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North Sea storm surge statistics based on projections in a warmer climate: How important are the driving GCM and the chosen emission scenario?

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[1] Climate models, simulating the effect of plausible future emission concentrations (scenarios), describe for the future an increase of high wind speeds over Northwest Europe during winter. With the help of a hydrodynamic model of the North Sea, these atmospheric future conditions are used to project storm surge heights for the Northwest European Shelf Sea. Four different projections are presented, all generated with the same Regional Climate Model, which itself is driven with two different Global Climate Model scenarios both exposed to two different emission scenarios. The analyses are carried out for a 30-year time-slice at the end of the 21st century. All four ensemble members point to a significant increase of storm surge elevations for the continental North Sea coast of between 15 and almost 25 cm. However, the different storm surge projections are not statistically distinguishable from each other but can provide a range of possible evolutions of surge extremes in a warmer climate. **Citation:** Woth, K. (2005), North Sea storm surge statistics based on projections in a warmer climate: How important are the driving GCM and the chosen emission scenario?, *Geophys. Res. Lett.*, *32*, L22708, doi:10.1029/2005GL023762.

1. Introduction

[2] The major geophysical threat for Northwest European coastal areas is related to storm tides, which have the potential to flooding low lying coastal areas. Assuming increasing greenhouse gases in the atmosphere, most state-of-the-art climate models point to an increase in high wind speeds over Northwest Europe at the end of the 21st century [e.g., *WASA Group*, 1998; *STOWASUS Group*, 2001; *Rauthe et al.*, 2004; *Rockel and Woth*, 2005]. Such an increase in high wind speeds would certainly lead to a change of the storm surge risks for the North Sea coast. These climatic change projections include a large range of uncertainties, coming from different sources.

[3] The EU-PRUDENCE project (**P**rediction of **R**egional scenarios and **U**ncertainties for **D**efining **E**uropea**N** **C**limate change risks and **E**ffects, 2001–2004 [*Christensen et al.*, 2002]) has taken a major step in reducing these uncertainties. By using a range of global and regional climate models, as well as different future emission scenarios, a series of regional climate projections were produced. *Woth et al.* [2005] evaluated parts of these data with respect to future storm surge statistics along the North Sea coast and found changing storm surge characteristics such as an increase in the amplitude, the frequency and the average duration of such extreme water heights, locally beyond the range of natural variations. The use of the different regional climate models (RCMs), when driven by the same general circulation model (GCM), did not lead to a wide range of different storm surge scenarios.

[4] Other studies as e.g. *Lowe et al.* [2001], *Langenberg et al.* [1999], or *Flather and Smith* [1998] also deal with dynamical modelling of possible evolution of North Sea storm surges in a warmer climate but with some limitations due to e.g. coarser spatial and temporal resolution or shorter time slices of the experiments. All these studies found an increase in local storm surge extremes, although to a different extent, when considering the southern North Sea coast.

[5] Methodologically, the present study follows the approach of *Woth et al.* [2005], dealing with storm surge statistics which focus on high percentiles and extends the analysis. Data are used exclusively from one RCM to force the hydrodynamic storm surge model. This time, the RCM itself was integrated with boundary conditions generated by *two* different GCMs, each exposed to *two* different emissions scenarios, resulting in an ensemble of four climate change projections [*Räisänen et al.*, 2004]. The scenarios were characterised in the *IPCC Special Report on Emission Scenarios* (SRES; http://www.grida.no/climate/ipcc/emission). Both chosen scenarios are based on a heterogeneous world, and focus on local and regional levels. One is focussed on significance self-reliance and preservation of local identities (A2) while the other, B2, is oriented toward more environmental protection and social equity.

[6] This study investigates first if the risk of large storm surges will increase or decrease in future climatic conditions, and second, whether changes estimated using different GCMs and different emission scenarios are distinguishable in a statistical sense. Neither the influence of an increase in mean sea level, nor the effect of the external part of water mass coming from the Atlantic, the so called ‘external surges’ are considered. Since the climate change effect is described as the differences between today’s climate and possible future climate, it is assumed that the effect due to external surges is unchanged. The effect of mean sea level rise on storm surge heights has been shown to be additive [*Kauker*, 1998; *Lowe et al.*, 2001]. The increase in modelled surge heights was not found to be sensitive to changes in mean sea levels.

[7] The present paper is organised as follows: In section 2 the hydro-dynamical model and the atmospheric data used to drive the tide-surge model are described,

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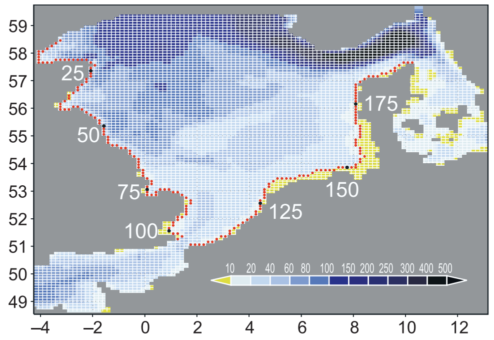

Figure 1. Model domain of the tide-surge model TRIMGEO: the bathymetry and the 196 near coastal grid cells (red points) located along the 10-m depth line along the North Sea coast beginning with 1 in Scotland and ending with 196 in Denmark.

section 3 describes the ensemble experiment and discusses the results.

2. Methodology

2.1. Tide-Surge Model

[8] The barotropic TRIMGEO model (Tidal Residual and Intertidal Mudflat) [*Casulli and Cattani*, 1994] is used for modelling water levels as the response to 6-hourly North Sea meteorological forcing (pressure at mean sea level and the horizontal wind components at 10-m height) simulated in the different regional climate model scenarios. Surge, defined as the water level minus the astronomical tide, emerges from the interplay of local wind and air pressure, the coastline and the bathymetry. To separate the surge part from the full sea level variations, a tide-only model run was performed without any meteorological forcing and the resulting water heights were subtracted from the climate response simulations.

[9] The model domain covers the North Sea (Figure 1) and is gridded with a mesh size of $6' \times 10'$ in latitude and longitude, which corresponds to a grid cell size of about 10 km × 10 km. At the model boundary across the northern North Sea and across the English Channel in the West, boundary conditions in terms of sea level anomalies are given by 17 partial tides. A net influx is prescribed from the Baltic Sea [*OSPAR Commission*, 2000] and from the largest rivers, specified from climatology.

[10] *Aspelien and Weisse* [2005] demonstrated the capability of the tide-surge model TRIMGEO of realistically describing surge levels by comparing observed and simulated sea level heights and surges for the southern North Sea for the period 2000 to 2002. Additional validation was done by *Woth et al.* [2005]. A comparison between a model hindcast and observations from a local tide gauge for the annual winter 99th percentile surge at Cuxhaven shows a correlation coefficient of 0.93 and a root mean square error of 19 cm for the period of 1958 to 2000, which is mainly caused by two years in which the model severely underestimates the observed 99th percentile, in particular the very stormy winter 1975/76.

2.2. Forcing Data and Simulations

[11] All atmospheric data to force the tide-surge model in this study, were generated by the regional climate model RCAO [*Döscher et al.*, 2002] from the Swedish Meteorological and Hydrological Institute. RCAO represents a coupled atmosphere-ocean model incorporating the Rossby Center's regional atmosphere model RCA2 [*Jones*, 2001; *Bringfelt et al.*, 2001] and their RCO Baltic Sea model [*Meier et al.*, 1999; *Meier*, 2001]. This RCM was used to regionalize the 'control climate' (1961–1990) and the A2 and B2 SRES scenarios (2071–2100) from both the Hadley Center General Circulation model HadAM3H (high-resolution global atmosphere model) [*Hudson and Jones*, 2002; *Hulme et al.*, 2002], and the ECHAM4/OPYC3 GCM [*Roeckner et al.*, 1999]. These six datasets were used to run the hydrodynamic model and produced the following ensemble of tide-surge runs:

$$\mathrm{RE\_CTL, RE\_A2, RE\_B2 \text{ and } RH\_CTL, RH\_A2, RH\_B2,}$$

where *R* stands for RCAO, *E* for ECHAM4/OPYC3 and *H* for HadAM3H. *CTL* stands for control conditions, *A*2 and *B*2 for the chosen emission scenario.

3. Results

[12] The following statistical analyses consider the interannual means of the seasonal December, January and February 99th percentile surge derived from computed half hourly values of surge elevation. The 99th percentile is exceeded on average 43 times (ca. 21/22 h) in one winter season, corresponding to 2–4 height surge events with a mean duration of 5 to 10 hours, depending on their local occurrence. Results are shown for the 10-meter depth line along the North Sea coast (red points in Figure 1).

[13] To assess the changes in surge heights, Figure 2 shows the long-year mean annual 99th percentile for both control runs, RE_CTL and RH_CTL. Systematically larger values occur in the control run (up to 15 cm) forced with ECHAM4/OPYC3 boundary conditions compared to those performed with HadAM3H data. In the German Bight the 99th percentile reaches almost 1 m (RE_CTL) and 85 cm (RH_CTL), respectively. However, the spatial pattern along the coastline is very similar in both model integrations.

[14] Figure 3 shows the changes in this percentile, calculated for all four climate change simulations relative

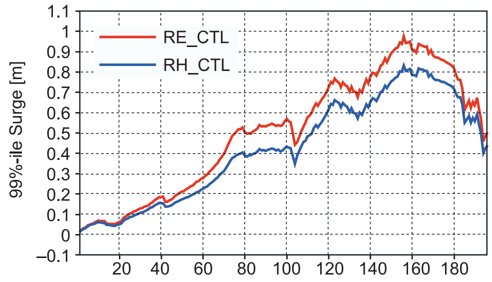

Figure 2. Long term mean of the annual 99th percentile of water level/surge for the control period 1961–1990 (DJF) for both control runs: RE_CTL (red) and RH_CTL (blue). Shown are values for the grid cells located along the 10-m depth line along the North Sea coast (for the numbering of locations, refer to Figure 1).

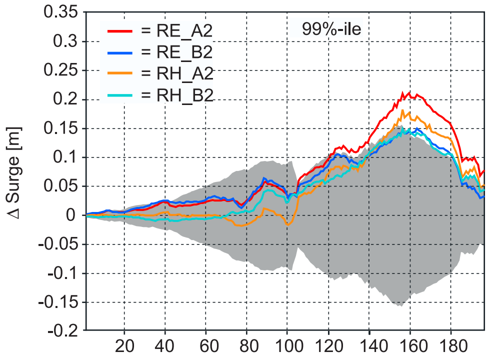

Figure 3. Differences "A2 − CTL" in long term mean of the annual 99th percentile of water level/surge (DJF) for all four ensemble members. The shading indicates the 95% confidence interval based on t-test statistics (see text). Depicted are grid cells located on the 10-m depth line along the North Sea coast (for the numbering of locations, refer to Figure 1).

to their control climate. Both A2 projections show an increase, locally limited, up to 22 cm and 18 cm, respectively. Both B2- projections show a similar spatial pattern but with a smaller increase of up to 15 cm in the German Bight.

[15] As a first part of this study, differences of the 99th percentile between the control- and scenario-runs are examined to determine if they could merely reflect natural variability or if the climate change projections differ significantly from the control climate conditions. We test the null hypothesis:

$$H_o : p_{99}(CTL\_M_x) = p_{99}(Sc_y\_M_x) \qquad (1)$$

where $p_{99}(CTL\_M_x)$ is the mean annual 99 percentile, derived in the control run with model M_x, for x = RE and RH. $p_{99}(Sc_y\_M_x)$ is the same quantity in a scenario Sc_y, for y = A2 and B2. The 95% confidence interval - depicted as grey band in Figure 3 - is derived from the student *t* distribution (critical values), using the standard deviation of the inter-annual 99th percentile surge residual derived from the hindcast simulation described by *Woth et al.* [2005]. The period of the hindcast analyzed was that of the present control climate, 1961–1990. This was undertaken as a result of, and to accommodate, the higher standard deviation found in the hindcast compared to the projections used in this study. The locations where the null hypothesis (1) is rejected are those grid cells not lying inside the confidence interval (Figure 3).

[16] Most parts of the continental coast show significant changes between future and today's condition in RE_A2–simulation. For RH_A2 and both B2 forced simulations, the number of grid cells showing significant changes decreases and are locally limited on the German Bight and the Danish coast.

[17] With the rejection of the null hypothesis (1) and thus the acceptance of at least a local limited change - a second question arises, namely: Are the climate change signals, resulting from differences between climate scenario and control conditions, *among* the four future surge scenarios statistically distinguishable? Two null hypotheses are tested:

$$H_o : \Delta p_{99}(A2, M_x) = \Delta p_{99}(B2, M_x) \qquad \text{for } M_x = \text{RE and RH} \qquad (2)$$

and

$$H_o : \Delta p_{99}(Sc_y, RE) = \Delta p_{99}(Sc_y, RH) \qquad \text{for } Sc_y = \text{A2 and B2} \qquad (3)$$

where (Δp99) is the difference of each climate change projection relative to today's climate in the mean 99th percentile. Thus, for both null-hypotheses two test-statistics are possible:

$$\Delta p_{99}(A2, RE) - \Delta p_{99}(B2, RE) \text{ and}$$
$$\Delta p_{99}(A2, RH) - \Delta p_{99}(B2, RH) : \text{in order to test } H_o(2);$$

$$\Delta p_{99}(A2, RE) - \Delta p_{99}(A2, RH) \text{ and}$$
$$\Delta p_{99}(B2, RE) - \Delta p_{99}(B2, RH) : \text{in order to test } H_o(3).$$

Accordingly, the changes in different emission scenarios, given a global forcing, are considered in (2), and the changes obtained with different GCMs, given an emission scenario, in (3). This time, the null hypothesis is tested with an ordinary 2-sided t-test, assuming the same variance in all model simulations. Figure 4 shows the result. Grid points at which the null hypothesis is rejected with a risk of 5% are outside the grey band, which represents the 95% range of differences consistent with the null hypothesis.

[18] When considering the continental coast, for which hypothesis (1) was rejected, only two future surge experiments can be discriminated statistically, namely the scenario runs A2 and B2 with ECHAM4/OPYC3 forcing (null hypothesis 2) for which differences lie outside the confidence interval locally limited along the Danish North Sea coast. The null hypothesis (3) dealing with different global

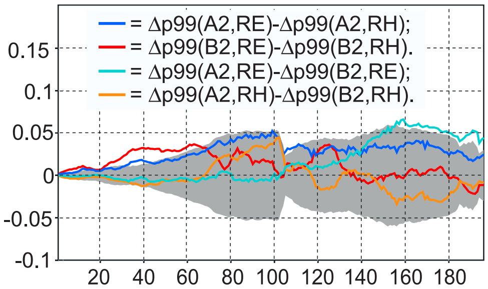

Figure 4. Differences in the shift of each climate change projection relative to today's climate in the mean 99th percentile (Δp99) of water level/surge (DJF) calculated between all four combinations of future simulations. Unit: [m]. The shading indicates the 95% confidence interval based on t-test statistics (see text). Depicted are grid cells located on the 10-m depth line along the North Sea coast (for the numbering of locations, refer to Figure 1).

forcings is rejected only for A2 at a few grid points located at the French Channel coast – but the rate of rejection is not multiply significant. Differences between GCMs using the same scenarios are distinguishable along parts of the coast of United Kingdom for B2, but without any climate change signal (hypothesis (1)).

4. Conclusions

[19] A state-of-the-art storm surge model was run for present day control conditions (1961–1990) and assumed future climate conditions (2071–2100) for the North Sea basin. Atmospheric forcing was taken from the Rossby Centre RCM, which has dynamically downscaled the 'control climate' and the A2 and the B2 SRES scenarios (IPCC) from two driving global models HadAM3H and ECHAM4/OPYC3.

[20] Analysis of changes between control climate and scenarios are based on the inter-annual mean of the 99th percentile of half hourly surge values for winter months. A climate change signal of increasing surge heights along most of the continental coast emerges for both scenarios, SRES A2 and SRES B2 as well as for both GCM forcings. In most locations these shifts, relative to the control simulations, are beyond the confidence limit characterizing natural variability, with highest values for the German Bight up to 21 cm. The spread of the 99 percentile in the ensemble is found to be less then 10 cm, approximately 10 to 15%.

[21] *Woth et al.* [2005] found that the use of different RCMs subjected to the same driving GCM forcing did not lead to distinguishable results. In this study a further question was addressed: whether a different GCM forcing or a different specification of future atmospheric emissions leads to more or larger uncertainties (differences) in the results simulated with the impact model.

[22] Concerning the 99th percentile of the surge residual, which is an important parameter for coastal protection, a clear statistical distinction was not possible between the four tide-surge climate change projections. Only the two SRES emission scenarios A2 and B2 driven with ECHAM4/OPYC3 forcing are locally distinguishable. The other experiments are not distinguishable statistically: neither the HadAM3H projection, forced with two different SRES emission scenarios, nor both projections, driven with two different GCM forcings.

[23] The results could be influenced by the similarity of the 'physics' of these GCMs and the rather limited experimental design. However this study confirms and extends results of earlier studies, which underline the robustness and the importance of these findings for the research field of coastal protection under climatic change conditions.

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