Ocean Dynamics (2006) 56: 3–15
DOI 10.1007/s10236-005-0024-3

Katja Woth · Ralf Weisse · Hans von Storch

Climate change and North Sea storm surge extremes: an ensemble study of storm surge extremes expected in a changed climate projected by four different regional climate models

Received: 20 December 2004 / Accepted: 29 June 2005 / Published online: 30 August 2005

Abstract The coastal zones are facing the prospect of changing storm surge statistics due to anthropogenic climate change. In the present study, we examine these prospects for the North Sea based on numerical modelling. The main tool is the barotropic tide-surge model TRIMGEO (Tidal Residual and Intertidal Mudflat Model) to derive storm surge climate and extremes from atmospheric conditions. The analysis is carried out by using an ensemble of four 30-year atmospheric regional simulations under present-day and possible future-enhanced greenhouse gas conditions. The atmospheric regional simulations were prepared within the EU project PRUDENCE (Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects). The research strategy of PRUDENCE is to compare simulations of different regional models driven by the same global control and climate change simulations. These global conditions, representative for 1961–1990 and 2071–2100 were prepared by the Hadley Center based on the IPCC A2 SRES scenario. The results suggest that under future climatic conditions, storm surge extremes may increase along the North Sea coast towards the end of this century. Based on a comparison between the results of the different ensemble members as well as on the variability estimated from a high-resolution storm surge reconstruction of the recent decades it is found that this increase is significantly different from zero at the 95% confidence level for most of the North Sea coast. An exception represents the East coast of the UK which is not affected by this increase of storm surge extremes.

Keywords Ensemble modelling · Dynamical downscaling · Storm surge · Extreme events · Climate change · North Sea

Responsible Editor: Jean-Marie Beckers

K. Woth (✉) · R. Weisse · H. von Storch
Institute for Coastal Research, GKSS-Research Centre,
Max-Planck-Str. 1, 21502 Geesthacht, Germany
E-mail: woth@gkss.de
Tel.: +49-4152-872819
Fax: +49-4152-872818

H. von Storch
Department of Meteorology, University of Hamburg,
Hamburg, Germany

1 Introduction

In historical times, serious floods have severely impacted coastlines of the North Sea. But also more recent floods in the twentieth century have highlighted the current potential for high-impact damage, threatening human life as well as property. The mechanism leading potentially to coastal floods is well understood. Given the configuration of the coastline and the bathymetry, the severity of the storm surge depends primarily on wind speed, wind direction and duration. The meteorological conditions are affected by the path and the velocity of the depression systems, moving across the North Sea. Mainly three different types of meteorological situations leading to potential high storm surges at the southern North sea coast, can be distinguished after Petersen and Rhode (1991): The Jutland-Type, developed over Newfoundland, traveling mostly very fast in a easterly direction from England over the North Sea to Jutland. The Scandinavia-Type is a slow-moving depression system, which forms over Greenland and Iceland and travel towards southeast. The track of the third type, the Skagerrak-Type lies between the other two types, travelling mostly from WNW to ESE (Gönnert et al. 2001).

When winds push water towards the coast, it tends to accumulate into what is commonly referred to as storm surge. If a particular high surge occurs together with a tidal maximum, both effects accumulate and serious flooding can result, depending on the coastal structure and their protection.

For the North Sea, many studies dealing with dynamical modelling of tide-surges exist. Examples are Dolata et al. (1983), Heaps (1983), Flather et al. (1998), Kauker (1998), Langenberg et al. (1999), and Kauker and Langenberg (2000), among others. They have shown that, provided that the meteorological forcing has sufficient accuracy, storm surges and their statistics can be satisfactorily modelled with hydrodynamic models, especially if the focus is on long-term statistics rather than on single events. Comparing simulations with a 3-dimensional baroclinic model (Kauker 1998) and a vertically integrated barotropic model, Kauker and Langenberg (2000) found that the latter ones are sufficient for a reasonable description of storm-related water-level variations along the North Sea coast.

Storm surge models have also been used in recent years to assess the potential effects of changing greenhouse gas concentrations on the North Sea storm surge climate. In the WASA project (Waves and Storms in the North Atlantic; WASA-Group 1998, Langenberg et al. 1999; Flather and Smith 1998) the wind and pressure data originated from two global high-resolution (T106) 5-year simulations, whereas 30-year time slice T106 simulations were used in STOWASUS-2100 project (Stowasus-Group 2001). These results show that under enhanced greenhouse gas conditions, an increase by up to 10% in extreme wind speeds in the North Sea and the Norwegian Sea may take place and can result in an increase in surges extremes of the same magnitude. Lowe et al. (2001) were the first, who applied the two-step procedure of a dynamical downscaling of coarse grid general circulation model (GCM) data followed by an integration of a hydrodynamical model. Their results indicate an increase in surge extremes statistically significant along a sizable fraction of the UK coastline under assumed future climate conditions.

Such numerical model integrations have the advantage to generate information at locations and for periods (such as under climate change conditions) without observations. Another advantage of model integrations is the high temporal sampling rate, every hour or even less, while observations are often only available for tidal maxima and minima. To have full access to this advantage, the meteorological forcing data must also be available with high temporal resolution and not just every 12 or 6 hours, as is common in many RCM simulations.

In the present study we follow and extend the way, the previous studies have pursued. Based on high-resolution regional wind and pressure conditions, dynamically downscaled from global General Circulation Model (GCM) output, the present study differs from these previous approaches by using an *ensemble* of regional atmospheric conditions. The ensemble is provided by a series of different RCMs, which are all forced with the same GCM. The wind and air pressure data are provided by the partners of the EU PRUDENCE project (Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects; Christensen et al. 2002), for paired 30-year "control" (1961–1990) and "climate change" (2071–2100) simulations. We use these ensemble members to drive a hydrodynamic tide-surge model at high spatial and temporal resolution. In contrast to previous work this allows us to not only assess the response of the storm surge model to a specific RCM but to systematically investigate similarities and differences in the storm surge climate due to the use of different state-of-the-art RCMs, a major goal of the PRUDENCE project.

Our study considers changes in storm surge *extremes* as only strong storm surge events endanger the coastal structure and the biotic and abiotic environment there. By definition, extreme values are rare. Two main methods are mainly used to characterize such extreme events, namely either the analysis of the largest events in a long series, or an extrapolation by fitting shorter data sets to a particular extreme value distribution (e.g., Coles 2001). The various RCM forced simulations provide us with long series of 30 years length, so that we can avoid the "extreme value statistics" extrapolation—as long as we are not asking for large return periods—which is rather sensitive to the choice of the distribution and the fitting procedure. Instead, we are able to provide a phenomenological characterization based on simple characterization of those distributions and underlying properties by means of high percentiles.

The analysis in this study is dealing only with the impact of changing regional wind conditions in the vicinity of the North Sea. In this way, two effects, which we believe to be minor for the *change* of surge statistics, have been neglected. These are the rise in mean sea level and the effect of so-called external surges.

In the context of future mean sea level heights, the IPCC expects a rise due to thermal expansion and the changing volume of glaciers and ice sheets for the end of this century (Houghton et al. 2001). In the A2 SRES scenario, which we use in this study, the rise due to thermal expansion could be about 40 cm, loaded with a large uncertainty (Houghton et al. 2001). For our study, the relevant question is if the storm surge heights are sensitive to changes in mean sea level. This was studied in detail by Kauker (1998) and Lowe et al. (2001), who found no significant differences in simulations with and without elevated mean sea level. The mean sea level rise essentially adds to the storm surge heights.

External surges are generated under certain weather conditions in the North Atlantic and propagate into the North Sea, pushing additional water masses into the basin. In our set-up, we cannot account for this effect. Instead, we assume that the intensity and frequency of external surges is not significantly altered in the scenario of future conditions. However, this assumption may not be fully justified: most recent studies indicate a strengthening North Atlantic storm track projected in GCMs for the A2 SRES scenario (e.g., Fischer-Bruns et al. 2005), even though some studies envisage other developments (e.g., Rauthe et al. 2004). A strengthening of the storm track would possibly lead to more frequent external surges in a future climate and, thus, the neglected effect of external surges would lead to an underestimation of the change of storm surge extremes.

The present paper is organized as follows: in Sect. 2 the hydro-dynamical model and the atmospheric data used to drive the tide-surge model are described and the applied statistical methods are introduced. Results and discussion follow in Sect. 3, which is divided into two parts: in Sect. 3.1 the control climates of the present-day atmospheric forcing (near surface winds and SLP) and those of the modelled storm surges are analysed and compared with the climates obtained in hindcasts of corresponding decades. Changes in the atmospheric forcing and subsequently in the storm surge distributions in a perturbed climate described by the A2 SRES scenario are analysed and discussed in Sect. 3.2. We conclude in Sect. 4.

2 Methodology and data

2.1 Surge model

The dynamical downscaling of storm surges is carried out by driving the numerical tide-surge model TRIMGEO (Tidal Residual and Intertidal Mudflat; Casulli and Catani 1994), a depth average tide-surge model, using geographical coordinates. This barotropic version of TRIMGEO is based on the shallow water equations with parameterizations for bottom friction and surface stress (Casulli and Catani 1994; Casulli and Stelling 1998). The equations are integrated on an Arakawa-C grid using a robust semi-implicit scheme with a time step of 10 min.

The model domain encloses the north-west European continental shelf from 4.25°W to 13.42°E and 48.55°N to 58.75°N with a mesh size of 6′×10′ in latitude and longitude, which corresponds to a grid cell size of about 10×10 km^2. Figure 1 shows the TRIMGEO integration area and the bathymetry. The bathymetry was provided by the German Federal Maritime and Hydrographic Agency (BSH) and is similar to the one used in their operational model.

The model domain has open boundaries in the North, along a line between Wick (UK) and Karmøy (N), and through the English Channel in the West; East of the Danish islands, along a line between the southern tip of Sweden and Rügen, a German Island, the domain is artificially closed, which is acceptable since reflecting waves, coming from that model boundary can hardly affect the North Sea area. A constant water level and net influx of 0.01498 m^3 s^{-1} from the Baltic Sea (Ospar Commission 2000) are prescribed. Following the operational procedure at BSH constant freshwater influxes from the 33 largest rivers are specified as climatological annual means. For imposing the astronomical tides, sea level anomalies calculated from the amplitudes and phases of 17 partial tides are prescribed along the open boundaries. These amplitudes and phases as well as corrections for each year were adapted also from BSH. For the northern model boundary, long-term observations from buoys were used to derive the tidal components, for the boundary model grid cells in the English Channel, published harmonic composites were adopted (e.g., Chabert d'Hieres and Provost 1978). For comparability, all TRIMGEO model runs are based on the same astronomical tidal coefficients and corrections.

The model was run with a calendar year consisting of 360 days since all RCM simulations simulate years of 360 days—a feature inherited from the driving global—the so-called climate mode. The tides are specified in continuous order so that dates of tidal minima and maxima in terms of real world 365-day calendar no longer fit to the 360-day calendar of the models. This is, however irrelevant, as the simulated weather stream in the RCM simulations cannot be tied to specific hours or days; their timing must be considered random relative to the timing of the tides.

2.1.1 *Model validation*

The model is validated by comparing model "hindcast" results of reconstructed water levels with statistics derived from a local tide gauge and by comparing percentiles along the 10-m depth line with simulations with an operational storm surge prediction model.

This "hindcasts" consist of two steps: first a regional reanalysis of atmospheric conditions was prepared (Feser et al. 2001) using the REMO model (Jacob 1995) with spectral nudging (SN-REMO; von Storch et al. 2000). The resulting marine wind and air pressure fields were found to be homogeneous and of satisfactory quality (e.g., Weisse and Feser 2003; Sotillo 2003; Weisse et al. 2005). In a second step, these "analysed" winds and air-pressure field were fed into the tide surge model.

The principle capability of the tide-surge model TRIMGEO to reasonably reconstruct observed regional sea level was recently demonstrated by Aspelien and Weisse (2005). They have shown that sea level heights and surge for the southern North Sea shelf for the period 2000–2002 are reasonably reproduced by the present model setup. Thus here we have limited ourselves to some additional validation focusing on the statistics of storm surges as discussed in the present paper. Figure 2 shows time series of the annual winter 99th percentile surge (DJF) for Cuxhaven derived from the model hindcast and from the local tide gauge data from 1958 to 2000. The hindcast percentiles fit to the percentiles derived from observations with a correlation coefficient of 0.93 and a root mean square error of 19 cm, which is mainly caused by 2 years in which the model severely underestimates the observed 99th percentile, in particular the very stormy winter 1975/76.

Additionally, we compare the performance of TRIMGEO in simulating extremes in grid boxes along the 10-m depth line of the model-bathymetry. This is motivated by the fact that our analysis of possible future conditions is focusing on just these gridboxes (see Sect. 2.3). However, observation data do not exist for this

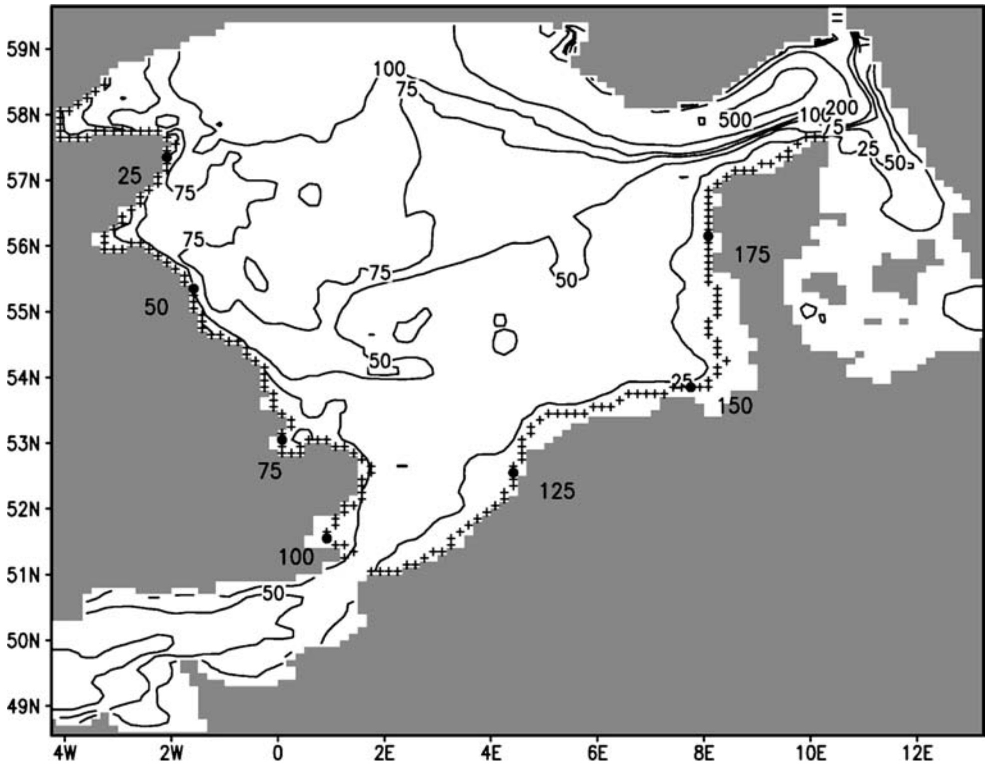

Fig. 1 Model domain of the tide-surge model TRIMGEO: the bathymetry (*isolines*) and the 196 near coastal grid cells (*crosses*) located on the 10 m bathymetry line along the North Sea coast beginning with 1 in Scotland and ending with 196 in Denmark

10-m depth line. Therefore we compare the TRIMGEO hindcast to a hindcast done with the TELEMAC-2D model of Bundesanstalt für Wasserbau (BAW). TELEMAC-2D is used by BAW for daily operations and is set up with high-resolution refinements along the coast, leading to a spatial resolution of down to 80 m. A TELEMAC-2D hindcast was performed with the same meteorological forcing as described above (A. Plüss, personal communication). An additional feature of this simulation is that it assimilates the actual water-level data from Aberdeen. This model has been found to reliably reproduce the observations taken at a number of different tide gauges. An extensive validation has been performed by e.g., Hervouet and Van Haren (1996) or Plüss (2003), with good results.

Figure 3 shows the mean of the annual 99th percentiles (based on 1 hourly data, winter month), derived from both, the TRIMGEO and from the TELEMAC-2D hindcast (1961 to 1990) along the same 10-m depth line. Differences occur along the Eastern coastline of UK. There, the advantage of assimilating Aberdeen-observations into TELEMAC-2D becomes obvious. Along the 10-m line of the continental North Sea coast, TRIMGEO deviates only by less than 10 cm from

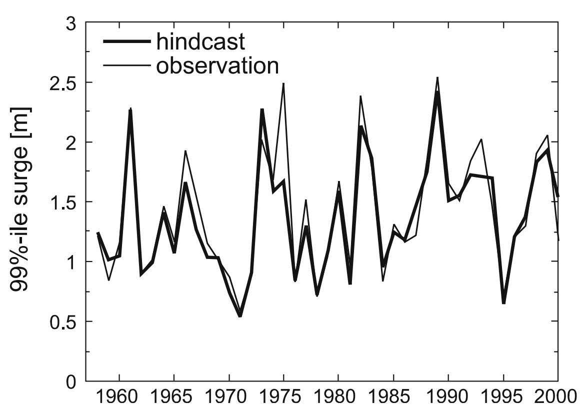

Fig. 2 Inter-annual mean of the 99th percentile of water level/surge (DJF) for Cuxhaven for the period 1958–2000 (unit: m). *Bold line*: modelled hindcast (TRIMGEO); *thin line*: tide-gauge observations. Calculations of percentiles are based on 1 hourly data.

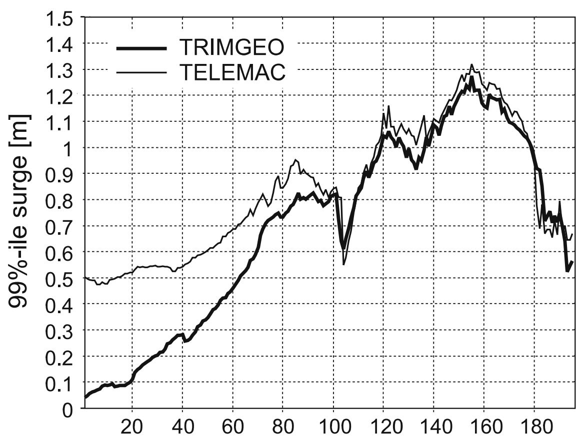

Fig. 3 Inter-annual mean of the 99th percentile of water level/surge (DJF) for the control period 1961–1990 (unit: m). *Bold line*: TRIMGEO; *thin line*: TELEMAC. Calculations of percentiles are based on 1 hourly data. Depicted are grid cells located along the 10-m depth line along the North Sea coast (for the numbering of locations, refer to Fig. 1)

TELEMAC-2D, likely reflecting the missing effect of the external surges in TRIMGEO. The overall spatial patterns are matching very well.

We consider the encouraging performance of the TRIMGEO hindcast as sufficient evidence for allowing TRIMGEO to be considered an adequate tool for studying the implications of possible future climate change on the statistics of storm surges, in particular along the southern and eastern shores of the North Sea.

2.2 Atmospheric driving data

This study uses near surface winds and sea level pressure as simulated by four RCMs, namely HIRHAM (High-Resolution regional model, with ECHAM physics) from the Danish Meteorological Institute DMI, RCAO (Rossby Centre regional Atmosphere-Ocean model) from the Swedish Meteorological and Hydrological Institute SMHI, the CLM (Climate version of the ‘‘Lokal-Modell’’, derived from the Limited area Model (LM) of the German Weather Service DWD) of GKSS, and REMO (Regional Model) of the Max-Planck Institute of Meteorology. All simulations were prepared for present-day (1961–1990) greenhouse gas concentrations and for future conditions (2071–2100) based on the Intergovernmental Panel on Climate Change A2 SRES emission scenario (Houghton et al. 2001).

HIRHAM, REMO and CLM are stand-alone atmosphere models, RCAO (Döscher et al. 2002) is a coupled atmosphere-ocean model, which incorporates the Rossby Centers regional atmosphere model RCA (Rummukainen et al. 2001; Jones et al. 2004) and their ocean model RCO (Meier et al. 2003).

Concerning the model dynamics the models have two origins. HIRHAM [an updated version of HIRHAM4 (Christensen et al. 1996)] and RCA are both off-springs from the regional weather forecast model HIRLAM (High-Resolution Limited Area Model; Machenhauer 1998; Källén 1996). CLM and REMO (Jacob et al. 1995) are climate versions of the weather forecast model developed and used by the DWD. The parameterizations of subgrid-scale processes (‘‘physics’’) of HIRHAM and REMO are based on the global atmospheric model ECHAM4, developed by Roeckner et al. (1996). The parameterizations from RCAO are mainly taken from HIRLAM. Most of the parameterizations in CLM are taken from the LM, but some, in particular with respect to the soil processes, are improved.

All four RCMs are set up for running on a rotated grid with a mesh size between 0.44 and 0.5°. This mesh size corresponds to about 50 km^2 over the North West European Shelf Sea. All four regional climate models were forced in lateral sponge zones with data prepared by the Hadley Center GCM HadAM3H (high-resolution global atmosphere model) under recent and future climate conditions. Sea ice coverage and sea surface temperature (SST) are the same as used by the HadAM3H model in HIRHAM, CLM and REMO. SST and sea ice coverage for the control run were derived from observations, which were processed by the Met Office Hadley Centre into a data set of monthly fields on a 1-degree latitude-longitude grid (Rayner et al. 2003). For the future time-slice SSTs from the coupled HadCM3 (Hadley Centre's Third generation Coupled Ocean-Atmosphere GCM) SRES A2 simulation (2071–2100) have been used with a statistical correction obtained from the present-day observed SSTs preserving the observed SST variability. An exception is the RCAO model, which is coupled with the Baltic Sea model so that SST and sea ice coverage are computed directly in interaction of these model modules.

To drive the tide-surge model, 6 hourly, instantaneous values of pressure at mean sea level and the horizontal wind components at 10 m height were extracted from each of the RCM simulations over the tide-surge model covering domain. These forcing data were interpolated linearly to match with the finer space-time grid of the hydro-dynamical model TRIMGEO.

The usage of 6-hourly is not optimal, but is unavoidable as the RCM output has been stored only once every 6 h. In case of the hindcast with TRIMGEO, hourly SLP and wind analysis prepared by SN-REMO (Feser et al. 2001) have been used. Hourly data are undoubtedly much better than 6-hourly data. We found the magnitude of the 99.5th surge percentile increased by about 10% when hourly forcing data are used instead of 6 hourly (not shown). We believe, however, that the effect of a too coarse temporal resolution of the forcing fields will not significantly bias the estimation of the *change* of surge statistics.

2.3 Processing results

The object of investigation is not the total water level at a certain time and location, but wind and pressure-related surge residuals, i.e., the deviations of the overall water level from the tide. Thus an additional ‘‘tidal run’’ was undertaken, using the same model setup, forced only by water- level variations at the open boundaries representing the global astronomical tidal dynamics. Resulting water levels of that ‘‘tidal run’’ were subtracted from the water level obtained in the control and climate change experiments, forced with the same astronomical tidal dynamics. Thus, nonlinear interactions of velocities with the tides are described in the meteorologically forced run. When subtracting the ‘tide-only’ run, all remaining phenomena are understood as being related to the forces exerted by wind and air pressure, including the interaction with the tides.

The state-variables (vertically averaged velocity, water level) are stored for all ‘‘wet’’ grid points of the model domain every 30 min. The first month of each simulation was discarded to account for potential spin-up effects.

Since most damage is expected in the coastal zone, storm surge residuals were analysed only along the

North Sea coastline (Langenberg et al. 1999). To avoid inconsistencies due to near-shore shallow water effects, which are not resolved in TRIMGEO, the analyses based all on a selected line, representing the 10-m depth line in the model bathymetry. This depth line comprises 196 grid cells ranging from the North of Scotland along the southern North Sea coast (Belgium, Netherlands and Germany) to the northeastern top of Denmark near Skagen (Fig. 1). As most severe storm surges are generally expected during the winter season, all statistical analyses in this study were carried out only for December, January and February (DJF), so that we get 29 seasons for each of the 30-year-long-time slice experiments, beginning with the first season Dec1961/Jan1962/Feb1962 and ending with the last season Dec1989/Jan1990/Feb1990 for the control runs. For the scenario time-slice the first season is Dec2071/Jan2072/Feb2072 and the last season is Dec2099/Jan2100/Feb2100.

In our study the principle statistical approach is a straightforward description of extreme climate conditions by high and low percentiles of the distribution.

In that way, we consider the 29-year means of intra-annual percentiles, namely the 99th percentile of wind speed at 10 m height and the 1st percentile for air pressure as characteristic quantities. Since a 90-day DJF season contains 4×90 = 360 intervals of 6-hour length, the 99th percentile is the wind speed, which is exceeded in 1% of 360 cases, i.e., 3 times in a season. Similarly, air pressure is lower than the 1st percentile only during 18 h (3 times).

The comparison of the storm surge residuals in the different experiments is based on the 99.5th percentile. In this case, we consider again 90-day winter seasons (DJF) but with 0.5-hourly data, so that per DJF season we have 90×48 cases. To have sufficiently rare events, we use the 99.5th percentile, which is exceeded on 22 half hours (approximately 12 h) in each DJF season. We calculate this percentile for each of the 29 seasons and determine the mean value of these 29 percentiles.

We define an extreme event as a period covering one or more half hourly intervals with surge levels reaching or exceeding the 99.5th percentile. The average duration and the number of such extreme storm surges are also determined. These temporal characteristics of storm floods are important parameters in the context of coastal protection.

3 Results and discussion

3.1 Control simulations versus hindcast

Before we assess changes in water-level statistics and in the atmospheric forcing induced by increasing greenhouse gas concentrations in a HadAM3H/RCM world, we want to examine the similarity of the control simulations, which are supposed to be representative for the 1961–1990 period, with the 1961–1990 SN-REMO hindcasts (Feser et al. 2001) in terms of atmospheric conditions and surge statistics (see Sect. 2.1.1).

3.1.1 Atmospheric forcing

Figure 4 shows the statistics of the extremes in deep sea level pressure as well as the extreme near surface wind as obtained in the atmospheric SN-REMO hindcast, described as the 29-long-year mean of the 1st percentile (SLP) and as the 99th percentile (10 m wind speed), respectively. In the hindcast, a gradient of sea level pressure from 970 hPa (North–West) to 982 hPa (South–East) of the North Sea area is found. Wind speeds between 17 and 20 m/s are produced, increasing from South to North.

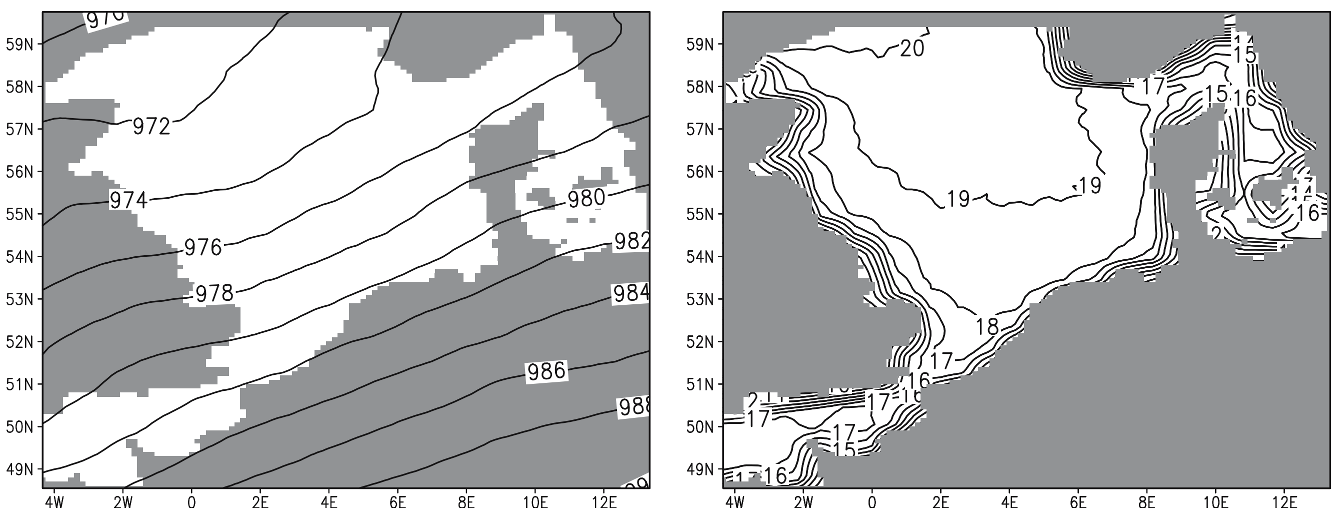

Fig. 4 Inter-annual mean of the 1st percentile sea level pressure (*left hand side*) and of the 99th percentile 10 m wind speed (*right hand side*) derived from REMO_SN, hindcast, 1996–1990. Units: hPa (SLP) and m/s (wind speed). Calculations of percentiles are based on 6 hourly data (DJF)

All four RCM control simulations show an overestimation of the deepest sea level pressures (Fig. 5). The largest deviations are found for the HIRHAM and RCAO runs and vary between about 3.5 and 6 hPa. For most of the control simulations, differences increase from West to East. An exception is provided by the CLM control run where the difference pattern is more North–South oriented with smallest differences of about 0.5 hPa occurring in the northern and largest differences of about 4.5 hPa occurring in the southern part of the model domain.

Corresponding to the overestimation of the lowest surface pressures, extreme near-surface wind speeds are underestimated in three of four control simulations compared to the hindcast (Fig. 6). Again, the CLM simulation is an exception. Compared to the hindcast, the 99th percentile is about 0.5 m/s higher in the southern and the south-western part of the analysed domain and the differences increase up to about 1.5 m/s in the north-eastern part. The spatial structure of difference in high wind speeds is similar for all other control simulations. While REMO underestimates severe wind speeds slightly by about −0.5 m/s in the Northern and about −1.5 m/s in the southern North Sea, HIRHAM and RCAO show larger differences in the order of about −2.5 m/s over a large fraction of the North Sea.

3.1.2 Surge residuals

Storm surge residuals derived from the TRIMGEO runs under control climate conditions and from the hindcast are compared in terms of their 99.5th percentiles (Fig. 7), Fig. 8 shows the mean frequencies and the mean durations of extreme events (i.e., episodes when this percentile is exceeded).

In the hindcast simulation, lowest storm surge extremes are generally found along the UK coast (Fig. 7). We had seen in Sect. 2.1.1, that TIMGEO underestimates surge levels along most of the UK eastern shore

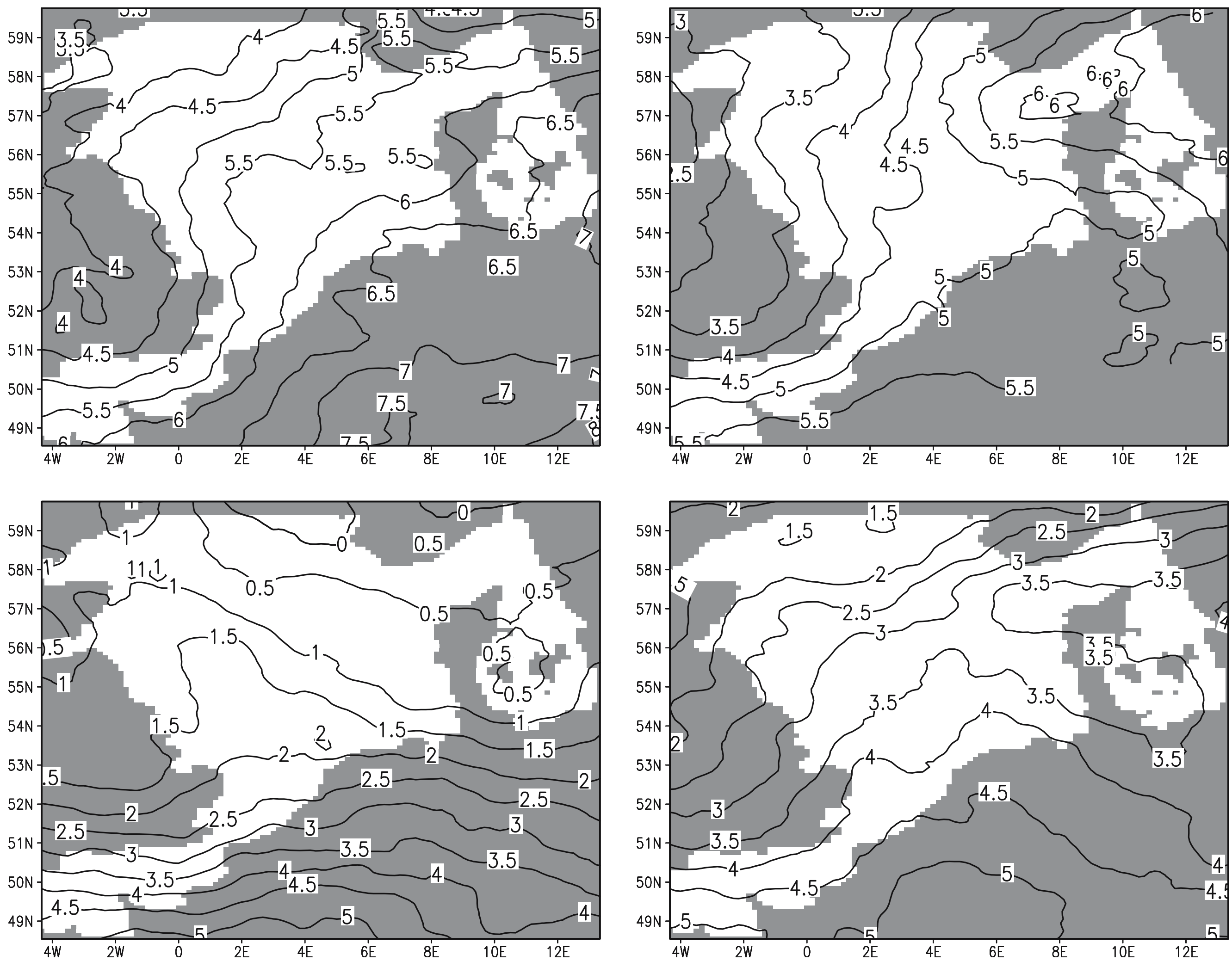

Fig. 5 Biases of the inter-annual mean of the 1st percentile of sea level pressure in the four considered models relative to REMO_SN hindcast in the control period 1961–1990 (unit: hPa). *Upper left*: HIRHAM, *lower left*: CLM, *upper right*: RCAO and *lower right*: REMO. Calculations of percentiles are based on 6 hourly data (DJF)

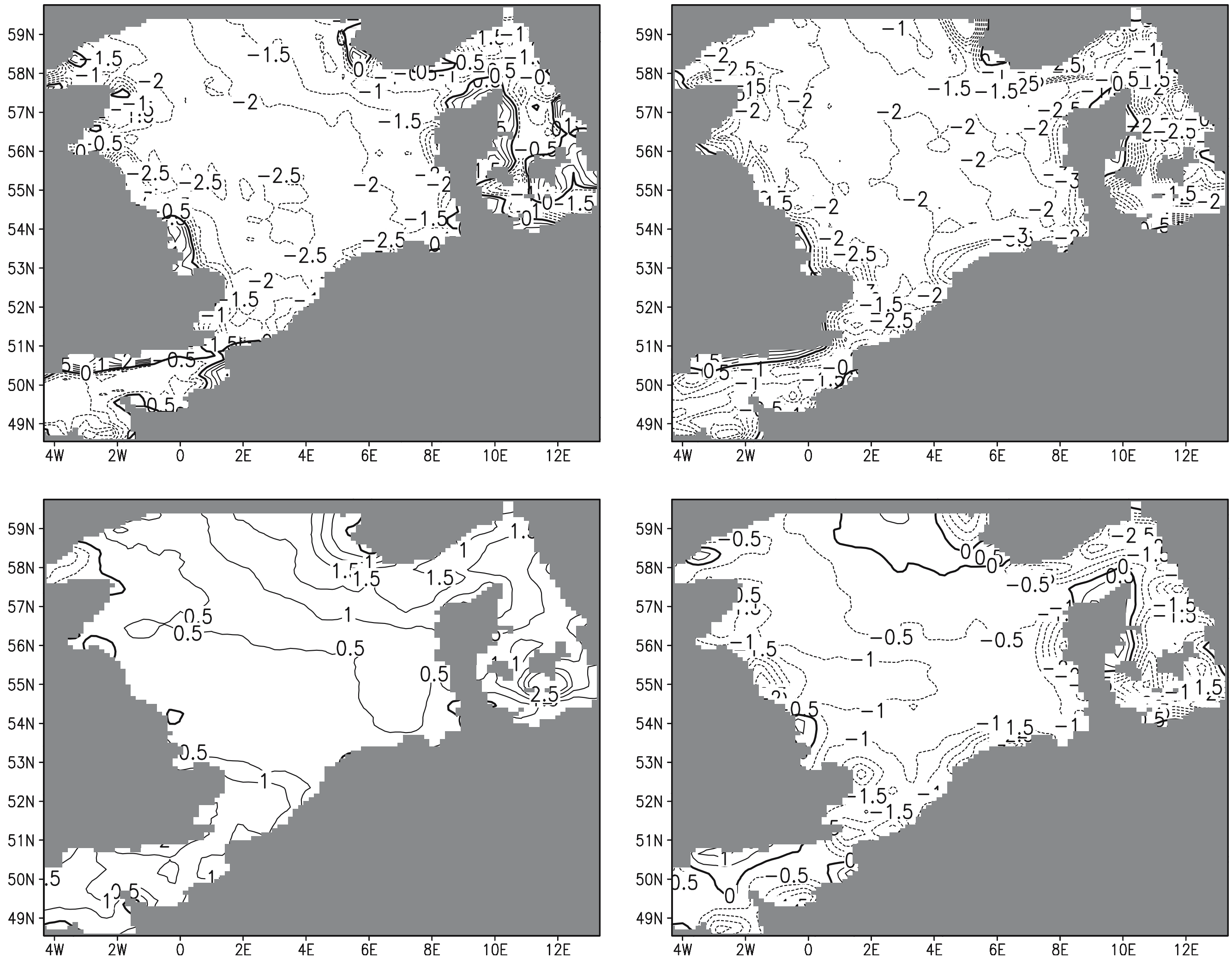

Fig. 6 Differences in the inter-annual mean of the 99th percentile of 10 m wind speed between the four considered models and the REMO_SN hindcast in the control period 1961–1990 (unit: m/s). *Upper left*: HIRHAM, *lower left*: CLM, *upper right*: RCAO and *lower right*: REMO. Calculations of percentiles are based on 6 hourly data (DJF)

because of tide-only constraints along the northern boundary of the model. Then the 99.5th percentiles increase eastward along the 10-m depth line with highest values obtained in the German Bight. Afterwards the height of the most severe surges decreases again. A similar spatial pattern is found for all storm surge control simulations. In correspondence with the differences in extreme wind speeds described above, the absolute value of the 99.5th percentile is underestimated in simulations driven with HIRHAM, RCAO and REMO forcing. Only the CLM wind and pressure fields lead to extreme storm surges of a magnitude comparable to those obtained in the hindcast. In particular, hindcast and CLM forced storm surge residuals reach maxima of up to 1.4 m in the German Bight while HIRHAM and RCAO forcing in this local area only lead to extreme surge heights of about 1 m. Extreme surge heights produced with REMO forcing are lying in between with maxima of about 1.2 m.

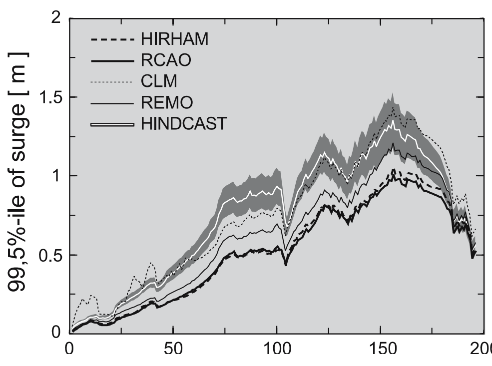

Fig. 7 Inter-annual mean of the 99.5th percentile of water level/surge (DJF) for the control period 1961–1990 (DJF) for all ensemble members and the hindcast. The *grey-shaded band* marks the 95% confidence interval of inter-annual natural variability, inferred from the hindcast. Depicted are grid cells located on the 10m depth line along the North Sea coast (for the numbering of locations, refer to Fig. 1)

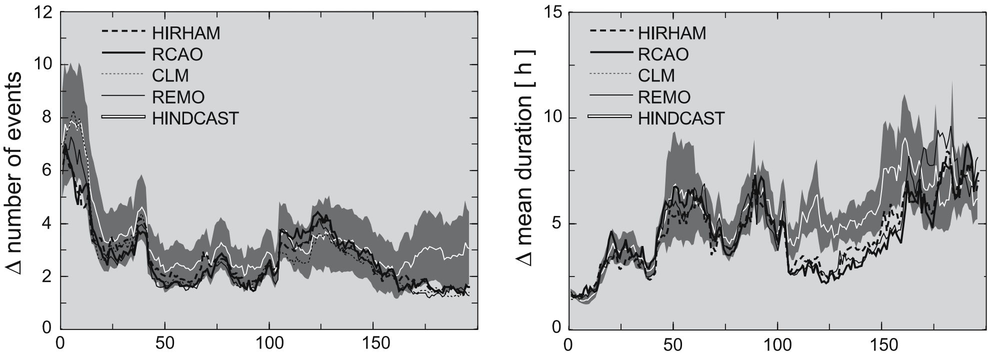

Fig. 8 Inter-annual mean of number of periods ('events') with percentiles above 99.5th percentile of water level **(a)** and mean duration of periods with water levels above 99.5 percentile **(b)** for the control period 1961–1990 (DJF) for all four ensemble members and the hindcast. The *grey-shaded band* marks the 95% confidence interval of inter-annual natural variability, inferred from the hindcast. Depicted are grid cells located on the 10-m depth line along the North Sea coast (for the numbering of locations, refer to Fig. 1)

Generally in all control storm surge simulations the annual frequency (Fig. 8a) of extreme events compare well with the hindcast with a decreasing number of extreme surges from the North of Scotland (six to eight events per year) to the end of the selected 10-m depth line at the top of Denmark (two events per year). Only along the Danish coast the number of such events is slightly underestimated. The mean duration of these events (Fig. 8b) is with about 2–5 h relatively short at the Scottish North Sea coast but it increases at the middle and southern English coast up to 7 h in the hindcast. This part is well reproduced in the control climate. Along the continental coast between the English Channel and the German Bight the duration is underestimated. At the North Frisian coast, with the highest 'hindcasted' mean duration of extreme surges (up to about 9 h) and near the Danish coast, with persistence of these events between 6 and 9 h in the mean, the control climate is again in good agreement with the hindcast.

3.2 Future climate projections

Because of the deviations between hindcast and control simulations of both, the atmospheric forcing as well as the storm surge residuals, we interpret the differences between scenario and control climate projections as a relative shift of present-day statistics in the projected future. By doing so, we assume that the systematic errors in both the control and the scenario simulations cancel to first order approximation. This assumption is inherent in all climate change studies and represents the best possible option so far.

3.2.1 Changes in meteorological forcing, 2071–2100

As all RCMs have been driven by the same GCM data, possible reasons for the different response of the storm surge model to atmospheric forcing from the different RCMs may be attributed to differences in the RCM model and experiment design such as for instance different parameterizations of the atmospheric boundary layer.

Possible reasons for the changes in storm surge statistics and their range, found in the different downscaling exercises, are rooted in the different atmospheric RCM formulations (Sect. 2.2) used to force the tide-surge model.

Thus, we analysed the different meteorological forcing conditions over the North Sea as changes between the control run and the SRES A2 scenario for SLP and near-surface wind speeds. The latter one is more relevant as a driving condition for storm surges.

Changes in SLP conditions between the CTL time-slice and the A2 scenarios are given by the changes of the 1st percentile level (not shown). All models show a similar pattern simulating a decrease of that percentile. The smallest decrease is simulated in the South West region (around 0.5 hPa), which is getting larger to the North and North Eastern part (from 2 hPa in HIRHAM, and RCAO over 2.5 hPa in REMO, to a decrease of even 4 hPa in CLM).

The changes in the 99th percentile in 10 m wind speed are again very similar for each of the four ensemble members, with a very slight increase of up to 1 m/s. The impact of changes in wind speed on storm surge extremes depends on the direction the strong wind is coming from. Thus, the analyses were extended by analysing eight different wind direction sectors, each enclosing 45°. The highest increase in wind speeds in the scenario is found in the sector with westerly wind directions. Figure 9 shows the differences in the 99th percentile of 6-hourly sampled 10 m wind speed (westerly sector) for each of the ensemble members. The RCAO wind is increasing by up to 1.4 m/s over large areas of the North Sea, whereas HIRHAM, REMO and the CLM model show an increase of up to 2 m/s.

3.2.2 Changes in surge height extremes, 2071–2100

The changes in extreme (99.5th percentile) storm surge statistics obtained from comparing the four IPCC A2

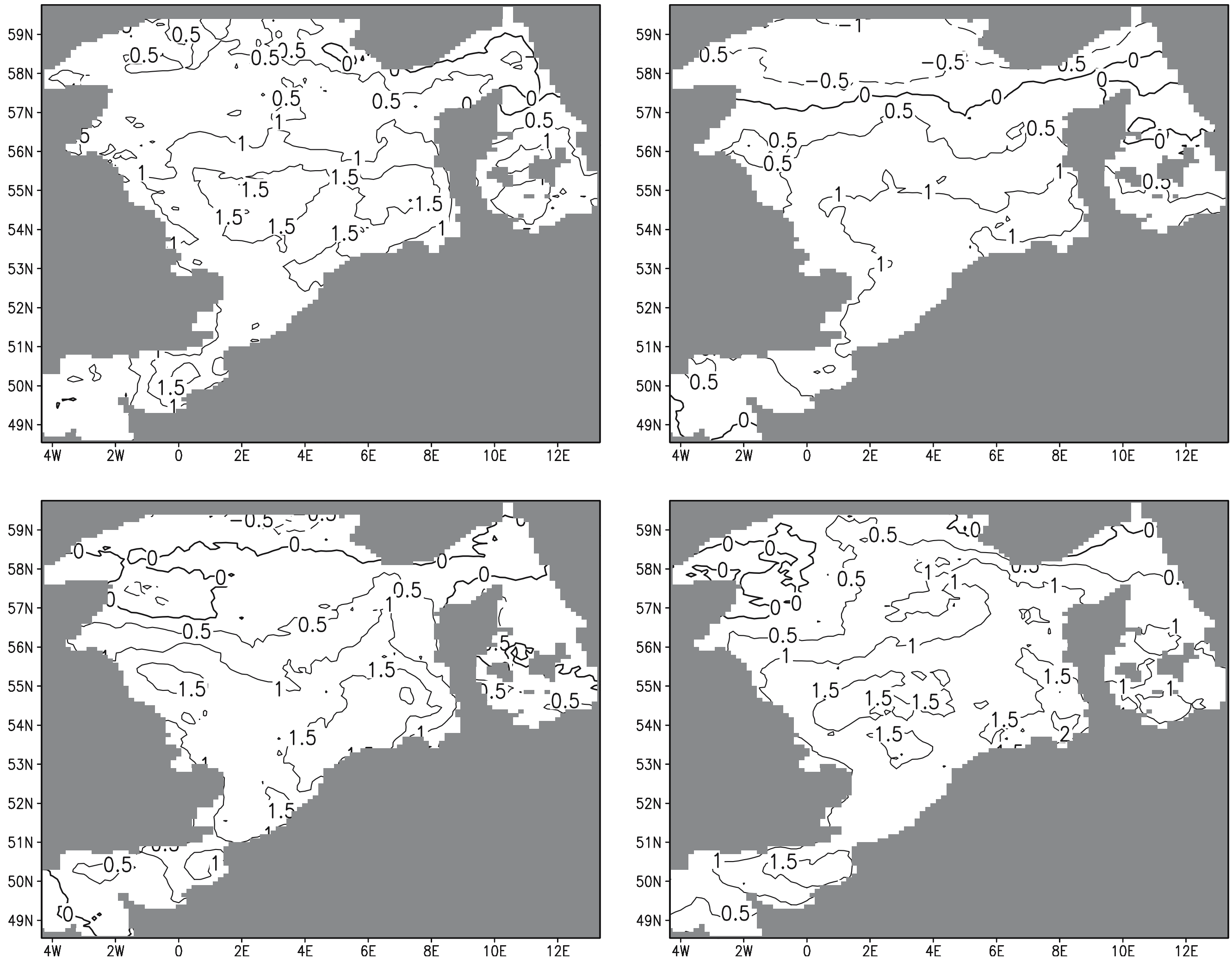

Fig. 9 Differences "A2–CTL" in 29-year inter-annual mean of the 99th percentile 10 m wind speed in the four considered models. Calculations of percentiles are based on 6 hourly data (DJF), only for west wind directions. Unit: m/s. *Upper left*: HIRHAM, *lower left*: CLM, *upper right*: RCAO and *lower right*: REMO

SRES scenario driven simulations and the control runs are shown in Figs. 10 and 11.

A series of null hypotheses (1)

$$H_o : p_x(CTL\_M) = p_x(A2\_M) \quad (1)$$

is tested to answer the question: is it plausible that the differences merely reflect natural variations and that they are not related to the changing forcing.

Where p_x(CTL_M) is the mean annual 99.5th percentile, derived in the control run with model M. *x* represents either the percentile, or the number of events above this percentile or the mean duration of periods with water level above this percentile. p_x(A2_M) is the same quantity in the A2 SRES scenario simulation with the model M.

To test these null hypotheses, we determine the 95% confidence interval deduced from a student *t* distribution for the percentiles from the hindcast 1961–1990 and determine for each grid box if the mean difference p_x(CTL_M) - p_x(A2_M) lies in the confidence interval or not. In the latter case we reject the null hypothesis (1).

Generally all climate change simulations show a similar spatial pattern:

Changes in the 99.5th percentile surge residual (Fig. 10) are minor along the 10 m bathymetry isoline along the UK coast. Here, the model has shown reduced skill in reproducing the observed statistics (Sect. 2.1.1). Eastwards of the West Frisian Islands changes increase up to 30 cm with highest values in the German Bight. In terms of absolute values the RCAO-driven simulations with an increase of up to 20 cm show the smallest changes within the ensemble. Along the North Frisian coast changes from all ensemble members are significantly different from zero at the 95% significance level compared to the natural variability obtained from the hindcast.

Changes in the frequency of extreme events are rather similar in all simulations. Figure 11a shows an

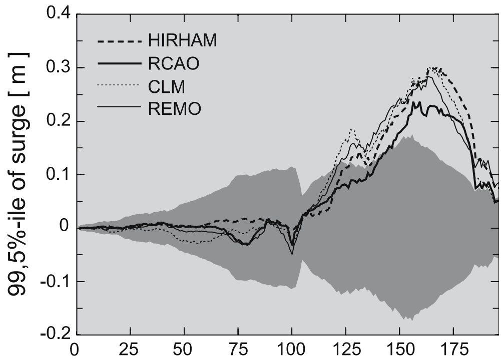

Fig. 10 Differences "A2–CTL" in inter-annual mean of the 99.5th percentile of water level/surge (DJF) for all four ensemble members. The 99.5th percentile is derived from the control period. The differences are compared to 95% confidence bands reflecting the inter-annual variability in the hindcast. Depicted are grid cells located on the 10-m depth line along the North Sea coast (for the numbering of locations, refer to Fig. 1)

increase in the number of severe storm surge events along the continental southern North Sea coast up to about Esbjerg which is significantly different from zero at the 95% confidence level. Here the mean number of severe storm surge events is increased by about two events per year in the period 2071–2100 compared to 1961–1990. This increase corresponds to a relative increase of 50–100%. The duration of severe storm surges (Fig. 11b) shows strongest changes along the North Frisian coast with statistically significant changes for all ensemble members of the magnitude of up to 5 h (about 50%), while changes are not significantly different from zero along the West Frisian coast and westwards of it.

4 Conclusions

A state-of-the-art storm surge model was run for present day (1961–1990) and assumed future climate conditions (2071–2100) for the North Sea. Atmospheric forcing was taken from four different state-of-the art regional atmosphere climate models, which dynamically downscale the 'control climate' and the A2 SRES scenario from IPCC. Analysis of changes between control and scenario period of this ensemble are based on a phenomenological characterization of extreme events. Using an ensemble simulation rather than a single one, we are able to detect the signal which is inherent in all storm surge simulations and the range of uncertainty introduced by the use of different RCMs to downscale a given global climate change.

The comparison of the tide-surge model runs forced with control climate conditions with a hindcast using reconstructed atmospheric data gave satisfactory results. On the positive side, the spatial structure of extreme events, with highest storm surges in the German Bight and relatively small values along the UK coast, was found to be in good agreement with reconstructed conditions. However, with the exception of the simulation forced with CLM atmospheric data, the intensity is generally too weak leading to an underestimation of the storm surge 99.5th percentile—a finding consistent with Flather's and Smith's (1998) results.

The overall structures of the changes between the scenario and the control simulations are rather similar for all ensemble members even though differences in absolute values and statistical significance of the results occur. Larger changes are obtained for the continental coast while differences are generally smaller and not statistically different from zero along the UK coast (where the surge model performs less well). In the western part of the continental coast the increase is primarily a result of more frequent extremes while in the eastern part, from the German Bight up to Denmark, changes in the duration and the intensity of the extremes become more important. Within the German Bight the 99.5th storm surge percentile along the 10 m bathymetry line is increased significantly in all scenario simulations by 20–30 cm which corresponds to a rise of around 20% surge heights. In a real world these differences would have different implications for coastal protection. A stand-alone increase in the frequency of extreme events would be less relevant for many coastal facilities, but an

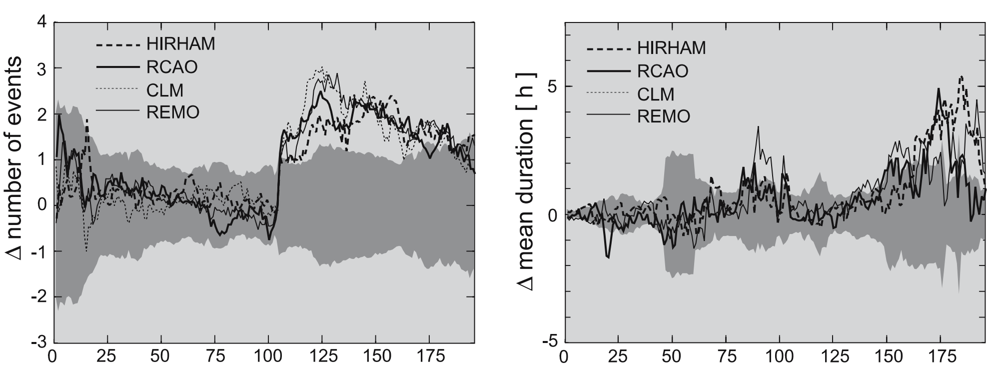

Fig. 11 Differences "A2–CTL" in inter-annual mean of number of periods ('events') with water levels above the 99.5th percentile **(a)** and mean duration of periods with water levels above the 99.5th percentile **(b)**. The 99.5th percentiles are derived from the control period. The differences are compared to 95% confidence bands reflecting the inter-annual variability in the hindcast. Depicted are grid cells located on the 10-m depth line along the North Sea coast (for the numbering of locations, refer to Fig. 1)

increase in duration and magnitude of extreme events could stretch their security limits.

When considering a rise of mean sea level heights due to thermal expansion, the IPCC expects in case of the A2 SRES scenario for the end of this century (Houghton et al. 2001) an increase of about 40 cm. (This number may change significantly because of the changing volume of ice sheets and glaciers.) Since the mean water levels adds to the storm surge height (Kauker and Langenberg 2000), at least as long as the water level changes are not very large, we have to add this number to our expected increase of extreme surge heights. This results in a possible increases of 60–70 cm in the 99.5th percentile along the 10-m depth line mainly within the German Bight—with a broad range of uncertainty mainly related to the emission scenarios, the unknown behaviour of ice sheets and glaciers, and differences in the global climate change simulations.

The difference in modelled surge statistics in the ‘control climate’, using the four different RCM meteorological forcings, is fully consistent with the analysed high 10 m wind speeds—which is larger in CLM, HIRHAM and REMO than in RCAO. In the future climate scenario all four RCM wind speeds show an increase in the 99th percentile. A maximum increase is found, when this analysis is limited to on westerly directions. This is consistent with the positive trend in surge extremes around the North Sea coast.

The response of the tide-surge model in that specific climate scenario of future storm surge conditions exhibit more similarities than differences between the ensemble members. We can specify a band as a first approximation, wherein the ensemble projections are ranging. This is a first step to explicitly account for the large uncertainties, to be inherent in all studies dealing with possible future climate change scenarios. In this study we only examined the uncertainty related to the use of different RCMs. The use of different emission scenarios and/or global circulation models may have a larger effect on changes of storm surge statistics. Recent studies (e.g., Leckebusch and Ulbrich 2004; Rauthe et al. 2004) indicate that there might be considerable variability in the response of the extra tropical atmospheric circulation in dependence on the used GCM and in dependence on the chosen greenhouse gas emission scenario. Dealing with such uncertainties will represent a major challenge for climate impact studies in the future.

Acknowledgements The research was carried out as part of the PRUDENCE (Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects) funded by the European Commission under Framework Programme V Key Action “Global change, climate and biodiversity”, 2002–2005. Contract No. EVK2-CT2001-00132. We are grateful to Saskia Esselborn and Reiner Schnur for many fruitful discussions and their technical support. Atmospheric data to drive our storm surge model were kindly provided by Frauke Feser (GKSS), Ole Bøssing Christensen (DMI), Anders Ullerstig (SMHI), Burkhardt Rockel (GKSS) and Tido Semmler (formerly MPIfM).

References

Aspelien T, Weisse R (2005) Assimilation of sea level observations for multi-decadal regional ocean model simulations for the North Sea. GKSS report 2005/2

Casulli V, Cattani E (1994) Stability, accuracy and efficiency of a semi-implicit method for three dimensional shallow water flow computers. Math Applic 27:99–112

Casulli V, Stelling GS (1998) Numerical simulation of 3D quasi-hydrostatic, free-surface flows. J Hydr Eng 124:678–698

Chabert d’Hieres G, Le Provost C (1978): Atlas des composantes harmoniques de la marée dans la Manche. Les annales hydrographiques, 6, Fascicule 3

Christensen JH, Christensen OB, Lopez P, VanMeijgaard E, and Botzet M (1996) The HIRHAM4 Regional Atmospheric Climate Model. Scientific report. DMI, Copenhagen 96–4: 51

Christensen JH, Carter T, Giorgi F (2002) PRUDENCE employs new methods to assess European climate change. EOS. 83:147

Coles S (2001) An introduction to statistical modeling of extreme values. Springer, Berlin Heidelberg New York

Davies HC (1976) A lateral boundary formulation for multi-level prediction models. Quart J R Meteor Soc 102:405–418

Döscher R, Willén U, Jones C, Rutgersson A, Meier HEM, Hansson U, Graham LP (2002) The development of the coupled regional ocean-atmosphere model RCAO. Boreal Env Res 7:183–192

Dolata LF, Roeckner E, Behr H (1983) Prognostic storm surge simulation with a combined meteorological/oceanographic model. In: Sündermann J and Lenz W (eds) North Sea dynamics. Springer: Berlin Heidelberg New York, pp 266–278

Feser F, Weisse R, von Storch H (2001) Multidecadel atmosperic modelling for Europe yields multi purpose data. EOS 82:305–310

Fischer-Bruns I, von Storch H, González-Rouco F, Zorita E (2005) Modelling the variability of midlatitude storm activity on decadal to century time scales. Clim Dyn (in press)

Flather R, Smith J (1998) First estimates of changes in extreme storm surge elevation due to doubling CO_2 Global Atmos. Ocean Sys 6:193–208

Flather R, Smith J, Richards J, Bell C, Blackman D (1998) Direct estimates of extreme surge elevation from a 40 year numerical model simulation and from observations. Global Atmos Ocean Sys 6:165–176

Gönnert G, Dube SK, Murty, Siefert T (hrsg) (2001) Global storm surges. Theory, observations and applications. Boyens& Co, Heide. Die Küste 63, 623 p. ISBN 3-8042-1054-6

Heaps NS (1983) Storm surges, 1967–1982. Geophys J R astr Soc 74:331–376

Hervouet JM, Van Haren L (1996) TELEMAC2D Version 3.0/ Principle Note. Rapport EDF HE-43/94/052/B. Electricité de France, Département Laboratoire National d’Hydraulique, Chatou CEDEX

Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (2001) Climate change 2001: the scientific basis. Cambridge University Press, Cambridge, pp 881

Jacob D, Podzun R, Claussen M (1995) REMO—A model for climate research and weather prediction. International workshop on limited-area and variable resolution models, Beijing, China, 23–27 October 1995, pp 273–278

Jones RG, Murphy JM, Noguer M (1995) Simulation of climate change over Europe using a nested regional-climate model I: assessment of control climate, including sensitivity to location of lateral boundaries. Q J R Meteorol Soc 121:1413–1449

Jones CG, Willén U, Ullerstig A, Hansson U (2004) The Rossby Centre regional atmospheric climate model part I: model climatology and performance for the present climate over Europe. Ambio. 33:4–5, 199–210

Källén E (1996) HIRLAM Documentation Manual, System 2.5. The Swedish Meteorological and Hydrological Institute (Available from SMHI, S-60176 Norrköping, Sweden)

Kauker F (1998) Regionalisation of climate model results for the North Sea. PhD Thesis, University of Hamburg

Kauker F, Langenberg H (2000) Two models for the climate change related development of sea levels in the North Sea. A comparison. Clim Res 15:61–67

Langenberg H, Pfizenmayer A, von Storch H, Sündermann J (1999) Storm-related sea level variations along the North Sea coast: natural variability and anthropogenic change. Cont Shelf Research 19:821–842

Leckebusch GC, Ulbrich U (2004) On the relationship between cyclones and extreme windstorm events over Europe under climate change. Glob planet change (In press)

Lowe JA, Gregory JM, Flather RA (2001) Changes in the occurrence of storm surges in the United Kingdom under a future climate scenario using a dynamic storm surge model driven by the Hadley Center climate models. Clim Dyn 18:197–188

Meier HEM, Döscher R, Faxén T (2003) A multiprocessor coupled ice-ocean model for the Baltic Sea: application to salt inflow. J Geophys Res 108: C8, 3273, doi:10.1029/2000JC000521

Machenhauer B, Windelband M, Botzet M, Hesselbjerg J, Déqué M, Jones GR, Ruti PM, Visconti G (1998) Validation and analysis of regional present-day climate and climate change simulations over Europe. Max-Planck Institute of Meteorology Hamburg, Report No. 275, 87 pp

OSPAR Commision (2000) Quality status report 2000. London

Petersen M, Rohde H (1991) Sturmflut. Die grossen Fluten an den Küsten Schleswig Holsteins und der Elbe. Neumünster

Plüss A (2003) Das Nordseemodell der BAW zur Simulation der Tide in der Deutschen Bucht. Die Küste 67:83–127

Rauthe M, Hense A, Paeth H (2004) A model intercomparison study of climate change-signals in extratropical circulation. Int J Climatol 24: 643–662

Rayner NA, Parker DE, Horton EB, Folland CK, Alexander LV, Rowell DP, Kent EC, Kaplan A (2003) Global analyses of SST, sea ice and night marine air temperature since the late nineteenth century. J Geophys Res, 108 (D14), 4407, doi:10.1029/2002JD002670

Roeckner E, Arpe K, Bengtsson L, Christoph M, Claussen M, Dümenil L, Esch M, Giorgetta M, Schlese U, Schulzweida U (1996) The atmospheric general circulation model ECHAM-4: model description and simulation of present-day climate, Report No. 218, 90 pp, Max-Planck-Institut für Meteorologie, MPI, Hamburg

Rummukainen M, Räisänen J, Bringfelt B, Ullerstig A, Omstedt A, Willén U, Hansson U, Jones C (2001) A regional climate model for northern Europe: model description and results from the downscaling of two GCM control simulations. Clim Dyn 17:339–359

Sotillo MG (2003) High resolution multi-decadal atmospheric reanalysis in the Mediterranean Basin. PhD Thesis

von Storch H, Langenberg H, Feser F (2000) A spectral nudging technique for dynamical downscaling purposes. Mon Wea Rev 128:3664–3673

STOWASUS-Group (2001) Regional storm, wave and surge scenarios for the 2100 century. Stowasus-final report, DMI. Available from the EU-Commission, DGXII

WASA-Group (1998) Changing waves and storm in the Northern Atlantic?. Bulletin of the American Meteorological Society 79:741–760

Weisse R, Feser F (2003) Evaluation of a method to reduce uncertainty in wind hindcasts performed with regional atmosphere models. Coast Eng 48:211–225

Weisse R, von Storch H, Feser F (2005) Northeast Atlantic and North Sea storminess as simulated by a regional climate model 1958–2001 and comparison with observations. J Clim 18:465–479