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Dynamical modelling of North Sea storm surge extremes under climate change conditions – an ensemble study

Katja Woth, Ralf Weisse, Hans von Storch

29 pages with 9 figures

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 modeling. 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 climate 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.

Dynamische Modellierung von Sturmflutereignissen an der Nordseeküste für ein Klimaänderungsszenario – eine Ensemble-Studie

Zusammenfassung

Küstenzonen sind besonders betroffen von Änderungen in der Sturmflut-Klimatologie und deren Folgen, hervorgerufen durch einen Klimawandel. In dieser Studie untersuchen wir diese möglichen Änderungen für die Nordsee mit Hilfe eines numerischen Wasserstandsmodells. Mit Hilfe dieses barotropen Modells (TRIMGEO, Tidal Residual and Intertidal Mudflat Model) modellieren wir Wasserstände aus regionalisierten, atmosphärischen Simulationen des heutigen Klimas sowie aus

Szenarien eines angenommenen zukünftigen Klimas unter ansteigenden CO^2-Konzentrationen. Für diese Wasserstandssimulationen leiten wir meteorologisch bedingte Extremwerte ab.

Das Ensemble von atmosphärischen Simulationen wurde in dem EU-Projekt PRUDENCE (Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects) hergestellt. Die Strategie des Projektes war es, unterschiedliche Realisationen regionaler Klimamodelle, basierend auf zunächst einem globalen ‚control' sowie einem ‚Klimaänderungsszenario', zu vergleichen. Diese globalen atmosphärischen Bedingungen wurden vom Hadley Center durchgeführt und sind repräsentativ für heutige Klimabedingungen (1961–1990) sowie für das zukünftige, so genannte A2 SRES-Szenario – definiert durch das Intergovernmental Panel on Climate Change – gegen Ende dieses Jahrhunderts, 2071–2100.

Die Ergebnisse zeigen, dass unter diesen angenommenen zukünftigen Bedingungen mit einem Anstieg der meteorologisch bedingten Wasserstandsextreme entlang der kontinentalen Nordseeküste zu rechnen ist. Dieser Anstieg ist für alle vier in dieser Studie verwendeten Projektionen statistisch signifikant, nimmt man die heutige Variabilität dieser Größe zur Grundlage. Die Nordseeküste entlang Großbritannien zeigt dagegen keine signifikante Veränderung.

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CONTENTS

1 INTRODUCTION

In historical times serious floods have severely impacted coastlines of the North Sea. But also more recent floods in the 20th century, have highlighted the current potential for high impact damage, threatening human life as well as property. The mechanism leading 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. 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 modeling of tide-surges exist. Examples are Dolata et al. (1982), 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 modeled with hydrodynamic models, especially if the focus is on long-term statistics rather than on single events. Comparing simulations with a three dimensional baroclinic model (Kauker 1998) and a vertically integrated barotropic one, 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 be expected 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 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 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 General Circulation Model (HadAM3H). The wind and air pressure data are provided by the partners of the EU PRUDENCE project (Christensen et al. 2002), for paired 30 year "control" (1961 to 1990) and "climate change" (2071 to 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 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 there the biotic and abiotic environment. 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 ask 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 characterisation 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, 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 melting 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 just 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 additionally water masses into the basin. In our set-up, we can not 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 be a bit too categorical: Most present studies indicate a strengthening rather than a weakening of North Atlantic storm tracks projected in General Circulation Models for the A2 SRES scenario (e.g., Fischer-Bruns et al. 2004). This would lead possibly to more frequent external surges in this future climate. Thus, the neglected effect of external surges may cause an underestimation of the change of storm surge extremes.

The present paper is organized as follows: In section 2 the hydro-dynamical model TRIMGEO 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 section 3, which is divided into two parts: In section 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 section 3.2. We conclude in section 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 Catani1994; 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 minutes.

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’ x 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.

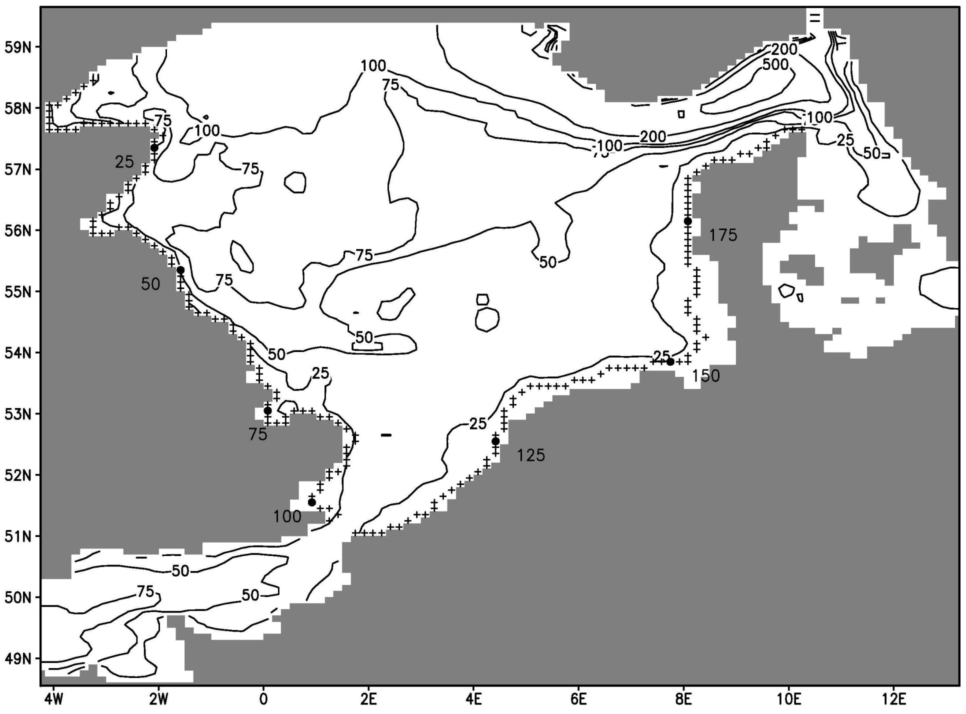

Figure 1: Model domain of the tide-surge model TRIMGEO: the bathymetry (isolines) and the 196 near coastal grid cells (crosses) located on the 10 m bathymetry line along the North Sea coast beginning with 1 in Scotland and ending with 196 in Denmark.

The model domain posses 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 south coast of Sweden and the German Peninsula Rügen, 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 about 0.01498 m^3s^{-1} from the Baltic Sea (Ospar Commission 2000) are prescribed. Freshwater influx from the 33 largest rivers is specified with climatological values, adopted from the operational forecast model of the BSH (Esselborn, pers. comm. 2003). Considering the astronomical tides, sea level anomalies calculated from the amplitudes and phases of 17 partial tides are prescribed

along the open boundaries. All TRIMGEO model runs are based on astronomical tidal coefficients and corrections representative for the time period 2001–2030.
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 HadAM3H model (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 timing of meteorological events in the RCM worlds is independent of the phase of tides.

Aspelien and Weisse (2004) demonstrated the regional capability of the tide-surge model TRIMGEO by analyzing reconstructions of sea level heights and surge for the southern North Sea shelf for the period 2000 to 2002. The results indicate that the TRIMGEO model is able to reproduce statistics of sea level height and surge in a satisfactory manner.

2.2 Atmospheric driving data

This study uses near surface winds and sea level pressure as simulated by four RCMs, namely HIRHAM from the Danish Meteorological Institute DMI, RCAO from the Swedish Meteorological and Hydrological Institute, the CLM of GKSS and REMO of the Max-Planck-Institute of Meteorology. All simulations were prepared for present day (1961–1990) greenhouse gas concentrations and future conditions (2071–2100) based on the Intergovernmental Panel on Climate Change A2 SRES emission scenario (Houghton et al. 2001).

Concerning the model dynamics two groups of model origins are distinguishable. While HIRHAM (an update version of HIRHAM4 [Christensen et al. 1996]) and RCAO are both off-springs from the regional weather forecast model HIRLAM (Machenhauer 1998 and Källén 1996), CLM and REMO (Jacob et al. 1995) are climate versions of the 'Lokalmodell' (LM; Steppeler 2003), a weather forecast model developed by the German Weather Service. The physics of HIRHAM and REMO based on ECHAM4, developed by Roeckner et al. (1996). The physics from RCAO based on HIRLAM and those used in CLM was developed from the LM. HIRHAM, REMO and CLM are stand alone atmosphere models, RCAO (Döscher et al. 2002) represents a coupled atmosphere-ocean model incorporating the Rossby Centers regional atmosphere model RCA (Rummukainen et al. 2001, Jones et al. 2004) and their RCO ocean model (Meier et al. 2003).

All four RCMs were set-up for running on a rotated grid with a mesh size between 0.44º and 0.5º. 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 General Circulation model (GCM) HadAM3H under recent and future climate conditions. Sea ice coverage and sea surface temperature (SST) are the same as used by the HadAM3H model. A special feature is that the used SST for the control run stems from observations. An exception is the RCAO model, which is coupled with an 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.

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, which results when the tide subtracted from the overall water level. Thus an additional “tidal run” was undertaken, using the same model set-up, 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. This was done for all "wet" grid points of the model domain every 30 minutes. 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 analyzed 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 the hydrodynamic model, the analysis based all on a selected isoline, representing the 10 meter depth line in the model bathymetry. This depth line comprises 196 grid cells ranging from the North of Scotland over the southern North Sea coast (Belgium, Netherlands and Germany) to the northeastern top of Denmark near Skagen (Figure 1). As most severe storm surges are generally expected during the winter season all statistical analysis 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.

In our study the principle statistical approach is a straight forward description of extreme climate conditions by high and low percentiles of the distribution. In that way, we consider 29-year means of intra-annual percentiles, namely the highest (99th) percentile of wind speed at 10m height and the lowest (1st) percentile for air pressure as a characteristic quantity. The comparisons of the storm surge residuals in the different experiments is based on the 99.5th percentile.

Since a 90 day DJF season contains 4×90 = 360 intervals of 6-hour length in case of the atmospheric forcings, the 99th percentile is the wind speed, which is exceeded in 1st percentile of 360 cases, i.e., 3 times in a season. Similarly, air pressure is lower than the 1st percentile only during 18 hours (3 times). For analysis of storm surge residuals, we consider again 90-day winter seasons (DJF) but with 0.5-hourly data, so that the 99.5th percentile is larger than 90*48 heights and exceeded on 22 time steps (around 12 hours) in each season. We calculate this percentile for each of the 29 seasons and determine the mean value of these 29 percentiles. Additionally the average duration of such extreme storm surges and the number of such periods when the 99.5th percentile are persistently exceeded is determined. An extreme event is defined as a period covering one or more half hourly intervals with surge levels reaching or exceeding the 99.5th percentile in the control run. These temporal characteristics of a storm flood is an important parameter 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 examine the similarity of the control simulations, which are supposed to be representative for the 1961–1990 period, with two 1961–1990 hindcasts, one for atmospheric conditions and one for the surge climate. The hindcasts consists of 2 steps: first a regional re-analysis of atmospheric conditions was prepared (Feser et al. 2001) using the REMO model with spectral nudging (SN-REMO) (Jacob 1995; von Storch et al. 2000). The reconstruction of marine winds and air pressure were found to be homogeneous and of satisfactory quality (e.g. Sotillo 2003; Weisse et al. 2004). In a second step, these reconstructed winds and air-pressure field were fed into TRIMGEO with good results (Aspelien and Weisse 2004, see above). For this hindcast simulation TRIMGEO was set-up identically to the control simulations only with the difference of hourly forcing fields whereas the control simulations were integrated with 6-hourly meteorological data.

Atmospheric forcing

Figure 2 shows the statistics of the extremes in deep sea level pressure as well as the extreme near surface wind as obtained in the atmospheric 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 REMO-SN 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.

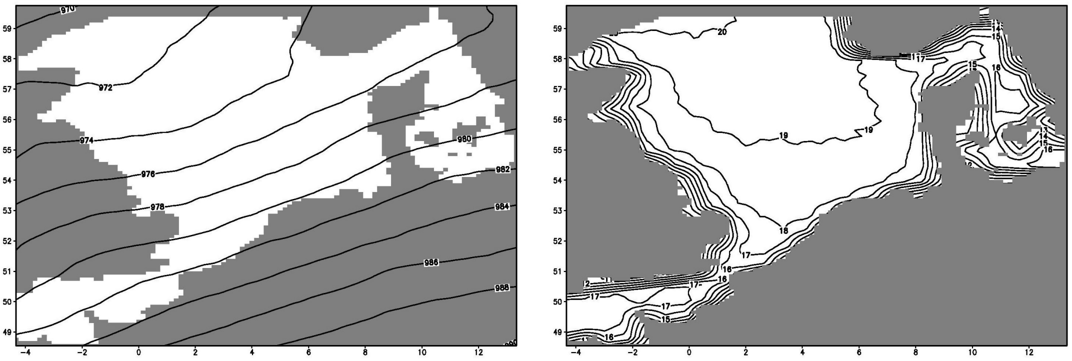

Figure 2: Inter-annual mean of the 1st percentile sea level pressure (left hand side) and of the 99th percentile 10 m wind speed (right hand side) derived from REMO_SN, hindcast, 1996–1990. Units: hPa (SLP) and m/s (wind speed). Calculations of percentiles are based on 6 hourly data (DJF).

All four RCM control simulations show an overestimation of the deepest sea level pressures (Figure 3). 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 generally 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 (Figure 4). 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 quite 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.

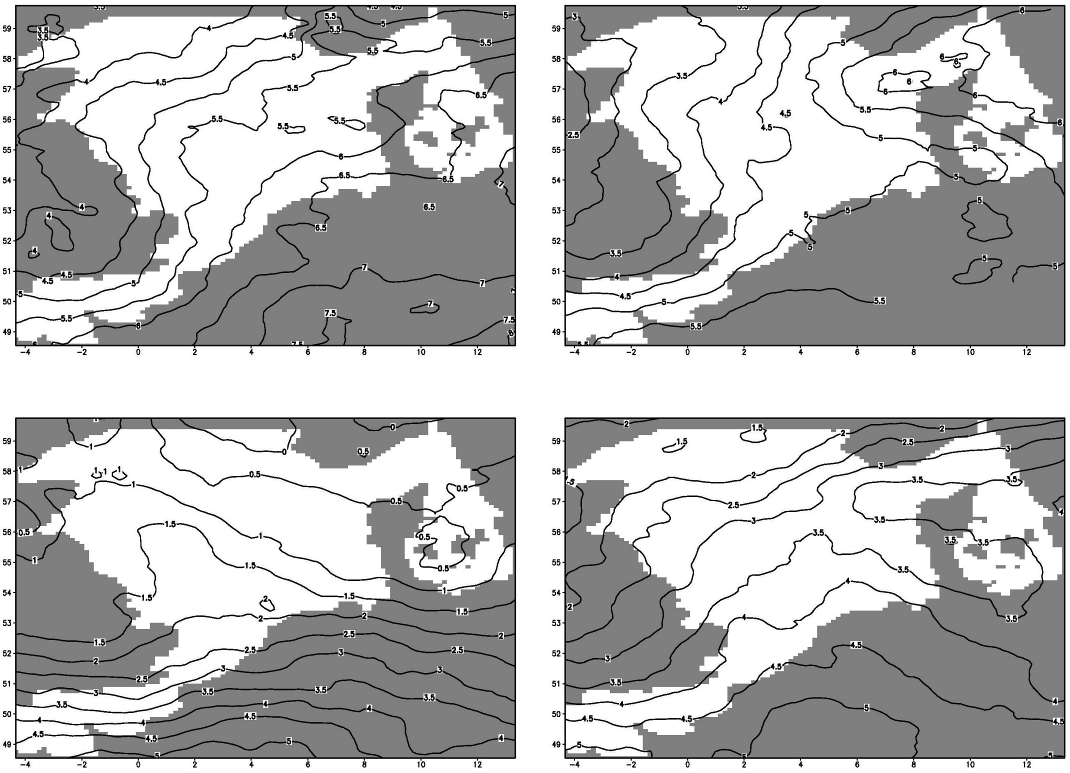

Figure 3: Biases of the inter-annual mean of the 1st percentile of sea level pressure in the four considered models relative to REMO_SN hindcast in the control period 1961 to 1990 (unit: hPa). Upper left: HIRHAM, lower left: CLM, upper right: RCAO and lower left: REMO. Calculations of percentiles are based on 6 hourly data (DJF).

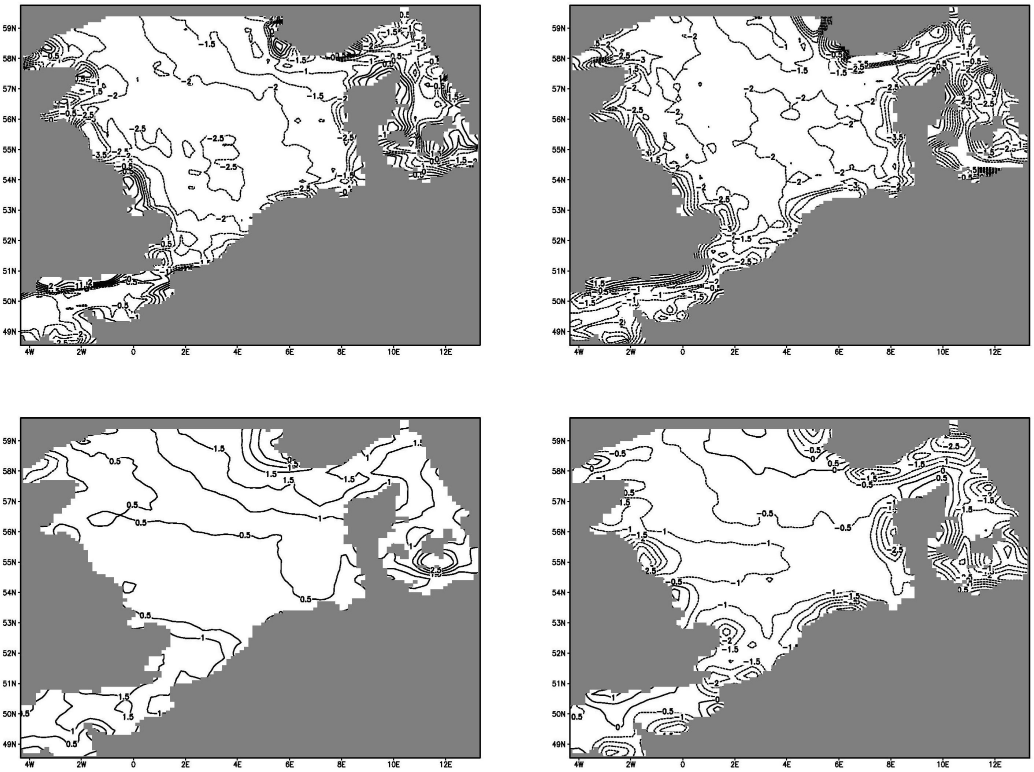

Figure 4: Differences in the inter-annual mean of the 99th percentile of 10 meter wind speed between the four considered models and the REMO_SN hindcast in the control period 1961 to 1990 (unit: m/s). Upper left: HIRHAM, lower left: CLM, upper right: RCAO and lower left: REMO. Calculations of percentiles are based on 6 hourly data (DJF).

Surge residuals

Storm surge residuals are compared, on the one hand derived from the hydrodynamic model runs under control climate conditions with surge height extremes derived from the hindcast on the other hand. Figure 5 shows the 99.5th percentile itself, Figure 6 show the mean frequency and the mean duration of events exceeding this mark.

In the hindcast simulation lowest storm surge extremes are generally found along the UK coast (Figure 5). Then the 99.5th percentile increase eastward along the 10 m depth isoline with highest values obtained in the German Bight. Afterwards the height of the most severe surges decreases again.

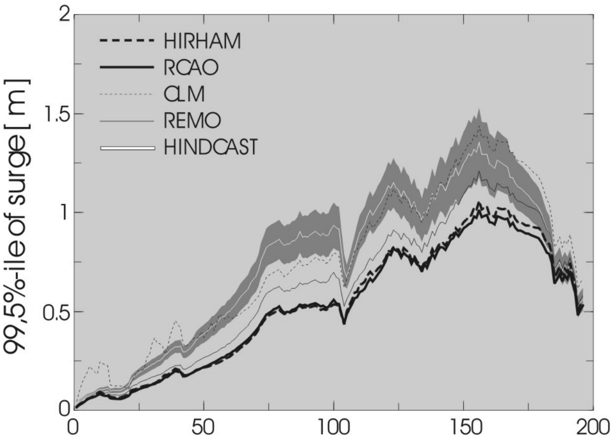

Figure 5: Inter-annual mean of the 99.5th percentile of water level / surge (DJF) for the control period 1961–1990 (DJF) for all ensemble members and the hindcast. The grey shaded band marks the 95 % confidence interval of inter-annual natural variability, inferred from the hindcast. Depicted are grid cells located on the 10 m depth line along the North Sea (for the numbering of locations, refer to Figure 1).

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 the magnitude of 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 leads to extreme surge heights of about 1m. Extreme surge heights produced with REMO forcing are lying in between with maxima of about 1.2 m.

Generally, in all control storm surge simulations the annual frequency (Figure 6 a) of extreme events compare very well with the hindcast with a decreasing number of extreme surges from the North of Scotland (6 to 8 events per year) to the end of the selected 10 m depth line at the top of Denmark (2 events per year). Only along the Danish coast the number of such events are slightly underestimated.

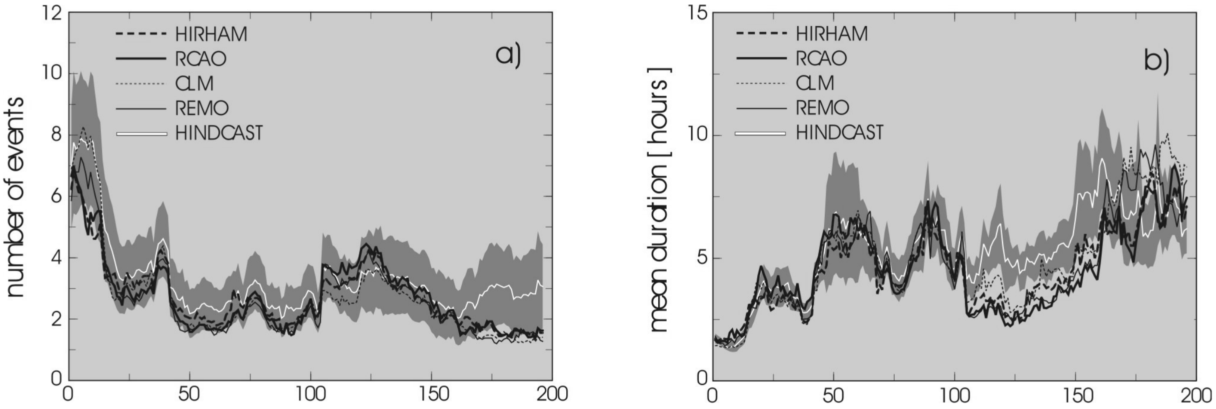

Figure 6: Inter-annual mean of number of periods (‘events’) with percentiles above 99.5 % tile of water level (a) and mean duration of periods with water levels above 99.5 percentile (b) for the control period 1961–1990 (DJF) for all four ensemble members and the hindcast.
The grey shaded band marks 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 (for the numbering of locations, refer to Figure 1).

The mean duration of these events (Figure 6 b) is with about 2–5 hours relatively small at the Scottish North Sea coast but it increases at the middle and southern English coast up to 7 hours in the hindcast. This part is reproduced in the control climate very well. On the continental coast between the English Channel and the German Bight the duration is rather underestimated. At the North Frisian coast, with highest ‘hindcasted’ duration of extreme surges (up to about 9 hours) and near the Danish coast, with persistence of these events between 6 and 9 hours 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. This assumption is inherent in all climate change studies and represents the best possible option so far.

Changes in meteorological forcing, 2071–2100

Possible reasons for the changes in storm surge statistics and their range, found in the different downscaling exercises, are rooted in the slightly different atmospheric RCM performances, used to force the tide-surge model. Therefore we analyzed 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 about 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 slightly increase of up to 1 m/s. Since the impact of changes in wind speed on storm surge extremes depends on the direction, strong wind is coming from, analyses conditioned on 8 different wind direction sectors, each of it enclosing 45 degrees, gives a bit different picture. The highest increase in wind speeds in the scenario is found in the sector with westerly wind directions. Figure 7 shows the differences in the 99th percentile of 6-hourly 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.

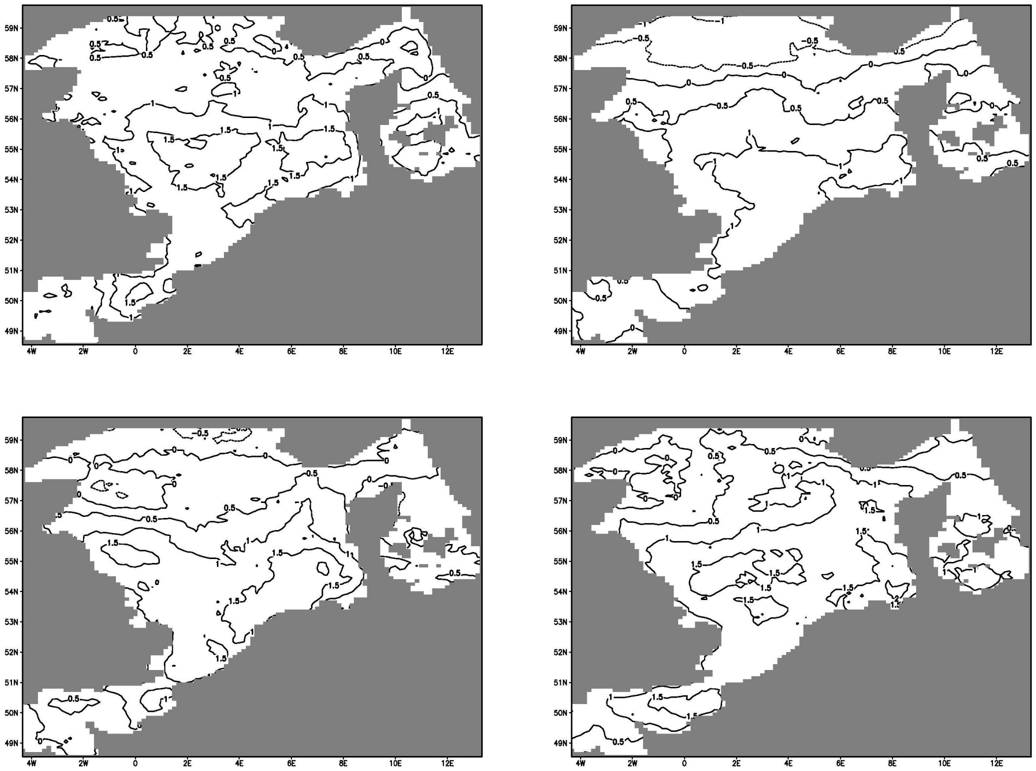

Figure 7: Differences “A2 – CTL” in 29-year inter-annual mean of the 99th percentile 10 m wind speed in the four considered models. Calculations of percentiles are based on 6 hourly data (DJF), only for west wind directions. Unit: m/s. Upper left: HIRHAM, lower left: CLM, upper right: RCAO and lower left: REMO.

Changes in surge height extremes, 2071–2100

The changes in extreme (99.5th percentile) storm surge statistics obtained from comparing the four IPCC A2 SRES scenario driven simulations and the control runs are shown in Figures 8 and 9. Generally all climate change simulations show a similar spatial pattern:

Changes in the 99.5th percentile surge residual (Figure 8) are minor along the 10 m bathymetry isoline along the UK coast. Eastwards of the West Frisian Islands changes increase of up to 30 cm with highest values in the German Bight. In terms of absolute values the RCAO driven simulations show with an increase of up to 20 cm 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.

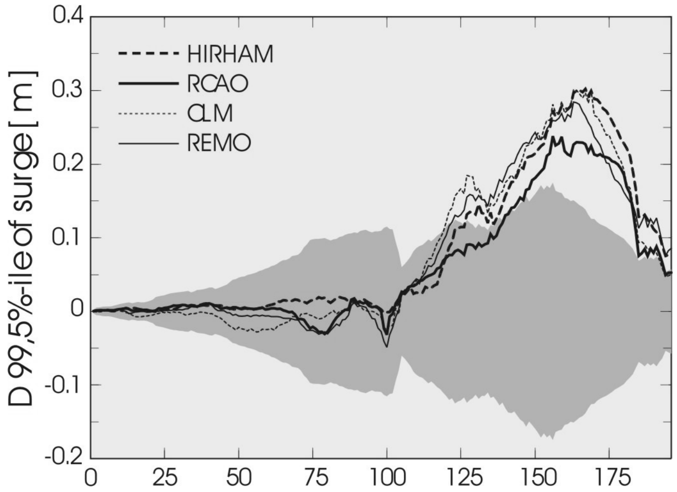

Figure 8: Differences "A2 – CTL" in inter-annual mean of the 99.5th percentile of water level / surge (DJF) for all four ensemble members. The 99.5th percentile is derived from the control period. The differences are compared to 95 % confidence bands reflecting the inter-annual variability in the hindcast. Depicted are grid cells located on the 10 m depth line along the North Sea (for the numbering of locations, refer to Figure 1).

Changes in the frequency of extreme events are rather similar in all simulations. Figure 9a shows an 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.

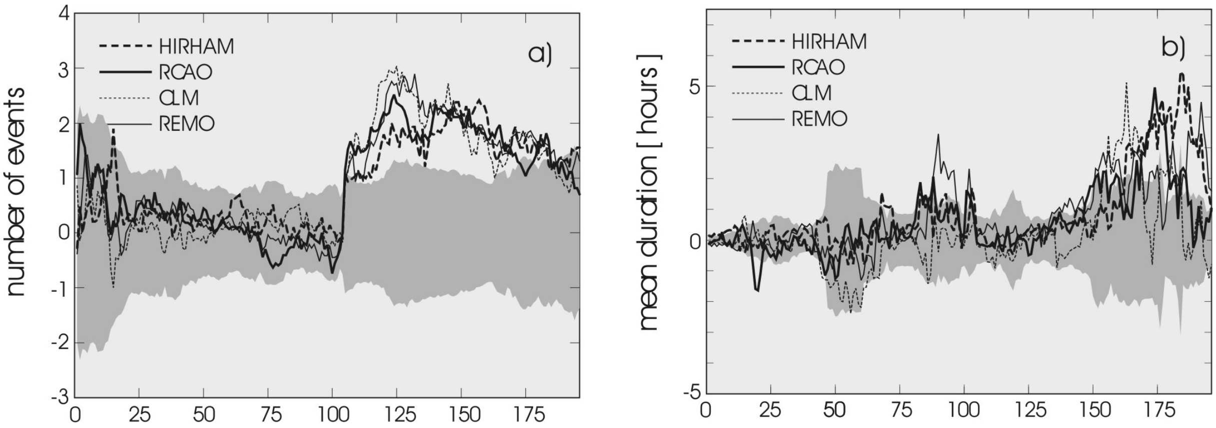

Figure 9: Differences "A2 – CTL" in inter-annual mean of number of periods ('events') with water levels above the 99.5th percentile (a) and mean duration of periods with water levels above the 99.5th percentile (b). The 99.5th percentiles are derived from the control period. The differences are compared 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 (for the numbering of locations, refer to Figure 1).

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 (Figure 9b) shows strongest changes along the North Frisian coast with statistically significant changes for all ensemble members of the magnitude of up to 5 hours (about 50 %) while changes are not significantly different from zero along the West Frisian coast and westwards from 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 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 the global climate fields.

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. But on the other side, 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, which is consistent with the findings from 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 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. 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 to 30 cm which corresponds to a plus 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 increase in duration and magnitude of extreme events could stretch their security limits.

The difference in modeled surge statistics in the 'control climate', using the four different RCM meteorological forcings, is fully consistent with the analyzed high 10 m wind speeds – which is larger in CLM, HIRHAM and REMO than in RCAO. In the future climate scenario all four RCMs 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 general circulation model 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.

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