The story of storminess in northwest Europe[1]

Hans von Storch

Institute for Coastal Research, GKSS, Geesthacht, Germany

Introduction

Storms represent the dominant weather hazard in Northern Europe. They are associated with abundant rainfall and excessive wind force. Wind storms cause different types of damages on land and on sea; on land, houses and other constructions may be damaged; also trees may break in larger numbers in forests. In the sea, wind pushes water masses toward the coasts, where the water levels may become dangerously high, overwhelm coastal defense and inundate low-lying coastal areas; also the surface of the sea is affected – wind waves are created, which eventually transform into swell. Obviously, ocean waves represent a major threat for shipping, off-shore activities and coastal defense.

We review a number of questions related to windstorms in the northeast Atlantic and northern European region, namely

How to determine decadal and longer variations in the storm climate? This issue has been dealt with in great detail in the European WASA project (WASA, 1998). The methodical problem is that many variables, which seem to be well suited for this purpose, are available only for a too short period or suffer from *inhomogeneities*, i.e., their trends are contaminated by signals related to the observation process (instrumentation, practice, or environment). From air pressure readings at a weather station and characteristics of water levels at a tide gauge useful indicators may be derived.

How has the storm climate developed in the last few decades and last few centuries? It turns out that an increase in storm activity over the considered region (northeast Atlantic, northern Europe) took place for a few decades since about the 1960s, which had replaced a downward trend since about 1900. When considering air pressure readings at two stations in Sweden since about 1800 no significant changes could be found.

How did wind storm impact on storm surges and ocean waves develop in the past decades, and what may happen in the expected course of anthropogenic climate change? Regionally detailed reconstructions of surface winds since about 1960 have been used to run dynamical models of water levels, currents and ocean waves in the North Sea. Changes were found to be consistent with the changes of storm activity, namely a general increase since 1960 to the mid 1990s and thereafter a decline – apart from the southern North Sea, where the upward trend is still going on. Scenarios based on a chain of assumed emissions, global and regional climate models point to a slightly more violent future of storminess, storm surges and waves in the North Sea. For the end of the century an intensification of up to 10% is envisaged, mostly independently of the emission scenario used. When not only the change in windiness but also the enlarged volume of the ocean is considered, then, for extreme water levels, an increase of 20 cm in year 2030 and of 50 cm in 2085 along the German Bight coast line are reasonable guesses for future conditions. Further inland, in the estuary of the river Elbe, the levels are heightened by another 10-20%.

1. How to determine decadal and longer variations in the storm climate?

A major problem with determining changes in windiness represents the homogeneity, or more precisely the lack of homogeneity, of observed time series. The term “inhomogeneity” refers to the presence of contaminations in a data set, so that the meteorological data, which are supposed to describe the meteorological conditions and their changes over time, are actually a mix of the looked-after signal and a variety of factors reflecting changing environmental conditions, changing instruments and observation practices (*Karl et al*., 1993).

---

[1] A similar text will be published as von Storch, H., and R. Weisse, 2007, Regional storm climate and related marine hazards in the North Atlantic, in Diaz, H. E., and Murnane, R. J. (eds.), *Climate Extremes and Society*, Cambridge University Press, Cambridge.

For instance, pressure readings usually depend not very much on the specifics of the location (apart from the height) and have been recorded over long periods of time with rather similar instruments, namely the mercury barometer. A rather different example represents wind measurements which depend very strongly on the details of the surrounding, in particular the exposure and obstacles. Also instruments and observation practices have changed frequently, particularly with wind observations and wind estimates over the sea.

Figure 1 displays a series of examples: The first example shows frequency distributions derived from visual estimates of wind speeds in the English channel – on distribution is derived from reports of ships without an anemometer, the other from reports of ships with an anemometer. Obviously, the presence of an instrument to measure the wind speed has a significant impact on reporting visual assessments – in the former case the median is 3 or 4 Bf, whereas for visual reports from ships with instrument the median5 Bf.

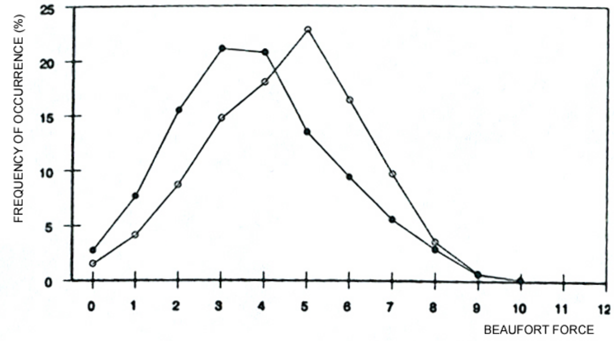

Figure 1a. Frequency distribution of wind estimates on the Beaufort scale, derived from voluntary ship reports in the English Channel after 1949. The solid dots are derived from reports from ships without an anemometer, whereas the open dots stem from observations made when an instrument was available. All reports are visual assessments of the sea state (*Peterson and Hasse*, 1987).

The second example shows annual 99%-iles of daily wind reports at six locations along the German North Sea coast. All stations are close to each other, 100 km distance, or so. Three are from island stations, the other three are reports from coastal cities. Obviously, the records show jumps, even in the most recent years. The relevant point is that these changes are not synchronously happening at the neighbouring stations – they represent effects of changing observation practices and environments – inhomogeneities. These data are quality controlled, but even scrupulous efforts by a professional weather service cannot help when the immediate environment of the instrument is changing (see marking).

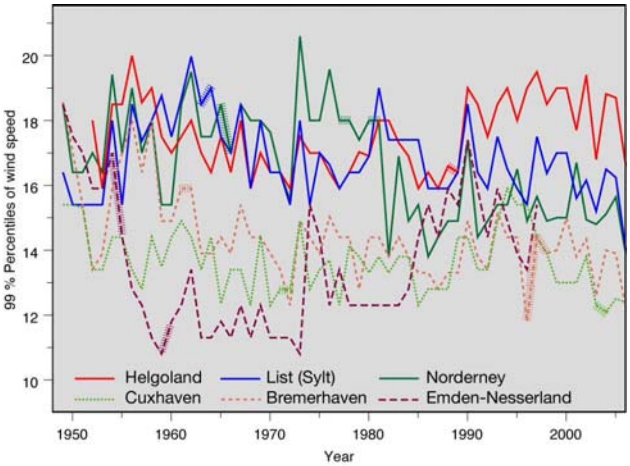

Figure 1b. Annual 99%-iles of daily wind reports at 6 locations along the German North Sea coast. Helgoland, List, and Norderney are island stations, whereas Cuxhaven, Emden, and Bremerhaven are coastal towns. Known inhomogeneities are marked by hatching. (Janna Lindenberg, pers. communication; using data kindly provided by the German Weather Service, DWD.).

Thus, direct observations of wind are almost never helpful to assess changes in windiness for decades of time. As an alternative, a number of proxies representative of the strength of windiness or storminess in a season or a year have been suggested and tested. They are mainly based on pressure readings. Specifically, spatial and temporal pressure differences are in use, and also the frequency of low pressure occurrences.

Schmidt and von Storch (1993) have suggested the calculation of geostrophic winds from triangles of pressure readings; in this way, one (or possibly more) geostrophic wind-speed per day is obtained for given location. From the distribution of all numbers within one season, or a year, high percentiles are derived as proxies for storminess. Figure 2 shows a comparison of percentiles derived from geostrophic wind estimates and local wind observations for a few years in modern times, and a remarkably linear link is found – suggestive that any change in real wind percentiles would be reflected in changes of the geostrophic wind and vice versa (K*aas et al*., 1996). Thus, time series of the geostrophic wind percentiles are considered as proxies of wind and storm condition changes in the course of time (*Schmidt and* *von Storch*, 1993; *Alexandersson et al*., 1998, 2000). Typically used percentiles are 95% or 99%.

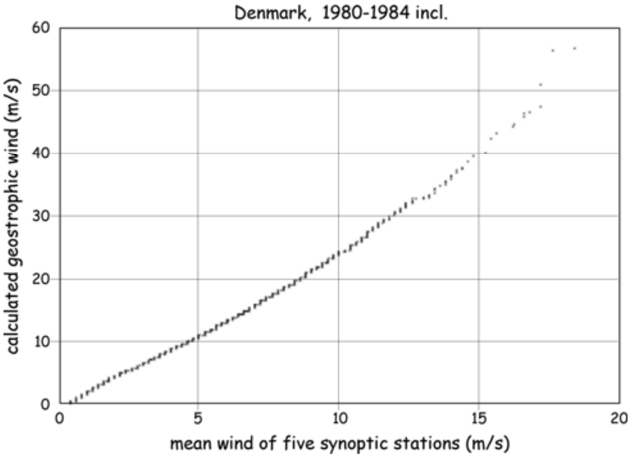

Figure 2. Percentile-percentile plot of daily wind speed and geostrophic wind speeds at one location derived from 5 years of data. (*Kaas et al.*, 1996).

An alternative proxy based on spatial differences of pressure readings is the annual frequency of days, when the geostrophic wind is larger than, say, 25 m/s.

Two alternative proxies are based on local pressure observations, reflecting the experience that stormy weather is associated with low pressure and a fall of the barometer reading (*Kaas et al*., 1996). This proxy has the advantage that it is available for very long time at some locations (*Bärring and von Storch*, 2004).

A totally different proxy is derived from short-term water variations at a tide gauge. Water levels at tide gauges are often changed by local water works but also by slow variations related to geological phenomena. Therefore, first the annual mean height tide is determined, and then the variations of the high tide relative to this mean high tide are considered (*von Storch and Reichardt*, 1997).

With these proxies, an assessment of past storminess in Northern Europe is possible (see next chapter). The different indices are mostly consistent among each other, with the exception of the number of deep pressure readings, which correlated only little with the other proxies.

For historical times, when barometers where not yet available, historical accounts help to assess wind conditions, for instance repair costs of Dikes in Holland during the 17th century (*de Kraker*, 1999) or sailing times of supply ships on pre-determined routes (e.g., *Garcia et al*., 2000).

2. How has the storm climate in the Northeast Atlantic developed in the last few decades and last few centuries?

Serious efforts to study changing storminess on the NE Atlantic began in the early 1990s, when meteorologists noticed a roughening of storm and wave conditions. Wave observations from light houses and ships (*Hogben*, 1994; *Cardone et al.*, 1990; *Carter and Draper*, 1988) described a roughening since the 1950s, and an analysis of deep pressure systems in operational weather maps indicated a steady increase of such lows since the 1930s (*Schinke*, 1992). Unfortunately, these analyses all suffered from the problems described above, namely either an insufficient length of data series or compromised homogeneity. For instance, the skill of describing weather details in weather maps has steadily improved in the course of time, because of more and better data reported to the weather services and improved analysis practices. For instance, for the case of global re-analysis the improvement related to the advent of satellite data on Southern Hemisphere analysis is described by *Kistler et al*. (2001). Another example on the effect of better data coverage is provided by *Landsea et* al. (2004) for an example of a tropical storm.

The breakthrough came when the proxies defined in the previous section were introduced, mostly in the EU project WASA (WASA, 1998). *Alexandersson et al*. (1998, 2000) assembled homogeneous series of air pressure readings from 1880 for a variety of locations covering most of Northern Europe. They calculated 99%iles of geostrophic winds from a number of station triangles. After some normalization and averaging they derived proxy time series for the greater Baltic Sea region and for the Greater North Sea region. According to this proxy, the storm activity intensified indeed between 1960 and 1995[2], but from the beginning of the record until about1960 there was a long period of declining storminess, and s The 1960-1995 increase in NE Atlantic storminess

---

[2] Interestingly, in the early 1990s there were widespread claims in Northern Europe (e.g., *Berz*, 1993; *Berz and Conrad*, 1994) that there was a significant increase in storminess, which would be consistent with anthropogenic climate change. Following this logic, one would had to assume that the trend would continue into the future, and thus wind-related risks would increase and cause problems for the insurance industry.

appears also as non-dramatic, when an even longer time window is considered, namely homogenized local air pressure readings at two locations in Sweden, Lund and Stockholm, which have been recorded since the early 1800s and earlier (*Bärring and von Storch*, 2004;). The number of deep pressure systems (Figure 3a) as well as the number of pressure falls of 16 hPa and more within 12 hours (not shown) is remarkably stationary since the beginning of the barometer measurements. This is remarkably because at the same time the regional temperatures, e.g., the winter mean temperatures for Denmark, rose markedly by almost 2K since 1874 (Figure 3b).

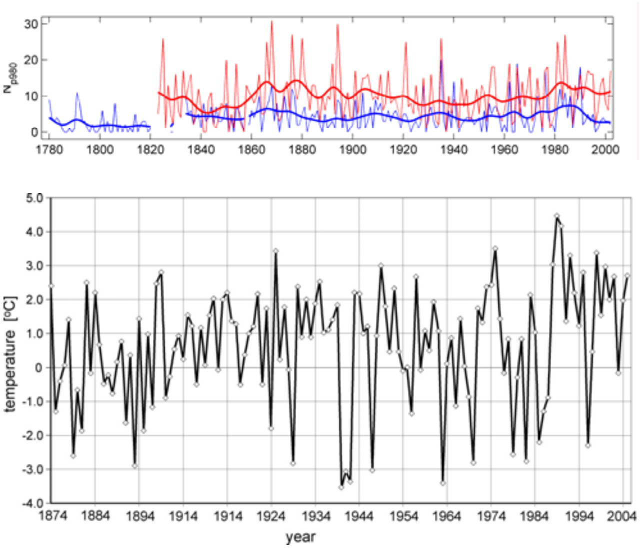

Figure 3. Climate indicators in Southern Scandinavia (a) Annual frequency of daily low-pressure readings in Lund (blue) and Stockholm (red) for since the end of the 18th century, showing decadal variability but no tendency towards higher storm activity in recent years. (*Bärring and von Storch*, 2004) (b) Winter mean temperatures in Denmark since 1974 (*J. Cappelen*, pers. comm.) showing an increase by almost 2K.

In the past, sometimes the argument was put forward that a general warming would lead to an increase of water vapor in the atmosphere, thus a warming would provide more "fuel" for the formation of storms. This hypothesis was examined in the framework of a millennium simulation with a state-of-the-art climate model, which was run with reconstructed natural and anthropogenic forcing since 1000 bp, and extended until the year 1990. It turned out that during pre-industrial and industrial times (i.e., until about the end of the 20th century), the hypothesized link could not be detected, even if significant temperature fluctuations were simulated. However, these hemispheric temperature fluctuations did not co-vary with the intensity or the location of the mid-latitude storm tracks (*Fischer-Bruns et a*l., 2005).

Indeed, there is no evidence that the Little Ice Age, and particularly the Late Maunder Minimum were storm-poor times; also, the cold season is the storm season and not the warmer summer. Clearly, not the mean level of temperature is the key parameter but the spatial gradients of temperature control the statistics of the formation of storms.

3. How did wind storm impact on storm surges and ocean waves develop in the past decades, and what may happen in the expected course of anthropogenic climate change?

Changes in storminess have a significant impact on a variety of socio-economic relevant activities and risks. An economic segment obviously sensitive to changes in wind-related risks is the insurance industry[3]. Other relevant aspects are related to ocean waves and storm surges, and their impact on off-shore activities, shipping, and coastal structures.

Using proxies, as described in the previous sections, indicates that a systematic roughening of storm-related risks has not happened in the past 200 years, or so. On the other hand, a worsening has taken place in the past 40 years, and data during that period are good enough to examine the changes of storm surge and ocean wave statistics.

The availability of good weather analyses – on the global basis for instance the NCEP re-analyses (*Kalnay et al*., 1996) and, for the European region, dynamical downscaling of this reanalysis (*Feser et al*. 2001) – allow a detailed analysis of changing ocean wave and storm surge conditions. To do so, 6-hourly (or even more frequent) wind- and air pressure analyses are used to run ocean wave (*Günther et al.*, 1998; *Sterl et al.*, 1998) and storm surge models (*Flather et al.*, 1998b; *Langenberg et al.*, 1999). In this way, homogeneous estimates of changes in the

---

[3] One should, however, not accept an assertion of the insurance industry as an unbiased and objective description of the situation without careful analysis – overestimating the risks involved does in general not harm the economic interests of an insurance company.

past 50, or so, years, can be constructed (*Weisse and Plüß*, 2005). Using the same models, also scenarios of expected climate change can be processed with respect to windstorms, ocean waves and storm surges (e.g., *Flather et al*., 1998a; *Kauker*, 1998; *Debernard et al.*, 2003; *Woth et al.*, 2005; *Woth*, 2005, *Lowe et al*., 2001, *Lowe and Gregory*, 2005.)

Along these lines, the "Feser"-analyses have been used to examine changes in patterns of storminess (*Weisse et al*., 2005). In most parts of the Northeast Atlantic, storminess – given as annual frequency of gales per grid box – increased until the early 1990s, south of about 50°N there was a decrease (Figure 4). This pattern reversed almost completely in the early 1990s apart of the southern North Sea, where the trend towards more storms continued, albeit somewhat decelerated towards the end of the period, at least until 2002 Accordingly, simulations of high tide statistics reveal an increase of water levels of a few mm/year, both in the seasonal mean as well as in the high levels relative to the mean (*Weisse and Plüß*, 2005, *Aspelien*, 2006), in particular along the German Bight coast line.

Furthermore, in the HIPOCAS project (*Soares et al*., 2002) statistics of ocean (surface) waves have been derived. Extreme wave heights have increased in the southeastern North Sea within the period 1958-2002 by rate of up to 1.8 cm/yr while for much of the UK coast a decrease is found. The increase in the southeastern North Sea, however, is not constant in time. The frequency of high wave events has increased until about 1985-1990 and remained almost constant since that time (*Weisse and Günther*, 2007). This development closely follows that of storm activity (*Weisse et al*., 2005).

Scenarios of future wind conditions have been derived by several groups. The most useful is possibly the set of simulations with the model of the Swedish Rossby Center, which features not only an atmospheric component but also lakes and a dynamical description of the Baltic Sea (*Räisänen et al*., 2004). This model was run with boundary conditions taken form two global climate models; also the effect of two different emission scenarios has been simulated. In these simulations, strong westerly wind events are intensified by less than 10% at the end of the 21st century (*Woth*, 2005).

Such changes of wind speed would have an effect on both North Sea storm surges and wave conditions. For the storm surges along the North Sea coast line, an intensification would be expected, which may amount to an increase of 30 cm, or so, to the end of the century (Figure 5a). To this wind-related change the mean level has to be added, so that for maximum values of 50 cm along the German Bight are plausible estimates for the increase of water levels during heavy storm surges. In the Elbe estuary, larger values up to 70 cm are derived. These numbers are associated with a wide range of uncertainty (± 50 cm) (*Grossmann et al*., 2007; Fig. 5b).

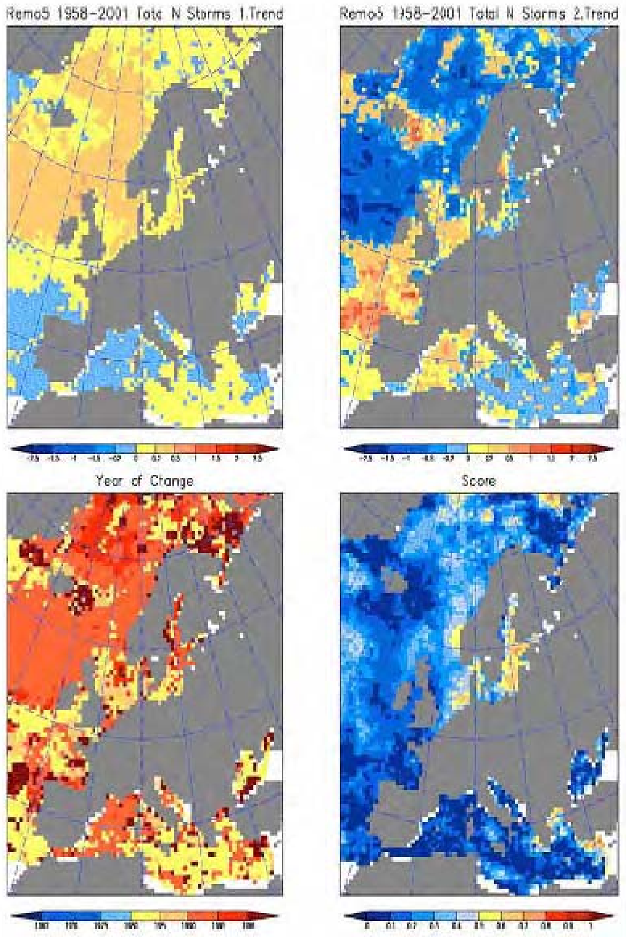

Figure 4. Piecewise linear trends in the total number of storms per year with maximum wind speeds exceeding 17.2 m s1. (a) Linear trend for the 1958–T period; (b) linear trend for the T–2001 period. Units in both cases are number of storms per year. (c) Year T at which a change in trends is indicated by the statistical model. (d) Brier skill score of the bi-linear trend fitting the data as compared to using one trend. (*Weisse et al.*, 2005) .

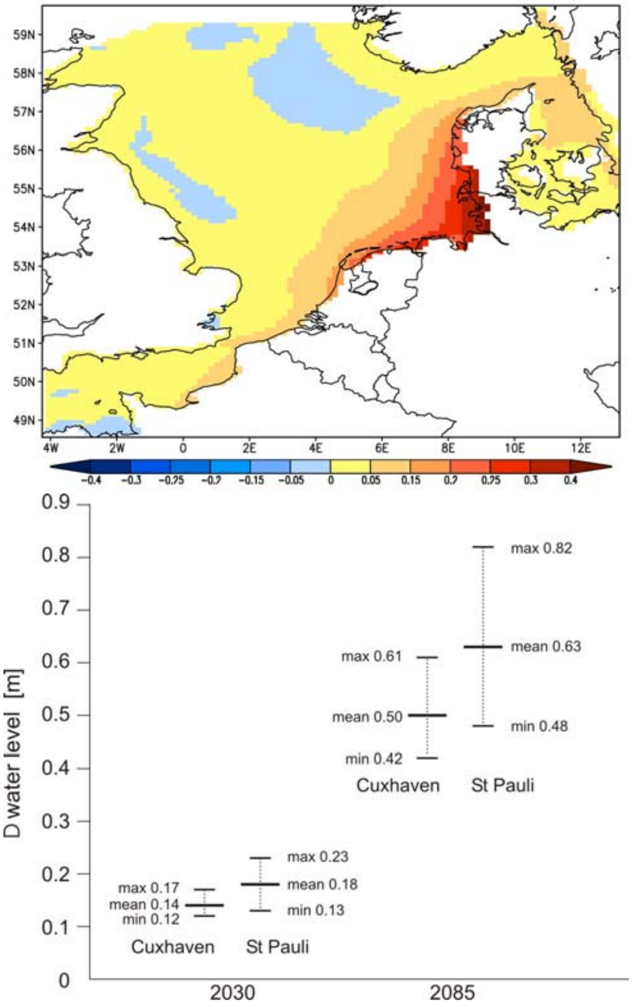

Figure 5. Expected changes in wind-related storm surge heights for the period 2070-2100; (top) maximum averaged across many years, RCAO model; units, m; Woth, pers. comm.) in the North Sea and local storm surge heights in 2030 and 2085 in Cuxhaven (at the mouth of the River Elbe) and in Hamburg St. Pauli (~140 km upstream the Elbe estuary); (bottom) including the effects of estimated mean sea level rise (*Grossmann et al*., 2007).

Scenarios of future wave conditions show large differences in the spatial patterns and the amplitude of the climate change signals. There is, however, agreement among models and scenarios that extreme wave heights may increase by up to 30 cm (7% of present values) in the southeastern North Sea by 2085 (*Weisse und Grabemann*, in prep.; not shown).

References

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

Aspelien, T., 2006, The use of long-term observations in combination with modelling and their effect on the estimation of the North Sea storm surge climate. PhD thesis, Hamburg, 106 pp.

Bärring, L., and H. von Storch, 2004, Northern European storminess since about 1800. *Geophys. Res. Lett.* 31, L20202, doi:10.1029/2004GL020441, 1-4.

Berz, G., 1993, Global Warming and the insurance industry, *Interdisc. Sci. Rev.*, 18 (2), 120-125.

Berz, G., and K. Conrad, 1994, Stormy weather: The mounting windstorm risk and consequences for the insurance industry, *Ecodecision*, 12, 65-68.

Cardone, V. J., J. G. Greenwood, and M. A. Cane, 1990, On trends in historical marine data, *J. Climate*, 3, 113-127.

Carter, D. J. T., and L. Draper, 1988, Has the northeast Atlantic be come rougher? *Nature*, 322, 494.

Debernard, J., Ø. Sætra, L. P. Røed, 2003, Future wind, wave and storm surge climate in the northern North Atlantic, *Climate Rev*., 23,39-49.

De Kraker, A. M. J., 1999, A method to assess the impact of high tides, storms and storm surges as vital elements in climate history. The case of stormy weather and dikes in the Northern part of Flanders, 1488-1609, *Climatic Change*, 43, 287-302.

Feser, F., R. Weisse, and H. von Storch, 2001, Multidecadal atmospheric modelling for Europe yields multipurpose data, *EOS*, 82, 305+310.

Fischer-Bruns, I., H. von Storch, F. González-Rouco and E. Zorita, 2005, Modelling the variability of midlatitude storm activity on decadal to century time scales. *Clim. Dynam.*, 25,461-476, DOI 10.1007/s00382-005-0036-1.

Flather, R. A., and J. A. Smith, 1998a, First estimates of changes in extreme storm surge elevation due to doubling CO_2. *Global Atmos.-Ocean Syst.*, 6, 193-208.

Flather, R. A., J. A. Smith, J. D. Richards, C. Bell, and D. L. Blackman, 1998b, Direct estimates of extreme storm surge elevations from a 40-year numerical model simulation and from observations, *Global Atmos.-Ocean Syst.*, 6, 165-176.

García, R., L. Gimeno, E. Hernández, R. Prieto, and P. Ribera, 2000, Reconstruction of North Atlantic atmospheric circulation in the 16th, 17th and 18th centuries from historical sources, *Climate Res*., 14, 147-151.

Grossmann, I., K. Woth, and H. von Storch, 2007, Localization of global climate change: Storm surge scenarios for Hamburg in 2030 and 2085, Die Küste 71 (in press)

Günther, H., W. Rosenthal, M. Stawarz, J. C. Carretero, 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 Atmos. Ocean. Syst.*, 6, 121-163

Hogben, 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.

Kaas, E., T-S. Li, T. Schmith, 1996, Statistical hindcast of wind climatology in the North Atlantic and northwestern European region, *Climate Res*., 7, 97-110.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. C. Mo, C. Ropelewski, J. Wang, A. Leetmaa, R. Reynolds, R. Jenne and D. Joseph, 1996, The NCEP/NCAR 40-Year Reanalysis Project, *Bull. Amer. Meteor. Soc.*, 77, 3, 437-471.

Karl, T. R., R. G. Quayle, and P. Groisman, 1993, Detecting climate variations and change: New challenges for observing and data management systems, *J. Climate*, 6, 1481-1494.

Kauker, F., 1998, Regionalization of climate model results for the North Sea. PhD thesis, University of Hamburg, 109 pp., GKSS 99/E/6.

Kistler, R., E. Kalnay, W. Collins, S. Saha, G. White, J. Woollen, M. Chelliah, W. Ebisuzaki, M. Kanamitsu, V. Kousky, H. van den Dool, R. Jenne and M. Fiorino, 2001: The NCEP/NCAR 50-year reanalysis. *Bull Amer. Meteor. Soc*, 82, 247-267.

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, 821-842.

Lowe, J. A., and J. M. Gregory, 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. A., J. M. Gregory, and R. A. Flather, 2001, Changes in the occurrence of storm surges in the United Kingdom under a future climate scenario using a dynamic storm surge model driven by the Hadley center climate models, *Clim. Dynam*., 18, 179–188.

Peterson, E. W., and L. Hasse, 1987, Did the Beaufort scale or the wind climate change?, *J. Phys. Oceanogr*. 17, 1071–1074.

Räisänen, J., U. Hansson, A. Ullerstig, R. Döscher, L. P. Graham, C. Jones, H. E. M. Meier, P. Samuelsson, and U. Willén, 2004, European climate in the late twenty-first century, regional simulations with two driving global models and two forcing scenarios. *Clim. Dynam*., 22, 13–31, doi 10.1007/s00382-003-0365-x.

Schinke, H., 1992, Zum Auftreten von Zyklonen mit niedrigen Kerndrücken im atlantisch-europäischen Raum von 1930 bis 1991. *Wiss. Zeitschrift der Humboldt Universität zu Berlin, R. Mathematik/ Naturwiss*. 41, 17-28.

Schmidt, H., and H. von Storch, 1993, German Bight storms analyzed, *Nature*, 365, 791.

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, Oslo, Norway, American Soc. of Mechanical Engineers, OMAE 2002-28604.

Sterl, A., G. Komen, and P. D. Cotton, 1998, Fifteen years of global wave hindcasts using winds from the European Centre for Medium Range Weather reanalysis, Validating the reanalyzed winds and assessing the wave climate. *J. Geophys Res.*. 103, C3, 5477-5492.

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

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

Weisse, R.. and H. Günther, 2007, Wave climate and long-term changes for the Southern North Sea obtained from a high-resolution hindcast 1958-2002. *Ocean Dynam.*, doi,10.1007/s10236-006-0094-x, 2007.

Weisse, R. and A. Plüß, 2005, Storm-related sea level variations along the North Sea Coast as simulated by a high-resolution model 1958-2002, *Ocean Dynam.*, DOI, 10.1007/s10236-005-0037-y.

Weisse, R., H. von Storch, and F. Feser, 2005, Northeast Atlantic and North Sea storminess as simulated by a regional climate model 1958-2001 and comparison with observations. *J. Climate*, 18, 465-479.

Woth, K., R. Weisse, and H. von Storch, 2005, Dynamical modelling of North Sea storm surge extremes under climate change conditions - an ensemble study, *Ocean Dynam*., DOI 10.1007/s10236-005-0024-3.

Woth, K., 2005, Projections of North Sea storm surge extremes in a warmer climate, How important are the RCM driving GCM and the chosen scenario? *Geophys. Res. Lett.*, 32, L22708, doi: 10.1029/2005GL023762.