Regional storm climate and related marine hazards in the NE Atlantic

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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, houses and other constructions may be damaged; also trees may break in larger numbers in forests. In the 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 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 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 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.
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 considered region (NE Atlantic, N 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.
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. This hypothesis is 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 2100 assuming scenarios for future greenhouse gas emissions. It turns out that during preindustrial 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 greenhouse gas concentrations strongly increased, a parallel development of NE Atlantic storm intensity and hemispheric temperature emerged.
4. ***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 of the Southern North Sea, where the upward trend is still going on. Scenarios prepared by 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 2030 and of 50 cm in 2085 along the German Bight coast line are reasonable guesses for future conditions.

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).

For instance, pressure readings usually depend not very much on the specifics of the location (apart of 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 exposition and obstacles. Also instruments and observation practices have changed frequently. This is in particular so with wind observations and wind estimates over sea.

Figure 1 displays a series of examples:

(a) shows the frequency of strong wind events in the city of Hamburg (Germany) per decade of years. Obviously a very strong decline took place from the 1940s to the 1950s – the explanation is that the instrument was moved from the harbor to the airport. This is a very obvious examples; the second example has been mistaken for evidence of a worsening storm climate in Northern Europe.

(b) displays the frequency of recorded stormy days (with wind speed ≥21 m/s) in Kullaberg (south-western Sweden; after Pruszak and Zawadzka (2005). Seemingly, in later years the number of such events was considerably more frequent than in earlier years. A closer inspection of the record reveals 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 later see that proxies of storminess indicate no such change in that area.

(c) is an example with marine winds from the Pacific. There, the stationary weather station (ship) P is located that is taking quality controlled wind observations. From the COADS data set, many other wind reports are available from ship (of opportunity) observations originating from a series of grid boxes surrounding the position of the weather station. However, when the ship observations are averaged for each year, and compared to the quality controlled data form the ocean weather station, a discrepancy emerges – the ship data indicate an upward trend, while station P reports variable but by and large stationary conditions. Obviously, the COADS data are not homogeneous.

Thus, direct observations of wind are almost never helpful to assess changes in windiness for decades of years. As an alternative, a number of proxies representative for 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, but also the frequency of low pressure occurrences.

(a) Schmidt and von Storch (1993) have suggested the calculation of geostrophic winds form 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 (Kaas et al., 1996). Thus, time series of the geostrophic wind percentiles are considered as proxies of wind- and storm conditions change in the course of time (Schmidt and von Storch, 1993; Alexandersson et al., 19998, 2000). Typically used percentiles are 95% or 99%.

(b) 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.

(c) 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).

(d) 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 (Pfizenmayer, 1997; 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, with the exception of the number of deep pressure readings as the following table of correlation coefficients demonstrates (95% and 99% stand for the 95%ile and the 99%ile of seasonal geostrophic wind; $\#F_{25}$ for the seasonal frequency of events with geostrophic winds stronger than 25 m/s, $\#|\Delta_p|$ for the seasonal frequency of a pressure fall of 16 hPa within 24 hours, and $\#p<980$ hPa for the frequency of barometer readings of less than 980 hPa)

correlations	**95%**	**$\#F_{25}$**	**$\#\|\Delta_p\|$**	**$\#p<980$ hPa**
99%	0.75	0.90	0.38	0.08
95%		0.64	0.44	0.15
$\#F_{25}$			0.35	0.07
$\#\|\Delta_p\|$				0.35

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 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 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. The time series are shown in Figure 3. According to this proxy, 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, and since about 1995 the trend is in most areas of the NE Atlantic reversed (Weisse et al., 2005).

A similar result is obtained when analyzing the record of high water tides 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, the annual man high tide and the annual 99%iles of the deviations of the high tide form the annual mean. The former, the annual mean, is influenced by a number of non-storm related processes, in particular water works, geological changes (land sinking) and global man sea level rise. Both locations exhibit a marked increase in mean high tide, but the rate of increase is different at the two locations, which is likely related to different regional processes related to water works and costal defence measures. The two other curves in Figure 4 display the temporal development of the 99%iles (after subtraction of the annual mean); 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 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 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 in view of the marked increase in regional temperatures, e.g., the winter mean temperatures for Denmark.

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. However, climate models exposed to variable solar, volcanic and greenhouse gas forcing provide good data, to study such links. 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 hemispheric mean temperatures for historical times (not shown); only during the anthropogenic climate change in the 21st century a

[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.

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 of mean temperatures and the level of storminess during historical times is demonstrated by Figure 5, which shows the spatial pattern of the difference of temperature and of storm frequency (given as number of gales per year and grid box) during the Late Maunder Minimum (1675-1710) and the pre-industrial period of the simulation (1550-1850). The Late Maunder Minimum was a 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 via increased availability of humidity to a roughened storm climate.

4. 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 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 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 50 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 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 and Gregory, 2001, 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 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, 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.

[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.

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, in prep.). 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).

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 coast line, an intensification is expected, which may amount to an increase of 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 (Weisse und Grabemann, in prep., Fig 7b).

Acknowledgements

We are grateful to the help provided by Drs. Fischer-Bruns, Iris Grabemann and to Beate Gardeike.

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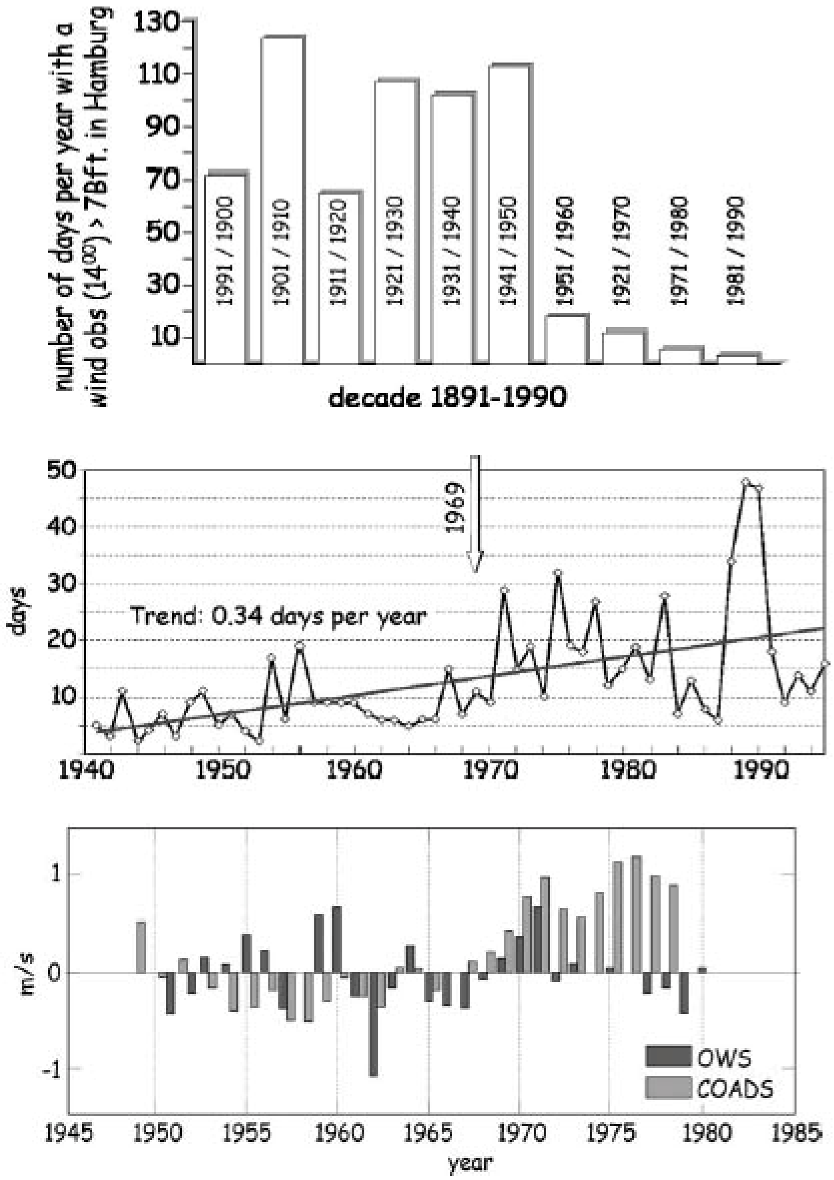

Fig. 1

(a) Reported number of days per years with wind speed of 7 Bft and more in Hamburg. In the early 1950s the observation was moved form the harbour to the airport. (After Schmidt, pers. communication).

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

(c) Estimated changes in mean wind speed 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)

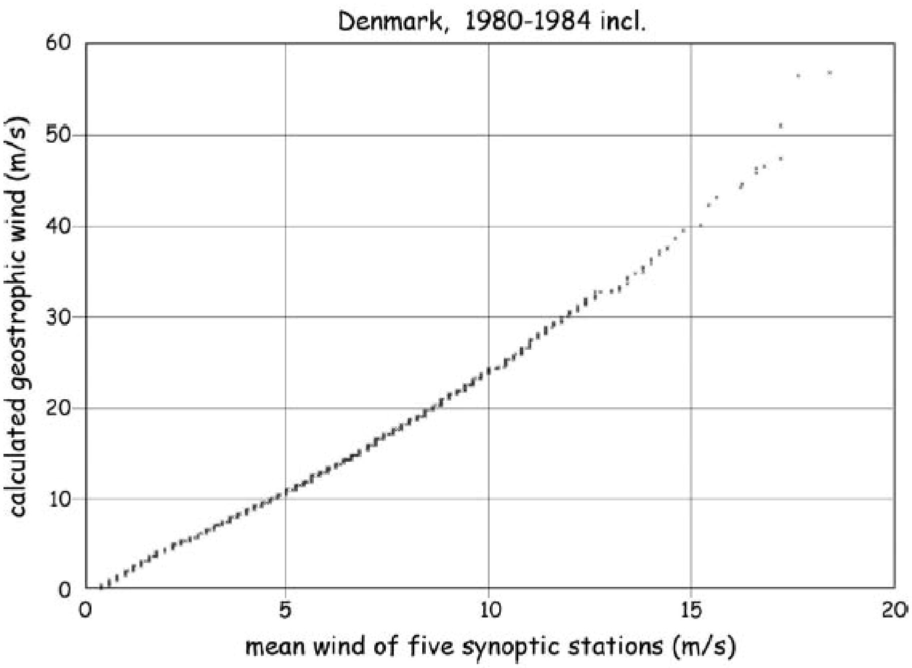

Fig. 2 Percentile-percentile plot of daily wind speed and geostrophic wind speeds at oen location derived form 5 years of data. (Kaas et al., 1996)

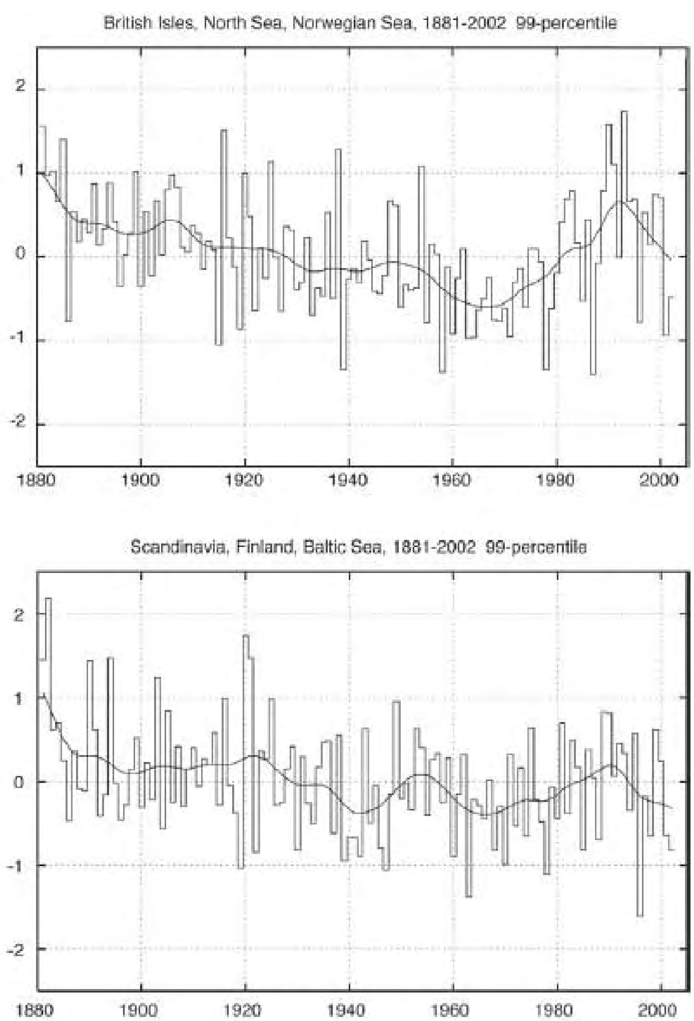

Fig. 3 Storm indicator derived from intra-annual percentiles of geostrophic winds derived form a series of triangles of stations for the greater North Sea (top) and the greater Baltic Sea region (bottom). Updated version of diagram provided by Alexandersson (2000).

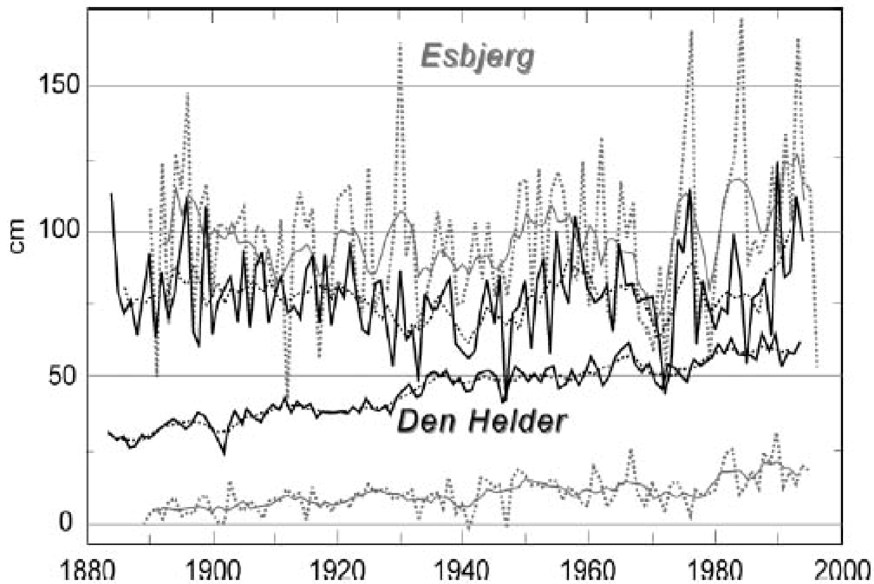

Fig. 4 Changing intraseasonal statistics of high tide water levels at Esbjerg (Denmark) and Den Helder (The Netherlands) since the late 19th century. The lower two curves display the seasonal means, and the upper two curves the 99%iles of intraseasonal variatons relative to the seasonal mean. The former reflect the presence of all kind of climatic as well as local effects, while the latter is a proxy for regional storm activity. After Pfizenmayer (1997).

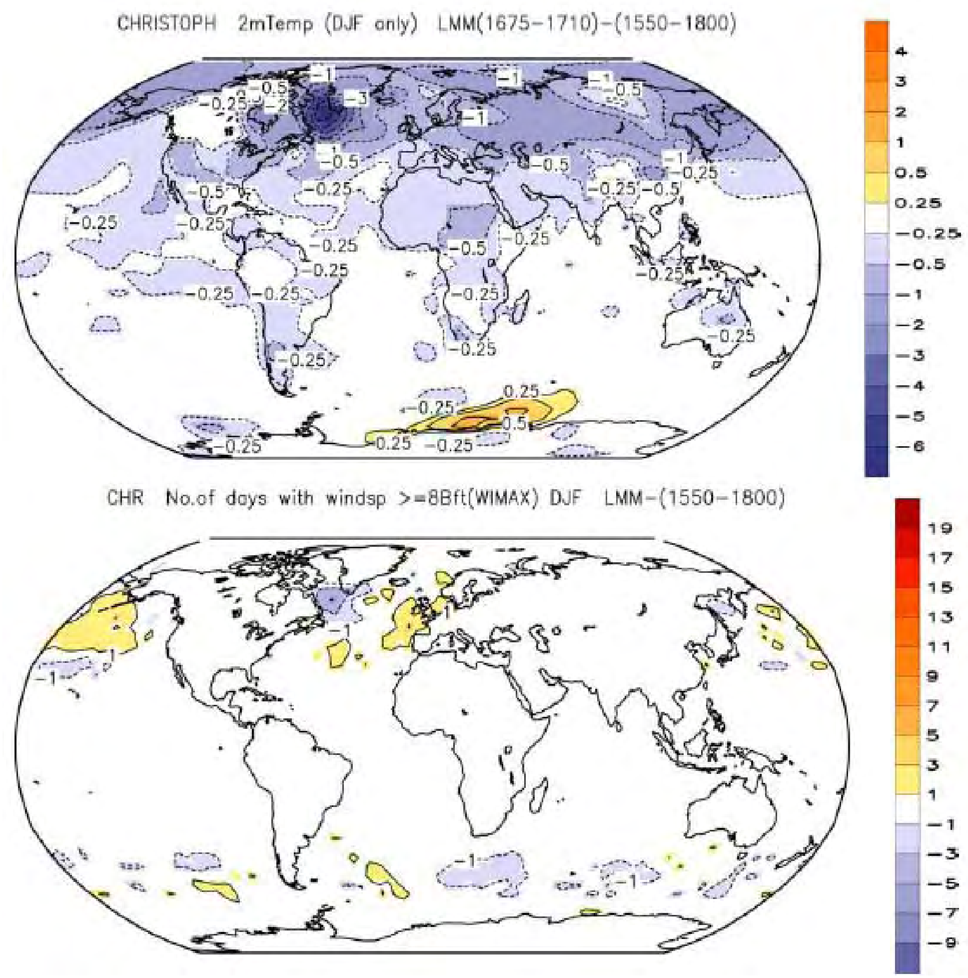

Fig. 5 Simulated differences in winter between the "Late Maunder Minimum" (LMM, 1675-1710) and the pre-industrial time (1550-1800) – in terms of air temperature (top, K) and in terms of number of gale days (wind speed 8 Bft and more). Note that the LMM is portrayed by the model as particularly cold,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

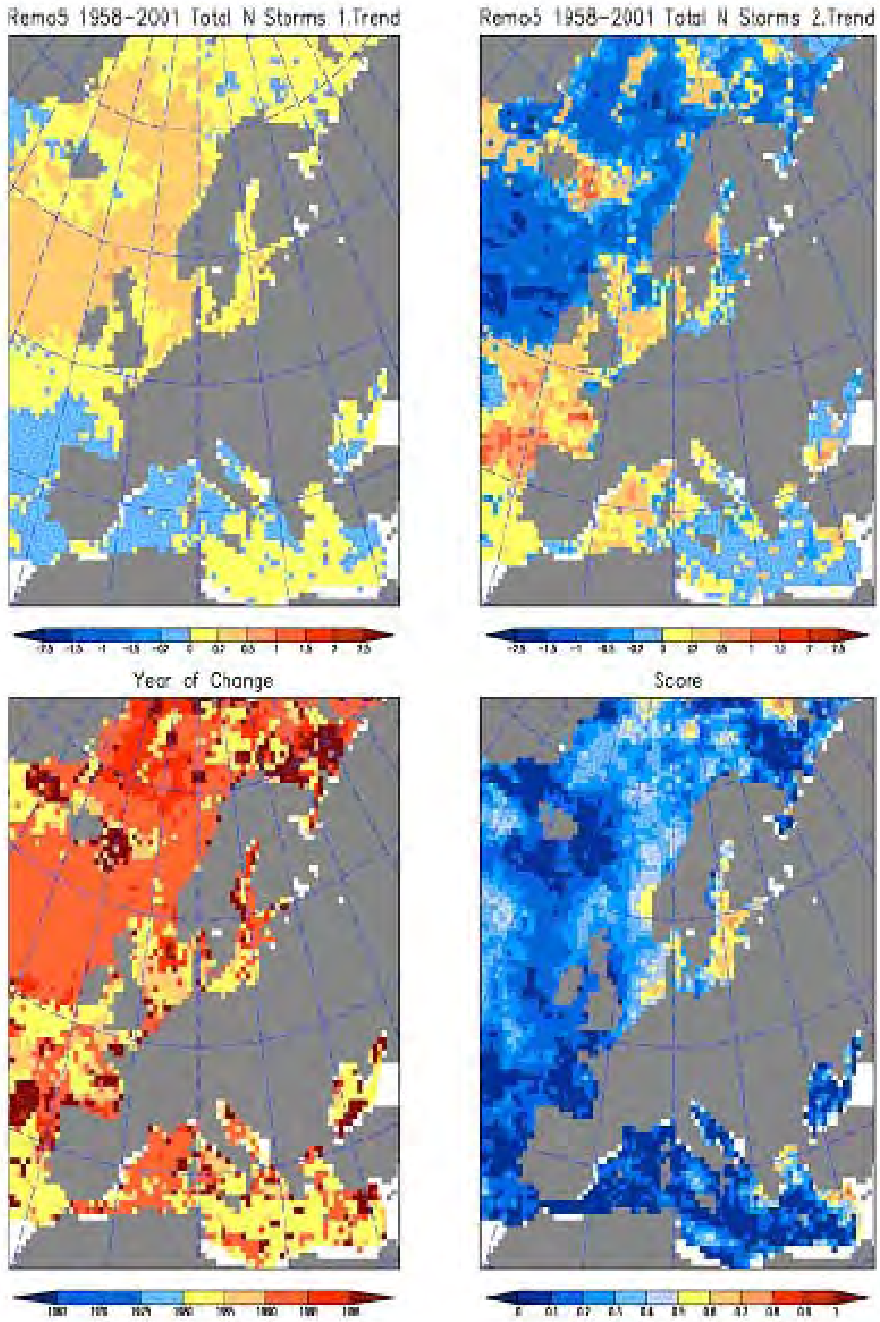

Fig. 6 Piecewise linear trends in the total number of storms per year with maximum wind speeds exceeding 17.2 m s1. (a) Linear trend for the 1958–T period; (b) linear trend for the T–2001 period. Units in both cases are number of storms per year. (c) Year T at which a change in trends is indicated by 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)

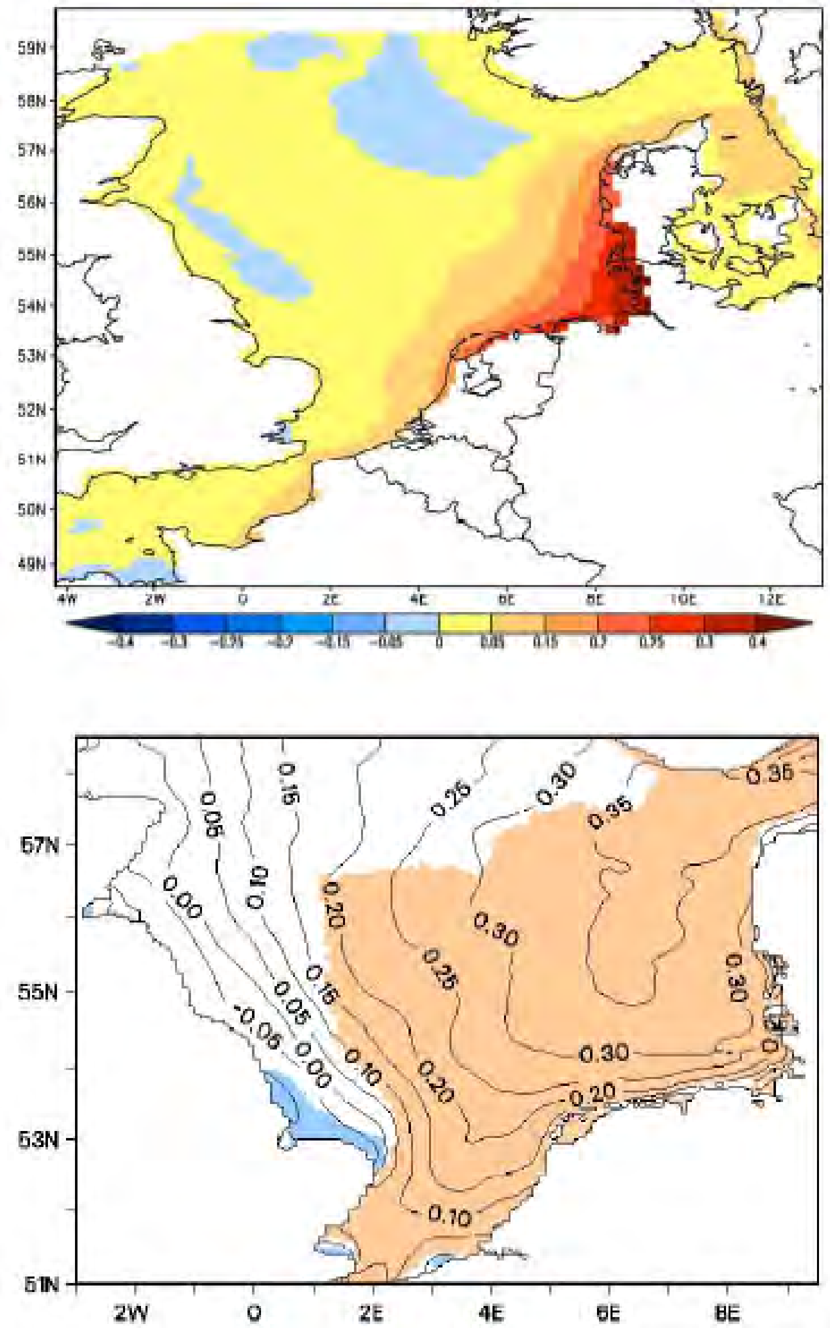

Fig. 7 Expected changes in wind-related storm surge heights (top; maximum averaged across many years, RCAO model) and ocean wave heights (bottom¸ change of 99-percentile; averaged across a series of simulations using different models and both emission scenarios A2 and B2. Shading indicates areas where 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 (emission scenario A2). Units: m. Courtesy Katja Woth and Iris Grabemann.