The nodal tide is the reason why often multiples of 18.6 years are considered within analyses of the North

Sea (e.g. Jensen et al., 1992; Jensen and Mudersbach, 2004; 2007). This is also done in this study. In the analysis of past RMSL changes in the German Bight 37-year trends, which is twice the nodal tide are considered (chapter 2).

The above definitions request the need of at least hourly data to determine a time series for the MSL. Apart from some exceptions, area-wide hourly and even higher frequent measurements only started in the late 1990s in the German Bight. This gives time series of less than 20-years. With such short time series no reliable assessment of MSL changes is possible, the above mentioned effect of the nodal tide and decadal variability could adulterate the results.

However, other types of measurements may be exploited in addition. For many places measurements of tidal high and tidal low waters are available for much longer periods (Fig. A.1). The *tidal high water* is the highest water level reached during a tidal cycle. Analogue, the *tidal low water* is the lowest water level during a tidal cycle. By averaging over tidal high and tidal low waters over a certain time period *mean tide level* (MTL) can be derived. The MSL and the MTL are only equal if the tide curve equals a sinusoidal function (Fig. A.2). Especially in the German Bight this is generally not the case. The tide curve is deformed due to shallow water effects (Pugh, 1987; Lassen, 1989; Wahl et al., 2008). In the Southern part of the North Sea these effects cause differences of partially more than 20 cm (Wahl et al., 2008; 2011). MSL can be derived from MTL using the so called *k-factor* method (Lassen, 1989; Wahl et al., 2008; 2010; 2011), which is also used in this work. So called *k-factors* are determined for each location and are used to convert the MTL to MSL. The k-factors are calculated for the time periods where both, high and low resolution data are available and describe the difference between MTL and MSL. With this method the much longer measurements of tidal high and tidal low water can serve for a MSL time series. The method is explained in some more detail in section 2.2 and appendix A.

The definition of the Hydrographic Dictionary refers to a *"fixed predetermined reference level"*. Sea level data from the 20^{th} century mainly result from tide gauge measurements. The *reference levels* are then benchmarks on the land close to the tide gauge. That is, tide gauges provide the height of sea level with respect to these benchmarks. Land uplift or subsidence changes the position of the benchmarks and accordingly the measured sea level height changes. Land uplift will result in a negative trend in the sea level time series and subsidence in a positive. Tide gauges thus give the *relative mean sea level* to a local benchmark. In contrast to that the *absolute mean sea level* is measured with respect to the center of the Earth. This can be done with satellite altimetry. These data are not affected by local disturbances. Sea level data from altimetry measurement are only available from 1993 on. In this work tide gauge data for the 20^{th} century are analysed. These *relative* sea level analysis is important, as the relative sea level change is what actually changes the local flooding risk at the coasts.

1.3. History of Mean Sea Level Measurements

Sea level reconstructions go far back into the past. As an example the MSL at Huon Peninsula (Papua New Guinea) for the last 140,000 years can be seen in Fig. 1.3. Such long records of course are not based on instrumental measurements. Instead, for early periods, proxy data - as e.g. fossil coral reefs or submerged tree stumps - are used. With this data the position of the former shoreline can be estimated (Lambeck and Chappell, 2001). Fig. 1.3 shows large fluctuations over time. Highest values can be seen in the last interglacial about 120,000 years ago. These values are similar to those measured in the recent past. Sea level is falling then and a minimum is achieved during the last glacial maximum, about 20,000 years ago, where it was about 130 m lower than today. Since then a strong increase has been noticed. The large amount of ice depressed the earth crust and with the melting this process was reversed. This effect of local land movement is called *glacial isostatic adjustment* (GIA) and is still ongoing for example in parts of Northern Europe or Canada. An overview about the effect of GIA can be found in Whitehouse (2009).

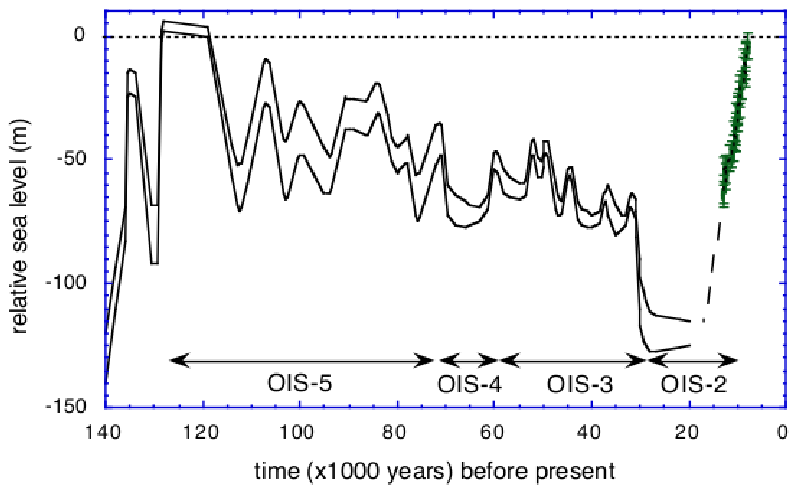

Figure 1.3. Estimated relative sea level at Huon Peninsula, Papua New Guinea. The last 13,000 years were derived from submerged fossil corals and the earlier record was reconstructed by the height-age relationships of raised reefs. The fluctuations in the time series result from the change of land-ice volumes. For the time of the last glacial maximum (LGM, about 20,000 years ago) the dashed line shows the sea level from North Western Australia as the record from Huon is missing for that period. Before the LGM upper and lower boundaries are shown and afterwards error bars. [Note: The periods of the major oxygen isotope stages (OIS) are shown. The OIS is a term from geology labeling warm and cold periods on Earth. Odd numbers refer to warm periods and even to cold periods.] From Lambeck and Chappell, 2001. Reprinted with permission from AAAS.

First tide gauge data are available from the 18^{th} century (Fig. 1.4). Data for this early period are e.g. available from Amsterdam (The Netherlands), Liverpool (UK) or Brest (France). However, the time series from Amsterdam is not useful to analyse MSL changes in the 20^{th} century as it ends in 1925. The data of Amsterdam were analysed in van Veen (1945). Spencer et al. (1988) updated and corrected the data, however the resulting time series is similar to the one of van Veen (1945). Woodworth (1999a; 1999b) provides analysis of the tide gauge of Liverpool and found a linear trend of 1.22 ± 0.25 in the 20^{th} century. The tide gauge of Brest is analysed in Wöppelmann et al. (2006). The author analysed linear trends of different time periods, in particular they found trends of -0.9 ± 0.15 mm/yr for 1807 – 1890, 1.3 ± 0.15 mm/yr for 1890 – 1980 and 3.0 ± 0.5 mm/yr for 1980 – 2004. As explained in section 1.2 MSL analysis needs at least hourly measurements. In these early records often only tidal high and tidal low water were measured. Hourly or even higher frequent data are for most locations only available for less than 20 years. If no hourly measurements are recorded, other sea level data as the MTL or annual mean high waters are used as an approximation.

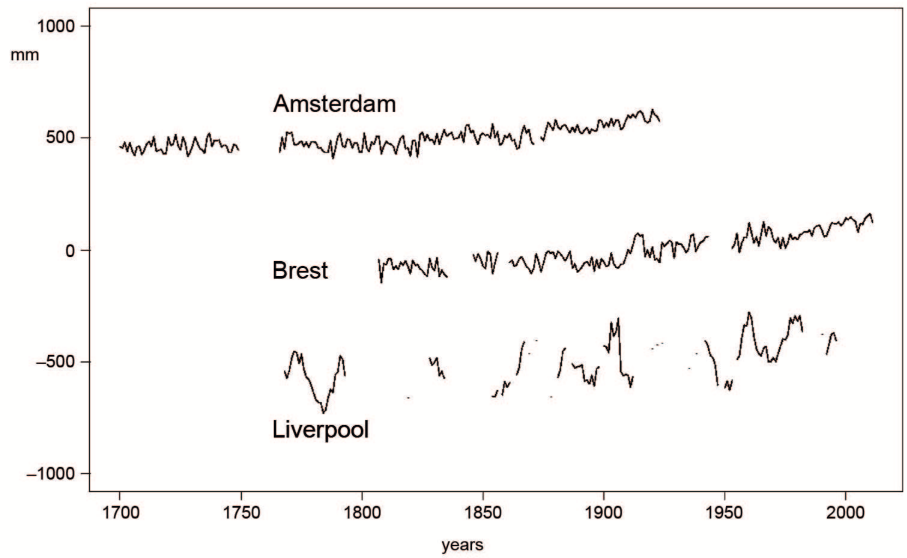

Figure 1.4. Long tide gauge records from Amsterdam, Brest and Liverpool. Data from PSMSL (`http://www.psmsl.org`). The time series are displayed with arbitrary offsets for presentation purposes.

Since 1993 data from altimetry monitoring are available. The first satellite measuring the sea surface height was TOPEX/Poseidon, from 2002 on measurements were continued by Jason-1, which was replaced by Jason-2 in 2008 (`http://sealevel.jpl.nasa.gov/missions/`). The latter is still in use. The concept of altimetry measurement is that satellites are sending radar waves, which reflect at the sea surface and return. The sea surface height is then measured using the time the radar wave needs to return to the satellite. These measurements are very reliable in the open ocean, however inaccuracies arise close to the coasts. Altimetry data are - in contrast to tide gauge data - not measured with respect to local references. Further, the measurements cover nearly the entire globe, ranging from 66° South to 66° North. In contrast to that, most tide gauges are located at the coast and are not equally distributed over the globe. However, the time period of altimetry measurements is too short for reliable statements about long-term trends in sea level changes. Decadal variability may appear as a long-term trend or mask one. Thus, for the analysis of MSL long-term trends in the 20^{th} century, tide gauges still provide the most useful information. A detailed explanation of the altimetry technique and its applications can e.g. be found in Seeber (2003) or Rosmorduc et al. (2011).

1.4. Global and Regional Mean Sea Level Changes in the 20^{th} Century

The time period considered for MSL analysis in this work is mainly the 20^{th} century, when instrumental records of sea level data are available. In this period, the main factors of change in GMSL are thermal expansion and melting ice sheets and glaciers (Bindoff et al., 2007). As outlayed in the previous section, data for MSL studies in the 20^{th} century come mainly from tide gauges. Altimetry data are available from 1993 on. Jevrejeva et al. (2006; 2008) reconstructed the GMSL from 1850 onwards, using tide gauge data. For the 20^{th} century this time series shows a linear trend of 1.9 mm/yr. For the period 1948 – 2002 Holgate and Woodworth (2004) analysed 177 tide gauges and estimated a rise of 1.7 ± 0.2 mm/yr. Holgate (2007) focused on a few tide gauges with very long records for his GMSL estimation. He found a rise of 1.74 mm/yr for the period 1904 – 2003. Using a different approach Church et al. (2004) reached similar conclusions. They combined both, tide gauge and altimetry data to construct a time series for the GMSL for the period 1950 – 2000. This approach was extended in Church and White (2006) to reconstruct the GMSL for 1870 – 2006 and in Church et al. (2011) for 1880 – 2009. For the period 1900 – 2000 both time series show the same linear trend of 1.7 mm/yr. The method of Church et al. (2004) was used and adapted by several other authors. Ray and Douglas (2011) constructed a time series of the GMSL for the period 1900 – 2006 using a modified version of the approach of Church et al. (2004). They found a linear trend of 1.7 ± 0.24 mm/yr for this period. Hamlington et al. (2011) also used a modification of the approach of Church et al. (2004). Their reconstructed time series shows a trend of 1.97 mm/yr for the period 1950 – 2009 and 3.22 mm/yr for the period 1993 – 2009. Several different estimations of time series for the GMSL in the 20^{th} century are shown in Fig. 1.5.

Nerem et al. (2010) analysed the change in GMSL during the period of altimetry data. An update of their analysis shows a rise of 3.1 ± 0.4 mm/yr for the years 1993 – 2012 (`http://sealevel.colorado.edu/`). The time series for the GMSL based on altimetry data can be seen in the black curve in Fig. 1.5. Compared to the calculated rates of the 20^{th} century, the measured rise of GMSL for the period of altimetry data is much higher. This result leads to the question whether there has been an acceleration in MSL rise in the recent past. This task has been worked on with different approaches and different results. Using tide gauge data Jevrejeva et al. (2006) found a linear trend of 2.4 ± 1.0 mm/yr for the period 1993 – 2000 and simultaneously showed that trends of similar magnitude already occurred in earlier periods. Based on that, they concluded no significant acceleration in the recent past. In a later work Jevrejeva et al. (2008) fitted a second order polynomial function to their sea level data. Calculating the second derivative of this fit, they found an acceleration of 0.01 mm/yr^2 which started in the 18^{th} century and continued until the end of the record. However, the authors found large fluctuation in decadal acceleration over the entire time period. Using 20-year running trends Church et al. (2008) found extraordinary high trends for the last five periods of the considered time period. From this fact they concluded that there has been an accelerating rise in the recent past. Ray and Douglas (2011) calculated 15-year running trends of their reconstruction. They also found extraordinary high values in the recent past. However, computing the same trends for the GMSL reconstruction of Church and White (2006) does not show an acceleration in the last periods.

The method of Church et al. (2004) and its modifications not only produce a time series for the GMSL, but also a spatial distribution of it (Fig. 1.6, a). This distribution is based on altimetry data. As the time period for which al-

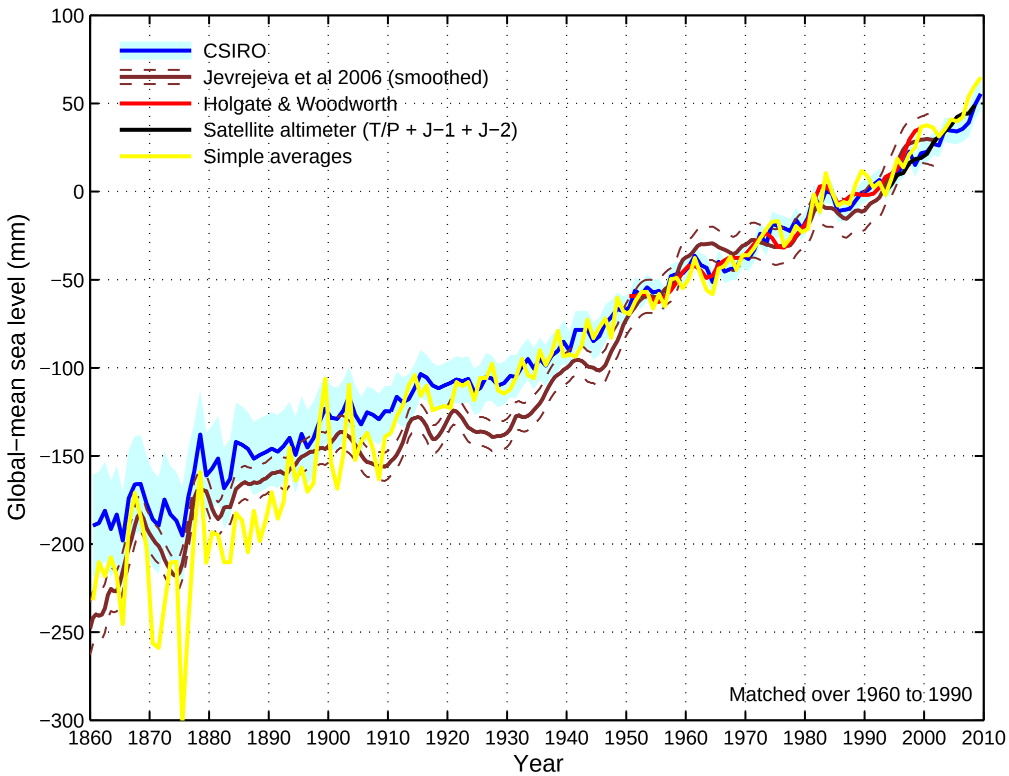

Figure 1.5. Different estimations of global mean sea level. The reconstruction of Church and White (2011, blue), Jevrejeva et al. (2006, brown), Holgate and Woodworth (2004, red) and from simple average of tide gauges (Church and White, 2011, yellow). The reconstructions are set to zero in 1990 and have the same average value over 1960 – 1990. The black curve shows satellite measurements from 1993 on. From Church et al. (2011).

timetry data are available is relatively short, its representativeness is a factor of uncertainty for long time periods. The main difficulty remains that data availability is decreasing in earlier times. In the beginning of the 20^{th} century only few tide gauges were implemented and most of them in coastal areas of Europe and North America. Fig. 1.6 clearly shows that there are considerable regional differences in MSL changes. The most important factors causing these differences are discussed in e.g. Gönnert et al. (2009) to be local land movements, regional differences in thermal expansion, land ice-melting and changes in the mean ocean or atmospheric circulation. The local land movements can result from different effects, as e.g. sediment accumulation, extraction of ground water, tectonic movements or volcanic activity. The most prominent among these effects is the GIA discussed in section 1.3. For the latter estimates from numerical model simulations are available (Peltier, 2004; Whitehouse, 2009). Knowledge about regionally different ocean heating leading to regionally different thermal expansion is summarised in Bindoff et al. (2007) (Fig. 1.6,b) and in Church et al. (2008). Land ice melting has an effect on regional sea level via an effect called self-gravitational attraction. An ice mass attracts water due to gravity. As a consequence sea level is higher than normal in the vicinity of the ice field while it is lower far away. If the ice mass reduces, the gravity reduces as well. Consequently, sea level decreases in near field while it rises further away. Thus, the additional water resulting from land ice melting does not distribute equally around the globe. Mitrovica et al. (2001) computed a geographical pattern for sea level changes caused by variations in either the Antarctic ice sheet, the Greenland ice sheet or the melting of glaciers. For 23 tide gauges the authors give projections of sea level trends that result from the continuing ice-mass changes and consider their deviation to assumed uniform trends. They found deviations from 80% to 120% with highest values in European tide gauges.

There are a number of studies analysing the effects of changes in large-scale atmospheric wind and pressure fields on RMSL. These changes will not affect the GMSL but may lead to a different distribution of the water. Most of these analyses use preselected patterns in the atmospheric field. Often the NAO, which describes a pressure dipole over the North Atlantic, is used to analyse the variability of MSL in North West Europe. For example, Yan et al. (2004) analysed the influence of the NAO on the MSL of several tide gauges in the North and Baltic Sea. The authors identified a significant correlation between both factors, which is especially pronounced in winter. Concentrating on winter, Jevrejeva et al. (2005) analysed the relationship between the MSL of different tide gauges in the North Sea and the North East Atlantic and the

NAO-index. Their analysis comprises the last 150 years and shows that the

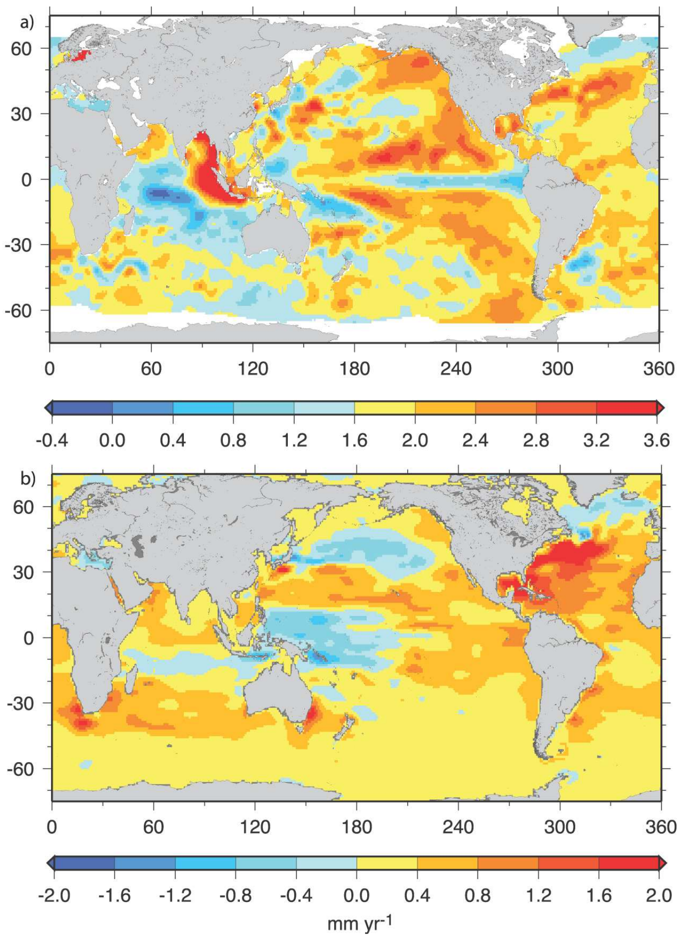

Figure 1.6. (a) Spatial distribution of long-term trends of MSL for the period 1955 – 2003. The reconstruction is based on tide-gauge and altimetry data and corresponds to an updated version of Church et al. (2004).
(b) Spatial distribution of long-term trends of MSL, only resulting from thermal expansion for 1955 – 2003. The result bases on temperature data down to 700 m from Ishii et al. (2006). [Note: The colours in (a) are shifted by +1.6 mm/yr compared to those in (b).] From Bindoff et al. (2007).

NAO-index explains about 10% to 35% of the variance of the winter MSL. They found highest values in the correlations in the North East part of the North Sea. Using both modeled and observed MSL data Wakelin et al. (2003) came to similar conclusions, for period 1955 – 2000. Most analysis of the connection between the NAO and MSL only include the correlations of detrended time series and a possible relation between the long-term trends is not considered. Kolker and Hameed (2007) analysed both variability and long-term trends for five tide gauges around the North Atlantic. Considering the period 1905 – 1993, they found for Cascais, Portugal that 80% of the observed long-term trend can be associated with the long-term trend of the NAO.

For the UK East coast MSL changes were analysed by Woodworth et al. (1999; 2009) and Haigh et al. (2009). Woodworth et al. (2009) analysed tide gauge data along the entire British coast. They analysed absolute MSL changes and estimated a linear trend of 1.4 ± 0.2 mm/yr for the 20^{th} century. Haigh at al. (2009) concentrated on the English Channel. As well considering the 20^{th} century, they found that for this region the trends vary between 0.8 – 2.3 mm/yr. Woodworth et al. (2009) further showed that the estimated linear trends were consistent with other locations in the North Sea area. In Katsman et al. (2008) the MSL of the Netherlands is analysed. The authors document a linear trend of 2.5 ± 0.6 mm/yr for the 20^{th} century. None of the authors found an extraordinary acceleration in the MSL in the recent past. Until recently, studies for the German Bight have been based mostly on changes in tidal high, tidal low waters or tidal ranges (e.g. Jensen et al., 1992; Lassen, 1995; Jensen and Mudersbach, 2007). In the AMSeL[1] project substantial effort were made to homogenise the tide gauge data of the German Bight (described in IKÜS, 2008; Wahl et al., 2008, 2010, 2011). This homogenised MSL data made new attempts to analyse MSL time series of the German Bight possible. Wahl et al. (2010) analyse MSL data of the tide gauges Helgoland and Cuxhaven and Wahl et al. (2011) constructed an index time series by using an arithmetic mean over data from different tide gauges. For the period 1901 – 2008 the authors found a linear trend of 1.7 ± 0.1 mm/yr for the German Bight. Also in these works no extraordinary acceleration in the recent past could be found.

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

1.5. Future Projections of Mean Sea Level

Future MSL is depending on future climate conditions, which to a large extent depend on the future greenhouse gas concentrations in the atmosphere. As the future development of the greenhouse gas concentrations is not known, usually different emission scenarios are considered. Different emission scenarios reflect different possible socio-economic developments that are translated into climate change projections by means of state-of-the-art climate models. The *Interna-*

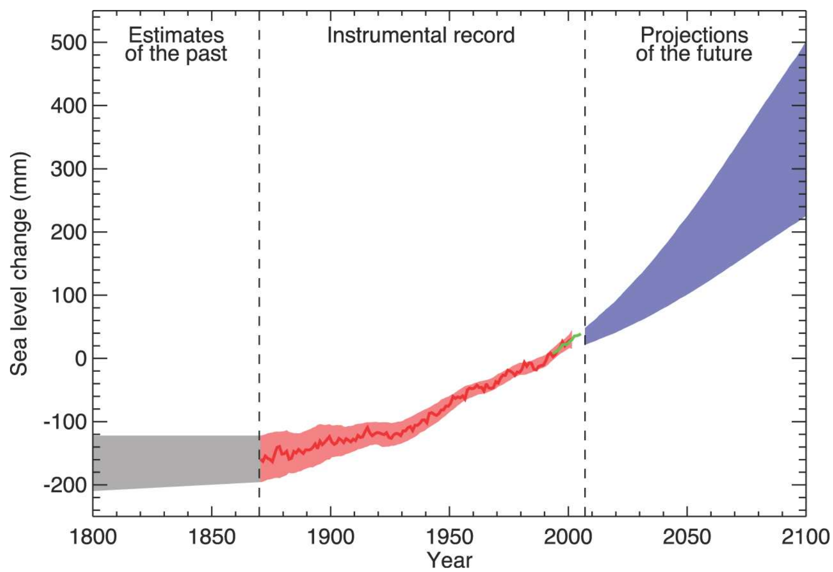

Figure 1.7. Overview of past global sea level estimations and future projections. For the period 1800 – 1870 no measurements are available. Sea level estimates for this period illustrated by the grey band were derived from proxy data (see Section 6.4.3 in Jansen et al. (2007) for further explanation). The period from 1870 until the beginning of the 21^{st} century shows a reconstruction based on tide gauge data (red line) together with uncertainty estimates (red shaded area). From 1993 onwards a reconstruction based on altimeters data is shown additionally (green). For the future, the blue area shows the range of model projections for a moderate emission scenario (SRES A1B). From Bindoff et al. (2007).

tional Panel on Climate Change (IPCC) summarises the scientific knowledge of climate change as a basis for political decisions. In its *Fourth Assessment Report* (AR4) the IPCC summarises projections of the GMSL until the end of the 21^{st} century (2090 – 2099) compared to the end of the 20^{th} century (1980 – 1999). The projections range between 18 and 59 cm, depending on the underlying climate scenario (Meehl et al., 2007). Fig. 1.7 shows the range of these projections for a moderate emission scenario (SRES A1B) together with estimations and measurements for past GMSL. According to the AR4, the largest factor for the future rise in GMSL is thermal expansion, contributing 10 – 41 cm (Meehl et al., 2007). Fig. 1.8 shows the results of the AR4 projections of thermal expansion derived from different *atmosphere-ocean general circulation models* (AOGCMs) for the 21^{st} century. A short explanation of these models and further literature is given in appendix B. The AR4 describes the land ice melting from glaciers, ice caps or the Greenland ice sheet as another positive factor for future GMSL rise (7 – 17 cm). In contrast to that the Antarctic ice sheet is projected to have a negative contribution due to increasing snow fall (Meehl et al., 2007). The authors further stated that there are possible larger dynamical changes in the ice sheets of Antarctica and Greenland than projected by the used climate models, because of the recent rapid mass losses. This factor is referred to as the *"scaled up dynamical ice sheet discharge"* and is - depending on the future temperature change - specified with up to 17 cm. That is, including this factor the projected rise of the IPCC AR4 for the 21^{st} century is 18 – 76 cm (Meehl et al., 2007).

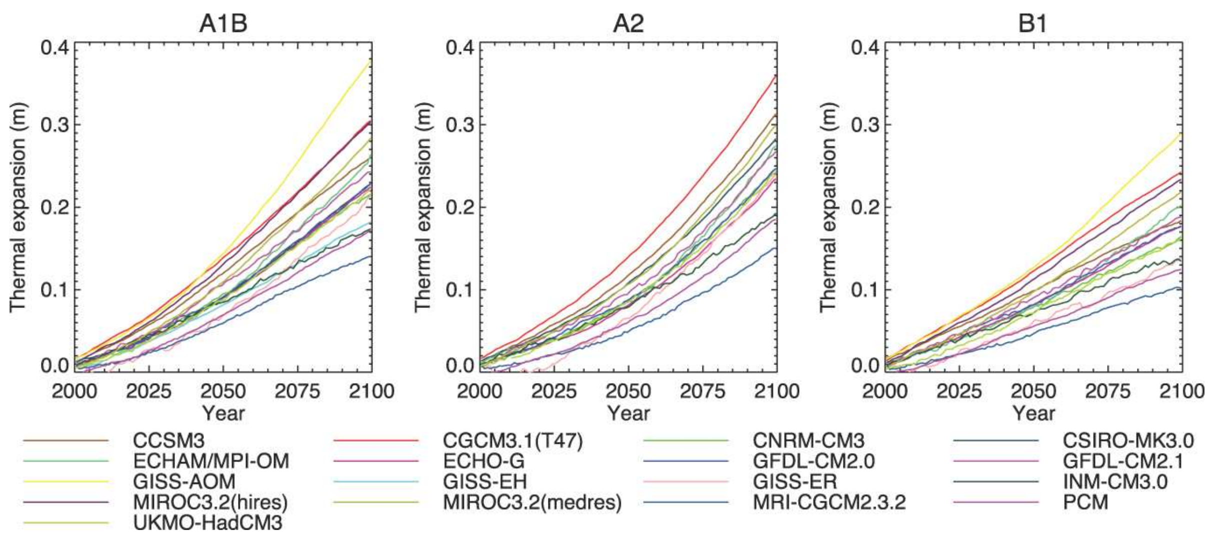

Figure 1.8. Global average sea level rise (m) caused by thermal expansion projected by climate models for the 21^{st} century. The values are relative to the period 1980 – 1999 and shown for three emission scenarios (SRES A1B, A2 and B1). From Meehl et al. (2007)

Recent studies of future MSL changes have used both, modeling and semi-empirical approaches. The results partly revise the AR4 conclusions, but they are also partly under discussion. Especially the contribution of the Antarctic and Greenland ice sheets were further analysed. In contrast to the position provided by the IPCC AR4, Shepard and Wingham (2007) stated that both ice sheets are loosing mass. That is also the ice sheet of Antarctica has a positive contribution to future GMSL. Rignot et al. (2011) found an acceleration in ice sheet loss in both, Antarctica and Greenland in the last 18 years and concluded that the ice sheets will be the dominant contributor to sea level rise until 2100 if this loss continues. More recently so-called semi-empirical approaches emerged in which a linear relationship between the global mean surface temperature and the GMSL rise is assumed (e.g. Rahmstorf, 2007). These models assume that the relationship between GMSL change and global mean temperature remains the same in the future as it was in the calibrating period. Applying this model to the SRES scenarios of the IPCC Rahmstorf (2007) concluded a rise of 50 – 140 cm over the period 1990 – 2100. This approach assumes that the response time scale of GMSL is long compared to the time scale of interest. Extending this model by adding a rapid response term, Vermeer and Rahmstorf (2009) projected even higher increases of 75 – 190 cm towards the end of this century. The results of the semi-empirical model developed in Rahmstorf (2007) have been challenged both, for statistical reasons and on physical grounds. Holgate et al. (2007) argued that a missing validation over different time periods of the model may lead to an over-fitting. The authors cross-validated the model and their result did not confirm such a linear relationship. Schmidt et al. (2007) argued that the regression analysis of Rahmstorf (2007) is incorrect because the trend of both time series falsified the results. Von Storch et al. (2008) tested the assumption of the approach of Rahmstorf (2007) using climate model data, whereas the sea level data from the climate model only represents the component of thermal expansion. The authors computed regression coefficients for sliding windows over the same time period Rahmstorf (2007) used in his analysis. The investigation of von Storch et al. (2008) showed large variations in the regression coefficients and the authors concluded that such a simple linear relation between the rate of GMSL rise and global mean temperature is not valid in the climate model data. They argued that it is unlikely that such a relationship holds in the real world, if it does not hold in the much simpler virtual reality. They found a more robust linear relationship - which is also physical plausible - between the rate of GMSL rise and the ocean heat-flux. However, the authors argued that this relationship does not help to project future GMSL rise, because no long records for the ocean heat-flux exist. A somewhat different approach was suggested by Grinsted et al. (2009). They also used a semi-empirical relationship between the global mean temperature and GMSL, but in contrast to Rahmstorf (2007) their approach is based on a 4-parameter, physically based differential equation. Instead of only using instrumental records Grinsted et al. (2009) analysed global sea level and global temperature reconstructions of 2000 years, by including paleoclimate data. The authors tested their model by calibrating it to the period before 1990 and validated it against the period afterwards. They project a rise of 90 – 130 cm until 2100 for the SRES A1B scenario. The objective of Pfeffer et al. (2008) is to give an upper bound for possible sea level rise until the end of the 21^{st} century. The authors concluded that a sea level rise of more than 200 cm until 2100 is physically not plausible, considering the dynamical changes of glaciers. The authors further stated that a rise of 80 cm until 2100 is more realistic. Reviewing current literature Nicholls et al. (2011) analyse GMSL change under the assumption of a rise of 4° C or more in global mean temperature until 2100. Based on that, they came up with estimates of 50 – 200 cm for the 21^{st} century.

Attempts to provide regional estimates of MSL only emerged very recently. A global picture of regional future changes until the end of the 21^{st} century is given in Slangen et al. (2012). The authors constructed a spatial distribution of MSL change based on the ensemble of climate model simulations also used in the IPCC AR4. The regional pattern of MSL projections is achieved by adding regional contributions of land-ice melting, steric effects and the global isostatic adjustment (GIA). For the SRES A1B scenario the projected MSL differs regionally between -391 cm and 79 cm with a global mean of 47 cm. Katsman et al. (2008) provide estimates for the MSL of the North East Atlantic for the years 2050 and 2100. Both, a moderate and a large atmospheric warming is considered. They obtain a projected rise of 15 – 25 cm for the moderate scenario for 2050 compared to 1990 and 30 – 50 cm for the same scenario until 2100. For the warm scenario they projected an increase of 20 – 35 cm until 2050 and 40 – 80 cm until 2100. Katsman et al. (2011) developed high-end scenarios for the Netherlands. Based on two different scaling factors for the transformation of the global mean contributions from ice masses to local variations they obtained two different results. Depending on that projected sea level varies between 40 – 105 cm and -5 – 115 cm respectively, for the period 1990 to 2100. Differences between global and regional projected sea level rise are mainly attributed to local steric effects, that is changes in ocean volume due to density changes, and the contribution of melting land-ice and the resulting changes in gravity (Katsman et al., 2011). Lowe et al. (2009) analysed projections of MSL changes for the UK. Their projections until 2095 range from 12 – 76 cm. A high-end projection, which is considered to be very unlikely, showed rises between 93 cm and 190 cm. As in the analyses of Katsman et al. (2008; 2011) these projections are based on the global projections of the IPCC AR4. Local oceanographic variations are then included to achieve regional projections. For the German Bight such regional projections are not available so far.

2. Determining sea level change in the German Bight[1]

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 1.64 mm/yr and 1.74 mm/yr with a 90%-confidence range of 0.28 mm/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.

[1] Albrecht F., Wahl T., Jensen J., Weisse R. (2011) Determining Sea Level Change in the German Bight. Ocean Dynamics, 61, 2037 – 2050, doi: 10.1007/s10236-011-0462-z

2.1. 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 1.7 mm/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; 2008). 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 2.4 mm/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 1.74 mm/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 1.8 mm/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 2.2 we first introduce the two approaches and the data used for the analysis. Subsequently, the index time series obtained are compared in section

2.3.1. 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 2.3.2 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 2.3.3. In particular, we separate between Lower Saxony and Schleswig-Holstein, two regions along German coast line. In section 2.3.4 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.

2.2. Data and Methods

We use homogenised annual mean sea level data 1843 – 2008 from 15 tide gauges (Fig. 1.1) in the German Bight as provided by the AMSeL[2] 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, 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 peri-

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

ods 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. 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 2.3.1). 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 $\mathbf{e}_j \in \mathbb{R}^{15}$, $j \in \mathbb{N}$ and associated coefficients (principal components) $\mathbf{a}_j(t_0) \in \mathbb{R}^{15}$, such that

$$\mathbf{x}(t_0, i) = \sum_{j=1}^{15} \mathbf{a}_j(t_0)\mathbf{e}_j(i),$$

for each $t_0 \in \{1, \ldots, k\}$. Within this representation we choose the first basis vector $\mathbf{e}_1 \in \mathbb{R}^{15}$ 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) $\mathbf{a}_1(t)$ 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 tothe 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 eigenvalues of C (von Storch and Zwiers, 1998). As for our case all reasonable reconstructions have explained variances of more than 90% (see section 2.3.1) we conclude that the principal component time series from the first EOF represents a reasonable approximation of the RMSL.

2.3. Results

2.3.1. Comparison of different Methods to estimate Regional Mean Sea Level

In section 2.2, two different methods to construct artificial index time series for the RMSL were introduced. Fig. 2.1 shows the results from the two approaches when applied to the same data from the German Bight. Both time series share strong similarities (Table 2.1) with comparable inter-annual fluctuations but also similar long-term trends (Table 2.2). Fig. 2.2 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 0.1 mm/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.

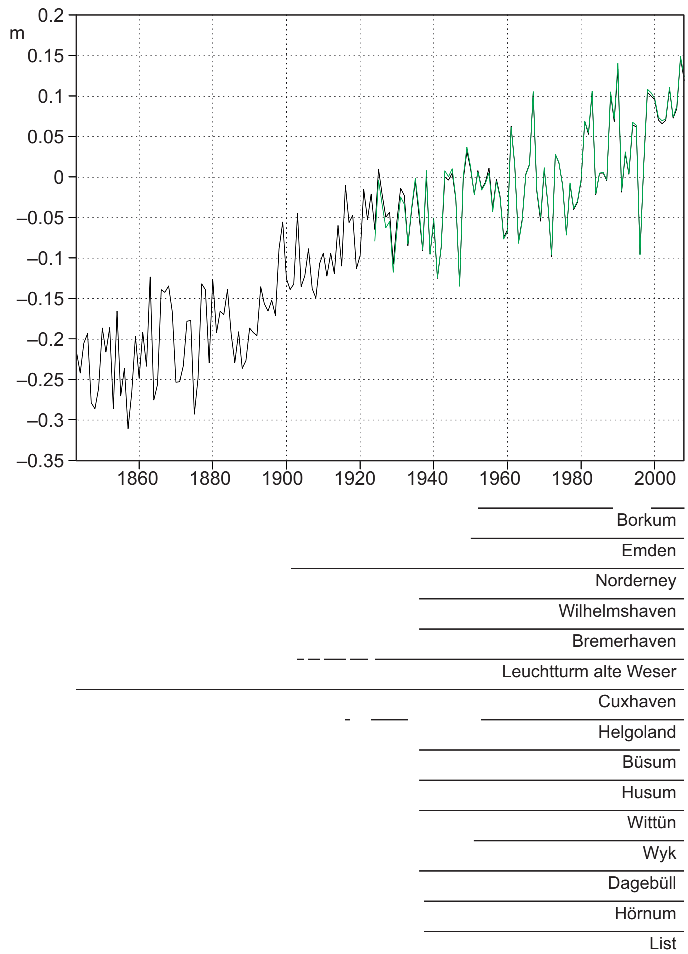

Figure 2.1. RMSL in the German Bight as estimated from two different approaches: mean approach 1843 – 2008 (black); EOF-approach 1924 – 2008 (green); data availability at the tide gauges used for the analysis (bottom).

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

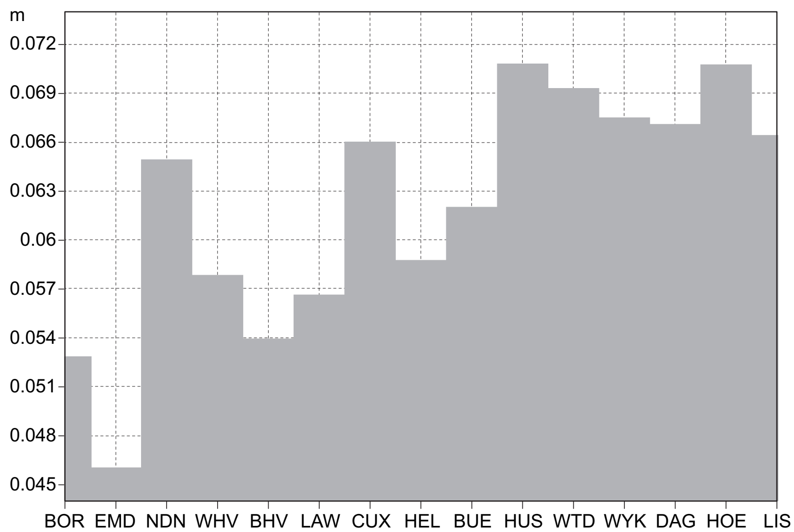

Figure 2.2. Pattern of the first EOF in the EOF-approach 1924 – 2008. Three letter codes indicate tide-gauges, from left to right: Borkum, Emden, Norderney, Wilhelmshaven, Bremerhaven, Lighthouse Alte Weser, Cuxhaven, Helgoland, Büsum, Husum, Wittdün, Wyk, Dagebüll, Hörnum and List.

Table 2.1. Correlation coefficients between different RMSL estimates and sea level in Cuxhaven for different time periods.

	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	-

Table 2.2. Linear trends derived from different RMSL estimates and sea level in Cuxhaven for different time periods. Additionally 90%-confidence intervals are shown.

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

the years before, or in other words whether the sea level changes in Cuxhaven are representative for the German Bight at least before 1924.

Table 2.1 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 2.2). 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. 2.3 and Fig. 2.4 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 3.7 mm/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 2.4). Here largest differences occur in the 1950s. They are up to 1.8 mm/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.

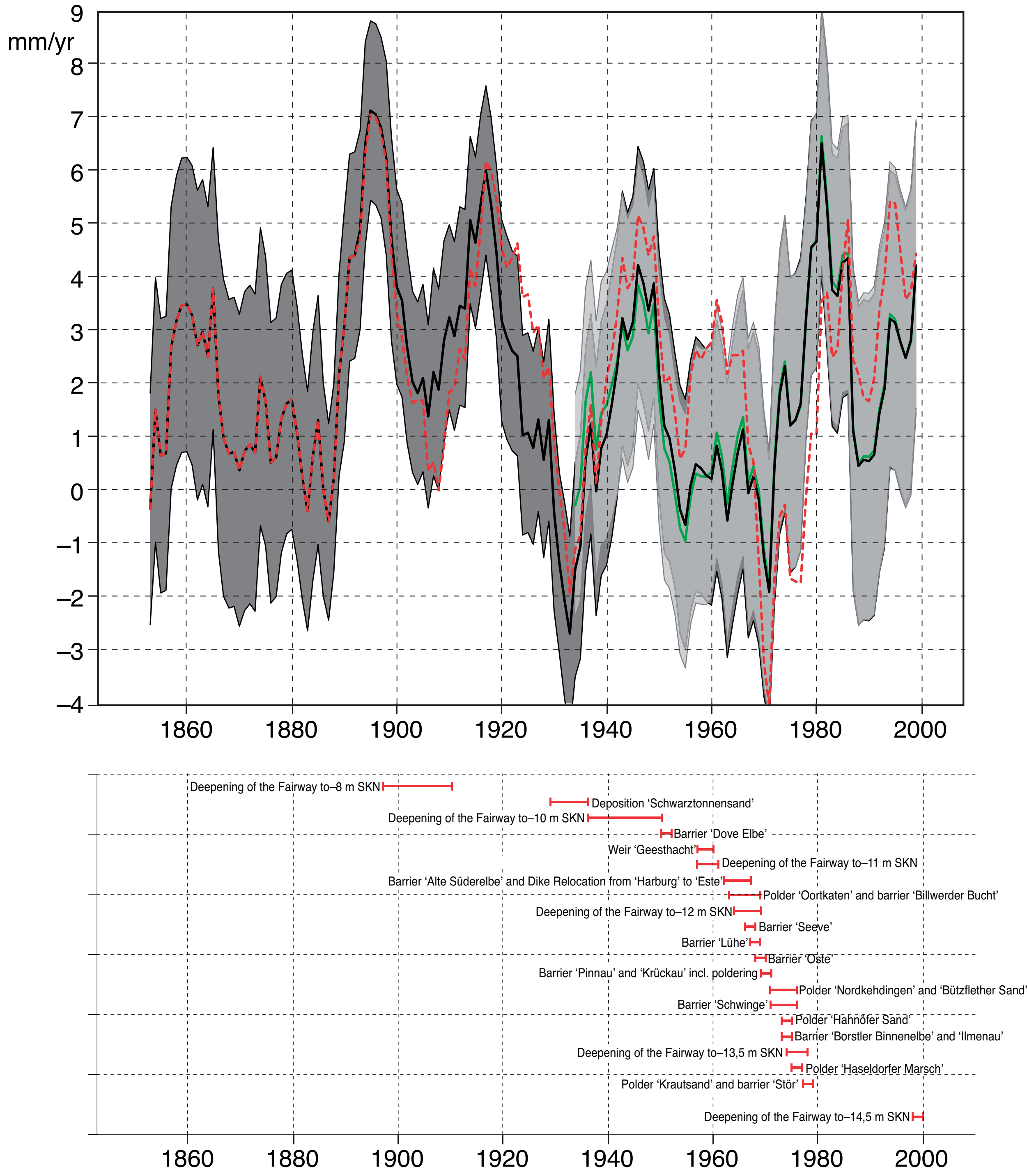

Figure 2.3. 20-year running trends of RMSL in the German Bight derived from the mean (black) and the EOF-approach (green) together with those derived from local sea level data in Cuxhaven (red). The 90%-confidence intervals for trends estimated from the RMSL time series are indicated in dark (mean approach) 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).

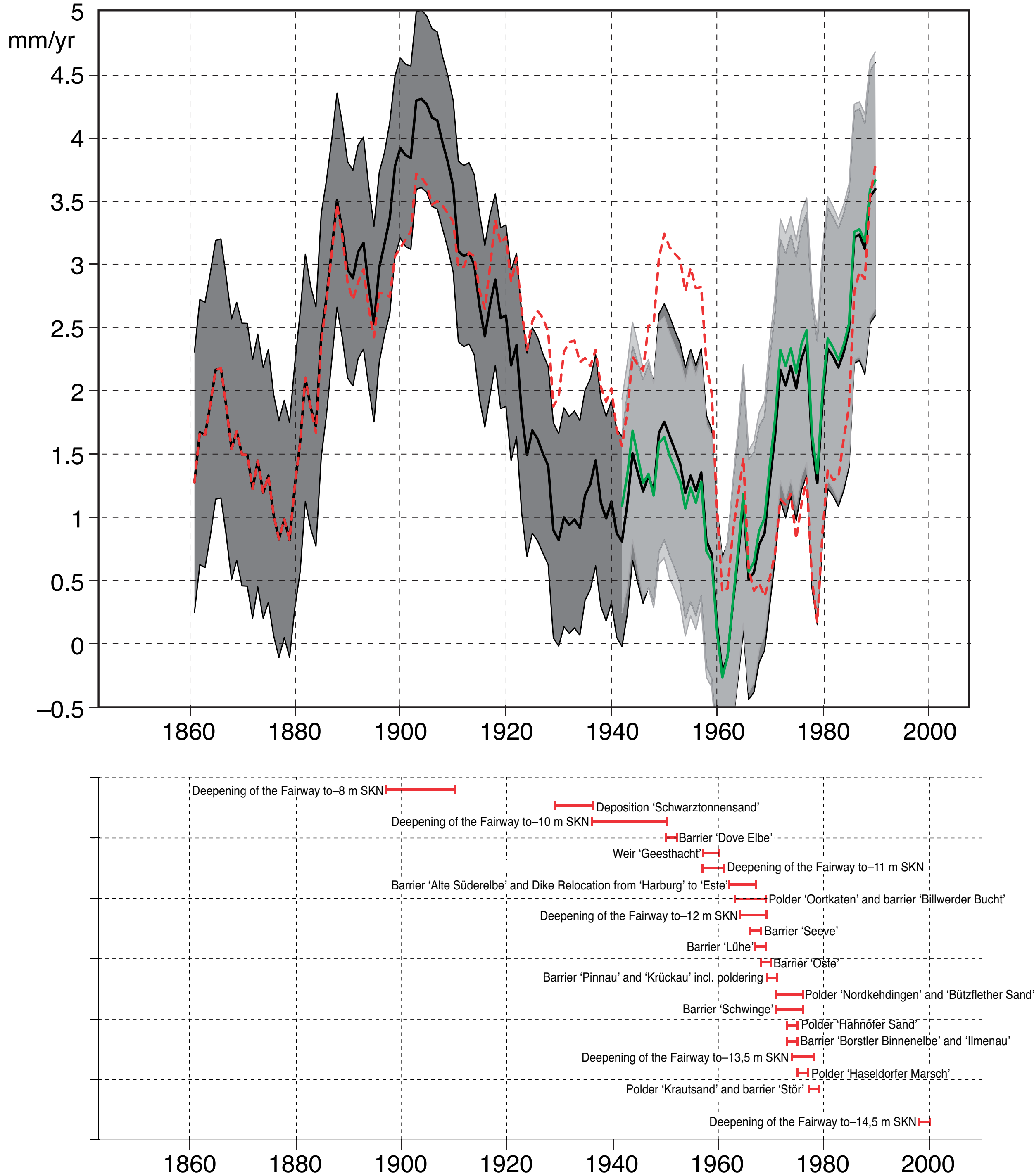

Figure 2.4. 37-year running trends of RMSL in the German Bight derived from the mean (black) and the EOF-approach (green) together with those derived from local sea level data in Cuxhaven (red). The 90%-confidence intervals for trends estimated from the RMSL time series are indicated in dark (mean approach) 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).

A possible reason for these differences could be that the water levels at the Cuxhaven tide gauge are influenced by local construction works. Fig. 2.3 and Fig. 2.4 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. 2.5). 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. 2.5 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. 2.4). 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. 2.4). 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 2.3.4).

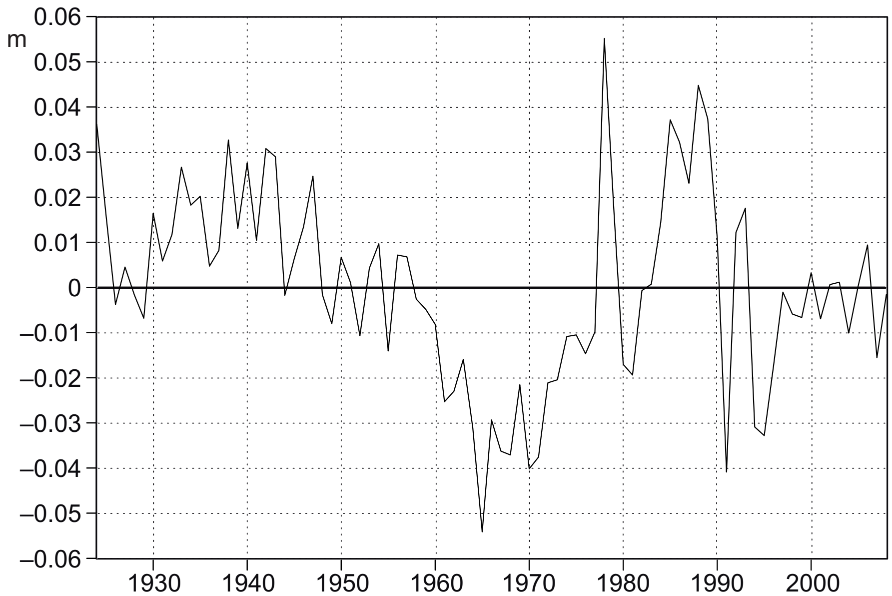

Figure 2.5. Residuals 1924 – 2008 in m between RMSL derived from the EOF-approach and local sea level in Cuxhaven.

2.3.2. Impact of Homogenization of Data

In section 2.3.1 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 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)[3] which are all located in Lower Saxony (Fig. 1.1), 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 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. 2.1) 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. 2.6 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 1.6 mm/yr and 1.53 mm/yr for the homogenised and the original data respectively. In both cases the 90%-confidence range is 0.4 mm/yr. Analysis of the differences between both time series (Fig. 2.6) 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 1.62 mm/yr and 2.27 mm/yr in the original and the corrected data respectively. However, the 90%-confidence range has a value of 1.5 mm/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 con-

[3]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.

structing 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 and 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. 2.7). 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 1 mm/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 0.4 mm/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.

2.3.3. Regional Differences in Mean Sea Level Changes

Fig 2.2 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 2.3.1

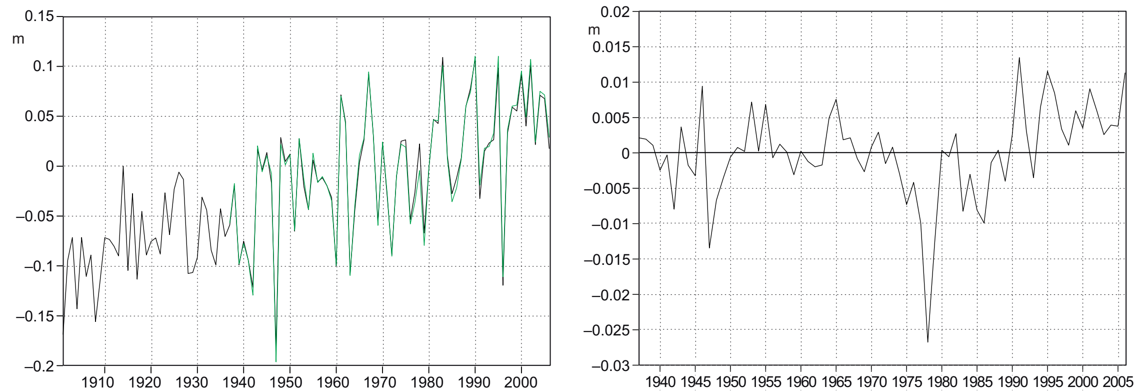

Figure 2.6. Left: RMSL in m in Lower Saxony derived from the EOF-approach using data from Emden, Norderney, Bremerhaven, Wilhelmshaven and Cuxhaven; original (GJ) data 1901 – 2006 (black); data from the AMSeL project 1936 – 2006 (green). Right: differences in m between the RMSL derived from the AMSeL data and from original (GJ) data for the common time period 1937 – 2006.

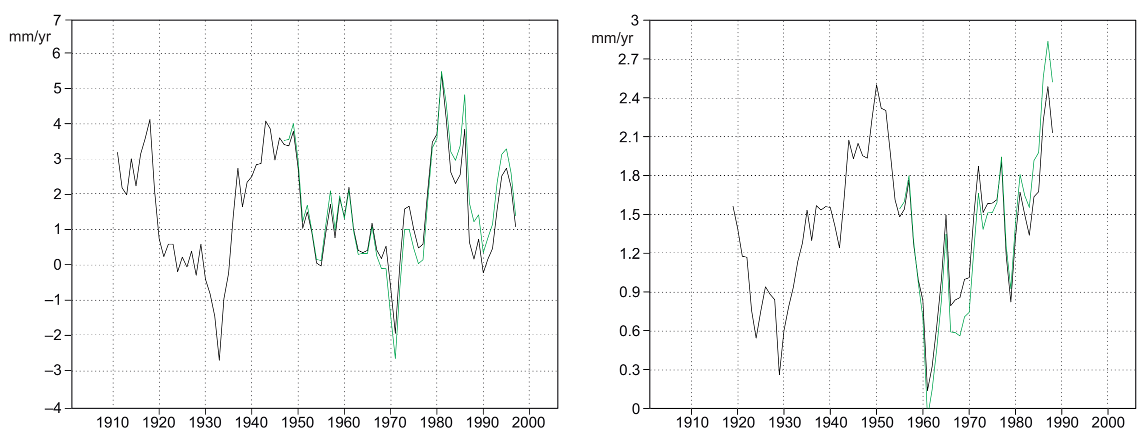

Figure 2.7. 20-year (left) and 37-year running trends (right) of the RMSL in Lower Saxony derived from the EOF-approach using data from Emden, Norderney, Bremerhaven, Wilhelmshaven and Cuxhaven; original (GJ) data (black); data from the AMSeL project (green).

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. 2.8. 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 linear trend for Lower Saxony has a value of 1.69 ± 0.3 mm/yr for the period from 1936 to 2008, while for Schleswig-Holstein a somewhat higher value of 2.02 ± 0.4 mm/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 ± 0.4 mm/yr. In each case the 90%-confidence range is given.

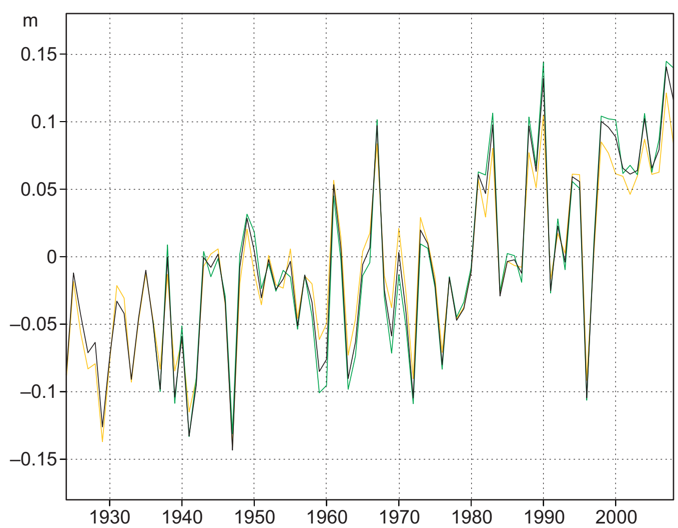

Figure 2.8. RMSL in m for Lower Saxony (yellow), Schleswig-Hostein (green) and the German Bight (black) as derived from the EOF-approach.

In Fig. 2.9 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 2.7 mm/yr and 1.4 mm/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. 2.2) indicate a significant spatial variability in the MSL of the German Bight.

In Fig. 2.9 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.

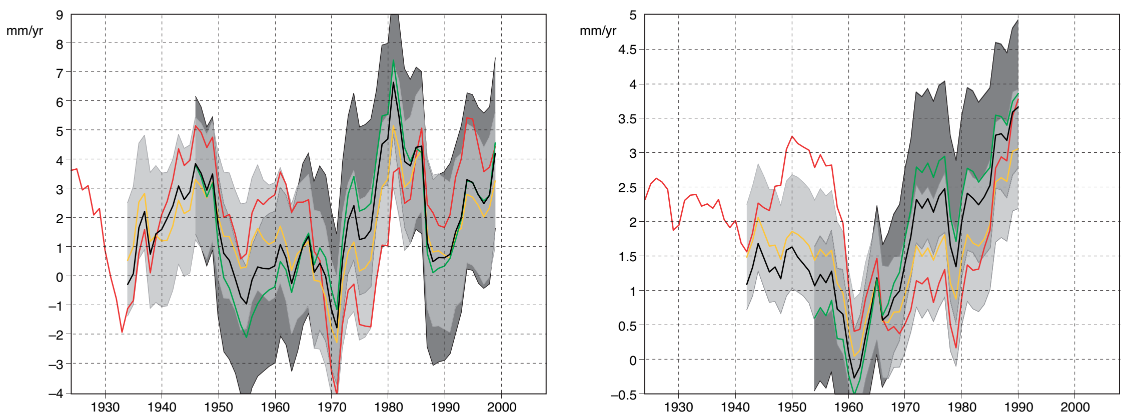

Figure 2.9. 20-year (left) and 37-year running trends (right) of RMSL in Lower Saxony (yellow), Schleswig-Hostein (green), and the German Bight (black) together with those derived from local sea level in Cuxhaven (red). The 90%-confidence intervals for trends estimated from the RMSL time series are indicated in dark (Schleswig-Holstein) and light grey (Lower Saxony).

2.3.4. Acceleration Changes in Regional Mean Sea Level

In this section we again consider the 20- and 37-year running trends in Fig. 2.3 and Fig. 2.4 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 2.3.1 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 2.3.1 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. 2.3 where the first three values of the trends differ by up to 1.2 mm/yr, while thereafter differences are generally smaller than 0.5 mm/yr. For the 37-year trends differences are generally smaller than 0.3 mm/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. 2.3 and Fig. 2.4 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 2.3.1), 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 4.4 mm/yr. The value of the 37-year trends within the last period centred around 1990 is 3.8 mm/yr. There are two other high peaks in this curve. One is around 1950 with a trend of 3.2 mm/yr and the other around 1903 with 3.7 mm/yr. Both are somewhat smaller than the most recent trend, but differences are still small.

Summarising we found that for all, the RMSL derived from two different approaches (Figs. 2.3, 2.4) and the original sea level data from Cuxhaven (Figs. 2.3, 2.4, 2.9), 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.

2.4. 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 1.64 mm/yr and 1.74 mm/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 1.1). 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 North Sea 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 0.62 mm/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; 2008) 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.

Acknowledgment

We thank Hanz Niemeyer from the NLWKN-Forschungsstelle Küste for providing us with the digitised data of the Gewässerkundlichen Jahrbücher (GJ). Furthermore we thank Ivan Haigh for the help with the English language. This work is a contribution to the "Helmholtz Climate Initiative REKLIM" (Regional Climate Change), a joint research project of the Helmholtz Association of German research centres (HGF).

3. Pressure effects on past regional mean sea level trends and variability in the German Bight[4]

Abstract The impact on a large-scale sea level pressure field to the regional mean sea level changes of the German Bight is analysed. A multiple linear regression together with an empirical orthogonal function analysis is used to describe the relationship between the sea level pressure and the regional mean sea level considering the time period 1924 – 2001. Both, the part of the variability and of the long-term trend that can be associated with changes in the sea level pressure are investigated. Considering the whole time period, this regression explains 58% of the variance and 33% of the long-term trend of the regional mean sea level. The index of agreement between the regression result and the observed time series is 0.82. As a proxy for large-scale mean sea level changes the mean sea level of the North East Atlantic is subsequently introduced as an additional predictor. This further improves the results. For that case the regression explains 74% of the variance and 87% of the linear trend. The index of agreement rises to 0.92. These results suggest that the sea level pressure mainly accounts for the inter-annual variability and parts of the long-term trend of regional mean sea level in the German Bight while large-scale sea level changes in the North East Atlantic account for another considerable fraction of the observed long-term trend. Sea level pressure effects and the mean sea level of the North East Atlantic provide thus significant contributions to regional sea level rise and variability. When future developments

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

are considered their scenarios for their future long-term trends thus need to be comprised in order to provide reliable estimates of potential future long-term changes of mean sea level in the German Bight.

3.1. Introduction

For the assessment of ongoing and potential future changes in mean sea level (MSL) research into the observed variability and its causes remains a central challenge. There are two principal sources of data from which MSL changes and variability can be analysed. Satellite data from altimeters provide nearly global coverage but are concentrated over the open ocean and are available only from 1993 onwards. The altimetry data, in particular provides the possibility of analysing sea level variations of different regions from a grid of observations which is continuous in time and regularly in space. Many different areas have been analysed using this data. For example Cheng and Qi (2007) used altimetry data to analyse sea level in the South China Sea. They found a long-term trend with a rise of 11.3 mm/yr for the period 1993 – 2000, followed by a decreasing of 11.8 mm/yr for the period 2001 – 2005. Trends of the tropical Pacific and the Indian Ocean Islands where analysed by Church et al. (2006) using altimetry and tide gauge data. The authors found a rise of up to 30 mm/yr in the Western Pacific and the Eastern Indian Ocean for the period 1993 – 2001. Simultaneously a fall of up to 10 mm/yr was found in the Eastern Pacific and the Western Indian Ocean. Data from tide gauges are available for much longer periods but are mostly concentrated in coastal areas in the Northern Hemisphere. Often, data are also in-homogeneous because of relocation of tide gauges, water level changes due to local water works etc..

The longest records from tide gauges dating back until the eighteenth century are available from various cities, e.g. Amsterdam (The Netherlands), Liverpool (UK) or Brest (France). While the record of Amsterdam ends in 1925 the other two tide gauges are still active. The tide gauge of Amsterdam was analysed in van Veen (1945) and the analysis was updated in Spencer et al. (1988). Analyses of the Liverpool data can be found in Woodworth (1999a, 1999b) and for Brest analyses are provided in Wöppelmann (2006). Over time, data from more and more tide gauges became available. Using observations from globally distributed tide gauges, Jevrejeva et al. (2006) constructed an index time series of global mean sea level (GMSL) dating back until 1850. A similar time series was constructed by Church and White (2006) using the approach described in Church et al. (2004). However, contrary to the time series derived in Jevrejeva et al. (2006) data from both, tide gauges and satellites were used to construct the GMSL time series. Church et al. (2006) come to the conclusion that a significant acceleration occurred in the 20^{th} century. Jevrejeva et al. (2006) found a trend of 2.4 ± 1.0 mm/yr for the GMSL in the period 1993 – 2000, but showed that trends of similar height have occurred in earlier periods. Thus, they do not assume a significant acceleration in the last decades. Several authors used a modified version of the method introduced by Church et al. (2004). For example Ray and Douglas (2011) reconstructed a time series for 1900 – 2006 and a linear long-term trend of $1.70 \pm\ 0.24$ mm/yr is computed. The linear trend for the period of altimetry data is higher than 3 mm/yr, but the authors state that such a high trend was possibly also reached between 1935 and 1950. The reconstruction of Ray and Douglas (2011) shows higher values than the one of Church and White (2006) until about 1955. Differences are especially visible when comparing decadal trends. Considering 15-year running trends the reconstruction of Ray and Douglas (2011) suggests extraordinary high trends in the recent past, the one of Church and White (2006) does not. Another reconstruction, based on a modified method of Church et al. (2004), is shown in Hamlington et al. (2011). They reconstructed a time series for the GMSL for the period 1950 – 2009. The authors found a long-term trend of 1.97 mm/yr for this time period and for the period 1993 – 2009 they computed a trend of 3.22 mm/yr. The latter reconstruction is in good agreement with satellite data for the period from 1993 on, however the spacial distribution of the sea level reconstruction shows regional discrepancies compared to other reconstructions, especially for longer time periods. The number of analysis and results concerning this topic shows its difficulty. The main problem remains that decreasingly data is available when going back in time. The approach of Church et al (2004) and its modified versions act on the assumption that this drawback can be balanced with the nearly globally available altimetry data for a much shorter time period.

Despite of some potential issues related with such reconstructions such as the limited spatial coverage of tide gauge data in the earlier years or introduction of potential in-homogeneities when satellite data are taken into account, GMSL index time series provide a valuable tool for assessing long-term changes and variability of MSL on a global scale. On a regional scale, their explanatory power is however limited, as large deviations from the global mean may occur (e.g. Church et al., 2008). Such deviations may, for example, result from regional differences in ocean temperature changes and corresponding differences in ocean thermal expansion (e.g. Church et al., 2008), self-gravitational effects from melting ice sheets and glaciers (e.g. Mitrovica et al., 2001), or regional sea level changes resulting from long-term and large-scale changes in ocean and/or atmospheric circulation. The latter is associated with large-scale changes in atmospheric wind and pressure fields that will leave the GMSL unaffected but that may play an important role in explaining regional deviations from the global mean and regional sea level variability.

There are a number of studies analysing the effects of changes in atmospheric circulation on regional mean sea level (RMSL) and variability. For example, Heyen et al. (1996) and Hünecke and Zorita (2006) analysed detrended time series of winter MSL in the Baltic Sea and found that a large part of the observed variability could be explained with corresponding variations in mean sea level pressure (SLP). Yan et al. (2004) analysed the connection between the North Atlantic Oscillation (NAO) and MSL from several tide gauges along the North and Baltic Sea coast. Again, the authors found a considerable part of the sea level variability explained by changes in the atmospheric circulation, but further concluded that the correlation in winter is better compared to the rest of the year. Considering the area of the North Sea and the European Atlantic coast Jevrejeva et al. (2005) analysed the connection between the winter MSL of different tide gauges and the winter NAO-index for the last 150 years. They found that from 10% to 35% of the variance of the winter MSL can be explained with the NAO. They found a spatial pattern in the correlations with the highest values in the North East part of the North Sea. The same pattern was found by Wakelin et al. (2003) for the period 1955 – 2000 for both, observed and modeled MSL data. Woolf et al. (2003) included satellite data in their analysis. They found a high correlation between the winter NAO Index and the winter sea level of the North Sea, especially the German Bight. However, the considered time period is short, consisting of only 9 years. Kolker and Hameed (2007) analysed the contribution of the NAO to MSL variability at 5 tide gauges around the North Atlantic. The strongest relation was found for Cascais, Portugal. Here variations in the NAO account for about 80% of the inter-annual variability and about 80% of the observed long-term trend 1905 – 1993. The relationship between the NAO and MSL of the German Bight are analysed in Dangendorf et al. (2012). Analysing the period 1937 – 2008, the authors found that the NAO strongly influence the MSL in the month January to March in both, the variability and the long-term trend.

In this paper we concentrate on RMSL variability in the German Bight (the most South Eastern Bight of the North Sea, Fig. 1.1) caused by large-scale changes in the atmospheric circulation. There are a number of studies analysing past sea level changes in the North Sea and a fewer those in the German Bight. Based on UK tide gauge data Woodworth et al. (1999; 2009) as well as Haigh et al. (2009) analysed MSL changes along the UK coast. Both used the same approach namely defining a so called 'sea level index' based on the long available records. Woodworth et al. (2009) calculated a linear trend of 1.4 ± 0.2 mm/yr for the UK and Haigh et al. (2009) found that the trends in the English Channel vary between 0.8 – 2.3 mm/yr, both for the 20^{th} century. Woodworth et al. (2009) further showed that the estimated linear trends were consistent with other locations in the North Sea area. For the Netherlands a constant rise of 2.5 ± 0.6 mm/yr for the 20^{th} century is documented in Katsman et al. (2008). In none of the cases an acceleration in MSL could be found. For the German Bight, index time series of RMSL were provided by Wahl et al. (2010; 2011) and Albrecht et al. (2011). While the details of the approaches differ, both authors report mainly consistent results with respect to RMSL variability and long-term change. For the time period 1924 – 2008 a linear trend of 1.7 mm/yr was calculated. The authors found an accelerating rise in the recent past, however they found similar rises in earlier decades and thus do not assume an extraordinary acceleration in RMSL.

In this paper we use the most recent RMSL time series for the German Bight provided in Albrecht et al. (2011) to investigate to what extent observed variability and long-term changes may be associated with corresponding changes in large-scale atmospheric pressure fields. In contrast to previous studies we do not use data from individual tide gauges, but rely on a reconstructed index time series in which in-homogeneities are filtered out to a large extent (Albrecht et al., 2011). We also consider the effects of SLP by using the full information available without the limitations arising from preselecting certain atmospheric pressure patterns (such as NAO) which might be suboptimal in describing regional sea level responses. Moreover, we focus not solely on inter-annual variability but also investigate the extent to which the observed long-term trend in RMSL in the German Bight might be associated with corresponding changes in atmospheric circulation. To include other factors like thermal expansion or the effect of land-ice melting, the MSL of the North East Atlantic (NEA) is included as a proxy for large scale MSL changes as a second predictor.

The structure of the paper is as follows. In section 3.2 we will briefly introduce the data and methods used for our analysis. We will then derive an empirical relation between RMSL and the large-scale SLP field that will be used to analyse the extent to which observed RMSL variability and trend can be explained from corresponding variations in the SLP field (section 3.3.1). In section 3.3.2 the empirical model will be extended by additionally using the MSL from the North East Atlantic as a predictor. In doing so, we additionally account for effects that may arise from any large-scale changes in MSL caused by e.g. ocean thermal expansion or halosteric changes. In section 3.3.3 both models will be analysed regarding their robustness while a summary and discussion is presented in section 3.4.

3.2. Data and Methods

Data

The time series of RMSL in the German Bight we use was derived in Albrecht et al. (2011). In that work a time series representing annual RMSL was constructed from the tide gauge data at 15 different locations (Fig. 1.1) using two different methods. We will here use the reconstruction derived from the so called "EOF-approach" covering the time period 1924 – 2008. No correction for glacial isostatic adjustment (GIA) was applied, that is only relative sea level is considered. Some tide gauges cover a longer time period, the longest data available is from Cuxhaven ranging back until 1843. The usage of the shorter time period 1924 – 2008 is a result of the applied method ("EOF-approach") to reconstruct the RMSL. A detailed description of the data and construction method can be found in Albrecht et al. (2011).

For SLP we use the HadSLP2r data which is a near-real-time update of the HadSLP2 data from the Met Office Hadley Center for Climate Change. It contains monthly means of SLP for the period 1850 – 2009.[5] Observa-

[5]Note that the update from 2005 on is not homogenous with the time series from 1850 – 2004, but a comparison for our special use of the data (EOF-analysis, see section 3.3.1) showed no differences in the first three patterns and principal components of the EOF-Analysis.

tions from 2228 stations were interpolated on a $5° \times 5°$ grid. The data can be downloaded at `http://www.metoffice.gov.uk/hadobs/hadslp2/data/download.html`. A detailed description of the dataset can be found in Allan and Ansell (2006). Here we computed annual means from that data and used the grid points from 30°N to 75°N and 70°W to 20°E covering large parts of the North Atlantic.

For MSL in the NEA we use the data described in Jevrejeva et al. (2006). That is a sea-level reconstruction based on data from tide gauges in the NEA, downloaded from the Permanent Service for Mean Sea Level (PSMSL, `http://www.psmsl.org`). No inverted barometer correction was applied. The tide gauge data was corrected for local datum shifts and GIA. More details can be found in Jevrejeva et al. (2006). The time series consists of monthly means for the period 1850 – 2001. An update of this time series is in progress but was unavailable to us. In this paper only annual means are used.

Methods

An *EOF-analysis* was used to find the dominant patterns and corresponding time series of the SLP data. In an EOF-analysis the data is decomposed in a number of spatial patterns such that they are ordered by their explained variance. We start from our data vector $X \in \mathbb{R}^n$, $n \in \mathbb{N}$ that is multiplied with a rotational matrix $R \in \mathbb{R}^{n \times n}$. This multiplication results in a new vector $Y \in \mathbb{R}^n$, carrying the same information as the original vector X, but displayed with respect to a new basis. The matrix R is chosen such that its columns consist of the eigenvectors $(\mathbf{e}_1, \mathbf{e}_2, \dots, \mathbf{e}_n)$ of the covariance matrix of X. These eigenvectors are also referred to as patterns of X. They are orthonormal and ordered by the absolute values of the eigenvalues starting from the highest one. As described in von Storch and Zwiers (1998) the subspace spanned by multiplying X with the first eigenvector $\mathbf{e}_1$ is the one representing the largest part of the variance of the data X, $\mathbf{e}_2$ the second largest and so on. Thus the data X can be reduced representing a large part of the variance by using only the most important patterns $\mathbf{e}_1, \ldots, \mathbf{e}_k$ with $k \in \mathbb{N}$, $k < n$. In the following EOF-analysis is used to find the dominant modes of SLP variability over the North Atlantic and their temporal behaviour. The latter is described by the corresponding principal components (PCs) obtained from the EOF analysis.

The second concept we use is *linear regression*. Both simple and multiple linear regressions are used. As the simple linear regression is a special case of the multiple linear regression we will not explain it separately. Details about its concept can be found in von Storch and Zwiers (1998). The intention of a linear regression is to describe a random vector $\mathbf{y} = (y_1, \ldots y_n)$, $n \in \mathbb{N}$ with one or more other random vectors $\mathbf{x}_1 = (x_{11} \ldots, x_{1n}), \ldots, \mathbf{x}_k = (x_{k1} \ldots, x_{kn})$, $k \in \mathbb{N}$. This relationship is supposed to be linear in $\mathbf{x}_1, \ldots \mathbf{x}_k$. That is

$$y_i = a_0 + a_1 x_{1i} + \cdots + a_k x_{ki} + \epsilon_i,$$

for all $i = 1, \ldots n$. Here a_j, $j = 0, \ldots k$ are appropriate coefficients such that the residuals ϵ_i are minimised. In our case we use least squares for error minimisation. As we only use anomalies of our time series a_0 is equal to zero. If we use matrix notation, we thus solve the minimisation problem

$$||X\mathbf{a} - \mathbf{y}|| \rightarrow min,$$

with $|| \cdot ||$ denoting the euclidian norm, $X = (\mathbf{x}_1, \ldots, \mathbf{x}_k)$ and $\mathbf{a} = (a_1, \ldots, a_k)$. The solution of this problem is - as we are only considering real variables - the solution of the normal equation

$$X^T X\mathbf{a} = X^T \mathbf{y}. \tag{3.1}$$

This solution is unique if X is a regular matrix. We are aware that there are algorithms testing for each variable whether the regression error is reduced statistical significantly (e.g. stepwise regression). Details for these concepts can also be found in von Storch and Zwiers (1998). We anyhow use the direct solution of (3.1) as we have some a priori information about physical relations.

In section 3.3.2 we use a simple linear regression build up on the residuals of another regression. The mathematical correct solution would be to use a multiple linear regression with all variables instead of using two independent regressions. As above the reason for that is physically motivated. We assume that the additional parameter should not change the relationship of the ones before but just bring some additional information.

To measure the quality of our regression result compared to the original time series we use *correlation coefficients* and *explained variances*. As the correlation coefficient is not able to show systematic errors in constant additive differences and differences in proportionality the *index of agreement* is additionally calculated. This index and its properties are described in detail in Willmott (1981). It takes values between 0 and 1 and measures to what extent a model is free of error, where 1 connotes total agreement between model and observations and 0 total disagreement. For the case, where the long-term trend is included we will also use the magnitude of the long-term trends of both time series to evaluate the regression results. We mainly focus on the percentage of the explained trends, but consider the absolute deviation of the trends at the end of section 3.3.3. Throughout the whole paper 90% confidence levels are given with the linear trends.

3.3. Results

3.3.1. Relation between large-scale sea level pressure and the RMSL of the German Bight

Changes in large scale atmospheric pressure fields are associated with corresponding changes in ocean water levels. There are several effects: Increasing/decreasing atmospheric pressure will lower/rise the sea surface by about 1 cm per 1 hPa atmospheric pressure change (e.g. Weisse and von Storch, 2009). This effect is generally known as inverse barometric effect. Moreover, the atmospheric pressure gradients are directly linked to wind speed and direction and any change in large-scale atmospheric pressure patterns will be associated with corresponding changes in the wind climate. Eventually, changes in the prevailing wind direction may set up changes in prevailing ocean circulation with corresponding changes in sea surface height while higher/lower wind speed may be associated with increasing/decreasing coastal water levels.

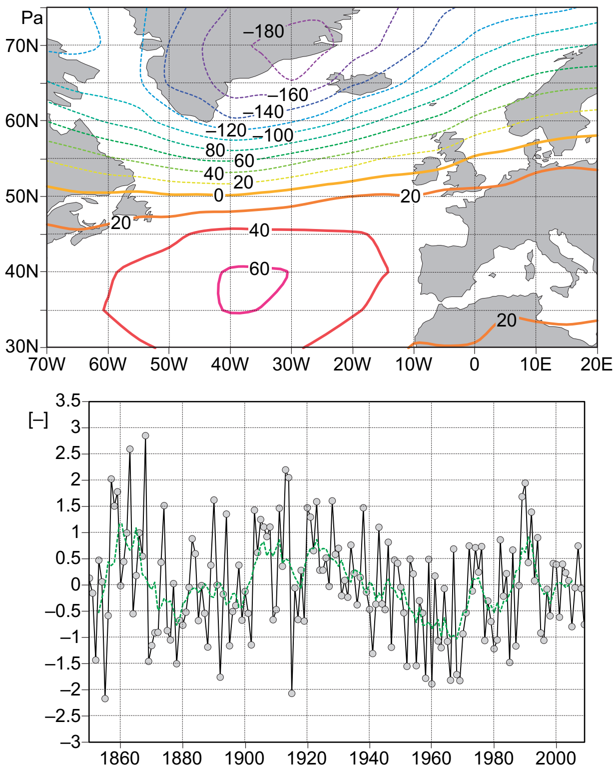

Figure 3.1. First EOF (top) and PC (bottom, black) for SLP data of the North Atlantic for the time period 1850 – 2009 (explained variance: 50.6%). The green curve in the lower panel is a 5-year running mean.

Any long-term change in large-scale atmospheric pressure fields may thus be associated with different regional changes in the MSL. In the following we elaborate on these effects for the German Bight. SLP fields from 30°N to 75°N and from 70°W to 20°E are used to represent the large scale atmospheric pressure fields over the North Atlantic. To identify the dominant modes of variability an EOF-analysis is performed (Figs. 3.1, 3.2 and 3.3). The leading three modes explain about 51%, 17%, and 11% of the observed variability. For higher EOFs explained variances are generally smaller than 6%. The first EOF pattern closely resembles the pattern of the so-called NAO; that is, a dipole with one pole centred over the Eastern part of Greenland and the other pole located in the Southern part of the analysis domain at about 20° longitude West of the Azores. Depending on sign, such a pattern is generally associated with westerly/easterly wind anomalies over the North Atlantic. The second and third EOF both resemble mono poles with either northerly/southerly wind anomalies or enhanced cyclonic/anticyclonic circulation over the North Sea respectively.

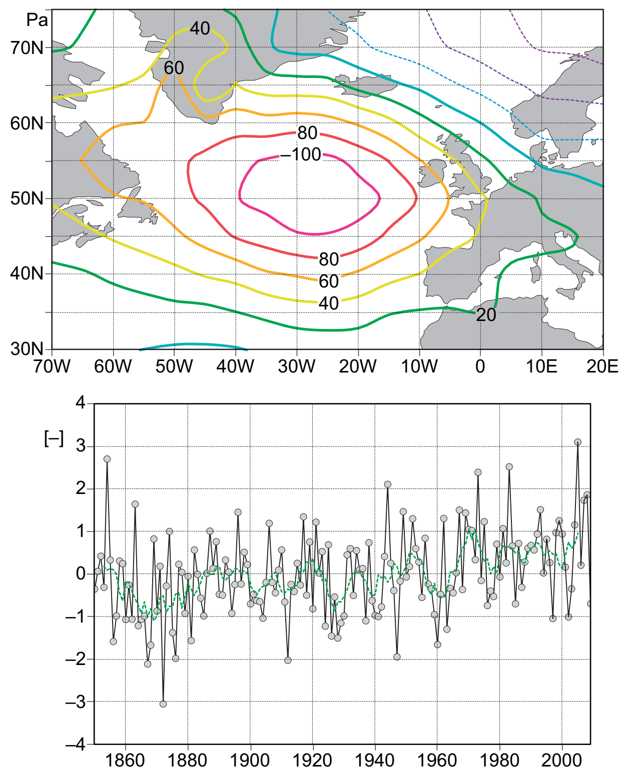

Figure 3.2. Second EOF (top) and PC (bottom, black) for SLP data of the North Atlantic for the time period 1850 – 2009 (explained variance: 16.75%). The green curve in the lower panel is a 5-year running mean.

A multiple linear regression is used (section 3.2) to derive a statistical relation between the RMSL in the German Bight and the corresponding SLP fields. Let $\mathbf{z}(t)$ be the time series of the RMSL and $\boldsymbol{\alpha}_1(t)$, $\boldsymbol{\alpha}_2(t)$, $\boldsymbol{\alpha}_3(t)$ be the PCs of the three leading EOFs of SLP, with t being the time from 1924 – 2001. The index "d" is used to denote the cases when detrended time series were used. In the following the regression is generally established for the detrended time series. This is done to ensure that the statistical relation not only reflects

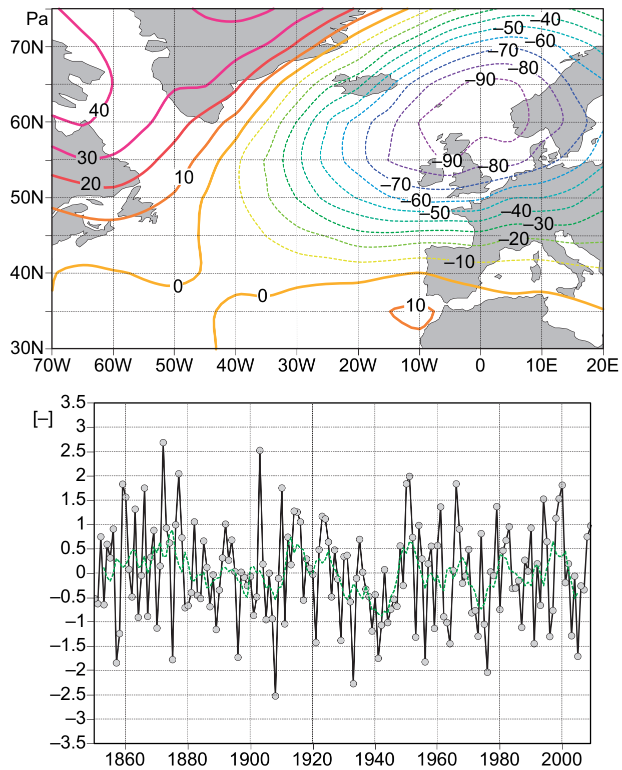

Figure 3.3. Third EOF (top) and PC (bottom, black) for SLP data of the North Atlantic for the time period 1850 – 2009 (explained variance: 10.88%). The green curve in the lower panel is a 5-year running mean.

common long-term trends in the time series but resembles the inter-annual and decadal variability. Subsequently the regression is applied to both the complete and the detrended time series as well. The latter shows how much of the variability in RMSL can be explained by corresponding SLP fluctuations while the other reveals how much of the observed trend in RMSL can be accounted for by corresponding long-term changes in atmospheric pressure fields. The regression can then be written as

$$\mathbf{z}_d(t) = a_1\boldsymbol{\alpha}_{1d}(t) + a_2\boldsymbol{\alpha}_{2d}(t) + a_3\boldsymbol{\alpha}_{3d}(t) + \boldsymbol{\epsilon}_1(t), \tag{3.2}$$

with a_1, a_2 and a_3 associated coefficients such that the error $\boldsymbol{\epsilon}_1$ is minimised (see section 3.2). Here RMSL is denoted in meters and while the PCs are dimensionless the coefficients a_1, a_2, a_3 are carrying the units.

Fitting this multiple regression model for the time period 1924 – 2001 results in coefficients of $a_1 = 0.0123$ m, $a_2 = 0.0227$ m and $a_3 = 0.0264$ m. This suggests that the second and the third EOF generally have more power in explaining sea level variations in the German Bight, a result that is consistent with wind field anomalies associated to the EOF patterns.

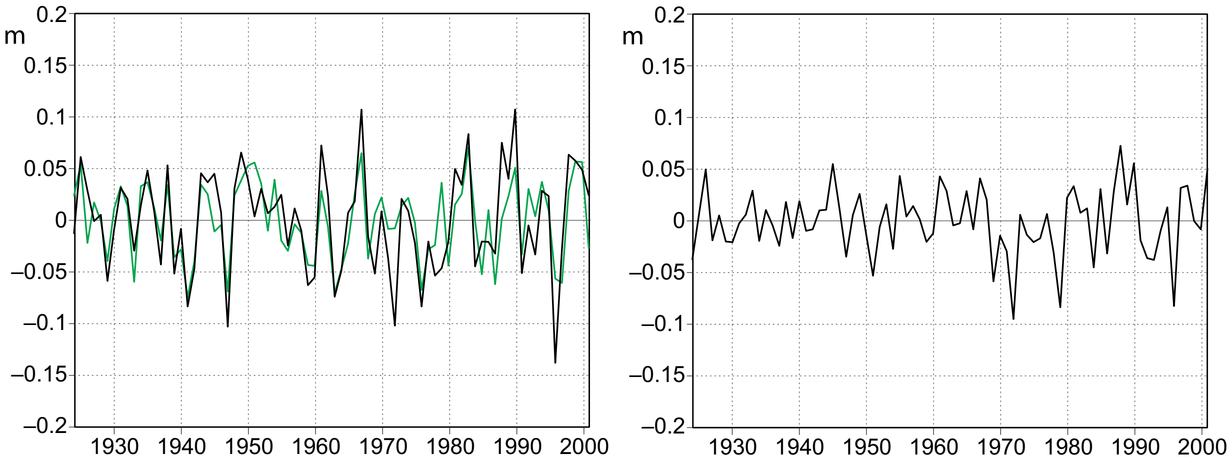

Figure 3.4. Left: Comparison of the RMSL of the German Bight without long-term trend ($\mathbf{z}_d(t)$, black) and the regression result of (3.2) applied to detrended data ($\tilde{\mathbf{z}}_d(t)$, green). Right: Residuals of the RMSL and the regression result ($\mathbf{z}_d(t) - \tilde{\mathbf{z}}_d(t)$).

The RMSL from applying this model to the detrended time series is referred to as $\tilde{\mathbf{z}}_d(t)$. A comparison of $\tilde{\mathbf{z}}_d(t)$ and $\mathbf{z}_d(t)$ and the associated residuals $\mathbf{z}_d(t) - \tilde{\mathbf{z}}_d(t)$ is shown in Fig. 3.4.

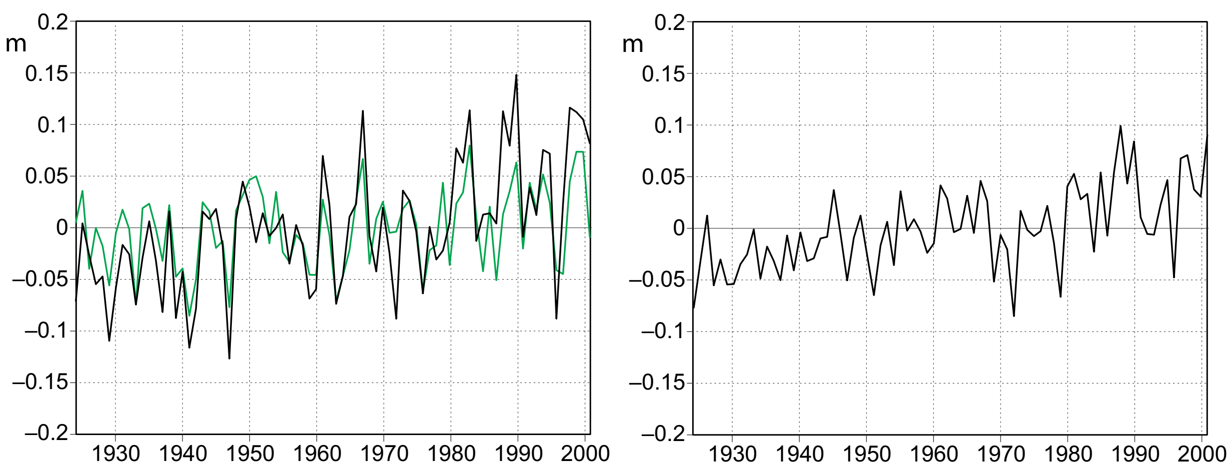

Figure 3.5. Left: Comparison of the RMSL of the German Bight ($\mathbf{z}(t)$, black) and the regression result of (3.2) applied to data with long-term trend included ($\tilde{\mathbf{z}}(t)$, green). Right: Residuals of the RMSL and the regression result ($\mathbf{z}(t) - \tilde{\mathbf{z}}(t)$).

The correlation coefficient between the two time series is 0.73 corresponding to an explained variance of 53%. The index of agreement has a value of 0.85. While in general a reasonable agreement is inferred, some problems are obvious in reproducing the observed RMSL in the 1970s. Here the residuals show relatively high values of up to -0.09 m. The RMSL time series declines in 1971 and rises extraordinary high in the following 20 years. The linear trend from 1971 to 1990 is about 6.7 mm/yr which is high above the average of all 20-year trends of 1.6 mm/yr. This exceptionally high decadal trend is also visible in the time series of the RMSL with the long-term trend subtracted and is obviously not associated with changes in the atmospheric pressure fields.

We now apply the regression model to the full time series of the PCs from SLP EOFs; that is, with the long-term trend included. We call the resulting time series $\tilde{\mathbf{z}}(t)$. A comparison of $\tilde{\mathbf{z}}(t)$ and $\mathbf{z}(t)$ and their residuals $\mathbf{z}(t) - \tilde{\mathbf{z}}(t)$ is shown in Fig. 3.5. The correlation coefficient between the two time series is 0.76 for the time period 1924 to 2001 corresponding to an explained variance of 58% rather comparable to that obtained from applying the model to the detrended data. The index of agreement has a value of 0.82 in this case. The long-term trend of $\tilde{\mathbf{z}}(t)$ has a value of 0.5 ± 0.2 mm/yr for the time period 1924 to 2001 compared to 1.5 ± 0.3 mm/yr which is the linear trend of $\mathbf{z}(t)$. That is about 33% of the linear trend in RMSL in the German Bight can be accounted for by corresponding long-term changes in the large-scale SLP field. As for the comparison of $\tilde{\mathbf{z}}_d(t)$ and $\mathbf{z}_d(t)$, the high decadal trend from 1971 to 1990 is obvious and not associated with corresponding variations in SLP.

3.3.2. Extension of the Regression

The results from our regression analysis suggest that long-term changes in large scale atmospheric pressure fields had a substantial effect on observed changes in RMSL. However, there are other factors influencing the RMSL, e.g. thermal expansion or the effect of land-ice melting. The latter will have influences on large scale sea levels as well. In the following we use MSL from the NEA as a proxy for such effects. The data used for NEA MSL are described in section 3.2 and the time series is shown in Fig. 3.6.

The regression model is extended the following way: As we aim at improving the regression derived in the previous section, in the following only the residuals $\mathbf{z}(t)-\tilde{\mathbf{z}}(t)$ are considered[6]. The time series for NEA MSL is referred to as $\mathbf{z}_{na}(t)$. As in section 3.3.1 detrended time series are denoted with the index "d" and t is again the time from 1924 to 2001. We thus conduct the simple linear regression

$$(\mathbf{z}(t) - \tilde{\mathbf{z}}_d(t)) = a_4\mathbf{z}_{nad}(t) + \boldsymbol{\epsilon}_2(t). \tag{3.3}$$

The coefficient a_4 is chosen such that the error $\boldsymbol{\epsilon}_2$ is minimised (see section 3.2). In this regression $(\mathbf{z}(t) - \tilde{\mathbf{z}}_d(t))$ and $\mathbf{z}_{nad}(t)$ both have the units meters and the regression coefficient a_4 is thus dimensionless.

Fitting the model to the data yields a regression coefficient of 0.48. As an indication on whether or not this regression is reasonable we computed the correlation coefficient between $(\mathbf{z}(t) - \tilde{\mathbf{z}}_d(t))$ and $\mathbf{z}_{nad}(t)$ which is about 0.3. The latter is significantly different from zero at the 99% confidence level when using a t-test statistics.

Our new approximation of the RMSL in the German Bight $\tilde{\tilde{\mathbf{z}}}(t)$ is thus the sum from both regressions (3.2) and (3.3)

$$\tilde{\tilde{\mathbf{z}}}_d(t) = \tilde{\mathbf{z}}_d(t) + a_4\mathbf{z}_{nad}(t) = a_1\boldsymbol{\alpha}_{1d}(t) + a_2\boldsymbol{\alpha}_{2d}(t) + a_3\boldsymbol{\alpha}_{3d}(t) + a_4\mathbf{z}_{nad}(t). \tag{3.4}$$

As in the previous section we first apply our model to the detrended time series (Fig. 3.7). A correlation coefficient of 0.79 is obtained corresponding to an explained variance of about 62% which means that by including MSL

[6] The linear trend is calculated as the slope of the linear regression between the time series and the time. Re-sorting of the sums shows that it does not matter whether we consider the detrended residuals $(\mathbf{z}_d(t) - \tilde{\mathbf{z}}_d(t))$ or the residuals with trend and subtract the trend afterwards $((\mathbf{z}(t) - \tilde{\mathbf{z}}_d(t)))$.

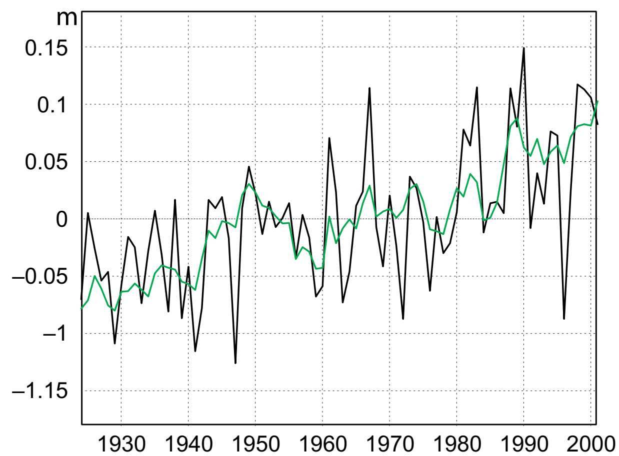

Figure 3.6. Time series of the RMSL of the German Bight (black) and the MSL of the NEA (green) for the time period 1924 – 2001.

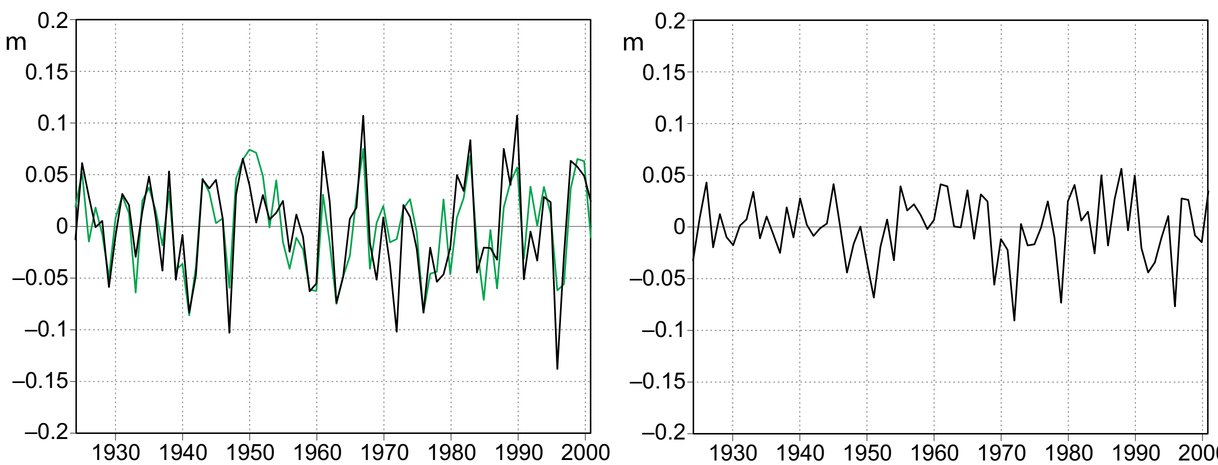

Figure 3.7. Left: Comparison of the RMSL of the German Bight without long-term trend ($\mathbf{z}_d(t)$, black) and the regression result of (3.4) applied to detrended data ($\tilde{\tilde{\mathbf{z}}}_d(t)$, green). Right: Residuals of the RMSL and the regression result ($\mathbf{z}_d(t) - \tilde{\tilde{\mathbf{z}}}_d(t)$).

changes from NEA the explained variance of detrended RMSL changes in the German Bight increased by about 9%. The index of agreement is 0.88 and thus slightly higher than without the NEA time series.

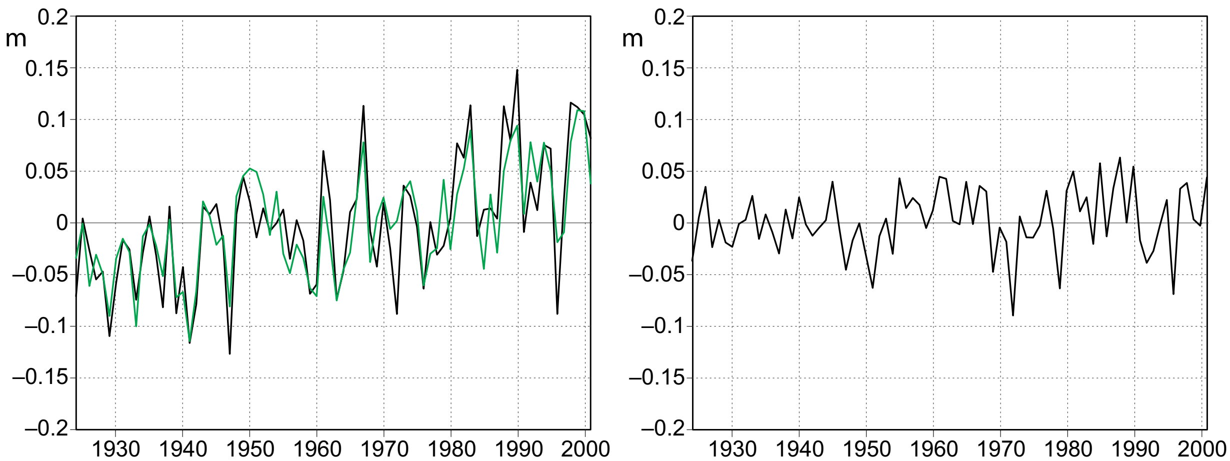

Figure 3.8. Left: Comparison of the RMSL of the German Bight ($\mathbf{z}(t)$, black) and the regression result of (3.4) applied to data with long-term trend included ($\tilde{\tilde{\mathbf{z}}}(t)$, green). Right: Residuals of the RMSL and the regression result ($\mathbf{z}(t) - \tilde{\tilde{\mathbf{z}}}(t)$).

Next we again applied the model fitted to detrended data to the full data set including the trend. This way inferences about the models capability in reproducing the observed trend in RMSL in the German Bight can be obtained. Results are shown in Fig. 3.8. The time series obtained from our simple statistical approach and that for the RMSL in the German Bight share a correlation coefficient of 0.86 corresponding to an explained variance of 74%. This corresponds to an increase in explained variance of about 16% compared to the regression model in which sea level effects from the NEA were excluded. The index of agreement increases to a value of 0.92 indicating a reduction in systematic errors. For the period 1924 – 2001 the linear trend obtained from the regression based on SLP fields and NEA MSL is about 1.3 ± 0.3 mm/yr compared to about 1.5 ± 0.3 mm/yr obtained directly from the RMSL time series of the German Bight for the same period. In other words, about 87% of the observed long-term trend in German Bight RMSL can be associated with corresponding changes in the large-scale SLP and MSL fields in the NEA. Compared to the model that only uses SLP as predictor, the latter represents an improvement of about 53%.

From introducing MSL of the NEA as an additional predictor, our model further improves the representation of inter-annual and decadal variability. We thus tested the predictive skill of a similar regression model using only NEA as predictor. That is to conduct a simple linear regression with the RMSL of the German Bight on the one side and the MSL of the NEA on the other side. Again the linear trend was subtracted before the regression coefficient was computed and then this coefficient was applied to the MSL of the NEA with long-term trend included. For the reconstruction from 1924 to 2001 the explained variance is 50% and the linear long-term trend is 2.2 ± 0.2 mm/yr compared to 1.5 ± 0.3 mm/yr of the RMSL, that is the model overestimates the trend by about 47%. The index of agreement is 0.84 and thus somewhat smaller compared to the model that uses both, SLP and NEA as predictors.

While there is considerable improvement in reconstructing observed long-term trends in RMSL when sea level variations in the NEA are taken into account, the problems in reconstructing decadal variations in the 1970s remain. Several other factors potentially being responsible for theses changes were investigated: Indices for global mean sea level (GMSL) (Church and White, 2006; Jevrejeva et al., 2006) do not show pronounced decadal variations around the 1970s. Similarly, anomalies in local thermal expansion can be excluded as a long-term temperature time-series from Helgoland (the central island in the German Bight, see Fig. 1.1, Wiltshire and Manly, 2004) does not show a corresponding behaviour either. Potential effects caused by changes in the ocean circulation were analysed using data from a high-resolution tide-surge hindcast for the North Sea driven by observed (reanalysed) wind and pressure patterns for the period 1948 – 2004 (Weisse and Plüß, 2006). As the sea level data obtained from this hindcast do not show a corresponding high trend from 1971 – 1990 changes in the wind driven ocean circulation might be excluded as well. Eventually, data inhomogeneities can not fully be excluded but remain highly unlikely to be responsible for the strong decadal changes in the 1970s as the signal is visible not only in German but also in Danish (e.g. Esbjerg) or Dutch (e.g. Delfzijl, Den Helder) tide gauges. A convincing explanation is missing so far.

3.3.3. Cross-Validation

So far the regression models considered were fitted to the entire detrended data set. In the following we elaborate on the robustness of these regression models by using a two-fold cross validation approach: The 78 years of data were split

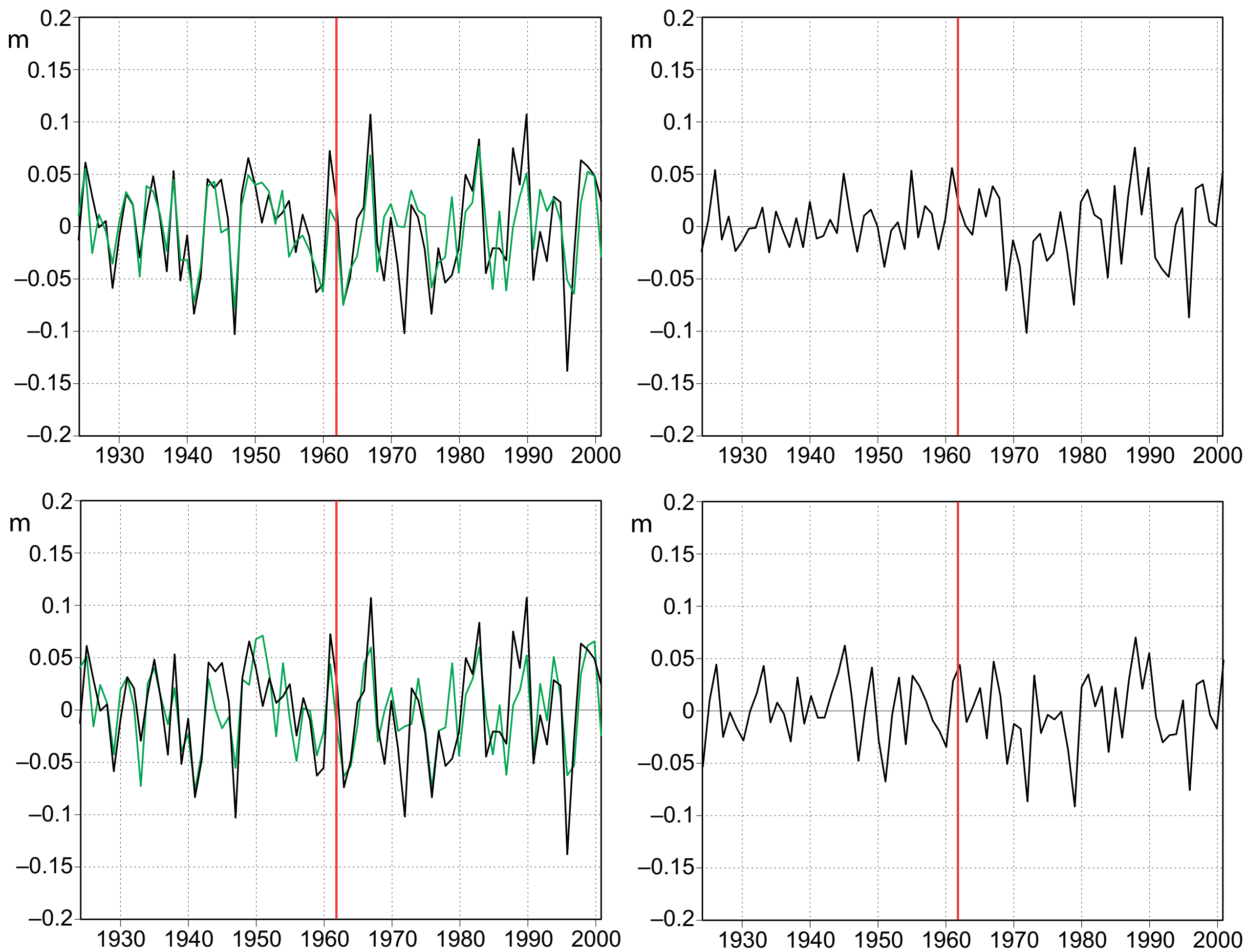

Figure 3.9. Top [left]: Comparison of the RMSL of the German Bight without long-term trend ($\mathbf{z}_d(t)$, black) and the regression result of (3.2) from 1924 – 1962 applied to detrended data ($\tilde{\mathbf{z}}_d(t)$, green) and [right] their residuals ($\mathbf{z}_d(t) - \tilde{\mathbf{z}}_d(t)$). Bottom: Analogue for the regression result from 1963 – 2001.

into two parts (1924 – 1962 and 1962 – 2001) of equal size. The models were then both fitted to one part of the data and compared to the other.

We first performed the cross-validation for the regression model using only SLP as predictor (equation (3.2), in the following referred to as SLP model). The coefficients are $a_1 = 0.0146$ m, $a_2 = 0.0285$ m and $a_3 = 0.0199$ m and $a_1 = 0.0104$ m, $a_2 = 0.0143$ m and $a_3 = 0.0339$ m when fitted to the first and the second part of the detrended data, respectively. These coefficients are rather similar to those obtained from fitting the regression model to the detrended data over the entire period. They retain the relative weights of each SLP pattern in the regression with the second and third patterns providing larger contributions than the first pattern.

Time series and residuals obtained from applying the model to the detrended data are shown in Fig. 3.9. The correlation coefficients of the cross validation are 0.72 for the time period 1924 – 1962 using the regression fitted to the period 1963 – 2001 and 0.68 for the time period 1963 – 2001 using the regression fitted to the period 1924 – 1962. Thus the explained variance is 52% in the first case and 46% in the second. The index of agreement for the period 1924 – 1962 is 0.84 and for 1963 – 2001 it is 0.79. In both periods the numbers are generally slightly smaller than for the entire period 1924 – 2001, where the correlation coefficient is 0.73 and the index of agreement 0.85.

We subsequently applied the SLP regression model to the data including the long-term trend using the cross validation approach described above. Time series and residuals are shown in Fig. 3.10. In this case the correlations of the cross validation are 0.69 for the time period 1924 – 1962 using the regression fitted to the period 1963 – 2001 and 0.70 for the time period 1963 – 2001 using the regression fitted to the period 1924 – 1962. Here, in both cases the correlations are slightly lower than 0.76, which is the value for the entire time period, but comparable for both validation periods. The explained variances for the validation periods are 48% for 1924 to 1962 and 49% for 1963 to 2001. The index of agreement for the period 1924 – 1962 is 0.82 and 0.79 for the period 1963 – 2001. These values are close to or even equal 0.82, which is the index of agreement for the whole time period 1924 – 2001.

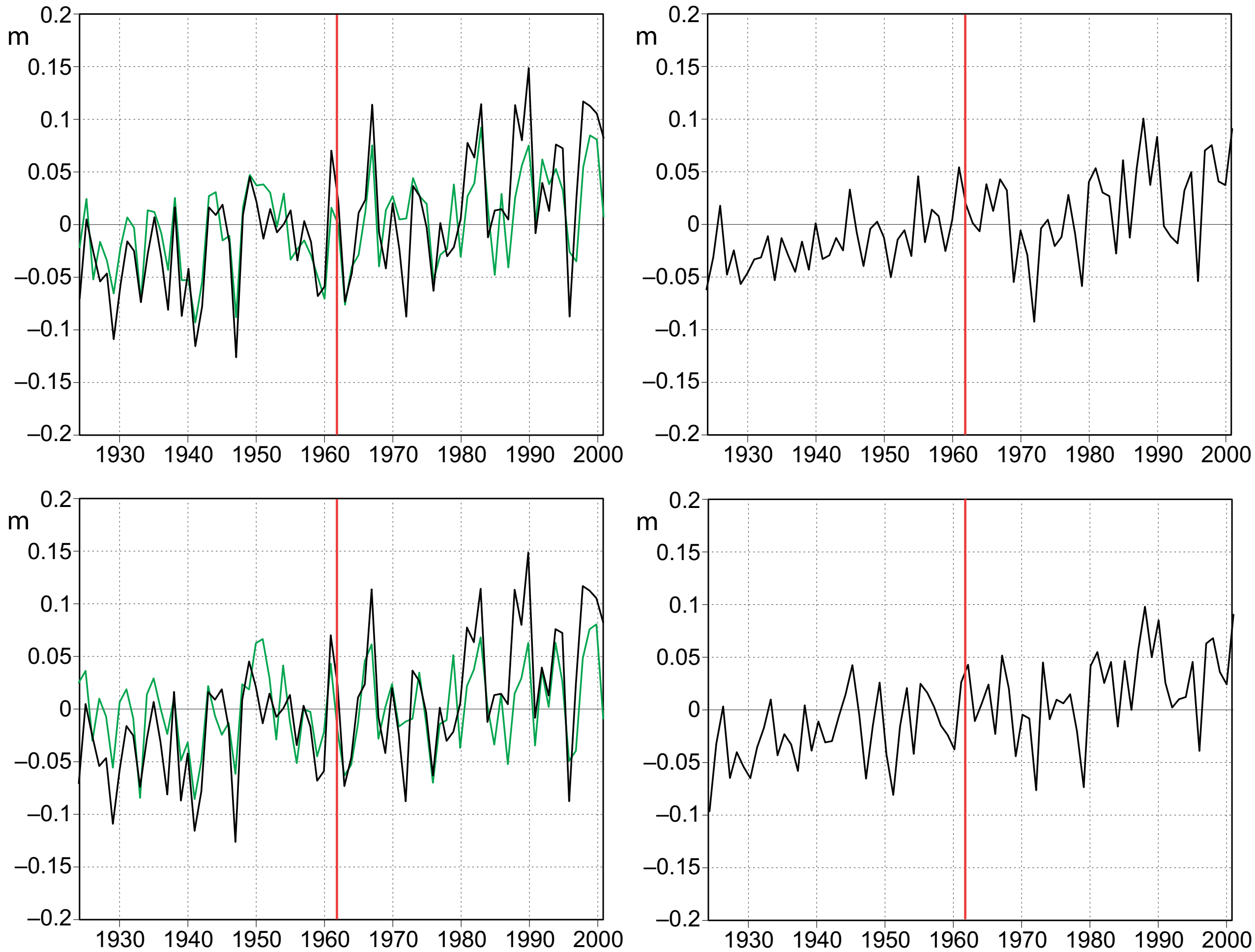

Figure 3.10. Top [left]: Comparison of the RMSL of the German Bight ($\mathbf{z}(t)$, black) and the regression result of (3.2) from 1924 – 1962 ($\tilde{\mathbf{z}}_d(t)$, green) and [right] their residuals ($\mathbf{z}(t) - \tilde{\mathbf{z}}(t)$). Bottom: Analogue for the regression result from 1963 – 2001.

Considering the data including trends, for the period 1924 to 1962 the regression result has a trend of 0.1 ± 0.7 mm/yr compared to 1.5 ± 0.8 mm/yr of the RMSL. Thus, the regression explains only 7% of the observed long-term trend. For the time period 1963 to 2001 the regression result has a trend of 1.1 ± 0.7 mm/yr compared to 2.6 ± 1.0 mm/yr derived from the observations, which corresponds to 42%. The ability of the statistical model in reproducing the observed long-term trend thus depends on the time period, which calls for a limited skill in using the model for prediction. However, the 90% confidence levels overlap in both cases. It should be noted that long-term trend estimates of a time series can change substantially when in- or excluding the first/last time step. If we e.g. consider the time period 1925 – 1961 the linear trend of the observed RMSL is 1.3 ± 0.9 mm/yr and the one of the regression result 0.4 ± 0.8 mm/yr - this complies with 31%. Further, the index of agreement for this time period takes the same value as for the whole time period. That is the systematic error for this period is not higher than for the whole time period.

The ability of the model to predict observed trends seems to depend strongly on the considered time period. However, we can conclude that there are time periods where the SLP contributes a non-negligible part to the long-term trend of the RMSL.

We now consider the model including both predictors: SLP and MSL of the NEA (equation (3.3), in the following referred to as SLP-NEA model). We conduct a second cross-validation using the residuals of the regressions with only SLP as described in section 3.3.2 (Fig. 3.9, note footnote 6). The statistical relevance of the additional parameter (i.e. MSL of the NEA) is analysed by considering the correlation coefficients of the residuals of the SLP model and the MSL of the NEA for both cases. The correlation coefficients are significantly different from zero at the 99% confidence level. The regression coefficients are $a_4 = 0.16$ for 1924 to 1962 and $a_4 = 0.86$ for 1963 to 2001 and thus differ substantially for the different time periods.

We again first apply the coefficients to the detrended time series. The results are shown in Fig. 3.11. The correlation coefficients are 0.74 for the time period 1924 – 1962 using the regression fit for 1963 – 2001 and 0.70 for the time period 1963 – 2001 using the regression fit for 1924 – 1962. An improvement compared to the SLP model in the explained variance can be seen for the validation period 1924 to 1962, which is 55%. Whereas it is slightly reduced for the period 1963 to 2001 to the value of 49%.[7] The index of agreement is 0.85 for the period 1924 – 1962 and 0.80 for 1963 – 2001. These numbers are very close to those

[7]This reduction is a result of the decision to use a physical motivated model. If we would e.g. use stepwise regression the correlation coefficient would of course always be higher adding an additional statistical significant variable.

of the SLP model, that is the systematic error does not change substantially including the MSL of the NEA. Considering the numbers above, the conclusion that the contribution of the MSL of the NEA to the inter-annual variability is small compared to the contribution of the SLP remains for the cross validation.

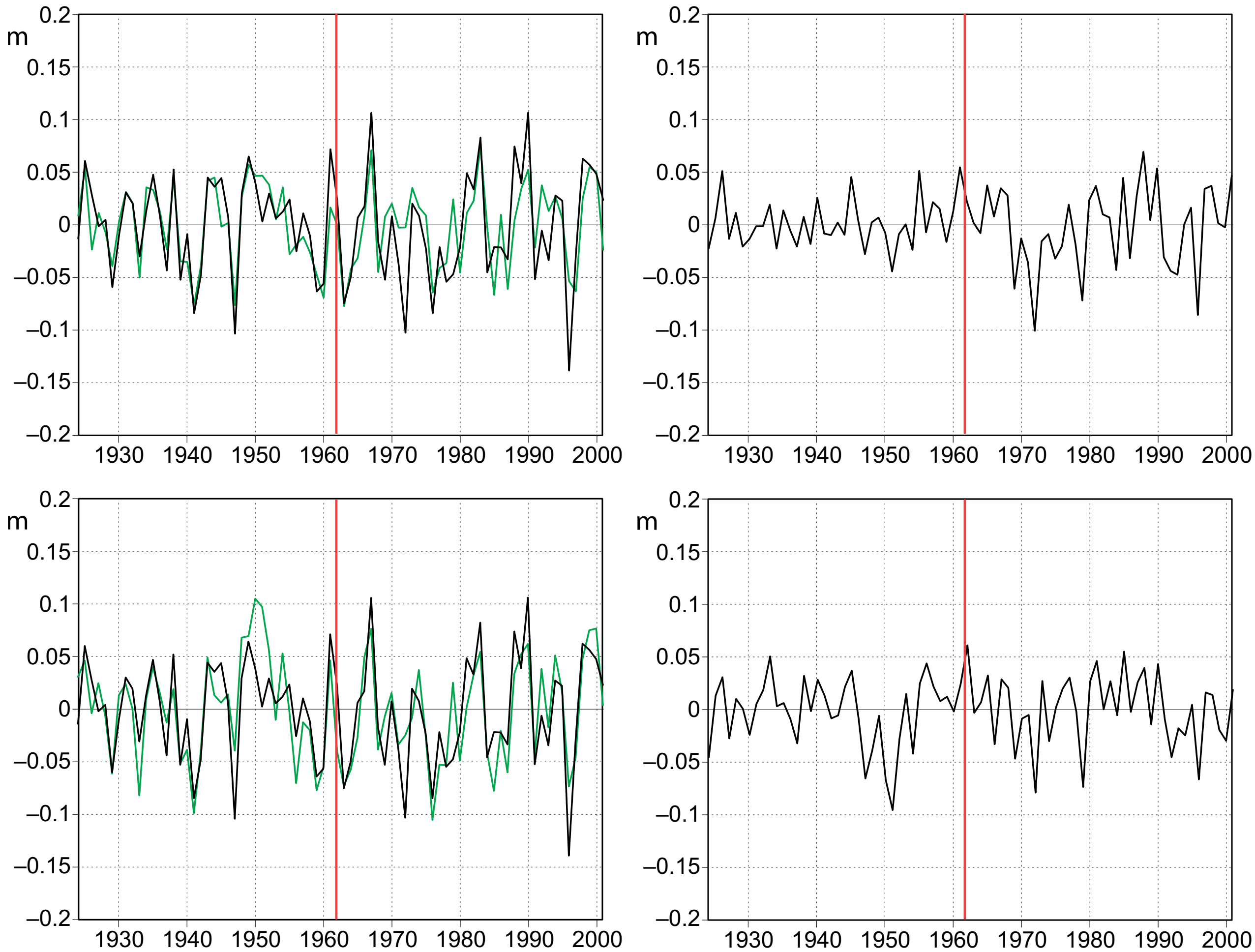

Figure 3.11. Top [left]: Comparison of the RMSL of the German Bight without long-term trend ($\mathbf{z}_d(t)$, black) and the regression result of (3.4) from 1924 – 1962 applied to detrended data ($\tilde{\tilde{\mathbf{z}}}_d(t)$, green) and [right] their residuals ($\mathbf{z}_d(t) - \tilde{\tilde{\mathbf{z}}}_d(t)$). Bottom: Analogue for the regression result from 1963 – 2001.

Next, we apply the coefficients to the data with trends included. The results can be seen in Fig. 3.12. The correlation coefficient for the period 1924 – 1962 resulting from the model fit to 1963 – 2001 is 0.78 and for the period 1963 – 2001 resulting from the fit from 1924 – 1962 is 0.74. In this case the explained variances in the validation periods are 61% for 1924 to 1962 and 55% for 1963 to 2001 which is an improvement in both cases compared to the SLP model. The index of agreement for the period 1924 – 1962 is 0.87 and for 1963 – 2001 it is 0.83. These values are not as high as 0.92, which is the index of agreement for the whole time period, but in both cases the values are higher than in the SLP model.

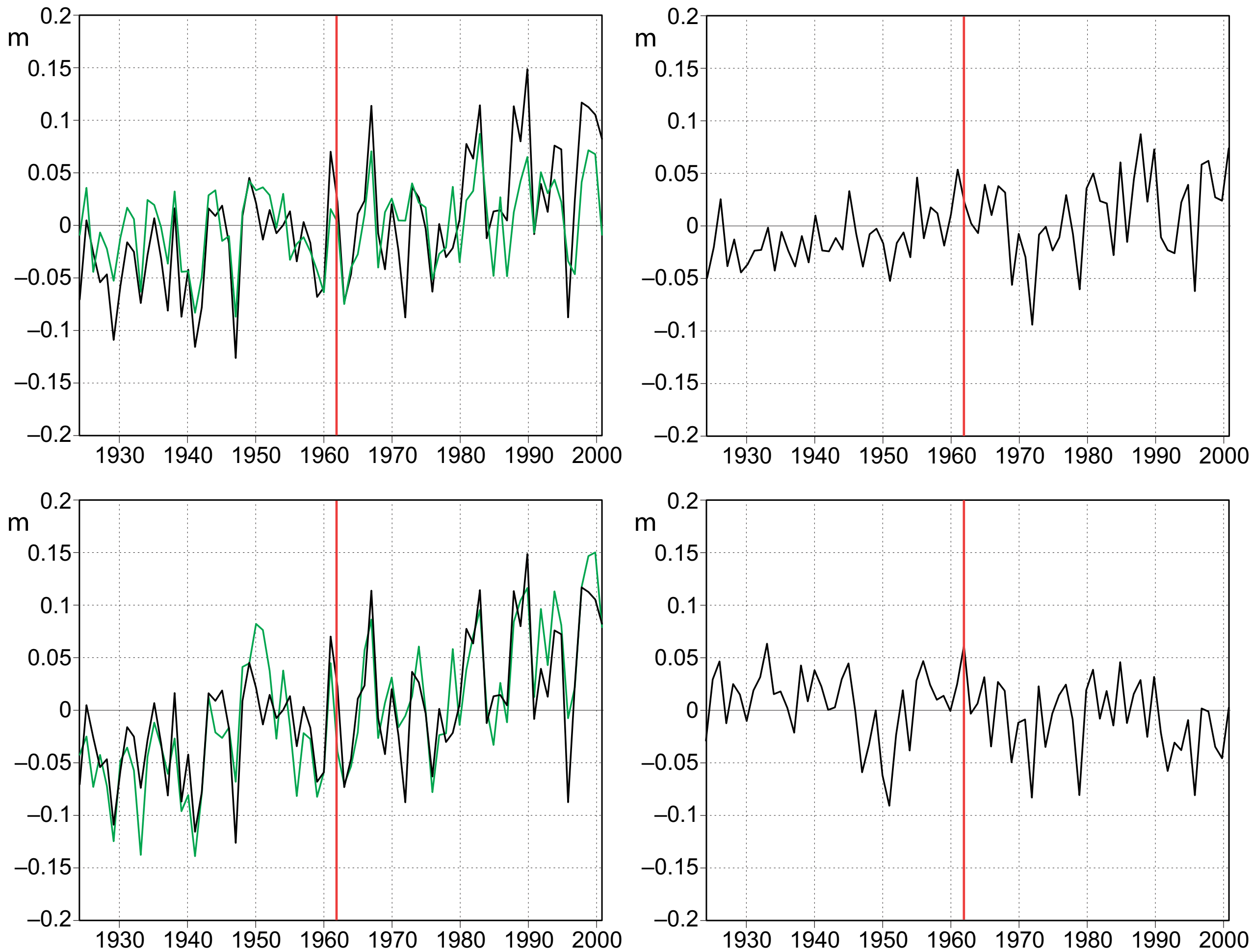

Figure 3.12. Top [left]: Comparison of the RMSL of the German Bight ($\mathbf{z}(t)$, black) and the regression result of (3.4) from 1924 – 1962 ($\tilde{\tilde{\mathbf{z}}}(t)$, green) and [right] their residuals ($\mathbf{z}(t) - \tilde{\tilde{\mathbf{z}}}(t)$). Bottom: Analogue for the regression result from 1963 – 2001.

For the period 1924 to 1962 the model resulting from the regression period 1963 to 2001 leads to a trend of 1.8 ± 0.9 mm/yr and the RMSL has a trend of 1.5 ± 0.8 mm/yr. That is the model overestimates the trend by about 20%. For the time period 1963 to 2001 the regression model for the period 1924 to 1962 shows a a trend of 1.5 ± 0.8 mm/yr compared to the observed trend of 2.6 ± 1.0 mm/yr. That is about 58% of the observed long-term trend in RMSL in the German Bight are associated with corresponding changes in the large-scale atmospheric pressure fields and sea level changes in the NEA. As with the SLP model the explained trends are very different for the two time periods. However, again the 90% confidence levels overlap. These results show that the MSL of the NEA certainly explains a great part of the long-term trend. Especially in the time period 1924 to 1962 the MSL of the NEA clearly is the main predictor of the long-term trend. Likewise, as in the SLP model a stability can be seen in the explained variances. They are about 50% to 60% in all cases and thus have only few variability for the different time periods.

As in the SLP model the values of the explained variances are certainly lower than for the whole time period. However, there is only a small reduction in the SLP contribution to the explained variances. It can be seen that the SLP is accountable for about 50% of the inter-annual variability in all considered validations. The index of agreement is also somewhat lower for the validation periods than for the whole time period. However, the values of 0.83 and 0.87 are still high and show that the systematical errors in the validation periods do not predominate. The predicted long-term trends also show larger differences compared to the observed values as when taking the entire time period into account. We still conclude that the MSL of the NEA is the main contributer to the linear long-term trend. However, the percentage of the predicted trend varies considerably within the validation periods.

A special issue of our work is to analyse the ability of trend prediction with the above model. So far, we analysed to what magnitude SLP and the MSL of the NEA influence the long-term trend of the RMSL. Our analysis showed that both factors contribute an important part to the linear trend, with the MSL of the NEA explaining the main part. Next, we want to analyse the magnitude of the errors for trend prediction using the SLP model and the SLP-NEA model. In the cross-validation used, two different regressions were performed and analysed. It is difficult to estimate the error made in trend prediction from these two regressions. For that reason we conduct another cross-validation. We cut 39 years of the time series of the RMSL - starting with the first 39 values and then incrementing the starting year by one in each step. That is, first 1924 – 1962 are cut off, then 1925 – 1963, and so on. The regression of section 3.3.1 and section 3.3.2 is then performed with the 39 years left in each case. That is for 1963 – 2001 in the first case, for 1924 and 1964 – 2001 in the second and so on. This result is then applied to the cut off 39 years.

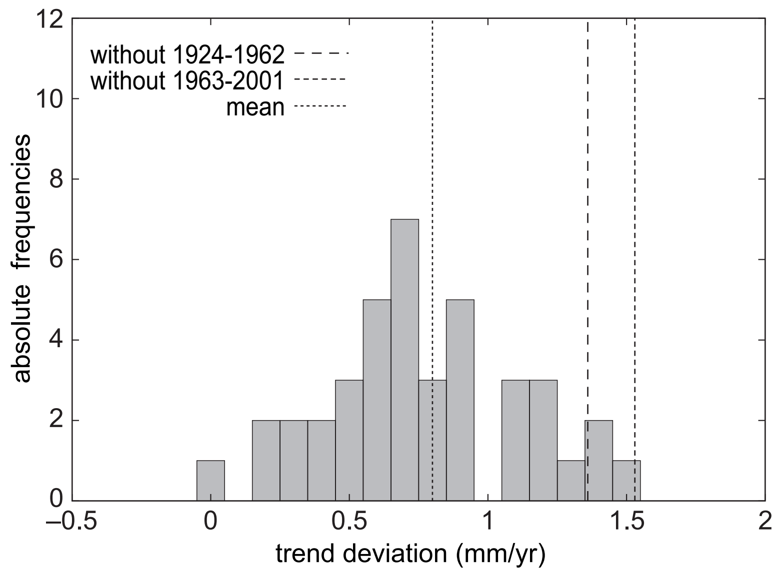

Figure 3.13. Distribution of the deviations of the 39-year SLP-model trends and the observed trends of the computed RMSL $(abs(tr(\tilde{\mathbf{z}}(t)) - tr(\mathbf{z}(t))))$.

This leads to a pool of 40 prediction periods of the same length with the two predictions considered above contained within this set. In each case we can compare the 39-year trend of the computed RMSL, with the predicted trend of the SLP model or the SLP-NEA model respectively. The distributions of the deviations can be seen in Fig. 3.13 and Fig. 3.14. We consider only absolute deviations, thus do not distinguish between under- and overestimation of the trend. However, we should mention that all projected trends underestimate the observed value in the SLP model, whereas in the SLP-NEA model both, under- and overestimation occur. The mean deviation to the observed trend is 0.8 mm/yr using the SLP model and 0.5 mm/yr with the SLP-NEA model. That is the additional variable is reducing the mean deviation. In Fig. 3.13 and

Fig. 3.14 the two above considered cases are specially marked. They are both at the margin of the distribution in the SLP model. In the SLP-NEA model the deviation of 1.1 mm/yr for the projection of the period 1963 to 2001 is at the margin of the distribution. Only one deviation has a higher value. That is the deviations in the above considered cross-validation seem not to be representative in most cases, but they are in general expected to be smaller.

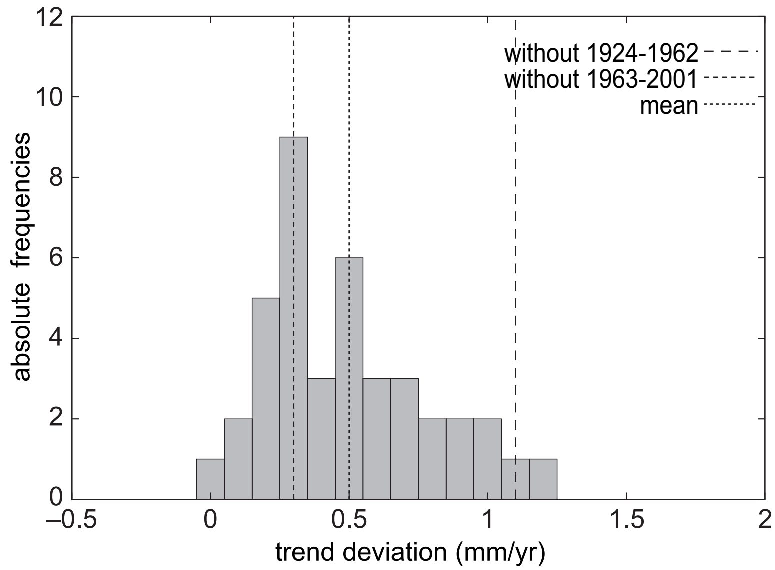

Figure 3.14. Distribution of the deviations of the 39-year SLP-NEA-model trends and the observed trends of the computed RMSL $(abs(tr(\tilde{\mathbf{z}}(t)) - tr(\mathbf{z}(t))))$.

3.4. Discussion

In this study, we developed an empirical model for predicting regional sea level changes associated with corresponding changes in large-scale atmospheric pressure and sea level fields. The results show that the SLP is the main factor to reconstruct and predict inter-annual variability, whereas the NEA time series is mostly accountable for trend reconstruction and prediction. However, the SLP also makes an important contribution to the long-term trend, but the contribution varies with time. For the time period 1924 to 2001 SLP explains 58% of the inter-annual variability and 33% of the long-term trend. The MSL of the NEA adds another 16% to the inter-annual variability and 53% to the long-term trend, such that using both variables 74% of the inter-annual variability are explained and 87% of the long-term trend. The index of agreement rises from 0.82 to 0.92 including the MSL of the NEA, thus also the systematic errors are reduced. Cross-validating the regression model approves that the SLP is mainly responsible for inter-annual variability and MSL of the NEA for the long-term trend. The explained variances are about 50% to 60% in all considered cases, whereas the main part comes from the SLP. The index of agreement varies from 0.79 to 0.87, that is systematic errors do not predominate. The relative contribution of the explained trends is quite different for both prediction periods. The SLP-NEA model overestimates the observed trend by about 20% for the period 1924 to 1962 and explains 58% for the period 1963 to 2001. However, the statement that an important part of the trend of the RMSL can be determined by the SLP and the MSL of the NEA remains valid. It is difficult to estimate the error made in trend prediction from these two numbers. For that reason we addressed this topic separately. An analysis of 40 different projections - all of the length of 39 years - leads to a mean deviation of 0.8 mm/yr of the linear trend of the RMSL using the SLP model and of 0.5 mm/yr using the SLP-NEA model. In this trend analysis the possible effect of GIA is not taken into account. During the last glacial maximum the ice depressed the earth crust and with the melting process this has been reversed. This process of land uplift is still going on and is called GIA. It is especially strong in high latitudes as in Scandinavia or Canada. However, it might also have influence in the German Bight. Subtracting the effect of GIA might change the linear long-term trend of our RMSL time series. That part of the linear trend determined by GIA can of course not be reproduced by the statistical model. Part of the differences in the trends of the observed RMSL and the model result might thus be explained by GIA. The estimations of vertical land movement resulting from a GIA model at different tide gauges in the German Bight are shown in Wahl et al. (2011). An interesting fact is, that the magnitude of the rise is about -0.5 mm/yr at all tide gauges. This complies with the mean trend difference the SLP-NEA model shows to the observed values.

As already discussed, in all reconstructed and predicted time series problems occur in the 1970s. The reason is an extraordinary high decadal trend in the RMSL of the German Bight. This high trend is also visible at the Danish and Dutch coast and cannot be explained with the two factors we use here. As mentioned in section 3.3.2 we tried to include other factors in the regression model in order to overcome these problems. We used time series of the GMSL and local temperature data, but neither of these time series could abolish the trend. We also could not find an indicator for a change in the ocean circulation. These problems can thus not be solved with our methods. There is thus either another factor influencing the RMSL of the German Bight which we could not constitute or the problems are due to the simplicity of the model.

As concluded above we think that the developed model can be used as an approach for projecting those parts of future regional sea level change associated with large-scale changes in atmospheric pressure and sea level. In particular, the above results suggest that pressure effects need to be considered when potential future changes in RMSL are trying to be quantified. So far, such effects are usually not accounted for in regional sea level projections (e.g. Katsman et al. 2008, Katsman et al. 2011). For future work it would thus be interesting to apply the developed model to future projections of the SLP to estimate the potential effect of wind and pressure effects to RMSL rise in the German Bight.

Acknowledgment

This work is a contribution to the ”Helmholtz Climate Initiative REKLIM” (Regional Climate Change), a joint research project of the Helmholtz Association of German research centres (HGF).

4. Pressure effects on regional mean sea level trends in the German Bight in the 21^{st} century

Abstract The effect of large scale atmospheric pressure changes on regional mean sea level projections in the 21^{st} century are considered. The statistical model developed in chapter 3 is applied to climate model data of sea level pressure for the 21^{st} century to assess the potential contribution of large scale atmospheric changes to future sea level changes in the German Bight. Using 78 experiments an ensemble mean of 1.4 cm rise in regional mean sea level is estimated until the end of the 21^{st} century. Changes are somewhat higher for realisations of the SRES A1B and the SRES A2 scenarios but generally do not exceed a few centimeters. This is considerably smaller than changes expected from steric and self-gravitational effects. Large scale changes in sea level pressure are thus not expected to provide a substantial contribution to 21^{st} century sea level changes in the German Bight.

4.1. Introduction

Determining and quantifying changes in MSL still remains a great challenge. Especially, possible future developments of sea level change are of great interest and need. Densely populated areas need reliable estimates of a possible rise in MSL to adapt their infrastructure. In chapter 1.5 an overview about the state-of-the-art future projections considering the change in MSL is given. The IPCC Fourth Assessment Report provides a range between 18 cm and 59 cm for the GMSL rise until the end of the 21^{st} century, compared to the end of the 20^{th} century (Meehl et al., 2007). These projections are based on different greenhouse gas emission scenarios. Global projections represent the average rise over all oceans. Regionally, considerable deviations from the global mean may occur. For example, additional water in the oceans resulting from melting of land-ice does not distribute equally over the oceans. As large ice sheets attract the water in their surrounding due to gravity, sea level is higher than average close to such ice sheets. When an ice sheet melts, the amount of the gravity is reduced. Therefore the sea level close to the ice sheet is even shrinking, although the amount of water in the ocean rises. On the other side, this effect leads to a rise higher than the mean further away from the ice sheet. Details of this effect are e.g. explained in Mitrovica et al. (2001) and Katsman et al. (2008). There are many more factors influencing the RMSL (see chapter 1.4). Among these factors is the change in large-scale atmospheric circulations. In contrast to e.g. land-ice melting this factor does not affect the GMSL as it only changes the distribution of the water but not its volume. However, a change in the distribution of pressure fields may influence the RMSL (chapter 3.3.1). For the German Bight this effect is analysed in chapter 3. The impact of the large-scale SLP-field of the North Atlantic to the RMSL of the German Bight is analysed, with the result being that about 50% of the inter-annual variability can be explained by this effect, for all for all periods considered.

Regional sea level projections for specific areas emerged only recently. Uncertainty in such projections originates from uncertainties related to the underlying emission scenarios but also from uncertainties in climate models and estimations of effects which cannot yet be determined by numerical models. One of the first attempts of regional future projections considering the MSL is provided by Katsman et al. (2008) and Katsman et al. (2011). Katsman et al. (2008) analyse the region of the North East Atlantic and Katsman et al. (2011) the Netherlands. These projections are based on analysing different factors influencing the RMSL and projecting their future impact to the RMSL. The different contributions are then added to achieve an estimate for the total future rise in RMSL. Regional projections for the UK are given in Lowe et al. (2009) and Slangen et al. (2012) provide a global pattern for regional mean sea level changes until the end of the 21st century. Results of these investigations are given in section 1.5. So far, none of these studies include effects of large-scale atmospheric circulations. To my knowledge, so far the only study providing an estimate of the amount the NAO influences future sea level is that of Tsimplis et al. (2005) for winter sea level changes in the UK. They came up with an estimate of less than 4 cm rise until 2080 in the highest of their considered scenarios. This complies less than 8% of the projected rise caused by thermal expansion in this scenario. The objective of this chapter is to analyse the effect of large-scale pressure effects to future MSL of the German Bight. In contrast to Tsimplis et al. (2005) the atmospheric changes are not reduced to the NAO, but the entire SLP-field of the North Atlantic is considered (Fig. 4.1). Further, Tsimplis et al. (2005) consider four different scenarios for the NAO, while in this work an ensemble of 78 projections of the SLP is used. The statistical model developed in section 3.3.1 is used and applied to the climate model data. The interest is, whether this model shows an impact to the long-term trend of the MSL of the German Bight and if it does, what magnitude it takes.

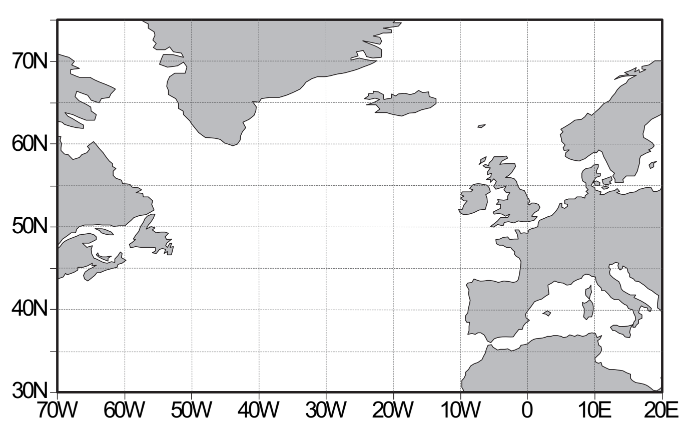

Figure 4.1. The area of the North Atlantic that is considered for the large-scale SLP-field (30°N – 75°N, 70°W – 20°E).

This chapter is structured as follows. In Section 4.2 the methods and data used in this chapter are explained. In section 4.3.1 the statistical model is applied to 78 different projections for future SLP and the corresponding change in terms of sea level change is analysed. These projections are divided by different scenarios in section 4.3.2 and the expected change in RMSL with respect to each scenario is analysed. Finally section 4.4 discusses the results.

4.2. Data and Methods

For the purpose of future MSL projections climate model data for the SLP are used. As in the entire work, annual means of the data are considered. The SLP data used, are from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset. These are the model output data considered in the International Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). The data comprise simulations for the past, the present and the future from worldwide modeling centers. A detailed description can be found in Meehl et al. (2007a). Reichler and Kim (2008) showed that the CMIP3 data better simulate present-day mean climate compared to previous model generations. In this study four different climate scenarios are considered: the commitment climate change experiment (commit) and three of the SRES emission scenarios (SRES A1B, SRES B1, SRES A2). The difference of the scenarios is related to different socio-economic developments and, as a consequence, to different greenhouse gas emissions for the future. In the commit scenario all radiation concentrations are fixed in the year 2000. SRES emission scenarios named with "A" simulate a more economical orientated future, whereas scenarios named with a "B" a more ecological orientated future. The numbers "1" and "2" stand for a more global orientated and a more regional orientated future, respectively. The A1B scenario is part of the A1 scenario family, which was subdivided by the assumption of the technological development. The A1B scenario assumes a balanced mix between fossil and regenerative energies. One of the major greenhouse gases is CO_2. Exact numbers for the assumptions of CO_2 development for each scenario can be found in appendix B or in Meehl et al. (2007a). Altogether 24 models are providing data for these scenarios. A total of 78 experiments can be used in this work, as not each model was run for all scenarios. The time period considered is the 21^{st} century and 64 of the experiments cover the time span 2001 – 2099. The other 14 experiments end earlier, but all in the 2090s. The time period is thus somewhat smaller than the one analysed in Meehl et al. (2007) and Katsman et al. (2008). In 15 of these models the commit scenario was performed, in 24 the A1B, in 19 the A2 and in 20 the B1 scenario. An overview of the models used, the provided scenarios and the time span covered is shown in Fig. B.1.

The impact of pressure effects on future RMSL of the German Bight is analysed by applying the statistical model (3.2) derived in chapter 3 to the SLP CMIP3 data. With the result of this model the impact of pressure effects to future RMSL of the German Bight can be analysed. The same area over the North Atlantic as in chapter 3 is used (30°N – 75°N, 70°W – 20°E, Fig. 4.1). To apply the model, the PCs $\boldsymbol{\alpha}_1$, $\boldsymbol{\alpha}_2$ and $\boldsymbol{\alpha}_3$ in (3.2) were simulated in the CMIP3 data for the time period 2001 – 2099. This was done by searching for the associated patterns resulting from the EOF analysis for the time period 1850 – 2009 (Figs. 3.1, 3.2, 3.3, in the following called P_1, P_2, P_3) in the climate model data. That is, for each experiment three multiple linear regressions were determined to simulate the three EOF patterns P_1, P_2 and P_3. The patterns P_j, $j = 1, 2, 3$ can be regarded as vectors in $\mathbb{R}^{190}$. Equally, the CMIP3 data can be regarded as vectors with the dimension of the grid points and depending on the time. Let Y_i, with i representing the time from 2001 – 2099, the vector of a specific experiment containing the SLP values for the year i. The regression can be formulated as follows:

$$Y_i = \sum_{i=1}^{t} \beta_{ij} P_j, \tag{4.1}$$

with $j = 1, 2, 3$ and t representing the time span. In this equation β_{ij} is an element of the vector $\boldsymbol{\beta}_j \in \mathbb{R}^t$. The solution of such a regression, as all considered variables are real, is given by the solution of the normal equation:

$$P_j^T P_j \boldsymbol{\beta}_j = P_j^T Y_i$$

for each $j = 1, 2, 3$. This solution is unique as far as P_j is a regular matrix. An explanation of a multiple linear regression is given in section 3.2 and in some more detail in von Storch and Zwiers (1998). The vector $\boldsymbol{\beta}_j$ is a time series and corresponds to $\boldsymbol{\alpha}_j$ in the formulation of (3.2). To perform the regression (4.1) both, P_j and Y_i need to have the same dimension. The CMIP3 data are calculated on different grids. As the observed SLP data are given on a $5° \times 5°$ grid, the CMIP3 data were converted to a $5° \times 5°$ grid using a bilinear interpolation, such that $Y_i \in \mathbb{R}^{190}$. An explanation of bilinear interpolation can e.g. be found in Deuflhard and Hohmann (1993).

4.3. Results

4.3.1. Impact of large-scale pressure effects on regional mean sea level in the German Bight in the 21st century

In chapter 3 the effect of the large-scale SLP-field of the North Atlantic to the RMSL of the German Bight is analysed. To quantify this part for the 21st century the statistical model (3.2) is applied to future projections of the SLP. For that purpose $\boldsymbol{\alpha}_j$ in (3.2) is replaced with the $\boldsymbol{\beta}_j$, $j = 1, 2, 3$ specified for each experiment via the regression (4.1). The coefficients a_1, a_2 and a_3 in the model (3.2) were calculated in chapter 3 for the period 1924 – 2001. The approach of the statistical model assumes that future climate conditions remain the same as in the calibration period. Therefore these coefficients are used in the application of this model to the 21st century. The result is a time series, representing that part of the RMSL that can be associated with large-scale pressure effects for the time period 2001 – 2099. The total number of projections is 78, as this is the number of experiments considered in this work. The results of these projections, sorted by climate models, are shown in appendix C. Note that some of these projections do not cover the entire time period.

Of particular interest is, whether a long-term trend is visible in these projections and if so what amplitude it takes. In Figs. C.1 to C.4 strong inter-annual variability and decadal trends are visible. However, high decadal trends can not be associated with certain time periods or certain models. In particular 20- and 37-year running trends were calculated for each projection to analyse whether the different models show similar periods of especially high or low decadal trends, but no such periods could be identified (not shown). A long-term trend is not ad hoc visible. However, the strong inter-annual variability may mask a possible long-term trend. To overcome this problem means for each 10 years are computed, that is for 2001 – 2010, 2011 – 2020, . . . , 2081 – 2090, 2090 – 2099. Then for each experiment the differences of the means 2011 – 2020, . . . , 2081 – 2090, 2090 – 2099 and 2001 – 2010 are calculated. These differences are called ΔSL_{1120}, . . . , ΔSL_{8190}, ΔSL_{9099}. Fig. 4.2 shows the distributions of these differences over time. Each boxplot displays a distribution of 78 differences, except the very last. The last only contains 64 values as not all experiments were run until 2099. The dark blue line in each box shows the median of the distribution and the upper and lower bound of the box are the 75- and 25-percentiles, respectively. The borders of the dashed lines represent the entire width of the distribution, with a maximum of 1.5 times the 25-/75-percentile values. Differences which have lower/higher values are plotted as separate crosses and are regarded as outliers.

The medians in Fig. 4.2 show a small rise over time. The highest value occurs in ΔSL_{8190}. Here the median has a value of 2.2 cm. The median of ΔSL_{9099} takes a value of 1.4 cm. That is 50% of the experiments show 1.4 cm or more of sea level rise in the German Bight that is caused by large-scale atmospheric changes. However, the uncertainties are high compared to this

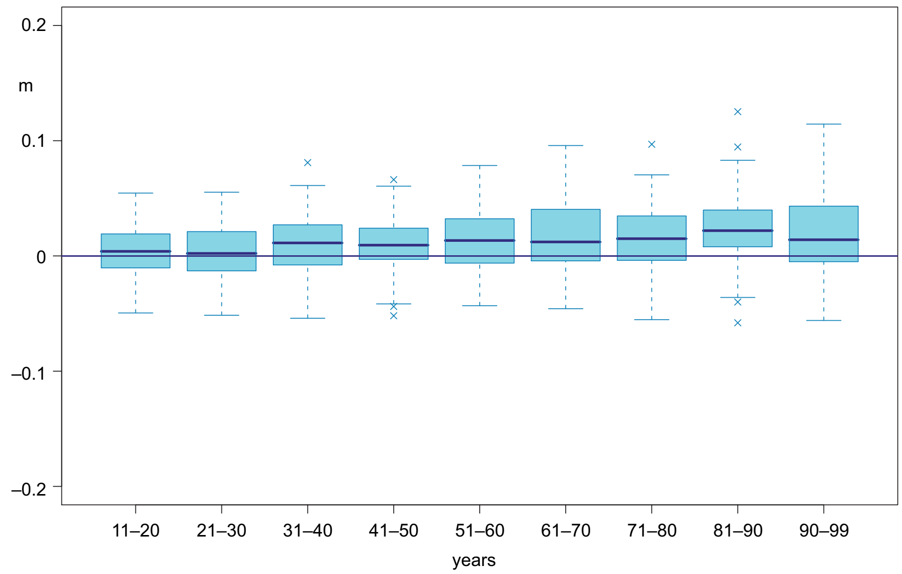

Figure 4.2. Boxplots of ΔSL for the 21^{st} century. The dark blue lines show the median of each distribution, the boxes border the 25/75-percentiles and the dashed lines cover the entire width of the distribution with the exception that values lower/higher 1.5 times the 25/75-percentiles are regarded as outliers and marked as separate crosses.

value. The distribution of ΔSL_{9099} is ranging from -5.6 cm to 11.4 cm and the 25-/75-percentiles are -0.5 cm and 4.4 cm, respectively. It would be desirable to investigate, whether these differences are statistical significantly different from zero. However, such a statistical test is not possible in this case. The ensemble of climate model scenarios for SLP cannot be regarded as a random sample. The underlying statistical population would consist of all possible projections for SLP, which could be produced using climate models. This is a set, which cannot be determined and therefore the statistical population is not well-defined (von Storch and Zwiers, 2013). Following the formulation of von Storch and Zwiers (2013) we can state: Using 64 climate experiments constructed with 21 climate models, the emission scenarios commit, SRES A1B, SRES A2 and SRES B1 we find that 37 experiments show an increase in the RMSL that can be associated with large-scale atmospheric changes in the German Bight until the end of the 21^{st} century.

To better classify this result, it is compared to the results of chapter 3. The resulting time series of the statistical model (3.2) shows a linear trend of

0.5 mm/yr for the time period 1924 – 2001 (Chapter 3). Considering 100 years this trend would yield to a rise of 5 cm. That is, the rise in the 21^{st} century is on average suggested to be smaller than in the period 1924 – 2001, but of the same magnitude. As a second comparison the method used for the 21^{st} century is applied to the time series representing RMSL changes caused by the large-scale SLP-field for the period 1924 – 2001 from chapter 3. That is 10-year means are computed and compared. For the time period 1924 – 1933, this time series has a mean of -1.3 cm and for the period 1992 – 2001 a mean of 2.4 cm. The difference shows a rise of 3.7 cm. This number cannot be compared to the average rise of 1.4 cm until the end of the 21^{st} century, as only 78 years are covered and not 100. So we compare it to rise until 2080 (ΔSL_{7180}), which covers 80 years. The median of this period is 1.5 cm. This leads to the same conclusion as above. That is, using the statistic of all climate experiments our model on average suggests a smaller rise due to pressure effects, than in the time period 1924 – 2001. However, the rise is in the same magnitude.

4.3.2. Impact of large-scale pressure effects on future Regional Mean Sea Level conditioned upon different emission scenarios

As in section 4.3.1 the projections for the RMSL of the German Bight for the 21^{st} century resulting from the statistical model (3.2) are considered. The range of 78 projections is now divided into the four scenarios (commit, SRES A1B, SRES A2, SRES B1) and the expected rise in RMSL is considered with subject to each scenario. Again the differences ΔSL are considered over time. In Fig. 4.3 the boxplots of the resulting distributions are shown. The plots carry the same information as Fig. 4.2.

Results from this analysis are broadly comparable with that obtained from the analysis of the full multi-scenario ensemble; that is the differences in the medians are in the order of a few centimeters. However, differences between the scenarios can be seen. In the commit and B1 scenarios no long-term trends are visible. The medians are oscillating around zero in the commit scenario and only take very small positive values in the B1 scenario. In the A1B and A2 scenarios on the other hand an increase over time can be seen. In some more

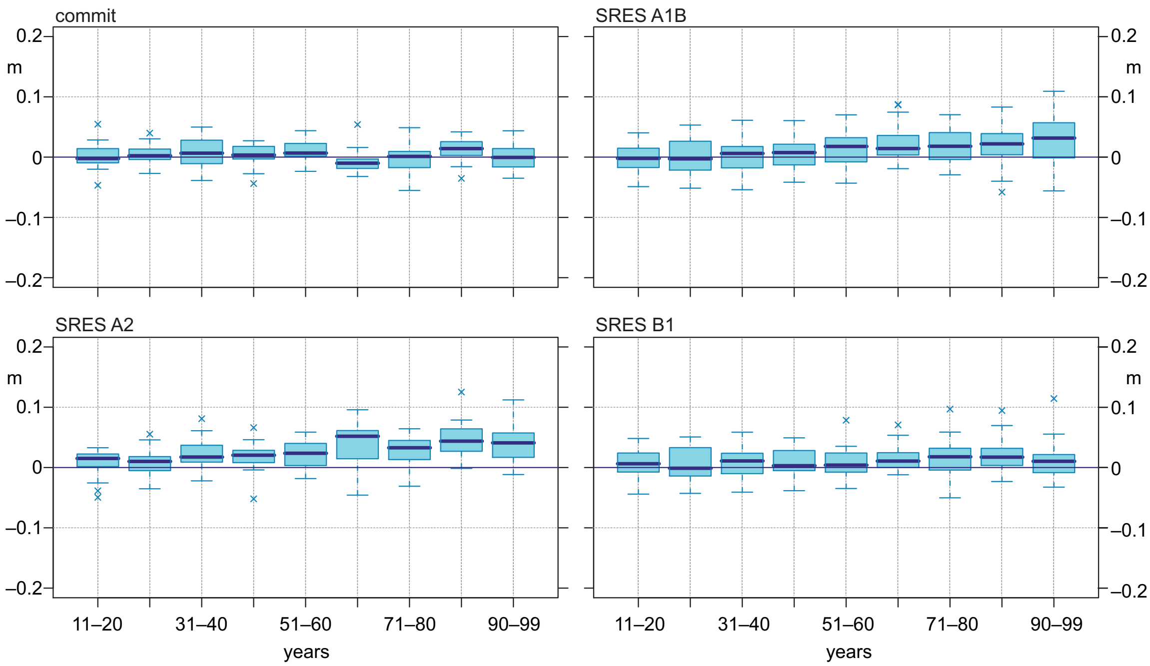

Figure 4.3. Boxplots of ΔSL for the 21^{st} century divided by different climate scenarios. Top left: commitment climate change experiment (commit), top right: SRES A1B, bottom left: SRES A2, bottom right: SRES B1. The dark blue lines show the median of each distribution, the boxes border the 25/75-percentiles and the dashed lines cover the entire width of the distribution with the exception that values lower/higher 1.5 times the 25/75-percentiles are regarded as outliers and marked as separate crosses.

detail, the distributions of the commit scenario contain 15 experiments, from which 13 were run until 2099. The median of ΔSL_{9099} is -0.05 cm. The 25- and 75-percentile boundaries are -0.6 cm and 1.4 cm, respectively and the range of the distribution varies from -3.5 cm to 4.4 cm. The boxplots of the A1B scenario contain 24 values and the distribution of the last difference ΔSL_{9099} contains 19 values. The median of ΔSL_{9099} has a value of 3.2 cm and the 25- and 75-percentiles are -0.09 cm and 5.9 cm. The range of the distribution lies between -5.6 cm and 10.9 cm. The A2 scenario contains 19 experiments and ΔSL_{9099} contains 15. The distribution of ΔSL_{9099} has a median of 4.1 cm, the 25-/75-percentiles are 3.8 cm and 6.1 cm. The entire distribution takes values between -1.2 cm and 11.2 cm. The distribution of the B1 scenario comprises

20 experiments where 17 are in ΔSL_{9099}. The latter has a median of 1 cm, the 25-/75-percentile boundaries are -0.6 cm and 2.2 cm, respectively. The width of the distribution ranges from -3.3 cm to 5.5 cm. One experiment takes a much higher value of 11.4 cm and is regarded as outlier. In the distributions of the B1 scenario outliers can be seen from ΔSL_{5160} on. All these outliers result from the same model, the miub_echo_g. However, this model has no conspicuous values within the other scenarios. The uncertainties compared to the rise in RMSL are very high in all cases. The results indicate that the rise of the RMSL that is caused by pressure effects is not a major contributor, but may have non-negligible effects for the scenarios A1B and A2. As in the case, when all 78 projections are considered together, a statistical test on whether these differences are significantly different from zero is not possible.

4.4. Summary and Discussion

The impact of large-scale pressure effects to future RMSL of the German Bight are analysed. The SLP data used, covers the area of the North Atlantic. CMIP3 data are used for future projections of the SLP. The effect to RMSL is then calculated with the statistical model (3.2) derived in chapter 3. The main interest is on whether or not there is a systematic contribution from the large-scale SLP-field on the long-term trend of the RMSL in the German Bight. To reduce the impact of the strong inter-annual variability means over 10-years are calculated, which are then considered as the decadal change of rise in RMSL. This is done for each experiment. Considering all 78 experiments of the 24 different models a rise of 1.4 cm, associated with a corresponding change in large-scale sea level pressure pattern, is visible in the medians. However, uncertainties associated with this value are high. The calculated rise of RMSL in the German Bight caused by the large-scale SLP-field in the 21^{st} century is smaller than the one calculated for the period 1924 – 2001. However, both are in the same order of magnitude.

Portioning the 78 projections in the four scenarios (commit, A1B, A2, B1) results are generally comparable, but differences within the scenarios can be seen. While the commit and the B1 scenario do not show a long-term trend, the A1B and A2 scenario do show a long-term trend. The differences of 2090 – 2099 and 2001 – 2010 are 3.2 cm for the A1B scenario and 4.1 cm for the A2 scenario, respectively. These results show that the rise of the RMSL caused by atmospheric changes is not a major contributor to future sea level changes. However, it may have a non-negligible effect, especially considering scenarios A1B and A2.

Chapter 3 showed that the explained part of the long-term trend due to the SLP-field of the North Atlantic seems to depend on the considered time period. In particular, it is thus not possible to make a statement about the percentage the calculated rise accounts for, compared to the entire rise of the RMSL. In other words, no estimation for the entire long-term trend of RMSL in the 21^{st} century is possible. This is a clear drawback of the developed model and further research necessary on that topic.

The calculations of this work confirm the result of Tsimplis et al. (2005) who found a rise of less than 4 cm for the UK winter sea level until 2080 caused by the NAO. An important question is, whether or not the effect of large-scale atmospheric changes should be included into RMSL projections for the German Bight. Projections of RMSL rise for the 21^{st} century for the German Bight are not available, however there are several works on that issue for regions relatively close to the German Bight. Katsman et al. (2008) projected a rise of 30 – 50 cm until 2100 for a moderate warming and 40 – 80 cm for a strong warming for the North East Atlantic. Lowe et al (2009) projected a rise of 12 – 76 cm for the UK until the end of the 21^{st} century and Katsman et al. (2011) developed a high-end scenario for the Netherlands until 2100 and projected a rise of 40 – 105 cm and -5 – 115 cm, respectively, depending on the scaling factor for the local contribution of ice-masses compared to the global mean. In none of these projections the effect of large-scale atmospheric changes is included. Main contributions are considered to be local steric effects and the effect of self-gravitational changes due to the melting of land ice. These projections show a large range. However, compared to most of these numbers the calculated rise of RMSL induced by large-scale pressure effects is small and seems to be a minor contributor for RMSL rise in the North Sea area, in the 21^{st} century.

Acknowledgment

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5. Summary and Discussion

The overall aim of this work is to assess and quantify RMSL changes in the German Bight. First, an analysis of past tide gauge data of the German Bight is presented. Two time series representing past RMSL are constructed and compared. For the common time period 1924 – 2008 both reconstructions show similar results and the linear long-term trend lies between 1.64 mm/yr and 1.74 mm/yr. Earlier reconstructions mostly rely on data from Cuxhaven, which is the longest record available - from 1843 onwards. Therefore it was elaborated, to which extend the record is representative for conditions in the German Bight and whether data from Cuxhaven may be used to make inferences about regional mean sea level changes in earlier periods. While the analysis shows, that this is not the case from the year 1924 on, no final conclusion is possible for the time period before. Assuming the main reason for the differences between the Cuxhaven record and the time series for the entire German Bight are construction works, it remains likely that Cuxhaven can be taken as a representative in the early years as construction works were mainly carried out after 1924.

Analysing decadal trends of the reconstructed RMSL time series shows an acceleration in the recent past, but such high and even higher decadal trends already occurred during earlier periods. Thus, it is concluded that the trends in the last periods are not extraordinary high. The investigation of a possible acceleration in the recent past confirms the results of other authors, who analysed RMSL in the North Sea area (Woodworth et al., 1999; 2009; Katsman et al., 2008; Haigh at al., 2009). None of them found an extraordinary high acceleration in the recent past. However, this analysis should be repeated in the future to analyse whether the decadal trends continue to rise.

The two above mentioned reconstructions are the first approaches to represent the MSL of the entire German Bight. All previous works in this area use either MSL time series of single tide gauges (e.g. Wahl et al., 2010) or in most cases proxies as mean tidal high, mean tidal low water, mean tidal range or MTL for MSL analysis (e.g., Jensen et al., 1992; Lassen, 1995; Jensen and Mudersbach, 2007). Therefore, such a time series delivers new possibilities in analysing the RMSL of the German Bight. The analysis and therewith the results are not restricted to single locations and it is known that proxies as the MTL can lead to errors in conclusions concerning the MSL (e.g. Lassen, 1989; Wahl et al., 2010; 2011). Wahl et al. (2011) e.g. calculated that the differences of MSL and MTL are up to 23 cm at the tide gauge of Emden.

The influence of large-scale atmospheric changes to MSL variability and long-term trend in the German Bight is analysed. A statistical model - using multiple linear regression - is developed to investigate the relationship between the large-scale SLP-field over the North Atlantic and the RMSL of the German Bight. The objective is not only the analysis of the influence of the SLP-field to the inter-annual variability of the RMSL, but also its effect to the long-term trend. The result shows that 58% of the inter-annual variability and 33% of the long-term trend can be explained by the large-scale SLP-field for the period 1924 – 2001. This result shows that a non-negligible part of the long-term trend may be associated with corresponding changes in SLP. However, a cross validation indicates that the explained part of the long-term trend depends on the time period. The MSL of the North East Atlantic is added to the regression model as a proxy for large scale sea level variations influencing regional sea level in the German Bight. The result shows that including the additional variable improves both, the explained inter-annual variance (73%) and the explained part of the long-term trend (87%) for the time period 1924 – 2001. However, again a cross-validation shows that the explained part of the long-term trend depends on the time period considered.

The dominant pattern of atmospheric large scale variability over the North Atlantic is the NAO. The relationship between the NAO and the West European climate is well established (e.g. Hurrel and van Loon, 1997; Trigo et al., 2002; Jones et al., 2003; Scaife et al., 2008). Therefore analyses of the relationship between MSL in the North Sea and the atmospheric pressure is in many works restricted to the NAO (e.g. Wakelin et al. 2003; Yan et al., 2004; Jevrejeva et al., 2005; Dangendorf et al., 2012). In this study the full information contained in the SLP field is exploited. No preselection of modes of variability is made. The results agree with previous studies that a large part of the variability of the RMSL can be explained with the atmospheric pressure field of the North Atlantic. However, the cited works do not analyse the impact of large-scale atmospheric changes to the long-term trend of the RMSL, which is an important issue in this study.

An objective of this work is to quantify this impact and to analyse whether large-scale atmospheric changes should be included in future sea level projections in this area. For that purpose the regression model between the SLP and the RMSL is used. The analysis shows that the influence of the SLP-field to the long-term trend of the RMSL is only a few centimeters. Compared to sea level projections of regions close to the German Bight, the influence of large-scale pressure changes seems to be small. For the North East Atlantic Katsman et al. (2008) projected a rise of 30 – 50 cm until 2100 for a moderate warming and 40 – 80 cm for a strong warming. Until the end of the 21^{st} century, UK estimations of sea level rise of 12 – 76 cm are given by Lowe et al. (2009). Katsman et al. (2011) gave two different estimations for a high-end scenario for the Netherlands until 2100. The authors projected rises of 40 – 105 cm and -5 – 115 cm, respectively. Therefore it is concluded that the atmospheric pressure changes are not a major contribution for future projections. The result fits to the analysis of Tsimplis et al. (2005), who projected a rise of less than 4 cm for the rise of UK winter sea level until 2080 due to the NAO.

In summary, this work delivers a contribution to the assessment of RMSL changes in the German Bight. Especially, the constructed time series of the tide gauge data makes more detailed analysis possible than it has been until now. However, there are more - non-digitised - tide gauge data available, resulting from analogue measurements in the past. A digitisation of this data would be time consuming, but after several homogenisation effort it could further improve this time series. An analysis of the RMSL of the entire North Sea and comparisons of different areas has recently been conducted in Wahl et al. (under review). The authors used the approach of Wahl et al. (2011) to construct RMSL time series (arithmetic means of the different locations). An EOF-analysis as performed in this work would be interesting in order to identify areas with similar variability in the North Sea. In addition, this would enable an analysis on whether certain tide gauges can be regarded as representative for a certain area of the North Sea, similar to that conducted in this work considering Cuxhaven. From 1993 on, altimetry data are available. A comparison of a time series representing the RMSL constructed with altimetry data and the time series constructed in this work for the RMSL of the German Bight or for the entire North Sea from Wahl et al. (under review), respectively would be interesting. Possible differences in these time series could describe several causes, as e.g. the influence of coastal and open ocean measurements or the different measuring systems. Further, reliable future projections of the RMSL of the German Bight are still missing. Here additional emphasis is needed as such projections are urgently needed by local governments to adapt the coasts to possible changes. In this work, a contribution was made towards estimating the effects that may be induced by changing mean SLP.

A. The k-factor method

The k-factor method is an approach to transform MTL to MSL. As defined in the Introduction (section 1.2) the MSL is the arithmetic mean of at least hourly values over a period of time, such that tidal influences are removed. However, long sea level time series usually only provide mean tidal high and mean tidal low water. Often the MTL, which is the sum of both divided by two, is used as an approximation for MSL. As demonstrated by Lassen (1989) and Wahl et al. (2008; 2010; 2011) the MTL often does not represent a good proxy of MSL. The MSL is only equal to the MTL if the tide curve is symmetric. In shallow water areas as the German Bight this is usually not the case as bottom friction leads to a deformation of the tide curve. In Fig. A.2 the difference is visualised. A possibility to address this issue is the k-factor method, which provides an approach to convert MTL time series derived from high and low waters to MSL records. The k-factor is defined as

$$k(t) = \frac{MHW(t) - MSL(t)}{MTR(t)}, \tag{A.1}$$

where MHW is the mean high water and MTR the mean tidal range. The variable t describes a possible time-dependence of k. Time-dependence may be caused by seasonal periodicity, trends or shifts. Lassen (1989) introduced this formula without time-dependence. The author argued that the deviation from the mean over time is small in his calculations. In contrast to that, Wahl et al. (2008; 2010; 2011) allowed a time-dependence of k. The monthly k-factors of each location are analysed for their time-dependence using statistical tests. If the k-factor is stationary, the mean value can be used to construct MSL time series from the MTL time series. For most of the considered tide gauges the result is a time-independent parameter k, however e.g. Wilhelmshaven and Hörnum show non-stationary character (IKÜS 2008; Wahl et al., 2011). This has to be considered, when the MSL time series for these locations are generated (details can be found in IKÜS 2008).

For generating the MSL time series, the k-factor of each tide gauge is calculated via equation (A.1), for the time period high resolution data are available. In case of stationarity the mean k of $k(t)$ is calculated and subsequently applied to the reminder of the time series where no high resolution data is available, using the formula

$$MSL(t) = MTR(t) \cdot (0.5 - k) + MTL(t).$$

The k-factor can be considered as a measure for the deformation of the tide curve. In the North Sea the MSL is usually higher than the MTL (Lassen, 1989). If the k-factor is equal to 0.5, MTL is equal to MSL; the lower its value the higher is the deformation. For the tide gauges considered in this work Wahl et al. (2011) calculated the lowest k-factor for Emden ($k = 0.4286$), which results in a difference of 23 cm between MTL and MSL and the highest for Norderney ($k = 0.4874$), which complies with a difference of 3 cm.

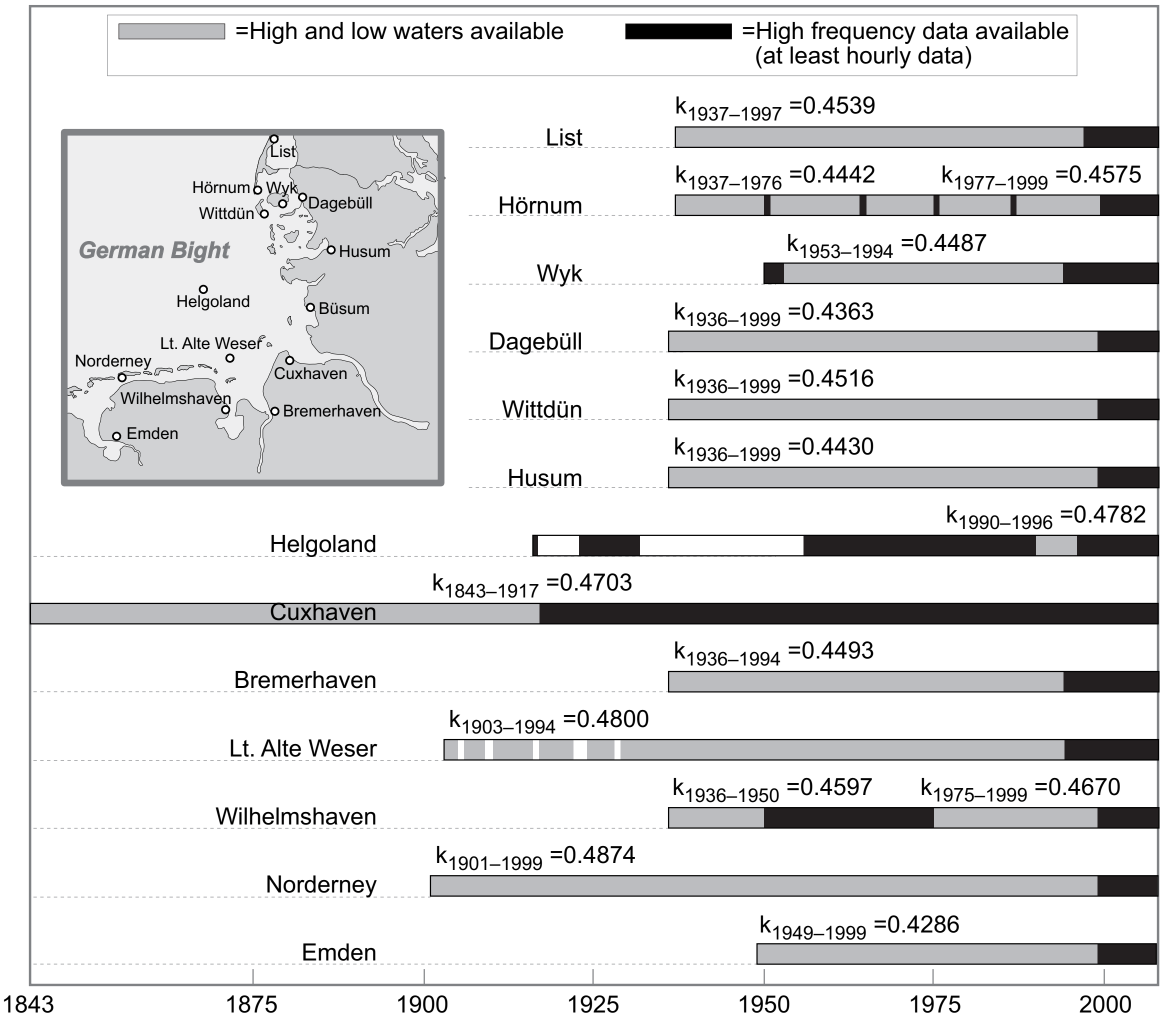

Figure A.1. Data availability and k-factors for 13 tide gauges of the German Bight. Shown are periods of high and low frequency data. Redrawn from Wahl et al. (2008).

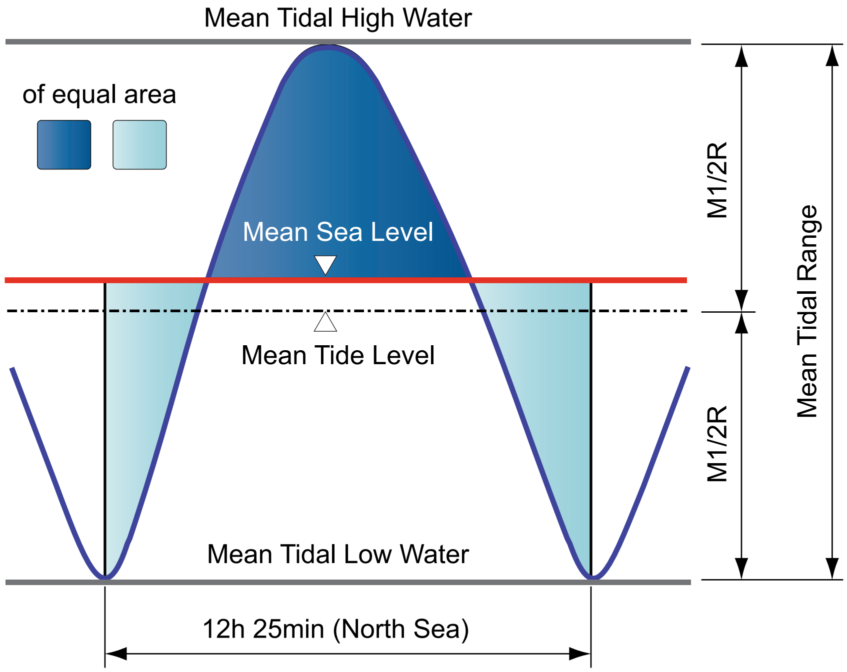

Figure A.2. Illustration of the difference between mean sea level and mean tide level. Redrawn from Wahl et al. (2008).

B. CMIP3 multi-model dataset

The analysis in chapter 4 uses the results of global climate models – more precisely of atmosphere–ocean coupled *general circulation models* (GCMs). GCMs describe the time development of climate variables of the atmosphere and the ocean on a mathematical and physical basis. That is, the fundamental physical dynamics for the atmosphere and ocean are combined to a set of differential equations. These equations are called the *primitive equations* and aim to simulate the atmosphere and ocean of the earth. An introduction to the physical concepts can e.g. be found in Etling (2002). In GCMs these equations are solved using numerical algorithms. An introduction to climate models is given in Weisse and von Storch (2009). A detailed description of climate models can e.g. be found in McGuffie and Henderson-Sellers (2005), and von Storch et al. (1999). Washington and Parkinson (2005) additionally explain some basic numerical concepts to solve the differential equations.

The application of GCMs is obviously restricted by the technical possibilities in running them and storing their data. The Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset developed by the World Climate Research Programme's (WCRP's) was the first time results of a large set of climate models were combined in one database and made freely available for everyone (Meehl et al., 2007a). The development and history of climate model data until the initiation of the CMIP3 multi-model dataset is documented in Meehl et al. (2007a). The CMIP3 data are based on the results of 17 modeling groups from 12 countries using 24 climate models. Most results were brought together in the years 2005 and 2006. The climate models are used to project time periods of the past, present and future. In this work the CMIP3 data are used for future projections of the 21^{st} century. However, other time periods are available. The CMIP3 multi-model dataset e.g. also helps to analyse the climate of the 20^{th} century and therefore to understand already observed climate change. Examples for that can be found in Meehl et al. (2007a). A list of the available climate variables and explanations can be found on the website `http://www-pcmdi.llnl.gov/ipcc/standard_output.html`. The variable used in this work is called *air pressure at sea level* and is analysed in all models for the 21^{st} century. As only annual means are considered in this work, all models fulfil the needed time resolution. This results in a large sample of experiments for the statistical analysis.

The CMIP3 data are divided by different climate scenarios. For the 21^{st} century data are provided by four scenarios, which are used in this work. In general, the difference of the scenarios lies in the assumed greenhouse gas emissions in the 21^{st} century. These emissions lead to a change of greenhouse gas concentration in the atmosphere. One of the major greenhouse gases is CO_2, therefore the numbers of change in CO_2 concentration in the atmosphere is often considered. One scenario used, is the commitment climate change experiment (commit), where the greenhouse gas concentration is fixed in the year 2000. It will take some time for the climate system to adjust to these greenhouse gas concentrations and therefore it will continue to respond to them, even if they are mitigated in future. This scenario thus describes the climate change that is unavoidable. Experiments using this scenario were run until the end of the 21^{st} century with a fixed CO_2 concentration of about 360 ppm. The remainder three scenarios are part of the *special report on emission scenarios* (SRES). The SRES scenarios available from the CMIP3 data are B1, A1B and A2. All these scenarios were run for the 21^{st} century, for the variable *air pressure at sea level*. Simplified, Meehl et al. (2007a) characterise the B1 scenario as a scenario with low forcing, the A1B with medium forcing and the A2 with high forcing. In this context the term forcing can be equalised with greenhouse gas concentration. Somewhat more precisely the SRES B1 emission scenario is based on the assumption that the CO_2 concentration in 2100 will be about 550 ppm, the SRES A1B assumes a concentration of about 700 ppm by 2100 and the SRES A2 of about 820 ppm by 2100 (Meehl et al. (2007a)). A detailed explanation and illustration of the greenhouse gas emissions and the resulting concentrations separated by the different gases and scenarios can be found in Meehl et al. (2007). An overview about the models used in this work and the available scenarios and time periods is given in Fig. B.1.

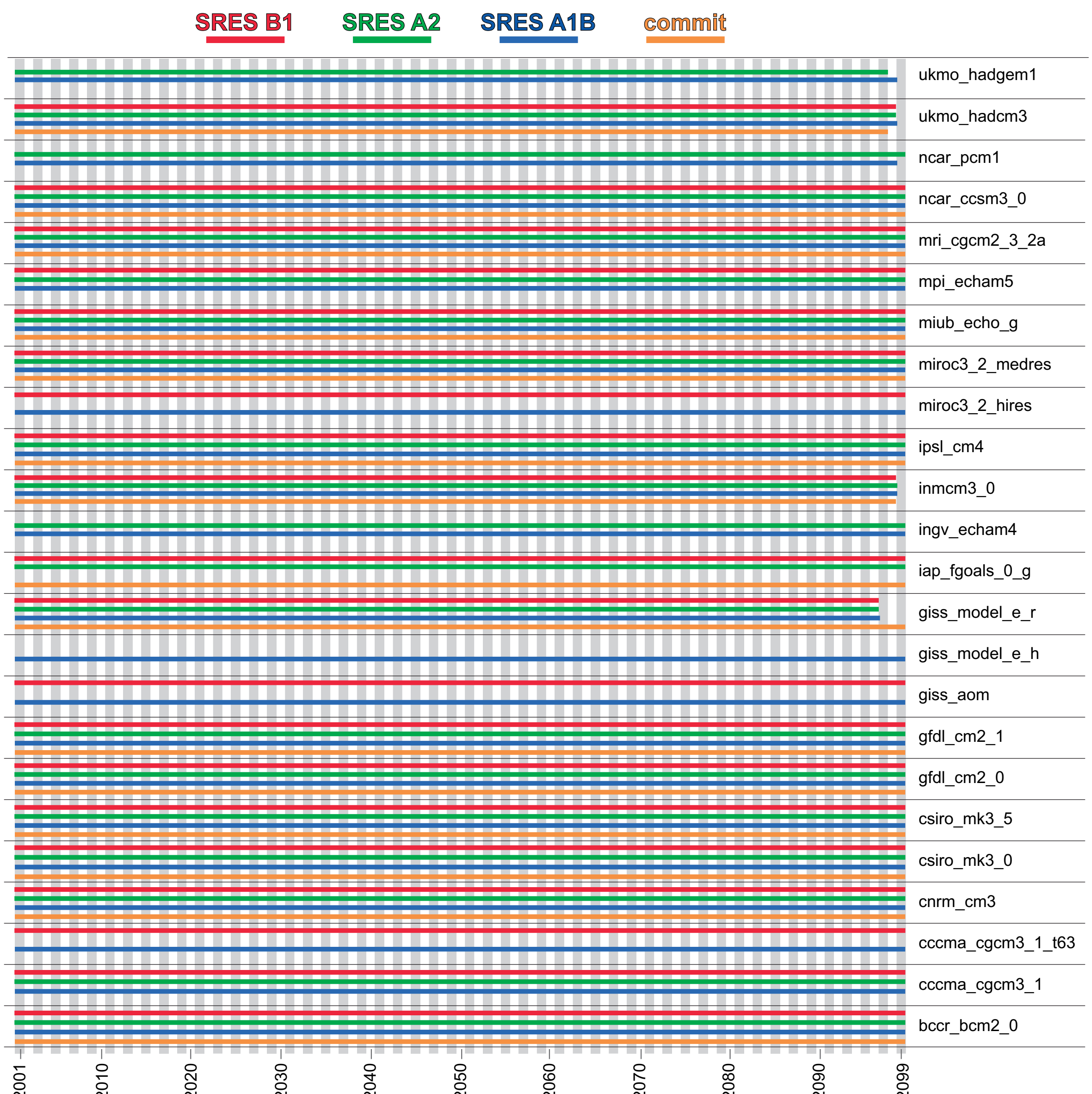

Figure B.1. A list of the climate models (right column) of the CMIP3 multi-model dataset that provide projections for the variable *air pressure at sea level* for the 21st century is shown. The coloured lines show the available experiments and time periods.

C. Additional plots

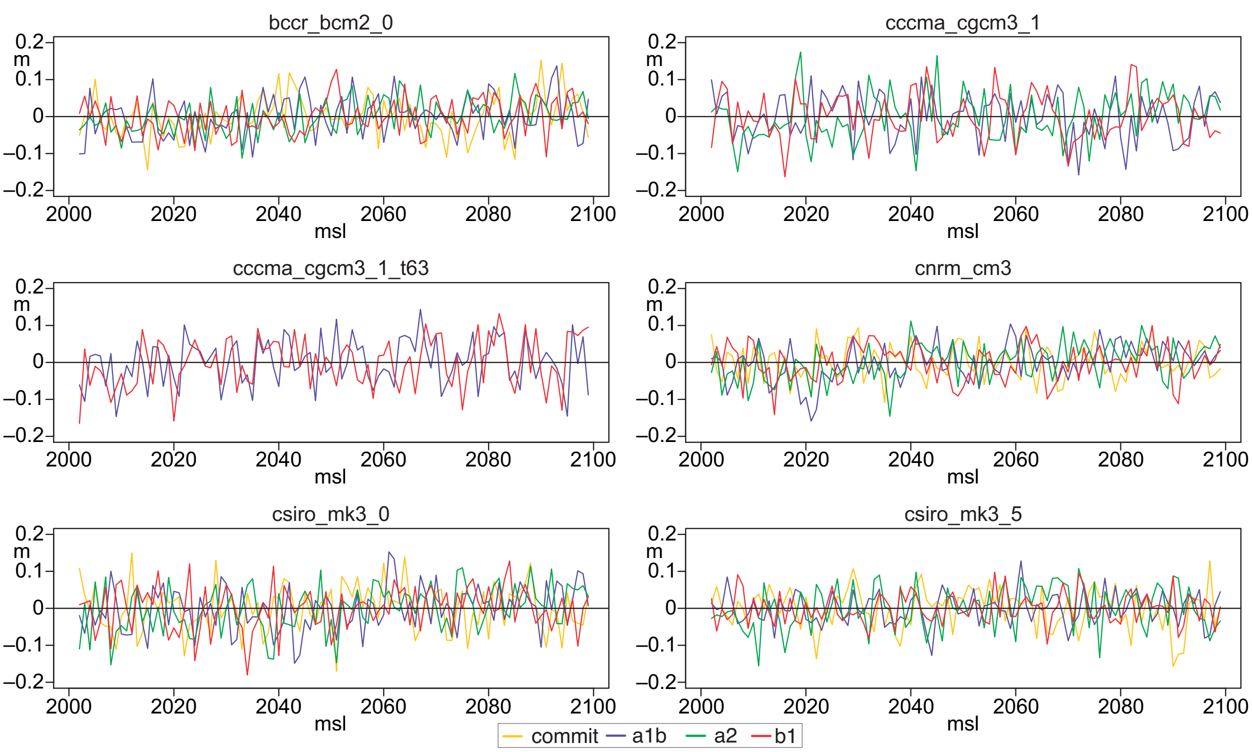

Figure C.1. Results of the statistical model (3.2) for future RMSL of the German Bight introduced by the large-scale SLP-field over the North Atlantic in the 21^{st} century. The results are given for each climate model and the scenarios are given in different colours. The name of the considered climate model is indicated in the headline.

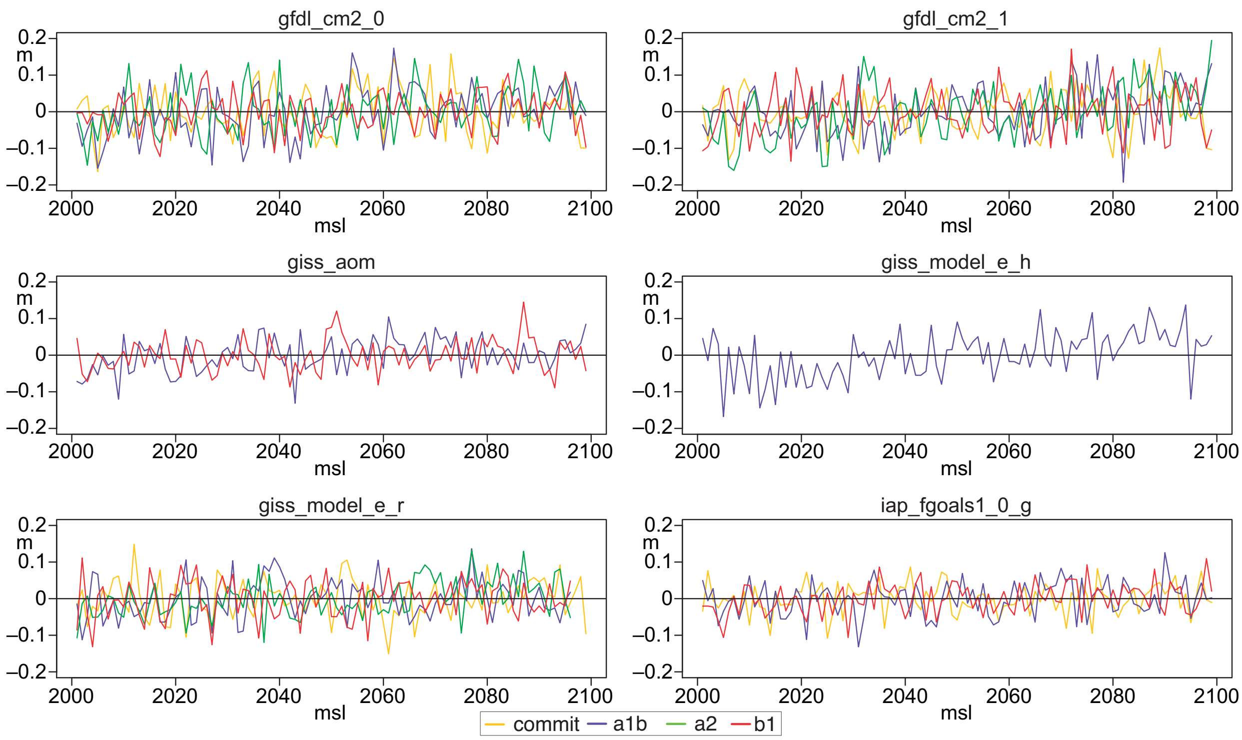

Figure C.2. Results of the statistical model (3.2) for future RMSL of the German Bight introduced by the large-scale SLP-field over the North Atlantic in the 21st century. The results are displayed for each climate model and the scenarios are given in different colours. The name of the considered climate model is indicated in the headline.

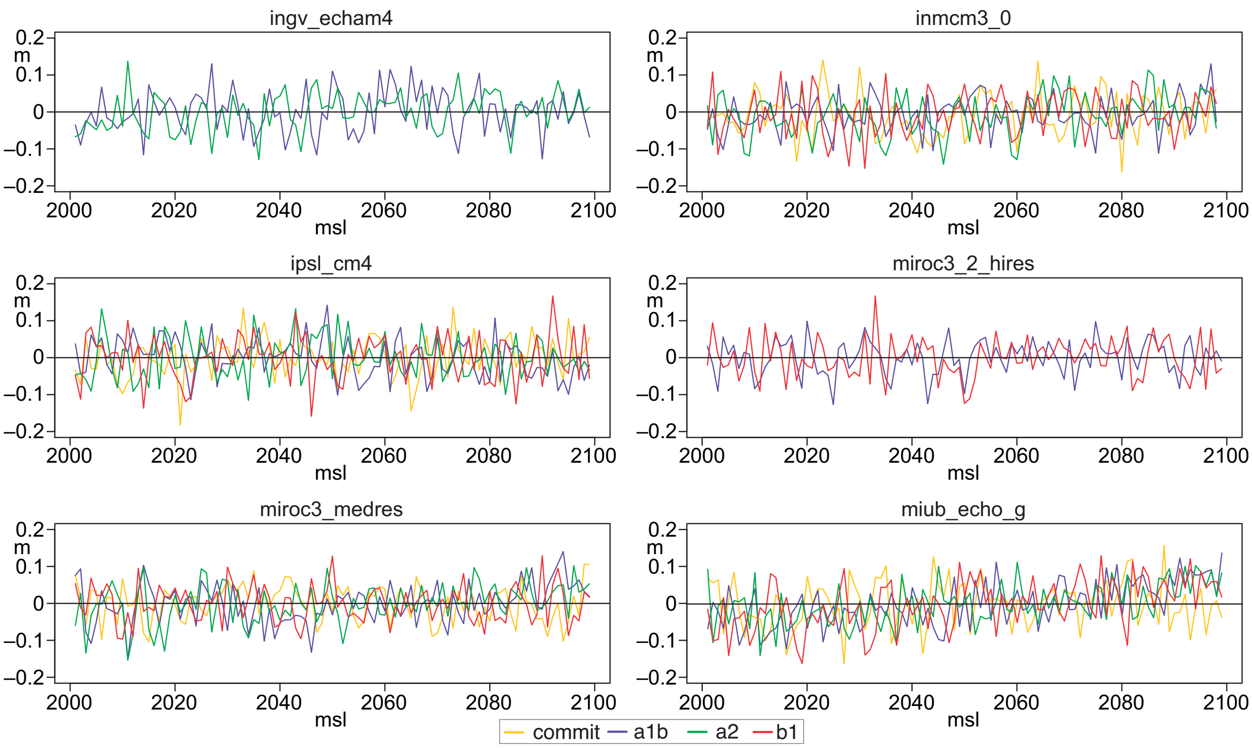

Figure C.3. Results of the statistical model (3.2) for future RMSL of the German Bight introduced by the large-scale SLP-field over the North Atlantic in the 21^{st} century. The results are displayed for each climate model and the scenarios are given in different colours. The name of the considered climate model is indicated in the headline.

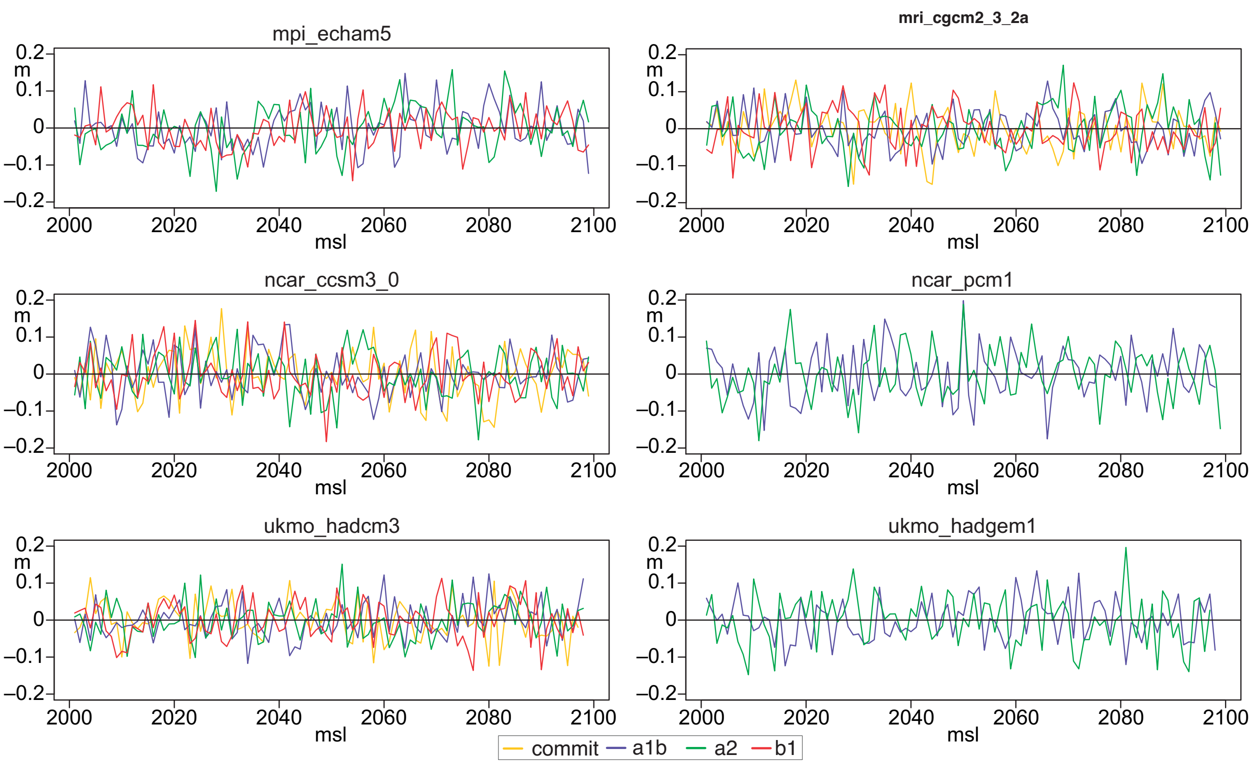

Figure C.4. Results of the statistical model (3.2) for future RMSL of the German Bight introduced by the large-scale SLP-field over the North Atlantic in the 21st century. The results are displayed for each climate model and the scenarios are given in different colours. The name of the considered climate model is indicated in the headline.

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Eidesstattliche Versicherung ***Declaration on oath***

Hiermit erkläre ich an Eides statt, dass ich die vorliegende Dissertationsschrift selbst verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

I hereby declare, on oath, that I have written the present dissertation by my own and have not used other than the acknowledged resources and aids.

Hamburg, den 04. April 2013
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