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Changing North Sea storm surge climate: An increasing hazard?

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ABSTRACT

Extreme sea levels provide a substantial hazard for low lying coastal areas in the Southern North Sea. They are caused by a combination of different factors such as high astronomical tides, a large-scale rise of the sea surface caused by high wind speeds and low atmospheric pressure (usually referred to as storm surges), or extreme wind-generated waves (sea states) caused by high wind speeds in atmospheric low pressure systems; that is extra-tropical storms. Long-term changes in any of these factors may substantially alter the hazard associated with extreme sea levels. Moreover, any long-term change in mean sea level such as observed over the past 100 years or as associated with future anthropogenic climate change will have an impact as it shifts the entire distribution of sea levels towards higher values; that is, it changes the baseline upon which storm induced sea levels have to be added. Moreover, in shallow waters non-linear interaction effects may occur. Here we review the present knowledge about long-term changes in any of these factors. We show that storm activity in the area underwent considerable variations on time scales of decades and longer, but that no clear long-term trend could be identified. Similar findings are obtained for long-term changes in the storm surge and wave climate. Mean sea level has increased in the Southern North Sea over the past centuries. Correspondingly an increase in extreme sea levels is found. For the future most projections point towards a moderate increase in storm activity in the area with corresponding changes in storm surge and wave climate. These changes will add to the expected future increase in mean sea level, leading to an increased hazard from extreme sea levels. The latter may have consequences for safety, especially in the low lying coastal areas in the Southern North Sea. Consequences for coastal protection and alternative strategies are discussed.

1. Introduction

Extreme sea levels represent a substantial hazard for the low lying coastal areas along the Southern North Sea coasts. They are caused by a combination of various factors that extend over a wide range of spatial and time scales:

1. High astronomical tides may contribute to extreme sea levels. Tidal sea level variations are caused by the gravitational forces exerted by the moon and the sun. These forces cause complicated spatially and time varying patterns in ocean sea level; but the patterns are generally regular and predictable. In shallow water the propagation of the tidal wave is significantly modified by bathymetry. The latter may become important when changes in bathymetry such as caused by construction works or similar may locally modify the tidal signal and thus the risk associated with extreme sea levels.
2. Storm surges, also referred to as meteorological residuals, are the response of the sea level to large-scale meteorological conditions. They are caused by storm wind fields pushing the water towards or away from the coast and, to a smaller extent, by the action of the atmospheric pressure on the sea surface; that is, when atmospheric pressure at the sea surfaces rises, the height of the sea surface is depressed and vice versa. This effect is known as the inverse barometric effect. The magnitude of the storm surge depends on a number of factors comprising the size, movement, and intensity of the storm system, the near-shore local bathymetry (water depth) or the shape of the coastline.
3. Extreme sea states refer to wind-generated gravity waves at the surface of the ocean. In the southern North Sea these waves are mostly generated locally in response to the local wind field. These waves may be superimposed with swell; that is, waves generated by the wind some distance away. Swell propagates freely across the oceans along great circle paths and may further add to the local wind sea; that is, waves that are still growing and sustained by the local wind field. The height of

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extreme sea states depends on a number of factors such as wind speed, duration or fetch. In very shallow water wave heights become depth limited. Extreme sea states may add to the coastal hazard caused by extreme sea levels by producing effects known as wave run-up; that is, the maximum vertical extent of wave up-rush on a beach or structure and overtopping; that is, the flow of water over a dike or structure caused by wave run-up.

4. Mean sea level refers to the average level of the sea surface relative to some local benchmark over a period long enough such that effects caused by tides, storm surges, and gravity waves are averaged out. Changes in mean sea level arise from several factors changing either the shape of the ocean basins (e.g. vertical or tectonic land movements) or the volume of water within the oceans which may be caused by changes in ocean density or mass. Changes in mean sea level may change the hazard caused by extreme sea levels as these changes tend to shift the frequency distribution towards higher values. Under otherwise similar astronomical and meteorological conditions extreme sea levels may vary due to different baselines or mean sea level values.

There is considerable interaction among the different factors contributing to extreme sea levels in particular in shallow waters. For example, Horsburgh and Wilson (2007) analysed tide-gauge data from five tide gauges equally spaced along the UK North Sea coast line and found that the peak meteorological residuals tend to avoid the times of nearest astronomical high water. Instead a tendency for surge maxima to occur most frequently on the rising tide is recognised (e.g., Doodson, 1929; Rossiter, 1961; Prandle and Wolf, 1978). Horsburgh and Wilson (2007) provide a simple mathematical explanation in which a phase shift of the tidal signal in combination with a modulation in surge production and propagation due to water depth (known as tide-surge interaction) provides a good description of the observed conditions.

The interaction of mean sea level changes and the astronomical tide was studied, for example, by Kauker (1999) and Plüß (2006). Both authors were interested in changes of the tidal signal in response to a rise in mean sea level. Kauker (1999) found that for an increase in mean sea level of 1 m, co-tidal lines of the M2 (principal lunar semidiurnal) tide show small shifts in the location of amphidromic points resulting in an increase of tidal range of about 1–4 cm for most of the southeastern North Sea. Using a spatially higher resolved model and a larger range of mean sea level changes Plüß (2006) produced similar results but found that the effects may be significantly enhanced near coasts and within estuaries. The modelled changes are, however, considerably smaller than those derived from observations, indicating either deficiencies in the models or that other processes unknown so far considerably contribute to the observed changes.

In the following we review present knowledge on changing hazards from extreme sea levels in the Southern North Sea. In Section 2 we describe past and potential future changes in North Sea storm activity which represents the main driver for changes in storm surge hazard and wave climate. The latter are considered in Sections 3 and 4. Mean sea level changes are reviewed in Section 5. The consequences of these changes on safety of coastal population together with alternative strategies to provide safety and protection are considered in Section 6. Finally, in Section 7 we conclude with a summary on challenges for future research.

2. North Sea storm activity

The North Sea is located in the mid-latitudes and under the influence of the prevailing atmospheric west wind belt; that is, the dominant west-to-east motion of the air in mid-latitudes. Mid-latitude or extra-tropical cyclones are the dominant weather phenomenon in this region. These are migratory atmospheric disturbances, often associated with large pressure gradients and strong wind speeds, developing at the interface between cold and warm air in mid-latitudes and generally propagating eastward controlled by the orientation of the flow within planetary-scale waves. They tend to occur within and to propagate along regionally confined areas, the so-called storm tracks. The North Sea is under the influence of the North Atlantic storm track, one of the two major storm tracks in the Northern Hemisphere (e.g., Weisse and von Storch, 2009, Fig. 2.6).

There have been a number of extra-tropical cyclones (storms) causing severe damage and flooding along the North Sea coast line. Two of the more recent examples are the storms affecting the coasts on 31 January and 1 February 1953 and on 16–17 February 1962. While the storm in 1953 was associated with exceptionally high wind speeds over the shallow continental shelf (Wolf and Flather, 2005) the 1962 storm mostly showed only moderate wind speeds (Koopmann, 1962). However, wind speeds were increasing over the Atlantic and moderate to strong northerly winds covered a relatively large area from Iceland to Northern Germany (Müller-Navarra et al., 2006). In both cases, the storms caused extreme storm surges and were associated with a widespread failure of coastal protection (Gerritsen, 2005; Baxter, 2005; Sönnichsen and Moseberg, 2001) mostly due to poor conditions in coastal defence constructions.

Storm activity in the North Sea region is not constant, but has underwent considerable variations over the past decades. Fig. 1 shows two indices for storm activity based on upper percentiles of geostrophic wind speed anomalies. For details on the construction of such indices see Schmidt and von Storch (1993), Alexandersson et al. (1998) and Rosenhagen and Schatzmann (2011); for details on the extent to which such indices relate to variations in the storm climate see Krueger and von Storch (2011). Both indices reveal considerable variability on inter-annual and on decadal time scales but show no clear long-term trend. In particular it can be inferred that storm activity was relatively low around and within the 1960s. Subsequently it strongly increased towards a maximum around the mid of the 1990s. Afterwards a strong decrease towards the relatively low levels of the 1960s can be inferred. Even longer time periods were considered in Bärring and von Storch (2004). They used air pressure records from two stations in Sweden to reconstruct storm activity in Northern Europe back to 1780. In agreement with the results shown here they noticed pronounced inter-annual and decadal variability but could not identify a substantial long-term trend.

There are a number of studies considering changes in storm activity over a shorter time period. Most of these are based on reanalysis data[1] typically covering periods from about 1958 onwards. For a review of such studies see e.g. Chang et al. (2002). Chang and Fu (2002) analysed Northern Hemisphere storm track activity and found that mean storm track intensities were increase by about 30% when the mid-1990s are compared to the late 1960s. The latter is in agreement with the variations shown by the two storm indices for the North Sea (Fig. 1). Other studies report a noticeable shift of the location of the North Atlantic storm track. For example, McCabe et al. (2001) showed that based on reanalysis data, storm frequency in mid-latitudes decreased during the

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[1] A reanalysis refers to the procedure of projecting the state of the atmosphere from a finite set of imperfect, irregularly distributed observations onto a regular grid using a frozen state-of-the-art numerical model and data assimilation system (Glickman, 2000). For a discussion see e.g. Weisse and von Storch (2009).

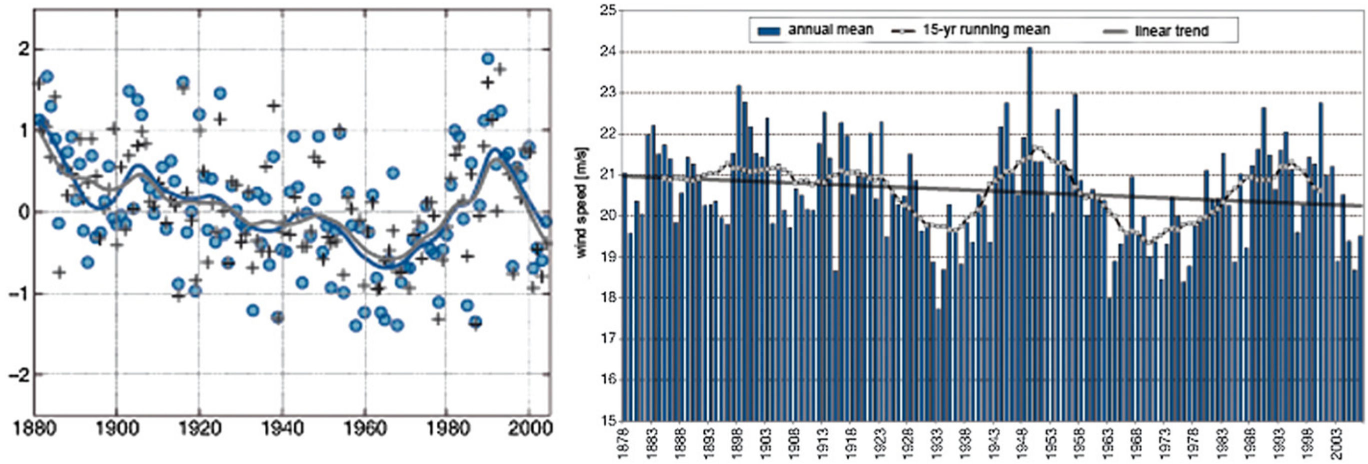

Fig. 1. (Left) Storm index for northwest Europe based on geostrophic wind speed percentiles according to the methodology described in Alexandersson et al. (1998). Blue circles are 95-percentiles, black crosses 99-percentiles of standardized geostrophic wind speed anomalies averaged over 10 sets of station triangles. The blue and black curves represent a decadal running mean. Redrawn from (Trenberth et al., 2007, Fig. 3.41). Reproduced by permission of the IPCC/Cambridge Univ. Press. (Right): Winter mean of geostrophic wind speeds in the German Bight together with decadal running mean and linear trend. Redrawn from Rosenhagen and Schatzmann (2011). Reproduced by permission of Springer Science + Business Media.

second half of the 20th century while an increase was found for the high latitudes north of 60 N. At the same time storm intensities increased at high latitudes, while in mid-latitudes they remained nearly constant with superimposed inter-annual and decadal variability. Corresponding results were obtained from similar analyses (e.g. Geng and Sugi, 2001; Paciorek et al., 2002; Weisse et al., 2005).

When potential future changes in extra-tropical storm climate in the course of anthropogenic climate change are considered the range of existing studies presents a rather mixed picture with the confidence in future changes in wind climate in Europe remains relatively low (Christensen et al., 2007). Potential changes in extra-tropical storm climate are usually related to changes in the meridional temperature gradient (e.g. Bengtsson et al., 2006), the increasing amount of water vapour (e.g. Chang et al., 2002; Bengtsson et al., 2006) or changes in sea surface temperatures (see discussion in Bengtsson et al. 2009). It is obvious that these processes are partly competing. Their relative contribution to observed and expected extra-tropical cyclone variability and change are disputed (see e.g. Bengtsson et al., 2006, 2009). In numerical models, the response depends on the balance of these processes which may differ from model to model explaining the range of different results obtained in simulating future changes in extra-tropical cyclone activity. Following the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) a consistent result emerging among more recent studies appears to be a tendency for a poleward shift in storm activity of several degrees latitude in both hemispheres (Meehl et al., 2007). Possible explanations have been discussed in, for example, Yin (2005) and Bengtsson et al. (2006, 2009) and are related to differential changes of the meridional temperature gradient with height and associated changes in vertical stability. Regionally, large deviations from this large scale picture are possible (e.g. Yin, 2005; Bengtsson et al., 2006). Earlier IPCC reports more strongly noted that the number of extra-tropical cyclones may decrease (e.g. Knippertz et al., 2000; Geng and Sugi, 2003) or show little change (e.g. Kharin and Zwiers, 2005; Watterson, 2005). Some studies are indicating that strong extra-tropical cyclones may become more frequent (e.g. Caires et al., 2006; Pinto et al., 2007). A number of studies report observed changes to be consistent with patterns expected in response to anthropogenic climate change (e.g. Wang et al., 2009) while others, mostly based on long and more homogeneous proxy records, concluded that observed changes are not inconsistent with natural variability (e.g. WASA-Group, 1998; Bärring and von Storch, 2004; Bengtsson et al., 2009).

3. Storm surge hazard

The contribution of surges; that is, the meteorologically induced fluctuations of the water levels, to the local variations in sea surface height can be assessed from the statistics of long tide-gauge records. A typical measure for the contribution of the weather-related effects to the total sea level variability is the standard deviation of the meteorological residuals (e.g. Pugh, 2004). The latter varies from a few centimetres (e.g. for open ocean islands; for example about 6 cm for Honolulu, Hawaii) to tens of centimetres for shallow waters subjected to frequent severe weather conditions (Pugh, 2004). Largest values are often found in bays or estuaries (e.g. about 49 cm in Buenos Aires, Argentina) (Pugh, 2004). For Cuxhaven, Germany, located at the southern North Sea coast within the estuary of the river Elbe approximately 36 cm can be derived (Weisse and von Storch, 2009) indicating a considerable contribution from surges to the overall water level variations.

Representing the sea level response to the large scale meteorological conditions, storm surges are intimately connected with storms. For Cuxhaven, for example, the seasonal variations in storm statistics strongly reflect the seasonal cycle of the weather patterns with the most severe surges generally occurring within the winter storm season from November to February (Weisse and von Storch, 2009).

When longer time scales such as years or decades of years are considered, the variations in storm surge statistics basically reflect those in storm activity described in Section 2. Fig. 2 shows two time series from Cuxhaven in which the total water level was split into two parts. The approach is based on an idea suggested by de Ronde (WASA-Group, 1998) to separate changes in mean sea level and storm surges. The approach is based on the assumption, that changes in mean sea level will shift the entire frequency distribution towards higher values; that is, the changes will be visible in both, mean and extreme sea levels, while changes in the statistics of storm surges will only be visible in the extremes leaving the mean almost unaffected. De Ronde suggested that the coherent part could be removed

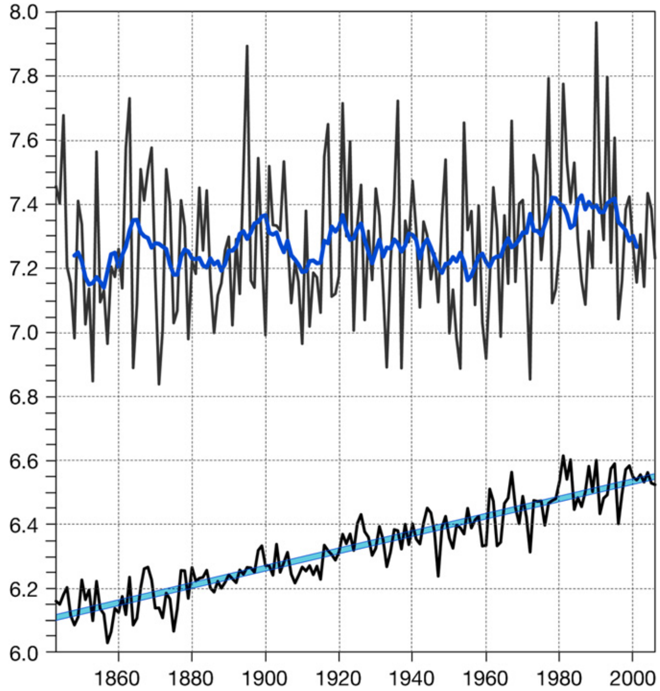

Fig. 2. Annual mean high water levels (black) relative to German North Sea gauge level (*NN* + 5.00 m) and linear trend (blue) in m at Cuxhaven, Germany and the corresponding difference in m between 99 percentile and annual mean high water levels (top, black) together with an 11-year running mean (top, blue). Redrawn from Weisse and von Storch (2009) with permission from Springer Sience + Business Media.

from the time series, e.g. by subtracting annual means from annual upper percentiles (e.g. 99 percentiles) and that the residual obtained represents a proxy for storm-related water level fluctuations or storm surges. Moreover, mean sea level variations could be analysed by studying the coherent part. The approach was tested and applied to water levels in Cuxhaven by von Storch and Reichardt (1997) and Fig. 2 shows an update of their analysis for the period 1843–2006 derived from Weisse and von Storch (2009). While the annual means show a pronounced increase over the more than 150 years considered the storm-related water level fluctuations appear remarkably constant with pronounced inter-annual and decadal variability superimposed. Closer inspection reveals that the decadal fluctuations are closely linked with that of storm activity in the southern North Sea (Fig. 1). In particular, the minima around the 1960s and at the end of the record as well as the maximum around the mid 1990s can be clearly recognised.

Fig. 2 implies that extreme sea levels indeed increased over the more than 150 years analysed but also suggests that this is primarily due to an increase in mean sea level while storm-related contributions remained relatively constant. Similar analyses were provided by Woodworth and Blackman (2004) and Menéndez and Woodworth (2010) who considered a tide-gauge data set with quasi-global coverage. They concluded that subtracting extreme and mean sea levels leads to a reduction in the magnitude of trends at most tide-gauges, suggesting that variations in mean and extreme sea levels have been largely coherent and that much of the change in extremes is caused by corresponding changes in mean values.

A different approach to separate the meteorologically driven sea level fluctuations from those caused by other factors is by using dynamical tide-surge models driven by observed atmospheric wind and pressure fields from the last decades of years. As changes due to other factors (such as mean sea level rise or modifications of bathymetry) are excluded by design, such simulations allow for an estimate of long-term changes and variability in the storm surge climate. For the North Sea such simulations were performed, for example, by Langenberg et al. (1999), Wakelin et al. (2003), or Weisse and Pluess (2006). While the analysis methods and the periods considered differ, the general observation was that the simulated changes and variations in storm surge climate closely relate to that derived from tide-gauges. In particular, an increase in storm surge heights along the southern and eastern coasts of the North Sea from the 1960s to the 1990s is reported about half of which is attributed to variable extreme weather conditions while the other half appears to be associated with changes in large scale (mean) atmospheric conditions such as represented by the North Atlantic Oscillation (von Storch et al., 2008a).

Future changes in storm surge climate depend on corresponding changes in atmospheric wind and pressure fields that are highly uncertain (Christensen et al., 2007, see also Section 2). This uncertainty is reflected in corresponding analyses on possible future changes in North Sea storm surge climate with the majority of existing studies showing either no (e.g. Sterl et al., 2009) or only little change (e.g. Langenberg et al., 1999; Kauker and Langenberg, 2000; Woth, 2005; Woth et al., 2006; Debernhard et al., 2008) mostly in the southeastern part of the North Sea of up to a few decimetres (e.g. Woth, 2005). Not in all studies were all changes reported found to be detectable; that is, some were within the range of natural variability. A somewhat larger change is described in Lowe and Gregory (2005) who found a 50–70 cm increase in 50-year storm surge return values towards the end of the century in response to anthropogenic climate change. These numbers deviate considerably from those provided by Lowe et al. (2001), Flather and Williams (2000), or Sterl et al. (2009) who, using similar analysis techniques, reported smaller or no changes.

Uncertainty in future storm surge projections largely arises from corresponding uncertainties in wind climate change. The latter has contributions from different sources: the use of different emission scenarios (reflecting uncertainty about future socio-economic development) used to force the global climate models with; the range of different results produced by different models using the same emission scenario (reflecting our imperfect knowledge about relevant processes in the climate system); and the range of results obtained from one and the same model using one and the same emission scenario (providing an assessment of internal (natural) climate variability). A particularly useful data set to assess potential future changes in storm surge climate in relation to its natural variability was described by Sterl et al. (2009). In this case a global climate model was used to simulate the period 1950–2100 seventeen times, using observed greenhouse gas concentration for the past and conditions obtained from the A1B emission scenario for the future. Weidemann et al., in press used wind and pressure fields from these simulations to drive a statistical downscaling model for storm surge heights along the German North Sea coast. Fig. 3 shows an example from their analysis for Husum, located at the Schleswig-Holstein coast. It can be inferred that changes in storm surge height and frequency vary considerably towards the end of the century, although all realisations were obtained by using wind fields from the same climate model and emission scenario. The range provided by the different realisations shows that natural variability is large and should be taken into account when climate change signals from a limited set of realisations are analysed and interpreted.

An important question is the extent to which there is an interaction between potential changes in storm surge climate and mean sea level. The effects were studied by several authors by comparing simulations in which a tide-surge model was rune twice under the same meteorological forcing but with different

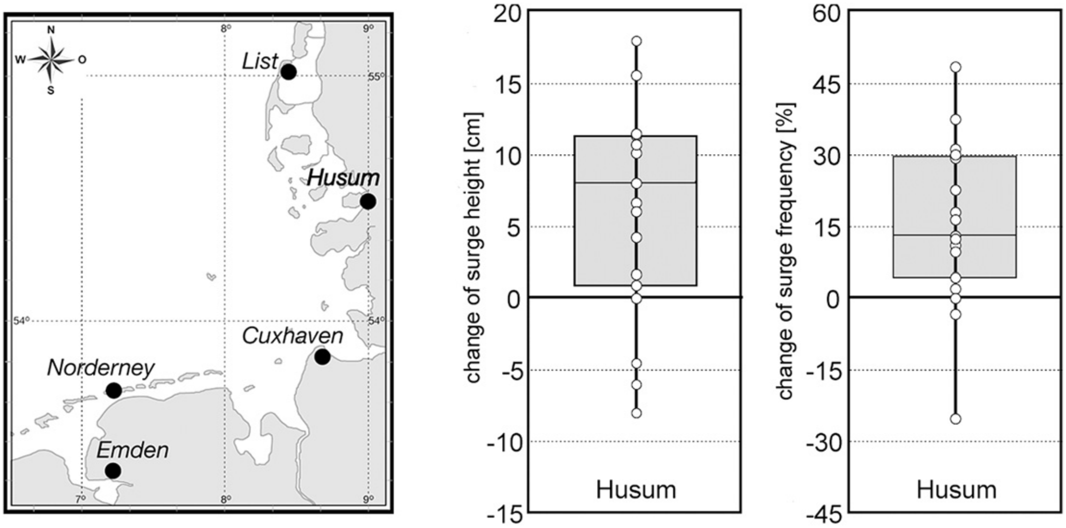

Fig. 3. Location of the tide-gauges analysed in Weidemann et al., in press (left) and changes in storm surge heights in cm (middle) and frequencies (right) within the 21st century derived from a statistical downscaling of 17 realizations of the A1B scenario using the same climate model. Shown are Box–Whisker plots with median and 25 and 75 percentiles (grey). Results from 17 realizations are shown as dots. For details see Weidemann et al., in press.

values for the mean sea level. Kauker and Langenberg (2000) used a relatively small mean sea level change of 10 cm and found no substantial differences between their simulations. Later Lowe and Gregory (2005) conducted a range of similar experiments with mean sea level changes up to about 0.5 m and concluded that to a first order approximation changes in mean sea level and storm surge heights can be added linearly. Sterl et al. (2009) obtained similar results for an increase of mean sea level of up to 2 m. For the Thames estuary, Howard and Lowe (2010) reached similar conclusions for a sea level rise of up to 5 m and noted that the primary effect of a sea level rise is on the timing of both, tides and surges supporting the idea of linear superposition of surge and mean sea level changes.

4. Wave climate

Wave run-up caused by extreme sea states may add to the coastal hazard produced by extreme sea levels as the occurrence of both is closely linked to the occurrence of severe weather. Wave set-up, a process that locally raises sea surface elevation when the waves break near the coast (Longuet-Higgins and Stewart, 1962), may further contribute to extreme sea levels. During a storm event wave set-up may be of the order of a metre at some places, although it is usually considerably smaller at most locations (Lowe et al., 2010).

In the late 1980s and early 1990s a series of papers were published analysing recent changes in North Atlantic and North Sea wave climate (e.g. Carter and Draper, 1988; Bacon and Carter, 1991; Hobgen, 1994; Neu, 1984). Analyses in these papers were typically based on observations comprising about 15–25 years of data. While most authors reported an increase in mean and partly in extreme wave heights all concluded that the time period for which data were available was too short to provide reliable statements about long-term trends. In fact the period considered largely coincides with a period in which storm activity increased in the area; however, taking longer periods into account this increase appeared to be within the range of variability observed before (see Section 2).

Similarly as for the case of storm surges, dynamical wave models driven by observed or reanalysed atmospheric wind fields over the past decades of years have become an increasingly popular tool in analysing long-term changes in offshore wave climate complementing the limited observational data. For the North Sea examples are provided in WASA (1998), Günther et al. (1998), or Weisse and Günther (2007). Generally, these studies confirm the results derived from the observations. In particular, increases in extreme (storm) wave heights from the early 1960s to the mid 1990s are reported with largest increases occurring in the southern North Sea and the German Bight.

A statistical approach for reconstructing extreme sea states backwards in time for longer periods is described in WASA (1998). For two locations, the oil fields Brent north of Scotland and Ekofisk in the central North Sea, WASA (1998) analysed long-term changes and variability for the period 1899–1994. They found, that their statistical model confirmed the increase found in the shorter observational records and the reconstructions using dynamical wave models, but concluded that this increase appeared “normal” when compared to the changes that may have taken place earlier in last century. By combining various data sets and approaches Vikebø et al. (2003) reconstructed monthly mean and annual maximum wave heights in the North Sea backwards until 1881. Analysing long-term changes and variability in this data set, they reached conclusions comparable and in agreement with that described above.

As in the case of storm surges, future changes in extreme wave climate depend on corresponding changes in the atmospheric wind fields that are highly uncertain (Christensen et al., 2007, see also Section 2). An impression is given in Fig. 4 which shows the expected changes in extreme wave heights in the North Sea towards the end of this century derived from a dynamical wave model driven by wind fields from two different climate models under two different greenhouse gas emission scenarios (Grabemann and Weisse, 2008). While in all cases there appears to be a tendency towards an increase of the most severe wave heights, the magnitude and the pattern of these changes are highly variable and uncertain.

There are a number of comparable studies for the North Sea and the Northeast Atlantic. So far, all studies utilise a time slice technique (see e.g. Cubasch et al., 1995; Douville, 2005); that is, they use wind fields from climate model runs in which first coarse resolution models are used to provide transient or time-dependent climate simulations. Subsequently, high-resolution simulations

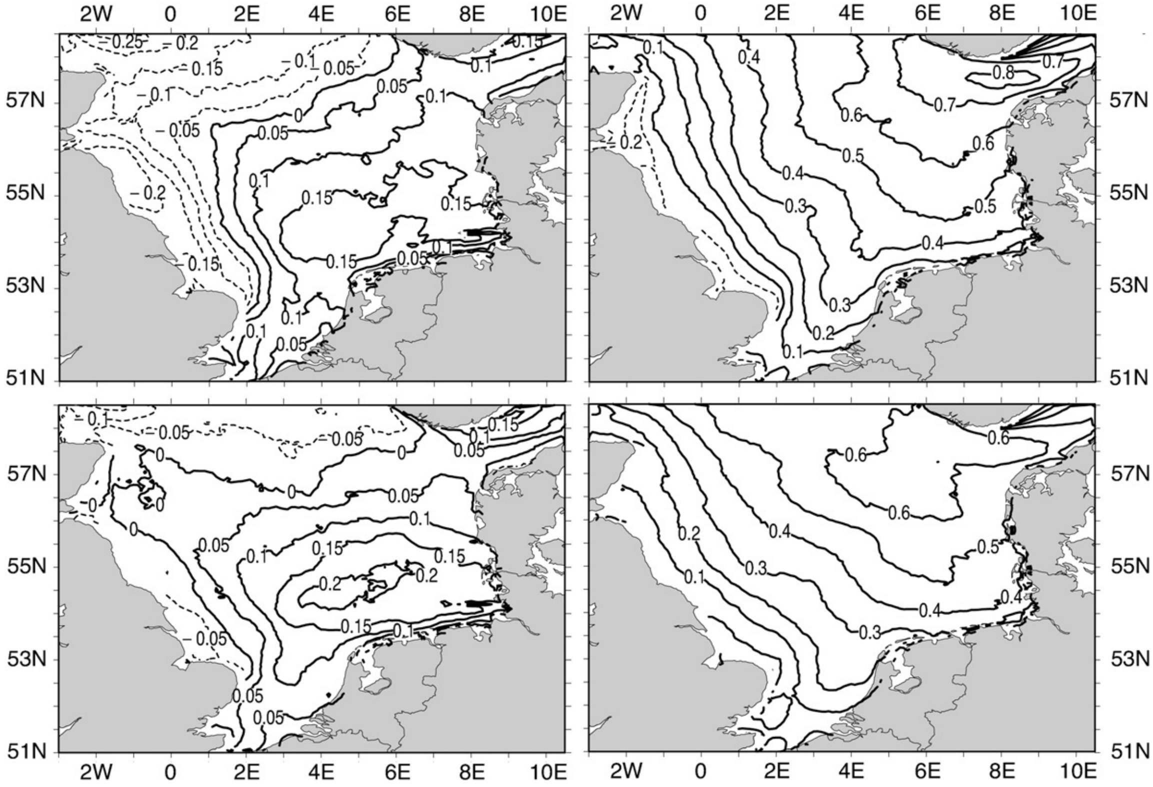

Fig. 4. Climate change signals in metres for extreme (long-term 99 percentile) significant wave height towards the end of the century relative to present day conditions. Changes are obtained from a dynamical wave model driven with downscaled HadAM3 (left) and ECHAM5 (right) wind fields for the A2 (top) and B2 (bottom) emission scenarios. Redrawn from Grabemann and Weisse (2008) and reproduced with permission from Springer Science + Business Media.

are performed for limited periods of time, the so-called time slices, by forcing high-resolution models with data from the coarse resolution transient runs for defined sub periods of the transient experiment. Time slice experiments thus represent a cost efficient way to obtain high-resolution climate change information for limited periods of time. Typically, a control (present climate) and a future climate period usually at the end of the 21st century are considered. Early studies on future wave climate changes typically produced time-slices between 5 and 20 (e.g. Rider et al., 1996; WASA, 1998; Debernhard et al., 2002) and 30-years (e.g. Kaas and Co-authors, 2001) using wind fields from one particular model and emission scenario. More recently multi-model ensembles using wind fields from a combination of climate models and scenarios but still retaining the time slice approach emerged (Grabemann and Weisse, 2008; Debernhard et al., 2008). While details of these studies differ, they all indicate some change in extreme significant wave heights in the North Sea towards the end of this century; however, patterns and magnitude of the described changes are highly variable.

There are some indications that the changes in extreme wave heights analysed from experiments using the time slice approach may still fall within the range of natural variability. Fig. 5 shows time series of extreme wave heights in the German Bight derived from a dynamical wave model driven by wind fields from different transient high-resolution climate change simulations (Groll, pers. comm. 2011). The results indicate, that while a noticeable difference in 30-year averages between present conditions and those projected towards the end of the century can be inferred, in some experiments similar values are obtained also within this century, indicating that reliable estimates of natural variability are needed to fully assess the signals obtained from (time slice) climate change simulations.

5. Mean sea level changes

Over the 20th century global mean sea level increased on average 1–2 mm/year (Church et al., 2001; Bindoff et al., 2007; Jevrejeva et al., 2008). For the satellite era from 1993 onwards somewhat higher estimates of about 3 mm/year are provided that are broadly consistent with that derived from tide-gauge data only (Jevrejeva et al., 2006; Church et al., 2008). Jevrejeva et al. (2006) showed that similarly high rates of sea level rise were also observed earlier within the 20th century; that is, between 1920 and 1945. Church et al. (2008) compared 20-year moving trends; that is, trends over 20-year long time intervals with the starting point of each interval incremented by one year. Similarly to Jevrejeva et al. (2006) they found periods with relatively strong sea level rise in the mid 20th century but concluded that the most recent rates were

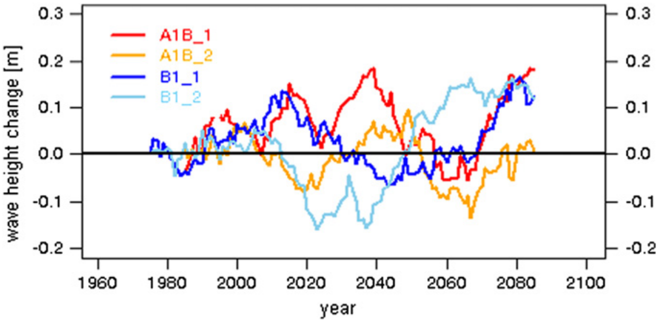

Fig. 5. Differences of extreme wave heights (30-year running means of annual 99 percentiles) between four different climate change simulations (colours) and present day conditions off Norderney, Germany (Groll, pers. comm. 2011).

the largest on record. The latter indicates that in terms of 20-year trends, global mean sea level rise was stronger within the last few decades compared to the rates observed over most of the 20th century. Based on analyses of tide-gauge records since 1700 Jevrejeva et al. (2008) concluded that beginning at the end of the 18th century acceleration in sea level rise of about 0.01 mm/year^2 emerged and when continued will lead to a global mean sea level rise of about 34 cm over the 21st century.

Mean sea level is not expected to change uniformly over the globe but regional deviations are expected (Church et al., 2008; Bindoff et al., 2007). There is considerably variability in the estimated rates of 20th century sea level change in the southern North Sea. For the coast of the Netherlands, Katsman et al. (2008) provide an estimate of about 2.5 mm/year and noted that they could not identify any acceleration within the recent decades. From analyses of German tide-gauge records rates broadly consistent with those estimated from global mean sea levels are obtained with rates being slightly higher/lower in the eastern/southern part of the German Bight (Wahl et al., 2010, 2011; Albrecht et al., 2011). Here rates over the 20th century show considerable variability with relatively high values within the most recent decades, but when compared to earlier periods no outstanding acceleration could be inferred. (e.g. Wahl et al., 2011; Albrecht et al., 2011). From an analysis of tide-gauge records around the UK considerably smaller values of about 1.4 mm/year were derived (Woodworth et al., 2009).

For the future a further increase in global mean sea level is expected primarily as a result of two processes, ocean thermal expansion in consequence to rising temperatures and freshwater input as a result of melting ice sheets, glaciers and ice caps. Contributions from melting ice sheets are thought to be minor for the 20th century but are potentially the largest contributors in the future (Church et al., 2008). For the end of the 21st century, the IPCC Fourth Assessment Report (AR4) projects an increase in global mean sea level of 18–59 cm (Meehl et al., 2007). When possible rapid dynamic responses of the Antarctic and Greenland ice sheets are included, a range from 18 to 79 cm is projected (Meehl et al., 2007). The latter is rather similar to the values reported in the IPCC Third Assessment Report, in particular for the upper end of the projected range (Church et al., 2010a).

As present rates of global mean sea level rise are near the upper bound of the AR4 projections (Church and White, 2011) several authors developed relatively simple parameterizations in which global mean sea level rise is modelled as a function of atmospheric temperatures (e.g. Rahmstorf, 2007; Horton et al., 2008). From these parameterizations generally higher rates of future sea level rise are derived compared to those projected in the AR4. Results from these models are, however, challenged by, for example, their inability to reproduce observed (Holgate et al., 2007) or modelled sea level rise (von Storch et al., 2008b). Church et al. (2010a) note most of the models were trained using data from a period in which sea level rise primarily resulted from contributions from ocean thermal expansion and glacier melt; a situation that is expected to change in the future in the course of anthropogenic climate change.

Sea level during the 21st century is not expected to rise uniformly over the globe. However, there is still little agreement in regional projections still indicating a substantial lack of understanding of the relevant physical processes and their implementation in models (Church et al., 2010b). For the North Sea the most comprehensive assessment was provided for the coast of the Netherlands (Katsman et al., 2011). In this assessment low-probability/high impact scenarios are developed taking into account local steric and elasto-gravity effects. Excluding land subsidence, Katsman et al. (2011) derived estimates of 0.40–1.05 m sea level rise for the coast of the Netherlands by 2100 and more than three times these local values by 2200. Note, however, that these values only refer to high-end (low-probability/high impact) scenarios and should not be used neither to assess uncertainty nor to provide ranges for possible future regional sea level changes. To our knowledge, comparable studies for other regions in southern North Sea are so far not available.

6. Consequences for coastal protection and alternative strategies

For low-lying coastal areas such as those in the southern North Sea, extreme storm surges represent a major threat to coastal protection structures and dunes preventing the inundation of the hinterland. Landward directed storms create a remarkable set-up of the water surface. Additionally, such storms are associated with high wind waves. With increasing water level set-up these waves are decreasingly damped as they are mostly depth-limited in the shallow waters of the Wadden Sea (Niemeyer, 1983; Niemeyer and Kaiser, 2001). As a consequence, storm surge heights only indirectly endanger the safety of structures and dunes, while it is the accompanying extreme sea states acting dynamically at structures and dunes produce strong forces that are able to create enormous damages and even failures.

During the last centuries water levels in the southern North Sea increased due to mean sea-level rise. However, water depths in the Wadden Sea remained nearly constant as the set-up from storm surges did not change substantially and the growth of beaches, intertidal flats and supra-tidal salt marshes over the last centuries was comparable to that of mean sea level. The situation may change in the future, in particular when water level set-ups due to storm surges will increase such as expected e.g. in Woth (2005) or Woth et al., (2006) or when strongly increasing rates of mean sea level rise will outperform the growth of beaches, intertidal flats and supra-tidal salt marshes (Müller et al., 2007). In both cases, the result would be larger water depths and more exposed coastal protection structures and dunes as higher waves are able to propagate towards the coast (Niemeyer, 2010; Niemeyer et al., 2011a,b). Consequently, stronger forces and higher risks may be expected.

In order to adapt to increasing mean seal levels The Coastal Zone Management Subgroup of the IPCC proposed three different strategies. In very general terms these are to retreat, to accommodate or to protect the current coast line (IPCC CZMS, 1990). In Dutch strategy evaluations, additionally the seaward movement of the coastal defence line is noted (Rijkswaterstaat, 1989). All of these four strategies reflect historic practise (Niemeyer, 2005). Later ComCoast (2007) more specifically differentiates between several alternative protection schemes such as setting back (e.g. the present dyke) or combined protection (see below).

While the effects of changing extreme sea level are known in principle and some adaptation strategies were identified in general, detailed studies are missing so far. An exception is the Ems-Dollard estuary, where changes in these effects as a consequence of potential future anthropogenic climate change together with alternative adaptation strategies are presently investigated (Niemeyer, 2010; Niemeyer et al., 2011a,b). Here scenarios of future hydrodynamics loads are generated from corresponding climate change scenarios. Subsequently, these scenarios are used to estimate consequences for present coastal protection and to evaluate alternative strategies.

In a first step, Niemeyer et al. (2011a,b) analysed the consequences of anthropogenic climate change for current design procedures and future safety levels. To do so, they enlarged the most unfavourable combination of the components for design water levels by a safety margin of 50 cm attributed at equal shares to a combination of sea-level rise and increased storm surge set-up; the latter being a consequence of possible increases in extreme wind speeds in the future (e.g. Rockel and Woth, 2007). The latter results in higher offshore waves, while the water level set-up due to increased storm surges reduces wave energy dissipation such that higher wave loads on coastal structures are obtained when no adaption of tidal flats and salt marshes is considered. It was found that even under these assumptions most of the structures of the current defence scheme in the region will withstand the increased force levels or could at least be strengthened to the necessary extent without extraordinary efforts. It was concluded that under the assumptions described above the safety of the lowland areas in the region could be maintained at present standards at least until about 2050 and probably even longer when possibly higher overtopping tolerance of the structures is considered (Niemeyer et al., 2011a).

In the second step, alternative strategies were considered, in particular

1. Setting back the dyke line landwards from the exposed coastline which aims at reducing storm surge levels and increasing wave energy dissipation (ComCoast, 2007). For the Ems-Dollard estuary modelling under realistic conditions, however, highlights opposite effects, namely no decrease in storm surge heights and an increase in wave heights and periods for design conditions (Fig. 6a; Niemeyer et al. 2011b). The main reason for these results is the slope of the land surface. Contradictory to assumptions (ComCoast, 2007), the height of the land surface is getting smaller when moving landwards away from the dyke. The latter is a consequence of terminating the silting-up of the low lying marshes after their embankment such that the height of the land still grows seawards of the dyke while there is no such growth any more on the inland side. In most coastal lowlands such embankments were carried out stepwise moving the protection line more and more seawards. Setting back the protection line, in these cases will increase the water depth in front of the new dyke. During storm surges, this will cause more wave energy and higher loads at the new dyke.
2. Combined protection: A combined protection scheme consists of two structures instead of one. Here the major structure protects the hinterland against inundation while a second wave dissipation structure located more seaward shields the main structure against wave attack. Compared to a single structure the major advantages of such a combination are the lower amounts of material needed and an increased safety level of the hinterland (ComCoast, 2007). For the Ems-Dollard estuary simulations under realistic conditions showed, however, a relatively low effectiveness of such a layout (Fig. 6b). In order to damp approaching waves sufficiently before approaching the main structure, enormous dimensions of the wave dissipation structure would be required with very limited effects and a negative cost–benefit relation (Niemeyer et al., 2011a,b).

These results for the Ems-Dollard estuary indicate that detailed studies instead of generalized statements are urgently needed when current and future safety levels of coastal protection are assessed and possible adaptation strategies are discussed.

7. Future challenges

Extreme sea levels represent a substantial hazard for the low lying coastal areas in the Southern North Sea. While in the past few years much progress was made in understanding the various

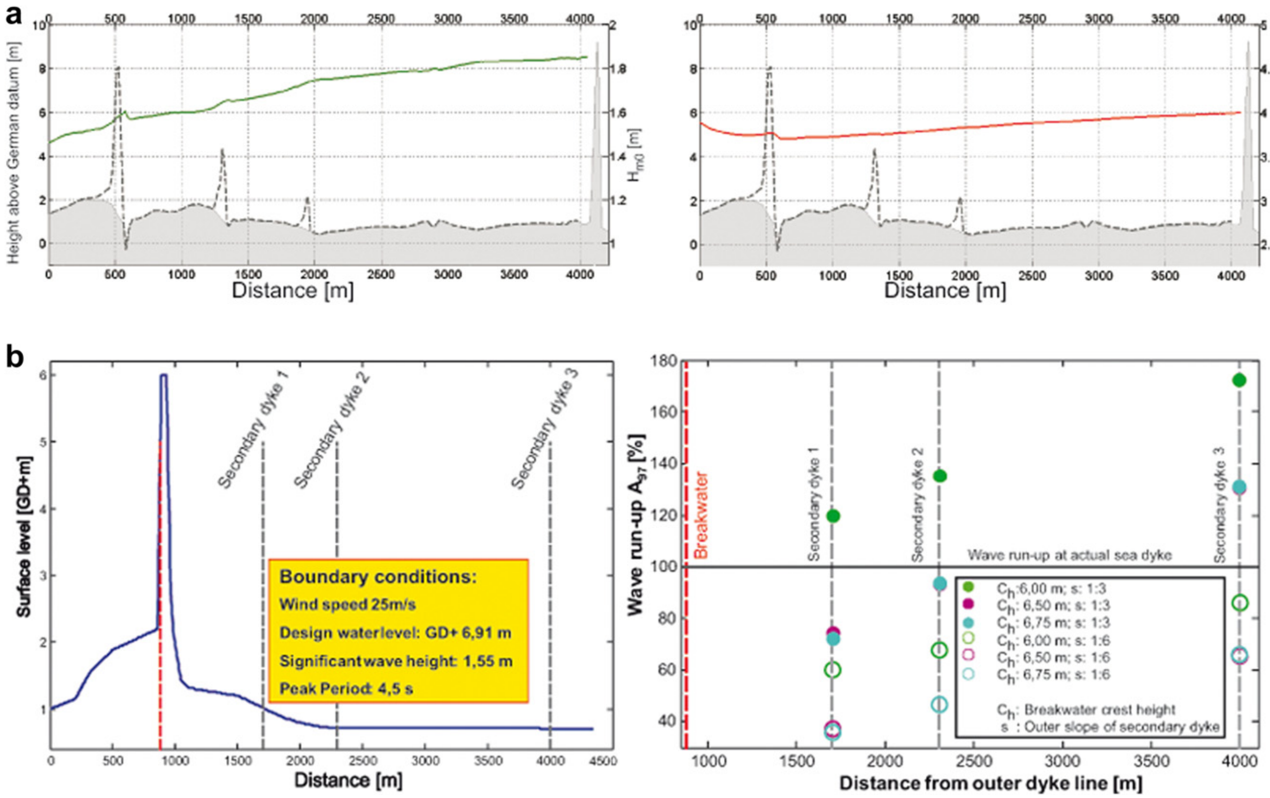

Fig. 6. (a) Increase of design wave height (left) and design wave period (right) due to set-back of dyke line in a polder area. (b) Comparison of combined protection effect on wave run-up on a secondary dyke with that on an existing sea dyke in the same position as the modelled breakwater.

factors contributing to extreme sea levels, their long-term variations and potential future changes, there is still a substantial lack of knowledge. Future challenges comprise

1. Improved understanding and assessment of past and potential future regional changes in extreme sea levels. As it is the combined effects of high astronomical tides, long-term changes in mean sea level and changes in the storm surge and wave climate all components contributing to changes in extreme sea levels and possible interactions need to be considered and accounted for. So far, mostly changes in mean sea level are emphasized, mostly because low-lying coastal areas appear to be vulnerable to even small changes in mean sea level and because global mean sea level rise is considered to be one of the more certain consequences of anthropogenic climate change (Houghton et al. (2001). In particular, further research is needed to provide comprehensive projections of regional mean sea level change; to assess potential regional and local changes in tidal regimes and their interaction with changes in underwater topography, mean sea level, storm surges and extreme waves; and to assess potential changes in local wave climate, in particular in combination with consequences for coastal processes such wave set-up and run-up. Moreover, when potential future developments are considered research is needed to develop sampling strategies that, to account for computational constraints, with a limited number of ensembles and ensemble members provide more comprehensive coverage of the sampling space so that improved and more scientifically based estimates of uncertainty ranges can be provided. Coordinated activities such as suggested by Hemer et al. (2010) are needed to overcome the fragmented picture and to provide designed ensemble approaches allowing a better assessment of the sources of uncertainty and their ranges. Combining dynamical modelling with statistical approaches may represent a way to further increase ensemble sizes allowing improved assessments of signal-to-noise ratios and natural variability. The use of time-slice experiments should be reduced as interpretation of results may be misleading in the face of long-term natural variability. Eventually, regional detection and attribution studies are needed to assess to which extent observed changes are consistent with projected ones, to make statements about time horizons at which projected changes should emerge from the background variability, and to monitor whether this indeed occurs. The latter provides a benchmark measuring our skill in understanding the system and the observed changes.
2. Improved knowledge of the consequences of these changes. So far existing studies are mostly concerned with changes in extreme sea levels and the factors contributing to these changes. Research is needed to provide assessments of the consequences for the coastal near-shore (shallow water) areas. This comprises transferring the knowledge about changing extreme sea levels, accompanying waves and their effects into knowledge about consequences for coastal protection, offshore operations, or about near-shore processes such as erosion and sedimentation rates or wave set-up and run-up. Moreover, climatically induced effects need to be considered in relation to that caused by other drivers such as changes in bathymetry or coastline, e.g. in response to natural processes or water works. The relevance of such processes as well as of climatically induced changes may vary from case to case.
3. Development of robust and flexible adaptation strategies. There is considerable uncertainty in the projections of future changes in extreme sea levels and the contributions from the various factors. Adaptation strategies need to cope with these uncertainties. Instead of developing and testing a strategy for a particular (mostly high-end) scenario, chances and risks for a strategy need to be assessed for a wide range of scenarios and possible developments. Adaptation strategies that cost-efficiently work under a broad range of possible scenarios (robust strategies) or which can be easily adopted to changing conditions in the course of time (flexible strategies) are most preferable. A comprehensive social dialogue communicating chances and risks is needed in developing such strategies. The latter comprises more detailed and local evaluation of the consequences of widely acknowledged generic approaches to respond to sea level rise such as planned retreat, accommodation, or protection (IPCC CZMS, 1990). For the Ems-Dollard estuary such a study has been performed (Niemeyer et al., 2011a,b), in this case indicating that present coastal protection strategies will work even under changing climate conditions and that no general change in strategy is required for the coming decades.

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References

Albrecht, F., Wahl, T., Jensen, J., Weisse, R., 2011. Determining sea level change in the German Bight. Ocean Dyn. doi:10.1007/s10236-011-0462-z.

Alexandersson, H., Schmith, T., Iden, K., Tuomenvirta, H., 1998. Long-term variations of the storm climate over NW Europe. Glob. Atmos. Oc. Syst. 6, 97–120.

Bacon, S., Carter, D., 1991. Wave climate changes in the North Atlantic and the North Sea. Int. J. Climatol. 11, 545–558.

Bärring, L., von Storch, H., 2004. Scandinavian storminess since about 1800. Gephys. Res. Lett. 31, L20202. doi:10.1029/2004GL020441.

Baxter, P., 2005. The East Coast Great Flood, 31 January–1 February 1953: A summary of the human disaster. Phil. Trans. R. Soc. A 363, 1293–1312.

Bengtsson, L., Hodges, K., Keenlyside, N., 2009. Will extra-tropical storms intensify in a warmer climate? J. Clim. 22, 2276–2301. doi:10.1175/2008JCLI2678.1.

Bengtsson, L., Hodges, K., Roeckner, E., 2006. Storm tracks and climate change. J. Clim. 19, 3518–3543.

Bindoff, N., Willebrand, J., Artale, V., Cazenave, A., Gregory, J., Gulev, S., Hanawa, K., Le Quéré, C., Levitus, S., Nojiri, Y., Shum, C., Talley, L., Unnikrishnan, A., 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Ch. Observations: Oceanic Climate Change and Sea Level.

Caires, S., Swail, V., Wang, X., 2006. Projection and analysis of extreme wave climate. J. Clim. 19, 5581–5605. doi:10.1175/JCLI3918.1.

Carter, D., Draper, L., 1988. has the north-east Atlantic become rougher? Nature 332, 494.

Chang, E., Fu, Y., 2002. Interdecadal variations in Northern Hemisphere winter storm track intensity. J. Clim. 15, 642–658.

Chang, E., Lee, S., Swanson, K., 2002. Strom track dynamics. J. Clim. 15, 2163–2182.

Christensen, J., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R., Kwon, W.-T., Laprise, R., Rueda, V.M., Mearns, L., Menéndez, C., Räisänen, J., Rinke, A., Sarr, A., Whetton, P., 2007. Regional climate projections. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tignor, M., Miller, H. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Church, J., Aarup, T., Woodworth, P., Wilson, W., Nicholls, R., Rayner, R., Lambeck, K., Mitchum, G., Steffen, K., Cazenave, A., Blewitt, G., Mitrovica, J., Lowe, J., 2010a. Sea-level rise and variability: synthesis and outlook for the future. In: Church, J., Woodworth, P., Aarup, T., Wilson, S. (Eds.), Understanding Sea-level Rise and Variabiliry. John Wiley & Sons, ISBN 978-1444334517.

Church, J., Gregory, J., Huybrechts, P., Kuhn, M., Lambeck, K., Nhuan, M., Qin, D., Woodworth, P., 2001. Changes in sea level. In: Houghton, J., Ding, Y., Griggs, D., Noguer, M., van der Linden, P., Dai, X., Maskell, K., Johnson, C. (Eds.), Climate

Change 2001: Working Group I: The scientific basis. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Church, J., Roemmich, D., Domingues, C., Willis, J., White, N., Gilson, J., Stammer, D., Köhl, A., Chambers, D., Landerer, F., Marotzke, J., Gregory, J., Suzuki, T., Cazenave, A., Taron, P.L., 2010b. Ocean temperature and salinity contributions to global and regional sea-level change. In: Church, J., Woodworth, P., Aarup, T., Wilson, S. (Eds.), Understanding Sea-level Rise and Variabiliry. John Wiley & Sons, ISBN 978-1444334517.

Church, J., White, N., 2011. Sea-level rise from the late 19th to the early 21st century. Surv. Geophys.. doi:10.1007/s10712–011–9119–1.

Church, J., White, N., Aarup, T., Wilson, W., Woodworth, P., Domingues, C., Hunter, J., Lambeck, K., 2008. Understanding global sea levels: past, present and future. Sustain. Sci. 3, 9–22. doi:10.1007/s11625–008–0042–4.

ComCoast, 2007. The Future of Flood Risk Management. http://www.comcoast.org.

Cubasch, U., Waszkewitz, J., Hegerl, G., Perlwitz, J., 1995. Regional climate changes as simulated in time-slice experiments. Clim. Change 31, 273–304.

Debernhard, J., Roed, L., 2008. Future wind, wave and storm surge climate in the Northern Seas: a revist. Tellus A 60, 427–438. doi:10.1111/j.1600–0870.2008.00312.x.

Debernhard, J., Sætra, Ø, Roed, L., 2002. Future wind, wave and storm surge climate in the Northern Seas. Clim. Res. 23, 39–49.

Doodson, A., 1929. Report on thames floods. Geophys. Memoirs 47, 1–26.

Douville, H., 2005. Limitations of time-slice experiments for predicting climate change over South Asia. Clim. Dyn. 24, 373–391.

Flather, R., Williams, J., 2000. Climate change effects on storm surges: methodologies and results. ECLAT-2 Workshop Report, No 3. In: Beersma, J., Agnew, M., Viner, D., Hulme, M. (Eds.), Climate Scenarios for Water-related and Coastal Impact, pp. 66–78.

Geng, Q., Sugi, M., 2001. Variability of the North Atlantic cyclone activity in winter analyzed from NCEP-NCAR reanalysis data. J. Clim. 14, 3863–3873.

Geng, Q., Sugi, M., 2003. Possible change of extratropical cyclone activity due to enhanced greenhouse gases and sulfate aerosols-study with a high-resolution AGCM. J. Clim. 16, 2262–2274.

Gerritsen, H., 2005. What happened in 1953? The big flood in the Netherlands in retrospect. Phil. Trans. R. Soc. A 363, 1271–1291.

Glickman, T. (Ed.), 2000. Glossary of Meteorology, second ed. American Meteorological Society, Boston, Massachusetts, U.S.A.

Grabemann, I., Weisse, R., 2008. Climate change impact on extreme wave conditions in the North Sea: an ensemble study. Ocean Dyn. 58, 199–212. doi:10.1007/s10236–008–0141–x.

Günther, H., Rosenthal, W., Stawarz, M., Carretero, J., Gomez, M., Lozano, I., Serrano, O., Reistad, M., 1998. The wave climate of the Northeast Atlantic over the period 1955-1994: the WASA wave hindcast. Glob. Atmos. Oc. Syst. 6, 121–164.

Hemer, M., Wang, X., Church, J., Swail, V., 2010. Modeling proposal: coordinating global ocean wave climate projections. Bull. Am. Met. Soc. 91, 451–454. doi:10.1175/2009BAMS2951.1.

Hobgen, N., 1994. Increases in wave heights over the North Atlantic: a review of the evidence and some implications for the naval architect. Trans. Roy. Inst. Naval Arch. W5, 93–101.

Holgate, S., Jevrejeva, S., Woodworth, P., Brewer, S., 2007. Comment on “A semi-empirical approach to projecting future sea level rise”. Science 317, 1866,. doi:10.1126/science.1140942.

Horsburgh, K., Wilson, C., 2007. Tide-surge interaction and its role in the distribution of surge residuals in the North Sea. J. Geophys. Res. 112, C08003. doi:10.1029/2006JC004033.

Horton, R., Hereijer, C., Rosenzweig, C., Lu, J., Gornitz, V., Ruane, A., 2008. Sea level rise projections for current generation CGCMs based on the semi-empirical method. Geophys. Res. Lett. 35, L02725.

Houghton, J., Ding, Y., Griggs, D., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C., 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, United Kingdom and New York.

Howard, T., Lowe, J., 2010. Interpreting century-scale changes in southern North Sea storm surge climate derived from coupled model simulations. J. Clim. 23, 6234–6247. doi:10.1175/2010JCLI3520.1.

Ipcc Czms, 1990. Strategies for adaptation to sea level rise. Tech. rep., Report of the Coastal Zone Management Subgroup, Response Strategies Working Group of the Intergovernmental Panel on Climate Change. Ministry of Transport, Public Works and Water Management, The Hague.

Jevrejeva, S., Grinsted, A., Moore, C., Holgate, S., 2006. Nonlinear trends and multiyear cycle in sea level records. J. Geophys. Res. 111 2005JC003229.

Jevrejeva, S., Moore, J., Grinsted, A., Woodworth, P., 2008. Recent global sea level acceleration started over 200 years ago? Geohys. Res. Lett. 35, L08715. doi:10.1029/2008GL033611.

Kaas, E., Co-authors, 2001. STOWASUS 2100-Regional Storm, Wave and Surge Scenarios for the 2100 century. Final Report ENV4-CT97-04989. Available from. Danish Meteorological Institute.

Katsman, C., Hazeleger, W., Drijfhout, S., van Oldenborgh, G., Burgers, G., 2008. Climate scenarios of sea level rise for the northeast atlantic ocean: a study including the effects of ocean dynamics and gravity changes induced by ice melt. Clim. Change 91, 351–374. doi:10.1007/s10584–008–9442–9.

Katsman, C., Sterl, A., Beersma, J.J., van den Brink, H.W., Church, J.A., Hazeleger, W., Kopp, R., Kroon, D., Kwadijk, J., Lammersen, R., Lowe, J., Oppenheimer, M., Plag, H.-P., Ridley, J., von Storch, H., Vaughan, D., Vellinga, P., Vermeersen, L., van de Wal, R., Weisse, R., 2011. Exploring high-end scenarios for local sea level rise to develop flood protection strategies for a low-lying delta. Clim. Change. doi:10.1007/s10584–011–0037–5.

Kauker, F., 1999. Regionalization of climate model results for the North Sea. Ph.D. thesis, Univ. of Hamburg, Hamburg, Germany, [Available as GKKS Rep. 99/E/6 from GKSS-Forschungszentrum, Geesthacht, Germany].

Kauker, K., 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.

Kharin, V., Zwiers, F., 2005. Estimating extremes in transient climate change simulations. J. Clim. 18, 1156–1172.

Knippertz, P., Ulbrich, U., Speth, P., 2000. Changing cyclones and surface wind speeds over the North Atlantic and Europe in a transient GHG experiment. Clim. Res. 15, 109–122.

Koopmann, G., 1962. Die Sturmflut vom 16./17. Februar 1962 aus ozeanographischer Sicht. Die Küste 10, 55–68.

Krueger, O., von Storch, H., 2011. Evaluation of an air pressure based proxy for storm activity. J. Clim.. doi:10.1175/2011JCLI3913.1.

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. Res. 19, 821–842.

Longuet-Higgins, M., Stewart, R., 1962. Radiation stress and mass transport in gravity waves, with application to ‘surf beats’. J. Fluid Mech. 13, 481–503. doi:10.1017/S0022112062000877.

Lowe, J., Gregory, J., 2005. The effects of climate change on storm surges around the United Kingdom. Phil. Trans. R. Soc. A 363, 1313–1328. doi:10.1098/rsta.2005.1570.

Lowe, J., Gregory, J., Flather, R., 2001. Changes in the occurrence of storm surges around the United Kingdom under a future climate scenario using a dynamic storm surge model driven by the Hadley Centre climate models. Clim. Dyn. 18, 179–188.

Lowe, J., Woodworth, P., Knutson, T., McDonald, R., McInnes, K., Woth, K., von Storch, H., Wolf, J., Swail, V., Bernier, N., Gulev, S., Horsburgh, K., Unnikrishnan, A., Hunter, J.R., Weisse, R., 2010. Past and future changes in extreme sea levels and waves. In: Church, J., Woodworth, P.L., Aarup, T., Wilson, S. (Eds.), Understanding Sea-level Rise and Variability. John Wiley & Sons, ISBN 978-1444334517, pp. 326–376.

McCabe, G., Clark, M., Serreze, M., 2001. Trends in Northern Hemisphere surface cyclone frequency and intensity. J. Clim. 14 (12), 2763–2768.

Meehl, G., Stocker, T., Collins, W., friedlingstein, P., Gaye, A., Gregory, J., Kitoh, A., Knutti, R., Murphy, J., Noda, A., Raper, S., Watterson, I., Weaver, A., Zhao, Z., 2007. Global climate projections. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tignor, M., Miller, H. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Menéndez, M., Woodworth, P., 2010. Changes in extreme high water levels based on a quasi-global tide-gauge data set. J. Geophys. Res. 115 (C10011), 15. doi:10.1029/2009JC005997.

Müller, J., Zitman, T., Stive, M., Niemeyer, H., 2007. Long-term morphological evolution of the tidal inlet Norderneyer Seegat. In: Smith, J.M. (Ed.), Proc. 30th Int. Conf. Coast. Eng. San Diego, September 1–8, 2006. New World Scientific, New Jersey 4035(11).

Müller-Navarra, S., Bork, I., Jensen, J., Koziar, C., Mudersbach, C., Müller, A., Rudolph, E., 2006. Modellstudien zur Sturmflut und zum Hamburg Orkan 1962. Hansa 43, 72–88.

Neu, H., 1984. Interannual variations and longer-term changes in the sea state of the North Atlantic. J. Geophys. Res. 89, 6397–6402.

Niemeyer, H., 1983. über den Seegang an einer inselgeschützten wattküste. In: on the wave climate at an island-sheltered coast. BMFT-Forschungsbericht MF. 0203.

Niemeyer, H., 2005. Coastal protection of lowlands: are alternative strategies purposeful for changing climate?. In: Proc. 14th Biennial Coastal Zone Conference New Orleans/La.July 17–21, 2005.

Niemeyer, H., 2010. Coastal protection of lowlands: are alternative strategies a match to effects of climate change?. In: Proc. 17th IAHR-APD-Conference Auckland/New Zealand.

Niemeyer, H., Kaiser, R., 2001. Design wave evaluation for coastal protection structures in the Wadden Sea. In: Edge, B., Hemsley, J. (Eds.), Ocean Wave Measurement and Analysis, vol. 2. Am. Soc. Civ. Engs., Reston/Va., USA.

Niemeyer, H., Kaiser, R., Berkenbrink, C., 2011a. Increased overtopping security of dykes: a potential for compensating future impacts of climate change. In: Smith, J.M. (Ed.), Proc. 32nd Int. Conf. Coast. Eng. Shanghai/China, June 30–July 5, 2010. New World Scientific, New Jersey.

Niemeyer, H., Kaiser, R., Knaack, H., Dissanayake, P., Miani, M., Elsebach, J., Berkenbrink, C., Herrling, G., Ritzmann, A., 2011b. Evalution of coastal protection strategies for lowlands in respect of climate change. In: Proc. 34th IAHR-Congress Brisbane/Australia.

Paciorek, C., Risbey, J., Ventura, V., Rosen, R., 2002. Multiple indices of Northern Hemisphere cyclone activity, Winters 1949–99. J. Clim. 15, 1573–1590.

Pinto, J., Ulbrich, U., Leckebusch, G., Spangehl, T., reyers, M., Zacharias, S., 2007. Changes in storm track and cyclone activity in three SRES ensemble experiments with the ECHAM5/MPI-OM1 GCM. Clim. Dyn. 29, 195–210. doi:10.1007/s00382–007–0230–4.

Plüß, A., 2006. Nichtlineare Wechselwirkung der Tide auf Änderungen des Meeresspiegels im Übergangsbereich Küste/Ästuar am Beispiel der Elbe. In: Gönnert, G., Grassl, H., Kellat, D., Kunz, H., Probst, B., von Storch, H., Sündermann, J. (Eds.). Klimaänderung und Küstenschutz.

Prandle, D., Wolf, J., 1978. The interaction of surge and tide in the North Sea and the river Thames. Geophys. J. R. Astr. Soc. 55, 203–216.

Pugh, D., 2004. Changing Sea Levels: Effects of Tides, Weather and Climate. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, ISBN 9780521532181.

Rahmstorf, S., 2007. A semi-empirical approach to projecting future sea-level rise. Science 315, 368–370. doi:10.1126/science.1135456.

Rider, K., Komen, G., Beersma, J., 1996. Simulations of the Response of the Ocean Waves in the North Atlantic and North Sea to Co2 Doubling in the Atmosphere Knmi scientific rep. wr 96-05., KNMI, [Available from KNMI, P.O. Box 201, 3730 AE De Bilt, the Netherlands.

Rijkswaterstaat, 1989. Kustverdediging na 1990. Ministerie voor Verkeer en Waterstaat, Den Haag.

Rockel, B., Woth, K., 2007. Extremes of near-surface wind speed over Europe and their future changes as estimated from an ensemble of RCM simulations. Clim. Change 82. doi:10.1007/s10584–006–9227–y.

Rosenhagen, G., Schatzmann, M., 2011. Das Klima der Metropolregion auf Grundlage meteorologischer Messungen und Beobachtungen. In: von Storch, H., Claussen, M. (Eds.), Klimabericht für die Metropolregion Hamburg. Springer Berlin, Heidelberg, New York, ISBN 978-3-642-16034-9, pp. 19–60.

Rossiter, J., 1961. Interaction between tide and surge in the thames. Geophys. J. R. Astr. Soc. 6, 29–53.

Schmidt, H., von Storch, H., 1993. German Bight storms analysed. Nature 365, 791.

Sönnichsen, U., Moseberg, J., 2001. Wenn die Deiche brechen: Sturmfluten und Küstenschutz an der schleswig-holsteinischen Westküste und Hamburg. Husum Druck- und Verlagsgesellschaft mbH & Co. KG, Husum, ISBN 3-88042-690-2.

Sterl, A., van den Brink, H., de Vries, H., Haarsma, R., van Meijgaard, E., 2009. An ensemble study of extreme storm surge related water levels in the North Sea in a changing climate. Ocean Sci. 5, 369–378.

Trenberth, K., Jones, P., Ambenje, P., Bojariu, R., Easterling, D., Tank, A.K., er, D.P., Rahimzadeh, F., Renwick, J., Rusticucci, M., Soden, B., Zhai, P., 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Ch. Observations: Surface and Atmospheric Climate Change.

Vikebø, F., Furevik, T., Furnes, G., Kvamstø, N., Reistad, M., 2003. Wave height variations in the North Sea and on the Norwegian Continental Shelf, 1881–1999. Cont. Shelf. Res. 23, 251–263.

von Storch, H., Gönnert, G., Meine, M., Woth, K., 2008a. Storm surges – an option for Hamburg, Germany, to mitigate expected future aggravation of risk. Environ. Sci. and Policy. doi:10.1016/j.envsci.2008.08.003.

von Storch, H., Reichardt, H., 1997. A scenario of storm surge statistics for the German Bight at the expected time of doubled atmospheric carbon dioxide concentration. J. Clim. 10, 2653–2662.

von Storch, H., Zorita, E., González-Rouco, J., 2008b. Relationship between global mean sea-level and global mean temperature in a climate simulation of the past millennium. Ocean Dyn. 58, 227–236. doi:10.1007/s10236–008–0142–9.

Wahl, T., Jensen, J., Frank, T., 2010. On analysing sea level rise in the German Bight since 1844. Nat. Hazards 10, 171–179. doi:10.5194/nhess–10–171–2010.

Wahl, T., Jensen, J., Frank, T., Haigh, I., 2011. Improved estimates of mean sea level changes in the German Bight over the last 166 years. Ocean Dyn.. doi:10.1007/s10236–011–0383–x.

Wakelin, S., Woodworth, P., Flather, R., Williams, J., 2003. Sea-level dependence on the NAO over the NW European Continental Shelf. Geophys. Res. Lett. 30, 1403,. doi:10.1029/2003GL017041.

Wang, X., Swail, V., Zwiers, F., Zhang, X., Feng, Y., 2009. Detection of external influence on trends of atmospheric storminess and northern ocean wave heights. Clim. Dyn. 32, 189–203. doi:10.1007/s00382–008–0442–2.

WASA-Group, 1998. Changing waves and storms in the Northeast Atlantic? Bull. Am. Meteorol. Soc. 79, 741–760.

Watterson, I., 2005. Simulated changes due to global warming in the variability of precipitation, and their interpretation using a gamma-distributed stochastic model. Adv. Water Resour. 28, 1368–1381.

Weidemann, H., Weisse, R., Grabemann, I. Statistisch regionalisierte sturmflutszenarien für die deutsche nordseeküste. Die Küste, in press.

Weisse, R., Günther, H., 2007. Wave climate and long-term changes for the southern north sea obtained from a high-resolution hindcast 1958-2002. Ocean Dyn. 57, 161–172. doi:10.1007/s10236–006–0094–x.

Weisse, R., Pluess, A., 2006. Storm-related sea level variations along the North Sea coast as simulated by a high-resolution model 1958–2002. Ocean Dyn. 56, 16–25. doi:10.1007/s10236–005–0037–y.

Weisse, R., von Storch, H., 2009. Marine Climate and Climate Change: Storms, Wind Waves and Storm Surges. Springer-Verlag, Berlin Heidelberg New York, ISBN 978-3-540-25316-7.

Weisse, R., von Storch, H., Feser, F., 2005. Northeast Atlantic and North Sea storminess as simulated by a regional climate model during 1958–2001 and comparison with observations. J. Clim. 18, 465–479. doi:10.1175/JCLI–3281.1.

Wolf, J., Flather, R., 2005. Modelling waves and surges during the 1953 storm. Phil. Trans. R. Soc. A 363, 1359–1375. doi:10.1098/rsta.2005.1572.

Woodworth, P., Blackman, D., 2004. Evidence for systematic changes in extreme high waters since the mid-1970s. J. Clim. 17 (6), 1190–1197.

Woodworth, P., Teferle, F., Bingley, R., Shennan, I., Williamas, S., 2009. Trends in UK mean sea level revisited. Geophys. J. Int. 176, 19–30. doi:10.1111/j.1365–246X.2008.03942.x.

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? Gephys. Res. Lett. 32, L22708. doi:10.1029/2005GL023762.

Woth, K., Weisse, R., von Storch, H., 2006. 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. Ocean Dyn. 56, 3–15. doi:10.1007/s10236–005–0024–3. online 2005.

Yin, J., 2005. A consistent poleward shift of the storm tracks in simulations of 21st century climate. Gephys. Res. Lett. 32, L18701. doi:10.1029/2005GL023684.