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

Frauke Albrecht*, Ralf Weisse**

* Center for Climate and Resilience Research, University of Concepción, Concepción, Chile
** Institute for Coastal Research, Helmholtz-Zentrum Geesthacht, Max-Planck-Str. 1, 21502 Geesthacht, Germany

Correspondence to: F. Albrecht (e-mail: frauke.albrecht@dgf.uchile.cl)

Abstract

The effect of large scale atmospheric pressure changes on regional mean sea level projections in the German Bight in the 21^{st} century are considered. A developed statistical model 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 *special report on emission scenarios* (SRES) A1B and A2, 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.

1 Introduction

Determining and quantifying changes in *mean sea level* (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. Based on different greenhouse gas emission scenarios, the *International Panel on Climate Change* (IPCC) *Fourth Assessment Report* (AR4) provides a range between 18 cm and 59 cm for the *global mean sea level* (GMSL) rise until the end of the 21^{st} century, compared to the end of the 20^{th} century (Meehl et al., 2007). Additionally, a so called *"scaled up dynamical ice sheet discharge"* of 17 cm is added, because of the recent large ice-sheet mass losses. More recent studies often use a semi-empirical approach, which are based on a simple physical assumption as e.g. a linear relationship between the global mean surface temperature and the GMSL. Rahmstorf (2007) projected a rise in GMSL of 50 – 140 cm until the end of the 21^{st} century, using this approach and Vermeer and Rahmstorf (2009) even 75 – 190 cm. However, these approaches are also partly under discussion (Holgate et al., 2007; Schmidt et al., 2007; von Storch et al., 2008).

Global projections represent the average rise over all oceans. Regionally, considerable deviations from the global mean may occur. Gönnert et al. (2009) name the most important of these factors, to be local land movements, regional differences in thermal expansion, land ice-melting and changes in the mean ocean or atmospheric circulation. In this work we will focus on the effect of large-scale atmosperic circulations to *regional mean sea level* (RMSL). This effect 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 in different ways. The fact that a pressure increase/decrease of 1 hPa leads to a fall/rise in sea level of about 1 cm is known as the *inverse barometric effect*. Further, the direction and the increase of the pressure gradients are directly connected to wind speed and wind direction. A change in large scale pressure pattern therefore leads to a change in the wind climate, which in turn causes a change in the distribution of the water.

Regional sea level projections for specific areas emerged only recently. One of the first attempts of regional future MSL projections is provided by Katsman et al. (2008), considering the region of the North Atlantic. For a moderate scenario they project a rise of 30 – 50 cm until 2100 compared to 1990 and 40 – 80 cm for a warm scenario, respectively. Katsman et al. (2011) analyse a high-end scenario for the Netherlands and project a rise of 40 – 105 cm. Regional projections for the UK are given in Lowe et al. (2009) and estimate a rise of 12 – 76 cm for the 21^{st} century. Slangen et al. (2012) provide a global pattern for regional mean sea level changes until the end of the 21^{st} century with a mean rise of 47 cm for the *special report on emission scenario* (SRES) A1B. 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. So far, none of these studies include effects of large-scale atmospheric circulations. To our knowledge, so far the only study providing an estimate of the amount the *North Atlantic Oscillation* (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 comprises less than 8% of the projected rise caused by thermal expansion in this scenario.

The objective of this paper is to analyse the effect of large-scale pressure effects on future MSL of the German Bight in the 21^{st} century, which is the southeast part of the North Sea (Fig. 1). For the 20^{th} century this effect is analysed in Albrecht and Weisse (2012, henceforth referred to as AW12). Using a statistical model the authors came to the result that 58% of the inter-annual variability and 33% of the long term trend can be explained by this effect for the time period 1924 – 2012. The authors further show, that the explained inter-annual variability seems to be stable around 50% for all time periods considered, whereas the explained part of the long-term trend seems to depend on the time period. In this work the statistical model developed in AW12 is used to quantify the influence of large-scale pressure effects to future MSL in this area. The interest is, whether this model shows an impact on the long-term trend of the MSL of the German Bight and if it does, what magnitude it takes in order to analyse whether this effect should be included in RMSL projections. 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. 2). 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.

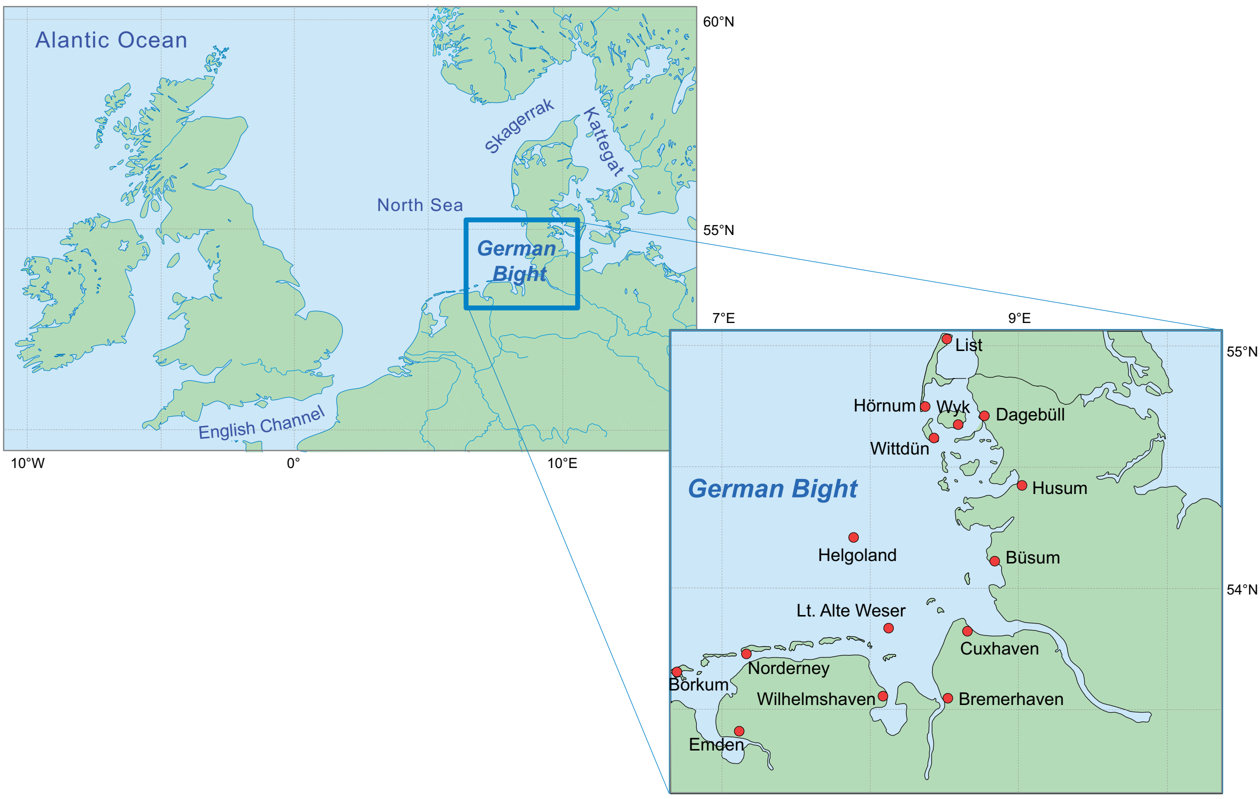

Fig. 1 Study area and locations of the tide gauges considered (red dots) for the constructed regional mean sea level time series of the German Bight for the time-period 1924 –2008 in Albrecht et al. (2011).

This work is structured as follows. In Section 2 the methods and data used are explained.

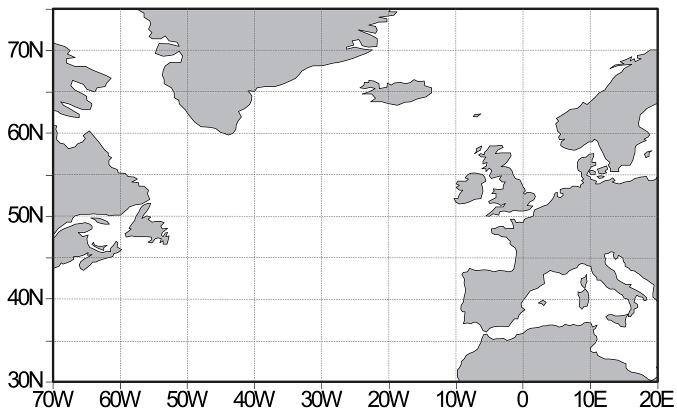

Fig. 2 The area of the North Atlantic that is considered for the large-scale SLP-field (30°N – 75°N, 70°W – 20°E).

In section 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 3.2 and the expected change in RMSL with respect to each scenario is analysed. Finally section 4 discusses the results.

2 Data and Methods

For the purpose of future MSL projections climate model data for the SLP are used. 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 IPCC 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 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. 5 of the appendix.

The impact of pressure effects on future RMSL of the German Bight is analysed by applying the statistical model derived in AW12. The formulation of the model is as follows:

$$\tilde{\mathbf{z}}(t) = a_1\boldsymbol{\alpha}_1(t) + a_2\boldsymbol{\alpha}_2(t) + a_3\boldsymbol{\alpha}_3(t), \tag{1}$$

where $\tilde{\mathbf{z}}(t)$ expresses that part of the RMSL explained by the SLP. In AW12, $\boldsymbol{\alpha}_1$, $\boldsymbol{\alpha}_2$ and $\boldsymbol{\alpha}_3$ are the first three *principal components* (PCs) resulting from the *empirical orthogonal function* (EOF) analysis of SLP data from the time period 1850 – 2009. The coefficients $a_1 = 0.0123$ m, $a_2 = 0.0227$ m and $a_3 = 0.0264$ m were determined using a multiple linear regression for the time period 1924 – 2001 between the observed RMSL on the one hand and the three PCs on the other hand (for details see AW12). The time series for the RMSL used is based on the tide gauge data of 15 locations (Fig. 1). For a detailed description see Albrecht et al. (2011) and AW12.

With the result of this model the impact of pressure effects on future RMSL of the German Bight can be analysed. The same area over the North Atlantic as in AW12 is used (30°N – 75°N, 70°W – 20°E, Fig. 2). To apply the model (1), the PCs $\boldsymbol{\alpha}_1$, $\boldsymbol{\alpha}_2$ and $\boldsymbol{\alpha}_3$ 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 performed in AW12 (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 observed SLP data is given on a $5° \times 5°$ grid, thus 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, be the vector of a specific experiment containing the SLP values for the year i. The regression can be formulated as follows:

$$Y_i = \sum_{i=1}^{t} \beta_{ij} P_j, \tag{2}$$

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 von Storch and Zwiers (1998). The vector $\boldsymbol{\beta}_j$ is a time series and corresponds to $\boldsymbol{\alpha}_j$ in the formulation of (1). To perform the regression (2) 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).

3 Results

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

In AW12 the effect of the large-scale SLP-field of the North Atlantic on the RMSL of the German Bight is analysed. To quantify this part for the 21^{st} century the statistical model (1) is applied to future projections of the SLP. For that purpose $\boldsymbol{\alpha}_j$ in (1) is replaced with the $\boldsymbol{\beta}_j$, $j = 1, 2, 3$ specified for each experiment via the regression (2). The coefficients a_1, a_2 and a_3 in the model (1) were calculated in AW12 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 21^{st} 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 the appendix (Figs. 6 to 9). 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. 6 to 9 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[1] (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 of each decade (2011 – 2020, . . . , 2081 – 2090, 2090 – 2099) and 2001 – 2010 are calculated. These differences are called ΔSL_{1120}, . . . , ΔSL_{8190}, ΔSL_{9099}. Fig. 3 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. 3 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 value.

[1]20- and 37-year trends were chosen, because 20 years are a period often considered in sea level analysis in literature and 37 years is twice the cycle of the nodal tide, which might influence decadal trends in the North Sea.

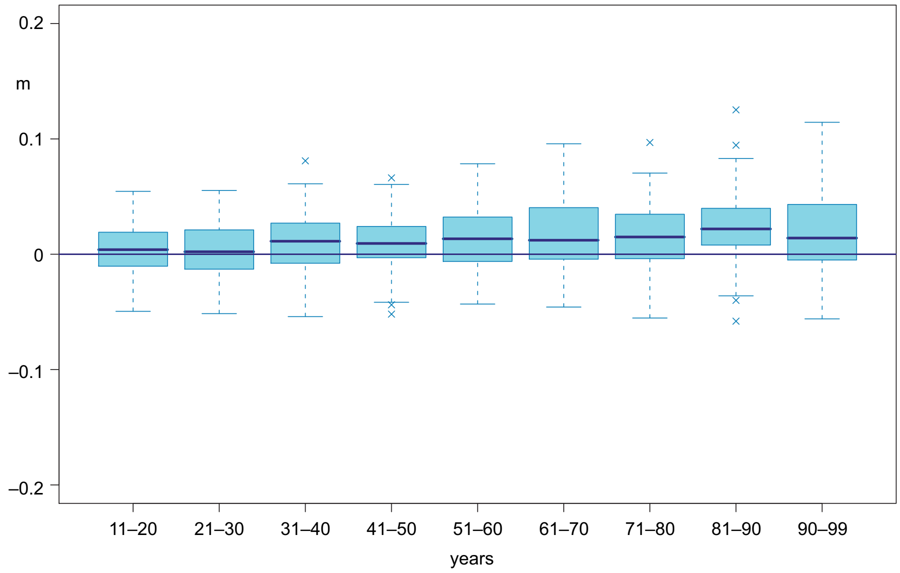

Fig. 3 Boxplots of the decadal differences relative to 2001 – 2010 (ΔSL) for the 21st century. The dark blue lines show the median of each distribution, the boxes border the 25/75-percentiles and the dashed lines cover the entire width of the distribution with the exception that values lower/higher 1.5 times the 25/75-percentiles are regarded as outliers and marked as separate crosses.

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) it can be stated: Using 64 climate experiments constructed with 21 climate models, the emission scenarios commit, SRES A1B, SRES A2 and SRES B1 it is found that 37 experiments show an increase in the RMSL that can be associated with large-scale atmospheric changes in the German Bight by the end of the 21st century.

To better classify this result, it is compared to the results of AW12. The resulting time series of the statistical model (1) shows a linear trend of 0.5 mm/yr for the time period 1924 – 2001 (AW12). Considering 100 years this trend would yield to a rise of 5 cm. That is, the rise in the 21st century is on average suggested to be smaller than in the period 1924 – 2001, but of the same order of magnitude. As a second comparison the method used for the 21st century is applied to the time series representing RMSL changes caused by the large-scale SLP-field for the period 1924 – 2001 from AW12. 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 order of magnitude.

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

As in section 3.1 the projections for the RMSL of the German Bight for the 21^{st} century resulting from the statistical model (1) 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 the boxplots of the resulting distributions are shown. The plots carry the same information as Fig. 3.

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 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 -1.7 cm and 1.7 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 -1.6 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.

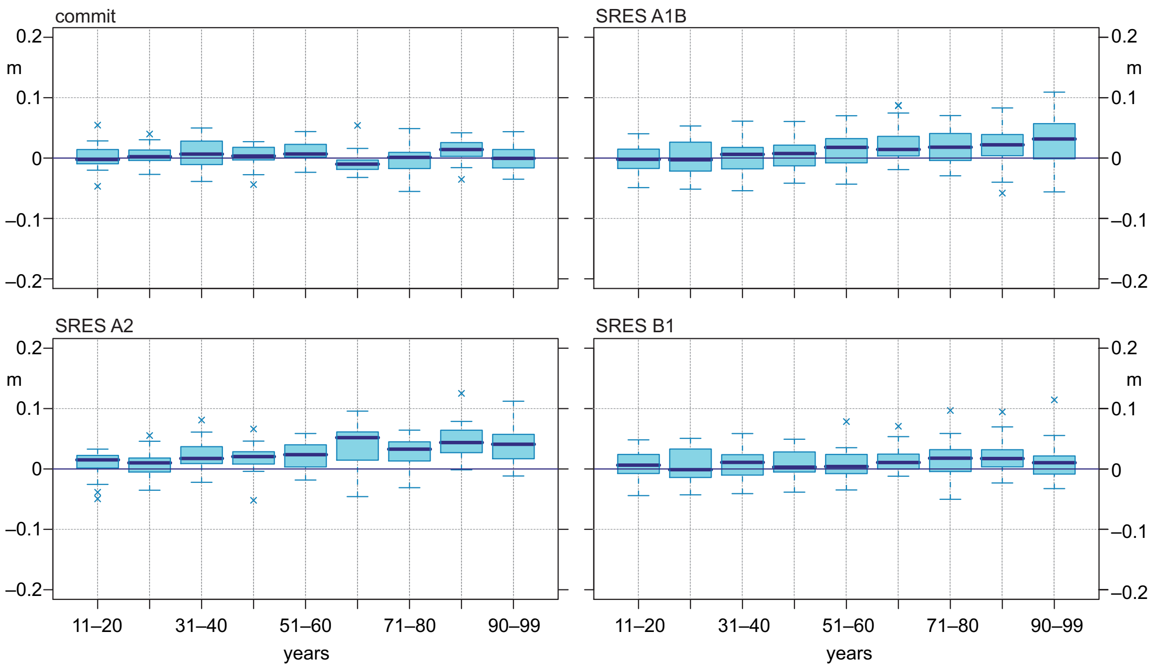

Fig. 4 Boxplots of ΔSL for the 21^{st} century divided by different climate scenarios. Top left: commitment climate change experiment (commit), top right: SRES A1B, bottom left: SRES A2, bottom right: SRES B1. The dark blue lines show the median of each distribution, the boxes border the 25/75-percentiles 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.

4 Summary and Discussion

The impact of large-scale pressure effects on 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 on RMSL is then calculated with the statistical model (1). 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.

AW12 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. 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.

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.

Acknowledgment

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Appendix: additional plots

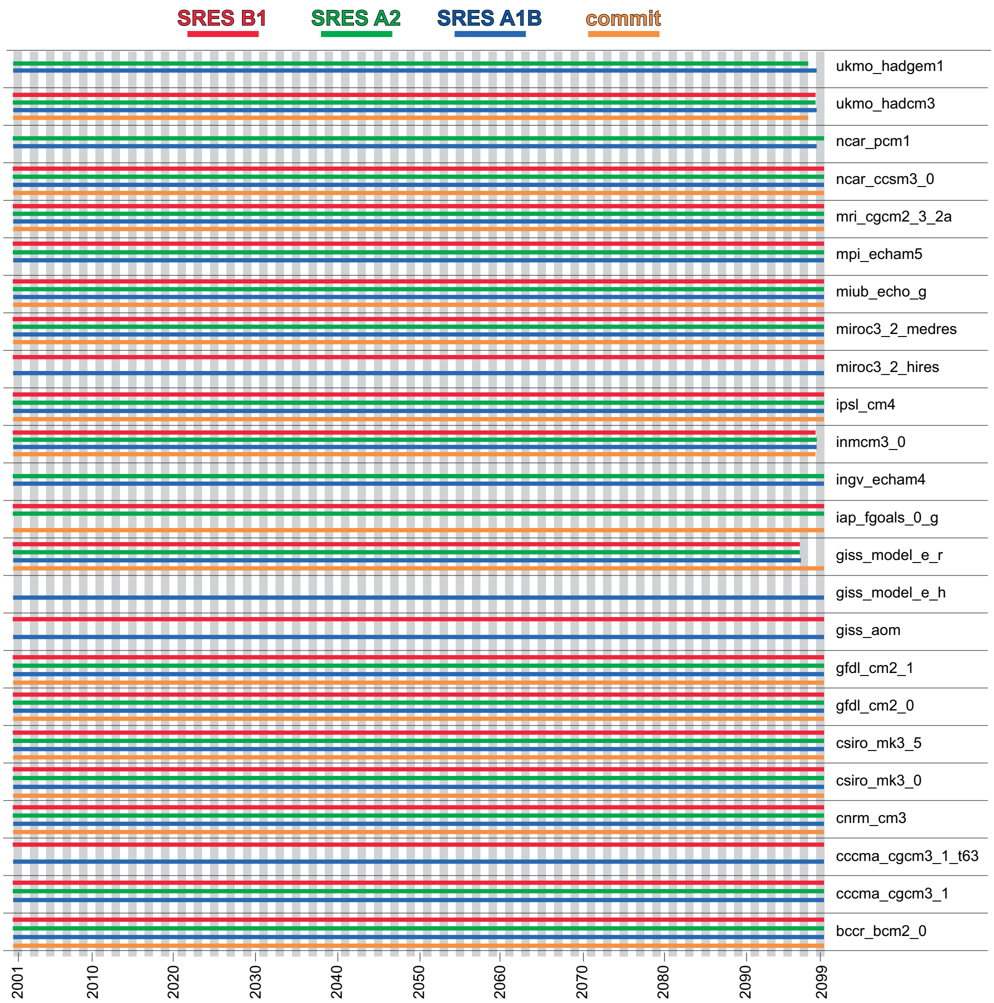

Fig. 5 A list of the climate models (right column) of the CMIP3 multi-model dataset that provide projections for the variable *air pressure at sea level* for the 21st century is shown. The coloured lines show the available experiments and time periods.

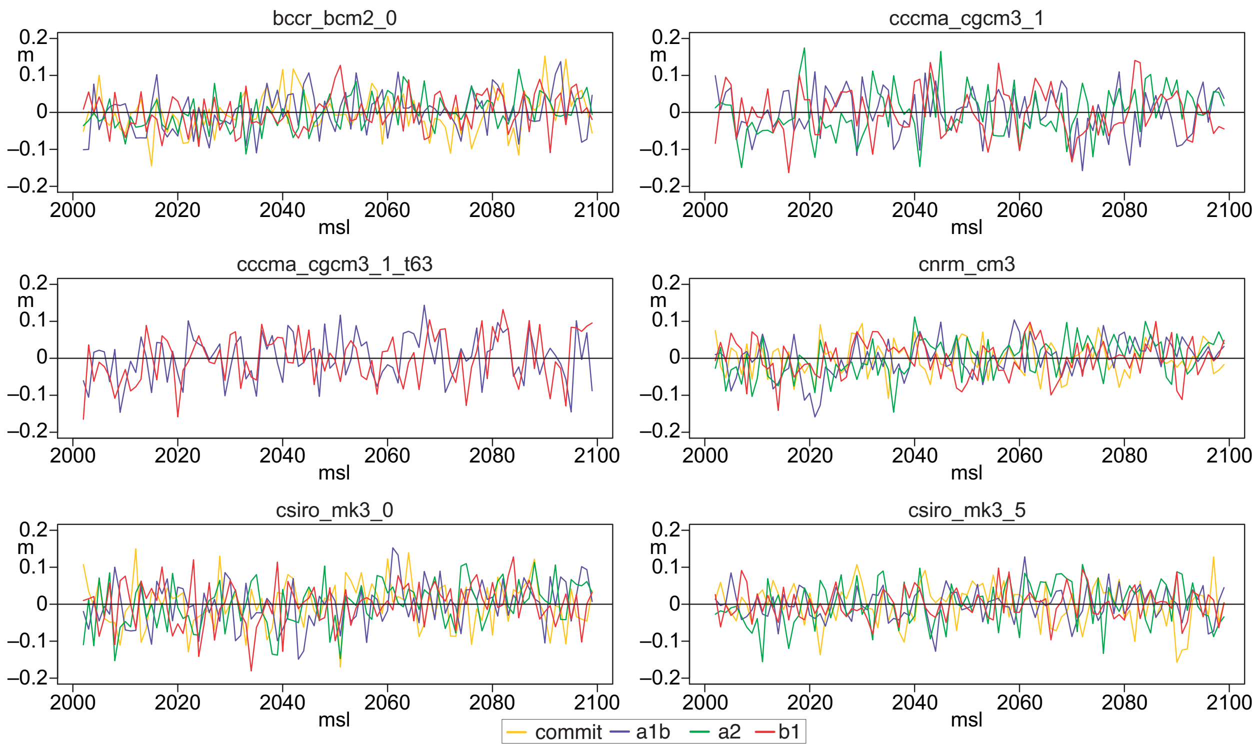

Fig. 6 Results of the statistical model (1) for future RMSL of the German Bight introduced by the large-scale SLP-field over the North Atlantic in the 21st century. The results are given for each climate model and the scenarios are given in different colours. The name of the considered climate model is indicated in the headline.

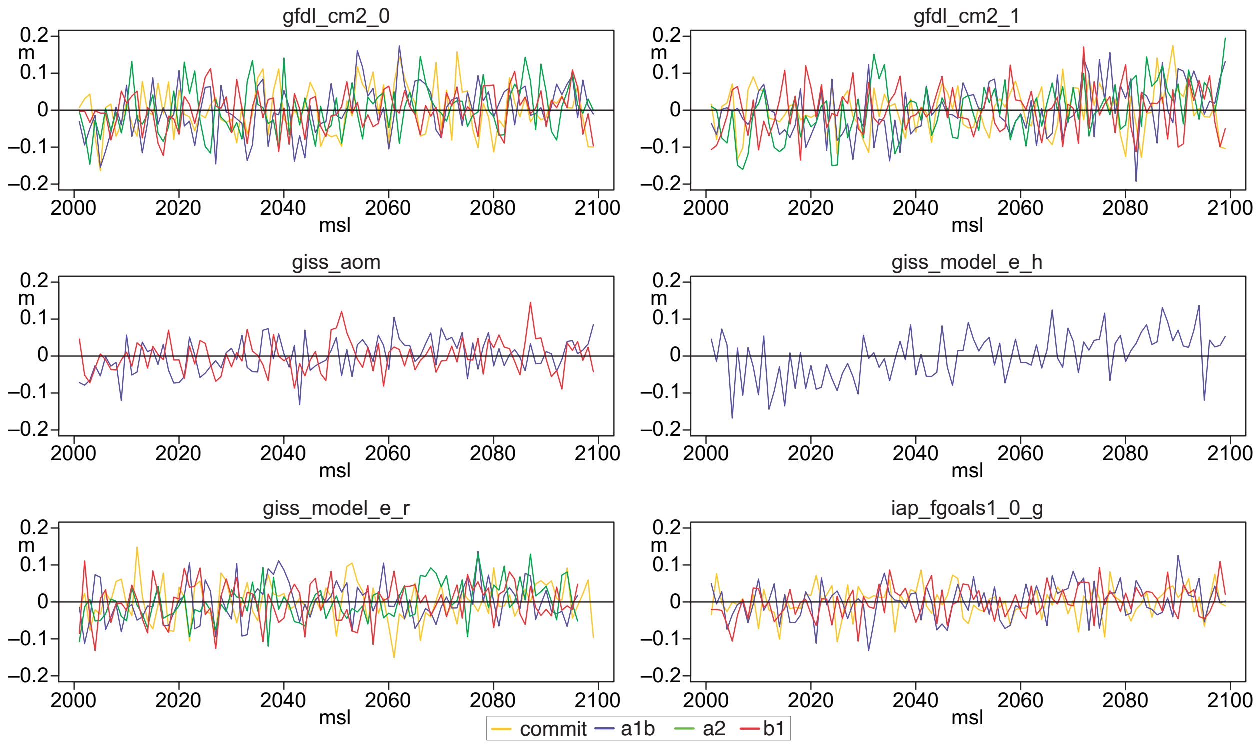

Fig. 7 Results of the statistical model (1) for future RMSL of the German Bight introduced by the large-scale SLP-field over the North Atlantic in the 21st century. The results are displayed for each climate model and the scenarios are given in different colours. The name of the considered climate model is indicated in the headline.

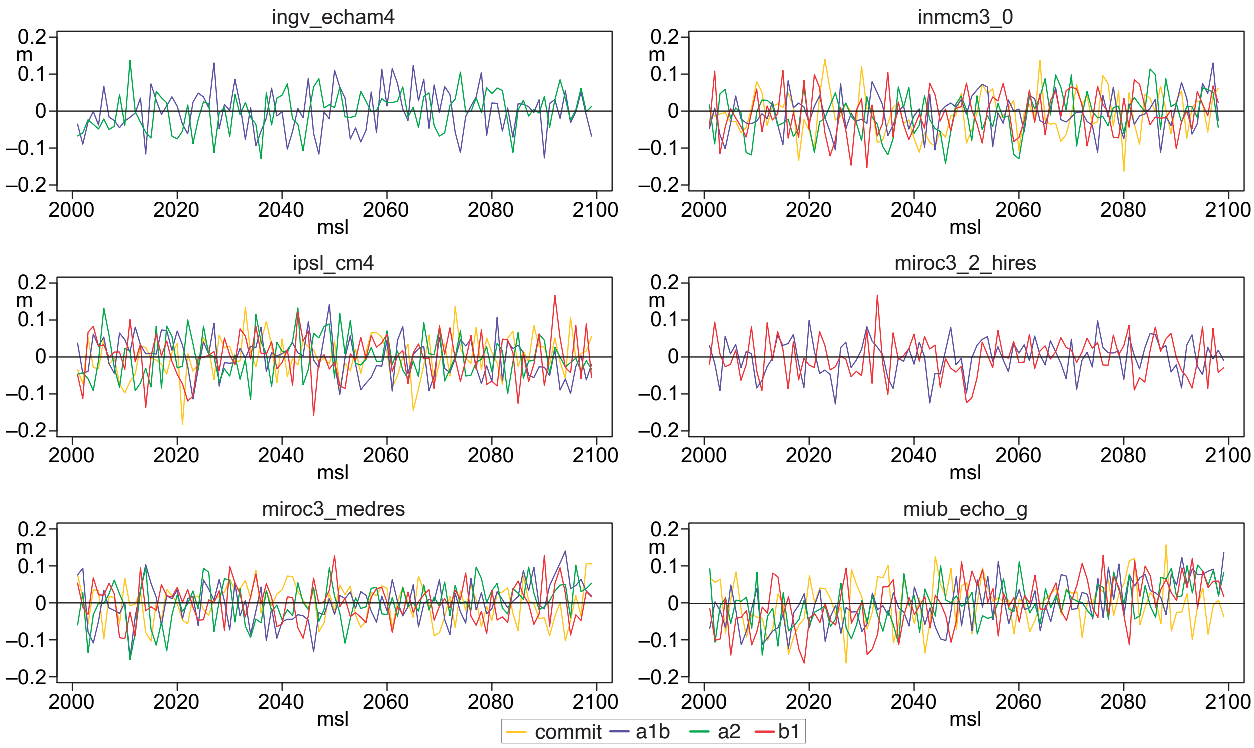

Fig. 8 Results of the statistical model (1) for future RMSL of the German Bight introduced by the large-scale SLP-field over the North Atlantic in the 21st century. The results are displayed for each climate model and the scenarios are given in different colours. The name of the considered climate model is indicated in the headline.

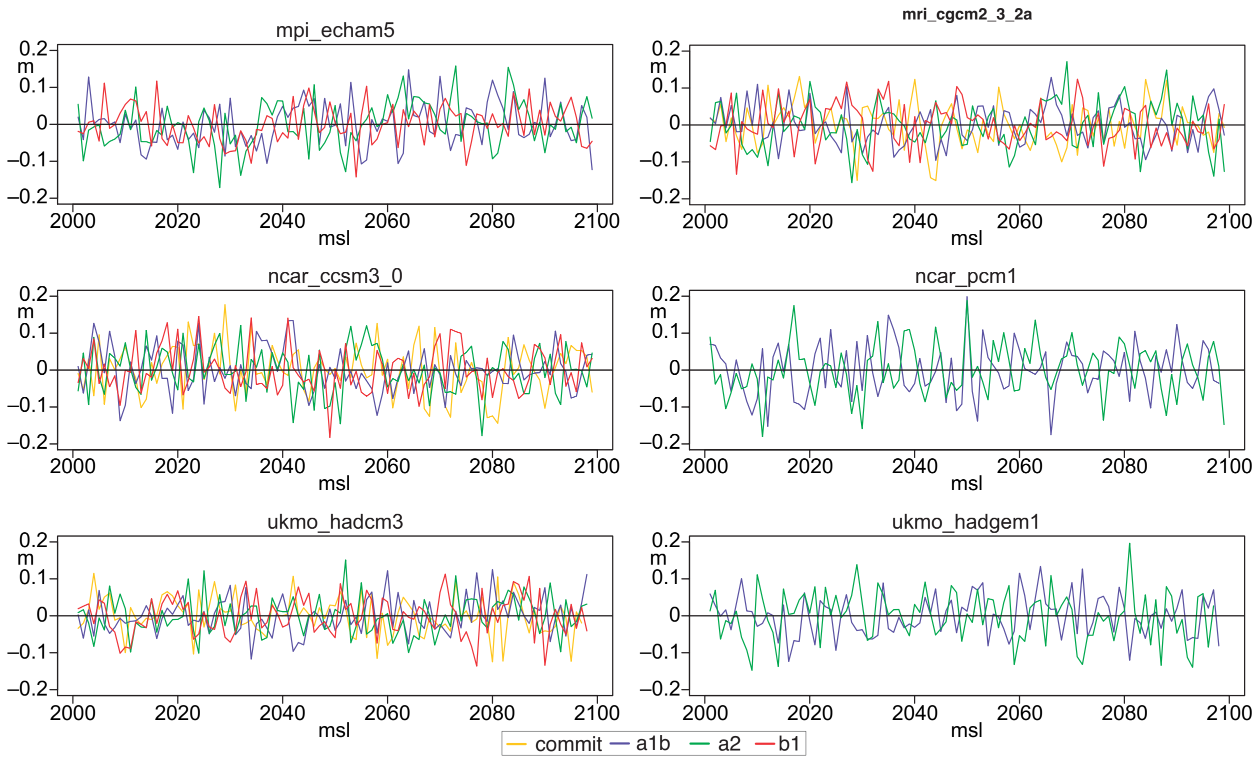

Fig. 9 Results of the statistical model (1) for future RMSL of the German Bight introduced by the large-scale SLP-field over the North Atlantic in the 21st century. The results are displayed for each climate model and the scenarios are given in different colours. The name of the considered climate model is indicated in the headline.

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