High resolution projections of possible future changes in North Sea storm surge extremes

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ABSTRACT

We examine the feasibility of a statistic downscaling approach, for deriving high resolution storm related sea level heights from a coarse resolution storm surge model. To this purpose a linear statistical relationship is calibrated between coarse and the high resolution hindcasts for present climate (1958 – 2002).

The two hindcasts are performed by different hydrodynamic 2D models. The high resolution hindcast was performed on an irregular grid with an increasing spatial resolution towards the coastline up to 80 m by 80 m. The other one was obtained with a coarse 10 km resolution model. Both hindcasts were forced by identical meteorological conditions. The downscaling model consists of an univariate linear regression between high resolution grid point surge quantiles and optimally correlated coarse resolution grid points. Thus the statistical function allows to transfer storm related water level heights from the coarse to the high resolution.

As an example application a series of high-resolution projections of possible future changes in storm-related sea level heights are derived for the southeastern coastal area of the northwest European shelf sea (German Bight, North and West Frisian coasts) for the time horizon 2071 to 2100.

KEYWORDS: storm surge, climate change, statistical downscaling, North Sea

1 INTRODUCTION

The major geophysical threat for Northwest European coastal areas is related to storm tides, which have the potential to flooding low lying coastal areas. During extreme storm tides, large areas of flood-prone coastal lowlands can be, and have been flooded (Rhode and

Petersen, 1977), causing loss of live and property. Additionally is the North Sea coast area one of the regions that may be adversely affected by changing climate conditions. 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, 2007). Such an increase in high wind speeds would certainly lead to a change of the storm surge risks for the North Sea coast.

By the use of statistical relationships or numerical tide-surge models, these atmospheric future conditions can be projected on hydrodynamic variables as e.g., local water level heights. This was done recently by several authors as e.g., von Storch and Reichardt, 1997, Flather and Smith 1998, Langenberg et al., 1999, Lowe et al., 2001, Debernard et al. 2002, Lowe and Gregory, 2005, Woth 2005, Woth et al. 2006. Their results show that under enhanced greenhouse gas conditions an increase of up to 10% in extreme wind speeds in the North Sea and the Norwegian Sea may take place at the end of the 21st century, when CO_2 concentrations are doubled (B2) or even tripled (A2). These changes suggest an increase in surge height extremes of similar proportion.

To obtain projections right on the shoreline, the surge-tide models mostly fail because of insufficient resolution (usually not better than 10 km* 10km grid cells), so that small scale morphological structures are not resolved in the model topography. However, it could be shown that such tide-surge model simulations are able to perform satisfying results of water level heights when the coast is steep, which is the case for large parts of the east coast of Great Britain (e.g., Flather and Smith,1998). In case of the southern and south-western North Sea, where the coast is flat and large areas are mudflats, sea level heights can realistically modelled up to the 10 m depth line (Woth et al., 2006).

For such flat coasts, a remedy is to built empirical models, which relate off-shore water level variations to local variations, recorded at local tide gauges (Langenberg et al., 1999). These empirical links are then used to estimate on-shore statistics by post-processing scenarios for off shore modelled water level statistics. For one- or two dimensional analyses close to the coast line, these studies fail, simply because tide gauge data are available at local spots and not all along the coast.

Hydrodynamic models with increasing spatial resolution towards the coast reach more accuracy. The disadvantage of high spatial resolution simulation is a significant increasing of the computational time for the model integration. Therefore, high accuracy model integration of several decades are not yet applied for future anthropogenic 'climate change' investigations.

Langenberg et al. (1999) and also Lassen et al. (2001) suggested an approach to enhance the information by applying a statistical relation between a modeled (hindcasted) grid box and observed water level at a tide gauge. Grossmann et al. (2007) used a similar approach to transfer future climate change projections of water heights on one specific tide gauge, namely St Pauli, Hamburg, situated more than 100 km inside the Elbe estuary (Germany), which is not resolved in the tide-surge model.

In this study we extend and enhance these statistical downscaling approaches by combining a high resolved hindcast with a coarse resolved hindcast. We use this transfer function to implement the complex coastal structure afterwards into a series of data sets modelled in different climate change experiments.

2 THE SURGE MODELS AND THEIR SET-UPS

Two model hindcasts were used to regionalize the possible future climate storm surge conditions. The models and their set-ups are briefly described in the following.

2.1 Tide-surge models

The high-resolution coastal North Sea model, using the TELEMAC2D code from Electricité de France (EDF) (Hervouet and Haren 1996), has been setting up and run by the Federal Waterways Research Institute, Coastal Division (BAW-AK). To consider the complex coastline, islands and bathymetric structure in the coastal zone, the model was set up on a unstructured mesh (triangles). The distances between its nodes varies between about 75 m near the coast and 27 km in open sea regions (Weisse and Plüß, 2006). An additional feature of this simulation is that it assimilates the actual water-level data from Aberdeen to account for long waves propagating from the North Atlantic into the North Sea basin (external surges). The 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 (2004), with good results. For details of the model and the model set-up refer to Plüß (2004). In the present study, the model output was interpolated on a regular 250 m grid.

The hindcast done with this model, in the following termed as *HC_highres*, in the near-shore coastal sea provides the predictors for the statistical downscaling model.

The coarse-resolution TRIMGEO model (Tidal Residual and Intertidal Mudflat) (Casulli and Catani, 1994) is 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 model domain covers the North Sea and is gridded 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. The off-shore water levels simulated by this model, in the following termed as *HC_lowres*, serves as predictand in the statistical downscaling model.

2.2 Atmospheric forcing and lateral boundary conditions:

Regionalized wind (TELEMAC2D) as well as wind and air pressure fields (TRIMGEO) were used as the external meteorological force at the interface between water and air to drive the hindcasts. These data were obtained from a regional atmosphere model (SN-REMO; von Storch et al.; 2000, Jacob 1995), forced with reanalysis data from the National Center for Environmental Predication (NCEP/NCAR) (Feser et al. 2001). The resulting marine wind and air pressure fields in one hourly temporal resolution and about 50 km spatial resolution were found to be homogeneous and of satisfactory quality (e.g., Weisse and Feser 2003; Sotillo 2003; Weisse et al. 2005).

At the models boundaries across the northern North Sea and across the English Channel in the west, boundary conditions in terms of sea level anomalies are prescribed by 17 partial tides. A net influx is prescribed from the Baltic Sea (OSPAR Commission, 2000) and from the largest rivers, specified from climatology. The bathymetry and the tidal coefficients were provided for both model set-ups by the German Federal Maritime and Hydrographic Agency (BSH).

Fig. 1 shows a comparison of the mean annual 99th percentiles (based on 1 hourly data, winter month), derived from both, the TRIMGEO and from the TELEMAC-2D hindcast for a 30-year period (1961 to 1990) along the 10-m depth line of both models. Differences occur along the Eastern coastline of UK. There, the advantage of assimilating Aberdeen-observations into HC_highres becomes obvious. Along the 10-m line of the continental North Sea coast, HC_lowres deviates only by less than 10 cm from TELEMAC-2D, likely reflecting the missing effect of the external surges in TRIMGEO. The overall spatial patterns match very well.

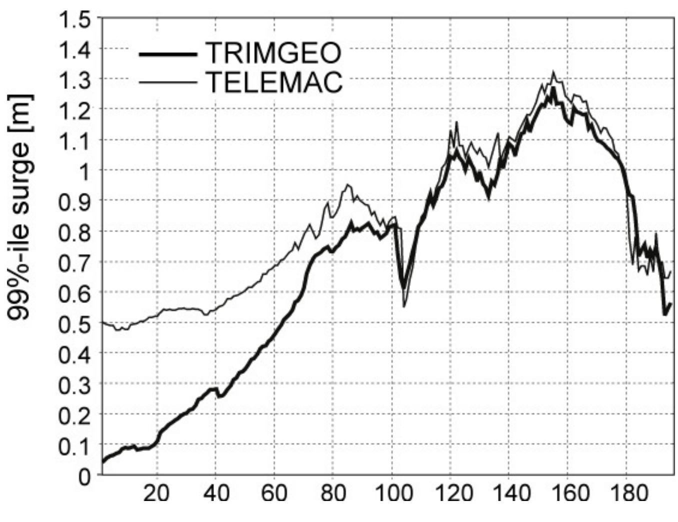

Figure 1: Inter-annual mean of the 99th percentile of water-level/surge (DJF) for the control period 1961 – 1990 (unit: m). Bold line: TRIMGEO; thin line: TELEMAC. Calculations of percentiles are based on 1 hourly data. Depicted are grid cells located along the 10-m depth line along the North Sea coast (for the numbering of locations, refer to Fig. 1) Adopted from Woth et al. 2006

3. DOWNSCALING MODEL

The statistical downscaling model consists of a linear regression of 99 intra-winter percentiles of sea level heights in HC_lowres on the HC_highres. (An intra-winter x-percentile, is the percentile derived from all values within a specific winter, so that x % of all values of that winter are smaller than the percentile, and 100 – x % are larger.). Thus predictors are 99 percentiles in the HC_lowres simulation, and the predictand are the 99 percentiles in the HC_highres simulation.

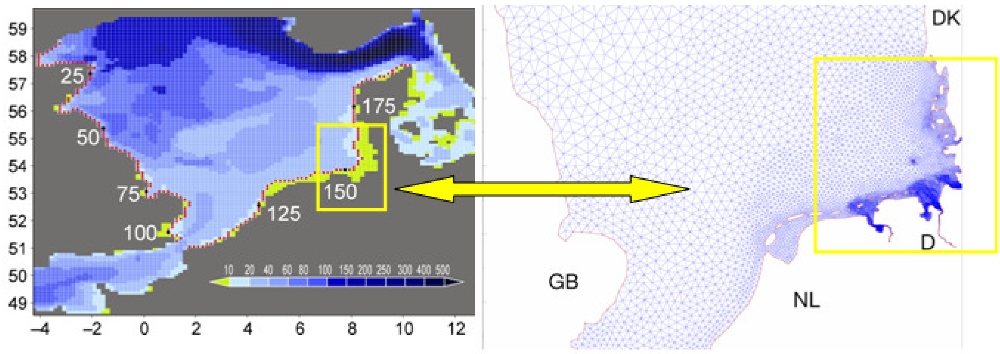

Figure 2: Schematic sketch of the predictor (left) and the predictand (right) of the downscaling model. Red points in the left panel, shows the 10 m bathymetry line from which predictor grid points are selected. Yellow window indicates study area for the high resolution scenario (German Bight).

Potential predictors are considered at grid points on the 10 m bathymetry line from Scotland to Denmark (see red points in fig. 2). In a first step, for each predictand grid point, that grid point is selected from the 10 m bathymetry line, which shows the best linear correlation coefficient. In a second step a least square linear regression is estimated between each predictand and the corresponding optimal predictor percentiles.

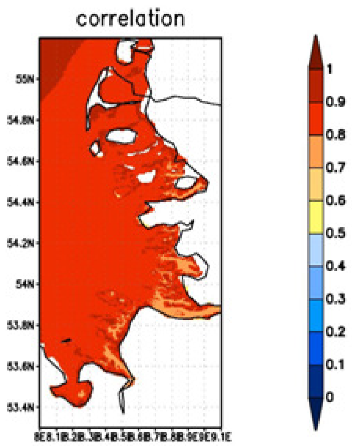

Figure 3: The linear correlation coefficient between predictor and predictand 99 percentiles.

The model is calibrated for the German Bight (yellow marked field in fig. 2). Figure 3 shows the optimal correlation for each predictand grid point. Typical values are between 0.8 and 0.95. Somewhat smaller values (typically 0.7) are obtained in smaller estuaries and bights.

Fig. 4 shows results from a cross validation of a statistical downscaling model using even years in 1962 – 1998 for validation and uneven years for calibration (left panel). The root mean square error (rmse) of the model varies between 3 and 5 cm for the selected optimal set of parameters. This correspond to approximately 10 % of the year-to-year standard deviation of surge 99 percentiles in HC_highres (shown in fig. 4, right panel). Thus the statistical model is capable of reproducing inter-annual surge heights variation at high accuracy.

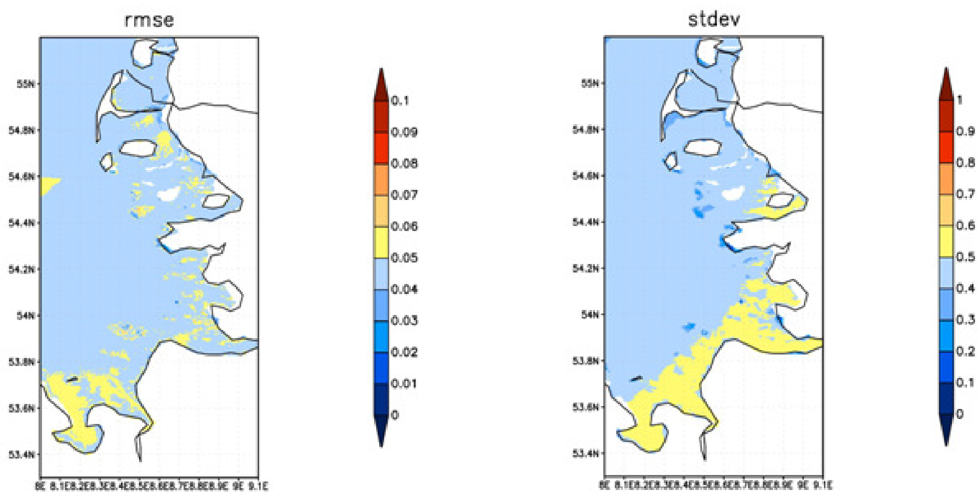

Figure 4: Cross validation results from the statistical model: root mean square error (left panel) compared to inter annual storm surge variability as quantified standard variation for 99 percentile from HC_highres (right panel).

4. RESULTS AND DISCUSSION

Here we applied the statistical downscaling model to several 30-year storm surge simulations under present-day conditions and possible future atmospheric greenhouse gas concentrations (based on different IPCC emission scenarios and global/regional climate models). Results for emission scenarios A2 and B2 and atmospheric forcings with two global climate models (ECHAM4/OPYC3, HadAM3H) are shown in Fig. 5.

The high resolution scenarios shows more fine-scale structures. Within the estuaries and narrow bays the projected changes are higher by typically between 10 and 30 % compared to the projections on the 10 m bathymetry line in the coarse resolution surge projections.

Compared to projections possible so far, the high resolution results points to a larger climate change response close to the coast. However, the increase of the response is of similar magnitude like the uncertainty of the projections quantifies by different climate models (compare fig. 5 a and c).

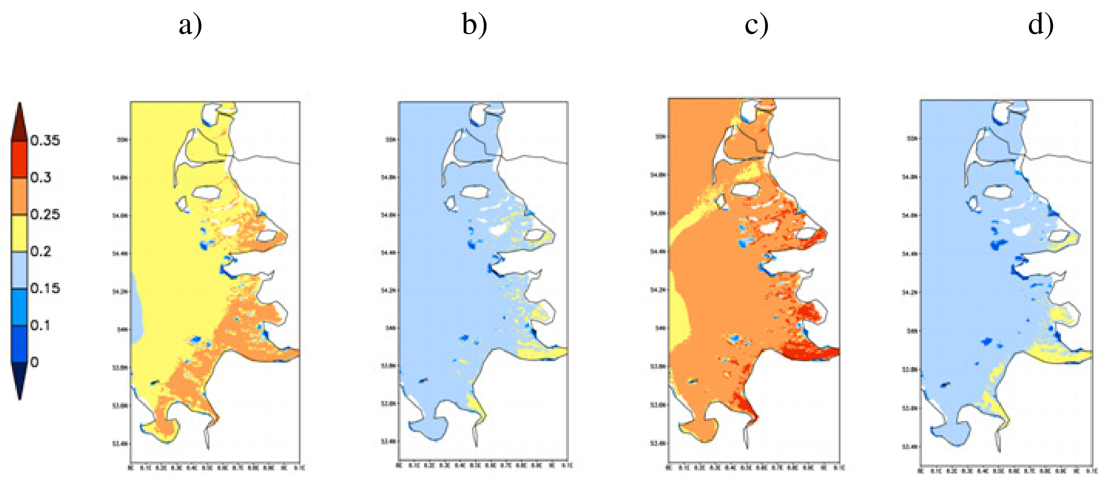

Figure 5: High resolution climate change scenarios of storm surge heights (changes in meter, between 2071 – 2100 and today's climate conditions) derived with the statistical downscaling model for different emission scenarios and climate models. From the left to the right: HadAM3H_A2; HadAM3H_B2; ECHAM/OPYC3_A2, ECHAM/OPYC3_B2. Dynamical downscaling from the global climate conditions were performed by the regional climate model from Røssby Center RCAO (Döscher et al. 2002).

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