Storm surge climatology for the NE Atlantic and the North Sea – where the new RCP 8.5 scenario lead us to?

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Long-term storm surge statistics, especially the behavior of extremes, is relevant for numerous applications including coastal protection, adaptation, management and various off-shore activities. Results from transient storm surge projections for the North Sea and parts of Northeast Atlantic obtained with a hydrodynamic model for the IPCC AR4 SRES A1B and B1 and the new IPCC AR5 RCP 8.5 scenarios have been analyzed in terms of stormy conditions. The new generation of RCP 8.5 projections is integrated and ranged in relation with fairly well assessed AR4 projections to better estimate uncertainties related to the ensemble of climate change projections. For assessing alterations in the storm surge climatology changes in the characteristics of the driving wind fields have been also analyzed as a key factor for the surge development and extremes. For the end of the 21st century it was found that changes in wind speed for the four RCP 8.5 projections are within or slightly exceeding the range spanned by the AR4 projections. Single simulated RCP 8.5 surge projection locally expand the range given by the SRES A1B and B1 projections, e.g. showing the tendency to a decrease in surge heights in parts of the southeastern North Sea for which the A1B and B1 projections give the tendency to an increase. Furthermore, the inter-decadal variations within the 21st century for RCP 8.5, A1B and B1 wind and surge changes are in the same order of magnitude as the absolute changes. Additionally, an increased mean sea level would contribute to the enhancement of storm surge extremes.

1 Introduction

Concentrated population and activities in coastal and near-shore areas together with potential high vulnerability of these areas lead to continuing investigation of the main impact factors, among others storm surge climatology. Because of probable climate change the consideration of past storm surge climatology seems to require extensions in form of future storm surge scenarios. In a warming climate the changes in extreme water level statistics due to altered regional atmospheric conditions as well as rising mean sea level are to be expected. A number of studies dealing with different aspects and parameters of storm surge climatology under future climate scenarios and focusing on different regions of the Northeast Atlantic and the North Sea have been conducted during the past decade (e.g., *Lowe and Gregory 2005; Woth et al. 2006, Sterl et al. (2009), Debernard and Roed (2008), Gaslikova et al (2013)*). Although partly varying in methodology, considered scenarios and time periods, the studies generated a pool of regional and/or local estimates of storm surge climatology for the end of the 21st century. A tendency to a slight increase in storm surge extremes for the southeastern North Sea, strong inter-decadal variability and comparable importance of underlying development scenarios and global/regional models used to simulate the projections are supported by at least one or more studies. Thus, it is important to extend the ensemble of existing storm surge projections in a consistent way for better understanding of uncertainties associated with both existent and new future development scenarios.

The recent Intergovernmental Panel on Climate Change report (AR5 IPCC) provided new socio-economic development scenarios and associated with them climate change scenarios. In particular, RCP 4.5, RCP 6.0 and RCP 8.5 scenarios which address global warming higher than 2°C with respect to pre-industrial conditions were developed (*Stocker et al 2013*). Within the CMIP5 (Coupled Model Intercomparison Project Phase 5) (e.g., *Taylor et al 2012, Knutti et al 2013*) a set of global circulation models (GCMs) has been used to construct an ensemble of future climate projections with prescribed greenhouse gas concentrations for RCP scenarios. Some global projections were downscaled within EURO-CORDEX (Coordinated Regional Downscaling Experiment) with different regional climate models (RCMs) for the Northeast Atlantic and European region. This allowed achieving an improved representation of regional atmospheric features, which is crucial for modelling and assessing the storm-induced water levels in the coastal areas (*e.g. Kotlarski et al 2014*). Present study investigates the extent of changes in regional meteo-marine climatology for the Northeast Atlantic and the North Sea (Fig. 1) under the RCP 8.5 climate change scenario.

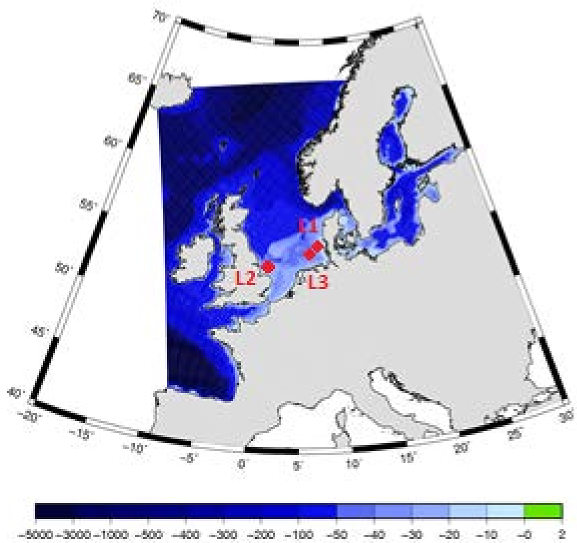

Fig. 1 Model domain and bathymetry for hydrodynamic model TRIM-NP and locations selected for more detailed analysis.

2 Data and methodology

Regional climate change projections used in this study were simulated with the RCA4 regional model and selected driving global models (EC-EARTH, CNRM, MPI-ESM and IPSL) (*http://www.smhi.se/publikationer/publikationer/cordex-scenarios-for-europe-from-the-rossby-centre-regional-climate-model-rca4-1.90272*). For the presented regional analysis the high emission climate change scenario RCP 8.5 from AR5 IPCC (*Stocker et al 2013*) was chosen. Near-surface wind and surface sea level pressure (SLP) fields with 0.11 degree spatial resolution are used for the estimates of atmospheric climatology changes. The data are split into control climate (1971-2005) and future projection (2006-2100) periods, which represent present day and climate change conditions under RCP 8.5 scenario accordingly.

A set of regional climate change projections based on IPCC AR4 scenarios is considered as well. This allows to expand the projection ensemble and to place the new RCP 8.5 scenario in the frame of existing projections. IPCC SRES emission scenarios A1B and B1 (*Houghton et al. 2001; Nakicenovic and Swart 2000*) obtained with ECHAM5-MPIOM1 global model and downscaled with CCLM regional model are used (for detailed description see e.g. *Gaslikova et al 2013*). Each scenario has a control (1961-2000) and a projection (2001-2100) period. Additionally, the global model had been started with two initial conditions, here referred to by _1 and _2, so in total there are four projections: A1B_1, B1_1 with a corresponding control climate C20_1 and A1B_2 and B1_2 with control climate C20_2. Regional near-surface wind and SLP fields are used on an 18 km x 18 km spatial resolution.

The non-hydrostatic shelf sea model TRIM-NP (*Kapitza 2008*) was used in barotropic 2D mode to simulate water levels for the North Sea region. The domain extends from the west of the British Isles to the Gulf of Finland in the east (Fig. 1) and water levels are modeled on a 12.8 km x 12.8 km regular spatial grid. Tidal forcing obtained from the global tidal data set (*Lyard et al 2006*) is used at lateral boundaries. The hydrodynamic model is forced by near-surface marine wind fields at 10-m height and surface SLP from the regional atmospheric climate change projections described above. In particular, SRES A1B_1, B1_1, A1B_2, B1_2 for 2001-2100 and RCP 8.5 based on EC-EARTH global climate projection for 2006-2100 with corresponding control climate simulations (1961-2000 or 1971-2005 respectively) are considered for analysis here. Hourly storm surges are estimated by subtracting the “tide-only” water levels, i.e. dynamically simulated without atmospheric forcing, from the projected water levels. In several previous studies (e.g., *Gaslikova et al 2013, Weisse et al 2015*) it has been shown that the TRIM-NP model realistically represents water level statistics and climatology. In the following description of results the differences between the 30-year means of annual 99-percentiles of projected values and respective control values are referred to as “climate change signal”.

3 Results

3.1 Wind

To assess potential future changes in strong wind conditions the climate change signal for wind speed is estimated for the period 2071-2100 with respect to 1971-2000. 99-percentile is considered as a relevant measure to reflect changes in storminess because the corresponding wind speed values are about 8 Beaufort which are classified as stormy winds. Fig. 2 shows spatial distribution of the differences between strong winds from various scenarios and corresponding control climates. No particular agreement about the potential changes for the eight projections is evident. The SRES scenarios show more consistency in spatial pattern characterized by more or less intense increase of 99th wind speed percentiles in the southern North Sea and a decrease off the Norwegian coast and between Scotland and Iceland. This can be at least partially explained by the fact that these SRES scenarios were initially produced with the same global model. The maximum changes of about 0.6 m/s were found for the A1B_1 realization. The changes in high wind speeds for RCP 8.5 for the North Sea region vary from about 0 or slightly negative in case of EC-EARTH to about 0.95 m/s for MPI-ESM. It needs to be pointed out that in Fig. 2 the changes estimated for the end of the 21st century are shown. However, generally there is no continuous increase in high wind speeds throughout the century (not shown), and for some projections higher wind speed 99-percentiles occur at the beginning or in the middle of the projection period. Fig. 3a depicts the running 30-year means of annual 99-percentiles of wind speed for the location L3 in the German Bight are depicted for the eight considered projections. The RCP 8.5 projections slightly expand the range of potential changes in 99-percentiles contributing to larger increase in high wind speeds in case of e.g. CNRM and stronger decrease e.g. in the EC-EARTH realization. Although most of the projections demonstrate local maxima at the end of 21st century, these values lie to large extend within the inter-decadal variability range. In case of e.g. B1_1 (or CNRM) the largest wind speed 99-percentile changes take place in 2010s (or 2050ies). Also wind direction is an important trigger for development of storm surges, their propagation and local impact. Thus a shift in direction for strong winds can cause changes in extreme surge statistics (e.g. *Gaslikova et al 2013*). The frequency of projected strong westerly winds in the German Bight throughout the 21st century with

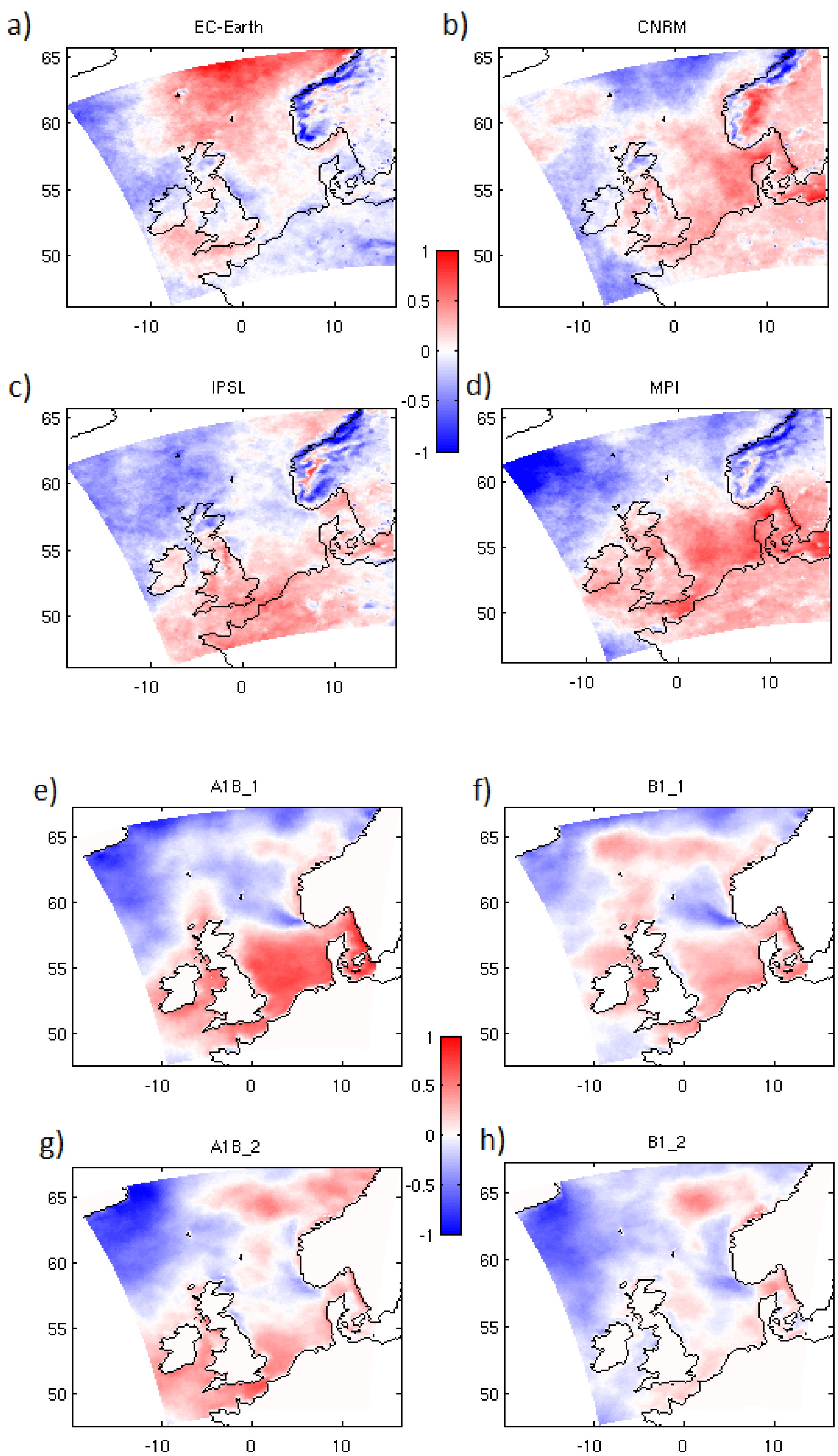

Fig. 2 Differences of mean annual 99-percentiles of wind speed in m/s between projection (2071-2100) and control period (1971-2000). (a-d) RCP 8.5 projected by different models (e-h) SRES scenarios projected with ECHAM5-MPIOM1.

respect to present-day conditions is depicted on Fig. 3b. Apart from the RCP 8.5 EC-EARTH realization, RCP 8.5 realizations show a slight increase towards the end of the 21st century in westerly winds comparable with that in the SRES scenarios. EC-EARTH realization tends to decrease in strong westerly winds. Apart from the RCP8.5 CNRM realization showing a slight increase in westerly winds comparable with that in the SRES scenarios, other RCP 8.5 projections tend to a decrease or almost no changes in strong westerly winds. Also for wind directions (as for wind speeds) the differences between various scenarios and models are comparable with the inter-decadal variability.

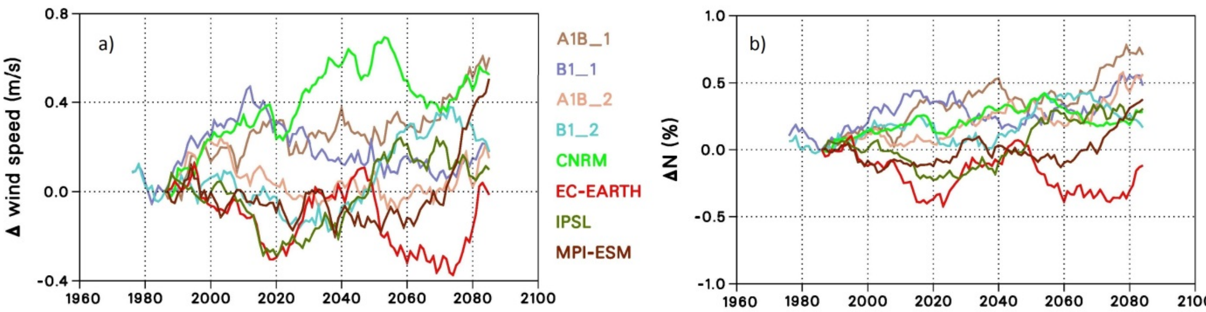

Fig.3 Timeseries of the differences between the 30-year running averages of scenario and 30-year mean of control (1971-2000) signals at L3 for (a) annual 99-percentile of wind speed in meter and (b) annual frequency of strong winds (wind speed > 17.2 m/s) coming from westerly directions (180deg-360deg) in percent of total amount of annual wind records. The wind data are from SRES scenarios (A1B_1, B1_1, A1B_1, B1_2) and RCP 8.5 scenario projected with different models.

3.2 Surge

At first the averaged high storm surges (30-year means of annual 99-percentiles) are in the scope of analysis. Fig. 4 shows spatial patterns of high surge climate change signals for different 30-year time slices within the 21st century. Exemplarily, scenarios A1B_1 and RCP 8.5 are compared. It can be seen that the areas of the strongest increase or decrease in potential future high surges vary both with time and considered projection. For A1B_1 there is a persistent increase of surge 99-percentiles for the south-eastern North Sea throughout the scenario period. For the end of the 21st century such pattern was also found for other SRES realization (not shown, see e.g. *Gaslikova et al 2013*), although local spatial distribution and magnitude varied. The new RCP 8.5 projection shows only slight changes (positive as well as negative) of high surge magnitudes for the south-eastern North Sea and an intensifying decrease for south-western North Sea. The spatial pattern differs significantly from those of the SRES scenarios. The transient timeseries of the climate change signal show strong inter-decadal variability for all realizations for the eastern (L1) as well as the western (L2) parts of the North Sea (Fig. 5). The changes in surge CCS for the end of the 21st century as well as variations of timeseries for selected locations (L1, L2) are in line with high wind speed statistics shown before. There is no one to one match between storm surge and wind statistics because the combination of local wind speed and direction together with the storm track and winds along this storm track form the surges.

Potential changes in extreme water levels are described in terms of 50-year return values estimated by fitting the generalized extreme value (GEV) distribution to the annual maxima timeseries for control and three projection periods of 30 years. The values for the eastern North Sea (L1) together with corresponding 95% confidence intervals are depicted in Fig. 6 (upper panel). Again, as in the case of strong storm surges, the results are dominated by strong inter-decadal variability showing increase (RCP 8.5) as well as uniform behavior (e.g. A1B_1) or decrease (e.g. B1_2) throughout the 21st century. Moreover, the absolute values for the control climate realizations differ as well. It should be pointed out that although the spatial and temporal patterns for average high events (e.g. annual 99-percentiles) and extreme events (50-year return values or annual 99.9-percentiles not shown here) may differ, the strong internal variability is a prevailing factor.

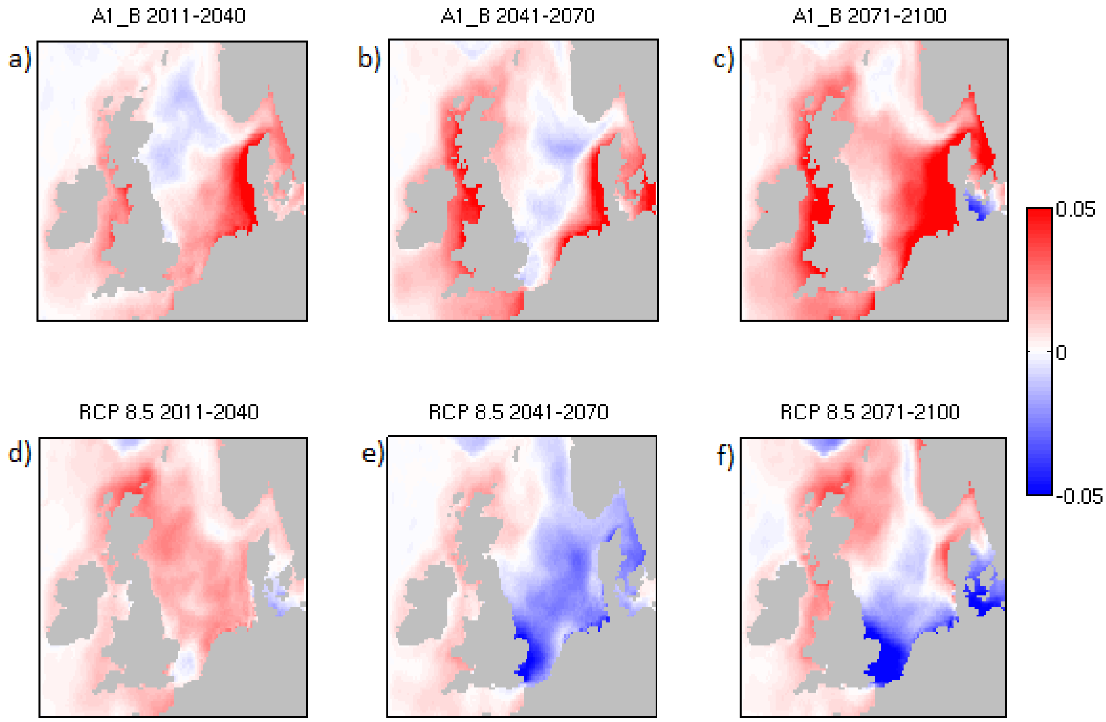

Fig. 4 Differences in mean 99-percentiles of storm surge in meter between projection periods 2011-2040 (a, d), 2041-2070 (b, e), 2071-2100 (c, f) and control period (1971-2000). (a)-(c) A1B_1 projected by ECHAM5-MPIOM1, (d)-(f) RCP 8.5 projected by EC-EARTH.

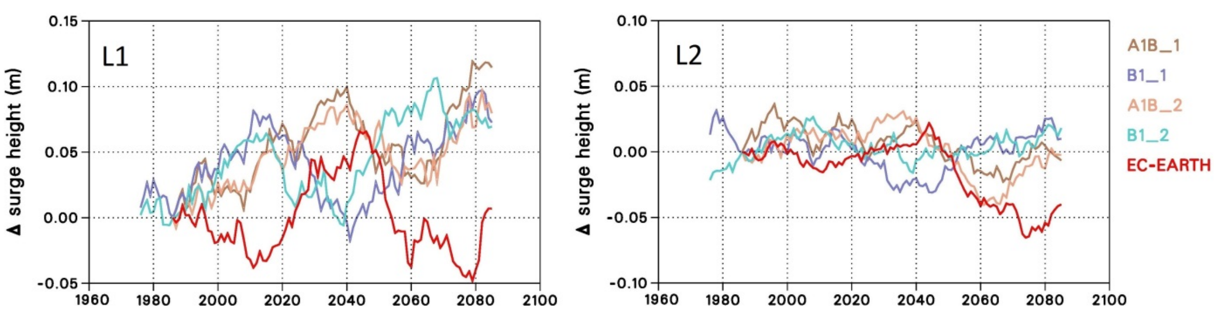

Fig. 5 Timeseries of the differences between the 30-year running averages of storm surge annual 99-percentiles from projection and 30-year average from the control period (1971-2000) simulations for L1 and L2 locations.

In addition to changing atmospheric conditions a sea level rise (SLR) can enhance potential future water levels. Although the main uncertainty in the magnitude of SLR comes from the future glacier melting rate (*Jevreeva et al 2014*), there are also regional differences in the distribution of SLR due to water mass redistribution, differences in steric expansion and spatially various glacial isostatic adjustment (e.g., *Grinsted et al 2015*). Moreover, the interaction between the raised sea level, tidal wave and surges are still subject to analysis (e.g., *Pelling et al 2013, Pickering et al 2012*). Assuming the linear superposition of SLR and water levels for off-shore areas in the North Sea and linear SLR up to 80 cm at in 2100, which corresponds to the median of estimates for global SLR associated with RCP 8.5 future development scenario (*Jevreeva et al 2014*), the 50-year return values for water levels are estimated anew (Fig. 6, lower panel). In this case, the increase in water level extremes at the end of the 21st century with respect to present-day conditions becomes significant for most of the considered projections.

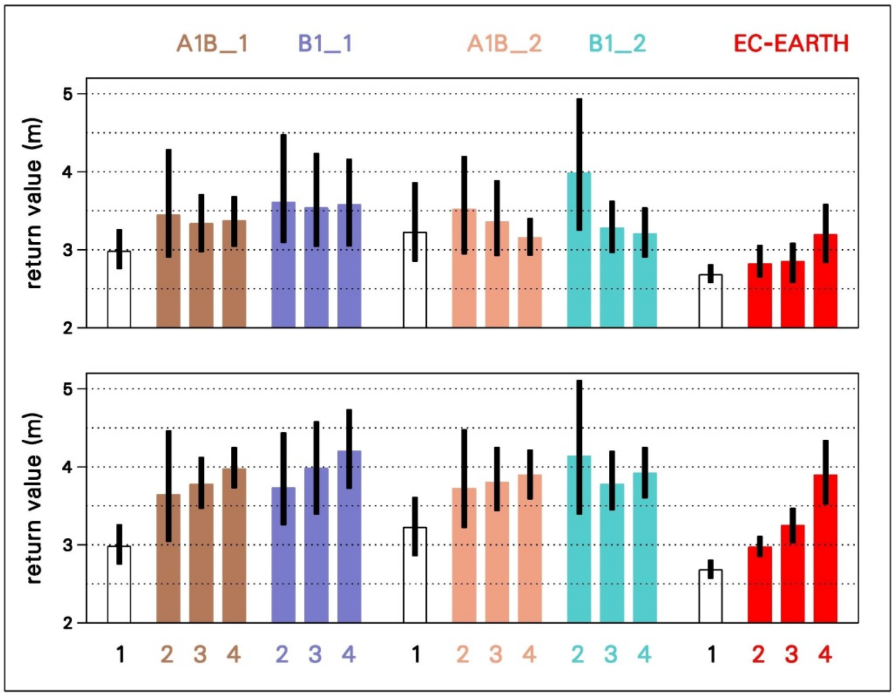

Fig. 6 50-year return values of water level at L1 estimated for control period 1 (1971-2000) and scenario periods 2 (2011-2040), 3 (2041-2070) and 4 (2071-2100). SRES scenarios and RCP 8.5 (top panel) and additionally a linear SLR up to 80cm at the end of 21st century (bottom panel). Black bars show 95% confidence intervals.

4 Summary

Transient future climate realizations for wind and water level have been analyzed to detect possible meteorologically induced changes in future water level conditions in the North Sea and adjacent Northeast Atlantic relative to present day conditions. This set of realizations includes four SRES A1B and B1 scenario based and four (one) RCP 8.5 scenario based projections for wind (water level). The changes in stormy wind speed and wind direction for the end of the 21st century obtained from the new RCP 8.5 projections are mostly within the range of changes given by the SRES projections or somewhat widen this range. In the western and northern North Sea the changes in stormy surge heights are comparably small. For the southern North Sea and southern parts of the German Bight stormy surge heights tend to decrease for the RCP 8.5-EC-EARTH projection whereas they tend to increase in the southeastern parts including the German Bight for the A1B and B1 projections. Thus, the RCP8.5 projection expands the range of wind induced water level changes for the end of the 21st century. It has to be pointed out that only one RCP 8.5 storm surge projection has been simulated and analyzed and that the RCP 8.5 projections based on other models may result in different pattern of changes. Within the 21st century wind speeds and directions as well as surge heights vary on inter-decadal time scales, and the variations for the RCP8.5 projections are in the same order of magnitude as those for the A1B and B1 projections. A rise in mean sea level which is expected to occur more steadily (linear in the shown case) could become, depending on its strength, as or more important than the meteorologically induced changes of the water level toward 2100.

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