Changing Coastal Weather and Extremes

Hans von Storch, Frauke Feser, Arnt Pfizenmayer and Ralf Weisse
Institute for Coastal Research, Max-Planck-Str. 1, 21502 Geesthacht, Germany

1. Introduction

Hardly any area in the whole world is undergoing such dynamical environmental and social change as the coastal regions of the world. Approximately 20% of the world's human population live within 30 km of the sea, and nearly double that number live within the nearest 100 km of the coast (IPCC 2001). Furthermore, a big part of economic activities is going on in these areas. In the coastal environment storms, storm surges, extreme waves, sea level rise as well as hinterland flooding put the safety of the coastal population at risk and threaten shoreline and off-shore activities.

Thus, coastal research will play an increasingly relevant role in advising the society and economy in avoiding unnecessary risks. Special emphasis has to be put on upcoming challenges related to expected anthropogenic climate change. Natural variability, in particular with respect to weather-related extremes, like storm surges, extreme waves and hinterland flooding, needs to be determined by reconstructing and analyzing the historical weather records. Regionally disaggregated scenarios for plausible future developments need to be derived from global climate change scenarios.

This talk exemplifies ways to constructively address the problem of detailed reconstruction of past coastal extremes and scenarios of future characteristics of extremes. Examples for the case of the North Sea coast in Europe are given.

2. The IPCC analysis and scenarios

So far, the IPCC has been reluctant to make any definite statements about changing climatic threats to coastal zones, apart of the general expectation of global and continental scale sea level rise. In the past hundred years global mean sea level seems to have risen by up to 4 cm, with thermal expansion being the largest contributor. The mountain glaciers are thought to be net sources, while Antarctica accumulation is believed to be a major sink. Greenland had almost no effect (Figure 1) according to this analysis.

For the future scenarios conditional upon future emissions of greenhouse gases and industrial aerosols have been designed ("SRES scenarios"). These scenarios would lead to a general increase of sea level, with maximum values of about 0.8 m and minimum values of 15 cm at the end of the 21st century (Figure 2).

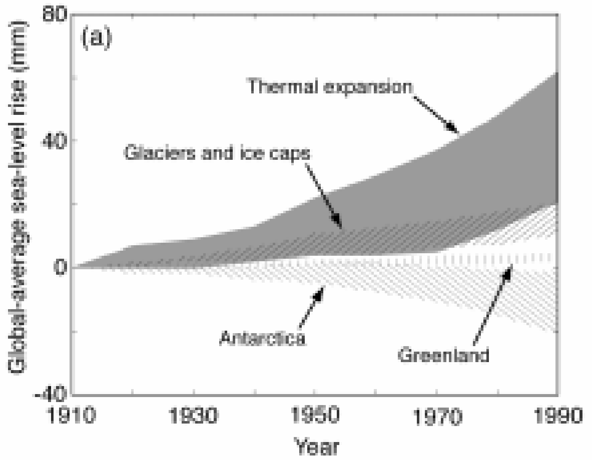

Figure 1. IPCC assessment of global mean sea level change in the past 100 years (1910-1990)

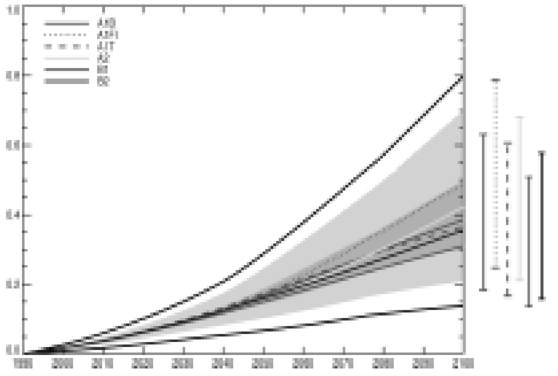

Figure 2. IPCC assessment of plausible but not necessarily likely future developments of global mean sea level. The bars on the right side represent variations in different scenarios without the effect of storage on ice sheets. The bounding black lines represent worst/best case estimates including the effect of storing water on ice sheets.

3. Coastal Vulnerability

Within the last decade the knowledge of the potential impacts of climate change on the coastal and offshore zones has considerably improved. However, the advances made have been far from uniform, either thematically or by geographical region. For the coastal zone the potential impacts of sea level rise have been emphasized, mostly because low-lying coastal areas appear to be especially vulnerable to even small changes in the mean sea level, and because global sea level rise was regarded as one of the more certain outcomes of global warming (IPCC 2001). Other impacts, such as those caused by changing storms, waves and surges have received much less attention so far.

Figure 3. Storm surge in Germany: Flooding of a polder [1]

According to the government of Schleswig Holstein (Germany) coastal protection is primarily aiming at the safety of people living at or near the coast and the protection of their property (Generalplan Küstenschutz). The measures implemented to fulfill these objectives comprise both, protection from flooding and coastal erosion. Within this framework mean sea level certainly represents a quantity relevant for coastal management, but the main factors for morphodynamic changes and socio-economic threats are related to wind storms, which are associated with storm surges and the threat of flooding (Figure 3) and with strong wave activity. Obviously the wave activity represents an important threat for shipping and off-shore industry, but also for coastal safety and, in particular to erosion (Figure 4).

Another threat (not only) to coastal safety is flooding of the hinterland caused by intense rainfall in the river catchments, which may be anthropogenically enhanced by channeling of rivers and the loss of retention areas.

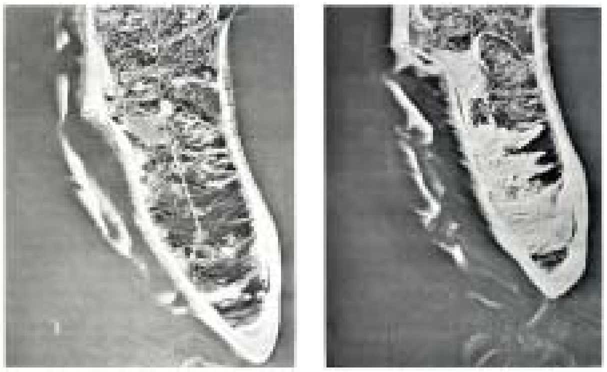

Figure 4. Erosion at the southern tip of the island of Sylt at the German North Sea Coast. The two photographs were taken in 1979 and 1984. [2]

4. Research challenges

There are two main research challenges apart of the identification of the regionally disaggregated vulnerability of the coastal zone, namely the description of past changes, including the extremes, and the outlook for the future of the next, say, 100 years. The analysis of the past is usually limited to the past 100 years, as longer observational records are hardly available (Section 4.1). As observations are almost always available only at scattered observations, a regionally detailed reconstruction cannot be obtained by observed data. A viable alternative is reconstructions with dynamical models (Section 4.2), which can also be used to assess the regional implications of anticipated global climate change (Section 4.3).

In the following we concentrate on storminess, storm surge statistics and wave heights mainly in the North Sea region.

4. 1 Analysis of the past

The assessment of changing wind, wave and storm surge statistics is difficult because of the homogeneity problem. Such an assessment requires long time series, and such time series are usually not homogeneous, i.e., the hydrodynamic regime near a tide gauge, measuring sea level, is affected by dredging water ways and other hydraulic works. Wind measurements are affected by changing locations and changing environments. Wave observations have undergone significant methodological changes, from visual to instrumental in the past decades so that any changes found for present conditions from previous conditions may either reflect a change in the wave statistics or a change in the observational practice. Thus, any assessment of ongoing change must carefully remove sources of inhomogeneity.

An example is given in Figure 5, dealing with about twice-daily high tide levels in Den Helder, The Netherlands, which have exhibited an ongoing increase since the begin of the observations around 1850. When annual means are formed, a clear increase of about 50 cm emerges reflecting a variety of factors as global sea level rise (see Figure 1) or the construction of the dyke closing the nearby Zuiderzee in the 1930s. At other locations along the North Sea, similar changes – clear signals in mean levels but not in storm-related variations – are found.

When the annual statistics of the deviation of this annual mean is considered, a different result emerges. In Figure 5 (bottom) the annual 95, 90, 80 and 50 percentiles of the about 720 annual high tides are plotted as time series. The percentiles may be seen as indicators of the intensity of the storm related water level variations, and these variations have undergone significant variations in the past 120 years, but a sustained upward trend suggesting an overall increase in storminess cannot be detected [3,4].

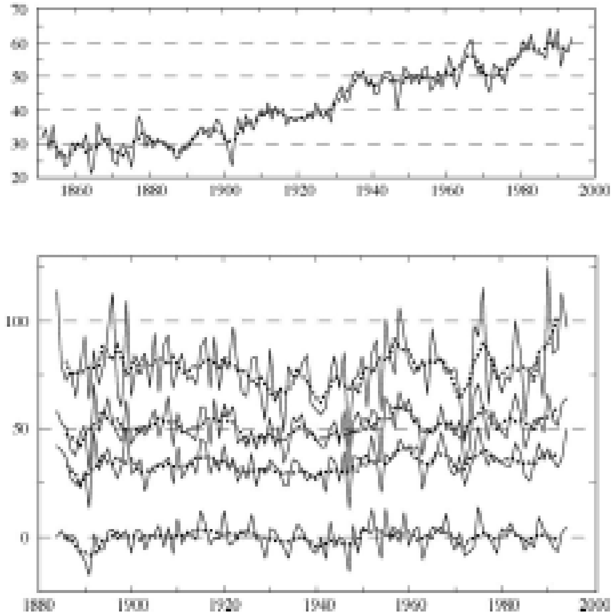

Figure 5. Annual Statistics of sea level (high tide) variations in Den Helder, The Netherlands in *cm*. Top: Annual mean; bottom: annual 95%, 90%, 80% und 50% quantiles after subtraction of the annual mean [3]

The problem of whether storminess has increased in the past can be robustly analyzed with the help of daily geostrophic winds derived from triangles of air pressure readings [5]. Air pressure measurements have the advantage that the method has hardly changed since 100 years, and that the reading is not significantly affected by changing of the ambient environment of the instrument. Any trend in real wind speeds would be reflected in a similar trend in the geostrophic wind speed. Alexandersson et al. [6,7] have made an extensive analysis of many triangles covering the North Sea region as well as the Baltic sea region, and found a significant increase in storminess since about 1960, which, however, did not extend over 1995, and was matched by a slow decrease since about 1880 (Figure 6).

Obviously, natural variability on time scales of a few decades is too large to assess whether a trend extending over, say, 30 years, may be ongoing or even reflecting anthropogenic climate change.

4.2 Dynamical modeling of the past

An alternative to the use of spatially scattered observations is the use of dynamical models of the regional atmosphere, ocean and ocean wave field.

An example is Langenberg's simulation of the North Sea hydrodynamics in 1955-1995 [4], in which she forced a North Sea hydrodynamic model with 6-hourly operational analyses prepared by the Norwegian Weather Service. As a result she obtained annual statistics of coastal sea level variations, as displayed in Figure 7. The solid curve describes the trend in the winter mean sea level. According to the model, the time mean sea level has risen at a rate of about 2 *mm/year* in Denmark and at a rate of about 1 *mm/year* in the German Bight. Along the English and Dutch coast, little change is found. The second dashed curve displays the trend in terms of the 95 percentile (cf. Figure 5), after subtraction of the winter mean, of high tide variations. This trend is within ±1 *mm/year*, or ± 4 *cm* within 40 years. These modelling results were consistent with the result of a statistical analysis of data from a series of tide gauges along the North Sea coast by Pfizenmayer [3, 4] – in the past 40 years, the mean sea level has risen, while the range of short term variations remained almost unchanged.

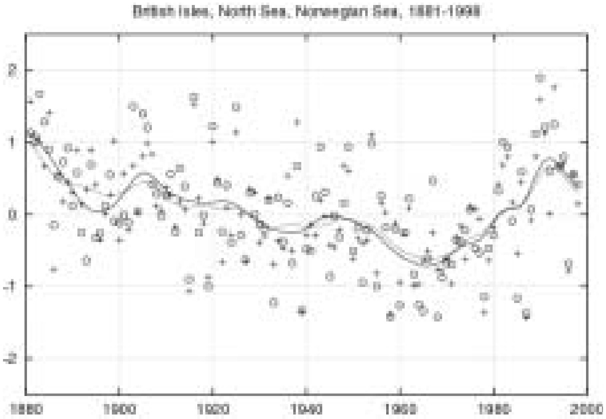

Figure 6. Normalized storm index, based on daily geostrophic wind derived from pressure reading triangles, for the British Isles, North Sea and Norwegian Sea, 1881-1998. The lines represent running means of different lengths. [7]

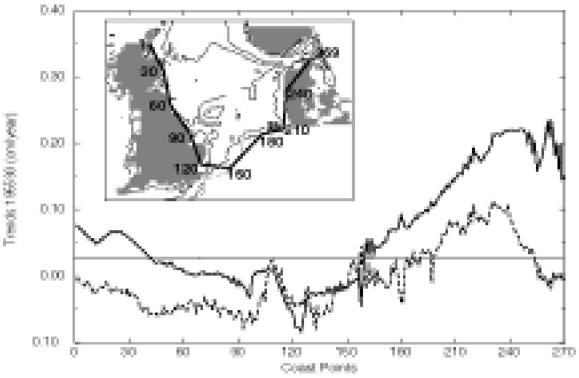

Figure 7. Trends in two statistics of annual simulated sea level variations along the North Sea coast (The inset shows the numbers of the locations, beginning with 1 in Scotland and ending with 269 in Sweden.) [4]

Another example is Feser's "dynamical downscaling" [8] of the NCEP global re-analysis to the European region. Using a regional atmospheric model, she generated a 40-year data set of 1-hourly wind (and other meteorological) data on a 0.5^o latitude-longitude grid. For a location at the German North Sea coast the success of the simulation is demonstrated in Figure 8 for the winter 1994/95. The bias (±1 *m/s*) and the rms (3.5 *m/s*) of the simulation remains stationary in the 40 years of simulation.

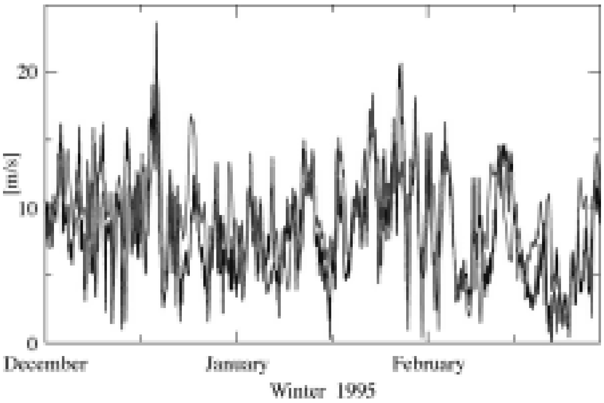

Figure 8. Simulated ("downscaled") (grey) and observed wind speeds (black; in *m*/s) at a location at the German North Sea coast for winter 1994/95 [8]

Another check of the skill of the regional reconstruction is provided by a comparison of the EOFs of the zonal wind, as derived from the downscaled data and from a careful analysis prepared by the German Weather Service for the recent past. This analysis is available only for a few years, while Feser's reconstruction covers the full 40 years since 1958 in a rather homogeneous way. Thus similarity between the reconstruction and the German Weather Service analysis lends further credit to the realisms of Feser's reconstruction. Figure 9 shows the first EOFs of the zonal wind in the German Bight from the two data sources. Indeed, the maps from the two sources are almost identical and describe a similar proportion of total variance.

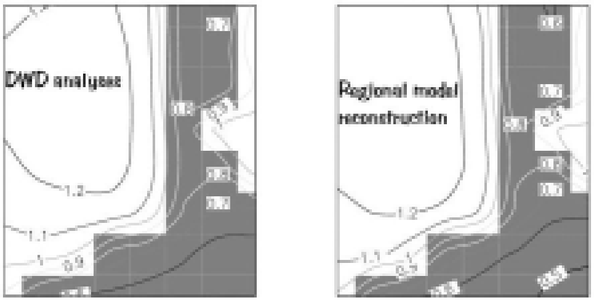

Figure 9. First EOF of zonal wind in the German Bight derived from 7 years of advanced analyses prepared by the German Weather Service and of the same number of years of the dynamically downscaled reconstruction

These wind fields have been used as forcing for dynamical models of the ocean waves. An example of such a simulation is shown in Figure 10 for an island in the German Bight. At that location, a radar system was remotely sensing wave characteristics and a wave buoy recorded in-situ wave heights and directions for part of the time. The light dots represent the wave height and wave direction as given by the radar system, the heavy dots the measurements made on the buoy and the line the result of the wave modelling run with the dynamically downscaled winds. Obviously, the wave characteristics are well reproduced, in particular at the later part of the time, when high wave heights prevailed.

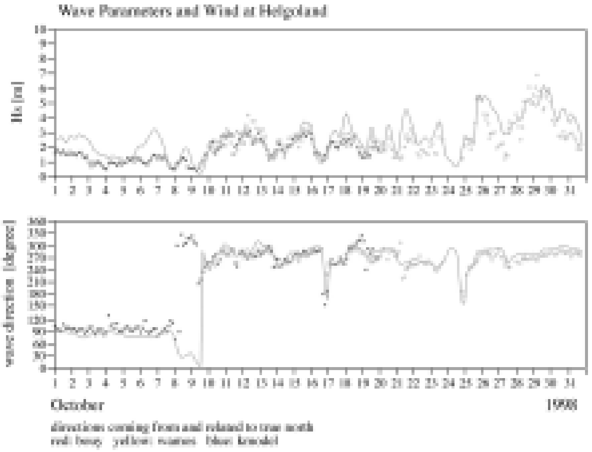

Figure 10. Wave height (top) and wave directions (bottom) at an island in the German Bight. Light dots: radar estimates; dark dots: in-situ measurements made by a wave buoy; line: wave model run with downscaled winds. Courtesy: Gerd Gayer.

The full 40-year wind data set for the North Sea and part of the North Atlantic has been used in the EU Project HIPOCAS [9] to reconstruct the coastal wave history along many of the European coasts. As an example the simulated and observed 99, 95 and 50 percentiles of annual wind speed and wave heights at the platform K13 off the Dutch coast are shown in Figure 11. The similarity of the observed wave height percentiles and the observed ones is remarkable; the absolute error since the beginning of the recording at K13 is less than 0.5 m. Also the wind speed is well simulated, even if the 99% are somewhat overestimated; the absolute error amounts to 1.5 *m/s* after 1985. Before 1985 the observed winds obviously suffered from under-recording. Figure 11 demonstrates nicely the added value of the 40 years of regionalized winds: At most locations, no winds are available at all, only in the more recent past observations have been made. Since the modeled data coincide well with these scattered observations, confidence in the overall simulation is warranted.

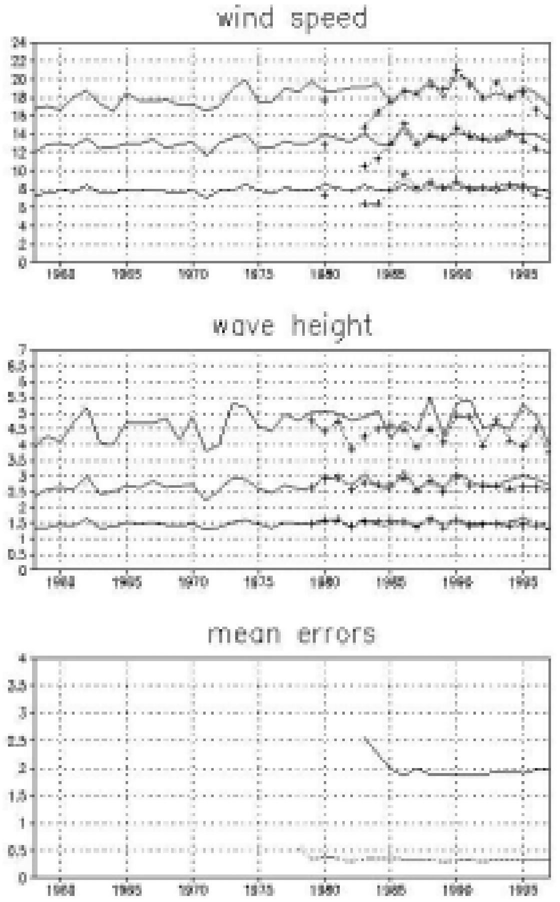

Figure 11. Simulated and observed wind speed (top; in *m/s*) and wave height quantiles (middle, in *m*) at the platform K13 in the Southern North Sea, and mean absolute errors of wave height (dashed) and of wind speed (solid) (bottom panel). In the two upper panels, the simulated 99%, 90% and 50% annual quantiles are given, with the solid line representing the simulations and the dashed line the observed data.

4.3 Modeling future scenarios

A major effort to derive scenarios of future wave height und storm surge statistics in the North Sea was made by the EU project WASA [10]. It was based on a pair of high-resolution climate change experiments, integrated with a T106 model (with a grid spacing of approximately 100 km) over 5 years [11]. One simulation was done with present day conditions, the other with sea surface temperatures and sea ice conditions as simulated in a coarse grid transient climate change experiment at the time doubled CO_2-concentrations. The limitation to only 5 years was due to limitations of computing power. The result, in terms of the change of the 90 percentile of daily wind speed is shown in Figure 12. Over most of the North Atlantic, the wind speed is reduced by 1 – 2 *m/s*, but in the European marginal seas a slight increase of up to 1 *m/s* is simulated.

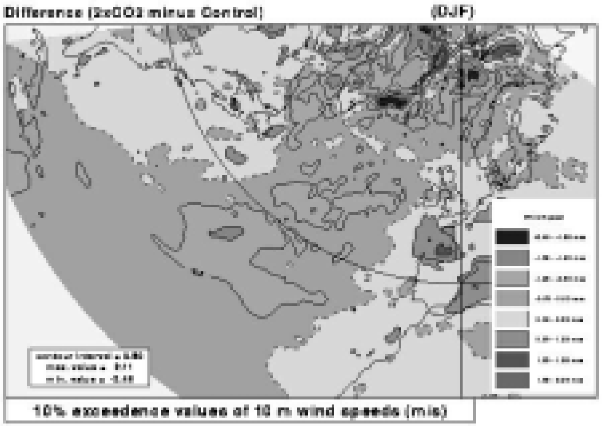

Figure 12. Change of 90 percentile of daily wind speed in the climate scenario used in the WASA project [9]

The wind fields simulated in the two integrations have been used to force both an ocean wave model and two storm surge models [4, 12].

Figures 13 and 14 shows the result of two simulations with models of the North Sea, describing water level variations along the coastline [12]. One model was a barotropic vertically averaged model that dealt only with changing wind statistics, whereas the other model was an 3-dimensional isopycnic model, featuring a homogeneous mixed layer, which dealt with changing wind statistics and thermal expansion. The result is displayed for the winter mean (Figure 13) and for the 95 percentiles of the deviations from the winter mean (Figure 14). The dark band represents the 95% confidence interval for present day conditions. When the simulated change is outside this band, the difference is considered significant, while changes within the band are considered as within the range of the normal variations. Note the “coast” refers here to the coastal grid boxes of the models; usually water levels right at the shore line are significantly larger than the grid box mean.

The expected changed wind causes a general increase of the mean coastal water level, of the order of up to 10 *cm*. The mean westerlies are intensified so that the counter-clock rotation of the North Sea circulation is accelerated, causing coastal sea level rise. The thermal effect is in the order of 20 *cm*, similar to the number prescribed at the boundaries of the model. This boundary value was taken form a global climate change simulation with a coupled ocean atmosphere GCMs.

The effect on the variations relative to the mean sea level, i.e., the storm related water level variations, is given by the change in the 95 percentiles shown in Figure 14. Again, the result for both models is shown [12]. In both cases the effect is within the range of natural variations of the present storm surge climate; also the effect of thermal expansion and its mean increase of water levels of about 20 *cm* (Figure 12) is small. Similar results were obtained by Flather et al. [13].

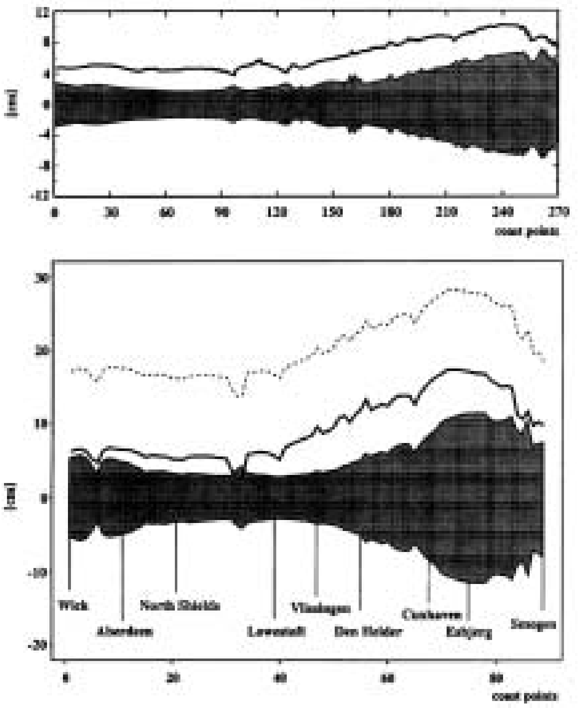

Figure 13. Simulated change of winter mean water level along the North Sea coast (for the numbering of locations, refer to Figure 7) at the expected time of doubled atmospheric carbon dioxide concentrations. Two dynamical model of different complexity were forced with the same T106 wind scenario. The hatched interval is the 95% confidence band representative for present conditions. The solid lines refer to changes only related to wind changes, and the dashed in the lower panel describes the effect of winds and thermal expansion of seawater. [12]

The wave modeling was done with the WAM model [14]. Again only a small change was found (Figure 15). The 10% exceedance values (90 percentiles) of the significant wave height in most of the Atlantic were simulated to be reduced by about 50 cm, but in the North Sea and in the Bay of Biscay an increase of up to 50 *cm* was found.

Later, the WASA study was repeated with a considerable longer simulation with a high-resolution climate model, namely 30 years [15]. Essentially the same results emerged.

Pfizenmayer [16] examined the simulated wave statistics in the central North Sea in more detail, and found that the wave height were not changing strongly, but the that the propagation direction has undergone significant changes [17]. On more occasions eastward propagating waves are prevailing, and in the course of climate change this feature is expected to accelerate. This effect may have a significant impact on the coastal erosion along the “downstream” coast, i.e., the west coast of Jutland, as indicated by a rough estimate of the wave energy displayed in Figure 16. In fact, the most recent variations are outside the range of “normal”, as represented by a 90% confidence interval.

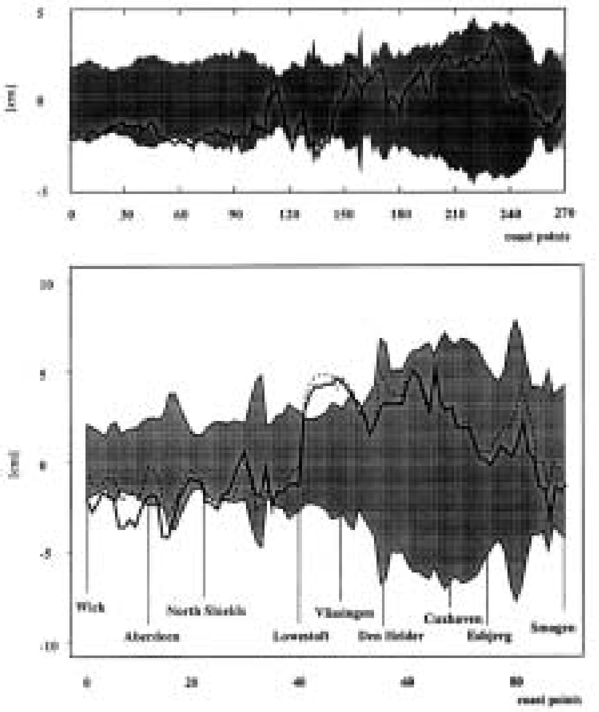

Figure 14. Simulated change of winter 95 percentiles of high tide levels along the North Sea coast (for the numbering of locations, refer to Figure 7) after subtraction of the seasonal mean (Figure 12) at the expected time of doubled atmospheric carbon dioxide concentrations. Two dynamical model of different complexity were forced with the same T106 wind scenario. The hatched interval is the 95% confidence band representative for present conditions. The solid lines refer to changes only related to wind changes, and the dashed in the lower panel describes the effect of winds and thermal expansion of seawater. [12]

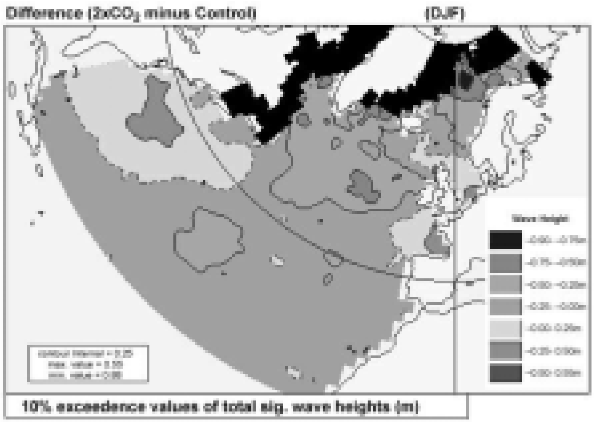

Figure 15. Simulated change in wave height [14, 10], resulting from a doubling of atmospheric carbon dioxide concentrations

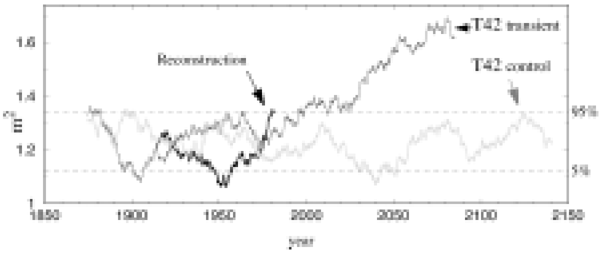

Figure 16. 30-year running mean of estimated wave energy (in^2) at the west coast of Jutland for the past century and for a transient climate change scenario until 2049. Also the results for a control simulation, without changing greenhouse gas concentrations, is shown as well as a 5%-95% confidence interval representative for present day natural variations. [16]

5. Outlook

The past experience has demonstrated that models and observational data are available to assess ongoing change in regional marine weather, including storm surges and wave heights. However, the most recent climate change scenarios have not been examined in this respect with state-of-the-art tools. In the European Union-funded project PRUDENCE, a series of different global climate change scenarios will be dynamically downscaled to the European theater, and evaluated in terms of storm surge statistics and other impact relevant quantities.

On the methodical side further efforts are needed to describe the wave statistics in the vicinity of the coast line and in topographically complex regions.

So far, this type of work has concentrated on the European waters, mostly the North Sea and the Baltic Sea. It would certainly be rewarding to extend such studies to other vulnerable coastal zones.

6. References

[1] Petersen, M., and H. Rohde, 1977, *Sturmflut. Die grossen Fluten an den Küsten Schleswig-Holsteins und in der Elbe*, Karl Wachholz Verlag, 148 pp.

[2] Ehlers, J., 1988, *The Morphodynamics of the Wadden Sea*, A.A.Balkema, Rotterdam.

[3] Pfizenmayer, A., 1997, *Zusammenhang zwischen der niederfrequenten Variabilität in der grossräumigen atmosphärischen Zirkulation und den Extremwasserständen an der Nordseeküste*, Diplomarbeit Institut für Geographie Universität Stuttgart.

[4] Langenberg, H., A. Pfizenmayer, H. von Storch, and J. Sündermann, 1999, "Storm related sea level variations along the North Sea coast: natural variability and anthropogenic change," *Cont. Shelf Res*., 19, pp. 821-842.

[5] Schmidt, H., and H. von Storch, 1993, "German Bight storms analyzed," *Nature,* 365, pp. 791.

[6] Alexandersson, H., T. Schmith, K. Iden, and H. Tuomenvirta, 1998, "Long-term trend variations of the storm climate over NW Europe," *Global Atmos. Oc. System,* 6, pp. 97-120.

[7] Alexandersson, H., T. Schmith, K. Iden, and H. Tuomenvirta, 2000, "Trends of storms in NW Europe derived from an updated pressure data set," *Clim. Res*., 14, pp. 71-73.

[8] Feser, F., R. Weisse and H. von Storch, 2001, "Multidecadal atmospheric modelling for Europe yields multi-purpose data," *EOS,* 82, pp. 305+310.

[9] Soares, C.D., R. Weisse, J.C Carretero, and E. Alvarez, 2002, "A 40-year hindcast of wind, sea level and waves in European waters," *Proceedings of the 21st International Conference on Offshore Mechanics and Artic Engineering*, 23-28 June, Oslo, Norway (in press).

[10] WASA, 1998, "Changing waves and storms in the Northeast Atlantic?" *Bull. Amer. Met. Soc*., 79, pp. 741-760.

[11] Bengtsson, L., M. Botzet, and M. Esch, 1996, "Will greenhouse gas-induced warming over the next 50 years lead to higher frequency and greater intensity of hurricanes?" *Tellus,* 48A, pp 57-73.

[12] Kauker, F. and H. Langenberg, 2000, "Two models for the climate change related development of sea levels in the North Sea. A comparison," *Clim. Res*., 15, pp. 61-67.

[13] Flather, R.A., J.A. Smith, J.D. Richards, C. Bell, and D.L. Blackman, 1998, "Direct estimates of extreme storm surge elevations from a 40-year numerical model simulation and from observations," *Global Atmos. Oc. System*, 6, pp 165-176.

[14] Günther, H., W. Rosenthal, M. Stawarz, Carretero, J.C., M. Gomez, I. Lozano, O. Serano, and M. Reistad, 1998, "The wave climate of the Northeast Atlantic over the period 1955-1994: The WASA wave hindcast," *Global Atm. Oc. System*, 6, pp. 121-163.

[15] Kaas, E., U.Andersen, R.A: Flather, J.A. Willimas, D.L. Blackman, P. Lionello, F. Dalan, E. Elvini, A. Nizzero, P. Malguzzi, A. Pfizenmayer, H. von Storch, D. Dillingh, M. Phillipart, J. de Ronde, M. Reistad, K.H. Midtbø, O.Vignes, H.Haakenstad, B. Hackett, I. Fossum, and L. Sidselrud, 2001, Synthesis of the STOWASUS-2100 project: "Regional storm, wave and surge scenarios for the 2100 century," *Danish Climate Centre Report,* 01-3, 22pp.

[16] Pfizenmayer, A., 2002, *Ein stochastischer Wellengenerator zur Simulation der dreistündigen lokalen Wellenhöhen und -richtungen in der Nordsee konditioniert auf das grossskalige Bodenluftdruckfeld und die CO2 Konzentration. (Analyse des simulierten und zukünftigen Seegangsklimas und daraus abgeleitete mögliche sozio-ökonomische Folgen),* PhD Thesis, Hamburg University, 78 pp.

[17] Pfizenmayer, A., and H. von Storch, 2001, "Anthropogenic climate change shown by local wave conditions in the North Sea," *Climate Res*., 19, pp 15-23.