Storm surges: perspectives and options

Hans von Storch · Katja Woth

Abstract This review paper attempts to summarize the scattered and fragmented knowledge about past and possible future changing storm-surge statistics using the particularly well-studied case of the North Sea as an example. For this region, a complete and robust analysis methodology has been developed in recent years. This methodology is based on dynamical and statistical models. Using the concept of dynamical downscaling, development during recent decades, when sufficiently good and homogeneous weather data exist, has been "reconstructed," and scenarios of possible future change are described. "Localization" allows estimation of changes at specific sites, e.g., harbors. As local water-level statistics depend not only on climate variations but also on local modifications of the local bathymetry, new options for adaptation emerge. For the case of Hamburg, an option for such future adaptations is discussed.

Keywords Storm surge · North Sea · Storms · Localization · Scenario · Climate change

Introduction

Storm surges are the major geophysical risk in coastal regions; they are often associated with significant losses of life and property (Fig. 1) [For a general overview, refer to Gönnert et al. (2001); for specific historical accounts of the German and Dutch North Sea coasts, refer to, e.g., Buisman (2006) or Petersen and Rhode (1977)]. Along the Bangladesh coast, tropical storms and their surges in 1876, 1891, 1970, and 1991 created a toll of >100,000 lives lost (Gönnert et al. 2001), which is comparable to the disaster created by the 2004 tsunami. In midlatitudes, the number of losses is usually several orders of magnitude smaller, namely, up to a few hundred, which is, of course, bad enough.

Most of the world's coasts are affected by storms surges—all coasts where strong storms pass by occasionally or regularly. There are two major types of storms: tropical and extratropical. In principle, there are more types, such as polar lows, which regionally play a role with storm surges, but for the sake of simplicity, we limit our discussion here to the two main types. The differing characteristics of these types and the associated surges are listed in Table 1.

Tropical storms cause storm surges along the east coast of North America, the Gulf of Mexico, Hawai'i, Mexico, the Caribbean Sea, the Bay of Bengal, the Arabian Sea, the South West and East Indian Ocean, the western tropical Pacific, the coasts of Australia, Japan, China, Korea, Philippines, Myanmar, Vietnam, and Thailand. Surges related to extratropical storm activity are common along the east coast of Canada, in the Great Lakes, in Argentina, and Europe in the North Sea, the Baltic Sea, the Irish Sea, the Mediterranean Sea, the Adriatic and Aegean seas, and the Black Sea (cf. Gönnert et al. 2001). Obviously, the risk emanating from storm surges is a global, albeit regionalized, phenomenon affecting a large percentage of the world population, many urban conglomerates, and centers of commerce and trade (cf. Mc Granahan et al. 2007; Hoozeman et al. 1993; Nicholls and Hoozemans 2000).

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Fig. 1 Historical engraving of a storm surge with dyke failure in the Netherlands in 1673

As statistics, and thus the risks of certain surge heights depend on the storms, any change in storminess will lead to a change in storm-surge heights. Of course, statistics depend also on mean sea level; both mean sea level and storm activity likely will change over the course of expected human-created climate change in the centuries to come (Solomon et al. 2007). As mean sea level is expected to rise, storms may become more frequent and violent in some regions and less so in others.

Tropical cyclones (the terms hurricanes and typhoons are alternative names used in different regions) are huge, thermodynamic machines that transform heat, mainly sucked from a very warm sea surface, into kinetic energy, i.e., wind. Extratropical storms, on the other hand, gain their energy from the horizontal temperature gradient, described in the frontal theory of Vilhelm Bjerknes (cf. Friedmann 1989). Extratropical and tropical storms differ with respect to size and intensity; their associated storm surges show characteristics consistent with these differences (cf. Table 1). The different characteristics of these types of storms, in particular concerning wind speeds and spatial scale, cause the differences listed in Table 1. In tropical regions, storm surges are much less frequent at a given position than at midlatitudes; they are also considerably more limited in extent. But if they hit, then the effect is usually stronger than in midlatitudes.

Knowledge about the direction of change for storms in the coming century is not yet complete. The knowledge base is relatively good for extratropical storms, whereas evidence for the change of tropical storms now and in the coming century is still under discussion.

Due to their large-scale nature, present-day climate models are capable of describing the formation and movement of extratropical storms (e.g., Lambert 1988; Lambert et al. 2002; Fischer-Bruns et al. 2005). Most models envisage a poleward migration of the major storm tracks, in particular over the North Atlantic and the Southern Ocean (e.g., Lambert 1995, 2004; Beersma et al. 1997; Ulbrich and Christoph 1999; Schubert et al. 1998; Fischer-Bruns et al. 2005, Lambert and Fyfe 2006). Regional climate models are successfully used to describe the spatial detail of marginal seas, such as the North Sea where the surges form, and which are insufficiently resolved by global climate models (e.g., Rockel and Woth 2007). Thus, the science is sufficiently well developed to provide projections of possible, internally consistent, future changes (i.e., scenarios) of storm-surge probabilities. Using the North Sea as an example, we provide in the last two sections of this article details of such an assessment, with special emphasis on one estuarine metropolis, namely, Hamburg, Germany.

Knowledge with respect to tropical cyclones (for a recent overview, refer to Bengtsson 2007) is less solid and considerably contested. One camp of scientists claims that there is "already" a clear sign of more, most intense, hurricanes in the Atlantic (e.g., Emanuel 2005; Holland and Webster 2007; Mann et al. 2007), whereas others point to the inadequate database—which is limited in time and suffers severely from inhomogeneities—and the detection of trends beyond the range of natural variations, which is difficult because of the low-frequency, natural variability of tropical storminess (e.g., Pielke Jr et al. 2008; Landsea et al. 1999; Landsea 2005, 2007). Also, projections of the future vary considerably; most projections indicate even

Table 1 Characteristics of storm surges causes by tropical storms (hurricanes, typhoons) and extratropical storms (after Gönnert et al. 2001)

Parameter	Tropical cyclone	Extratropical cyclone
Spatial scale of storm	500 ± 200 km	1,000 ± 500 km
Representation in weather reanalyses of recent decades (since 1960)	In earlier decades underrepresented; sometimes cyclones are missed	Mostly well described, in particular in well-monitored Northern Hemisphere regions; some inhomogeneities remain
Surge amplitude	Larger: hurricane Camille caused a surge of 7.5 m in Gulfport, MS, USA, in August 1969	Smaller: surges of 5 m are infrequent events
Surge duration	Several hours, up to half a day	2–5 days
Length of coastline affected by the surge	Less: usually <200 km	Several hundred kilometers
Storm geometry	Compact and nearly symmetrical	Ill-defined and sprawling geometry

fewer storms, whereas others predict more storms. However, there are indications that the fewer storms may be strengthening. In his simulations, Bengtsson (2007) reports an increase in maximum wind speeds of 5–10% by the end of the twenty-first century.

The application of regional models to specify spatial details of the wind and air-pressure fields associated with a tropical storm, which eventually drive the storm surges, are still under development (e.g., Landman et al. 2005; Knutson et al. 2007; Feser and von Storch 2008). Thus, not surprisingly, systematic, multidecadal modeling studies on scenarios of future storm-surge developments of tropical cyclones are not yet known.

In early historic times, the dangers related to storm surges were relatively easily dealt with, when the defense was limited to the immediate housing area and population was sparse (cf. Fig. 2; Petzelberger 2000). Large areas were flooded, but the elevated water levels were minor. This changed when dikes were built to protect against flooding to allow for more effective agriculture and higher population densities [for the Dutch rivers, this development was carefully analyzed by Tol and Langen (2000)]. Ever since, keeping dikes in order was a challenge, and keeping the dangers of storm surges at bay was an important community task, the activity of which can nowadays partly be reconstructed by studying costs to repair dikes in historical times (de Kraker 1999). A more modern account of the history of managing the risk of storm surges along the North Sea coast is provided by Niemeyer et al. (1995).

Obviously, there is significant concern among the public that anthropogenic climate change may lead to unsafe conditions in low-lying coastal areas. The section "The special case of Hamburg" provides the example of the river Elbe and the city of Hamburg.

In general, research about storm surges suffers from multiple fragmentation, so that not all knowledge is as widely available as one would hope. One fragmentation is due to the different disciplines involved, chiefly, coastal engineering (e.g., Niemeyer et al. 1995) and oceanography. The other is related to the relatively small scale of storm surges, so that the problem is perceived as a regional problem, and scientific insights and methods developed for one part in the world do not necessarily find their way into other parts affected by storm surges. Unfortunately, this paper hardly overcomes these regrettable divides and remains, to some extent, parochial, with a focus on the North Sea.

Physics, multidecadal modelling, and storm-surge statistics

Physics

The physics of storms surges are well understood. The first-order processes can be very well described by mostly the vertically integrated shallow-water equations: mass and momentum are conserved. In the momentum equation, a source and a sink of momentum are introduced in parameterized form, namely, wind input at the surface and the bottom friction (e.g., Kowalik and Murty 1993). Also, the effect of spatially inhomogeneous air pressure is usually incorporated. To get higher accuracy, interaction with tides, ocean-wave field and, in the case of estuaries, river currents must be taken into account (e.g., Gönnert et al. 2001). In enclosed or semienclosed basins, such as the Baltic Sea, the situation is more complex, because eigenoscillations (seiches) play an important role. Also, the filling of such a basin varies, so that wind-driven and eigen motions take place in a time-variable geophysical environment.
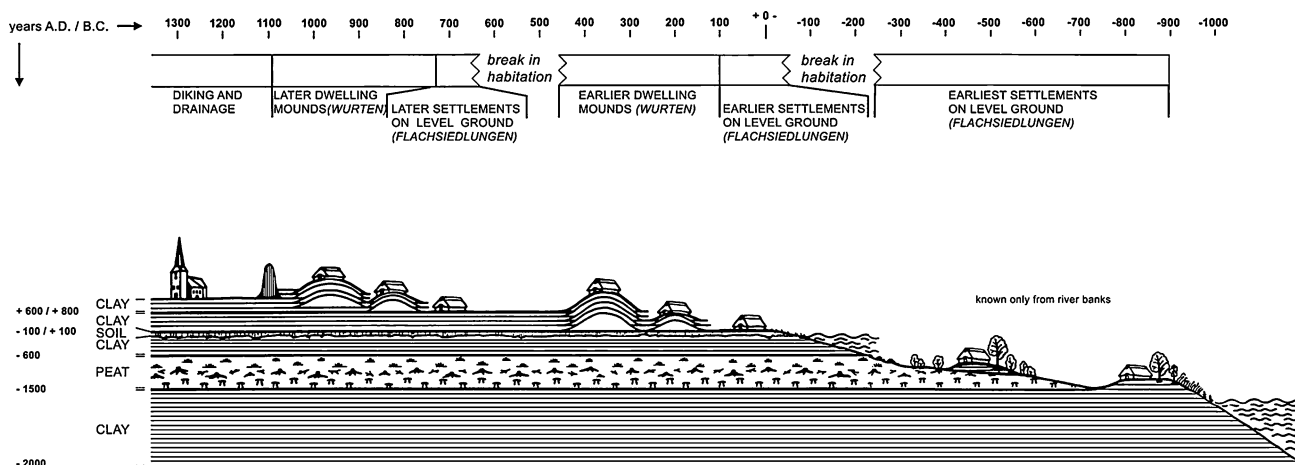
Fig. 2 Development of coastal housing and coastal defense in the North Sea area since the mid-Holocene (note the rise in water level increase during the Holocene). From Petzelberger (2000)

Dynamical modelling

Since the early 1960s, hydrodynamic numerical models have become an established tool for studying tidal and surge phenomena, e.g., Fischer (1959), Heaps (1967, 1983), Jelesnianki (1965, 1967). A review of the development of methodologies until the early 1990s is provided by Kowalik and Murty (1993). (An exciting account of how numerical models not only match but surpass the skill of mechanical models is given by Sündermann and Vollmers 1972.)

In the past, mostly case studies were considered, i.e., simulations over a rather limited time with a few tidal cycles or a storm-surge event (e.g., Dolata et al. 1983; Plüß 2005). Such simulations are useful for studying the relative importance of involved processes and as test cases for models being used as forecast tools. Only in the mid 1990s, specifically in the Waves and Storms in the North Atlantic (WASA) Group (1998) project, was the utility of such models to describe long-term statistics and changes thereof, as well as to construct scenarios of possible changes to future storm-surge statistics, explored and demonstrated.

For these continuous "climate" simulations, two-dimensional (2D) models such as CSX (used by Flather et al. 1998), Tidal, Residual, and Intertidal Mudflat Model (TRIM) (used by Woth et al. 2005 and Aspelien and Weisse 2005) and TELEMAC2d (used by Weisse and Plüß 2005) have turned out to do a reasonable job, continuously for several decades, in simulating wind-related variability in the North Sea. Kauker and Langenberg (2000) compared a rather complex isopycnic layer model with a 2D-model [Hamburg Shelf Ocean Model (HAMSOM)] and found virtually identical results.

Such long-term simulation by tide-surge models using multidecadal observed or simulated wind fields are in use at several places in Europe, including at the Institute of Coastal Research (of GKSS) near Hamburg (Woth et al. 2005), the Federal Waterways Engineering and Research Institute in Hamburg (Plüß 2004), the Proudman Ocean Laboratory in Liverpool (Flather 1998), and in Italy (Lionello et al. 2003, Lionello 2005); see also the report by Kaas et al. (2001) on the European Storms, Waves, Surges Scenarios (STOWASUS) project.

In tropical regions, many numerical surge models have been used for case studies (e.g., Gönnert et al. 2001; Hu et al. 2007), but for describing changing storm-surge statistics, extended, multidecadal simulations are required; we are not aware of such simulations. It remains to be seen how a dynamical model has to be configured for simulating the statistics of surges caused by smaller and more energetic tropical storms.

The problem of simulating the statistics of storm surges with dynamical models is somewhat more easily dealt with in extratropics. One issue is storm size, which is roughly double in extratropics compared with the tropics (cf. Table 1) (There are exceptions, of course. The "Anatol storm" in 1999 in the North Sea area, for instance, was a rather small, fast-moving storm with a fetch of 100–200 km, whereas there are considerably larger tropical storms, such as "Winnie," which crossed Taiwan in August 1997). Another reason is that formation of extratropical storms as growing baroclinic disturbances along the polar front makes them easier to specify (Branstator 1995) and allows for empirical downscaling schemes, which relate seasonal mean circulation anomalies to intraseasonal storm-surge statistical anomalies (von Storch and Reichardt 1997; Langenberg et al. 1999).

Observational data

Of course, an important source for storm-surge statistics and their gradual change over time is the collection of tide-gauge readings and, more recently, satellite-based data. The former local data suffer, however, as many climate data do, from inhomogeneities; i.e., they not only reflect changes in wind-related water-level variations or mean sea level but also local variations, such as changing harbor configurations, dam building, improving coastal defense and local morphology, gas pumping, and secular land sinking and rising. For instance, Jensen and Mudersbach (2005) report an increase of mean tidal level in the last 60–100 years for List of 1.25 mm/year, for neighboring Wittdün of 1.96 mm/year, for Dagebüll of 1.07 mm/year, and for Bremerhaven of only 0.61 mm/year (the former three stations are within a few tens of kilometers of each other; Bremerhaven is some 200 km further south). A closer inspection shows marked abrupt increases at different times, pointing to the presence of nonclimatic signals in the records, which makes separation of weather-related changes and local anthropogenic effects difficult. Attempts are underway to try a separation by comparing records with hindcasts (as mentioned above) with numerical models driven with details of weather analyses extending over decades. A stark example is the situation in Hamburg, 140 km upstream in the estuary of the Elbe, where human interference has led to a rise of storm-surge heights of about 60 cm since the 1960s (Grossmann et al. 2007); see section "The special case of Hamburg".

Tide-gauge data can, however, be used to determine the temporal change of the intensity of the weather-related variability by first subtracting, for instance, the annual mean high tide (i.e., for some gauges, only the high-tide water level at the time of the maximum astronomical tide is recorded) and then determining the intra-annual percentiles of high tidal variations (e.g., von Storch and Reichardt

1997). For a series of tide gauges along the southern and eastern coasts of the North Sea, no significant ongoing changes could be detected in weather-related phenomena (Langenberg et al. 1999).

The other source of information, satellite data, is usually accurate and powerful in describing spatial distribution (e.g., Høyer and Andersen 2003) but suffers from relatively short series and the need for complicated manipulations for correcting a variety of factors, e.g., the geoid. It may take some time before such data show their full potential in assessing long-term trends related to climate variability.

The case of the North Sea

It seems that the North Sea, next to the Irish Sea and the Adriatic Sea, is the best studied regional sea with respect to changing storm-surge statistics and scenarios. As sketched in the "Introduction," dynamical models have been used for multidecadal reconstructions, or hindcasts, of storm-surge histories of the last 50 or so years. Estimates of changes in the past 100 or so years have been derived with statistical models. Scenarios of plausible, possible, and internally consistent futures (scenarios) have been constructed using dynamical and statistical models. Following we show some modeling results for the North Sea and, more specifically, the German Bight.

Modelling the past decades

Many regional North Sea studies exist dealing with dynamical modeling of tide surges. Besides case studies on specific storms and process studies on specific processes such as bottom stress, several multidecadal hindcasts for the second half of the twentieth century up to the present have been successfully performed in the last few years. They provide high-resolution multidecadal data sets of water-level variations in the North Sea area (Flather et al. 1998; Kauker 1998; Langenberg et al. 1999; Weisse and Plüß 2005, Aspelien and Weisse 2005; Woth 2005b). The quality of such hindcasts depends on the accuracy of the atmospheric wind and pressure fields as provided by operational analyses or (regionalized) "reanalysis" of atmospheric conditions. Prime examples of reanalyses are those of the National Center for Atmospheric Research and National Centers for Environmental Prediction (NCAR/NCEP) (http://www.cdc.noaa.gov/cdc/reanalysis/reanalysis.shtml) and ERA-40 (http://www.ecmwf.int/research/era/, and of a regionalized reanalysis of the CoastDat data set of Feser et al. (2001).

The model hindcasts all point to a weather-related increase of storm-surge heights (e.g., in terms of percentiles of intra-annual high-water distributions) along the southern and eastern coasts of the North Sea since the 1960s, with a net effect of up to 15 cm, with 5–10 cm due to changes in the mean weather-driven water level and another 5–10 cm to variable weather conditions. This change is commonly attributed to the parallel intensification of the North Atlantic Oscillation, which, however, showed a trend reversal in the mid-1990s   (http://www.ldeo.columbia.edu/res/pi/NAO/). Similar numbers for wind-related percentiles of water levels have been reported by Langenberg et al. (1999) after a statistical analysis of time series of tide-gauge intra-annual percentiles. Weisse and Plüß (2005) have shown, based on the CoastDat hindcast data for the North Sea area, that most positive trends found in the mean high-water level derived from tide-gauge observations are influenced by additional factors and can hardly be related to changes in atmospheric conditions.

Scenarios

During the twenty-first century, storms and storm-surge characteristics are expected to undergo changes not only due to natural variability but also as a response to increasing atmospheric CO_2 concentrations. A number of studies, using either statistical or dynamical approaches (as, e.g., von Storch and Reichardt 1997; Flather and Smith 1998; Langenberg et al. 1999; Lowe et al. 2001; Debernard et al. 2003; Lowe and Gregory 2005; Woth 2005; Woth et al. 2005), demonstrate how an increase of up to 10% in extreme wind speeds in the North Sea and the Norwegian Sea may take place when CO_2 concentrations are doubled (B2) or almost tripled (A2). These changes suggest an increase in surge-height extremes of the same proportion.

The most recent set of scenarios, e.g., descriptions of possible, plausible, and internally consistent future conditions for the North Sea, have been prepared by Woth (2005a,b) and Woth et al. (2005), who used a series of different global and regional climate-change scenarios for the time horizon 2070–2100, which have been generated in the European Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects (PRUDENCE) project (Christensen et al. 2002). Their results are remarkably consistent across the different global and regional models and across two rather different scenarios of the driving atmospheric greenhouse gas concentrations. Woth's scenarios are broadly consistent with earlier results, which made use of a less broad set of global and regional climate-change scenarios.

Figure 3 shows a diagram of Woth's scenario (2005a), namely, the change of intrawinter 99th percentiles of local sea levels from present-day conditions (1960–1990) to
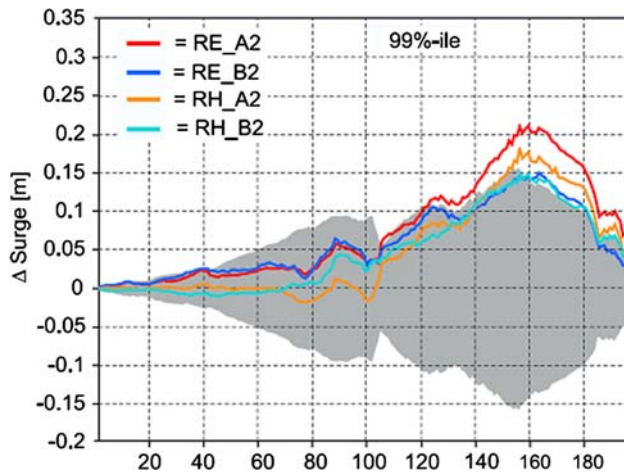
Fig. 3 Differences ''A2 vs. CTL'' in long-term mean of the annual 99th percentile of water level/surge (DJF) for four ensemble members with two emissions scenarios (A2 and B2), two different global models [European Centre Hamburg Model (ECHAM) and HadAm), and the same regional model. *Shading* indicates the 95% confidence interval representative for natural variations. Depicted are grid cells located on the 10-m depth line along the North Sea coast [the *first grid box* is in northern Scotland, *number 100* about at Dover, *number 125* near Amsterdam, *number 150* in east Frisia, and *number 175* close to Esbjerg; for details see Fig. 1 in Woth (2005a)]. From Woth (2005a)

conditions calculated for 2070–2100 along the coastal 10-m depth line from Scotland down the English coast to the Netherlands, Germany, and eventually Denmark. The shaded area displays variations considered normal within the range of natural variations. The four curves show results of two emission scenarios and two global models, whereas the regional climate model and the hydrodynamic model of the North Sea were the same in all four cases. Figure 4 shows a map of the change in strong wind speeds and water level for one of the four cases for all of the North Sea—the strong winds rise by about 1 m/s at the end of the century, which corresponds to about 5–10%; the wind-related surge increase is limited mostly to the German Bight area, with maximum values of about 20–25 cm.

Noticing this convergence across time (the newest scenarios are consistent with those prepared with older models using older scenarios) and across models (global and regional climate models; models of the hydrodynamics of the North Sea), we consider Woth's numbers robust, but one has to keep in mind that a number of caveats prevail.

Caveats

The uncertainty of future storm-surge statistics remains large, chiefly because of the uncertainty in emission scenarios, which lead to the assumed future wind and pressure
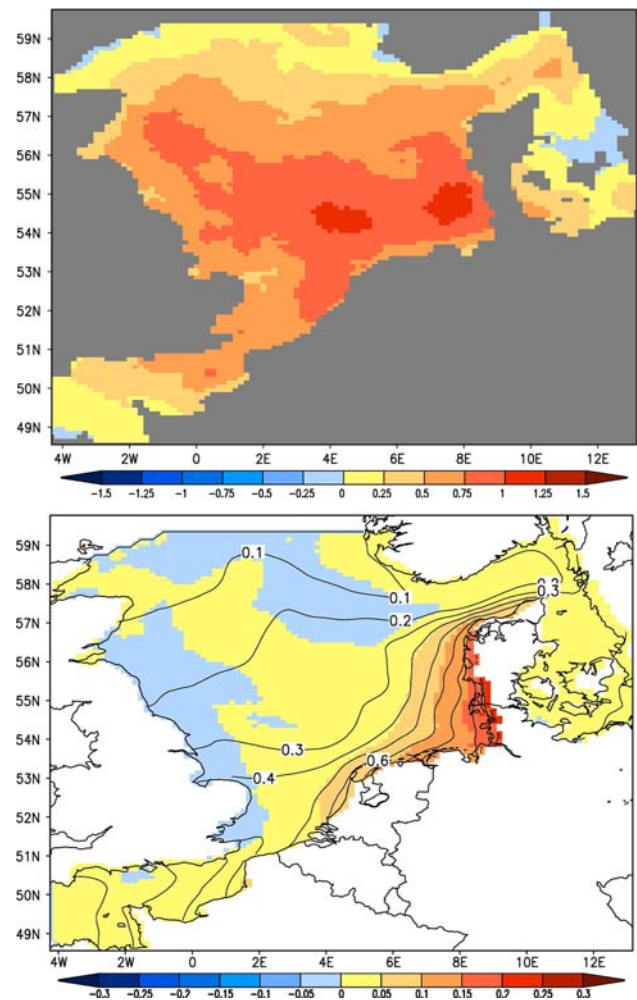
Fig. 4 Change in 99th percentile of strong winds (*top*) and in wind-related water levels (*bottom*) between 1960 and 1990 control period and 2070–2100, as given by SRES emissions scenario A2 (e.g., Houghton et al. 2001). The models used are HadAM for global climate, Rossby Centre Regional Atmosphere-Ocean Model (RCAO) for regional climate, and TRIM for hydrodynamics of the North Sea

conditions. Also, close to the coast where mud flats are the main part of the coast, an important factor for future evolution will be whether or not the mud flats can accumulate and thus grow to a similar degree as the time-averaged increase in sea level. Other caveats refer to

- The rise in global sea level (Solomon et al. 2007).
- The rise in regional sea level, which may differ significantly from the global rise (e.g., Landerer et al. 2007). The regional sea level may also be affected by secondary geological responses to lowering the weight of the Greenland ice sheet.
- A relevant question in the context of storm-surge modeling is whether storm-surge heights are sensitive to changes in mean sea level. It could be that the increase in time-averaged sea level has, in addition to

the direct effect of increasing surge height, significant indirect effects by changing the surge height and propagation. This problem was studied by Kauker (1998) and Lowe et al. (2001) in coarse resolution models, who found no significant differences in simulations with or without elevated mean sea level. Lowe and Gregory (2005) confirmed these findings for the North Sea area. However, case studies with highly increased local spatial resolutions as, e.g., carried out by Plüß (2004), have shown that in shallow coastal areas especially, changes in mean sea level result in significant modulation of tidal dynamics. This is in consequence of a change in basin geometry as flat areas were flooded.

Near-coastal developments

When local details are needed, a localization step is needed. Two avenues are possible: either spatial refinement of numerical grids, as done by Plüß (2005) and Weisse and Plüß (2005), or the employment of empirical transfer functions, first suggested by Langenberg et al. (1999) and later refined by Grossmann et al. (2007). Transfer functions relate state variables well resolved by numerical models in hindcast and scenario simulations, such as water level at the 10-m depth line, to on-shore variations measured at tide gauges.

A combination of the two avenues, spatial refinement and transfer function, has recently been implemented by Woth and Weisse (2008). As predictors, they use sea levels along the 10-m depth line, which are provided by scenario calculations. As predictands, they no longer use the (spatially sparse) local observed time series but near-shore sea levels hindcasted with a variable grid-resolution model, which resolves details along the coast.

Figure 5 shows for the four combinations of two emission scenarios (A2 and B2) and the two global models [European Centre Hamburg Model (ECHAM) and HadAM; identical regional climate model and hydrodynamic model] that have already been employed in Fig. 3 the differences in near-coastal surge changes. In all cases, the surge-level changes increase slightly toward the shoreline; the scenario with higher emissions (A2) leads to slightly higher changes.

The special case of Hamburg

Hamburg is a harbor in the estuary of the river Elbe, some 140 km upstream. The estuary opens up to the northwest into the German Bight, which is prone to storm surges. The
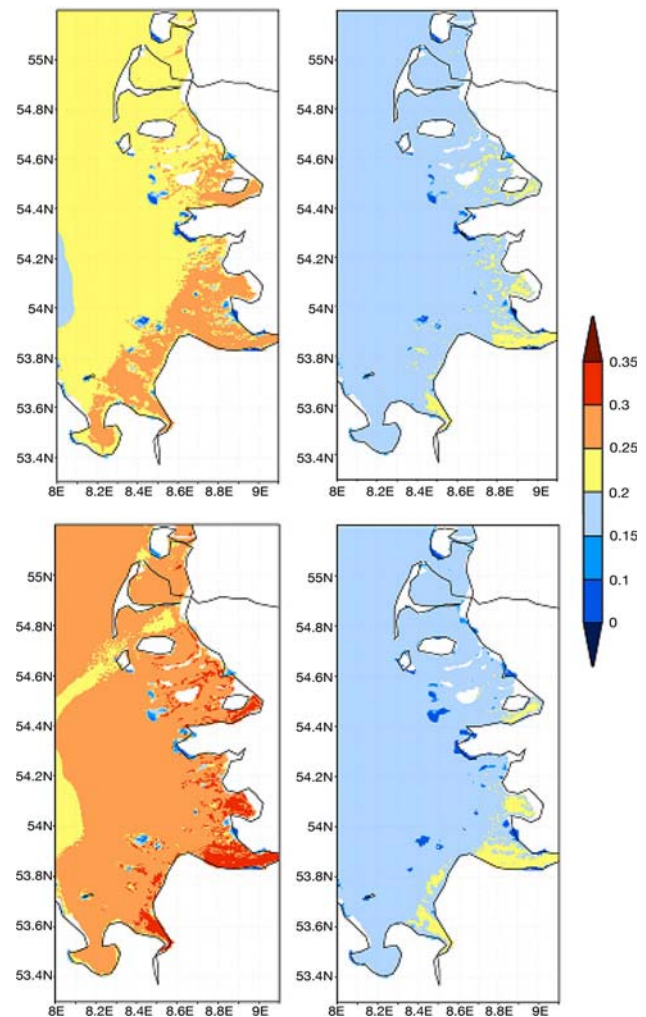
Fig. 5 Estimates of changes of surge in 2070–2100 compared with 1960–1990 using two different emissions scenarios (A2, *left column*; B2 *right column*) and two different global models [European Centre Hamburg Model (ECHAM, *bottom*; HadAM, *top*], and the same regional climate model (RCAO) and hydrodynamic model (TRIM) as in Fig. 3

history of storm surges in Hamburg, as documented since 1750, has three phases: a frequent-damage period prior to 1850, a calm period from 1855 to 1962, and a period of elevated but well-managed storm-surge levels since 1962. The storm-surge disaster in 1962 that left more than 300 people dead in Hamburg functioned as an alarm bell.

In the eighteenth century, storm surges and breaking dikes were relatively frequent in Hamburg. The dike failures took place at water levels of about normalnull (NN) + 5.20 m or so (NN is the traditional German reference height. NN = 0 was considered mean sea-level height. NN + 5.20 m refers to water level 5.20 m above this formally defined water level of 0). Interestingly, these storm surges came along in clusters. After the severe storm surge in 1825, dike heights were raised to NN + 5.70 m;

from then until 1962, only one severe storm surge occurred, namely, in 1855. After this storm flood, for more than 100 years before 1962, the improved dike levels were not really challenged. All gauge readings were well below NN + 5.00 m.

After the 1962 catastrophe, massive investments into the coastal defense were made, and dikes were raised to NN + 7.20 m. A very strong flood occurred in 1976, well above the 1962 level, namely, NN + 6.45 m. However, the newly enforced costal defense held, and damages were insignificant in Hamburg. Nevertheless, dikes were raised again to a level between NN + 8.00 m and NN + 9.30 m. Since 1962, several very high storm surges took place with heights between NN + 5.50 m and NN + 6.00 m, but only minor damage was reported.

It has been speculated that the increase in Hamburg—St. Pauli since 1962 contains a significant component reflecting global human-created climate change. This is very likely false: the main part of the increase is due to improved coastal defense. Another cause is the dredging of the shipping channel. The intensification of the North Atlantic Oscillation between 1960 and 1995 may have contributed a minor increase in level (Weisse and Plüß 2005). A measure of the effect of the former two causes is the difference of storm-surge heights in Cuxhaven, at the mouth of the Elbe estuary, and in Hamburg. Before 1962, storm surges in Hamburg were on average about 30 cm higher than in Cuxhaven. After 1962, this difference rose to about 1 m (Grossmann et al. 2007). Experts estimate that about three quarters of this increase is related to coastal defense measures and one quarter to the deepening of the shipping channel from less than 11 to 14.50 m. Thus, modifications of the river Elbe significantly increased the storm-surge height in Hamburg, whereas climatic effects were rather minor (cf. Weisse and Plüß 2005; WASA 1998; Alexandersson et al. 2000).

Based on the North Sea storm-surge scenarios discussed above, Grossmann et al. (2007) used an empirical link between coastal and estuarine water-level variations to derive a consistent estimate for Hamburg. Their results, shown in Fig. 6, took into account the mean sea-level rise by simply adding the global mean estimate (due to thermal expansion as a reaction to global warming) to the elevated wind-driven surges. According to these projections, water level extremes, in terms of mean maximum water level in a storm season, would rise by 15 ± 5 cm in Cuxhaven at the mouth of the river and 20 ± 5 cm in Hamburg until around 2030, relative to 1980–1990 levels. Such an increase does not cause significant concern among coastal engineers. However, at a later time in the twenty-first century—say 2085, representing the last three decades of the century—the increase may amount of about 50 ± 15 cm in Cuxhaven and 60 ± 20 cm in
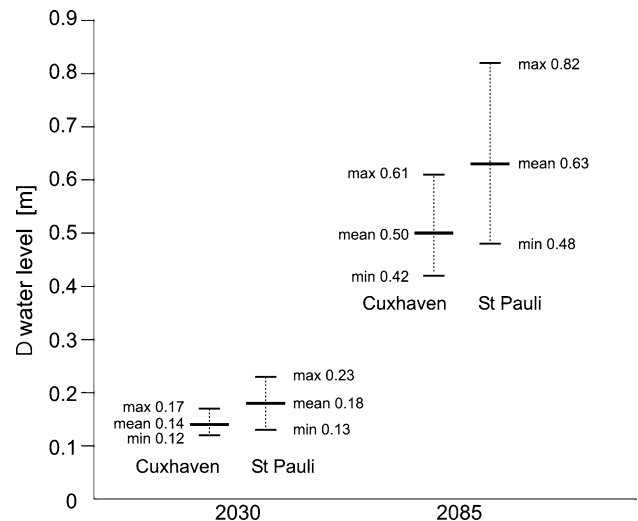
Fig. 6 Best estimates of expected rise in storm-surge heights in Hamburg, which is 140 km upstream on the estuary of the Elbe, and Cuxhaven, at the mouth of the estuary. The effects of mean sea-level rise and changing storm conditions are simply added. Note that unchanged morphological conditions of the estuary are assumed. After Grossmann et al. (2007)

Hamburg. Such an increase would require adaptations in both places.

The options the authorities in Hamburg and the neighboring municipalities face—apart from no action and hoping that the efforts to stop global climate change by reducing emissions will invalidate the scenarios—are to prepare adaptation measures to face the expected change in risk. One measure is to enforce coastal defense so that the probability of failures under the assumed future conditions are similar to presently accepted levels. The second measure is to allow for rare but controlled floodings by changing habits, risk management, and housing standards. The third measure is to change the morphology of the estuary. Climate-change projections have been calculated under the assumption that the river topography will remain unchanged. In fact, it seems unlikely that this assumption will be realized. Because of disadvantageous patterns of sediment transport, plans are now being made to slow the hydrodynamic regime in the Elbe estuary, as outlined in the German-written "Concept for a sustainable development of Tidal Elbe River as an artery of the metropolitan region of Hamburg and beyond" of the Hamburg Port Authority (http://www.tideelbe.de/pdf/Strategiepapier_Tideelbe_deu.pdf). When the tidal regime in the Elbe is slowed down, then not only ecology and sediment transport is affected but also water movement, including tides and storm surges. Therefore, part of the earlier increase in storm-surge heights in Hamburg may possibly be reversed so that the perspectives for future storm surges may be smaller than that envisaged under unchanged topographic conditions in

Fig. 6. The first two options will be available for all coastal cities; the last option may be specific for Hamburg, but it would be worth studying such possibilities for other locations.

Conclusions

Storm surges are the major geophysical risk in low coastal areas. Climate change, with rising sea level and changing storm tracks, will modify the regional distributions of these hazards. Whereas these changes depend strongly on regional and local details, a joint methodology has been developed over recent years. This methodology makes use of the downscaling concept (von Storch 1995), according to which the statistics of weather in the atmosphere, and the ocean on a smaller scale, may be understood as the result of an interplay of the same statistics at larger scales, with regional and local physiographic details and with forcing terms acting at regional and local scales.

In case of storm surges, this methodology has been tested and developed for European marginal seas, specifically the North Sea, the Irish Sea, and the Aegean Sea. The methodology consists of first determining developments over recent decades when reasonably good and homogeneous weather analysis is available. In a second step, using the same dynamical models, scenarios of possible future conditions are derived. When different scenarios are computed, statements about convergence or divergence of future conditions can be obtained. In case of the North Sea, results point to moderately higher storm surges—consistent across models and scenarios.

In a third step, conditions in harbors and in near-shore regions are determined, which can be obtained with dynamical or empirical models. At this step, the effect of water works and other modifications of the bathymetry and coastline can also be factored in.

For other parts of the world, in particular the tropics, this methodology is under development; a major obstacle is the fact that simulation of tropical storms, which are usually much smaller than extratropical storms, is a considerably greater challenge. Therefore, most studies for this part of the world have been case studies and have hardly addressed the change in statistics derived from multidecadal detailed simulations.

A major challenge at this time is to make the strategy applicable to tropical and polar coasts. Another challenge is to interpret historical records of coastal storm surges in terms of the scenarios, in the sense of detection and attribution, to determine whether ongoing changes should be understood as a response to intermittent climate variability, to anthropogenic climate change, or to regional modifications in the coastal zone.

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