Storminess over the North Atlantic and Northwestern Europe - A Review

by F. Feser, M. Barcikowska, O. Krueger, F. Schenk, R. Weisse, L. Xia

Abstract

This review assesses storm studies over the North Atlantic and Northwestern Europe regarding the occurrence of potential long-term trends. Based on a systematic review of available articles, trends are classified according to different geographical regions, data sets, and time periods. Articles that used measurement and proxy data, reanalyses, regional and global climate model data on past and future trends are evaluated for changes in storm climate. The most important result is that trends in storm activity depend critically on the time period analysed. An increase in storm numbers is evident for the reanalyses period for the most recent decades, whereas most long-term studies show merely decadal variability for the last 100-150 years.

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/pi.2364

Storm trends derived from reanalyses data and climate model data for the past are mostly limited to the last four to six decades. The majority of these studies find increasing storm activity north of about 55-60°N over the North Atlantic with a negative tendency southward. This increase from about the 1970s until the mid-1990s is also mirrored by long-term proxies and the North Atlantic Oscillation and constitutes a part of their decadal variability. Studies based on proxy and measurement data or model studies over the North Atlantic for the past which cover more than 100 years show large decadal variations and either no trend or a decrease in storm numbers. Future scenarios until about the year 2100 indicate mostly an increase in winter storm intensity over the North Atlantic and Western Europe. However, future trends in total storm numbers are quite heterogeneous and depend on the model generation used.

1. Introduction

Storms over the North Atlantic (NA) and Northwestern Europe (NWE) have a large impact on population, shipping and offshore industries, forestry and agriculture as well as on buildings and property. The most severe storms in this area occur in winter time and may lead to high waves and storm surges. At higher atmospheric levels close to the tropopause the polar jet stream develops between cold polar air masses and warm air from the subtropics with strong westerly winds. This wind band is not a straight line, but is often deviated due to the land-sea contrast and takes a meandering path, the Rossby waves form. Within these atmospheric waves low pressure (over the wave troughs) and high pressure systems (below the wave crests) evolve, e. g. the Icelandic Low and Azores High. Storms originate in intense low pressure systems with large temperature and pressure gradients along the Rossby waves.

Storms are characterized by strong pressure gradients, high wind speeds, and they may be accompanied by heavy precipitation, hail, thunder, and lightning. A storm with strong wind speeds as a result of strong pressure gradients is defined as wind storm; storminess is used in this article as the state of being stormy. Storminess may be expressed either by direct measures like wind speed or sea level pressure or by indirect measures, for instance storm-related sea level variations or storm losses. The path of a storm over time is called storm track; but this term may also describe track clusters of low pressure systems in certain geographical regions. One of them is located over the North Atlantic, here extratropical cyclones travel with the Rossby waves eastward along the polar jet stream. The storm tracks are subject to many external factors, like land-sea contrasts, near-surface temperatures, atmospheric waves and large-scale weather patterns, or topography.

Usually storm intensity is defined by wind speed at a height of 10 m. Measurements often use a 10 min mean value while gusts characterize maximum values on very short, almost instantaneous time scales. The Beaufort (Bft) scale is used to classify observed wind strength. Gales are defined as Bft 8 (17.2 - 20.7 m s^{-1}) and storms as Bft 10 (24.5 - 28.4 m s^{-1}) and larger. But wind measurements may be inhomogeneous due to, for instance, station relocations, instrumental changes, different environmental influences, or changes in measurement routines or frequencies. These inhomogeneities can lead to artificial trends or jumps in the time series. Mean wind speed over the oceans in measurements, reanalyses, and satellite data show differences which depend on atmospheric stability and ocean currents (Kent et al. 2012). Nevertheless, some studies use wind speed directly to determine changes in storm frequency and intensity (see Table 1) for the last 30-60 years (e.g. Smits et al. (2005) for the Netherlands since 1962; Earl et al. (2012) for the UK since 1980) or on longer timescales (e. g. Esteves et al. 2011; Ciavola et al. 2011; Franzén 1991; Schiesser et al. 1997; Sweeney 2000; Usbeck et al. 2010). A way to minimize these inhomogeneities is to use mean sea level pressure (MSLP) measurements. Geostrophic wind speed can then be derived from MSLP as a proxy[1] for near-surface wind speed (Alexandersson et al. 2000; Bakker and van den Hurk 2012; Krueger and von Storch 2011; Schmidt and von Storch 1993; Wang et al. 2009, 2011). This proxy is less prone to changes in the measurement technique, the station location or to differences in the vicinity of stations and therefore more reliable. It works best for smooth topographic areas. But it should be remembered that the geostrophic wind does not represent the full wind vector as the ageostrophic component may be large under stormy and strongly transient conditions.

Satellite-based observations became a new source of wind speed products since the 1980s. Blended SeaWinds provided by the National Oceanic and Atmospheric Administration's National Climatic Data Center (www.ncdc.noaa.gov/oa/rsad/seawinds.html) and Near Real Time Blended Surface Winds from the French ERS Processing and Archiving Facility of the French Research Institute for Exploitation of the Sea (www.ifremer.fr/cersat/en/index.htm) blend sea surface wind speed data retrieved from microwave signals, to a global 0.25° grid in 6 hourly time steps. But the quality of these products depends on the accuracy of the input data and sampling scheme of the observations, which is strongly skewed towards the late 1990s. Moreover, microwave signal observations are sensitive to rain conditions occurring often during high winds, which limit the accuracy of storm wind speed estimations. Finally, relatively short periods of availability constrain the feasibility of long-term trend analyses. .

Storms are also affected by large-scale weather patterns and atmospheric oscillations. One of them is the North Atlantic Oscillation (NAO), which describes the pressure variability between the Icelandic Low and Azores High. It is the dominant mode of lower to mid-

[1] The term proxy is used in this article in its Latin meaning as a surrogate of a meteorological variable for another variable, independent of the variable’s quality.

Accepted Article

tropospheric pressure variability over the North Atlantic and has a large influence on the generation of storms (e. g. Wanner et al. 2001; Pinto and Raible 2012). For a high NAO index (NAO+), which often occurs in winter, pressure differences increase and so does the frequency of low pressure systems. The low pressure's frontal system and associated large temperature and pressure gradients (baroclinic activity) may lead to increased storm genesis. An increased zonal flow with on average higher wind speeds and more pronounced storm seasons over central to northern Europe can be observed. A weak pressure gradient (NAO-) leads to below average winds and a displacement of low pressure systems towards the Mediterranean Sea. As can be seen in Fig. 3, the NAO-index for boreal winter (DJFM) since 1823/24 is characterized by large inter-annual to multi-decadal variations. Strong positive phases dominated during the 1910s, 1930s and 1980-90s with strong negative phases during the 1960-70s and in recent years. The NAO explains about one third of winter storm variations although the link is not stationary over time (e. g. Matulla et al. 2007) with strong correlations in recent decades (Alexander et al. 2005) and a rather weak link back in time (Alexandersson et al. 1998). Although a positive NAO index leads to more frequent and intense storms, severe storms can also occur during negative phases (Pinto et al. 2009b).

Numerous studies on storms over the NA and NWE exist. There already are some review articles on storms: Keim et al. (2004) assembled literature for both tropical and extratropical coastal storms over the NA for the last decades. A more general review article on extratropical storms for both hemispheres was presented by Ulbrich et al. (2009). Bader et al. (2011) reviewed storm activity over the NA with a focus on sea ice; Albrecht et al. (2009) with a focus on effects for forestry. The most recent storm results are summarized in the IPCC (Intergovernmental Panel on Climate Change) special report: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX, Field et al.

2012). For further readings on storm surges we refer to Weisse et al. (2012). This article is intended to give a systematic evaluation and most recent update on storm variability and trends over the NA and NWE. Current literature on the past and future storm climate of the NA and NWE derived from measurement or proxy data, reanalyses, regional or global climate model data was analysed. Thereby the storm trend table of Albrecht et al. (2009) was largely extended, articles were sorted according to their study areas and input data, and the most recent studies were added. The key question is whether there are changes in storm climate, both for the past decades or centuries and for future scenarios. The available literature was analysed for storm frequency trends, minima or maxima within these trends, changes in cyclone numbers or intensities, and whether a shift in the storm tracks was detected.

In the next chapter we review the most commonly used methods for storm analysis and then present the data used for the past and future in chapter 3. Chapter 4 gives storm trends for the last decades up to the last centuries, for proxy and measurement data as well as for climate models and reanalyses. In chapter 5 we will assemble results for future scenario simulations, for regional and global climate models and for global coupled atmosphere-ocean models. Chapter 6 analyses possible shifts in the storm tracks. In the summary and conclusions section the main results are recapitulated.

2. Methods for analysing variations in storm activity

Storms may be examined by using the Eulerian approach (e. g. analysing extremes in wind speed or pressure distributions) or by applying Lagrangian approaches like tracking algorithms to extract cyclones in near-surface atmospheric fields. Of course the storms detected by the Lagrangian approach may later also be analysed with Eulerian techniques like

e. g. percentiles, extreme value analysis or peak over threshold methods.

2.1 Eulerian approach

In principle, there are two ways of looking at a flow field, the Eulerien and the Lagrangian approach. The entire flow field visualized at a certain instant is described by the Eulerian approach. Here, the main attention is put on specific locations through which the fluid flows over time. To derive extremes with this approach, block extremes or peak over threshold statistics can be computed (Visser and Petersen 2012). Block extremes are obtained by taking the most extreme values in a block of measurements, like a season or year. This could be, for example, the winter maximum of near-surface wind speed. Another block value may be a high percentile, like the 95th or 99th percentile. Further storm measures include lower percentiles of pressure, mean values of absolute pressure tendencies, storm frequencies, duration or intensity.

For the peak over threshold method a certain threshold can be defined which marks, for instance, the number of storm days per year. Now all points are sampled that exceed this predefined threshold. Then a suitable probability function needs to be identified which represents the distribution of the observed extremes (von Storch and Zwiers 1999). Usually the generalized Pareto distribution, that describes the behavior of extreme values above a defined threshold (Coles 2001), is suited for this purpose. The chosen extreme value distribution has to be fitted to the sampled extreme values. There are several methods for fitting, such as the methods of moments, the method of maximum-likelihood, the method of probability weighted moments, or the method of L-moments (Coles 2001). Afterwards return values can be estimated for certain time periods, which represent particular thresholds. These thresholds are exceeded, on long-term average, once per return period (von Storch and

Zwiers 1999). Typical storm measures are annual or seasonal frequencies of absolute pressure tendencies or the number of deep lows exceeding certain thresholds. Under the Eulerian approach storm information may also be derived by calculating the variance or covariance of filtered MSLP or geopotential height fields on synoptic time scales (about 2.5-8 days, Blackmon 1976; Ulbrich et al. 2008; Woollings et al. 2012), which leads to information on intensities and frequencies of cyclone activity.

2.2. Lagrangian approach

The Lagrangian approach follows the path line of a single particle trough space and time. For storm detection this approach is known as tracking. It provides an effective way to study spatial and temporal variability of both tropical and extratropical cyclones (Ulbrich et al. 2009; Neu et al. 2013 and references therein). Automatic tracking algorithms allow for the analysis of long-term cyclone trends, cyclone formation and decay, travelling speeds, lifetime and cyclone intensities.

Usually automatic Lagrangian tracking methods contain three parts: pre-processing, detection and tracking. First, often spatial filters are applied to remove large-scale weather systems or small-scale noise (Hoskins and Hodges 2002; Zahn and von Storch 2008; Xia et al. 2012). Different fields are chosen to track storms, e. g. MSLP fields (Geng and Sugi 2001; Gulev et al. 2001; Hoskins and Hodges 2002; Muskulus and Jacob 2005; Rudeva and Gulev 2011; Serreze 1995; Wernli and Schwierz 2006; Zahn et al. 2008), geopotential height at 1000 hPa (Z1000, Blender et al. 1997; Blender and Schubert 2000; Raible and Blender 2004; Raible et al. 2007; Schneidereit et al. 2010), vorticity fields (Hodges 1995; Scharenbroich et al. 2010), or the Laplacian of pressure or geopotential (Murray and Simmonds 1991; Wang et al. 2006; Pinto et al. 2007). For the detection part, extremes in these fields are identified and retained as the locations of cyclones (Murray and Simmonds 1991; Blender et al. 1997; Geng and Sugi 2001; Zahn et al. 2008). Some tracking methods detect minima or maxima in sub-regions (Hodges 1994, 1995; Muskulus and Jacob 2005; Scharenbroich et al. 2010). The extremes have to meet certain gradient criteria in order to exclude weak or unrealistic cyclones (Geng and Sugi 2001; Raible and Blender 2004; Raible et al. 2007; Zahn et al. 2008). To avoid potential MSLP interpolation errors for steep topography, minima in a terrain-height above 1500m were excluded in some studies (Geng and Sugi 2001; Pinto et al. 2007). The next tracking step is to connect extremes to form trajectories. Blender et al. (1997) and Zahn et al. (2008) use the nearest neighbor positions. Track points of consecutive time steps are chosen to connect, taking into account the whole cyclone history and its most probable movement (Murray and Simmonds 1991; Muskulus and Jacob 2005; Geng and Sugi 2001; Scharenbroich et al. 2010). Hodges (1994, 1999) obtained smooth tracks by applying a cost function of track direction and speed. Many studies make use of further criteria like minimum cyclone lifetime or intensity (e. g. Blender et al. 1997; Pinto et al. 2007; Raible et al. 2007).

Any differences in these three parts may influence the cyclone statistics and characteristics. Raible et al. (2008) found that different technical settings in three tracking methods can lead to track deviations. A change in a few thresholds may actually lead to large deviations in cyclone statistics also on climatological terms (Neu et al. 2013). Xia et al. (2012) showed that different filter approaches applied in the pre-processing part result in different track locations and statistics. Hoskins and Hodges (2002) stated that tracking of different fields and levels has an impact on the numbers of cyclones (even for the same data set). An overview and comparison of various tracking algorithms was given by Neu et al. (2013). Recently, the dependency of a potential anthropogenic climate change signal for Northern Hemisphere extratropical cyclone activity on the tracking method applied was analysed by Ulbrich et al. (2013). They concluded that for extreme cyclones the results of most methodologies are consistent.

3. Data sources

3.1 Data sets for analysing past variations in storm climate

3.1.1 Proxy data and in-situ measurements

Wind measurements are influenced by many factors, like the measurement method, sampling frequency, station location or instrument type. These often change over time leading to inhomogeneities in the observed time series. A typical example of inhomogeneities introduced by station relocations and measurement frequencies are coastal stations for the North Sea (Lindenberg et al. 2012). Apart from these mostly abrupt jumps in wind time series, Vautard et al. 2010 and McVicar et al. 2012 suggest that the continental-scale "atmospheric stilling" in near-surface winds in the period 1979-2008 is caused by meso- to large-scale changes in surface roughness due to land use changes. Due to the above mentioned potential inhomogeneities in wind time series and land use changes, direct wind measurements are often regarded as too inconsistent to be used directly as a measure for storms. An alternative is to derive geostrophic wind speed values from mean sea level measurements (Alexandersson et al. 2000; Krueger and von Storch 2011; Wang et al. 2009, 2011). The geostrophic wind speed serves as a proxy for wind speed close to the surface. Since MSLP is a large-scale variable it is not very sensitive to local conditions or non-climatic disturbances. This proxy is most reliable over flat terrain of latitudes far away from the equator (where the Coriolis force is negligible) and for weather conditions leading to a small ageostrophic wind component. Therefore it is well suited for the NA and Baltic Sea areas.

Proxies based on surface pressure readings to describe past storm activity can be classified into either proxies based on readings from a single station, or geostrophic wind speed statistics. In general, the proxies based on air pressure readings from a single station originate from synoptic experience. They are expected to reflect cyclone and storm activity changes in the area around a weather station. The proxies used most commonly throughout the literature are the annual or seasonal number of deep lows (that is the number of local pressure measurements below a chosen threshold), annual or seasonal lower percentiles of pressure, the annual or seasonal frequency of absolute pressure tendencies exceeding certain thresholds, as well as annual or seasonal high percentiles and mean values of absolute pressure tendencies.

All of these proxies have been used in several studies analysing storm activity in the North Atlantic and European regions (Schmith et al. 1998; Jónsson and Hanna 2007; Allan et al. 2009; Bärring and von Storch 2004; Bärring and Fortuniak 2009; Alexander et al. 2005; Matulla et al. 2007; Hanna et al. 2008). In Krueger and von Storch (2012) the informational content of the above mentioned proxies is examined within the virtual reality of a regional climate simulation in order to quantify the relation between the pressure-based proxies and storm activity. The results indicate that the proxies are generally linearly linked to storm activity with weak to moderate informational value only.

Proxies based on single station readings seek to detect atmospheric disturbances, which often do not relate to storms directly. However, wind speeds in the mid-latitudes, as a first order approximation, directly relate to a pressure gradient that determines geostrophic wind speeds, which can be used to build statistics to assess the past storm climate. As pressure measurements reaching back long times usually do not cover large areas comprehensively, the derivation of pressure gradients requires spatial interpolation of observed pressure values. The simplest approach to obtain pressure gradients is to make use of pressure readings from three different stations that form a triangle. After interpolating the pressure over the triangle, the geostrophic wind speed and its annual or seasonal statistics can be calculated (Schmith 1995; Wang et al. 2009; Krueger et al. 2013b). The derived statistics of geostrophic wind speeds represent past storm activity within the area of such a triangle.

The approach was used for the first time in Schmidt and von Storch (1993) for the purpose of assessing storminess in the German Bight (North Sea). Later studies (Schmith 1995; Alexandersson et al. 1998, 2000; Matulla et al. 2007; Wang et al. 2009), which adopted the method, analysed geostrophic storm activity over the Northeast Atlantic and Europe starting at about 1880. Krueger and von Storch (2011) confirmed that geostrophic wind speed statistics describe past storminess in general. Further, they showed that the informational value of geostrophic wind speed statistics is quite high and superior to that of proxies based on single station readings.

There are also a number of non-meteorological parameters that may serve as proxies for storm activity as they are directly related to some properties of the storms such as wind speed, direction or duration. Often such proxies are associated with storm impacts. Typical examples are, for instance, forest and building losses due to wind storms and storm related sea level variations such as storm surges or extreme sea states; that is, wind generated waves at the sea surface. Information from such proxies often is particularly valuable as their measurements are usually separate from meteorological measurements and therefore provide independent data sources for proving or disproving hypotheses.

3.1.2 Reanalyses

Reanalyses are available for the last decades (e. g. NCEP/NCAR, Kalnay et al. 1996; Kistler et al. 2001; ECMWF, Uppala et al. 2005) or century (The Twentieth Century Reanalysis, 20CR, (Compo et al. 2011)). Measurement data is used as input for a global weather model in order to achieve a relatively homogenous atmospheric data set, to gain additional meteorological variables, equal grid spacing, and equal time intervals. Changes in observation density and measurement techniques (e. g. the introduction of satellites) may still lead to inconsistencies, though presumably less than in raw measurement data. Many articles analysed storms in reanalysis data (among others Blender et al. 1997; Donat et al. 2011; Geng and Sugi 2001; Gulev et al. 2001; Hodges et al. 2003; Hoskins and Hodges 2002; Sickmoeller et al. 2000; Wang et al. 2006; Wernli and Schwierz 2006; Trigo 2006). The ERA15 (1979-1993, T106 (1.125°, ~125 km), 31 levels, Gibson et al. 1997) or the ERA40 (1957-2002, T159 (1.125°, ~125 km), 60 levels, Uppala et al. 2005) reanalyses from the European Centre for Medium-Range Weather Forecasts (ECMWF) were applied. Other popular data sets are the NCEP/NCAR Reanalysis I (1948-present; T62 (1.875°, ~210km), 28 levels, Kalnay et al. 1996; Kistler et al. 2001) and JRA-25 (1979-2004, T106 (1.125°, ~125 km), 40 levels, Onogi et al. 2007). More recent reanalyses at higher resolution are the ECMWF Interim Reanalysis (ERA-Interim, 1979-present, T255 (0.7°, ~80 km), 60 levels, Simmons et al. 2007), the National Aeronautics and Space Administration Modern Era Retrospective-Reanalysis for Research and Applications (NASA MERRA, 1979-present, 0.5° (~55 km), 72 levels, Rienecker et al. 2011), and the NCEP Coupled Forecast System Reanalysis (NCEP CFSR, 1979-2010, 0.5° (~55 km), 64 levels, Saha et al. 2006, 2010). The NOAA-CIRES 20th Century Reanalysis V2 (20CR; 1871-2010, T62 (1.875°, ~210km), 28 levels, Compo et al. 2011) was released recently. In contrast to previous reanalyses, 20CR used only surface and sea level pressure measurements, monthly sea surface temperatures, and sea ice distributions as boundary conditions for short-term forecasts of a numerical weather prediction model (NCEP). An ensemble of realizations was computed in order to get an estimate of internal model variability.

3.2 Climate model data for analysing both past variations and potential future changes in storm climate

The World Climate Research Programme (WCRP) Working Group on Coupled Modelling collected model output from future, past, and present simulations. Two model simulation collections of the WCRP are most prominent since they were used for the IPCC Assessments Reports (AR 4 and 5), CMIP3 (collected in 2005 and 2006 for AR4), and recently WCRP CMIP5 (used for AR5). The CMIP5 multi-model experiment used twice as many models as CMIP3, including also more Earth System Models. The models average temporal and horizontal resolution increased and physical schemes of stratospheric dynamics were developed further. These differences led to an improvement of the spatial representation of storm tracks and their intensity. In particular, some of the higher-resolution models tend to have a better representation of the tilt of the North Atlantic storm track and of winter cyclone intensities. But the North Atlantic storm track still tends to be too zonal and cyclone intensity is underestimated (Zappa et al. 2013). Numerous studies used global climate models directly to quantify storm activity (Fischer-Bruns et al. 2005; Hall et al. 1994; Knippertz et al. 2000; Lambert 1995, 2004; Lambert et al. 2002; Pinto et al. 2007; Ulbrich et al. 2008; Woollings et al. 2012; Yin 2005). Other studies used global climate models as input for regional climate model studies of the present climate (Beersma et al. 1997; Bengtsson et al. 2006, 2009; Leckebusch et al. 2006), or for future scenario simulations (Beniston et al. 2007; Dorn et al. 2003; Rockel and Woth 2007).

3.2.1 Global climate models (GCMs)

A large number of GCMs was used to analyse storms over the NA and WE. Some studies employed pre-CMIP3 atmospheric GCMs like e.g. ECHAM3 (Roeckner et al. 1992), HadCM3 (Gordon et al. 2000), or Arpege/IFS (Déqué et al. 1994), many used CMIP3 GCMs, for instance ECHAM5 (Roeckner et al. 2003, 2004). Others utilized atmosphere-ocean coupled general circulation models (AOGCMs) of the pre-CMIP3 model generation, like ECHAM4/HOPE-G (Legutke and Voss 1999), ECHAM4/OPYC3 (Oberhuber 1992) HADCM2CON (Johns et al. 1997), or CCCma (Flato et al. 2000). More recent studies used coupled models of the CMIP3 and CMIP5 generations, for instance ECHAM5/MPI-OM (Jungclaus et al. 2006), or the Community Climate System Model CCSM 2.0.2 (Kiehl and Gent 2004). The horizontal grid distance of the GCMs used for the studies reviewed in this article ranged from T30 (about 420 km) to T120 (about 125 km).

3.2.2 Regional climate models (RCMs)

Numerous RCMs were applied to detect storms both for the past and for possible future scenarios. Among others the following RCMs were used: HIRHAM (Christensen et al. 2007b, 1996), REMO (Jacob and Podzun 1997), COSMO-CLM (Rockel and Hense 2008; Steppeler et al. 2003), MM5 (Grell et al. 1994; Dudhia 1993), CHRM (Lüthi et al. 1996), HadRM (Jones et al. 1995), RACMO (van Meijgaard et al. 2008), PROMES (Castro et al. 1993), RCAO (Döscher et al. 2002), and FOOT3DK (Pinto et al. 2009a). Some studies used RCMs of intercomparison studies like the EU-funded projects PRUDENCE (Christensen et al. 2007a) or ENSEMBLES (van der Linden et al. 2009). These studies showed the predominant influence of the GCM boundary conditions which are more important than the choice of the RCM itself (e. g. Donat et al. 2010a). The horizontal grid distance of the RCM configurations used here ranges from about 50 to 5 km.

4. Storm trends for the past

A short tabular overview of the studies considered in this review article is given in Table 1. The trends in this review were evaluated in the following way: If a study noted a trend in the written text this trend was taken, even if it was not documented in a figure. If there was no written statement given concerning trends, but a clear trend was visible in a figure of an article, then this trend was taken from the figure. Mainly trends were given for absolute storm numbers, and these were assembled in Tables 2 and 3 for the last decades and centuries. Especially for future scenario simulations a reasonable number of studies exist that also give trends of storm intensities, which were assessed for Table 4 in addition to the trends on storm numbers.

4.1 Proxy and measurement study results

Although historical wind measurements are often problematic and affected by inhomogeneities, large efforts have been undertaken to digitize and improve such records. Together with other indirect storm proxies like documentary reports, weather diaries, storm related gauge records or pressure-based storm indices, an abundance of historical data allows to study the historical storm climate on multi-decadal to centennial timescales over the Euro-Atlantic region. Historical wind records and indirect storm proxies are presented in section 4.1.1 separately from pressure-based storm proxies. Pressure-based proxies usually allow a more robust trend analysis and are presented in section 4.1.2. The information of both data types regarding long-term changes in storm numbers are collected in Table 2.

4.1.1 Historical measurement data

The southern coast of the North Sea region is characterized by a long history of coastal defenses to protect the low-laying hinterlands against storm damages. The longest indirect historical information on storm variations can be found for Northern Flanders (Belgium). Based on scant historical documents about dike repair costs, de Kraker (1999) did not find any long-term trend in the period 1488-1609. Coastal damages due to storms reflect rather large multi-decadal variations similar to storm variations in contemporary times. An update of the loss index with water level measurements at Flushing (Western Scheldt estuary) from 1848 to 1990 indicates a strong increase of spring tides in the 1990s. However, also a sea-level rise of about 30 cm over this period has to be considered.

Cusack (2012) made use of homogenized wind measurements for The Netherlands to calculate a storm loss index. For the period 1910-2010, he found a weak negative tendency in decadal running means of annual damaging storm numbers. Large decadal variations dominate with stormy periods in the 1920s and 1990s and a very calm period around 1960. Ciavola et al. (2011) collected numerous different national storm related data and shortly noted potential changes: Storm related surge data for the Netherlands show a decrease in storm frequency from 1890 to 2008. For Belgium, the storm intensity derived from national wind, wave and surge measurements show no trend between 1925 and 2007. Barredo (2010) analysed storm losses for Europe in the period 1970-2008; they found no trend at the European scale after adjusting for inflation, wealth, and population changes.

As the British Isles are directly affected by severe storms from the open sea, a systematic interest in storm variations and damages has been documented over time. Sweeney (2000) calculated the number of storms per decade from historical reports in the Dublin region. For the period 1715-1999, he found large multi-decadal variations but no visible long-term trend.

An analysis of storm records derived from a daily weather diary at Armagh (Ireland) indicates large decadal variations over the period 1798-1999 (Hickey 2003). Monthly mean wind speeds at the Bidston observatory at the northern Irish Sea exhibit a significant negative trend for the period 1929-2002 (Esteves et al. 2011). For the Irish Sea, the maximum monthly wind speed measurements do not indicate any trend in the period 1929-2002 (Ciavola et al. 2011). For southern Britain, Hammond (1990) calculated an annual windiness index from different national stations. Based on the annual average of monthly mean wind speeds over the Boscombe Down area, no long-term trend exists in the period 1881-1989.

Some studies analysed long-term storm variations also over the Northern Alpine region. Based on observations from northern Switzerland, Schiesser et al. (1997) found a significant negative trend for the number of days and the duration of storms exceeding 7 Beaufort in the period 1894-1994 (1871-1991 for storm duration at Zürich). Brönnimann et al. (2012) though found no significant change in gale days in wind measurements for Zürich from 1891 to 2008. Usbeck et al. (2010) looked at wind speed measurements and forest damages in the same region and found large decadal maximum wind speed changes and an increase since the 1970s. Non-homogenized wind measurements from Vienna show a clear negative tendency for the number of gale days (>8 Beaufort) between 1872 and 1992 (Matulla et al. 2007).

For the Baltic Sea region, there is only little information about historical storm variations. Nilsson et al. (2004) assessed the damaged volume of forests to calculate the number of damaging storms. Based on this storm proxy, a positive trend exists over Sweden in the period 1901-2000. However, the authors also note that changes in forestry may have contributed to increased damages. Franzén (1991) combines the annual number of gale days (> 7 Beaufort) from Gothenburg 1860-1930 with those of a nearby station at Vinga (> 21 m s⁻

[1]) since 1920 and finds a negative tendency for the period 1860-1989 for SW-Sweden. More homogeneous wind records from 1940-1990 show a positive trend. This was also confirmed by Ciavola et al. (2011) for the Polish Baltic Sea coast.

Sea level variations obtained from tide gauges represent another frequently used tool to derive information on changing storm activity (Vilibic and Sepic 2010). While such measurements are usually influenced by a variety of factors unrelated to variations in storm activity (e.g. astronomical tides, changes caused by modifications to local water works, or land uplift or subsidence), the idea is that generally the contributions from these factors may be removed retaining only the variations associated with changes in the storm climate. There are a number of different approaches on how this may be achieved (see e. g. Woodworth and Blackman 2002). de Ronde (WASA 1998) suggested that changes in storm climate mostly influence the upper tail of the sea level distribution while changes associated with other factors (e.g. mean sea level rise or land subsidence) will have comparable influences on both the median and the extremes. Subtracting the extremes from the mean or, in other words, considering only the variations of the extremes relative to the means therefore provides a proxy for changes in storm climate.

The approach was used in von von Storch and Reichardt (1997) to analyse storm-related sea level fluctuations at various tide gauges in the German Bight (Southern North Sea). These were found to be relatively constant over the past approximately 150 years with pronounced decadal and inter-annual fluctuations broadly consistent with those known from geostrophic wind speed percentiles (e. g. Schmidt and von Storch 1993). Updates of these analyses until 2008 (Weisse and von Storch 2009) and 2012 (Emeis et al. 2013) confirmed these results. A similar approach was taken in Woodworth and Blackman (2004) and Menéndez and

Woodworth (2010) on a global basis. Analysing data from tide gauges with quasi global coverage they showed that extreme sea levels have indeed increased over the past decades for most places worldwide. This is primarily a consequence of rising mean sea levels (and partly of a long nodal tidal cycle) rather than systematic changes in storm activity.

Changes in wave climate are also associated with corresponding changes in storm activity and may complement the information available. In the late 1980s and early 1990s a series of papers were published analysing recent changes in North Atlantic and North Sea wave climate (e.g. Carter and Draper (1988); Bacon and Carter (1991); Hogben (1994); Neu (1984)) based on relatively short measurement records of about 15-25 years. Generally, the authors reported increases in mean and partly in extreme wave heights, but all concluded that the length of available records was too short to provide reliable conclusions. In fact the period considered in these studies largely coincides with a period in which storm activity increased in the area; however, taking longer periods into account this increase appeared to be within the range of natural variability observed before (Weisse et al. 2012).

4.1.2 Pressure-based storm indices

The European project WASA (WASA 1998) analysed changes in the storm climate over the NE Atlantic and the North Sea based on air pressure measurements and high-frequency tide gauges variance. Changes in wave climate were assessed by running a wave model and deriving wave statistics. The main result was that storms and waves show large decadal variability and an increase in recent decades. But this intensity increase seems to be comparable to an increase at the beginning of the last century. Before the digitized records from the WASA Group (1998) were available, Kaas et al. (1996) used optimal predictor maps to produce hindcasts of monthly mean pressure tendencies at ten stations in Denmark, the

Faeroe Islands, Finland, Greenland, Norway and Sweden starting in 1903. They did not find any long-term trend. Schmith et al. (1998) extended the analyses of Kaas et al. (1996), but used the (now digitized) pressure measurements from WASA (1998). They mentioned that storm numbers in the Northeast Atlantic exhibit interdecadal variability as their major feature and confirmed the results of Kaas et al. (1996) as they did not find any trend in the time series.

Schmidt and von Storch (1993) investigated annual frequency distributions of geostrophic wind speeds in the German Bight (North Sea) and concluded that storm activity remained almost constant for the examined period of over 100 years. Later studies (Schmith 1995; Alexandersson et al. 1998, 2000; Matulla et al. 2007; Wang et al. 2009, 2011), which adopted the method, analysed geostrophic storms over the Northeast Atlantic and Europe starting at about 1880 or earlier. Alexandersson et al. (1998), as part of the results published by WASA (1998), and Alexandersson et al. (2000) analysed annual high percentiles of geostrophic wind speeds over the Northeast Atlantic and the Baltic from 1881 onwards. They found that storm numbers in the late 19th century were at high levels, followed by a gradual decrease until the mid-1960s, a subsequent increase until the 1990s, and a drop afterwards (Figure 2). Overall, they did not find any long-term trend and noted that the time series would exhibit mainly interdecadal variability. This result was confirmed by a number of studies, e.g. by Jónsson and Hanna (2007), Hanna et al. (2008), and Matulla et al. (2007).

The NAO index (Figure 3) exhibits a quite similar behavior over time compared to the storm index after Alexandersson et al. (1998, Figure 2). High values appear in the beginning of the 19th century (a little later than the high storm index values of Figure 2), a decrease until the mid-1960s is followed by a subsequent increase until the 1990s (as in Malberg and

Bökens,1993) and a drop thereafter. Alexandersson et al. (2000) calculated the correlation between 95th (99th) percentiles of geostrophic wind speeds and the NAO to be 0.57 (0.38) for NA storms, respectively 0.52 (0.40) for storms over the Baltic Sea. Hanna et al. (2008) investigated if the NAO plays an important role for storm frequency in the North Atlantic-European region. In general, they find positive correlations of two NAO indices with winter storms in northern regions and smaller or negative correlations in the South. Hanna et al. (2008) further demonstrate that the link connecting storm activity and the NAO is not stationary over time. Pinto and Raible (2012) discuss changes of the NAO poles' location over time periods of decades to centuries and showed that these changes lead to a different influence of the NAO on the European climate. This may also be a reason for the non-stationarity of the relationship between the NAO and storm activity over the NA and NWE.

Alexander et al. (2005) examined the extended winter season frequency of strong pressure changes, which is used as a measure for the number of severe storms, over the British Isles and Iceland. They found an increasing number of such storm events in the period 1949-2003. The correlation with the NAO is 0.8 over Iceland and 0.5 in the UK. Allan et al. (2009) also examined storms over the British Isles from 1920 to 2004. The correlation between autumn storms and the NAO was weak (0.17), but higher for winter storms (0.44). However, they noted that the correlation is not stationary, which agrees with Hanna et al. (2008). Matulla et al. (2007) looked at the annual link between the NAO index and storminess indices. They mentioned that 'the NAO index is not very helpful to describe storminess' as the found correlation is 0.40 for the Northeast Atlantic and Scandinavia and just -0.15 for Central Europe.

Cornes and Jones (2012) analysed MSLP time series developed by the European and North Atlantic Daily to Multidecadal Climate Variability (EMULATE) project. They added that the storm activity increase in winter towards the end of the 20th century over the North Sea was associated with an increased zonal flow in connection with a general intensification of the North Atlantic storm track. Bärring and von Storch (2004), later extended by Bärring and Fortuniak (2009), analysed several storm indices, among them the annual frequency of low pressure readings, absolute pressure tendencies exceeding 16 hPa in 12 hours, or other wavelet and bandpass filtered indices at Lund and Stockholm in south Sweden from 1780 onwards. Nilsson (2008) calculated upper winter percentiles of the zonal component of geostrophic wind speeds over Southern Sweden for the period 1823-2006. Those studies did not find a significant upward trend in storm numbers in Southern Sweden. A storm frequency maximum is visible in the 1870s and the late 1980s, and a minimum around 1960.

The authors of a later study, Wern and Bärring (2009), which covers different periods (1901-2008, and 1951-2008) and is based on geostrophic wind speeds, concluded quite similarly for southern Sweden, but found significant negative trends for mean and extreme geostrophic wind speeds for northern parts of Sweden. Over southern and central Finland, Suvilampi (2009) found a negative tendency for annual 95th percentile geostrophic wind speeds in the period 1884-2007 alike to Wern and Bärring (2009) over Sweden, and a weak non-significant positive trend since the middle of the 20th century. Based on homogenized pressure records, Schenk and Zorita (2012) use nonlinear statistical analog-upscaling to reconstruct daily wind fields over Northern Europe. Their extended reconstruction (Gustafsson et al. 2012) shows no robust long-term changes in seasonal wind speeds over the central Baltic Sea region in the period 1850-2006.

Table 2 shows trends in storm frequency as given by individual measurement and proxy studies (sections 4.1.1 and 4.1.2) that were analysed for this article. The bars show the time period regarded in each study, reaching back as far as the 18th century until the begin of the 21st century. Some studies look at almost 300 years of data (Sweeney 2000) while others focus on more recent decades. The results were sorted according to the geographical regions presented in Figure 1. The bar colour indicates the storm trend given by the study: green for no trend, blue for a decreasing and red for an increasing trend. The clearest result is found for the North Sea and the British Isles where most studies show no trend at all. Over Central Europe most studies found a decrease. For the NE Atlantic most studies show no trend, while many articles also detect an increase. The Baltic Sea region gives inconsistent results, with as many articles returning increasing as decreasing storm numbers. Overall, a large number of proxy studies detect no storm trend at all (33 out of 75 articles), while 24 studies describe a decrease and 18 studies an increase.

4.2 Reanalyses and model studies for the past

To identify changes in future storm climate it is necessary to simulate the climate of the past reliably. The model simulations for the past can then be compared to measurement data or reanalyses. These validation periods are limited in time to the last few decades when reanalyses data are available, although the model simulations sometimes cover several past centuries. The model studies for the past can be divided into three categories according to their study length: The reanalysis period covering the last about 50 years, the late 19th century until today, and long-term reconstructions for the last centuries up to the last millennium. The amount of measurement data included for the long-term reconstructions and the late 19th century studies is strongly reduced in comparison to shorter studies for the reanalysis period. Storm trends derived from these data sets depend greatly on the reconstruction method and the types of proxies used.

4.2.1 Reanalysis period

Most model simulations for the past are limited to the last few decades, spanning mostly about 50-60 years. Hofherr and Kunz (2010) statistical-dynamically downscaled both the ERA-40 reanalysis and measurement data and analysed trends at several measurement stations in Germany based on the three most severe storms within a year. Some stations showed positive or negative trends, but an overall significant trend was not found. An RCM was applied by Weisse et al. (2005) to downscale NCEP/NCAR reanalyses dynamically for the last decades. The results are mixed, with an increasing trend in storm numbers for the North Sea, an increasing trend for the high-latitude NE Atlantic until the mid-1990s and a decreasing trend afterwards. This trend is reversed for the North Atlantic south of 60°N.

Changes in storm climate may also be inferred from storm-related sea level variations. One approach to separate the storm induced sea level variations from those caused by other effects is by using numerical tide-surge models driven by atmospheric wind and pressure usually from reanalyses. For the North Sea such simulations were performed, for example, by Langenberg et al. (1999), Sterl et al. (2009), Wakelin et al. (2003), or Weisse and Plüß (2006). The general conclusion was that the simulated changes and variations in storm surge climate closely relate to that derived from tide-gauges. In particular, an increase in storm surge heights along the southern and eastern coasts of the North Sea from the 1960s to the 1990s is reported. About half of the increase is attributed to variable extreme weather conditions while the other half appears to be associated with changes in large-scale (mean) atmospheric conditions such as represented by the NAO index (von Storch et al. 2008) which consistently shows an upward trend during these decades (see Figure 3). As for the case of storm surges, numerical wave models driven by reanalysed wind fields have become popular tools in complementing the fragmented measurement picture (e. g. Günther et al. (1998) and Weisse and Günther (2007) for the North Sea, Dodet et al. (2010) for the NE Atlantic or Musić and Nicković (2008) and Cieślikiewicz and Paplińska-Swerpel (2008) for the eastern Mediterranean and the Baltic Sea respectively). Again findings from these studies are broadly consistent with knowledge available from analysing reanalyses and geostrophic wind speed percentiles (Weisse and von Storch 2009).

Many other studies that took into account the last four to six decades examined mostly NCEP/NCAR or ERA40 reanalyses. Some authors compared both data sets, like e.g. Raible et al. (2008) who tracked cyclones in both NCEP/NCAR and ERA 40 reanalyses for the Northern hemisphere. For the high-latitude North Atlantic they found an increase in winter cyclone numbers, extreme cyclone intensity and activity (defined as the product of number and extreme intensity) for both data sets. In the mid-latitude NA a decrease in cyclone numbers and activity is seen in both reanalyses. The extreme cyclone intensity is decreasing in ERA40 and increasing in the NCEP/NCAR reanalyses. Paciorek et al. (2002) report an increase of intense cyclones numbers in the NCEP/NCAR reanalyses, while they find no trend in absolute cyclone numbers. A global climatology for extratropical cyclone activity was derived by Wang et al. (2006) from NCEP/NCAR and ERA40 reanalyses from 1958 to 2001. Over the high-latitude NA an increasing trend in strong-cyclone activity was found, while over the mid-latitude NA a decreasing trend prevails. A small increasing trend was detected over northern Europe. Trigo (2006) tracked ERA40 and NCEP/NCAR reanalyses for winter storms over Europe and the Atlantic. For the high-latitude NA the number of storms increases in both reanalyses. The opposite trend is found for the mid-latitude NA (again in both reanalyses). A comparison of extratropical cyclones in the recent reanalyses ERA-

Interim, NASA MERRA, NCEP CFSR, and JRA-25 was given by Hodges et al. (2011). They found that cyclones of the Northern Hemisphere correspond well between the different reanalyses products.

Chang and Fu (2002) examined interannual variations in Northern Hemisphere winter storm tracks extracted from NCEP/NCAR reanalyses. A weaker storm track was found until the 1970s, and a stronger storm track afterwards until 1998. Geng and Sugi (2001) tracked NCEP/NCAR reanalyses for the NA from 1958-1998 and detected an increasing number of winter storms. Simmonds and Keay (2002) found positive trends for the number of extreme cyclones. In a similar way Gulev et al. (2001) tracked NCEP/NCAR reanalyses for the Northern hemisphere winters 1958-1999. A decreasing cyclone number was found for the whole Northern hemisphere, the North Atlantic in general, as well as for medium and weak cyclones over the NA. Siegismund and Schrum (2001) derived wind statistics over the North Sea from the NCEP/NCAR reanalyses, the annual mean wind speed for the North Sea shows a rising trend of about 10% between October and March.

ERA40 reanalyses were examined by Leckebusch et al. (2008a) by looking at daily maximum wind speed, gusts and a storm severity index. An increase in winter storm severity was found for the ERA40 time period. A peak over threshold extreme value analysis was applied to ERA40 by Della-Marta et al. (2009) to analyse return periods of wind storms over Europe. Schneidereit et al. (2007) tracked winter storms over Iceland and the NA in ERA40. The cyclone number and intensity show an increase close to Iceland consistent with the NAOHanson et al. (2004) tracked ERA15 reanalyses from 1979-2000. For weaker storms an increase was detected whilestronger storms showed first a decrease between the 1980s and mid-1990s, and an increase afterwards. They also looked at NCEP/NCAR reanalyses and found an increase in weaker cyclones between the mid-1980s and the mid-1990s. This trend is reversed for stronger storms (Bft 9 and above).

4.2.2 Late 19th century until today

A long simulation was computed by Lambert (2004) who also used an AOGCM to simulate winter storm trends for the last 140 years, they detected decreasing storm activity for this period. Another way to generate storm trends for the past is to directly extract these from reanalyses. Most of these studies analyse the last about 50 years, only those which are based on the new 20CR data set reach back in time for more than 130 years (Brönnimann et al. 2012; Donat et al. 2011; Harvey et al. 2012; Wang et al. 2012). For these long reanalysis studies mostly an increase in storm frequency was found, for the high-latitude NA (Wang et al. 2012), the North Sea (Donat et al. 2011), and also for Northern Europe (Wang et al. 2012). The only exception was found for the mid-latitude NA where no changes were detected (Wang et al. 2012). If only the last 50 years are regarded, the increasing trend over the high-latitude NA is strongly enhanced (Wang et al. 2012).

But the quality of long-term trends derived from 20CR is currently under debate (e. g. Ferguson and Villarini 2012; Krueger et al. 2013b,a; Dangendorf et al. 2014). Krueger et al. (2013b) showed that especially for the first half of the 19th century long-term storm trends over the Northeast Atlantic derived from 20CR and from observed mean sea level pressure are inconsistent. After about 1950 both time series converge. The authors suppose that an increasing station density over time used for 20CR contributes to these inhomogeneities during the earlier decades of the reanalysis. Wang et al. (2013) claim that newly discovered measurement errors (single outliers occurring from time to time), the sampling frequency, and aliasing play an important role, and if correcting for these, the inconsistencies would diminish. However, after repeating the analyses of Krueger et al. (2013b), and considering measurement errors and a constant sampling frequency, Wang et al. (2013) demonstrate how robust the geostrophic wind speed statistics are against the influence of measurement errors and changes in the sampling frequencies (Fig. 4a,b in Wang et al., 2013) and affirm the results of Krueger et al. (2013b). Wang et al. (2011) already showed that alias artefacts may be present in the data, but do not affect results notably. The results by Krueger et al. (2013a) are confirmed by Dangendorf et al. (2014) using surge level records for Cuxhaven at the German North Sea coast since 1843. While the surge record is marked by a considerable inter-annual to decadal scale variability with a stationary link to large-scale atmospheric forcing in the region, no evidence for the existence of a significant long-term trend was found. By applying simplified empirical wind-surge formulas to the wind and pressure fields from 20CRv2, the authors further confirmed the inconsistencies in the 20CRv2 reanalysis for the North Sea region before 1910. We therefore conclude that caution should be applied when using reanalysis data (with changing station density over time) for such long-term trend analyses.

4.2.3 Long-term reconstructions

One very long model simulation was presented by Fischer-Bruns et al. (2005) with an AOGCM for the past about 450 years. They used the peak over threshold method for wind speed in winter and found no large changes over the North Atlantic for the last centuries. The longest climate model simulation study for almost 1000 years until the end of the last century was analysed by Xia et al. (2013). Storms were detected by using a tracking algorithm and subsequent cluster analysis. Some yearly and decadal variability was found, but no long-term changes in storm numbers, track length, or location. The absence of robust trends in direct wind measurements and pressure-based storm indices on longer timescales (at least since the late 19th century) over the Euro-Atlantic region (see Figure 2) seems to support these model studies for the last centuries.

Based on a comparison of the Coupled Model Intercomparison Project phase 3 (CMIP3) models, Gómez-Navarro and Zorita (2013) do not find a detectable influence of external forcing onto long-term atmospheric circulation patterns over the last millennium. As this includes also the NAO, the long-term NAO and wind observations in addition to a broad suite of long GCM simulations suggest quasi-stationary behavior of the NAO, related wind, and storm climate over Europe on centennial timescales. As noted by Gómez-Navarro and Zorita (2013), the model results are in conflict with proxy reconstructions e. g. of the NAO (Trouet et al. 2012) showing persistent positive values for the Medieval Climate Anomaly and negative values during the Little Ice Age. Only for the future climate under increased greenhouse gas conditions, the GCM simulations start to show an impact of external forcing onto the wind climate (e. g. Fischer-Bruns et al. 2005; Ulbrich et al. 2009).

Table 3 gives storm trends for reanalysis data and climate model data for the past decades and centuries until today, reaching back until the year 1000. The results were sorted according to the geographical regions defined in Figure 1. The bar colour indicates the storm trend given by the study: green for no trend, blue for a decreasing and red for an increasing trend. Most of these trends are restricted to the time from about 1960 to 2000. All long-term model studies though, which consider the last 100 years up to the last 1000 years, show either no trend or a decrease in storm counts. This result is in accordance with the majority of long-term proxy and measurement studies. For the high-latitude NA most studies give increasing trends while only few studies indicate decreasing storm numbers or no change. This increase in storm numbers coincides with an increase of the storm index after Alexandersson et al. (1998)

which constitutes part of its long-term decadal variability (see the trend for the reanalysis period in Figure 2). It is also reflected in the NAO index increase between 1960 and the mid-1990s (compare Figure 3). In the mid-latitude NA the same number of studies indicate increasing or decreasing trends, four note no trend at all and several studies show mixed trends. For the North Sea and the Baltic Sea most studies indicate higher storm numbers for more recent years, only three studies give no trend for the North Sea, and there are no articles that find lower storm activity. For Central Europe only two studies were accounted for which found an increase and no trend in storm numbers. Overall, the reanalysis and model data studies give an increase in storm counts for the high-latitude NA, no clear trend for the mid-latitude NA, and rather higher storm numbers over the North Sea and the Baltic Sea.

5. Storm trends for the future

Many studies (e. g. Bengtsson et al. 2006; Della-Marta and Pinto 2009; Fischer-Bruns et al. 2005; Kunz et al. 2010; Lambert et al. 2002; Leckebusch et al. 2008b,a; Raible and Blender 2004; Walter et al. 2006) demonstrated the ability of GCMs and RCMs to simulate realistic storm tracks. They suggest that climate models are useful to investigate changes of extratropical cyclones and the physical mechanisms of these changes in a future climate. In this chapter we review recent studies, which analyse extratropical cyclone climatologies under warming climate conditions. The studies regarded can be grouped according to their model simulations into pre-CMIP3, CMIP3 and the CMIP5 phase. Hereafter we will focus on track frequency and track intensity.

Studies of extratropical cyclone climatologies under anthropogenic climate change suggest that there are noticeable changes over the Northern Hemisphere. Early pre-CMIP3 single-model based studies (Lambert 1995, 2004; Carnell and Senior 1998) as well as those forced by IPCC SRES (Special Report on Emissions Scenarios - SRES) scenarios (Bengtsson et al. 2006; Pinto et al. 2007) found a reduction of the total number of extratropical cyclones, consistent with a decreased surface meridional temperature gradient. Such a reduction was also found by Lambert and Fyfe (2006) in an analysis of the ensemble mean of 16 CMIP3 GCMs.

Studies based on the CMIP3 model phase using the same tracking algorithm for different scenarios returned increasing activity of strong storms south of 60° N over the northeast Atlantic and western Europe with an overall reduced cyclone density for central Europe (Leckebusch et al. 2006). But analyses with the pre-CMIP3 ECHAM4/OPYC3 model gave an increased track density northwards of 60° N, and significant negative changes over central Europe (Leckebusch et al. 2006; Pinto et al. 2006). Applications of different storm tracking algorithms in single-model based studies (Bengtsson et al. 2006; Geng and Sugi 2003) showed a clear increase in track density for the eastern NA and the British Isles region (Pinto et al. 2009b). Della-Marta and Pinto (2009) and Pinto et al. (2009b) detected shortened return periods for intense storms in ECHAM5 scenario simulations. These imply a probability of more frequent strong storms under anthropogenic climate change conditions over the British Isles, the North Sea and NWE.

An analysis of synoptic wave variability by Blackmon (1976) applied to an ensemble of 16 GCMs from CMIP3 (Ulbrich et al. 2008), showed an increase of extratropical cyclone activity over the eastern NA which extends towards WE. Harvey et al. (2012) applied the same analysis for both CMIP3 and CMIP5 projections and found that the responses of storm tracks to the mean global temperature are in general agreement. Although the CMIP3 model responses spread is much wider, both projections present an increase in storm activity in the mid-latitudes and a decrease in subpolar regions of the Northern Hemipshere. In CMIP5 model responses the spread is reduced, with a weaker positive and a stronger negative response. Storms detected in CMIP5 models with an objective-feature tracking algorithm confirm those findings (Zappa et al. 2013). For the northern part of the NA (north of 60°N) the AOGCMs ECHAM5/OM1, HadAM3P, and HadCM3 show a significant decrease in cyclone track density (Bengtsson et al. 2006; Geng and Sugi 2003; Leckebusch and Ulbrich 2004; Pinto et al. 2007). CMIP5 ensemble simulations, which already included high-frequency output facilitating the use of cyclone-tracking methods, confirmed these results. They reflect a robust response (weakly sensitive to historical bias) of a decrease in the Norwegian Sea and an eastward extension of storm activity towards central Europe and the British Isles.

Walter et al. (2006) looked at wind velocities in regional model scenario simulations for the time 2070–2099 using three different RCMs (REMO, CCLM, and MM5). They found an almost unchanged wind climate over central Europe, but an increase over the Baltic Sea, especially in winter. Also Rockel and Woth (2007) analysed wind in regional climate model projections, but for European land areas. For winter, an increase in extreme wind speed percentiles is projected, and a decrease for autumn. Pinto et al. (2010) assessed wind storm impacts under climate warming conditions over Western Germany. An increase in storm numbers and wind gusts was projected until the end of this century. Changes in gust wind speeds over Germany under climate warming conditions were also analysed by Rauthe et al. (2010). They describe an increase over Northern Germany, but a slight decrease over central and Southern Germany. A dynamical downscaling study for European winter storms until 2100 was presented by Leckebusch et al. (2006). They found a reduced track density for the total number of storms over central Europe, but an increasing cyclone activity for intense storms over NWE. Beniston et al. (2007) examined extreme events, again until 2100, for Europe. The study shows that extreme wind speeds between 45°N and 55°N and the number of storms over the North Sea will increase. Some studies assessed storm indices that describe storm severity (Leckebusch et al. 2008a) or meteorological forcings of storm severity (Pinto et al. 2012). Leckebusch et al. (2008a) found higher wind speeds for the NE Atlantic, a larger spatial extent of storms, and larger storm-affected areas, which lead to a higher severity index for possible future scenarios. The indices used by Pinto et al. (2012) show shorter storm return periods and higher losses in many European countries, except for Norway.

Table 4 summarizes the results for climate model scenario studies for the future until about the year 2100 for the different geographical regions defined in Figure 1. The reference pre-industrial or present-time periods are given as grey boxes. The coloured boxes for future scenarios mark trends in storm numbers: grey – no trend given, red – increasing trend, green – no trend, blue – decreasing trend. The studies show about as many increasing as decreasing storm trends (26 to 24), only 2 studies show no trend at all. Most studies which indicate a decrease in storm numbers cover the NA north of 60°N. For the NA south of 60°N there are more studies which project an increase in storm numbers, a similar result is given for the North Sea. For the Baltic Sea and central Europe about the same number of studies return either an increasing or a decreasing trend.

While the studies of extratropical cyclone frequency give quite inconsistent results and vary substantially at the regional scale, intensity tendencies related to baroclinic wave activity are more univocal. Many studies indicated a high risk of more intense storms under anthropogenic climate change conditions, especially for the British Isles, the North Sea and NWE. Early GHG-forced low-resolution projections (T42) with ECHAM4 found an increase of the number of deep cyclones (MSLP < 970 hPa) (Knippertz et al. 2000) or increase in wind speed (~ 1.5 - 2 m s-1), especially for the northern part of central Europe (Andersen et al. 2001). GCM projections with a resolution not higher than T63 (~200 km), forced by IPCC SRES scenarios, mostly indicated an increasing extratropical cyclone intensity for central Europe and the southern Baltic Sea region (Bengtsson et al. 2006; Leckebusch et al. 2006; Donat et al. 2010b).

Other single-model based studies using CMIP3 models: e.g ECHAM5, HadAM3P, HadCM3, or JMA891 (Bengtsson et al. 2006, 2009; Geng and Sugi 2003; Leckebusch and Ulbrich 2004; Leckebusch et al. 2006; Pinto et al. 2009b) present an increase in track density of strong cyclones over the NA, especially in the vicinity of Europe. Analyses of CMIP3 ensemble simulations (Lambert and Fyfe 2006; Yin 2005; Ulbrich et al. 2008) confirmed an increase in storm intensity. High-resolution (T213, ~ 63 km) projections with ECHAM5 (Bengtsson et al. 2009) showed a minor storm intensity increase (~1 m s-1), but a significant increase in total precipitation. de Winter et al. (2013) used an ensemble of 12 CMIP5 models over the North Sea and describe results that are in line with CMIP3 studies: no change in annual maximum wind speed was found under changed climate conditions in this region.

An eastward extension of the storm-tracks from the Eastern NA towards Europe seems to be a robust result, found in studies using different models and different storm identification techniques. Studies from CMIP3 models and pre-CMIP3 single-model studies show an increased storm activity over the British Isles, western and central Europe (Geng and Sugi 2003; Leckebusch and Ulbrich 2004; Pinto et al. 2007; Bengtsson et al. 2006). Results from CMIP5 confirm those findings. Mizuta (2012) analysed a CMIP5 ensemble of 11 GCMs and found an increase in frequency of intense cyclones around the British Isles, and a decrease in the northern part of the NA (Iceland, Scandinavia). Such a pattern was found in many previous studies (for instance in Geng and Sugi 2003; Bengtsson et al. 2006; Pinto et al. 2007). Zappa et al. (2013) analysed a CMIP5 ensemble of 19 GCMs and described the response in DJF wind intensity changes as a tripolar pattern: reduction in the Norwegian and Mediterranean Seas and over the subtropical central Atlantic, and an increase for central Europe.

The intensities of storms in future scenario simulations are also given in Table 4. The coloured glow around the boxes for future scenarios indicates the trend in storm intensity. Not all studies gave intensity trends. But generally, most trends show an increasing intensity (43 studies, 2 returned no trend (for the high-latitude NA) and 4 a decreasing trend (NA north of 60°N and central Europe). This increase in storm intensity is clearly visible in all geographical regions analysed. Overall, there is no common trend in storm numbers for future scenario simulations, but a slight tendency towards an increase south of 60°N and a decrease north of 60°N was found for the NA and the North Sea. On the contrary storm intensities show a clear trend towards higher values for future greenhouse conditions.

6. Changes in storm tracks

6.1 Past Changes

Harnik and Chang (2003) describe a northward shift of the Atlantic storm track by about 5° and an intensified storm track. A northward shift of storm tracks was also mentioned by Hickey (2003) and Trigo (2006). Also Wang et al. (2006) report a northward shift (181 km) of the mean storm track position over the North Atlantic. According to Schneidereit et al. (2007) the cyclone density over the NA shifted northward with particular increase between South Greenland and Iceland. For high NAO index winters, Atlantic cyclone density shifts northwards and more stationary cyclones occur (Sickmoeller et al. 2000). On the contrary, Weisse et al. (2005) analysed a north–south shift for the North Atlantic storm track.

Schiesser et al. (1997) suggested a NE shift of wind measurements, they also detected the period before 1940 to be windier than afterwards. Gulev et al. (2001) found a high correlation between the NAO and Atlantic cyclone frequency. Both shift in the late 1970s to the East. Also Lehmann et al. (2011) analysed an eastward shift of the NAO in NCEP reanalysis and SMHI measurement data; a shift to the North was found for the NA storm track. Xia et al. (2013) obtained almost unchanged track positions, shapes and lengths for the last about 1000 years.The majority of articles (6 out of 11) suggest a shift of Atlantic storm tracks to the North for the past. These studies are mostly based on older pre-CMIP3 or CMIP3 data sets.

6.2 Future Changes

Bengtsson et al. (2006) simulated a poleward shift of storm activity for climate change experiments. Also Bengtsson et al. (2009) and Fischer-Bruns et al. (2005) analysed a general poleward migration of storm tracks. Yin (2005) found a poleward and upward shift and intensification of storm tracks in 15 AGCMs of the 4th IPCC report. Ulbrich and Christoph (1999) show a northeastward shift of the NAO variability centers and an intensified storm track in a coupled ECHAM4/OPYC3 240-year simulation. Hall et al. (1994) describe a shift in the NAO to the North and downstream. Andersen et al. (2001) detected a moderate downstream shift and extension of the Atlantic storm track and an overall zonalization of the mean flow between 50° and 70°N. Knippertz et al. (2000) report a northeastward shift of the storm track over the eastern NA and Europe. Löptien et al. (2008) though describe a strengthened mid-latitudinal eastern Atlantic-European storm track that shows no distinct shift in a future climate.

For doubled CO2 concentrations, Schubert et al. (1998) report an eastward shift of storm tracks. Also Woollings et al. (2012) describe an eastward shift of storm tracks in AOGCMs for CMIP3 models for the future. Ulbrich et al. (2008) report enhanced storm track activity over the eastern North Atlantic, and thus a downstream and slightly southward shift of the NA storm track in an ensemble of CMIP3 coupled GCMs. A tripole storm track pattern (reduction in track density over the Norwegian Sea, the Mediterranean and subtropical central Atlantic, and an increase for the British Isles) and a resulting eastward extension of the storm track into Europe was derived by Zappa et al. (2013) from CMIP5 simulations. Harvey et al. (2012) compared mean CMIP3 and CMIP5 model simulations in terms of storm track changes in a future climate and found the CMIP5 response to be more negative in the ice-edge regions of the Arctic than the CMIP3 response. Geng and Sugi (2003) analysed a southeastward shift of strong cyclones in the northern North Atlantic region. Leckebusch and Ulbrich (2004) detected a southward shift for extreme cyclones in A2 scenario simulations. Carnell and Senior (1998) found shortened storm tracks over the eastern North Atlantic with an almost unchanged position. Also Lambert and Fyfe (2006) found no discernible spatial change in storm tracks for future greenhouse conditions.

The scenario simulations for the future show heterogeneous results. Many older pre-CMIP3 and CMIP3 studies show a poleward shift of the NA storm track (for instance Bengtsson et al. 2009; Fischer-Bruns et al. 2005; Yin 2005). More recent studies using simulations of the CMIP3/CMIP5 data base show an eastward extension of the NA storm track into Europe instead (Ulbrich et al. 2008; Woollings et al. 2012; Zappa et al. 2013).

7. Summary and Conclusions

A large number of studies are available on storms over the North Atlantic and Northwestern Europe, but they sometimes show quite contradictory results on long-term storm trends. This review gives a more objective evaluation of these trends by grouping the studies according to the geographical region regarded, the data used, and the time frames taken into account. For analysing past variations in storm climate proxy data and in-situ measurements were used. Some articles derive storm trends directly from wind speed measurements, but as these are often influenced by changing conditions in the vicinity of the measurement station or by other potential inhomogeneities, more often proxies based on surface pressure readings are taken into account. These may be used to derive geostrophic wind speeds which serve as a very reliable measure of storm activity over topographically flat terrain. The proxy and measurement studies for the last decades and centuries generally show no storm trends. This result is most distinct over the British Isles, the North Sea, and the NE Atlantic. For the Baltic Sea there are about the same number of studies showing an increase, a decrease, or no trend at all. A decrease was found for Central Europe.

Past changes in storm frequency and intensity may also be deducted from reanalysis data. A multitude of reanalyses exists, spanning the last about 35 to 65 years, and, in one case, the last 140 years. Their grid distance ranges from more than 200 km up to about 50 km. Storm trends for the past were also extracted from climate model data, both from regional and global climate models. The global climate models used a grid distance of about 100 to more than 400 km; the regional models a much higher resolution between 5 and 50 km. Most model and reanalysis studies for the past indicate an increase in storm activity for the high-latitude NA, the North Sea, and the Baltic Sea while there is no clear common trend for the mid-latitude NA. Most of these articles cover only the last few decades. Those model studies which evaluate trends for the last centuries up to the year 1000 mainly show no trend or a decrease in storm events. For the past, most articles based on older pre-CMIP3 or CMIP3 simulations indicate that there was a shift of the Atlantic storm track to the North.

To assess potential future changes in storm climate again climate models are applied. They mostly compare a reference present-time period to a scenario simulation that covers the last decades of this century. Overall, no clear trend in storm numbers was found; about the same numbers of articles gave increasing as decreasing trends. Most studies which return a decrease in storm numbers cover the high-latitude NA, an increase is mainly found for the mid-latitude NA and the North Sea; no clear result was given for the Baltic Sea and Central Europe. But for storm intensities almost all studies agree on intensification for the future, this result clearly holds for all geographical regions analysed. For a possible shift of the North Atlantic storm track results are inhomogeneous and depend on the model generation used. Older simulations tend to show a poleward shift, while newer model runs return an eastward extension of the storm track towards Europe.

To summarize, it is a challenging task to bring together the multitude of approaches available for storm trends over the North Atlantic and Western Europe. For the past, it is crucial which data are used and which time period is analysed. Proxy and measurement data generally show no changes in storm numbers or a decrease; only for the Baltic Sea there is a larger variance in trends. These studies mostly cover more than the last 100 years. However, when only the last four to six decades are taken into account, as is the case for the majority of reanalysis and model studies of the past, most studies show increasing trends (compare trends for entire and reanalysis period in Figure 2). This agrees with proxy studies for the last more than 100 years that show large decadal fluctuations, no discernible overall trend, and (among others) an increase in storm numbers from the 1970s until the mid-1990s (e. g. Alexandersson et al.

1998, 2000; WASA 1998, see Figure 2). If longer time scales are regarded, also the model studies show no trends or rather a decrease. For possible future scenario simulations the articles lead to contradictory results in storm numbers and track variations which are up to the model generation used. The closest agreement between the different articles analysed by our review study is given for an increase in storm intensity for the future, no matter which area is regarded.

Acknowledgments

The authors would like to thank all authors of the studies analysed in this review for their research on the important topic of storminess over the North Atlantic and Northwestern Europe. The work was supported (in parts) through the Cluster of Excellence 'CliSAP', University of Hamburg, funded through the German Science Foundation (DFG-EXC177). This work is a contribution to the Helmholtz Climate Initiative REKLIM (Regional Climate Change), a joint research project of the Helmholtz Association of German research centres (HGF). We thank B. Gardeike for her help with some of the figures. The authors would also like to thank the two anonymous reviewers for their constructive comments which helped to improve the article.

References

Albrecht, A., D. Schindler, K. Grebhahn, U. Kohnle, and H. Mayer, 2009: Storminess over the North-Atlantic European region under climatic change – a review. *Allg. Forst Jagdztg.*, **5/6**, 109–118.

Alexander, L. V., S. F. B. Tett, and T. Jonsson, 2005: Recent observed changes in severe storms over the United Kingdom and Iceland. *Geophys. Res. Lett.*, **32**, L13704–L13704.

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

Alexandersson, H., H. Tuomenvirta, T. Schmith, and K. Iden, 2000: Trends of storms in NW Europe derived from an updated pressure data set. *Clim. Res.*, **14**, 71–73.

Allan, R., S. Tett, and L. Alexander, 2009: Fluctuations in autumn–winter severe storms over the British Isles: 1920 to present. *Int. J. Climatol.*, **29**, 357–371, doi:10.1002/joc.1765.

Andersen, U. J., E. Kaas, and W. May, 2001: *Changes in the storm climate in the North Atlantic/European region as simulated by GCM timeslice experiments at high resolution*. http://www.dmi.dk/dmi/dkc01-1.pdf.

Bacon, S., and D. J. T. Carter, 1991: Wave climate changes in the North Atlantic and North Sea. *Int. J. Climatol.*, **11**, 545–588.

Bader, J., M. D. S. Mesquita, K. I. Hodges, N. Keenlyside, S. Østerhus, and M. Miles, 2011: A review on Northern Hemisphere sea-ice, storminess and the North Atlantic Oscillation: Observations and projected changes. *Atmos. Res.*, **101**, 809–834, doi:10.1016/j.atmosres.2011.04.007.

Bakker, A. M. R., and B. J. J. M. van den Hurk, 2012: Estimation of persistence and trends in geostrophic wind speed for the assessment of wind energy yields in Northwest Europe. *Clim. Dyn.*, **39**, 767–782, doi:10.1007/s00382-011-1248-1.

Barredo, J. I., 2010: No upward trend in normalised windstorm losses in Europe: 1970-2008. *Nat. Hazards Earth Syst. Sci.*, **10**, 97–104, doi:10.5194/nhess-10-97-2010.

Bärring, L., and H. von Storch, 2004: Scandinavian storminess since about 1800. *Geophys. Res. Lett.*, **31**, L20202–L20202, doi:10.1029/2004GL020441.

Bärring, L., and K. Fortuniak, 2009: Multi-indices analysis of southern Scandinavian storminess 1780-2005 and links to interdecadal variations in the NW Europe-North Sea region. *Int. J. Climatol.*, **29**, 373–384.

Beersma, J. J., K. M. Rider, G. J. Komen, E. Kaas, and V. V. Kharin, 1997: An analysis of extra-tropical storms in the North Atlantic region as simulated in a control and 2xCO2 time-slice experiment with a high-resolution atmospheric model. *Tellus A*, **49**, 347–361.

Bengtsson, L., K. I. Hodges, and E. Roeckner, 2006: Storm Tracks and Climate Change. *J. Climate*, **19**, 3518–3543.

Bengtsson, L., K. I. Hodges, and N. Keenlyside, 2009: Will Extratropical Storms Intensify in a Warmer Climate? *J. Climate*, **22**, 2276–2301.

Beniston, M. and Coauthors, 2007: Future extreme events in European climate: an exploration of regional climate model projections. *Climatic Change*, **81**, 71–95, doi:http://dx.doi.org/DOI 10.1007/s10584-006-9226-z.

Blackmon, M. L., 1976: A climatological spectral study of the 500 mb Geopotential Height of the Northern Hemisphere. *J. Atmos. Sci.*, **33**, 1607–1623.

Blender, R., and M. Schubert, 2000: Cyclone tracking in different spatial and temporal resolutions. *Mon. Weather Rev.*, **128**, 377–384.

Blender, R., K. Fraedrich, and F. Lunkeit, 1997: Identification of cyclone-track regimes in the North Atlantic. *Q. J. R. Meteorol. Soc.*, **123**, 727–741.

Brönnimann, S., O. Martius, H. von Waldow, C. Welker, J. Luterbacher, G. P. Compo, P. D. Sardeshmukh, and T. Usbeck, 2012: Extreme winds at northern mid-latitudes since 1871. *Meteorol. Z.*, **21**, 13–27, doi:10.1127/0941-2948/2012/0337.

Carnell, R. E., and C. A. Senior, 1998: Changes in mid-latitude variability due to increasing greenhouse gases and sulphate aerosols. *Clim. Dynam.*, **14**, 369–383.

Carter, D. J. T., and L. Draper, 1988: Has the north-east Atlantic become rougher? *Nature*, **332**, 494–494.

Castro, M., C. Fernández, and M. A. Gaertner, 1993: Description of a mesoscale atmospheric numerical model. *Mathematics, Climate and Environment. Rech. Math. Appl. Ser. Mason*, **In Díaz JI, Lions JL (eds)**, 230–253.

Chang, E. K. M., and Y. Fu, 2002: Interdecadal Variations in Northern Hemisphere Winter Storm Track Intensity. *J. Climate*, **15**, 642–658.

Christensen, J. H., O. L. Bøssing Christensen, P. Lopez, E. van Meijgaard, and M. Botzet, 1996: *The HIRHAM4 Regional Atmospheric Climate Model. Scientific Report 96-4.*

Christensen, J. H., T. R. Carter, M. Rummukainen, and G. Amanatidis, 2007a: Evaluating the performance and utility of regional climate models: the PRUDENCE project. *Climatic Change*, **81**, 1–6, doi:10.1007/s10584-006-9211-6.

Christensen, O. B., M. Drews, J. H. Christensen, K. Dethloff, K. Ketelsen, I. Hebestadt, and A. Rinke, 2007b: *The HIRHAM Regional Climate Model Version 5 (beta), Technical Report 06-17*. http://www.dmi.dk/dmi/tr06-17.pdf.

Ciavola, P., O. Ferreira, P. Haerens, M. Van Koningsveld, C. Armaroli, and Q. Lequeux, 2011: Storm impacts along European coastlines. Part 1: The joint effort of the MICORE and ConHaz Projects. *Environmental Science & Policy*, **14**, 912–923, doi:10.1016/j.envsci.2011.05.011.

Cieślikiewicz, W., and B. Paplińska-Swerpel, 2008: A 44-year hindcast of wind wave fields over the Baltic Sea. *Coast. Eng.*, **55**, 894–905.

Coles, S., 2001: *An Introduction to Statistical Modeling of Extreme Values*. Springer, 209 pp.

Compo, G. P. and Coauthors, 2011: Review Article The Twentieth Century Reanalysis Project. *Q. J. R. Meteorol. Soc.*, **137**, 1–28, doi:10.1002/qj.776.

Cornes, R. C., and P. D. Jones, 2012: An examination of storm activity in the northeast Atlantic region over the 1851–2003 period using the EMULATE gridded MSLP data series. *J. Geophys. Res.*, **116**, D16110–D16110, doi:10.1029/2011JD016007.

Cusack, S., 2012: A 101 year record of windstorms in the Netherlands. *Climatic Change*, 1–12, doi:10.1007/s10584-012-0527-0.

Dangendorf, S., S. Müller-Navarra, J. Jensen, F. Schenk, T. Wahl, and R. Weisse, 2014: North Sea storminess from a novel storm surge record since AD 1843. *J. Clim.*, doi:10.1175/JCLI-D-13-00427.1.

Della-Marta, P. M., and J. G. Pinto, 2009: Statistical uncertainty of changes in winter storms over the North Atlantic and Europe in an ensemble of transient climate simulations. *Geophys. Res. Lett.*, **36**, L14703–L14703, doi:10.1029/2009GL038557.

Della-Marta, P. M., H. Mathis, C. Frei, M. A. Liniger, J. Kleinn, and C. Appenzeller, 2009: The return period of wind storms over Europe. *Int. J. Climatol.*, **29**, 437–459, doi:http://dx.doi.org/DOI: 10.1002/joc.1794.

Déqué, M., C. Dreveton, A. Braun, and D. Cariolle, 1994: The ARPEGE/IFS atmosphere model: a contribution to the French community climate modelling. *Clim. Dynam.*, **10**, 249–266, doi:10.1007/BF00208992.

Dodet, G., X. Bertin, and R. Taborda, 2010: Wave climate variability in the North-East Atlantic Ocean over the last six decades. *Ocean Modelling*, **31**, 120–131, doi:10.1016/j.ocemod.2009.10.010.

Donat, M. G., G. C. Leckebusch, J. G. Pinto, and U. Ulbrich, 2010a: European storminess and associated circulation weather types: future changes deduced from a multi-model ensemble of GCM simulations. *Clim. Res.*, **42**, 27–43, doi:10.3354/cr00853.

Donat, M. G., G. C. Leckebusch, J. G. Pinto, and U. Ulbrich, 2010b: Examination of wind storms over Central Europe with respect to circulation weather types and NAO phases. *Int. J. Climatol.*, **30**, 1289–1300, doi:10.1002/joc.1982.

Donat, M. G., D. Renggli, S. Wild, L. V. Alexander, G. C. Leckebusch, and U. Ulbrich, 2011: Reanalysis suggests long-term upward trends in European storminess since 1871. *Geophys. Res. Lett.*, **38**, L14703–L14703, doi:http://dx.doi.org/10.1029/2011GL047995.

Dorn, W., K. Dethloff, A. Rinke, and E. Roeckner, 2003: Competition of NAO regime changes and increasing greenhouse gases and aerosols with respect to Arctic climate projections. *Clim. Dynam.*, **21**, 447–458, doi:http://dx.doi.org/DOI 10.1007/s00382-003-0344-2.

Döscher, R., U. Willén, C. Jones, A. Rutgersson, H. E. M. Meier, U. Hansson, and L. P. Graham, 2002: The development of the coupled regional ocean-atmosphere model RCAO. *Boreal Environ. Res.*, **7**, 183–192.

Dudhia, J., 1993: A nonhydrostatic version of the Penn State – NCAR mesoscale model: Validation tests and simulation of an atlantic cyclone and cold front. *Mon. Wea. Rev.*, **121**, 1493–1513.

Earl, N., S. Dorling, R. Hewston, and R. von Glasow, 2012: 1980–2010 Variability in U.K. Surface Wind Climate. *J. Climate*, **26**, 1172–1191, doi:10.1175/JCLI-D-12-00026.1.

Emeis, K. C. and Coauthors, 2013: THE NORTH SEA - A SHELF SEA IN THE ANTHROPOCENE. *submitted to Journal of Marine Systems*,.

Esteves, L. S., J. J. Williams, and J. M. Brown, 2011: Looking for evidence of climate change impacts in the eastern Irish Sea. *Natural Hazards and Earth System Science*, **11**, 1641–1656, doi:http://dx.doi.org/10.5194/nhess-11-1641-2011.

Ferguson, C. R., and G. Villarini, 2012: Detecting inhomogeneities in the Twentieth Century Reanalysis over the central United States. *J. Geophys. Res.*, **117**, D05123–D05123, doi:10.1029/2011JD016988.

Field, C. B. and Coauthors, 2012: *IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change*.

Fischer-Bruns, I., H. von Storch, J. 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.

Flato, G. M., G. J. Boer, W. G. Lee, N. A. McFarlane, and D. an. R. Ramsden, 2000: The Canadian Centre for Climate Modeling and Analysis global coupled model and its climate. *Clim. Dynam.*, **16**, 451–467, doi:10.1007/s003820050339.

Franzén, L. G., 1991: The changing frequency of gales on the swedish west coast and its possible relation to the increased damage to coniferous forests of Southern Sweden. *Int. J. Climatology*, **11**, 769–793, doi:http://dx.doi.org/10.1002/joc.3370110705.

Geng, Q., and M. Sugi, 2001: Variability of the North Atlantic cyclone activity in winter analyzed from NCEP-NCAR reanalysis data. *J. Climate*, **14**, 3863–3873.

Geng, Q., and M. Sugi, 2003: Possible Change of Extratropical Cyclone Activity due to Enhanced Greenhouse Gases and Sulfate Aerosols—Study with a High-Resolution AGCM. *J. Climate*, **16**, 2262–2274.

Gibson, J. K., P. Kållberg, S. Uppala, A. Hernandez, A. Nomura, and E. Serrano, 1997: *ERA Description*. ftp://ftp.ecmwf.int/pub/era/era15/1_ERA15_Description.ps.gz.

Gómez-Navarro, J. J., and E. Zorita, 2013: Atmospheric annular modes in simulations over the past millennium: No long-term response to external forcing. *Geophys. Res. Lett.*, **40**, 3232–3236, doi:10.1002/grl.50628.

Gordon, C., C. Cooper, C. A. Senior, H. Banks, J. M. Gregory, T. C. Johns, J. F. B. Mitchell, and R. A. Wood, 2000: The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. *Clim. Dynam.*, **16**, 147–168.

Grell, G. A., J. Dudhia, and D. R. Stauffer, 1994: *TN-398: A Description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5)*. http://nldr.library.ucar.edu/collections/technotes/asset-000-000-000-214.pdf.

Gulev, S. K., O. Zolina, and S. Grigoriev, 2001: Extratropical cyclone variability in the Northern Hemisphere winter from the NCEP/NCAR reanalysis data. *Clim. Dynam.*, **17**, 795–809.

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 Atm. Oc. System*, **6**, 121–163.

Gustafsson, B. and Coauthors, 2012: Reconstruction of the Development of the Baltic Sea Eutrophication 1850-2006. *AMBIO*, **41**, 534–548, doi:10.1007/s13280-012-0318-x.

Hall, N. M. J., B. J. Hoskins, V. P. J., and C. A. Senior, 1994: Storm tracks in a high-resolution GCM with doubled carbon dioxide. *Q. J. R. Meteorol. SOC.*, **120**, 1209–1230.

Hammond, J. M., 1990: Storm in a teacup or winds of change? *Weather*, **45**, 443–448, doi:10.1002/j.1477-8696.1990.tb05582.

Hanna, E., J. Cappelen, R. Allan, T. Jónsson, F. Le Blancq, T. Lillington, and K. Hickey, 2008: New Insights into North European and North Atlantic Surface Pressure Variability, Storminess, and Related Climatic Change since 1830. *J. Climate*, **21**, 6739–6766.

Hanson, C. E., J. P. Palutikof, and T. D. Davies, 2004: Objective cyclone climatologies of the North Atlantic – a comparison between the ECMWF and NCEP Reanalyses. *Clim. Dynam*, **22**, 757–769, doi:10.1007/s00382-004-0415-z.

Harnik, L., and E. K. M. Chang, 2003: Storm Track Variations As Seen in Radiosonde Observations and Reanalysis Data. *J. Climate*, **16**, 480–495.

Harvey, B. J., L. C. Shaffrey, T. J. Woollings, G. Zappa, and K. I. Hodges, 2012: How large are projected 21st century storm track changes? *Geophys. Res. Lett.*, **39**, doi:10.1029/2012GL052873.

Hickey, K. R., 2003: The storminess record from Armagh Observatory, Northern Ireland, 1796-1999. *Weather*, **58**, 28–35.

Hodges, 1995: Feature tracking on the unit sphere. *Mon. Weather Rev.*, **123**, 3458–3465.

Hodges, K., 1994: A general method for tracking analysis and its application to meteorological data. *Mon. Weather Rev.*, **122**, 2573–2586.

Hodges, K., 1999: Adaptive constraints for feature tracking. *Mon. Weather Rev.*, **127**, 1362–

1373.

Hodges, K. I., B. J. Hoskins, J. Boyle, and C. Thorncroft, 2003: A Comparison of Recent Reanalysis Datasets Using Objective Feature Tracking: Storm Tracks and Tropical Easterly Waves. *Mon. Weather Rev.*, **131**, 2012–2037.

Hodges, K. I., R. W. Lee, and L. Bengtsson, 2011: A Comparison of Extratropical Cyclones in Recent Reanalyses ERA-Interim, NASA MERRA, NCEP CFSR, and JRA-25. *J. Climate*, **24**, 4888–4906, doi:10.1175/2011JCLI4097.1.

Hofherr, T., and M. Kunz, 2010: Extreme wind climatology of winter storms in Germany. *Clim. Res.*, **41**, 105–123.

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.

Hoskins, B. J., and K. I. Hodges, 2002: New perspectives on the northern hemisphere winter storm tracks. *J. Atmos. Sci.*, **59**, 1041–1061.

Jacob, D., and R. Podzun, 1997: Sensitivity studies with the Regional Climate Model REMO. *Meteor. Atmos. Phys.*, **63**, 119–129.

Johns, T. C., R. E. Carnell, J. F. Crossley, J. M. Gregory, J. F. B. Mitchell, C. A. Senior, S. F. B. Tett, and R. A. Wood, 1997: The second Hadley Centre coupled ocean-atmosphere GCM: Model description, spinup and validation. *Clim. Dynam.*, **13**, 103–134.

Jones, P. D., T. Jonsson, and D. Wheeler, 1997: Extension to the North Atlantic oscillation using early instrumental pressure observations from Gibraltar and south-west Iceland. *Int. J. Climatology*, **17**, 1433–1450.

Jones, R. G., J. M. Murphy, and M. Noguer, 1995: Simulation of climate change over Europe using a nested regional climate model I: Assessment of control climate, including sensitivity to location of lateral boundaries. *Q. J. R. Meteorol. SOC.*, **121**, 1413–1449.

Jónsson, T., and E. Hanna, 2007: A new day-to-day pressure variability index as a proxy of Icelandic storminess and complement to the North Atlantic Oscillation index 1823-2005. *Meteorologische Zeitschrift*, **16**, 25–36, doi:10.1127/0941-2948/2007/0177.

Jungclaus, J. H. and Coauthors, 2006: Ocean Circulation and Tropical Variability in the Coupled Model ECHAM5/MPI-OM. *J. Climate*, **19**, 3952–3972, doi:10.1175/JCLI3827.1.

Kaas, E., T. S. Li, and T. Schmith, 1996: Statistical hindcast of wind climatology in the North Atlantic and northwestern European region. *Clim. Res.*, **07**, 97–110, doi:10.3354/cr0007097.

Kalnay, E. and Coauthors, 1996: The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society*, **77**, 437–471.

Keim, B. D., R. A. Muller, and S. G. W., 2004: Spatial and temporal variability of coastal storms in the North Atlantic Basin. *Mar. Geol.*, **210**, 7–15, doi:http://dx.doi.org/10.1016/j.margeo.2003.12.006.

Kent, E. C., S. Fangohr, and D. I. Berry, 2012: A comparative assessment of monthly mean wind speed products over the global ocean. *Int. J. Climatology*, doi:10.1002/joc.3606.

Kiehl, J. T., and P. R. Gent, 2004: The Community Climate System Model, version 2. *J. Climate*, **17**, 3666–3682.

Kistler, R. and Coauthors, 2001: The NCEP–NCAR 50-Year Reanalysis: Monthly Means CD-ROM and Documentation. *Bull. Amer. Meteor. Soc.*, **82**, 247–267.

Knippertz, P., U. Ulbrich, and P. Speth, 2000: Changing cyclones and surface wind speeds over the North Atlantic and Europe in a transient GHG experiment. *Clim. Res.*, **15**, 109–122.

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

Krueger, O., and H. von Storch, 2011: Evaluation of an Air Pressure–Based Proxy for Storm Activity. *J. Climate*, **24**, 2612–2619.

Krueger, O., and H. von Storch, 2012: The informational value of pressure-based single-station proxies for storm activity. *J. Atmos. Oceanic Technol.*, **29**, 569–580.

Krueger, O., F. Feser, L. Bärring, E. Kaas, T. Schmith, H. Tuomenvirta, and H. von Storch, 2013a: Comment on "'Trends and low frequency variability of extratropical cyclone activity in the ensemble of twentieth century reanalysis'" by Xiaolan L. Wang, Y. Feng, G. P. Compo,V. R. Swail, F. W. Zwiers, R. J. Allan, and P. D. Sardeshmukh, Climate Dynamics, 2012. *Clim. Dyn.*, doi:10.1007/s00382-013-1814-9.

Krueger, O., F. Schenk, F. Feser, and R. Weisse, 2013b: Inconsistencies between Long-Term Trends in Storminess Derived from the 20CR Reanalysis and Observations. *J. Climate*, **26**, 868–874, doi:10.1175/JCLI-D-12-00309.1.

Kunz, M., S. Mohr, M. Rauthe, R. Lux, and C. Kottmeier, 2010: Assessment of extreme wind speeds from Regional Climate Models – Part 1: Estimation of return values and their evaluation. *Nat. Hazards Earth Syst. Sci.*, **10**, 1–15.

Lambert, S., J. Sheng, and J. Boyle, 2002: Winter cyclone frequencies in thirteen models participating in the Atmospheric Model Intercomparison Project (AMIP1). *Clim. Dynam.*, **19**, 1–16, doi:http://dx.doi.org/10.1007/s00382-001-0206-8.

Lambert, S. J., 1995: The effect of enhanced greenhouse warming on winter cyclone frequencies and strengths. *J. Climate*, **8**, 1447–1452, doi:10.1175/1520-0442(1995)008<1447:TEOEGW>2.0.CO;2.

Lambert, S. J., 2004: Changes in winter cyclone frequencies and strengths in transient enhanced greenhouse warming simulations using two coupled climate models. *Atmosphere-Ocean*, **42**, 173–181, doi:http://dx.doi.org/10.3137/ao.420302.

Lambert, S. J., and J. C. Fyfe, 2006: Changes in winter cyclone frequencies and strengths simulated in enhanced greenhouse warming experiments: results from the models participating in the IPCC diagnostic exercise. *Clim. Dynam.*, **26**, 713–728, doi:http://dx.doi.org/DOI 10.1007/s00382-006-0110-3.

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.

Leckebusch, G. C., and U. Ulbrich, 2004: On the relationship between cyclones and extreme windstorm events over Europe under climate change. *Global Planet. Change*, **44**, 181–193.

Leckebusch, G. C., B. Koffi, U. Ulbrich, J. G. Pinto, T. Spangehl, and S. Zacharias, 2006: Analysis of frequency and intensity of European winter storm events from a multi-model perspective, at synoptic and regional scales. *Clim. Res.*, **31**, 59–74.

Leckebusch, G. C., D. Renggli, and U. Ulbrich, 2008a: Development and application of an objective storm severity measure for the Northeast Atlantic region. *Meteorol. Z.*, **17**, 575–587, doi:10.1127/0941-2948/2008/0323.

Leckebusch, G. C., A. Weimer, J. G. Pinto, M. Reyers, and P. Speth, 2008b: Extreme wind storms over Europe in present and future climate: a cluster analysis approach. *Meteorol. Z.*, **17**, 1067–1082.

Legutke, S., and R. Voss, 1999: *The Hamburg atmosphere-ocean coupled model ECHO-G.Technical Report 18*. http://www.mad.zmaw.de/fileadmin/templates/fileicons/pdf.gif.

Lehmann, A., K. Getzlaff, and J. Harlaß, 2011: Detailed assessment of climate variability in the Baltic Sea area for the period 1958 to 2009. *Clim. Res.*, **46**, 185–196, doi:10.3354/cr00876.

Van der Linden, P., J. F. B. Mitchell, and P. Gilbert, 2009: *ENSEMBLESClimate change and its impacts at seasonal, decadal and centennial timescalesSummary of research and results from the ENSEMBLES project*. http://ensembles-eu.metoffice.com/docs/Ensembles_final_report_Nov09.pdf.

Lindenberg, J., H.-T. Mengelkamp, and G. Rosenhagen, 2012: Representativity of near surface wind measurements from coastal stations at the German Bight. *Meteorol. Z.*, **21**, 099–106.

Löptien, U., O. Zolina, A. Gulev, M. Latif, and V. Soloviov, 2008: Cyclone life cycle characteristics over the Northern Hemisphere in coupled GCMs. *Clim. Dyn.*, **31**, 507–532, doi:10.1007/s00382-007-0355-5.

Lüthi, D., A. Cress, H. C. Davies, C. Frei, and C. Schär, 1996: Interannual Variability and Regional Climate Simulations. *Theor. Appl. Climatol.*, **53**, 185–209.

Malberg, H., and G. Bökens, 1993: Änderungen im Druck-, Geopotential- und Temperaturgefälle zwischen Subtropen und Subpolarregion im atlantischen Bereich im Zeitraum 1960-1990. *Meteorol. Z.*, **2**, 131–137.

Matulla, C., W. Schöner, H. Alexandersson, H. von Storch, and X. Wang, 2007: European storminess: late nineteenth century to present. *Clim. Dynam.*, **31**, 125–130, doi:10.1007/s00382-007-0333-y.

McVicar, T. R. and Coauthors, 2012: Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation. *Journal of Hydrology*, **416-417**, 182–205, doi:10.1016/j.jhydrol.2011.10.024.

Van Meijgaard, E., L. H. van Ulft, W. J. van de Berg, F. C. Bosveld, B. J. J. M. van den Hurk, G. Lenderink, and A. P. Siebesma, 2008: *KNMI Technical Report: The KNMI regional atmospheric climate model RACMO, version 2.1.Available from KNMI, Postbus 201, 3730 AE, De Bilt, The Netherlands*.

Menéndez, M., and P. L. Woodworth, 2010: Changes in extreme high water levels based on a quasi-global tide-gauge data set. *J. Geophys. Res.*, **115**, doi:10.1029/2009JC005997.

Mizuta, R., 2012: Intensification of extratropical cyclones associated with the polar jet change in the CMIP5 global warming projections. *Geophys. Res. Lett.*, **39**, L19707–L19707, doi:10.1029/2012GL053032.

Murray, R., and I. Simmonds, 1991: A numerical scheme for tracking cyclone centres from digital data Part I: development and operation of the scheme. *Aust. Meteor. Mag.*, **39**, 155–166.

Musić, S., and S. Nicković, 2008: 44-year wave hindcast for the Eastern Mediterranean. *Coast. Eng.*, **55**, 872–880.

Muskulus, M., and D. Jacob, 2005: Tracking cyclones in regional model data□: the future of Mediterranean storms. *Adv. Geosci.*, **2**, 13–19.

Neu, H. J. A., 1984: Interannual variations and longer-term changes in the sea state of the North Atlantic. *J. Geophys. Res.*, **89**, 6397–6402.

Neu, U. and Coauthors, 2013: IMILAST: A Community Effort to Intercompare Extratropical Cyclone Detection and Tracking Algorithms. *Bull. Amer. Meteor. Soc.*, **94**, 529–547, doi:10.1175/BAMS-D-11-00154.1.

Nilsson, C., 2008: Windstorms in Sweden - Variations and Impacts. Dissertation, Lund University, 30pp., Lund, .

Nilsson, C., I. Stjernquist, L. Bärring, P. Schlyter, A. M. Jänsson, and H. Samuelsson, 2004: Recorded storm damage in Swedish forests 1901-2000. *Forest Ecol. Manag.*, **199**, 165–173, doi:10.1016/j.foreco.2004.07.031.

Oberhuber, J. M., 1992: *Report No.7 - The OPYC Ocean General Circulation Model*. http://cera-www.dkrz.de/DKRZ_Reports/ReportNo.7.ps.

Onogi, K. and Coauthors, 2007: The JRA-25 Reanalysis. *J. Meteor. Soc. Japan*, **85**, 369–432.

Paciorek, C. J., R. J. S., V. Ventura, and R. D. Rosen, 2002: Multiple Indices of Northern Hemisphere Cyclone Activity, Winters 1949–99. *J. Climate*, **15**, 1573–1590.

Pinto, J. G., and C. C. Raible, 2012: Past and recent changes in the North Atlantic oscillation. *WIREs Clim Change*, **3**, 79–90, doi:10.1002/wcc.150.

Pinto, J. G., T. Spangehl, U. Ulbrich, and P. Speth, 2006: Assessment of winter cyclone activity in a transient ECHAM4-OPYC3 GHG experiment. *Meteorol. Z.*, **15**, 279–291, doi:10.1127/0941-2948/2006/0128.

Pinto, J. G., U. Ulbrich, G. C. Leckebusch, T. Spangehl, M. Reyers, and S. Zacharias, 2007: Changes in storm track and cyclone activity in three SRES ensemble experiments with the ECHAM5/MPI-OM1 GCM. *Clim. Dynam.*, **29**, 195–210, doi:http://dx.doi.org/DOI 10.1007/s00382-007-0230-4.

Pinto, J. G., C. P. Neuhaus, A. Krüger, and M. Kerschgens, 2009a: Assessment of the wind gust estimates method in mesoscale modelling of storm events over West Germany. *Meteorol. Z.*, **18**, 495–506.

Pinto, J. G., S. Zacharias, A. H. Fink, G. C. Leckebusch, and U. Ulbrich, 2009b: Factors contributing to the development of extreme North Atlantic cyclones and their relationship with the NAO. *Clim. Dynam.*, **32**, 711–737, doi:http://dx.doi.org/DOI: 10.1007/s00382-008-0396-4.

Pinto, J. G., C. P. Neuhaus, G. C. Leckebusch, M. Reyers, and M. Kerschgens, 2010: Estimation of wind storm impacts over Western Germany under future climate conditions using a statistical–dynamical downscaling approach. *Tellus A*, **62**, 188–201, doi:10.1111/j.1600-0870.2009.00424.x.

Pinto, J. G., M. K. Karremann, K. Born, P. M. Della-Marta, and M. Klawa, 2012: Loss potentials associated with European windstorms under future climate conditions. *Clim. Res.*, **54**, 1–20, doi:10.3354/cr01111.

Raible, C., and R. Blender, 2004: Northern Hemisphere midlatitude cyclone variability in GCM simulations with different ocean representations. *Clim. Dynam.*, **22**, 239–248.

Raible, C., Yoshimori M., Stocker T. F., and C. Casty, 2007: Extreme midlatitude cyclones and their implications for precipitation and wind speed extremes in simulations of the Maunder Minimum versus present day conditions. *Clim. Dynam.*, **28**, 409–423.

Raible, C., P. M. Della-Marta, Schwierz C., and B. R., 2008: Northern Hemisphere extratropical cyclones: a comparison of detection and tracking methods and different reanalyses. *Mon. Weather Rev.*, **136**, 880–897.

Rauthe, M., M. Kunz, and C. Kottmeier, 2010: Changes in wind gust extremes over Central Europe derived from a small ensemble of high resolution regional climate models. *Meteorol. Z.*, **19**, 299–312, doi:10.1127/0941-2948/2010/0350.

Rienecker, M. M. and Coauthors, 2011: MERRA: NASA's Modern-Era Retrospective Analysis for Research and Applications. *J. Climate*, **24**, 3624–3648.

Rockel, B., and K. Woth, 2007: Extremes of near-surface wind speed over Europe and their future changes as estimated from an ensemble of RCM simulations. *Climatic Change*, **81**, 267–280.

Rockel, B. W., and A. Hense, 2008: The regional climate model COSMO-CLM (CCLM). *Meteorol. Z*, **12**, 347–348.

Roeckner, E. and Coauthors, 1992: *MPI-Report No. 93 - Simulation of the present-day climate with the ECHAM model: Impact of model physics and resolution*. http://www.mpimet.mpg.de/fileadmin/publikationen/Reports/MPI-Report_93.pdf.

Roeckner, E. and Coauthors, 2003: *MPI-Report No. 349 - The atmospheric general circulation model ECHAM 5. PART I: Model description*. http://www.mpimet.mpg.de/fileadmin/publikationen/Reports/max_scirep_349.pdf.

Roeckner, E. and Coauthors, 2004: *MPI-Report No. 354 - The atmospheric general circulation model ECHAM5 Part II: Sensitivity of simulated climate to horizontal and vertical resolution*. http://www.mpimet.mpg.de/fileadmin/publikationen/Reports/max_scirep_354.pdf.

Rudeva, I., and S. K. Gulev, 2011: Composite analysis of North Atlantic extratropical cyclones in NCEP-NCAR reanalysis data. *Mon. Weather Rev.*, **139**, 1419–1446.

Saha, S. and Coauthors, 2006: The NCEP Climate Forecast System. *J. Climate*, **19**, 3483–3517.

Saha, S. and Coauthors, 2010: The NCEP Climate Forecast System reanalyses. *Bull. Amer. Meteor. Soc.*, **91**, 1015–1057.

Scharenbroich, L., G. Magnusdottir, P. Smyth, H. Stern, and C. Wang, 2010: A Bayesian framework for storm tracking using a hidden-state representation. *Mon. Weather Rev.*, **138**, 2132–2148.

Schenk, F., and E. Zorita, 2012: Reconstruction of high resolution atmospheric fields for Northern Europe using analog-upscaling. *Clim. Past*, **8**, 1681–1703, doi:10.5194/cp-8-1681-2012.

Schiesser, H. H., C. Pfister, and J. Bader, 1997: Winter storms in Switzerland North of the Alps 1864/1865-1993/1994. *Theor. Appl. Climatol.*, **58**, 1–19, doi:10.1007/BF00867428.

Schmidt, H., and H. von Storch, 1993: German Bight storms analysed. *Nature*, **365**, 791–791.

Schmith, T., 1995: Occurrence of severe winds in Denmark during the past 100 years. Proc. Sixth Int. Meeting on Statistical Climatology, Galway, Ireland, All-Ireland Statistics Committee and Cosponsors, All-Ireland Statistics Committee and Cosponsors, 83–86 http://imsc.pacificclimate.org/proceedings/6IMSC.pdf.

Schmith, T., E. Kaas, and T.-S. Li, 1998: Northeast Atlantic winter storminess 1875–1995 re-analysed. *Clim. Dynam.*, **14**, 529–536.

Schneidereit, A., R. Blender, K. Fraedrich, and F. Lunkeit, 2007: Icelandic climate and North Atlantic cyclones in ERA-40 reanalyses. *Meteorol. Z.*, **16**, 017–023, doi:10.1127/0941-2948/2007/0187.

Schneidereit, A., R. Blender, and K. Fraedrich, 2010: A radius –depth model for midlatitude cyclones in reanalysis data and simulations. *Q. J. R. Meteorol. SOC.*, **136**, 50–60, doi:10.1002/qj.523.

Schubert, M., Perlwitz J., R. Blender, K. Fraedrich, and F. Lunkeit, 1998: North Atlantic cyclones in CO2-induced warm climate simulations: frequency, intensity and tracks. *Clim. Dynam.*, **14**, 827–837.

Serreze, M. C., 1995: Climatological aspects of cyclone development and decay in the arctic. *Atmos. Ocean*, **33(1)**, 1–23.

Sickmoeller, M., Blender R., and K. Fraedrich, 2000: Observed winter cyclone tracks in the northern hemisphere in re-analysed ECMWF data. *Q. J. R. Meteorol. SOC.*, **126**, 591–620.

Siegismund, F., and C. Schrum, 2001: Decadal changes in the wind forcing over the North Sea. *Clim. Res.*, **18**, 39–45.

Simmonds, I., and K. Keay, 2002: Surface fluxes of momentum and mechanical energy over the North Pacific and North Atlantic Oceans. *Meteorol. Atmos. Phys.*, **80**, 1–18.

Simmons, A., S. Uppala, D. Dee, and S. Kobayashi, 2007: ERA-Interim: New ECMWF reanalysis products from 1989 onwards. *ECMWF Newsletter, No. 110, ECMWF, Reading, United Kingdom*, 25–35.

Smits, A., A. M. G. Klein Tank, and G. P. Können, 2005: Trends in Storminess over the Netherlands, 1962–2002. *Int. J. Climatol.*, **25**, 1331–1344, doi:10.1002/joc.1195.

Steppeler, J., G. Doms, U. Schättler, H. W. Bitzer, A. Gassmann, U. Damrath, and G. Gregoric, 2003: Meso-gamma scale forecasts using the nonhydrostatic model LM. *Meteorol. Atmos. Phys.*, **82**, 75–96.

Sterl, A., H. van den Brink, H. de Vries, R. Haarsma, and E. van Meijgaard, 2009: An ensemble study of extreme North Sea storm surges in a changing climate. *Ocean Sci. Discuss.*, **6**, 1031–1059.

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.

Von Storch, H., and F. W. Zwiers, 1999: *Statistical Analysis in Climate Research*. Cambridge University Press, 494 pp.

Von Storch, H., G. Gönnert, and M. Meine, 2008: Storm surges – an option for Hamburg, Germany, to mitigate expected future aggravation of risk. *Env. Sci. Pol.*, **11**, 735–742, doi:10.1016/j.envsci.2008.08.003.

Suvilampi, E., 2009: Voimakkaiden geostrofisten tuulten alueellisuus ja muutokset Suomessa vuosina 1884-2100. Pro Gradu- tutkielma. Turun yliopisto, maantieteen laitos, http://cdn.fmi.fi/legacy-fmi-fi-content/documents/Pro_gradu_elina_suvilampi.pdf.

Sweeney, J., 2000: A three-century storm climatology for Dublin 1715-2000. *Irish Geography*, **33**, 1–14, doi:http://dx.doi.org/10.1080/00750770009478595.

Trigo, I. F., 2006: Climatology and interannual variability of storm-tracks in the Euro-Atlantic sector: a comparison between ERA-40 and NCEP/NCAR reanalyses. *Clim. Dynam.*, **26**, 127–143, doi:http://dx.doi.org/DOI 10.1007/s00382-005-0065-9.

Trouet, V., J. D. Scourse, and C. C. Raible, 2012: North Atlantic storminess and Atlantic Meridional Overturning Circulation during the last Millennium: Reconciling contradictory proxy records of NAO variability. *Global Planet. Change*, **84-85**, 48–55, doi:10.1016/j.gloplacha.2011.10.003.

Ulbrich, U., and M. Christoph, 1999: A shift of the NAO and increasing storm track activity over Europe due to anthropogenic greenhouse gas forcing. *Clim. Dynam.*, **15**, 551–559.

Ulbrich, U., J. G. Pinto, H. Kupfer, G. C. Leckebusch, T. Spangehl, and M. Reyers, 2008: Changing Northern Hemisphere Storm Tracks in an Ensemble of IPCC Climate Change Simulations. *J. Climate*, **21**, 1669–1679, doi:http://dx.doi.org/DOI: 10.1175/2007JCLI1992.1.

Ulbrich, U., G. C. Leckebusch, and J. G. Pinto, 2009: Extra-tropical cyclones in the present and future climate: a review. *Theor. Appl. Climatol.*, **96**, 117–131, doi:http://dx.doi.org/DOI 10.1007/s00704-008-0083-8.

Ulbrich, U. L., I. Rudeva, I. Simmonds, N. D. Tilinina, I. F. Trigo, S. Ulbrich, X. L. Wang, and H. Wernli, 2013: Are Greenhouse Gas Signals of Northern Hemisphere winter extra-tropical cyclone activity dependent on the identification and tracking methodology? *Meteorol. Z.*, **22**, 61–68, doi:10.1127/0941-2948/2013/0420.

Uppala, S. M. and Coauthors, 2005: The ERA-40 re-analysis. *Quart. J. Roy. Meteor. Soc.*, **131**, 2961–3012.

Usbeck, T., T. Wohlgemuth, C. Pfister, R. Volz, M. Beniston, and M. Dobbertin, 2010: Wind speed measurements and forest damage in Canton Zurich (Central Europe) from 1891 to winter 2007. *Int. J. Climatology*, **30**, 347–358, doi:10.1002/joc.1895.

Vautard, R. C., P. Yiou, J.-N. Thépaut, and P. Ciais, 2010: Northern Hemisphere atmospheric stilling partly attributed to an increase in surface roughness. *Nat. Geosci.*, **3**, 756–761, doi:10.1038/ngeo979.

Vilibic, I., and J. Sepic, 2010: Long-term variability and trends of sea level storminess and extremes in European Seas. *Global and Planetary Change*, **71**, 1–12, doi:10.1016/j.gloplacha.2009.12.001.

Visser, H., and A. C. Petersen, 2012: Inferences on weather extremes and weather-related disasters: a review of statistical methods. *Clim. Past*, **8**, 265–286, doi:10.5194/cp-8-265-2012.

Wakelin, S. L., P. L. Woodworth, R. A. Flather, and J. A. Williams, 2003: Sea-level dependence on the NAO over the NW European continental shelf. *Geophys. Res. Lett.*, **30**, 1403–1403, doi:10.1029/2003GL017041.

Walter, A. and Coauthors, 2006: A high resolution reference data set of German wind velocity 1951–2001 and comparison with regional climate model results. *Meteorol.*

Z., **15**, 585–596, doi:10.1127/0941-2948/2006/0162.

Wang, X., F. Zwiers, V. Swail, and Y. Feng, 2009: Trends and variability of storminess in the Northeast Atlantic region, 18742007. *Clim. Dyn.*, **33**, 1179–1195, doi:10.1007/s00382-008-0504-5.

Wang, X. L., V. R. Swail, and F. W. Zwiers, 2006: Climatology and changes of extratropical cyclone activity: comparison of ERA40 with NCEP-NCAR reanalysis for 1958-2001. *J. Climate*, **19**, 3145–3166.

Wang, X. L. and Coauthors, 2011: Trends and low-frequency variability of storminess over western Europe, 1878–2007. *Clim. Dyn.*, **37**, 2355–2371, doi:10.1007/s00382-011-1107-0.

Wang, X. L., Y. Feng, G. P. Compo, V. R. Swail, F. W. Zwiers, R. J. Allan, and P. D. Sardeshmukh, 2012: Trends and low frequency variability of extra-tropical cyclone activity in the ensemble of Twentieth Century Reanalysis. *Clim. Dyn.*, doi:10.1007/s00382-012-1450-9.

Wang, X. L., Y. Feng, G. P. Compo, F. W. Zwiers, R. J. Allan, V. R. Swail, and R. D. Sardeshmukh, 2013: Is the storminess in the Twentieth Century Reanalysis really inconsistent with observations? A reply to the comment by Krueger et al. (2013b). *Clim. Dyn.*, doi:10.1007/s00382-013-1828-3.

Wanner, H., S. Brönnimann, C. Casty, D. Gyalistras, J. Luterbacher, C. Schmutz, D. B. Stephenson, and E. Xoplaki, 2001: North Atlantic Oscillation – Concepts And Studies. *Surveys in Geophysics*, **22**, 321–381.

WASA, G., 1998: Changing Waves and Storms in the Northeast Atlantic? *Bull. Amer. Meteor. Soc.*, **79**, 741–760, doi:10.1175/1520-0477(1998)079<0741:CWASIT>2.0.CO;2.

Weisse, R., and A. Plüß, 2006: 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., and H. Günther, 2007: Wave climate and long-term changes for the Southern North Sea obtained from a high-resolution hindcast 1958-2002. *Ocean Dynamics*, **57**, 161–172, doi:10.1007/s10236-006-0094-x.

Weisse, R., and H. von Storch, 2009: *Marine Climate and Climate Change. Storms, Wind Waves and Storm Surges*. Springer Praxis, 219 pp. http://www.springer.com/earth+sciences+and+geography/book/978-3-540-25316-7.

Weisse, R., H. von Storch, and F. Feser, 2005: Northeast Atlantic and North Sea Storminess as Simulated by a Regional Climate Model during 1958-2001 and Comparison with Observations. *J. Climate*, **18**, 465–479.

Weisse, R. von S., H. D. Niemeyer, and H. Knaack, 2012: Changing North Sea storm surge climate: An increasing hazard? *Ocean Coast. Manage.*, **68**, 58–68, doi:10.1016/j.ocecoaman.2011.09.005.

Wern, L., and L. Bärring, 2009: *Sveriges vindklimat 1901-2008 - Analys av förändring i geostrofisk vind.*

Wernli, H., and C. Schwierz, 2006: Surface cyclones in the ERA-40 dataset (1958-2001). Part I: novel identification method and global climatology. *J. Atmos. Sci.*, **63**, 2486–2507.

De Winter, R. C., A. Sterl, and B. G. Ruessink, 2013: Wind extremes in the North Sea Basin under climate change: An ensemble study of 12 CMIP5 GCMs. *J. Geophys. Res.*, **118**, 1601–1612, doi:10.1002/jgrd.50147.

Woodworth, P. L., and D. L. Blackman, 2002: Changes in extreme high waters at Liverpool since 1768. *International Journal of Climatology*, **22**, 697–714, doi:10.1002/joc.761.

Woodworth, P. L., and D. L. Blackman, 2004: Evidence for Systematic Changes in Extreme High Waters since the Mid-1970s. *J. Climate*, **17**, 1190–1197.

Woollings, T., J. M. Gregory, J. G. Pinto, M. Reyers, and D. J. Brayshaw, 2012: Response of the North Atlantic storm track to climate change shaped by ocean–atmosphere coupling. *Nat. Geosci.*, doi:http://dx.doi.org/DOI: 10.1038/NGEO1438.

Xia, L., H. von Storch, and F. Feser, 2013: Quasi-stationarity of centennial Northern Hemisphere midlatitude winter storm tracks. *Clim. Dyn.*, **41**, 901–916, doi:10.1007/s00382-012-1543-5.

Xia, X., M. Zahn, K. Hodges, F. Feser, and H. von Storch, 2012: A Comparison of Two Identification and Tracking Methods for Polar Lows. *Tellus A*, **64**, doi:10.3402/tellusa.v64i0.17196.

Yin, J. H., 2005: A consistent poleward shift of the storm tracks in simulations of 21st century climate. *Geophys. Res. Lett.*, **32**, L18701–L18701, doi:http://dx.doi.org/10.1029/2005GL023684.

Zahn, M., and H. von Storch, 2008: Tracking Polar Lows in CLM. *Meteorol. Z.*, **17**, 445–453, doi:10.1127/0941-2948/2008/0317.

Zahn, M., H. Von Storch, and S. Bakan, 2008: Climate mode simulation of North Atlantic polar lows in a limited area model. *Tellus Series A-dynamic Meteorology and Oceanography*, **60**, 620–631, doi:http://dx.doi.org/10.1111/j.1600-0870.2008.00330.x.

Zappa, G., L. C. Shaffrey, K. I. Hodges, P. G. Sansom, and D. B. Stephenson, 2013: A multi-model assessment of future projections of North Atlantic and European extratropical cyclones in the CMIP5 climate models. *J. Climate*, doi:10.1175/JCLI-D-12-00573.1.

Study	Data	Scenario	Method	Full time span	Period A vs. Period B	Season	Region	NAO or track shift
Alexander and Tett, 2005	SLP observations		N dSLP >10 hPa in 3 h	1959 - 2003	1959-1982 - 1983-2003	ONDJFM	UK, Iceland	Correlation Iceland: 0.8, UK 0.5 in SONDJF
Alexandersson et al., 1998, 2000	SLP observations		High percentiles of geostrophic wind speeds (triangle)	1871 - 1998		ANN	North Atlantic	DJF linked to NAO
Andersen et al., 2001	ECHAM4, T106	IS92a	SLP, WS stat., 500hPa high frequency variability	1970 to 1999 and 2060 to 2089	1970 to 1999 and 2060 to 2089	NOV-MAR	30°-80°N, 90°W-50°E	Moderate downstream shift/extension of the Atlantic storm track and an overall zonalization (i.e., enhanced westerlies) of the mean flow between 50 and 70°N
Bakker and van den Hurk, 2012	ECHAM5/MPI-OM	SRES A1B	WS percentiles, cyclone activity	Obs SLP: 12 long time series between 1861 and 2010; Model: 1950–2100	Model: 1950–2000 and 2001–2100	ANN	Northwest Europe	
Barredo, 2010	Windstorm loss data, NATHAN database Munich Re		Normalisation of windstorm event losses	1970–2008		ANN	Europe	
Bärring and von Storch, 2004	SLP observations		N < 980hPa, N > 16hPa/16h (absolute dSLP) etc. per year	1780 - 2002		ANN	S Sweden	
			N < 980 hPa Lund	1780 - 2002		ANN	Lund	
			P95 and P99 of annual dp/dt	1823 - 2002		ANN	Stockholm	
Bärring and Fortuniak, 2009	SLP observations		Eight different indices, Stockholm and Lund, PC1 over 8 cyclone activity indices	1780 - 2005		ANN	S Sweden	
Barstad et al., 2012	Arpege/IFS model, ERA40, averaged annual power production	A1B with 4 GCMs, bias and drift corrected for future for SST and sea-ice			1971-2001 - 2020-2049	ANN	N-Atlantic + NW Europe	
Beersma et al., 1997	ECHAM3 T106, ECMWF, DNMI	20C, 2xC02 after 60 years after mid-1980s	500hPa height var., MSLP, surf. WS, core pressure, POT (WS),	5 years within 1979-1988 and 5 years 60 years later (2xCO2)	5Y in mid-1980s and 5Y in mid-2040s; comp. with ECMWF: 1986-1990 (low NAO) and 1991-1995 (high NAO)	DJF	NA, Europe, 14°-86°N, 83°W-54°E	
							North Atlantic	
							North Sea, Bay of Biscay	
Bengtsson and Hodges, 2006	ECHAM5-OM, coupled, T63	A1B for 2000-2100	Tracking algorithm with 850 hPa vorticity(Hodges, 1995, 1996, 1999)	Historical, A1B	1961-90, 2071-2100	DJF, MAM, JJA, SON	Global	Poleward shift of storm activity for climate change
Bengtsson et al., 2009	ECHAM5, T213 (63 km)	A1B		1959-90, 2069-2100	1959-90, 2069-2100	All	NH+SH (globally)	General poleward migration
						All-JJA	NH	
						JJA	NH	
						All	southern Europe	
						DJF	northern Europe	
							Arctic	
Beniston et al., 2007	RCMs, PRUDENCE	A2	Maxima, percentiles, POT, PDF	1961-1990 and 2071-2100	1961-1990 and 2071-2100	DJF	Europe, Eastern North Atlantic	WS becomes more north-westerly
							45°-55°N, Ocean, North Sea, Western Europe	
							Below 45°N and above 55°N	
Blender et al., 1997	ECMWF, 1000hPa height field, 1.0x1.0, 6h		Lagrangian climatology, cluster analysis	1990-1994		Winter (NOV-MAR)	North Atlantic, 80°W-30°E, 30°N-80°N	
Brönnimann et al., 2012	20CR		Block approach, POT	1871-2008	1871-2008 and 1950-2008	DJF	Northern hemisphere mid-latitudes	Poleward shift of NA storm track
Carnell and Senior, 1998	HADCM2CON, 2.5x3.75 degree, 19L, ocean 20L	20C, GHG: 1%CO2/Y from 1990, SUL: GHG+sulphate aerosols	Tracking	1990-2110	2006-2036 and 2070-2100	DJF	Northern hemisphere	Shortened storm track over eastern North Atlantic, almost unchanged position
							GHG, SUL, North Atlantic	
Carter and Draper, 1988	Wave observations		significant wave height from observations	1962 - 1990		ANN		
Chang and Fu, 2002	NCEP/NCAR 2.5x2.5 deg., radiosonde obs		EOFs, 24h difference filter	1948-1998		DJF	Northern hemisphere	
							90°W-50°E North Atlantic	
Ciavola et al., 2011	Water level, observations		Storm intensity, storm duration, storm frequency	1963 - 2008		ANN	UK, Irish Sea	
(collected in Tab. 3 from MICORE)	Max monthly wind speed, observations		Storm intensity, storm duration, storm frequency	1929 - 2002		ANN	UK, Irish Sea	
	Significant wave height, hindcast		Storm intensity, storm duration, storm frequency	1960 - 2007		ANN	UK, Irish Sea	
	Wind, waves and surge, only observations		Storm intensity	1925 (1955) - 2000 (2007)		ANN	Belgium	
	Wind and surge, waves from hindcast		Storm intensity	1890 (1962) - 1990 (2008)		ANN	Netherlands	
	Wind and surge, waves from hindcast		Storm frequency	1890 (1962) - 1990 (2008)		ANN	Netherlands	
	Surge, waves and storm energy, waves from hindcast		Storm intensity, storm duration, storm frequency	1947 (1958) - 2000 (2007)		ANN	Poland, S-Baltic	
Cornes and Jones, 2011	MSLP, EMULATE		Seasonal percentiles of geostr. WS	1851–2003		DJF, JJA	65°W–45°E, 30°N–65°N	
Cusack, 2012	Wind observations		N of damaging storms per year and storm loss index, decadal running mean, from homogenized WS observations, 99 annual pctl. from empirical loss index with cubic relation to WS	1910 - 2010		ANN	Netherlands	

Table 1: Overview of reviewed studies: Models and data used, scenarios, methods, time span, compared time periods, season, region and possible shift of storm tracks or the North Atlantic Oscillation (NAO).

Study	Data	Scenario	Method	Full time span	Period A vs. Period B	Season	Region	NAO or track shift
de Kraker, 1999	Proxy Historical Documentary		Dyke repair costs, "storm severity in points"	1488 - 1609		ANN	NE coast Flanders	
	Water level, observations		Storm surges and storminess, max. height in cm, when high tide exceeded	1848 - 1990		ANN	Flushing	
de Winter et al., 2013	12 CMIP5 GCMs	rcp4.5 and rcp8.5	Annual maximum wind speed, WS direction	1950–2100	1950–2000, 2050–2100	ANN	North Sea Basin	Poleward shift in storm tracks
Della-Marta et al., 2009	ERA40		POT, RP of WS and wind gusts	1957-2002		OCT-APR	NA and Europe, 35°W to 35°E, and 35 to 73°N	
Della-Marta and Pinto, 2009	ECHAM5/OM1, NCEP/NCAR, ERA40	A1B, A2	Tracking, Return Periods of min CP and max VOR	1860-2100	1960-2000, 2060-2100	OCT-MAR	North Atlantic, 35°N–70°N, 80°W–0°E	
							45N–65N, 30W–10E	
							British Isles/North Sea/western Europe, 45°N-60°N, 10°W-30°E	
Dodet et al., 2010	Yearly mean of Hs values higher than the annual Hs 90 pctl.		Spectral wave model forced by NCEP	1953 - 2009		ANN	55°N, 12.5°W (NE-Atlantic)	Strong positive correlation to mean winter NAO
				1953 - 2009		ANN	45°N, 12.5°W	
				1953 - 2009		ANN	35° N, 12.5° W	Weak negative correlation to mean winter NAO
Donat et al., 2010a	ERA40		MSLP, daily max WS	1961-2000		OCT-MAR	Central Europe, focus at 50°N, 10°E	
Donat et al., 2010b	9 AOGCMs, ENSEMBLES project, ERA40 for validation	20C, A1B	MSLP, max. WS, tracking, gale days, POT	1960-2000, 2070-2100	1960-2000, 2070-2100	OCT-MAR	Europe	Increased mean westerly flow during winter
							NE Atlantic, North Sea	
Donat et al., 2011	20th Century Reanalysis MSLP, windspeed		High percentiles of daily max wind speeds + gale index (press. Differences)	1881-2008		Annual, Seasonal	Northsea/UK/Scandinavia /Central Europe	
Dorn et al., 2003	HIRHAM4 0.5 x 0.5 deg., 19L, forced with ECHAM4/HOPE-G and ECHAM4/ OPYC3	20C, IS92a	NAO variability studied	1860-2050	12 x 6 years; concentrations from 1860-1990 (obs) and 1990-2050 (IS92a)	DEC-MAR	Artic north of 65°N	NAO shifted to the west
Esteves et al., 2011	Wind observation, Bidston Observatory, Hill at 70 m		Monthly mean WS	1929 - 2002		ANN	UK, Irish Sea, Bidston Observatory	
Fischer-Bruns et al., 2005	ECHAM4/HOPE-G, T30, C20, A2, B2	Historical, A2, B2	POT, WS	1550–1990, 1990-2130	1550–1990, 1990-2130	Winter (DJF for NH, JJA for SH)	Global	Poleward shift of storm track for future
							NA, 1550-1990	
							NA, 1990-2130	NE shift of storm track
Franzen, 1991	Wind observations, Rung anemometer		Gale if at least 10 min. exceeding 21 m/s, N days exceeding 21 m/s (Bft. 8)	1940 - 1990		ANN	SW Sweden, coast	
	Wind observations, Gales		N gale days per year, Gothenburg 1860-1930, Vinga since 1920, gale defined as Gothenburg > 8 Bft., Vinga > 21 m/s	1860 - 1989		ANN	SW Sweden, coast	
Geng and Sugi, 2001	NCEP, 6h		Tracking (Murray and Simmonds 1991)	1958-1998		DJF	North Atlantic	
Geng and Sugi, 2003	AGCM, T106	20C, GHG + sulphate aerosols Year: 2050 from transient climate change experiment	tracking algorithm, cyclone density for 4,5 x 4,5 area per season	1978-1998	1978-1998,1978-1998	DJF, JJA	Global	Strong cyclones shift southeastward in the northern North Atlantic region
Gómez-Navarro and Zorita, 2013	MILLENNIUM project simulations, CMIP5		Principal Component Analysis	Last Millenium		DJF	Global	
Gulev et al., 2001	NCEP/NCAR, SLP 2.5x2.5 degree, Northern Hemisphere		Tracking algorithm	1958-1999		Winter (JAN-MAR)	Northern Hemisphere	High correlation Atlantic cyclone frequency with NAO
							Atlantic :all cyclones	NAO and storm track shift in late 1970s to the East
							Atlantic :980-1000hPa	
							Atlantic:<980hPa	
Gustafsson et al., 2012	Seasonal wind speeds		Analog-upscaling after Schenk and Zorita (2012)	1850-2006		ANN	Baltic Sea	
Jonsson and Hanna, 2007	SLP observations		Daily pressure variability index, annual N of dp/24h > 15 hPa (strong)	1823 - 2005		ANN	SW + W Iceland	
	SLP observations		Daily pressure variability index, annual N of dp/24h < 3 hPa (weak)	1823 - 2005		ANN	SW + W Iceland	
	SLP observations		Daily pressure variability index, annual mean N of dp/24h (dp(abs))	1823 - 2005		ANN	SW + W Iceland	
Hall et al., 1994	GCM, 2.5 x 3.75 deg.	20C, 2xCO2	Transient eddy correlations 250 and 700 hPa	14 years C20, 16 years 2xCO2	14 years C20, 16 years 2xCO2	DJF	Global	NAO shifted northward and downstream; northward shift of 5 deg. in maxima of high-pass transients in NA storm track
Hanna et al., 2008	SLP observations		Means of absolute daily pressure tendencies	1823 - 2006		ANN, DJFM	SW Iceland	Positive correlation in the North (Iceland+Faroe islands), negative correlatior in the South
				1833 - 2006		ANN, DJFM	N Atlantic + N Europe	
Hanson et al., 2004	ERA15 (extended from 1994-2001 w. oper. anal.), NCEP/NCAR		Tracking	1979–2000		OCT-MAR	80°N–20°N and 80°W–30°E	
							ERA15	
							NCEP/NCAR	
Harnik and Chang, 2003	NCEP/NCAR, radiosonde data (12h)		300-hPa meridional winds variance, 24h diff. filter	1949-1999		DJF	20°N–80°N	Northward shift of Atlantic storm track by about 5 deg.
Harvey et al., 2012	CMIP3 and CMiP5 GCMs, 20CR	CMIP3: SRESA1B, CMIP5: RCP4.5	Extra-tropical wintertime storm tracks	CMIP3: 1961–2100, CMIP5: 1976–2099	CMIP3: 1961–2000, 2081–2100, CMIP5: 1976–2005, 2070–2099	Winter (DJF for NH, JJA for SH)	Global	No shift of wintertime storm tracks

Table 1, continued

Study	Data	Scenario	Method	Full time span	Period A vs. Period B	Season	Region	NAO or track shift
Hickey 2003	Proxy Historical Documentary		Daily weather diary record of storms from observatory of Armargh	1796 - 1999		ANN	Armagh, Irland	
	Wind observation, Armagh Observatory		N gales per year, instrumental and observations from observatory of Armargh, hill, 2x daily on the roof, since 1883 hourly by Robinson anemometer	1844 (1883) - 1999		ANN	Armagh, Irland	Comparison of different observations 1970-1999 indicate a northward shift of storm tracks
Hodges et al., 2011	JRA-25 (125km), ERA-Interim (80 km), NASA MERRA (55 km)(all 6h), NCEP CFSR (38 km)(1h), 6h compared		MSLP and vorticity tracking; climatology comparison	1979–2009 for JRA-25, NASA MERRA, NCEP CFSR, 1989–2009 ERA-Interim		Winter, DJF NH, JJA SH	global extratropics, N and S of 30°	
Hofherr and Kunz, 2010	Obs WS, wind gusts, CCLM initialized by ERA40, KAMM		Extreme value statistics	1971-2000		SEP-APR	Germany	
Hogben 1994	Wave observations		Significant wave height, measurements	"past 30 years"		ANN	North Atlantic	
Hoskins and Hodges, 2002	ERA15, 6h, MSLP, vorticity		Eulerian, tracking (Hodges, 1995,1996,1999)	1979-2000		DJF	Northern Hemisphere	
Kaas et al., 1996	SLP observations from 10 stations		Downscaling of large-scale atmospheric flow (CCAs of SLP, SST, monthly mean pressure tendencies)	1903 - 1987		monthly, but discussion restricted to lowpass-filtered (3 years) values	Northeast Atlantic	
Kent et al., 2012	Measurements, Reanalyses		Monthly mean WS	1987-2009		ANN	Global oceans	
Knippertz et al., 2000	ECHAM4/OPYC3, T42, L19	IPCC IS92a	WS percentiles, cyclone activity	1880-2089	1880 to 1930 and 2039 to 2089	DJF	Europe, North Atlantic and Eastern North America	Northeastward shift of storm track over eastern NA and Europe
							30°W to 30° E, 35° to 80° N	
Kunz et al., 2010	REMO-UBA (10km), CCLM (18km)		Extreme value statistics, max WS	1971-2000, 2012-2050 A1B		OCT-MAR	47° to 55°N, 5.5° to 15.5°E	
Lambert, 1995	CCCma coupled	double CO2	TC centers identif. With MSLP treshold			Winter	NH and SH	
Lambert et al., 2002	13 AMIP1 GCMs, ERA40, NCEP/NCAR		Cyclone tracking, cyclone counts	1979-1988		DJF	global	
Lambert, 2004	CCCma coupled			1850-2100		Winter	NH and SH	
Lambert and Fyfe, 2006	15 GCMs, coupled	A1B, 380 km	TC centers identif. with MSLP threshold	1961-2300	1961-2000, 2081-2100		NH and SH	No discernible spatial change in storm tracks
Leckebusch and Ulbrich, 2004	HadCM3, T42, L19	20C, A2, B2	Tracking, maxima of Laplacian of MSLP, 95th perc. WS	1860-2099	1960-1989 and 2070-2099	OCT-MAR	Northeast Atlantic and Europe	For extreme cyclones in A2: southward shift
Leckebusch et al., 2006	4 RCMs driven by 4 GCMs	20C, A2	tracking, extreme WS (POT)	1960-2099	1960-1989 and 2070-2099	OCT-MAR	NE Atlantic and Western Europe, 35–72° N, 15°W–43° E	
Leckebusch et al., 2008a	ECHAM5-OM1 T63, ERA40	A1B and B2	Daily max. WS, gust WS, Area and Event Storm Severity Index	ERA: 1961 to 2000; ECHAM5-OM1: 1971–2000 and 2071–2100	1971–2000 and 2071–2100	OCT-MAR	Northeast Atlantic	
Leckebusch et al., 2008b	NCEP/NCAR,2.5° x 2.5°, 12h; ECHAM4/OPYC3, T42	IS92a	Cluster analysis, PCA	1958-1998	MY 120-170 and 279-329	OCT-MAR	35°W to 35°E, and 35°N to 70°N	
Lehmann et al., 2011	Gridded high resolution SMHI observations		Mean geostrophic WS	1958 - 2008	1970-1988 - 1989-2008	DJF	S + central Baltic	NE
	Gridded high resolution SMHI observations		Mean geostrophic WS		1970-1988 - 1989-2008	DJF	Bothnia Bay	NE
	Gridded high resolution SMHI observations		Mean geostrophic WS		1970-1988 - 1989-2007	MAM	Baltic Sea	NE
	Gridded high resolution SMHI observations		Mean geostrophic WS		1970-1988 - 1989-2007	SON	W + central Baltic	
	Gridded high resolution SMHI observations		Mean geostrophic WS		1970-1988 - 1989-2007	SON	Bothnia Bay	
	Gridded high resolution SMHI observations		N < 980hPa		1970-1988 - 1989-2008	DJF + MAM	Baltic Sea	NE
	Gridded high resolution SMHI observations		N < 980hPa		1970-1988 - 1989-2007	SON	Baltic Sea	
	NCEP Reanalysis		N < 980hPa, NCEP			DJFM	North Atlantic	NE
Löptien et al., 2008	ECHAM5/OM and ECHAM4/OPYC3, ERA-40, NCEP/NCAR	A1B	Cyclone activity and life cycle	1978-2190	1978–1999, 2070–2090, 2170–2190	JFM, JAS	Global	Northward shift of storm track over the sub polar North Atlantic and European Arctic
Malberg and Bökens, 1993	SLP observations, Radio Sounding, T2m		Meridional gradients subpolar - subtropics, SLP, geopot. height at 500 hPa, relative topography	1960 - 1990		DJF	N-Atlantic + Europe	
Matulla et al., 2008	SLP observations		High percentiles of geostrophic wind speeds (triangle) + p95 of 24h pressure changes	1871 - 2005		ANN	North Atlantic, Scandinavia, Central Europe	For NE Atlantic correlation 0.4; "the NAO index is not very helpful to describe storminess over the past 130 years"
McVicar et al., 2012	Review of 148 regional studies on zonal WS		Terrestrial near-surface WS	1880-2010		ANN	Global	
Mizuta 2012	CMIP5 GCMs	RCP4.5	Cyclone detection and tracking	1979-2099	1979–2003, 2075–2099	DJF	Northern hemisphere	Shift of storm track to polar side and downstream
Nilsson et al., 2004	Proxy Storm Damage, N damaging storms		Damaged volume of forestry, N damaging storms	1901 - 2000		ANN	Sweden	

Table 1, continued

Study	Data	Scenario	Method	Full time span	Period A vs. Period B	Season	Region	NAO or track shift
Nilsson et al., 2008	SLP observations		Zonal geostroph. component, Lund – Stockholm, 99, 95 pctl. NW-SE index, SLP observations, 3x per day	1823 (1850) - 2006		SONDJF	SW Sweden, coast, Stockholm	
	Model, RCA3 ECHO-G		99, 95 pctl. NW-SE index, SLP from RCA3-ECHO-G, time slices	1000 -1199		SONDJF	SW Sweden, coast, Stockholm	Dominating SW and E wind direction
	Model, RCA3 ECHO-G		99, 95 pctl. NW-SE index, SLP from RCA3-ECHO-G, time slices	1550 - 1749		SONDJF	SW Sweden, coast, Stockholm	> 30 m/s speeds mainly from E
	Model, RCA3 ECHO-G		99, 95 pctl. NW-SE index, SLP from RCA3-ECHO-G, time slices	1750 - 1929		SONDJF	SW Sweden, coast, Stockholm	S to W dominate highest wind speeds
Paciorek et al., 2002	NCEP-NCAR reanalysis		Storm activity and forcing indices	1949-1999		DJF	20°–70°N	Possible downstream shift/extension in Atlantic storm track
Pinto et al., 2007	ECHAM5/MPI-OM1,20C,A1B,A2,B1,MSLP		Eulerian, tracking (Murray and Simmond 1991)		1960-2000-2060-2100	OCT-MAR	Northern Hemisphere	
Pinto et al., 2009	NCEP/NCAR, T62, 6h; ECHAM5/MPI-OM1, T63, 6h	20C, A1B	Tracking	1958–1998 NCEP, 1960-2100 GCM	1960–2000 and 2060–2100	OCT-MAR	North Atlantic, Europe	
Pinto et al., 2010	FOOT3DK (20x20km and 5x5km), ECHAM5 (T63), ERA-40/ECMWF and NCEP, DWD wind data, insurance data	20C, A1B, A2	Cluster analysis	1960–2000 and 2060–2100	1960–2000 and 2060–2100	OCT-MAR	North Rhine-Westphalia (Western Germany)	
Pinto et al., 2012	ECHAM5	B1, A1B, A2	Potential storm losses: rank statistics, return periods, POT	1960-2100	1960-2000, 2060-2100	OCT-MAR	Countries of Western Europe	
Pryor et al, 2006	Energy density, 50year return period, probal. Empiric downscaling, GCMs		Ensemble average difference	1961-1990 - 2081-2100	2060 to 2089	ANN	N-Europe	
Rauthe et al., 2010	CCLM, REMO	SRES A1B, A2, B1	Extreme value statistics, gust WS	1971-2050	1971–2000, 2021–2050	OCT-MAR	Germany	
Raible and Blender, 2004	ECHAM/HOPE, three simplified ocean simulations, T30		Eulerian, tracking(Blender 1997), clustering	100 years		DJF	Northern Hemisphere	
Raible et al.,2007	CCSM 2.0.2, T31,		Tracking (Blender 1997)	1640-1715 Maunder Minimum		DJF, MAM, JJA, SON	Northern Hemisphere	
Raible et al., 2008	NCEP/NCAR, ERA-40, both interpolated to 2.5x2.5, 6h		Tracking (Blender 1997)	1957-2002		DJF, MAM, JJA, SON	Northern Hemisphere	
Rockel and Woth, 2007	8 RCM (Prudence), 50km	IPCC SRES/A2	Maximum daily wind speed	1961–1990 and 2071–2100		All	Europe	
							British Isles	
							Iberian Peninsula	
							France	
							Central Europe	
							NE Europe	
							Alps	
							Mediterranean	
							East Europe	
Rudeva and Gulev, 2011	NCEP/NCAR, SLP, 2.5x2.5,6h		Composite Analysis, Tracking (Gulev 2001)	1948-2007		Winter (JAN-MAR)	North Atlantic	
Schiesser et al., 1997	Wind observation		N over threshold, Bft. 7, 8 and 9, hourly observations of WS Zürich (Basel, Bern, Säntis)	1864 (trend 1894) - 1994		OCT-MAR	Switzerland, N Alps	NE shift and less south suggested, period before 1940 windier than afterwards
	Duration of storm events		Duration of storm events, estimated for 6x 20a periods, > 7 Bft.	1871 - 1991		OCT-MAR	Zürich	
	SLP observations, DWD weather maps		Circulation type 2 (west cyclonic), DWD, after Hess and Berzowsky 1966, annual frequency for Oct-Mar	1881 - 1992		OCT-MAR	Europe + N-Atlantic	
Schmidt and von Storch, 1993	SLP observations		50, 90, 99 pctl. Geostr. WS, SLP observations, triangle	1876 - 1990		ANN	German Bight	
Schmith et al. 1998	SLP observations		50, 90, 99 pctl. Geostr. WS of absolute daily pressure tendencies	1871-1997 (original WASA dataset)		DJF ("winter", not clear if extended season)	Northeast Atlantic	
Schneidereit et al., 2007	ERA40, T106, 6h		Tracking, cyclone density	1957-2002		DJF	North Atlantic, 90°W–40°E, 20° − 90°N	Cyclone density in NA shifted northward with particular increase between South Greenland and Iceland
							Iceland, 60°–70°N, 30°–10°W	
Schneidereit et al., 2010	ERA-40, ECHAM5/MPI-OM	A1B	Geometric cyclone property analysis	1950-2200	ERA-40: 1957-2002, GCM: 1950-2000, 2150–2200	DJF, JJA	Northern hemisphere	Less distinctive shift of cyclone tracks to the North for 20C
Schubert et al., 1998	ECHAM3, T42(2.8x2.8), 500hPa gh, 1000hPa gh		Eulerian and tracking (Blender 1997)	100yr future IPCC		DJF	North Atlantic and Europe	2xCO2, track shift eastward (Eulerian)
Sickmoeller et al., 2000	ECMWF reanalyses, 1.125x1.125, 1000 hPa gh, NH		Eulerian, tracking(Blender 1997), clustering	1979-1994		DJF	North Atlantic	For high NAO winters, Atlantic cyclone density shifts northwards, more stationary cyclones
Siegismund and Schrum, 2001	NCEP/NCAR, T62, 6h, 10m WS		Wind density function	1958-1997		OCT-JAN; FEB-MAR	North Sea	
						OCT-JAN		
						FEB-MAR		

Table 1, continued

Study	Data	Scenario	Method	Full time span	Period A vs. Period B	Season	Region	NAO or track shift
Simmonds and Keay, 2002	NCEP/NCAR, 6h		Tracking (Simmonds and Murray 1999)	1958-1997		Winter and Summer	North Atlantic and Pacific	
Smits et al., 2005	10m wind observations, high quality dataset within HYDRA, NCEP/NCAR, ECMWF		N over threshold, weak, moderate, strong	1962-2002		ANN	Netherlands	
Sterl et al., 2009	WAQUA/DCSM98, ECHAM5/MPI-OM, ERA-40	SRES A1B	RP storm surge height, maximum likelihood method	1950–2100	1950–2000, 2050–2100	ANN	North Sea, Dutch coast	
Suvilampi, E. 2009	SLP observations		90, 95, 99 pctl. Geostr. WS from triangle	1884 - 2007		ANN	SW Finland	
	SLP observations		N > 25 m/s per year	1884 - 2007		ANN	SW Finland	
	SLP observations		N > 25 m/s per year	1959 - 2007		ANN	Finland	
Sweeney, 2000	Proxy Historical Documentary		N storms per decade from documentary reports	1715 - 1999		ANN	Dublin region	
	Wind observation, cap anomemeter, since 1945 Dines pressure recorder		N storms per decade exceeding 58 knots (30 m/s)	1903 - 1999		ANN	Dublin region	
Trigo, 2006	ERA-40 (1.125º), NCEP/NCAR (2.5º)		1000 hPa height, tracking	1958-2000		DEC-MAR	85°W-70°E, 20°N-75°N	Northward shift of storm-tracks in Euro-Atlantic sector
							Atlantic-South ERA40	
							Atlantic-North ERA40	
							Atlantic-South NCEP	
							Atlantic-North NCEP	
Ulbrich and Christoph, 1999	ECHAM4+OPYC3,T42, scenario	IPCC IS92a	Eulerian	300 years		DJF	Europe	NAO northeastward shift
Ulbrich et al., 2008	23 member ensemble, 16GCMs	A1B for 2000-2100			1961-00, 2080-2100		Western NA, western Europe	
Vautard, 2010	Wind observations, in-situ	1979 - 2008	Checked for breaks and gaps			ANN	Europe	
	Wind observations, rawinsonde data		850 hPa level	1979 - 2008		ANN	W-Europe	
	SLP observations		Geostr. WS from pressure differences	1979 - 2008		ANN		
Vilibic and Sepic, 2010	Sea level data, tide gauges		Extreme sea level amplitudes	1955-2004		ANN	European seas	Northward shift in storm tracks
Walter et al., 2006	WS DWD stations, REMO, CCLM, MCCM/MM5		Cross validation	Obs 1951-2001, RCM 1960-2099; Evaluation period 1979-1993	1960-1989 and 2070-2099 (REMO and MM5)	ANN	Germany, future	
							Central Europe, future	
							Baltic Sea, future	
Wang et al.,2006	ERA40, NCEP/NCAR,6h, SLP		Tracking (Simmonds and Murray 1999)	1958-2001		Winter(JFM), Spring(AMJ), Summer(JAS), Autumn(OND)	Global	Mean position of storm track shift 181km northward over the North Atlantic
Wang et al., 2009	SLP observations		High percentiles of geostrophic wind speeds (triangle)	1874 - 2008		Seasonal	North Atlantic	DJF and MMA storminess highly correlated (DJF order of 0.5) to NAO
Wang et al., 2011	SLP observations		High percentiles of geostrophic wind speeds (triangle)	1874 - 2008 (NA),1878-2007 (Europe)		Seasonal	North Atlantic and West Europe	Highly correlated to NAO in DJF over Atlantic, negatively correlated over Europe
Wang et al., 2012	Twentieth Century Reanalysis (20CR), 2.0x2.0, 6h, NCEP/NCAR,2.5x2.5		Tracking	1871-2010		ANN	Global	Poleward shift NH storm tracks (1951-2010)
						DJF	North Atlantic, NCEP and 20CR	
						DJF	High-lat North Atlantic, 20CR	
						DJF	High-lat North Atlantic, 20CR	
						DJF	Mid-lat North Atlantic, 20CR	
						DJF	Northern Europe, 20CR	
						DJF	Northern Europe, 20CR	
WASA Group	SLP observations		95, 99 percentile geostr. WS from triangle	1881 - 1995		ANN	NE Atlantic to Baltic	
Weisse and Plüß, 2005	Storm surge model TELEMAC2D		Storm related sea level variations analysed	1958-2002		ANN, NOV-MAR	North Sea / Geman Bight	
						NOV-MAR	UK, Netherland coast	
						NOV-MAR	Parts of German (North Frisian)/Danish coast	
Weisse et al., 2005	REMO		10m WS, POT	1958-2001		DJF	North Atlantic/Western Europe	North–south shift in North Atlantic storm track
							NE Atlantic north of 50°N	
							NE Atlantik, south of 50°N	
							Southern North Sea	

Table 1, continued

Study	Data	Scenario	Method	Full time span	Period A vs. Period B	Season	Region	NAO or track shift
Wern and Bärring, 2009	SLP observations		Annual potential wind energy, from triangles	1901 - 2008		ANN	S Sweden	
	SLP observations		Mean geostr. WS	1901 - 2008		ANN	S Sweden	
	SLP observations		N > 25 m/s per year, from triangles	1901 - 2008		ANN	S Sweden	
	SLP observations		Mean geostr. WS from triangles	1951 - 2008		ANN	N Sweden	
	SLP observations		Mean geostr. WS from triangles	1951 - 2008		ANN	Central + S Sweden	
Wernli and Schwierz, 2006	ERA40, SLP,6h		Tracking	1958-2001		DJF, MAM, JJA, SON	Global	
Woollings et al., 2012	Third Coupled Model Intercomparison Project (CMIP3) models		Eulerian		2060-2099-1960-1999	DJF	North Atlantic	Eastward shift of storm tracks in AOGCMs
Woodworth and Blackman, 2002	Proxy, tide gauge data from Liverpool		Annual maximum high water and surge at annual maximum high water	1768 - 1999		ANN	Liverpool, NW England	
	Proxy, tide gauge data from Liverpool		Annual maximum surge-at-high-water	1768 - 1999		ANN	Liverpool, NW England	
Xia et al., 2012a	ECHAM4/HOPE-G, T30 atmosphere (3.75°), T42 ocean (2.8°)	20C	Cyclone tracking and clustering	1000-1990		DJF	Global	No large shifts
Yin, 2005	15 AGCMs of IPCC AR4	20C, A1B	Eddy kinetic energy, Eady grow	1981-2100	1981-2000 and 2081-2100	ANN	Global	Poleward and upward shift and intensification of storm tracks
Zappa et al., 2012	CMIP5 GCMs	RCP4.5, RCP8.5	Cyclone tracking	1976-2099	1976-2005, 2070-2099	DJF, JJA	North Atlantic and Europe	Eastward extension of storm track towards British Isles, less storms at storm track flanks

Table 1, continued

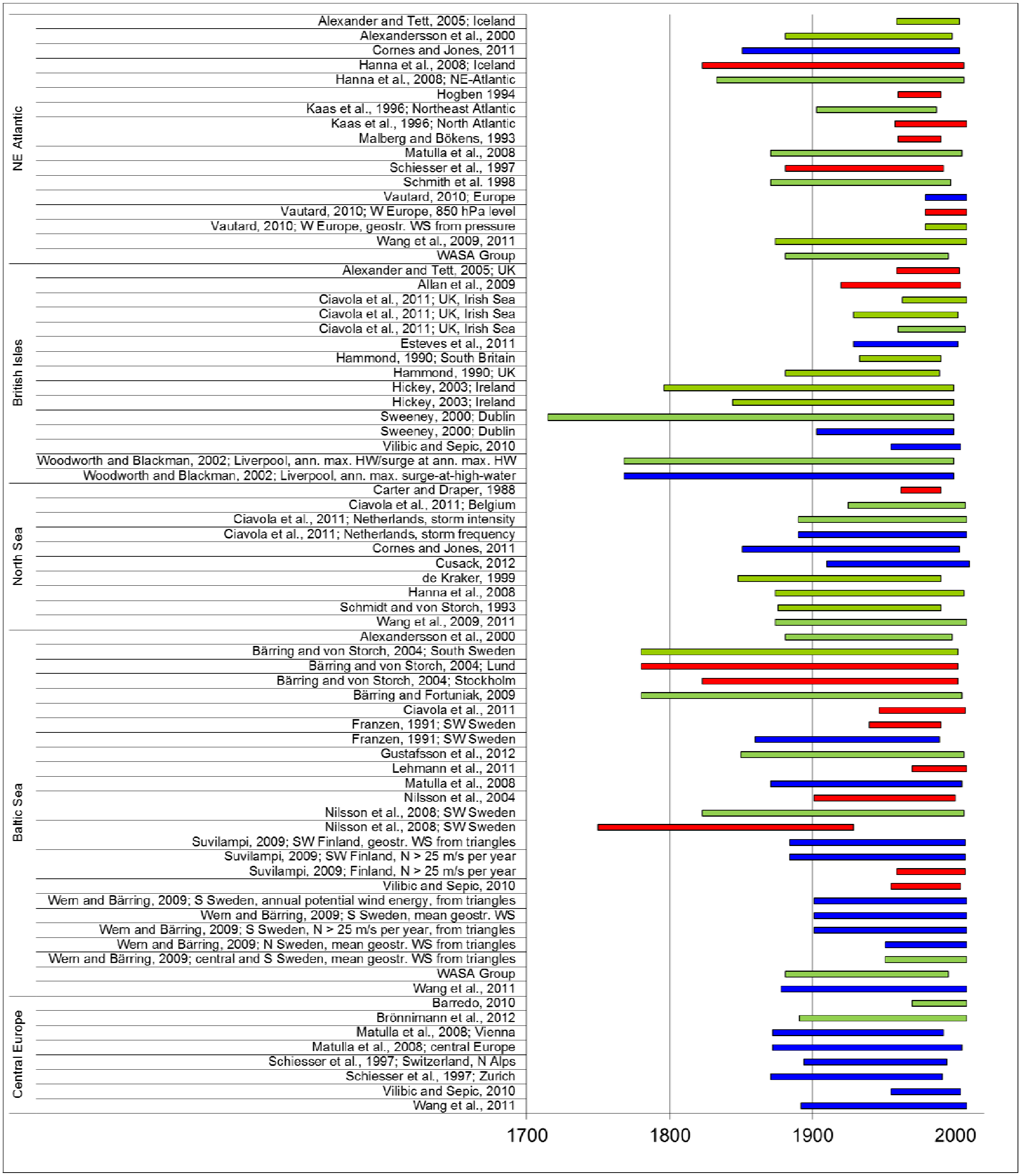

Table 2: Proxy and observation data study results

The bars show the time period regarded in each study, the colours denote an increasing (red), decreasing (blue) or no trend (green) in storm frequency over time as given in the articles.

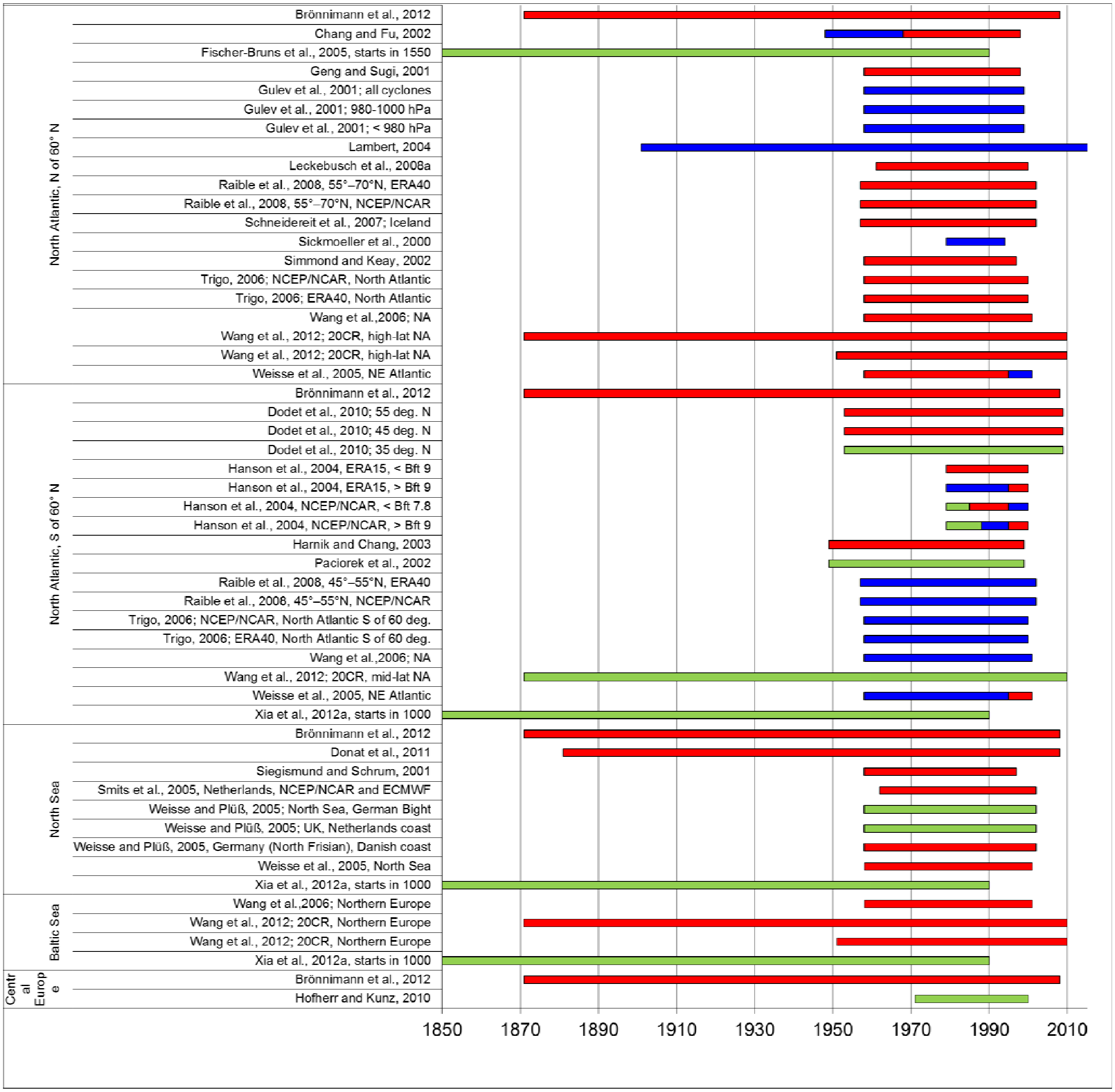

Table 3: Reanalysis and model data study results for the past decades
The bars show the time period regarded in each study. The colours denote an increasing (red), decreasing (blue) or no trend (green) in storm frequency over time as given in the articles. Some studies presented changing trends over time; this is indicated by multi-coloured trend boxes.

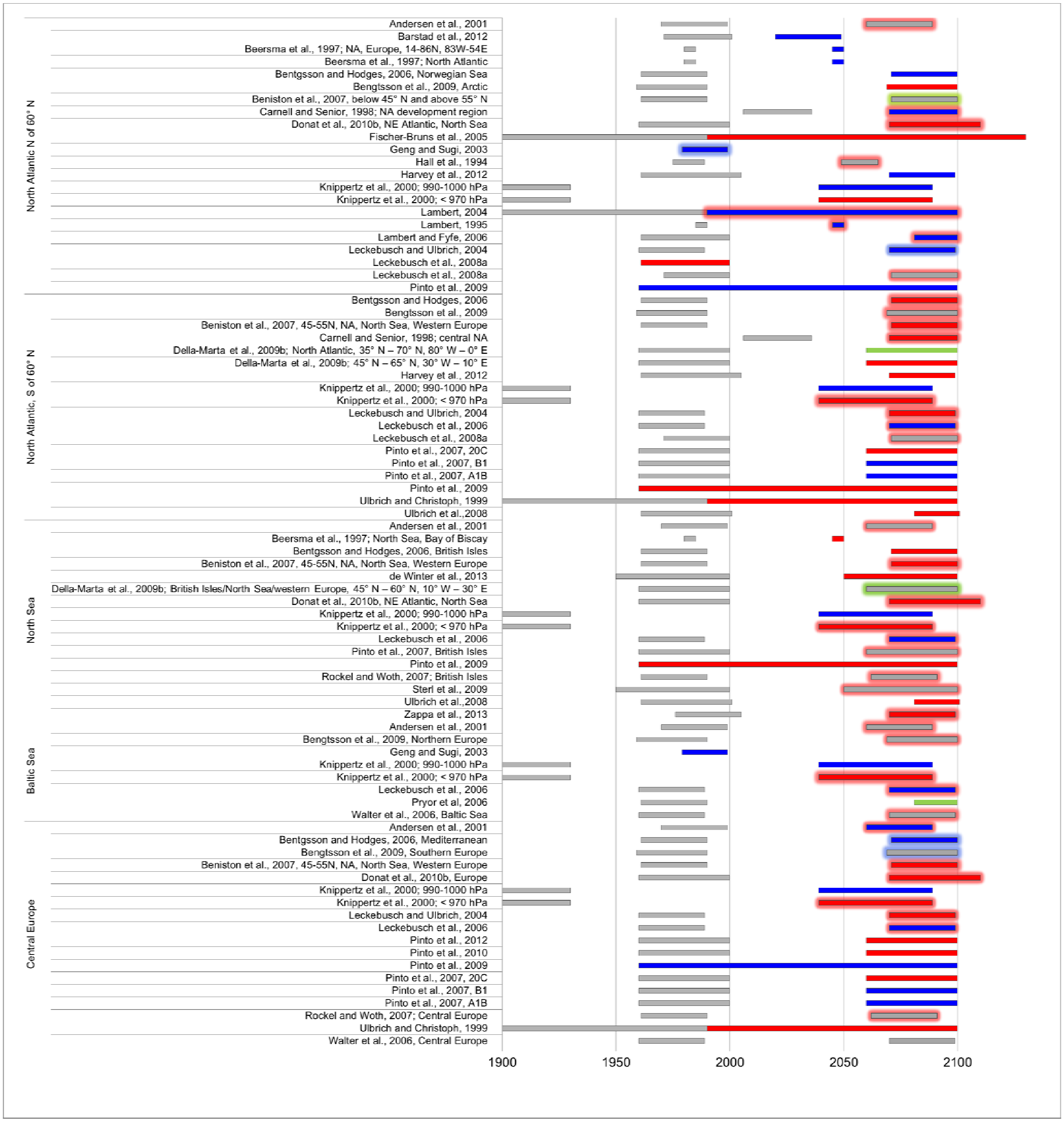

Table 4: Model data study results for future scenarios

The bars show the time period regarded in each study. Both the reference pre-industrial or present-time period and the future time period are given. The colours denote an increasing (red), decreasing (blue) or no trend (green) in storm numbers over time as given in the articles. Grey colours indicate that no trend was given in the article. The coloured glow around the trend boxes show a trend in storm intensity, again red denotes an increasing, blue a decreasing and green an unchanged trend.

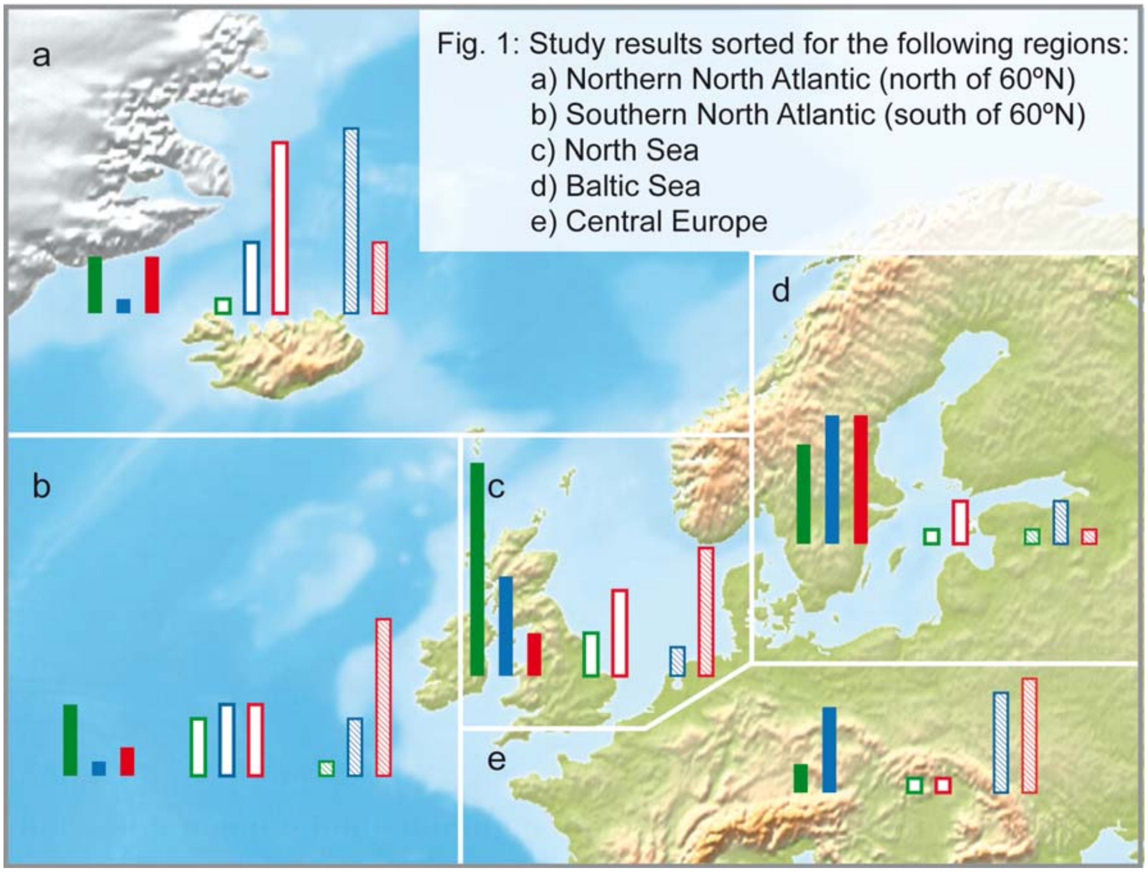

Figure 1: Studies analysed in this review and their geographical location. Filled bars symbolize proxies/observation studies (given in table 2), empty bars symbolize reanalyses and model studies for the past (table 3), and shaded bars symbolize model studies for future scenarios (table 4). The colors show trends in storm numbers as given in the tables, red shows an increasing, blue a decreasing, and green no trend. The length of the bars reflects the number of studies which return a certain trend in a particular area.

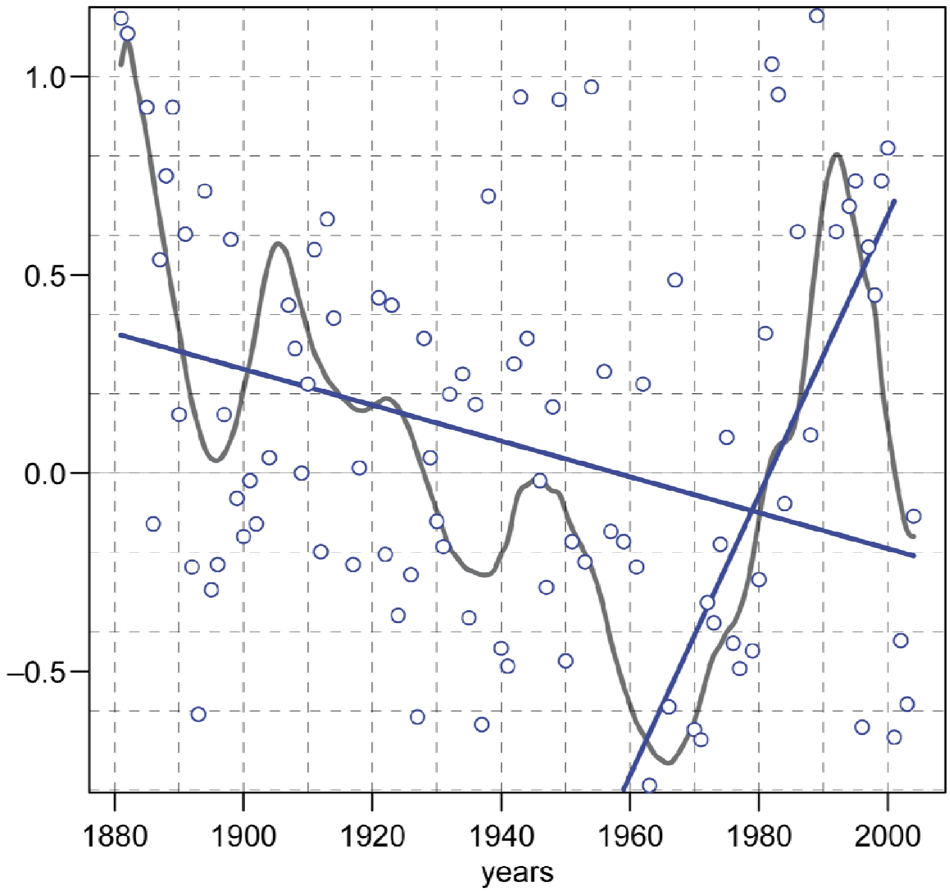

Figure 2: Storm index for northwestern Europe (British Isles, North Sea, Norwegian Sea) for 1881-2004 based on geostrophic wind speed percentiles according to the methodology described in Alexandersson et al. (1998). Blue circles are 95-percentiles of standardized geostrophic wind speed anomalies averaged over 10 sets of station triangles. The grey curve represents low-pass filtered data. The blue lines show linear trends of 95-percentiles, for the entire time period 1881-2004, and for the ERA-40 period (1957-2001).

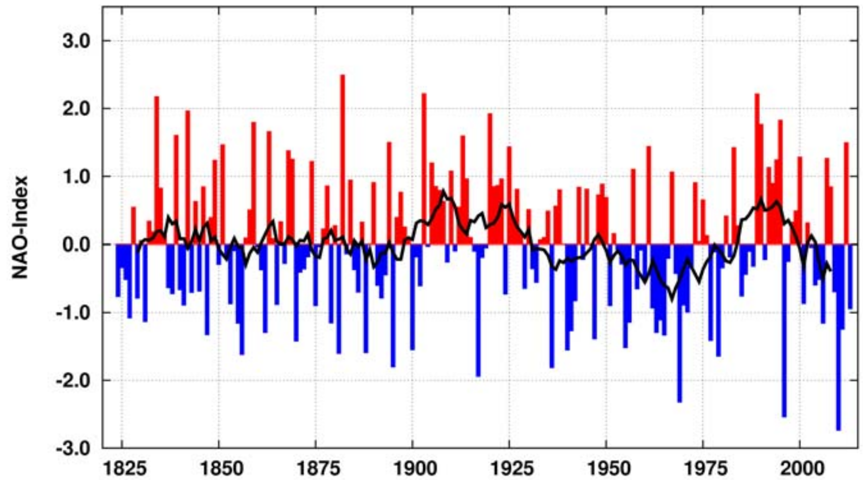

Figure 3: Updated NAO-Index after Jones et al. (1997) for boreal winter (DJFM) 1823/24 - 2012/13 re-normalized with respect to the full time period. The black line shows an 11-year running mean.