Regional storm climate and related marine hazards in the Northeast Atlantic

Hans von Storch and Ralf Weisse

Institute for Coastal Research, GKSS, Geesthacht, Germany

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

We review a number of questions related to windstorms in the North East Atlantic and Northern European region, namely

1. *How to determine decadal and longer variations in the storm climate?* The methodical problem is that many variables, which seem to be well suited for this purpose, are available only for too short a period or suffer from *inhomogeneities*, i.e., their trends are contaminated by signals related to the observation process (changes in instrumentation, observational practice, or surrounding environmental conditions). From air pressure readings at weather stations and statistics of water levels at a tide gauges useful indicators may be derived.
2. *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 Northeast Atlantic and Northern Europe took place for a few decades since about the 1960s which had replaced a downward trend since about 1900. When longer periods are considered (such as by analysing air pressure readings at stations in Sweden since about 1800) no significant changes could be found.
3. *How is storm climate variability linked to hemispheric temperature variations?* Sometimes it is argued 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. The hypothesized link between large-scale temperature fluctuations and storminess 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 for the past 500 years, and extended until the year 2100 assuming scenarios for future greenhouse gas emissions. It turns out that during pre-industrial and industrial times (i.e., until about the end of the 20century), the hypothesized link could not be detected, even if significant temperature fluctuations were simulated. Only when future greenhouse gas concentrations were strongly increased, a parallel development of Northeast Atlantic storm intensity and hemispheric temperature emerged.
4. *How did the impact of windstorms 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 of the Southern North Sea, where the upward trend is still going on.. Scenarios prepared by a chain of assumed emission scenarios, 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 thermal expansion of the ocean is considered increases of 20-30 cm in 2030 and of 50 cm in 2085 appear to be reasonable guesses for future conditions of extreme water levels along the German Bight coast line.

There have been many publications about changing storminess in the recent past. Here we focus on changes that have appeared in the past and that may occur in the future over the Northeast Atlantic and Northern Europe. The article is not aiming at presenting all new material but is summarizing results available from a series of reviewed manuscripts, mostly beginning with the landmark WASA (1998)-paper. We also limit ourselves to the discussion of the four questions outlined above. We do not explicitly discuss other issues such as changes in the North Atlantic Oscillation which has been shown to be closely linked to the variability of North Atlantic storminess and have been discussed in detail elsewhere (e.g. Hurrell et al., 2002).

We touch the issue of expected changes of North Atlantic storminess due to anthropogenic climate change only briefly. This will be the subject of a detailed account by the forthcoming Fourth Assessment report of the IPCC. Also Lambert and Fyfe (2006) discuss the issue in detail. However, we discuss details of the expected change in storms and their impact in the case of the North Sea in Section 4.

In the following, the material is not presented in great detail because our intention is to provide an overview about the issues. However, details are available from the referenced literature. Where possible, review papers or manuscripts with extended references have been cited, tackling much of the aspects not explicitly addressed in this paper and containing much of the references not explicitly accounted for here because of space limitations. However, the article is not meant as a review which is covering and evaluating all material related to the issue of Northeast Atlantic storminess published.

This article has no section with conclusions – we consider conclusions unnecessary as the main conclusions are listed in the four research questions (and brief answers) given above.

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

A major problem with determining changes in windiness concerns the homogeneity, or more precisely the lack of homogeneity, of observed time series. The term “in-homogeneity” 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 sought-after signal and a variety of factors reflecting changing environmental conditions, changing instrumentation and observation practices (Karl et al., 1993). For instance, air pressure usually depends not very much on the specifics of the location (apart from the height of the instrument which is routinely be corrected for) and has been recorded over long periods of time with virtually unchanged instruments, namely the mercury barometer. A rather different case represent wind measurements which depend very strongly on the details of the surrounding of the measurement site, in particular the exposure and obstacles. Also instruments and observation practices have changed frequently. This is in particular so with wind observations and wind estimates over sea (e.g. Gulev et al. 2003; Gulev and Grigorieva 2004).

The problem is illustrated in Figure 1 for a series of examples. A very obvious example is presented in Figure 1a where the frequency of strong wind events in the city of Hamburg (Germany) per decade of years is shown. Obviously a very strong decline took place from the 1940s to the 1950s, the explanation for which is that the instrument was moved from the harbor to the airport.

A less obvious example that has occasionally been mistaken as evidence for a worsening of the storm climate in Northern Europe is illustrated in Figure 1b. It shows the frequency of recorded storm days (with wind speed ≥21 m/s) in Kullaberg, south-western Sweden (after Pruszak and Zawadzka 2005). Apparently, the number of storm days was considerably more frequent in later than in earlier years. It seems, however, that a severe wind storm damaged the surrounding forest in 1969, so that the locally recorded winds became stronger after the wind break and the associated reduction of surface roughness. We will see later that proxies of storminess indicate no such change in storminess in that area.

Another example of in-homogeneous data records is shown in Figure 1c. The example is based on surface marine wind measurements from the Pacific Ocean in the vicinity of the stationary weather ship (OWS) P. While the OWS is expected to take quality controlled wind measurements, there are additional wind reports available from ships traveling nearby the stationary OWS. These reports enter the so-called COADS data set from which the ship observations can be averaged for each year and compared to the quality controlled data form the ocean weather station. Doing so, a strong discrepancy emerges: while the ship data indicate an upward trend in average wind speed conditions, the OWS P reports variable but by and large stationary conditions. Obviously, at least one of the data products is not homogeneous. In addition it becomes plausible, that interpreting in-homogenous records may become particularly misleading when long-term changes and trends are analyzed.

The in-homogeneity problem has been frequently overlooked and ignored. Direct wind measurements are almost never helpful to assess changes in storminess for longer periods such as decades of years. As an alternative, a number of different proxies for storminess in a year or season have been examined. They are mainly based on air pressure readings and water levels obtained from tide gauge records.

Schmidt and von Storch (1993) have suggested the calculation of geostrophic winds from triangles of air pressure readings. This way, one (or possibly more) geostrophic wind-speed per day is obtained for given location. Subsequently, from the distribution of all numbers within a season or a year, high geostrophic wind-speed percentiles are derived that serve as a proxy index for storminess in that season or year. Long-term changes can then be studied from annual or seasonal proxy index time series. Figure 2 demonstrates that such a proxy indeed reflects the observed wind and storm conditions. It shows a comparison between percentiles derived from geostrophic wind speed estimates and local wind observations at five stations that have been known to be quite homogeneous for the 5-year period 1980-1984, A remarkably linear link is found that suggests that any change in local high wind speed percentiles would be reflected in changes of the geostrophic wind speed index and vice versa (Kaas et al. 1996). Thus, time series of the geostrophic wind percentiles can be considered as proxies for changing wind- and storm conditions change over time (Schmidt and von Storch, 1993; Alexandersson et al., 1998, 2000). Typically, 95- or 99-percentiles are used.

Alternatively, the annual frequency of days, when the geostrophic wind speed exceeds a certain threshold, say 25 m/s, are used

Two alternative proxies are based on local pressure observations, reflecting the experience that stormy weather is usually associated with low air pressure and a rapid fall of the barometer reading (Kaas et al., 1996). These proxies have the advantage that they are available for very long periods of time at some locations (Bärring and von Storch, 2004). The latter is essential to avoid misinterpretation of short-term fluctuations as representing long-term, trends. Changes in the statistics of the local proxies may be related to a change in the level of general storm activity or to a change of spatial patterns. Table 1 demonstrates that the different indices are mostly consistent among each other, with the exception of the number of deep pressure readings. The latter becomes intuitively clear, as low pressure alone is not necessarily sufficient for high wind conditions, but strong pressure gradients are required.

correlations	p_{95}	F_{25}	Δ_{16}	N_{980}
p_{99}	0.75	0.90	0.38	0.08
p_{95}		0.64	0.44	0.15
F_{25}			0.35	0.07
Δ_{16}				0.35

Table 1: Correlation coefficients between different proxies for storminess. p_{95} and p_{99} represent the 95- and the 99-percentile of seasonal geostrophic wind speeds, F_{25} the seasonal frequency of events with geostrophic wind speeds stronger than 25 m/s, Δ_{16} the seasonal frequency of air pressure tendencies of 16 hPa and more decrease within 24 hours, and N_{980} the frequency of barometer readings of 980 hPa and less. Data are from a case study for Denmark (reprinted from WASA 1998)

Other proxies for storminess may be derived from the variations of water levels at tide gauges as first suggested by John de Ronde (RIKZ). While local water level variations at tide gauges are often influenced by local construction works and by slow variations related to global mean sea level rise or geological phenomena such as land-subsidence or uplift, some pre-processing is required to derive proxy storm indices from tide gauge data. One option is to first determine annual mean high-water levels to subsequently consider variations of the high-water levels relative to this annual mean (Pfizenmayer, 1997; von Storch and Reichardt, 1997, Langenberg et al., 1999). Other options to determine storm proxies from tide gauge records are presented for example in Woodworth and Blackman (2002).

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) although the homogeneity of such sources has to be considered with care. Micro-seism intensity has been examined if they may serve as a proxy for regional storm activity (Essen et al., 1999; Grevemeyer, et al., 200) – even if the microseismic records contains signals related to wave activity and thus storminess, a homogeneous long-term record representative for a well-defined region can not be extracted.

With the proxies discussed above, an assessment of past storminess in Northern Europe and the Northeast North Atlantic appears possible. In the following we will describe, how storm activity has evolved in the area.

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

Serious efforts to study changing storminess over the Northeast 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 et al., 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 that have been 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) or Bromwich et al. (2006). Another example on the effect of better data coverage is provided by Landsea et al. (2004) for an example of a tropical storm.

A breakthrough came when most of the proxies defined in the previous section were introduced, mostly within 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-percentiles 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. The time series are shown in Figure 3. According to these proxies, the storm activity intensified indeed between 1960 and 1995[1], but from the beginning of the record until about1960 there was a long period of declining storminess (Alexandersson et al. 1998, 2000), and since about 1995 the trend is reversed in most areas of the Northeast Atlantic (Weisse et al., 2005).

A similar result is obtained when analyzing the record of high-water levels in Den Helder and Esbjerg, two harbours at the Dutch and Danish North Sea coast (Pfizenmayer, 1997). Figure 4 displays two statistics for each of the two tide gauges, namely annual mean high-water levels and the annual 99-percentiles of the deviations of the observed high-water levels from the annual mean. While the former, the annual mean, is influenced by a number of non-storm related processes such as local construction works, geological changes (land-subsistence) and global mean sea level rise, the upper percentiles of the deviations from this mean are expected to be more homogeneous and to better represent long-term storm related fluctuations (e.g. von Storch and Reichardt 1997). Both locations exhibit a marked increase in annual mean high-water levels, but the rate of increase is different at the two locations. The latter is likely related to different regional processes related to water works and the implementation of costal

[1] 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.

defence measures. The 99-percentiles of the deviations from the annual mean high-water reveals a somewhat different figure. Again, an increase is found for the period 1960 to the 1990s which is, however, not significant when compared to the development prior to 1960.

The 1960-1995 increase in NE Atlantic storminess also does not appear dramatic, when even longer time windows are considered. Bärring and von Storch (2004) analyzed homogenized local air pressure readings at two locations in Sweden, Lund and Stockholm, which have been recorded since the early 1800s and earlier. The number of deep pressure systems as well as the number of rapid pressure falls of 16 hPa and more within 12 hours (not shown) is remarkable stationary since the beginning of the barometer measurements. This is remarkably in view of the marked increase in regional temperatures, e.g., in Denmark (Cappelen, 2005). Using storm indices derived from tide-gauge data other authors reached similar conclusions. For instance, Woodworth and Blackman (2002) analyzed changes in extreme high-waters in Liverpool since 1768. Considering the entire period they found considerable inter-annual variability but no clear long-term trend. Bijl et al. (1999) considered sea level variations from a number of stations in the coastal zones of Northwest Europe over the past 100 years. Similarly they concluded that there is strong natural variability present in the data but no sign of a significant increase in storm related water levels.

3. How is storm climate variability linked to hemispheric temperature variations?

The link between decadal and centennial variations of mean temperature and storminess has hardly been studied because of the lack of sufficient data. Specifically, it has been argued that a general warming would be associated with elevated water vapour levels which in turn would be associated with stronger extra-tropical storms. Obviously, this argument is to first order symmetric, so that a general cooling would be associated with less storminess. The history of climate variability in the past centuries is a good frame to test such a hypothesis.

Climate models exposed to time-variable solar, volcanic and greenhouse gas forcing of the past centuries provide good data, to study historical co-variability of temperature and storminess. This was done by Fischer-Bruns et al. (2002, 2005), who counted for each model's grid box the annual frequency of gales in a simulation beginning in 1550 and extending to 2100 (using the IPCC A2 scenario for 2000-2100). They found no obvious link between the levels of storm activity and hemispheric mean temperatures for historical times (not shown). Only during the anthropogenic climate change in the 21st century a parallel development of storminess and temperature is simulated, which is associated mainly with a spatial displacement of the storm track to the Northeast and not a major intensification.

The lack of a link between hemispheric mean temperatures and the level of storminess during historical times is demonstrated by Figure 5, which shows the spatial patterns of the differences of temperature and of storm frequency (given as number of gale days per year and grid box) between the Late Maunder Minimum (1675-1710) and the pre-industrial period of the simulation (1550-1850). The Late Maunder Minimum was the coldest period of the Little Ice Age, at least in Europe, and the model simulation indicates that this cooling was of almost global extent, affecting all of the Northern Hemisphere. This period was, at least in the model, not associated with a reduced level of storminess in the North Atlantic or in the North Pacific.

Thus, neither the admittedly very limited empirical evidence discussed in the previous section nor the modelling study by Fischer-Bruns et al. (2002, 2005) support the hypothesis that a general warming would lead, plausibly via increased availability of humidity, to a roughened storm climate.

The parallel development of changes in storminess and temperature in scenario simulations is likely related not to the general increase in temperature but to changes of temperature gradients.

4. How did impact of windstorms on North Sea storm surges and ocean waves developed 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 the risk of wind-related damages is the insurance industry (Berz, 1993; Berz and Conrad, 1994)[2]. Other relevant aspects are related to ocean waves and storm surges, and their impact on offshore activities, shipping, and coastal protection 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 50 years, and data during that period are good enough to examine the changes of storm surge and ocean wave statistics in more detail.

The availability of good weather analyses – on the global basis for instance the NCEP re-analyses (Kalnay et al., 1996; Kistler et al. 2001) and, for the European region, dynamical downscaling of this reanalysis (Feser et al. 2001) – allows 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 past 50, or so, years, can be constructed (Weisse and Plüß, 2006). 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., 2006; Woth, 2005, Lowe and Gregory, 2001, 2005).

Along these lines, the downscaled NCEP reanalyses (Feser et al. 2001) have been used to examine changes in the 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 6). 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, storm surge simulations of reveal an increase of high-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, 2006, Aspelien, 2006), in particular along the German Bight coast line.

[2] 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.

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 Guenther, 2006). 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 provided by 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). A similar result was found by Pryor et al. (2006) who empirically downscaled climate change scenarios from ten coupled global climate models and found changes in the mean and 90-percentile wind speeds to be small (less than about 15%) for Northern Europe.

These changes of wind speed will have an effect on both North Sea storm surges and wave conditions. For the storm surges along the North Sea coastline, an intensification is expected, which may amount to an increase of 20-30 cm, or so, to the end of the century (Figure 7a). 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., 2006).

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 (Grabemann and Weisse, in prep., Fig 7b).

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Fig 1:

(a) Number of days per years with wind speeds of 7 Beaufort and more in Hamburg. (after Schmidt, pers. communication).

(b) Frequency of stormy days per year (wind speed ≥21 m/s) in Kullaberg, south-western Sweden (after Pruszak and Zawadzka 2005).

(c) Annual mean wind speed anomalies in the North Pacific in the area of ocean weather station OWS P. Data from the ocean weather station are marked as "OWS" (ocean weather ship) and those from the ships of opportunity in the vicinity of OWS as "COADS" (after Isemer, pers. communication).

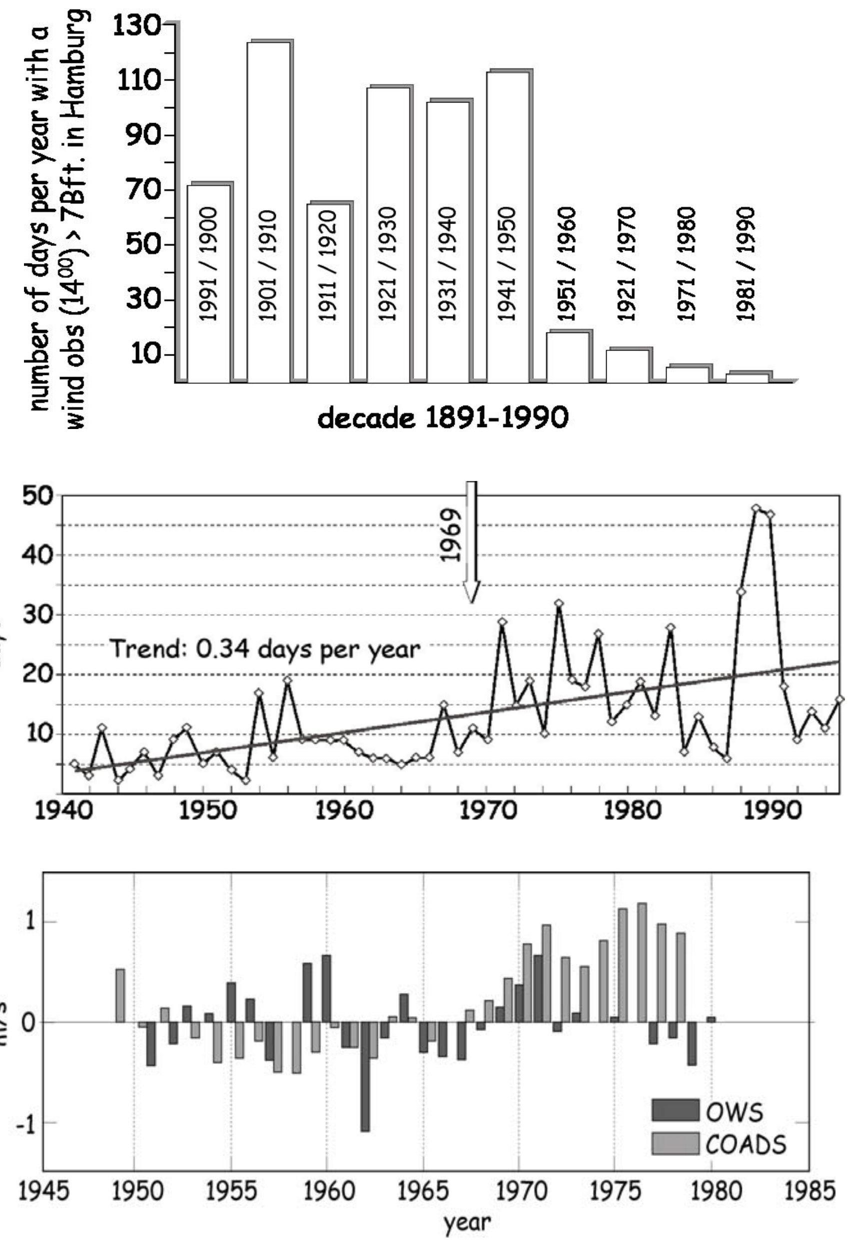

Fig 2 – Percentile-percentile plot of observed daily near-surface wind speeds averaged over five synoptic stations for which homogeneous wind measurements have been available for 1980-1984 and geostrophic wind speeds derived from station pressure data (after Kaas et al. 1996)

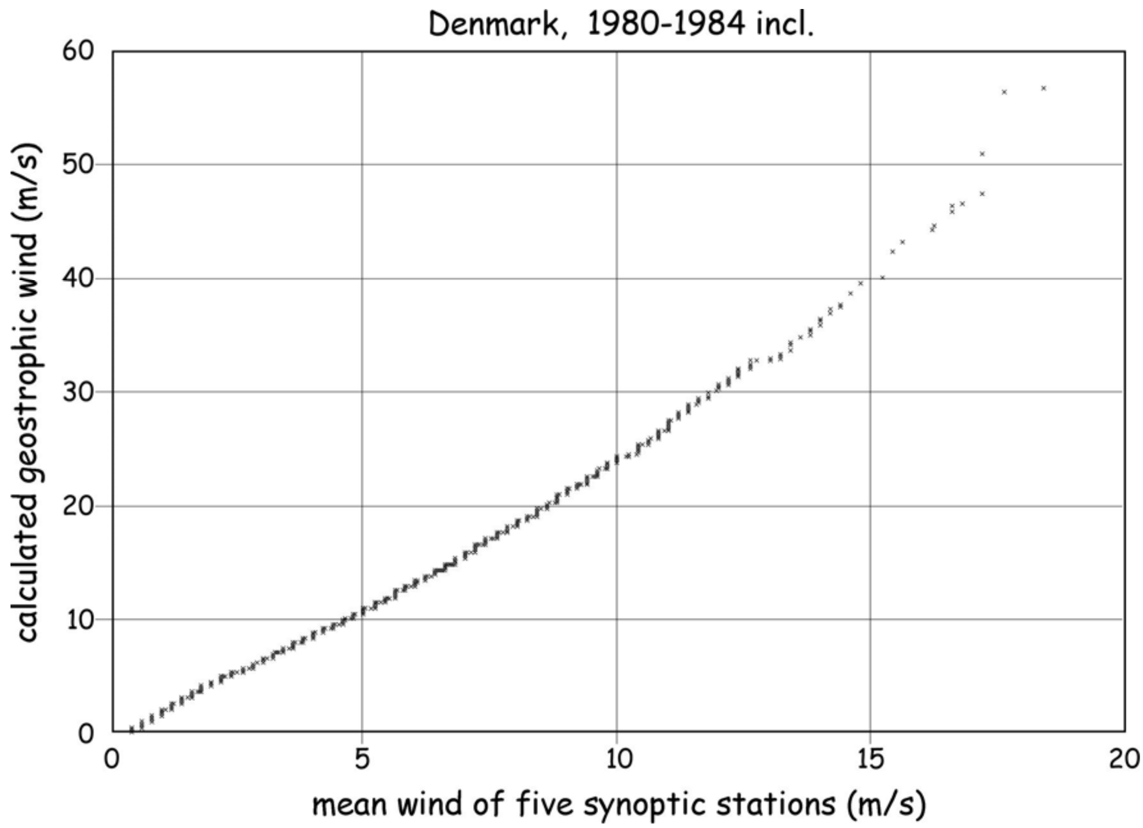

Fig 3 – Proxy index of Storm activity derived from intra-annual percentiles of geostrophic wind speeds derived from air pressure measurements at a series of triangles of stations for the greater North Sea region (top) and the greater Baltic Sea region (bottom). The index time series were normalized and are thus dimensionless. Updated version of diagram provided by Alexandersson et al. (2000).

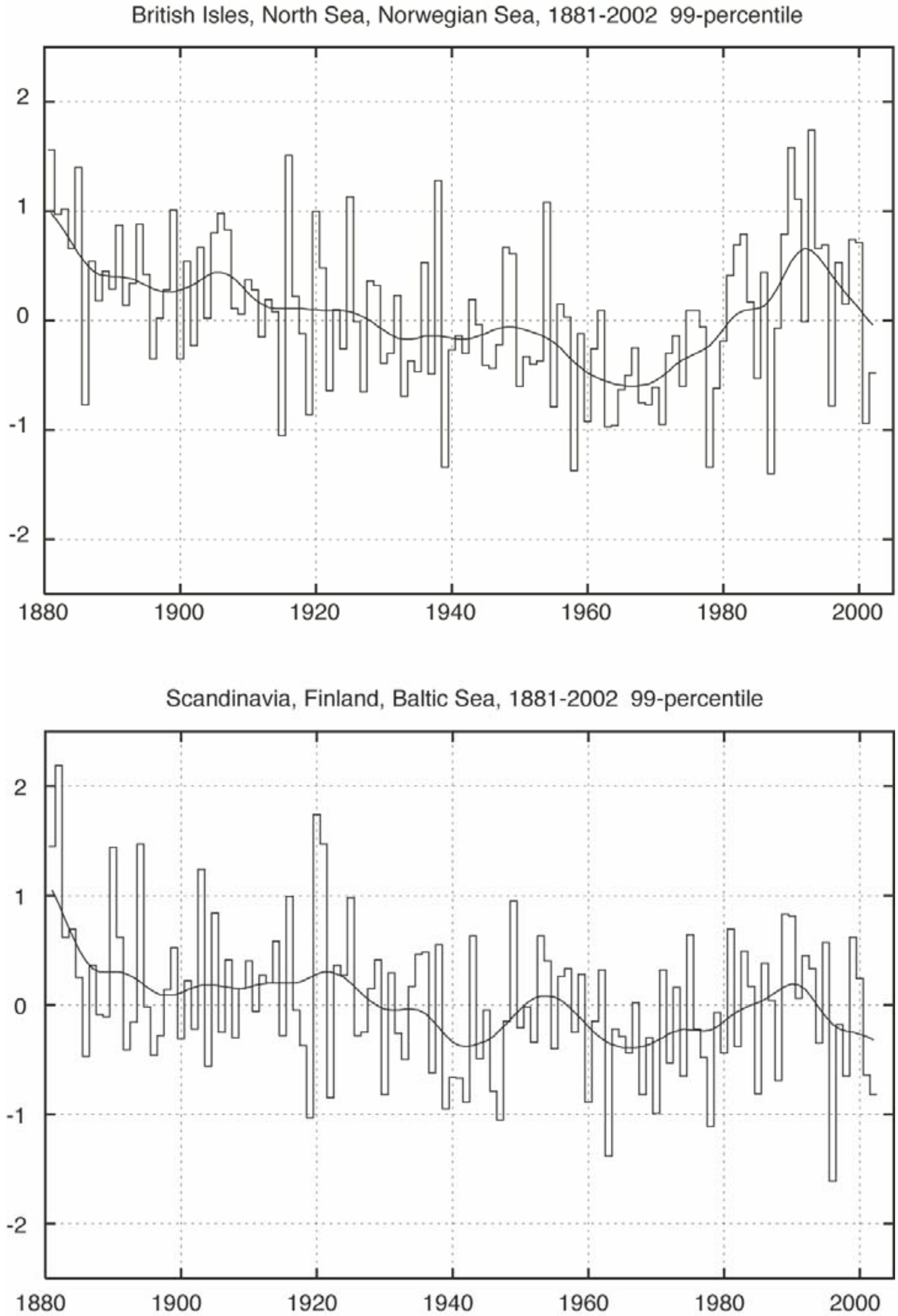

Figure 4: Intra-annual statistics of high-water levels at Esbjerg (Denmark) and Den Helder (The Netherlands) since the late 19th century. The lower two curves display the annual mean high-water, the upper two curves represent annual 99-percentiles of the variatons around the annual mean (after Pfizenmayer 1997).

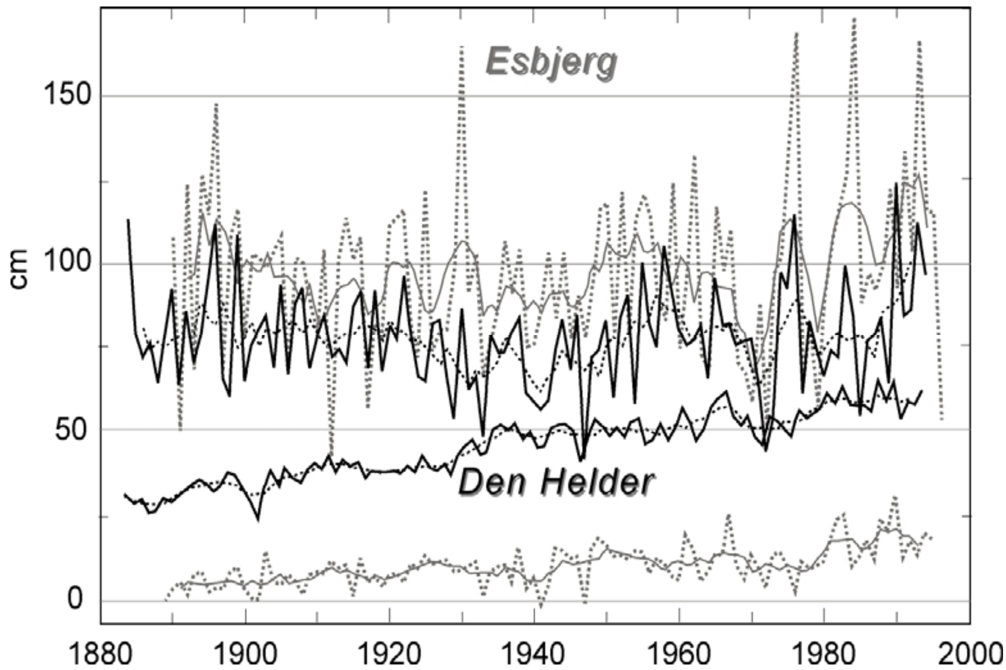

Figure 5 – Simulated differences in winter between the "Late Maunder Minimum" (LMM, 1675-1710) and the pre-industrial time (1550-1800) – in terms of air temperature (top, K) and in terms of number of gale days (wind speeds of 8 Beaufort and more). Note that the LMM is portrayed by the model as particularly cold, but the storm activity shows little changes. Courtesy: Irene Fischer-Bruns.

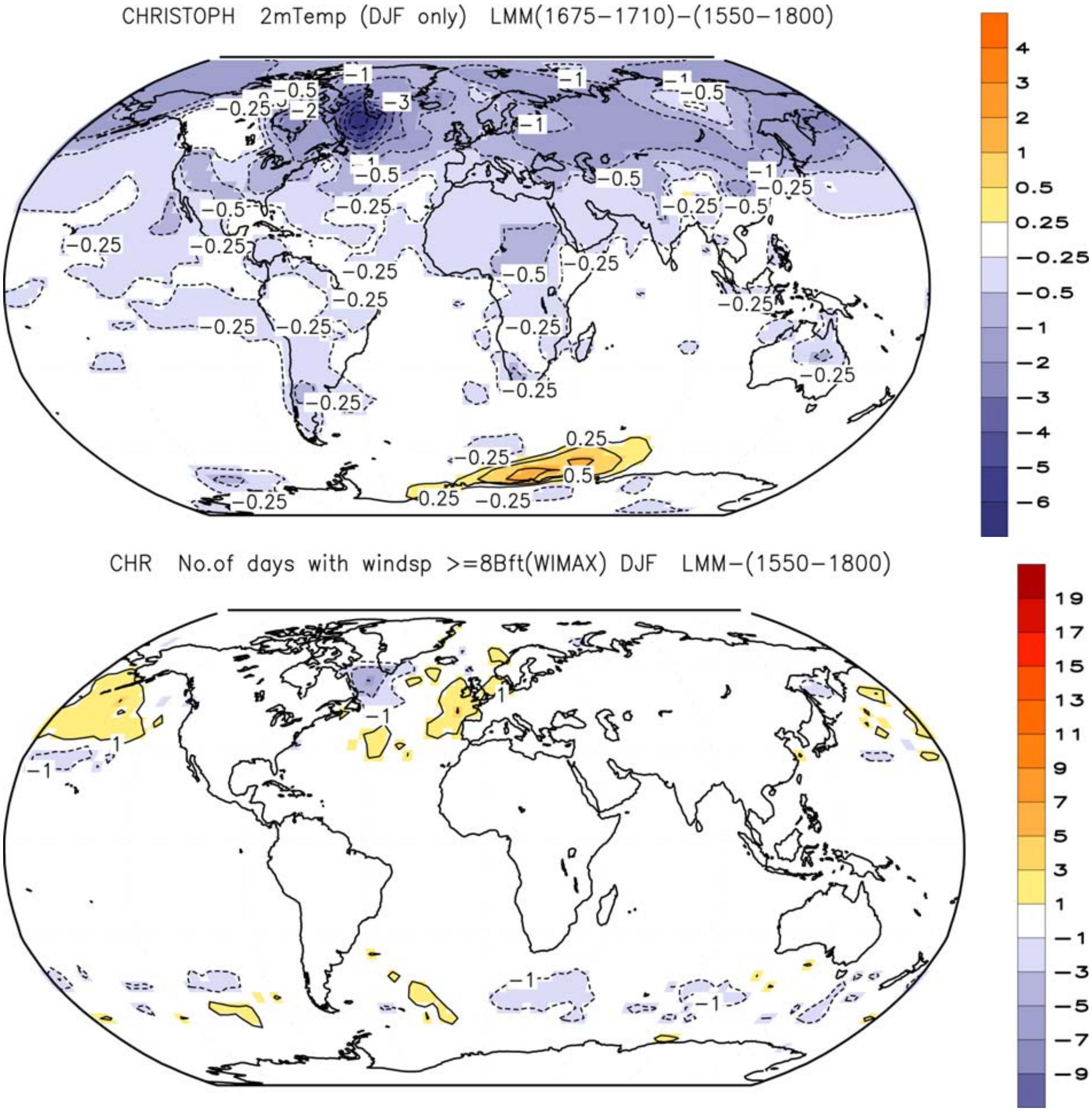

Figure 6: Piecewise linear trends prior and after a change point T in the total number of storms per year with maximum wind speeds exceeding 17.2 m/s. Both the trends as well as the change point are determined by a best fit to the data time series. (a) trends for the first period 1958–T; (b) trends for the second period T–2002. 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 for the entire period. After Weisse et al. (2005)

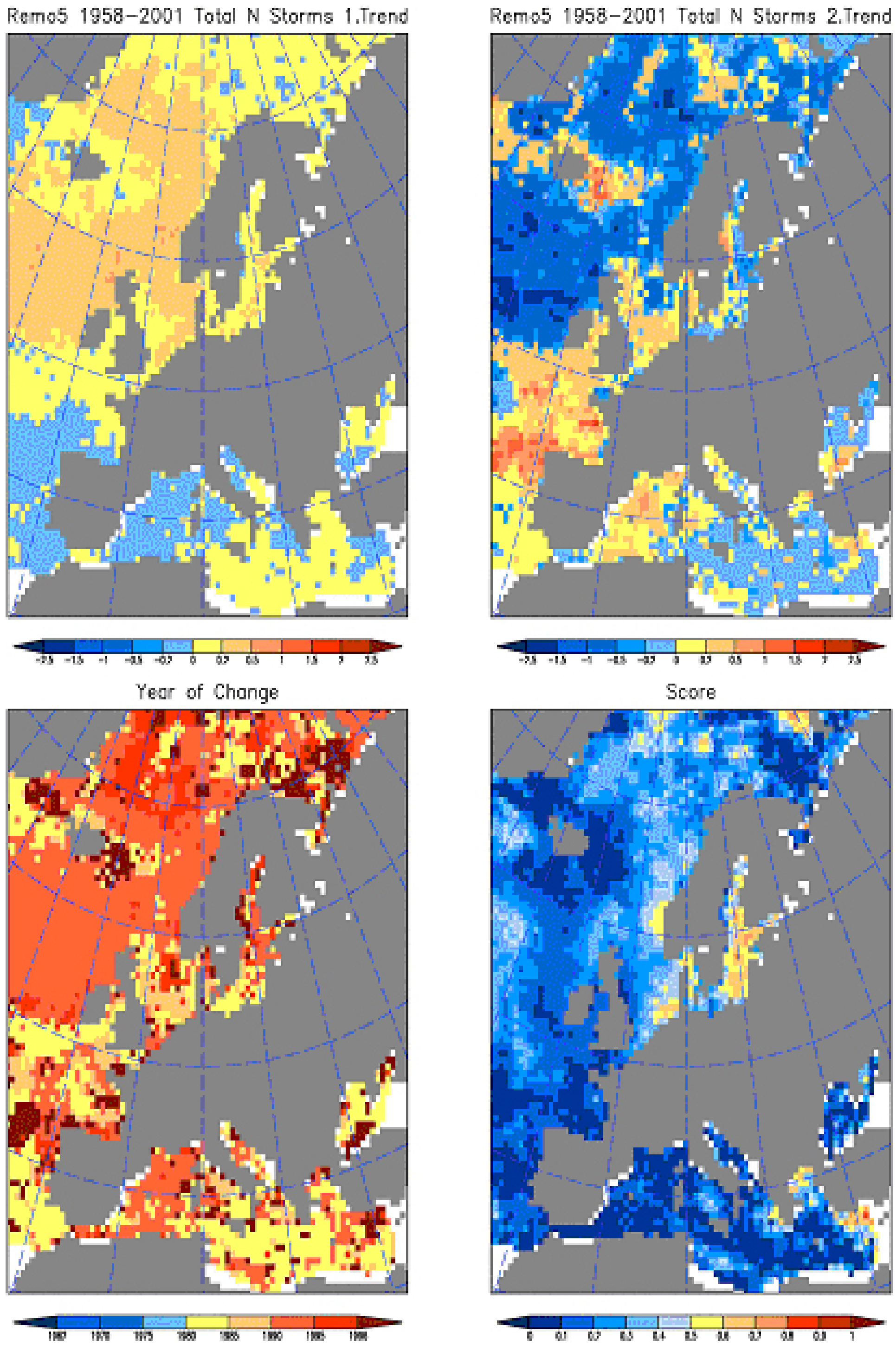

Figure 7: Expected changes in wind-related storm surge heights (top; maximum averaged across many years, RCAO model, emission scenario A2) and ocean wave heights (bottom, change of 99-percentile; averaged across a series of simulations using different models and both emission scenarios A2 and B2. Shading indicates areas where signals from all models and scenarios have the same sign; red-positive, blue-negative.) in the North Sea at the end of the 21st century.. Units: m. Courtesy Katja Woth and Iris Grabemann.