

Review

# Review on the Projections of Future Storminess over the North Atlantic European Region

Tina Mölter <sup>1</sup>, Dirk Schindler <sup>1,\*</sup>, Axel Tim Albrecht <sup>2</sup> and Ulrich Kohnle <sup>2</sup>

<sup>1</sup> Environmental Meteorology, Albert-Ludwigs-University of Freiburg, Werthmannstrasse 10, D-79085 Freiburg, Germany; tina@moelter.eu

<sup>2</sup> Department of Forest Growth, Forest Research Institute Baden-Wuerttemberg, Wonnhaldestrasse 4, D-79100 Freiburg, Germany; axel.albrecht@forst.bwl.de (A.T.A.); ulrich.kohnle@forst.bwl.de (U.K.)

\* Correspondence: dirk.schindler@meteo.uni-freiburg.de; Tel.: +49-761-203-3588

Academic Editor: Robert W. Talbot

Received: 16 February 2016; Accepted: 15 April 2016; Published: 22 April 2016

**Abstract:** This is an overview of the results from previously published climate modeling studies reporting on projected aspects of future storminess over the North Atlantic European region (NAER) in the period 2020–2190. Changes in storminess are summarized for seven subregions in the study area and rated by a categorical evaluation scheme that takes into account emission scenarios and modeling complexity in the reviewed studies. Although many of the reviewed studies reported an increase in the intensity of high-impact wind speed and extreme cyclone frequency in the second half of the 21st century, the projections of aspects of future storminess over the NAER differed regionally. There is broad consensus that the frequency and intensity of storms, cyclones, and high-impact wind speed will increase over Central and Western Europe, and these changes will probably have the potential to produce more damage. In contrast, future extratropical storminess over Southern Europe is very likely to decrease. For Northern and Eastern Europe the results of the evaluation are inconclusive, because there is an indication of increasing as well as decreasing development of the evaluated aspects of future storminess. Concerning the storm track, we found indications of a likely north- and eastward shift in most assessed studies. Results from three studies suggest a northeastward shift of the North Atlantic Oscillation.

**Keywords:** storminess; climate projections; storms; cyclones; storm track

## 1. Introduction

Synoptic winter storms are a typical feature of the climate over the North Atlantic European region (NAER). Over continental Europe, they bear a high damage potential to property, infrastructure, and the environment and cause deaths and injuries. In the period 1980–2014, loss associated with the ten costliest European winter storms amounted to more than US\$63 billion and close to 500 fatalities occurred through the passage of these storms [1]. In Central Europe, severe winter storms are the most loss-relevant natural hazard events [2]. They are also part of the natural disturbance dynamics of European forest ecosystems with severe winter storms currently representing the main hazard, because of their large expansion and high-impact near-surface flow field characteristics. In recent decades (1950–2010), they have caused 51% of all damaged timber and thus more than all other natural hazards (mainly fire, snow, and bark beetles) together [3]. Furthermore, severe storms chronically act on Atlantic coastlines and induce sand drift and erosion [4–6].

The North Atlantic Oscillation (NAO) is linked to changes in extratropical storm tracks and large-scale circulation patterns over Europe [7–11]. Since the NAO is more pronounced during winter, most severe synoptic storms occur between December and March [7,12,13]. In the period 1500–1995, 66% of all high-impact storm events occurred between October and March [14], with most storms

passing over Europe during December. There is evidence that the NAO currently has at least two modes with periods of 10.4 and 62 years, the latter being related to long-term changes in Atlantic sea surface temperature [15].

Winter storms regularly disturb the planning of thinning and harvesting operations in forestry, and forest management seeks robust information on the future development of storminess, because goals of forest management are defined over a period of several decades. However, not only stakeholders in the forestry sector are interested in robust information on future storminess. Knowledge about the characteristics of future high-impact storms is also of great interest for a number of other socio-economic sectors. For the insurance sector, storms are of major importance, because (re)insurance companies usually hedge financial risk induced by storms and are keen to assess storm-induced loss potentials [16,17]. Wind turbine operators have to shut down their installations to avoid damage during the passage of storms [18,19]. In aviation, severe storms affect airline operations [20,21].

A large number of climate modeling studies report on the projected future development of storminess over the NAER. Due to the importance of the issue, main outcomes and various aspects from these studies have already been summarized and discussed in review articles in recent years: The study of [22] summarized the importance of high-impact winter storms for European forest ecosystems and forestry. A review of cyclone characteristics in the mid-latitudes under current and future climate in the southern and northern hemisphere was presented by [23], while [11] reported on the effect of sea ice variability on storm tracks and NAO-variability. The most recent review on storminess over the North Atlantic and Northwestern Europe analyzed the available literature for storm frequency trends, changes in cyclone activity, and storm tracks [24].

The present review is an update and further development of the reviews of [22,24]. It combines a refined version of the study evaluation methodology applied by [22] with the regional evaluation approach for different parts of the NAER presented by [24]. Furthermore, we defined and evaluated the reviewed studies for the categories “storms”, “cyclones”, and “wind speed” separately, which were often used to quantify aspects of projected future storminess. For these categories, we assessed changes in frequency, intensity, and/or activity. For the assessment, we divided the NAER into seven subregions, which we believe to represent regional differences in aspects of current storminess over the study area.

The goal of this review is to provide a comprehensive overview of the projected changes of measures that are commonly used to quantify storminess under future climate conditions over the NAER. The intention of using a categorical evaluation scheme is to meet the growing demand for information on the future development of storminess for strategic management processes and decision-making in various ecological and socio-economic sectors that are exposed to the atmospheric environment.

## 2. Methods

### 2.1. Literature Search

This review is based on an extensive literature search in the databases Google Scholar, ScienceDirect, Thomson Reuters Web of Science, Wiley Online Library, and Catalog, plus the library of the Albert-Ludwigs-University of Freiburg (Freiburg, Germany). We searched for articles that reported on aspects of projected future storminess over the NAER. Keywords related to “wind”, “storm”, “cyclone”, “storminess”, “North Atlantic European region”, “Europe”, “climate model”, and “projection” were used and combined during the search process. To assess the general suitability of the search results for this review, we started reading the abstracts and selected relevant articles for further analysis based on our expert knowledge. All 58 studies—including basic information on the models used to project aspects of future storminess over the NAER—that have finally been evaluated in this review are listed in Appendix A, Table A1.

## 2.2. Terms and Definitions

While reviewing studies on projected storminess over the NAER, it quickly became evident that the definition of the term “storminess” is ambiguous. In the evaluated studies it was either characterized directly by different measures of wind speed and/or pressure or indirectly by impact-related variables such as storm-induced damage and losses. Furthermore, the definition of “storm” was inconsistent. For example, “storm” has not only been defined as a strong gale (near-surface wind speed  $\geq 9$  Bft) but also as severe cyclone.

Due to the ambiguity of the definitions of storminess, we provide a number of definitions of indicators that we used to evaluate and interpret projections of aspects of future storminess:

- Extratropical cyclones can be defined as a minimum in the mean sea level pressure field or at the 1000 hPa geopotential height [25].
- Cyclone frequency can be quantified by counting the number of cyclones occurring in gridded datasets [23]. Changes in cyclone frequency are often expressed as changes in cyclone return period [26–30].
- Cyclone intensity is characterized by the depth of a pressure center at sea level or by the relative pressure minimum at the 1000 hPa geopotential height. Low pressure is always associated with high cyclone intensity. Alternative measures of cyclone intensity are magnitude of vorticity, precipitation intensity, or wind speed [23,31].
- Cyclone activity was defined and reported as the product of the number of cyclones and their mean intensity [32]. This entails that it was not always possible to attribute changes in cyclone activity to either changes in cyclone frequency or changes in cyclone intensity. Cyclone activity can also be quantified by cyclone track density [23].
- Cyclone track density was defined as the number of cyclone tracks which can be counted over time in gridded datasets [23]. Cyclone track density does not provide any information on the intensity of the counted cyclones [33]. We therefore interpreted information on cyclone track density as a measure of cyclone frequency.
- A storm track is the path of a storm over time. Originally, a storm track referred to preferred regions of storm/cyclone activity. “Storm track” was also used to describe clusters of cyclone tracks in different geographical regions [24]. We interpreted information on storm track activity as a measure of cyclone activity [34].
- Storm intensity can be characterized by wind speed measurements made at 10 m above the ground. In the reviewed literature, it was reported as (i) peak wind speed values averaged over 1–3 s; (ii) mean wind speed averaged over 10 min intervals; or (iii) percentiles (e.g., 90–98 percentiles) of maximum daily wind speed values [13,16,35–38].

Due to the numerous definitions of “storminess” it proved to be impossible to always unambiguously interpret the future development of stormy conditions based on the reviewed studies. Especially, the terms “storm” and “extreme cyclone” were often improperly defined, not only between studies, but also in one and the same study. When the definition of storm and extreme cyclone was ambiguous within the very same study, we interpreted the reported results as changes in cyclone characteristics.

Additionally ambiguous was the use of the term “wind speed”. Wind speed has either been used as a measure for storm intensity or cyclone intensity, or was investigated without relating to storms and/or extreme cyclones. In the following analysis, we use the term “wind” as an abbreviation for “high-impact wind speed”.

Table B1 in Appendix B summarizes the emission scenarios and the variables investigated in the evaluated studies and their assignment to categories (frequency, intensity, activity) of aspects (storms, extreme cyclones, high-impact wind speed) of projected storminess assessed in this review.

### 2.3. Study Evaluation and Rating

The present analysis is a modification of the approach of [22]. In their review of the past, present, and future storminess over the NAER, they interpreted findings from 32 studies on the basis of a categorical evaluation scheme of

- data volume differentiated for the categories (i) measured/observed data; (ii) data from reanalysis; (iii) combination of reanalysis and climate change scenarios, and
- methodology with the categories (i) trend analysis/simple statistics; (ii) output from an individual model/complex statistics; and (iii) output from multi-model ensembles.

We basically adopted this classification scheme, but focused on projections of the future development of storminess, which implies that we did not include measured/observed data and data from reanalysis into the present assessment. The rating of the significance of an evaluated study was completed with the type of emission scenario ( $S$ ) and the number ( $N$ ) of general circulation models (GCMs) used to project future storminess, with grades from 1 (lowest rating) to 3 (highest rating).

To assess  $S$ , we differentiated between (i) CO<sub>2</sub>-experiments or IS92-scenarios [39] ( $S = 1$ ); (ii) Special Report on Emission Scenarios (SRES) [40] ( $S = 2$ ); and (iii) Representative Concentration Pathways (RCP) [41] ( $S = 3$ ). The differentiation between the emission scenarios was based on the assumption that newer emission scenarios better represent the current state of scientific knowledge in emission scenario modeling.

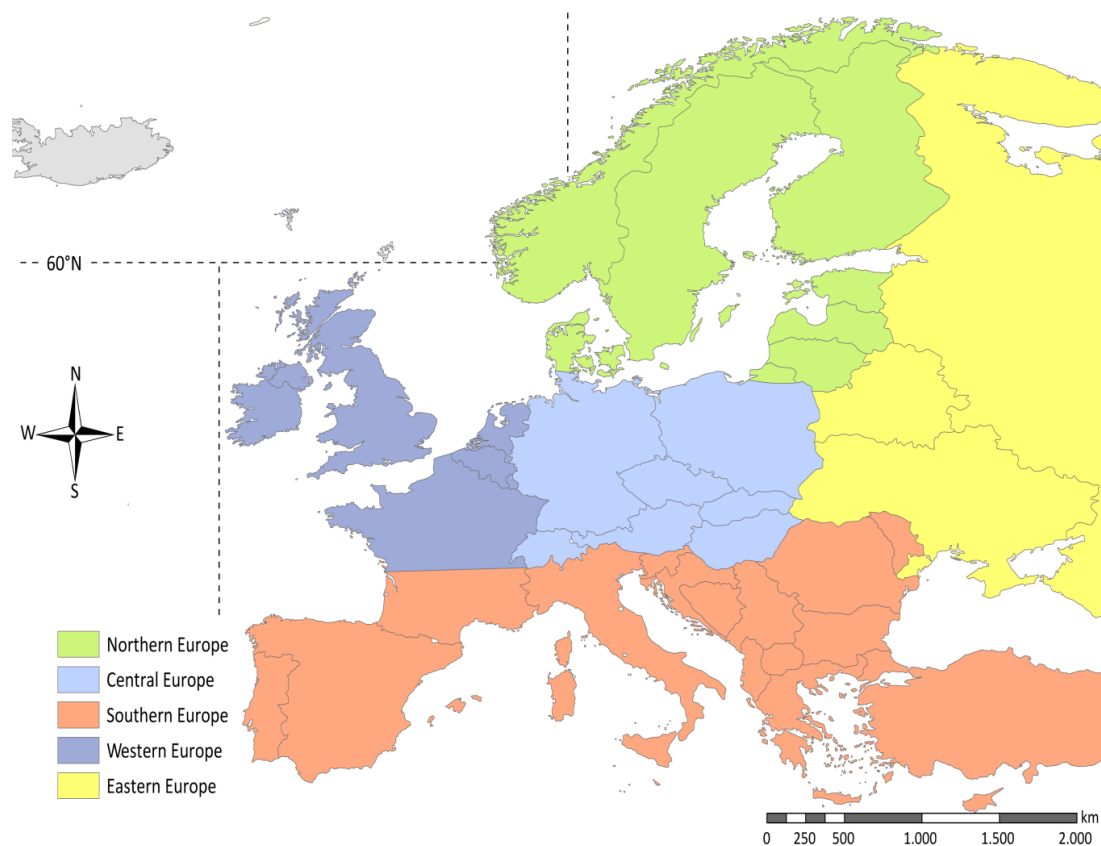
The assessment of the applied methodology was based on the number of applied GCMs. The number of regional climate models (RCMs) was not considered because it has been demonstrated that GCM-forcing affects projection results more strongly than RCM-outputs [13,42,43]. Although the spread produced by the RCMs is smaller than the GCM-spread, it had an effect on the results reported in the evaluated studies. However, we did not take the number of RCMs into account, because this would have reduced the total number of evaluated studies. The categorical interpretation key for assessment of  $N$  differentiates between (i) single models (one GCM or one GCM together with one or more RCMs,  $N = 1$ ); (ii) multiple GCMs ( $2 \leq \text{number of GCMs} < 10$ ,  $N = 2$ ); and (iii) multi-model ensembles (number of GCMs  $\geq 10$ ,  $N = 3$ ). The differentiation between the numbers of applied models was based on the assumption that the combined information of multiple models generally improves the accuracy, reliability, and consistency of projections [44]. The differentiation between the  $N$ -values of 2 and 3 was made at ten GCMs to balance the number of studies assigned to these two categories.

The evaluation score ( $ES$ ) for individual studies was calculated emphasizing the effect of the applied GCMs on projections of storminess over the assumed future scenario [13] as follows:

$$ES = S + 2 \cdot N \quad (1)$$

After the comparison (data not shown) of several combinations of weighted and unweighted  $S$ - and  $N$ -values, it turned out that the applied weighting scheme allows for the intended differentiation between the evaluated studies without affecting the overall subregion-specific  $ES$ -pattern.

To better account for typical large-scale circulation patterns known to occur over the NAER, we divided the study area into the seven subregions (Figure 1) in a similar fashion, as has been done by [24]. The subregions we defined are (i) North Atlantic north of 60°N; (ii) North Atlantic south of 60°N; (iii) Northern Europe (including Baltic Sea); (iv) Central Europe; (v) Southern Europe; (vi) Western Europe (including North Sea); and (vii) Eastern Europe. Based on the individual study-specific  $ES$ -values, total  $ES$ -scores and mean  $ES$ -values ( $\overline{ES}$ ) were calculated to provide the total and mean weight of all studies pooled for one of the subregions.



**Figure 1.** Differentiation of the study area (North Atlantic European region: NAER) into seven subregions. The horizontal dashed line at 60°N divides the North Atlantic into the subregions North Atlantic north of 60°N and North Atlantic south of 60°N. The vertical dashed lines indicate the eastern boundaries of the two North Atlantic subregions.

We assigned the projected and reported long-term evolution of aspects of storminess to the categories frequency, intensity, and activity of storms and extreme cyclones to these subregions based on the definitions provided above. This means that we do not always report on the meteorological variables actually presented in the reviewed studies (e.g., the future development of wind speed measured at 10 m above ground, change of wind speed at different pressure levels such as the 850 hPa pressure level) but interpreted them in terms of their projected long-term changes in frequency, intensity, and activity as either “storms” or “extreme cyclones” or “high-impact wind speed”. The reported tendency (*T*) in the long-term evolution of the reported variables was assessed and quantified using the categorical interpretation key (i) *T* = −1 for a decreasing tendency; (ii) *T* = 0 for no tendency; and (iii) *T* = +1 for an increasing tendency. Interestingly enough, in total, only four [45–48] out of the 58 evaluated studies reported no tendency in any one of the assessed categories of future storminess.

To allow for a quantitative comparison of the evaluation results obtained for the seven subregions, an effective tendency (*eT*) was computed based on subregions-related *ES*- and *T*-values:

$$eT = \frac{\sum_{j=1}^n (ES_j \cdot T_j)}{\sum_{j=1}^n ES_j} \tag{2}$$

Results (data not shown) from a sensitivity analysis demonstrated that different combinations of weighted *S*- and *N*-values induced only minor changes in the *eT*-score (maximum  $\Delta eT = 0.06$ ) and did not change the structure of the presented inter-subregional results.

For the overall inter-subregional assessment, the  $eT$ -score puts more weight on studies with high  $ES$ -values and varies between  $-1.00$  and  $1.00$ . More negative values indicate a stronger tendency for a decreasing storminess in the future, while increasingly positive values indicate a stronger tendency for increasing storminess. With regard to the results from this study, we interpret  $eT$ -values as indicators for the reliability of the tendency of future projections, which implies that  $eT$ -values close to either  $-1.00$  or  $1.00$  indicate clear decreasing or increasing tendencies in the evaluated aspects of projected storminess.

In addition to the assessment of future storminess in the seven subregions, we summarized results reported in the evaluated studies on projected changes of NAO- and storm track characteristics over the NAER. Although we also scored the applied emission scenario and methodology to calculate study-specific  $ES$ -values, we do not provide  $T$ - and  $eT$ -values, because projected changes in NAO- and storm track characteristics were spatially interpreted.

No differentiation of the evaluation results was made concerning the projection periods because the respective starting points in time, lengths, and endpoints were too diverse, leading to too many subgroups with too few members.

Provided that multiple projections were performed in a study, we evaluated only the study's overall results and not the results obtained from individual projections included in the respective study. We focused on the overall results because synthesized results have been reported to be superior to results reported from individual projections [44]. Moreover, systematically considering the problems associated with individual projections in the evaluated studies, e.g., physical backgrounds, metrics of model validation, model dependences, experimental design, and model tuning [44], was beyond the scope of this paper. We, however, are aware that the chosen approach has an influence on our results and our interpretation of the future development of storminess.

Altogether, the reviewed studies cover the period 2020–2190. The spectral grid resolutions of the GCMs used in these studies varied at least between T21 and T213, which equal horizontal grid resolutions of 500 km to 49 km in the study area. With one exception [47], the evaluated studies have a focus on the European cold season including the months September to April. Typical terms and acronyms found in the reviewed studies referring to the cold season were “winter” without specifying individual months and “DJF” (December, January, and February). One reviewed study modeled future storminess for the month February representing winter conditions [49].

The evaluated studies summarized in tables in the Results section are primarily ranked in descending order based on the study-specific  $ES$ -value and secondarily based on the surname of the lead author.

### 3. Results

#### 3.1. North Atlantic North of $60^{\circ}N$

In the North Atlantic region north of  $60^{\circ}N$ , highest  $N$ -ratings were awarded to two [50,51] out of eleven evaluated studies (Table 1, [9,13,25,27,37,50–55]), because they used multi-model ensembles with ten or more GCMs. In addition, the simulations of [51] were based on RCP-projections which, together with the large number of GCMs, yield  $ES = 9$ . Studies that reported results obtained from less than ten GCMs or from only one GCM (e.g., [25,52]) typically got lower  $N$ -ratings.

The majority of the studies reported on changes of projected frequency of extreme cyclones and cyclone intensity. It is obvious that, in all analyzed categories of storminess a prevalingly decreasing development is found. One exception is the study of [25], who expected an increase in both projected frequency of extreme cyclones and cyclone intensity.

The subregion-related total  $ES$ -score is 65,  $\overline{ES}$ -score is 5.0, and the  $eT$ -value equals  $-0.82$ , which, according to our evaluation scheme, implies a strong decreasing tendency of projected future storminess.

**Table 1.** Studies reporting on projections of aspects of future storminess in the North Atlantic subregion north of 60°N.

Study	Model(s)	S	N	ES	T	Category	Reference Period(s), Projection Period(s), Month(s), Season	Region(s)
Harvey <i>et al.</i> (2012) [50]	GCM: 19 RCM: -	3	3	9	-1	Storm activity	1976–2005, 2070–2099, DJF	Ocean basin north of 60°N, Barents Sea
Zappa <i>et al.</i> (2013) [51]	GCM: 19 RCM: -	3	3	9	-1	Wind intensity	1976–2005, 2070–2099, DJF	Norwegian Sea
Gregow <i>et al.</i> (2012) [53]	GCM: 9 RCM: -	2	2	6	-1	Wind intensity	1971–2000, 2046–2065, 2081–2100, September–April	Norwegian Sea
Leckebusch <i>et al.</i> (2006) [13]	GCM: 4 RCM: 4	2	2	6	-1	Frequency of extreme cyclones	1961–1989, 2071–2099, October–March	Norwegian Sea, Iceland
Schwierz <i>et al.</i> (2010) [27]	GCM: 2 RCM: 2	2	2	6	-1	Storm intensity	1961–1990, 2071–2100, October–March	Iceland
Bengtsson <i>et al.</i> (2006) [9]	GCM: 1 RCM: -	2	1	4	-1	Cyclone intensity	1961–1990, 2071–2100, DJF	Northern part of the North Atlantic and Norwegian Sea
Leckebusch and Ulbrich (2004) [54]	GCM: 1 RCM: 1	2	1	4	-1	Frequency of extreme cyclones	1960–1989, 2070–2099, October–March	Norwegian Sea
Pinto <i>et al.</i> (2007) [37]	GCM: 1 RCM: -	2	1	4	-1	Wind intensity	1960–2000, 2060–2100, October–March	Polar latitudes
Pinto <i>et al.</i> (2009) [55]	GCM: 1 RCM: -	2	1	4	-1, -1	Frequency of extreme cyclones, cyclone intensity	1960–2000, 2060–2100, October–March	Barents Sea, Iceland, Norwegian Sea
Geng and Sugi (2003) [52]	GCM: 1 RCM: -	1	1	3	-1	Frequency of extreme cyclones	1978–1998, ~2050, DJF	Greenland Sea, Norwegian Sea
Pinto <i>et al.</i> (2006) [25]	GCM: 1 RCM: -	1	1	3	+1, +1	Frequency of extreme cyclones, cyclone intensity	1880–1930, 2039–2089, October–March	Northern North Atlantic

### 3.2. North Atlantic South of 60°N

Compared to the North Atlantic region north of 60°N, a different picture emerges in the North Atlantic region south of 60°N (Table 2, [2,9,13,31,45,47,50,52,54,56–62]). Results from 16 evaluated studies demonstrate that it is indisputable that storminess is projected to generally increase. Almost all studies indicated a positive change in at least one of the analyzed aspects of future storminess. Results from several studies suggested not only an increase in storm and cyclone frequency but also an increase in storm and cyclone intensity. From the results of the study of [2], it can be inferred that future wind intensity will also increase. Results of the study of [50], which scored  $ES = 9$ , showed an increase in cyclone activity in a large number of projections made in their study. Only one study did not identify a change in wind intensity [47].

The subregion-related total  $ES$ -score amounts to 95, the  $\overline{ES}$ -value is 4.8, and the  $eT$ -value equals 0.96. It is the highest  $eT$ -value of this assessment and clearly points to an increasing tendency of the projected storminess in this subregion.

### 3.3. Northern Europe

The results of the 20 studies evaluated for Northern Europe are more diverse ( $eT = 0.54$ ) than the results obtained for the two North Atlantic regions north and south of 60°N (Table 3, [17,27,28,30,31,37,46,49,53–55,62–69]). Northern Europe is, together with Eastern Europe, a subregion for which we found no study that achieved  $ES = 9$ . However, for the evaluated aspects of projected storminess, our scoring includes all categories of  $T$ , with the study of [46] being the only study that found no change in their analyzed aspect (wind intensity) of future storminess. The subregion-related total  $ES$ -score is 108, and the  $\overline{ES}$ -value equals 4.5.

Since only a few of the assessed studies reported on future development of “storms” no conclusive tendency can be identified for this variable. In two studies [30,62], expected future storm frequency decreased while two other studies projected an increase in storm intensity [28] and storm activity [63].

Most often studied were the future developments of extreme cyclone frequency and wind intensity. In both categories, model results support the conclusion that the number of cyclones as well as the wind intensity will increase towards the end of the 21st century. One study reported results that were obtained from projections of several RCMs without explicitly specifying a GCM [49].



**Table 2.** Same as Table 1 but for the North Atlantic subregion south of 60°N.

Study	Model(s)	S	N	ES	T	Category	Reference Period(s), Projection Period(s), Month(s), Season	Region(s)
Harvey <i>et al.</i> (2012) [50]	GCM: 38 RCM: -	3	3	9	1	Cyclone activity	1976–2005, 2070–2099, DJF	Ocean basin in the mid-latitudes
Ulbrich <i>et al.</i> (2008) [56]	GCM: 15 RCM: -	2	3	8	1	Cyclone activity	1960–2000, 2081–2100, winter	Eastern North Atlantic
Donat <i>et al.</i> (2010) [2]	GCM: 7 RCM: -	2	2	6	+1, +1	Cyclone intensity, wind intensity	Various model– dependent periods, October–March	North Atlantic to Western Central Europe
Leckebusch <i>et al.</i> (2006) [13]	GCM: 4 RCM: 4	2	2	6	1	Frequency of extreme cyclones	1961–1989, 2071–2099, October–March	Northeast Atlantic
Leckebusch <i>et al.</i> (2008) [57]	GCM: 7 RCM: -	2	2	6	1	Storm frequency	1961–2000, 2081–2100, winter	Northeast Atlantic
Bengtsson <i>et al.</i> (2006) [9]	GCM: 1 RCM: -	2	1	4	+1, +1	Frequency of extreme cyclones, cyclone intensity	1961–1990, 2071–2100, DJF	North Atlantic region between 45°N–60°N
Bengtsson <i>et al.</i> (2009) [31]	GCM: 1 RCM: -	2	1	4	1	Cyclone intensity	1959–1990, 2069–2100, DJF	North Atlantic south of 60°N
Hanson <i>et al.</i> (2003) [45]	GCM: 1 RCM: 1	2	1	4	1	Frequency of extreme cyclones	1961–1990, 2070–2099, October–March	North Atlantic north and west of the UK
Leckebusch <i>et al.</i> (2008) [58]	GCM: 1 RCM: -	2	1	4	1	Storm intensity	1971–2000, 2071–2100, October–March	Northeast Atlantic

Table 2. Cont.

Study	Model(s)	S	N	ES	T	Category	Reference Period(s), Projection Period(s), Month(s), Season	Region(s)
Leckebusch and Ulbrich (2004) [54]	GCM: 1 RCM: 1	2	1	4	+1, +1	Frequency of extreme cyclones, cyclone intensity	1960–1989, 2070–2099, October–March	Northeast Atlantic
Lionello <i>et al.</i> (2008) [59]	GCM: 1 RCM: 1	2	1	4	+1, +1	Frequency of extreme cyclones, cyclone intensity	1961–1990, 2071–2100, winter	Northeast Atlantic
McDonald (2011) [60]	GCM: 1 RCM: -	2	1	4	1	Storm frequency	1960–1990, 2070–2100, DJF	North Atlantic southwest of the UK and west of France
Pinto <i>et al.</i> (2007) [61]	GCM: 1 RCM: -	2	1	4	1	Frequency of extreme cyclones	1960–2000, 2060–2100, October–March	Northeast Atlantic
Semmler <i>et al.</i> (2008) [47]	GCM: 1 RCM: 1	2	1	4	0	Wind intensity	1985–2000, 2085–2100, May–December	Northeast Atlantic
Beersma <i>et al.</i> (1997) [62]	GCM: 1 RCM: -	1	1	3	1	Storm frequency	1980s, 2040s, -	Bay of Biscay
Geng and Sugi (2003) [52]	GCM: 1 RCM: -	1	1	3	1	Frequency of extreme cyclones	1978–1998, ~2050, DJF	North Atlantic in the mid-latitudes, west of the British Isles

**Table 3.** Same as Table 1 but for the Northern Europe subregion.

Study	Model(s)	S	N	ES	T	Category	Reference Period(s), Projection Period(s), Month(s), Season	Region(s)
Gastineau and Soden (2009) [64]	GCM: 16 RCM: -	2	3	8	1	Wind intensity	1995–2000, 2095–2100, -	Northern Europe
Pryor <i>et al.</i> (2006) [46]	GCM: 10 RCM: -	2	3	8	0	Wind intensity	1961–1990, 2046–2065, 2081–2100, -	Scandinavia
Donat <i>et al.</i> (2011) [17]	GCM: 7 RCM: 9	2	2	6	1	Wind intensity	1960–2000, 2021–2050, 2071–2100, October–March	Baltic Sea, Southern Scandinavia
Gregow <i>et al.</i> (2012) [53]	GCM: 9 RCM: -	2	2	6	1	Wind intensity	1971–2000, 2046–2065, 2081–2100, September–April	Eastern (20°E–40°E) and Northern Europe
Löptien <i>et al.</i> (2008) [65]	GCM: 2 RCM: -	2	2	6	1	Frequency of extreme cyclones	1978–1999, 2070–2090, 2170–2190 -	Southern Sweden
Nikulin <i>et al.</i> (2011) [66]	GCM: 6 RCM: 1	2	2	6	1	Wind intensity	1961–1990, 2071–2100, -	Baltic Sea
Schwierz <i>et al.</i> (2010) [27]	GCM: 2 RCM: 2	2	2	6	−1, −1	Frequency of extreme wind speed, wind intensity	1961–1990, 2071–2100, October–March	Northern and Central Scandinavia, Scandinavia
Bengtsson <i>et al.</i> (2009) [31]	GCM: 1 RCM: -	2	1	4	+1, +1	Frequency of extreme wind speed, wind intensity	1959–1990, 2069–2100, DJF	Northern Europe
Giorgi <i>et al.</i> (2004) [63]	GCM: 1 RCM: 1	2	1	4	1	Storm activity	1961–1990, 2071–2100, DJF	Northern Europe
Karremann <i>et al.</i> (2014) [30]	GCM: 1 RCM: -	2	1	4	−1	Storm frequency	1960–2000, 2060–2100, October–March	Scandinavia (parts of Sweden), Denmark

Table 3. Cont.

Study	Model(s)	S	N	ES	T	Category	Reference Period(s), Projection Period(s), Month(s), Season	Region(s)
Leckebusch and Ulbrich (2004) [54]	GCM: 1 RCM: 1	2	1	4	-1	Frequency of extreme cyclones	1979–1989, 2070–2099, October–March	Northern Europe
Mizuta <i>et al.</i> (2011) [67]	GCM: 1 RCM: -	2	1	4	+1, +1	Frequency of extreme cyclones, frequency of extreme wind speed	1979–2003, 2075–2099, DJF	Scandinavia, Baltic Sea
Pinto <i>et al.</i> (2007) [37]	GCM: 1 RCM: -	2	1	4	1	Wind intensity	1960–2000, 2060–2100, October–March	Baltic Sea
Pinto <i>et al.</i> (2009) [55]	GCM: 1 RCM: -	2	1	4	1	Frequency of extreme cyclones	1960–2000, 2060–2100, October–March	Northern Europe
Pinto <i>et al.</i> (2012) [28]	GCM: 1 RCM: -	2	1	4	1	Storm intensity	1960–2000, 2060–2100, October–March	Denmark
Pryor <i>et al.</i> (2012) [68]	GCM: 1 RCM: 2	2	1	4	1	Wind intensity	1961–1990, 2036–2065, 2070–2099, -	Southwestern Scandinavia, Baltic Sea
Beersma <i>et al.</i> (1997) [62]	GCM: 1 RCM: -	1	1	3	-1	Storm frequency	1980s, 2040s, -	Northern Europe
Knippertz <i>et al.</i> (2000) [69]	GCM: 1 RCM: -	1	1	3	+1, +1, +1	Frequency of extreme cyclones, cyclone activity, wind intensity	1880–1930, 2039–2089, DJF	Northern Europe
Walter <i>et al.</i> (2006) [49]	GCM: - RCM: 4	-	1	2	1	Wind intensity	1969–1989, 2070–2099, February	Northern Baltic Sea

### 3.4. Central Europe

The studies reviewed for Central Europe (Table 4, [2,17,27,28,30,31,37,38,49–51,54,55,61,63,64,70–76]) indicated an increase in almost all of the assessed aspects of storminess. However, although we reviewed 23 studies for this subregion, we found no clearly interpretable results on projected changes in future cyclone activity.

With respect to the applied methodology, we rated the studies of [50,51,64] as complex, multi-model approaches ( $M = 3$ ). A shift towards a higher storm activity was identified by [50], while [51] projected an increase in the frequency of extreme cyclones, which are associated with high wind speed at the 850 hPa pressure level. Results from [64] suggested a shift of the 95–100 percentiles towards higher wind speed values at the 850 hPa pressure level; for the purpose of our study, we interpreted this shift as an increase in wind intensity.

Compared to most of the other subregions, for Central Europe the majority of the results were reported for storm frequency and wind intensity. In each case, the eight studies we evaluated, strongly indicated an increase. Furthermore, three studies projected an increasing storm intensity [2,28,70], and two studies suggested an increasing storm activity [50,63]. Results from [28] suggested an increase in wind-induced damage in the future. The study of [74] gave an overview of the future development of storminess over Germany. They used one GCM to drive three RCMs which projected gust speed as an indicator for storminess at a rather high horizontal resolution (<20 km). Their results basically implied a slight decrease of gust wind speed over Central and Southern Germany but suggested an increase of gust wind speed over Northern Germany.

The subregion-related total  $ES$ -score amounts to 151,  $\overline{ES} = 4.7$ . The  $eT$ -value of 0.95 is the second highest  $eT$ -value of our evaluation and clearly indicates an increasing tendency of the future subregion-related storminess.

**Table 4.** Same as Table 1 but for the Central Europe subregion.

Study	Model(s)	S	N	ES	T	Category	Reference Period(s), Projection Period(s), Month(s), Season	Region(s)
Zappa <i>et al.</i> (2013) [51]	GCM: 19 RCM: -	3	3	9	+1, +1	Frequency of extreme cyclones, cyclone intensity	1976–2005, 2070–2099, DJF	Central Europe
Gastineau and Soden (2009) [64]	GCM: 16 RCM: -	2	3	8	1	Wind intensity	1995–2000, 2095–2100, -	Central Europe
Harvey <i>et al.</i> (2012) [50]	GCM: 19 RCM: -	2	3	8	1	Storm activity	1976–2005, 2070–2099, DJF	Central Europe
Donat <i>et al.</i> (2010) [2]	GCM: 7 RCM: -	2	2	6	+1, +1	Storm frequency, storm intensity	Various model-dependent periods, October–March	Central Europe (50°N, 10°E)
Donat <i>et al.</i> (2011) [17]	GCM: 7 RCM: -	2	2	6	1	Wind intensity	1960–2000, 2021–2050, 2071–2100, October–March	Northern Central Europe
Schwierz <i>et al.</i> (2010) [27]	GCM: 2 RCM: 2	2	2	6	+1, +1	Frequency of extreme wind speed, wind intensity	1961–1990, 2071–2100, October–March	Germany, Poland, Baltic Sea, Central Europe in a belt south of Great Britain
Bengtsson <i>et al.</i> (2009) [31]	GCM: 1 RCM: -	2	1	4	+1, +1	Frequency of extreme cyclones, cyclone intensity	1959–1990, 2069–2100, DJF	Central Europe
Beniston <i>et al.</i> (2007) [70]	GCM: 1 RCM: 7	2	1	4	1	Storm intensity	1961–1990, 2071–2100, DJF	Central Europe (45°N–55°N)
Fink <i>et al.</i> (2009) [38]	GCM: 1 RCM: 2	2	1	4	1	Storm frequency	1970–1999, 2070–2099, winter	Central Europe, Germany, Poland

Table 4. Cont.

Study	Model(s)	S	N	ES	T	Category	Reference Period(s), Projection Period(s), Month(s), Season	Region(s)
Gerstengarbe <i>et al.</i> (2013) [71]	GCM: - RCM: 1	2	1	4	1	Storm frequency	1984–2008, 2011–2040, 2041–2070, -	Germany
Giorgi <i>et al.</i> (2004) [63]	GCM: 1 RCM: 1	2	1	4	1	Storm activity	1961–1990, 2071–2100, DJF	Central Europe
Karremann <i>et al.</i> (2014) [30]	GCM: 1 RCM: -	2	1	4	1	Storm frequency	1960–2000, 2060–2100, October–March	France, Germany
Klaus <i>et al.</i> (2011) [72]	GCM: - RCM: 2	2	1	4	1	Storm frequency	1971–2000, 2031–2060, winter	Northwestern Germany
Leckebusch and Ulbrich (2004) [54]	GCM: 1 RCM: 1	2	1	4	1	Frequency of extreme cyclones	1979–1989, 2070–2099, October–March	Central Europe
Pinto <i>et al.</i> (2007) [37]	GCM: 1 RCM: -	2	1	4	1	Wind intensity	1960–2000, 2060–2100, October–March	Central Europe
Pinto <i>et al.</i> (2007) [61]	GCM: 1 RCM: -	2	1	4	1	Wind intensity	1960–2000, 2060–2100, October–March	Central Europe
Pinto <i>et al.</i> (2009) [55]	GCM: 1 RCM: -	2	1	4	1	Storm frequency	1960–2000, 2060–2100, October–March	Central Europe
Pinto <i>et al.</i> (2010) [73]	GCM: 1 RCM: 1	2	1	4	+1, +1	Storm frequency, wind intensity	1960–2000, 2060–2100, October–March	Western Germany
Pinto <i>et al.</i> (2012) [28]	GCM: 1 RCM: -	2	1	4	1	Storm intensity	1960–2000, 2060–2100, October–March	France, Germany

Table 4. Cont.

Study	Model(s)	S	N	ES	T	Category	Reference Period(s), Projection Period(s), Month(s), Season	Region(s)
Rauthe <i>et al.</i> (2010) [74]	GCM: 1 RCM: 3	2	1	4	+1/−1	Wind intensity	1971–2000, 2021–2050, winter	Northern, Central and Southern Germany
Rockel and Woth (2007) [75]	GCM: 1 RCM: 8	2	1	4	+1, +1	Frequency of extreme wind speed, wind intensity	1961–1990, 2071–2100, -	Central Europe
Leckebusch <i>et al.</i> (2008) [76]	GCM: 1 RCM: -	1	1	3	+1, +1, +1	Storm frequency, cyclone intensity, frequency of extreme wind speed	1880–1930, 2039–2089, October–March	Central Europe
Walter <i>et al.</i> (2006) [49]	GCM: - RCM: 4	-	1	2	1	Wind intensity	1969–1989, 2070–2099, February	Germany



### 3.5. Southern Europe

The findings of the eleven studies for Southern Europe (Table 5) indicated, without exception, decreasing long-term behavior of storminess, including the two studies [51,64] for which we rated  $ES = 9$ . While the majority of the studies addressed projected future changes in wind intensity, three studies presented results on the expected future development of the frequency of extreme cyclones [31,69,77]. For all other assessed categories, a maximum of two studies was found that reported on projected aspects of storminess. Based on our evaluation scheme, the subregion-related total  $ES$ -score is 63, the  $\overline{ES}$ -value is 5.3, and  $eT = -1.00$ , which unambiguously suggests a decreasing tendency of the projected future extratropical storminess.

### 3.6. Western Europe

The 33 studies available for this subregion (Table 6, [2,5,9,13,17,19,26–28,30,37,45,48–51,54–58,60–62,67,70,74–76,78–81]) allowed for the evaluation of all categories of aspects of projected future storminess. The majority of the evaluated studies projected an increase in frequency, intensity, and activity of storms and cyclones, as well as an increase in frequency and intensity of high-impact wind speed.

Results of [50] obtained from an ensemble of 19 CMIP3-models, implied an increase in storm activity. From the results of [51,78], an increasing frequency of extreme cyclones can be inferred, while another study [56] reported an increase in cyclone activity. The results of the study of [5] showed an increase in cyclone intensity and at the same time a decreasing storm frequency.

Two of the evaluated studies also reported on the future development of storm damage. While the results from [17] indicated an increase of wind-induced damage, the study of [28] suggested a decrease in projected wind-induced damage. In two further studies, no change in analyzed long-term development of storminess was found: One study [48] did not identify a change in expected wind intensity over the North Sea, and another study [45] reported no change in cyclone intensity over the UK.

The subregion-related total  $ES$ -score is 221, the  $\overline{ES}$ -value equals 4.7, and the  $eT$ -value is 0.84; thus, we strongly assume that projected future storminess will increase in this subregion.

### 3.7. Eastern Europe

Altogether we found five studies for the Eastern Europe subregion (Table 7). Therefore, the results of our evaluation in this subregion are probably the least robust in comparison to the other subregions, not only because of the low number of available studies but also because of the limited (according to our evaluation scheme) methodological complexity of the evaluated studies. Among the studies available for evaluation, there was no study comprising RCP-scenarios and/or multi-model ensembles. Only two studies used more than one GCM [17,53]. Their results suggested an increase in future wind intensity. While one study [17] investigated the change of the ensemble mean of extreme wind speed, another study investigated the strength of extreme wind speed events with a return period of ten years [53].

Overall, results concerning the future development of storminess over Eastern Europe are inconclusive. While findings from the study of [59] implied a decrease for Russia, another study projected an increasing number of cyclones over parts of Russia [67]. The subregion-specific total  $ES$ -score amounts to 36,  $\overline{ES} = 4.5$ , and  $eT = 0.56$ .

**Table 5.** Same as Table 1 but for the Southern Europe subregion.

Study	Model(s)	S	N	ES	T	Category	Reference Period(s), Projection Period(s), Month(s), Season	Region(s)
Zappa <i>et al.</i> (2013) [51]	GCM: 19 RCM: -	3	3	9	-1	Cyclone intensity	1976–2005, 2070–2099, DJF	Mediterranean region
Gastineau and Soden (2009) [64]	GCM: 16 RCM: -	2	3	8	-1	Wind intensity	1995–2000, 2095–2100, -	Southern Europe
Donat <i>et al.</i> (2011) [17]	GCM: 7 RCM: 9	2	2	6	-1	Wind intensity	1960–2000, 2021–2050, 2071–2100, October–March	Mediterranean region
Nikulin <i>et al.</i> (2011) [66]	GCM: 6 RCM: 1	2	2	6	-1	Wind intensity	1961–1990, 2071–2100, -	Europe south of 45°N
Schwierz <i>et al.</i> (2010) [27]	GCM: 2 RCM: 2	2	2	6	-1	Wind intensity	1961–1990, 2071–2100, October–March	Mediterranean region
Bengtsson <i>et al.</i> (2006) [9]	GCM: 1 RCM: -	2	1	4	-1	Cyclone intensity	1961–1990, 2071–2100, DJF	Mediterranean region (30°N–45°N, 0°E–40°E)
Bengtsson <i>et al.</i> (2009) [31]	GCM: 1 RCM: -	2	1	4	-1, -1	Frequency of extreme cyclones, cyclone intensity	1959–1990, 2069–2100, DJF	Southern Europe (30°N–47.5°N, 10°W–40°E)
Beniston <i>et al.</i> (2007) [70]	GCM: 1 RCM: 7	2	1	4	-1	Storm intensity	1961–1990, 2071–2100, DJF	Southern Europe (Alps and south of the Alps)
Fink <i>et al.</i> (2009) [38]	GCM: 1 RCM: 2	2	1	4	-1	Storm frequency	1970–1999, 2070–2099, winter	Mediterranean region
Giorgi <i>et al.</i> (2004) [63]	GCM: 1 RCM: 1	2	1	4	-1	Storm activity	1961–1990, 2071–2100, DJF	Southern Europe
Muskulus and Jacob (2005) [77]	GCM: 1 RCM: 1	2	1	4	-1	Frequency of extreme cyclones	1961–2099, winter	Mediterranean region

**Table 6.** Same as Table 1 but for the Western Europe subregion.

Study	Model(s)	S	N	ES	T	Category	Reference Period(s), Projection Period(s), Month(s), Season	Region(s)
Mizuta (2012) [78]	GCM: 11 RCM: -	3	3	9	1	Frequency of extreme cyclones	1979–2003, 2075–2099, DJF	British Isles
de Winter <i>et al.</i> (2012) [48]	GCM: 12 RCM: -	3	3	9	0	Wind intensity	1950–2000, 2050–2100, -	North Sea
Zappa <i>et al.</i> (2013) [51]	GCM: 19 RCM: -	3	3	9	1	Frequency of extreme cyclones	1976–2005, 2070–2099, DJF	United Kingdom
Harvey <i>et al.</i> (2012) [50]	GCM: 19 RCM: -	2	3	8	1	Storm activity	1976–2005, 2070–2099, DJF	British Isles
Ulbrich <i>et al.</i> (2008) [56]	GCM: 15 RCM: -	2	3	8	1	Cyclone activity	1960–2000, 2081–2100, winter	Western Europe
Barstad <i>et al.</i> (2012) [19]	GCM: 4 RCM: -	2	2	6	−1	Wind intensity	1971–2001, 2020–2049, -	North Sea
Donat <i>et al.</i> (2010) [2]	GCM: 7 RCM: -	2	2	6	+1, +1	Storm frequency, storm intensity	Various model– dependent periods, October–March	Northeast Atlantic, British Isles, North Sea
Donat <i>et al.</i> (2011) [17]	GCM: 7 RCM: 9	2	2	6	1	Wind intensity	1960–2000, 2021–2050, 2071–2100, October–March	Western Europe, North Sea region, British Isles
Leckebusch <i>et al.</i> (2006) [13]	GCM: 4 RCM: 4	2	2	6	+1, +1, +1	Frequency of extreme cyclones, frequency of extreme wind speed, wind intensity	1961–1989, 2071–2099, October–March	British Isles

Table 6. Cont.

Study	Model(s)	S	N	ES	T	Category	Reference Period(s), Projection Period(s), Month(s), Season	Region(s)
Leckebusch <i>et al.</i> (2008) [57]	GCM: 7 RCM: -	2	2	6	1	Storm frequency	1961–2000, 2081–2100, winter	Western Central Europe
Schwierz <i>et al.</i> (2010) [27]	GCM: 2 RCM: 2	2	2	6	1	Frequency of extreme wind speed	1961–1990, 2071–2100, October–March	Northern Great Britain, English Channel, North Sea, Netherlands
Bengtsson <i>et al.</i> (2006) [9]	GCM: 1 RCM: -	2	1	4	+1, +1	Frequency of extreme cyclones, cyclone intensity	1961–1990, 2071–2100, DJF	British Isles
Beniston <i>et al.</i> (2007) [70]	GCM: 1 RCM: 7	2	1	4	1	Storm frequency	1961–1990, 2071–2100, DJF	North Sea coast
Della-Marta and Pinto (2009) [26]	GCM: 1 RCM: -	2	1	4	1	Frequency of extreme cyclones	1960–2000, 2060–2100, October–March	British Isles, North Sea/Western Europe (45°N–60°N, 10°W–30°E)
Hanson <i>et al.</i> (2003) [45]	GCM: 1 RCM: 1	2	1	4	0	Cyclone intensity	1961–1990, 2070–2099, October–March	United Kingdom
Karremann <i>et al.</i> (2014) [30]	GCM: 1 RCM: -	2	1	4	1	Storm frequency	1960–2000, 2060–2100, October–March	France, Netherlands, British Isles
Leckebusch and Ulbrich (2004) [54]	GCM: 1 RCM: 1	2	1	4	+1, +1, +1	Storm frequency, frequency of extreme cyclones, cyclone inten- sity	1960–1989, 2070–2099, October–March	Western Europe, Western Central Europe, British Isles
Leckebusch <i>et al.</i> (2008) [58]	GCM: 1 RCM: -	2	1	4	1	Storm intensity	1971–2000, 2071–2100, October–March	Western Central Europe
McDonald (2011) [60]	GCM: 1 RCM: -	2	1	4	1	Storm frequency	1960–1990, 2070–2100, DJF	North Sea, British Isles

Table 6. Cont.

Study	Model(s)	S	N	ES	T	Category	Reference Period(s), Projection Period(s), Month(s), Season	Region(s)
Mizuta <i>et al.</i> (2011) [67]	GCM: 1 RCM: -	2	1	4	+1, +1	Frequency of extreme cyclones, frequency of extreme wind speed	1979–2003, 2075–2099, DJF	Scotland, North Sea
Pinto <i>et al.</i> (2007) [37]	GCM: 1 RCM: -	2	1	4	+1, +1, +1	Storm frequency, frequency of extreme cyclones, wind intensity	1960–2000, 2060–2100, October–March	Western Europe, North Sea
Pinto <i>et al.</i> (2007) [61]	GCM: 1 RCM: -	2	1	4	+1, +1	Frequency of extreme cyclones, wind intensity	1960–2000, 2060–2100, October–March	British Isles, Western Europe
Pinto <i>et al.</i> (2009) [55]	GCM: 1 RCM: -	2	1	4	+1, +1	Frequency of extreme cyclones, cyclone intensity	1960–2000, 2060–2100, October–March	British Isles and environs, North Sea
Pinto <i>et al.</i> (2012) [28]	GCM: 1 RCM: -	2	1	4	1	Storm intensity	1960–2000, 2060–2100, October–March	Belgium, France, Great Britain, Ireland, Netherlands
Rauthe <i>et al.</i> (2010) [74]	GCM: 1 RCM: 3	2	1	4	1	Wind intensity	1971–2000, 2021–2050, winter	Netherlands, Northwestern North Sea
Rockel and Woth (2007) [75]	GCM: 1 RCM: 8	2	1	4	+1, +1	Frequency of extreme wind speed, wind intensity	1961–1990, 2071–2100, -	British Isles
Sterl <i>et al.</i> (2009) [79]	GCM: 1 RCM: -	2	1	4	1	Wind intensity	1950–2000, 2050–2100, -	Southern North Sea (53°N–55°N)
Beersma <i>et al.</i> (1997) [62]	GCM: 1 RCM: -	1	1	3	1	Storm frequency	1980s, 2040s, -	North Sea
Carnell <i>et al.</i> (1996) [80]	GCM: 1 RCM: -	1	1	3	+1, +1	Cyclone intensity, frequency of extreme wind speed	1983–1992, -, DJF	British Isles

Table 6. Cont.

Study	Model(s)	S	N	ES	T	Category	Reference Period(s), Projection Period(s), Month(s), Season	Region(s)
Leckebusch <i>et al.</i> (2008) [76]	GCM: 1 RCM: -	1	1	3	1	Frequency of extreme wind speed	1880–1930, 2039–2089, October–March	British Isles
Lozano <i>et al.</i> (2004) [5]	GCM: 1 RCM: -	1	1	3	+1, −1	Storm frequency, cyclone intensity	1970–1999, 2060–2089, winter	Coastal zone of Ireland and Southern Scotland
Ulbrich and Christoph (1999) [81]	GCM: 1 RCM: -	1	1	3	+1	Cyclone activity	1860–2100, DJF	Northwestern Europe
Walter <i>et al.</i> (2006) [49]	GCM: - RCM: 4	-	1	2	1	Wind intensity	1969–1989, 2070–2099, February	North Sea, English Channel

**Table 7.** Same as Table 1 but for the Eastern Europe subregion.

<b>Study</b>	<b>Model(s)</b>	<b>S</b>	<b>N</b>	<b>ES</b>	<b>T</b>	<b>Category</b>	<b>Reference Period(s), Projection Period(s), Month(s), Season</b>	<b>Region(s)</b>
Donat <i>et al.</i> (2011) [17]	GCM: 7 RCM: -	2	2	6	1	Wind intensity	1960–2000, 2021–2050, 2071–2100, October–March	Eastern Europe
Gregow <i>et al.</i> (2012) [53]	GCM: 9 RCM: -	2	2	6	1	Wind intensity	1971–2000, 2046–2065, 2081–2100, September–April	Eastern Europe (20°E–40°E), Northern Europe
Lionello <i>et al.</i> (2008) [59]	GCM: 1 RCM: 1	2	1	4	−1, −1	Frequency of extreme cyclones, cyclone intensity	1961–1990, 2071–2100, winter	Russia
Mizuta <i>et al.</i> (2011) [67]	GCM: 1 RCM: -	2	1	4	+1, +1	Frequency of extreme cyclones, frequency of extreme wind speed	1979–2003, 2075–2099, DJF	Parts of Russia
Rockel and Woth (2007) [75]	GCM: 1 RCM: 8	2	1	4	+1, +1	Frequency of extreme wind speed, wind intensity	1961–1990, 2071–2100, -	Eastern Europe

### 3.8. Changes in the North Atlantic Oscillation and Storm Tracks

The studies summarized in Table 8 [9,25,31,36,38,48,50–52,54,56,59–61,63–65,69,80–87] report on projections of future NAO- and storm track characteristics over the NAER. The reported results are quite diverse. Sixteen out of the 26 assessed studies indicated that future storm tracks will at least partly shift either northward, northeastward, eastward, or poleward. However, findings from ten studies implied storm tracks shifting south- or southeastward. Furthermore, there were five studies that suggested no shifts in the long-term development of storm tracks. With respect to NAO-characteristics, the results from three of the studies indicated a northeastward shift of the NAO in the future. The NAO- and storm track-related total *ES*-score amounts to 129, and  $\overline{ES}$  equals 5.0.

**Table 8.** Studies reporting on projections of future NAO- and/or storm track characteristics over the NAER.

Study	S	N	ES	Change in NAO	Change(s) in Storm Track
Harvey <i>et al.</i> (2012) [50]	3	3	9	-	No change
de Winter <i>et al.</i> (2012) [48]	3	3	9	-	Northward
Zappa <i>et al.</i> (2013) [51]	3	3	9	-	Eastward extension
Gastineau and Soden (2009) [64]	2	3	8	-	Northward
Lambert and Fyfe (2006) [82]	2	3	8	-	No change
Ulbrich <i>et al.</i> (2008) [56]	2	3	8	-	Slightly southward
Yin (2005) [83]	2	3	8	-	North- and eastward
Löptien <i>et al.</i> (2008) [65]	2	2	6	-	No change
Bengtsson <i>et al.</i> (2006) [9]	2	1	4	-	Northward
Bengtsson <i>et al.</i> (2009) [31]	2	1	4	-	Northward
Fink <i>et al.</i> (2009) [38]	2	1	4	Northeastward	-
Fischer-Bruns <i>et al.</i> (2005) [36]	2	1	4	-	Northward
Giorgi <i>et al.</i> (2004) [63]	2	1	4	-	Northward (JJA)
Laine (2009) [84]	2	1	4	-	Poleward and upward
Leckebusch and Ulbrich (2004) [54]	2	1	4	-	Southward
Lionello <i>et al.</i> (2008) [59]	2	1	4	-	Northward
McDonald (2011) [60]	2	1	4	-	Southward in eastern North Atlantic otherwise northward
Pinto <i>et al.</i> (2007) [61]	2	1	4	Northeastward	Eastward
Carnell <i>et al.</i> (1996) [80]	1	1	3	-	Northward
Catto <i>et al.</i> (2011) [85]	1	1	3	-	Northeastward (in 2 CO <sub>2</sub> -experiments), no change (in 4 CO <sub>2</sub> -experiments)
Geng and Sugi (2003) [52]	1	1	3	-	Southeastward
Knippertz <i>et al.</i> (2000) [69]	1	1	3	-	Northeastward
Lambert (1995) [86]	1	1	3	-	No change
Pinto <i>et al.</i> (2006) [25]	1	1	3	-	Northward
Schubert <i>et al.</i> (1998) [87]	1	1	3	-	Eastward (in 2 CO <sub>2</sub> -experiments), southeastward (in 3 CO <sub>2</sub> -experiments)
Ulbrich and Christoph (1999) [81]	1	1	3	Northeastward	-



#### 4. Summary and Conclusions

Our research on the current literature yielded a total of 58 studies modeling aspects of the projected future storminess over the NAER. Through a categorical evaluation scheme based on the ranking of emission scenarios and modeling complexity, we attempted a joint evaluation of the methodologically highly diverse studies. The intention was to disclose to which degree the studies yielded either shared or differing general tendencies in the projected future development of storminess. In our evaluation, we did not attempt to treat the NAER as a whole but differentiated for seven subregions for the following two reasons: On the one hand, the spatial reference of the evaluated studies allowed for a differentiation, as they all clearly referred to subregions within the NAER. On the other hand, it is highly improbable that aspects of storminess will show consistent development throughout the NAER in the future.

Not unexpectedly, a heterogeneous picture of the projected future storminess emerges from the evaluation. From a total of 156 ratings, (i) 76% suggest an increase; (ii) 21% indicate a decrease; and (iii) 3% of the ratings do not indicate any change in the projected aspects of storminess. With respect to the assessed categories of storminess (Table 9), most of the ratings refer to results from studies addressing future changes in the intensity of high-impact wind speed (43 ratings) and frequency of extreme cyclones (35 ratings).

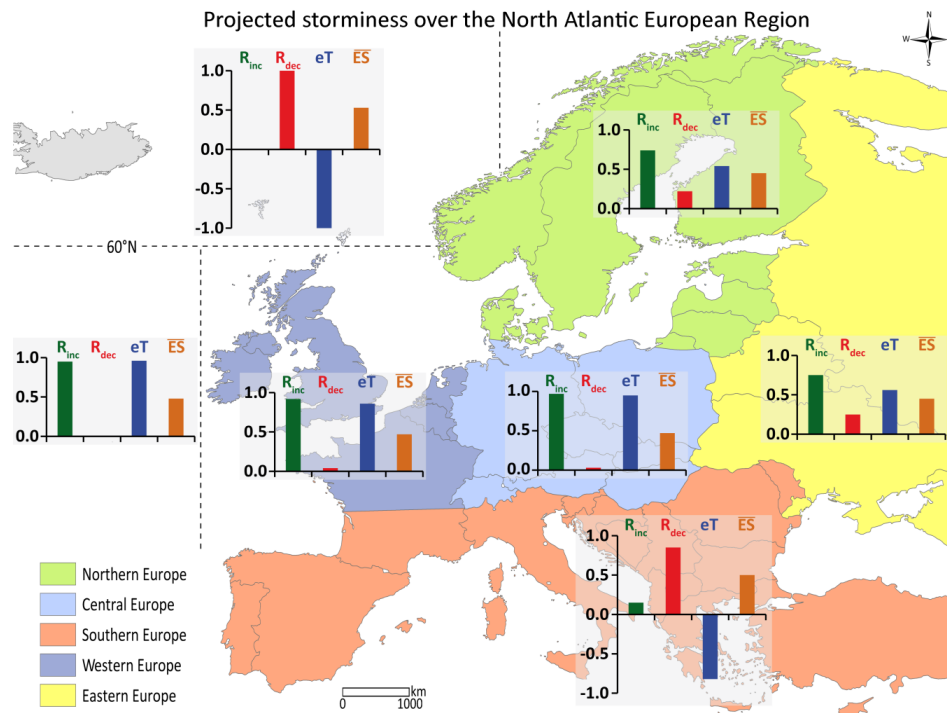
**Table 9.** Number of ratings assigned to categories of aspects of projected future storminess over the NAER.

Category	Number of Ratings
Wind intensity	43
Frequency of extreme cyclones	35
Storm frequency	23
Cyclone intensity	20
Frequency of extreme wind speed	14
Other categories	21

Despite the noteworthy differences in the number and quality of studies available for the evaluated subregions, it is apparent that the projected future development of storminess is quite heterogeneous and not consistent in the NAER. However, within the subregions, results on projected aspects of future storminess are clearer. For the three subregions Central Europe, North Atlantic south of 60°N, and Western Europe, the evaluated studies clearly indicate (>90% of the ratings) increasing tendencies for projected aspects of future storminess (Figure 2). For Eastern and Northern Europe, the majority of ratings (75% and 74%) also indicates increasing tendencies in projected aspects of future storminess; however, the studies available for these two subregions also indicate, in more than 20% of the ratings, decreasing tendencies of aspects of future storminess. Predominantly decreasing tendencies of aspects of storminess are indicated for subregions North Atlantic north of 60°N (85% of the ratings) and Southern Europe (100% of the ratings).

The relative distribution of the subregion-related ratings is mirrored by the summary of the subregion-related  $eT$ -values. While  $eT$ -values computed for Central Europe, the North Atlantic region south of 60°N and Western Europe indicate clear tendencies for an increasing storminess in these subregions,  $eT$ -values computed for the North Atlantic region north of 60°N and the Southern Europe region strongly suggest decreasing tendencies in storminess. Based on the  $eT$ -values, we deemed the results on the projected future development of storminess over Eastern and Northern Europe as inconclusive. However, we believe that, in particular, the interpretation of our findings for Eastern Europe and Southern Europe is limited for two reasons: For Eastern Europe, there were only few studies available, and the evaluation of studies available for the Southern European subregion was restricted to the projected development of extratropical storms and cyclones. In the evaluation, we did not address the projected future development of tropical storms and cyclones, which might be of

importance for the long-term evolution of storminess in this particular subregion. For example, results from [59] implied an increase in wind intensity associated with tropical cyclones, while there was indication that wind intensity associated with extratropical cyclones would simultaneously decrease. In addition, there is an indication that tropical cyclones might transform into extratropical cyclones as they move northward. Since tropical cyclones are expected to intensify in a warmer climate, this could also boost extratropical storms in the summer and autumn [31].



**Figure 2.** Relative proportions of ratings indicating either increasing ( $R_{inc}$ ) or decreasing ( $R_{dec}$ ) tendencies of aspects of projected future storminess, subregion-related  $eT$ -, and  $\overline{ES}$ -values for the seven subregions of the NAER. The  $\overline{ES}$ -values were divided by 10 to adapt them to the scaling. The height of the columns corresponds to the numbers given in the subregion-related text sections.

Across the evaluated subregions, the  $\overline{ES}$ -values vary between 4.5 and 5.3, which hints at a nearly balanced mean weighting of the seven analyzed subregions.

The results from the majority of studies that reported on the future development of storm tracks over the NAER point in a similar direction, as they mostly suggested a north- and eastward shift of storm tracks. Regardless of the results reported for the Northern Europe subregion, based on the storm track-related findings, it must be concluded that Northern Europe is probably the most strongly subject to potential increases in aspects of future storminess.

The comparison of the results presented in this review with results from previous reviews [11,22–24] on the storminess over NAER is limited. This is mainly due to methodological reasons. We did not only use a different evaluation scheme, but we have also assessed changes in categories of aspects of projected storminess in subregions of the NAER which are based on a pool of studies that differed from the pools of studies included in previous reviews.

**Author Contributions:** Tina Mölter developed the research idea, designed the study, carried out the study evaluation, and co-wrote the manuscript. Dirk Schindler developed the research idea and wrote the manuscript. Axel Tim Albrecht developed the research idea and commented on the manuscript. Ulrich Kohnle helped to refine the research idea and commented on the manuscript.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A

**Table A1.** Models used or mentioned in the reviewed studies and subregion(s) covered by the model grids. Although not all listed models are general circulation models, GCM is used to indicate the global scale of the model grid. RCM stands for regional climate model or indicates the regional scale of the model grid. The listed studies are sorted according to the surname of the lead author.

Study	Model(s)	Subregion(s), NAO/Storm Track
Barstad <i>et al.</i> (2012) [19]	GCM: Arpege/IFS, GFDL V2.0, ECHAM5, HADCM3, CCSM3 RCM: -	Western Europe
Beersma <i>et al.</i> (1997) [62]	GCM: ECHAM3 RCM: -	North Atlantic south of 60°N, Northern Europe, Western Europe
Bengtsson <i>et al.</i> (2006) [9]	GCM: ECHAM5/MPI-OM RCM: -	North Atlantic north of 60°N, North Atlantic south of 60°N, Southern Europe, Western Europe, change of storm/cyclone track or NAO
Bengtsson <i>et al.</i> (2009) [31]	GCM: ECHAM5 RCM: -	North Atlantic south of 60°N, Northern Europe, Central Europe, Southern Europe, change of storm/cyclone track or NAO
Beniston <i>et al.</i> (2007) [70]	GCM: HadAM3H RCM: HIRHAM, HadRM3H/P, RAO, REMO, CHRM, CLM, RASMO3	Central Europe, Southern Europe, Western Europe
Carnell <i>et al.</i> (1996) [80]	GCM: UKMO RCM: -	Western Europe, change of storm/cyclone track or NAO
Catto <i>et al.</i> (2011) [85]	GCM: HiGEM1.1 RCM: -	Change of storm/cyclone track or NAO
Della-Marta and Pinto (2009) [26]	GCM: ECHAM5/OM1 RCM: -	Western Europe
Donat <i>et al.</i> (2010) [2]	GCM: BCCr-BCM2, CNRM-CM3, DMI-ECHAM5, FUB-EGMAM, IPSL-CM4, MPI-ECHAM5, METO-HC-HadGEM1 RCM: -	North Atlantic south of 60°N, Central Europe, Western Europe
Donat <i>et al.</i> (2011) [17]	GCM: BCCr-BCM2, CNRM-CM3, DMI-ECHAM5, FUB-EGMAM, IPSL-CM4, MPI-ECHAM5, METO-HC-HadGEM1 RCM: C4I-RCA3, HC-HadRM3, ETHZ-CLM, CNRM-RM4.5, DMI-HIRHAM, METNO-HIRHAM, KNMI-RACMO2, MPI-REMO, SMHI-RCA3	Northern Europe, Central Europe, Southern Europe, Western Europe, Eastern Europe
Fink <i>et al.</i> (2009) [38]	GCM: ECHAM5/MPI-OM RCM: REMO, COSMO-CLM	Central Europe, Southern Europe, change of storm/cyclone track or NAO
Fischer-Bruns <i>et al.</i> (2005) [36]	GCM: ECHAM4/HOPE-G RCM: -	Change of storm/cyclone track or NAO
Gastineau and Soden (2009) [64]	GCM: CGCM3.1 (T47), CGCM3.1 (T63), CSIRO-Mk3.0, CSIRO-Mk3.5, CNRM-CM3, GFDL-CM2.0, GFDL-CM2.1, GISS-AOM, FGOALS-g1.0, INM-CM 3.0, IPSL-CM4, MIROC3.2, MIUB/ECHO-G, ECHAM5/MPI-OM, ECHAM5/INGV, MRI_CGCM2.3.2 RCM: -	Northern Europe, Central Europe, Southern Europe, change of storm/cyclone track or NAO

Table A1. Cont.

Study	Model(s)	Subregion(s), NAO/Storm Track
Geng and Sugi (2003) [52]	GCM: JMA8911 RCM: -	North Atlantic north of 60°N, North Atlantic south of 60°N, change of storm/cyclone track or NAO
Gerstengarbe <i>et al.</i> (2013) [71]	GCM: - RCM: STARS	Central Europe
Giorgi <i>et al.</i> (2004) [63]	GCM: HadAM3H RCM: HadRM3H	Northern Europe, Central Europe, Southern Europe, change of storm/cyclone track or NAO
Gregow <i>et al.</i> (2012) [53]	GCM: BCCR-BCM2.0, CGCM3.1, CNRM-CM3, ECHAM5/MPI-OM, GFDL-CM2.1, IPSL-CM4, MIROC3.2, MRI-CGCM2.3.2, NCAR-CCSM3 RCM: -	North Atlantic north of 60°N, Northern Europe, Eastern Europe
Hanson <i>et al.</i> (2003) [45]	GCM: HadAM3H RCM: HadRM3H	North Atlantic south of 60°N, Western Europe
Harvey <i>et al.</i> (2012) [50]	GCM: BCC-CSM1.1, CanESM2, CNRM-CM5, CSIRO-Mk3.6.0, EC-EARTH, FGOALS-g2, GFDL-ESM2G, GFDL-ESM2M, HadGEM2-CC, HadGEM2-ES, INM-CM4, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC-ESM, MIROC-ESM-CHEM, MIROC5, MPI-ESM-LR, MRI-CGCM3, NorESM1-M (CMIP5 models)  BCCR-BCM2.0, CGCM3.1 (T47), CGCM3.1 (T63), CNRM-CM3, CSIRO-CM3, CSIRO-Mk3.0, CSIRO-Mk3.5, ECHAM5/MPI-OM, ECHO-G, GFDL-CM2.0, GFDL-CM2.1, GISS-AOM, GISS-ER, INVG-SXG, INM-CM3.0, IPSL-CM4, MIROC3.2, MRI-CGCM2.3.2, NCAR CCSM3 (CMIP3 models) RCM: -	North Atlantic north of 60°N, North Atlantic south of 60°N, change of storm/cyclone track or NAO  North Atlantic south of 60°N, Central Europe, Western Europe
Karremann <i>et al.</i> (2014) [30]	GCM: ECHAM5/MPI-OM1 RCM: -	Northern Europe, Central Europe, Western Europe
Klaus <i>et al.</i> (2011) [72]	GCM: ECHAM5/MPI-OM1 RCM: -	Central Europe
Knippertz <i>et al.</i> (2000) [69]	GCM: ECHAM4/OPYC3 RCM: -	Northern Europe, Southern Europe, change of storm/cyclone track or NAO
Laine (2009) [84]	GCM: CNRM-CM3, IPSL-CM4 RCM: -	Change of storm/cyclone track or NAO
Lambert (1995) [86]	GCM: GCMII RCM: -	Change of storm/cyclone track or NAO
Lambert and Fyfe (2006) [82]	GCM: CCCMA (T47), CNRM, GFDL2.0, GFDL2.1, GISS-AOM, GISS-EH, GISS-ER, INM, IPSL, MIROC, ECHAM5/MPI, MRI, NCAR-PCM, NCAR-CCSM RCM: -	Change of storm/cyclone track or NAO

Table A1. Cont.

Study	Model(s)	Subregion(s), NAO/Storm Track
Leckebusch and Ulbrich (2004) [54]	GCM: HadCM3 RCM: HadRM3H	North Atlantic north of 60°N, North Atlantic south of 60°N, Northern Europe, Central Europe, Western Europe, change of storm/cyclone track or NAO
Leckebusch <i>et al.</i> (2006) [13]	GCM: ECHAM4/OPYC3, ECHAM5/MPI-OM1, HadAM3P, HadAM3H RCM: HadRM3P, HIRHAM4, CHRM, RCAO	North Atlantic north of 60°N, North Atlantic south of 60°N, Western Europe
Leckebusch <i>et al.</i> (2008) [57]	GCM: MPI-ECHAM5, DMI-ECHAM5, IPSL-CM4, FUB-EGMAM, CNRM-CM3, BCCR-BCM2, HadGEM1 RCM: -	North Atlantic south of 60°N, Western Europe
Leckebusch <i>et al.</i> (2008) [58]	GCM: ECHAM5-OM1 RCM: -	North Atlantic south of 60°N, Western Europe
Leckebusch <i>et al.</i> (2008) [76]	GCM: ECHAM4/OPYC3 RCM: -	Central Europe, Western Europe
Lionello <i>et al.</i> (2008) [59]	GCM: HadAM3H (HadCM3 provides SST) RCM: RegCM	North Atlantic south of 60°N, Eastern Europe, change of storm/cyclone track or NAO
Löptien <i>et al.</i> (2008) [65]	GCM: ECHAM4/OPYC3, ECHAM5/OM RCM: -	Northern Europe, change of storm/cyclone track or NAO
Lozano <i>et al.</i> (2004) [5]	GCM: ECHAM4 A-GCM (boundary conditions derived by OA-GCM) RCM: -	Western Europe
McDonald (2011) [60]	GCM: HadAM3P (driven by boundary conditions derived from observations and HadCM3 experiments) RCM: -	North Atlantic south of 60°N, Western Europe, change of storm/cyclone track or NAO
Mizuta (2012) [78]	GCM: BCC-CSM1.1, CCSM4, CSIRO- Mk3-6-0, GFDL-ESM2G, HadGEM2-CC, INMCM4, IPSL-CM5A-LR, MIROC5, MPI-ESM-LR, MRI-CGCM3, NorESM1-M RCM: -	Western Europe
Mizuta <i>et al.</i> (2011) [67]	GCM: MRI-AGCM3.1 RCM: -	Northern Europe, Western Europe, Eastern Europe
Muskulus and Jacob (2005) [77]	GCM: ECHAM4/OPYC3 RCM: REMO 5.1	Southern Europe
Nikulin <i>et al.</i> (2011) [66]	GCM: ECHAM5, CCSM3, HadCM3, CNRM, BCM, IPSL RCM: RCA3	Northern Europe, Southern Europe
Pinto <i>et al.</i> (2006) [25]	GCM: ECHAM4/OPYC3 RCM: -	North Atlantic north of 60°N, change of storm/cyclone track or NAO
Pinto <i>et al.</i> (2007) [37]	GCM: ECHAM5/MPI-OM1 RCM: -	North Atlantic north of 60°N, Northern Europe, Central Europe, Southern Europe, Western Europe
Pinto <i>et al.</i> (2007) [61]	GCM: ECHAM5/MPI-OM1 RCM: -	North Atlantic south of 60°N, Central Europe, Southern Europe, Western Europe, change of storm/cyclone track or NAO
Pinto <i>et al.</i> (2009) [55]	GCM: ECHAM5/MPI-OM1 RCM: -	North Atlantic north of 60°N, Northern Europe, Central Europe, Western Europe
Pinto <i>et al.</i> (2010) [73]	GCM: ECHAM5/MPI-OM1 RCM: FOOT3DK	Central Europe
Pinto <i>et al.</i> (2012) [28]	GCM: ECHAM5/MPI-OM1 RCM: -	Northern Europe, Central Europe, Western Europe

Table A1. Cont.

Study	Model(s)	Subregion(s), NAO/Storm Track
Pryor <i>et al.</i> (2006) [46]	GCM: BCCR-BCM2.0, BCC-CM1, CGCM3.1, CNRM-CM3, ECHAM5/MPI-OM, GFDL-CM2.0, GISS-ModelE20/Rusell, IPSL-CM4, MIROC3.2, MRI-CHCM2.2.2 RCM: -	Northern Europe
Pryor <i>et al.</i> (2012) [68]	GCM: ECHAM5/MPI-OM RCM: HIRHAM5, RCA3	Northern Europe
Rauthe <i>et al.</i> (2010) [74]	GCM: ECHAM5/MPI-OM RCM: CCLM1 and 2, REMO	Central Europe, Western Europe
Rockel and Woth (2007) [75]	GCM: HadAM3H, (HadCM3 provides SST and sea ice conditions) RCM: HIRHAM, CHRM, CLM, HadRM3, RACMO, REMO, RCAO, PROMES	Central Europe, Western Europe, Eastern Europe
Schubert <i>et al.</i> (1998) [87]	GCM: ECHAM3 (ECHAM1/LSG provides SST and sea ice conditions) RCM: -	Change of storm/cyclone track or NAO
Schwierz <i>et al.</i> (2010) [27]	GCM: HadAM3, ECHAM5 RCM: CLM, CHRM	North Atlantic north of 60°N, Northern Europe, Central Europe, Southern Europe, Western Europe
Semmler <i>et al.</i> (2008) [47]	GCM: ECHAM5-OM1 RCM: RCA3	North Atlantic south of 60°N
Sterl <i>et al.</i> (2009) [79]	GCM: ECHAM5/MPI-OM RCM: -	Western Europe
Ulbrich and Christoph (1999) [81]	GCM: ECHAM4/OPYC3 RCM: -	Western Europe, change of storm/cyclone track or NAO
Ulbrich <i>et al.</i> (2008) [56]	GCM: CCCma (T47), CCCma (T63), CNRM-CM3, CSIRO-mk3.0, ECHAM5/OM1, ECHO-G, FRAU IPSL-CM4, GFDL-CM2.0, GISS-AOM, GISS E-R, IAP, FGOALS-g1.0, INM-CM3.0, MIROC3.2, MRI-CGCM2.3.2, NCAR CCSM3 RCM: -	North Atlantic south of 60°N, Western Europe, change of storm/cyclone track or NAO
Walter <i>et al.</i> (2006) [49]	GCM: - RCM: REMO5.0 and 5.1, CLM, MCCM/MM5	Northern Europe, Central Europe, Western Europe
de Winter <i>et al.</i> (2012) [48]	GCM: CanESM2, CSIRO-Mk3-6-0, EC-Earth, GFDL-ESM2G, GFDL-ESM2M, HadGEM2-CC, HadGEM2-ES, IOSL-CM5a-MR, MIROC-ESM-CHEM, MIROC5, MPI-ESM-LR, MRI-CGCM3 RCM: -	Western Europe, change of storm/cyclone track or NAO
Yin (2005) [83]	GCM: MIROC3.2, CCSM3, ECHAM5/MPI-OM, GFDL-CM2.0, GFDL-CM2.1, CNRM-CM3, MIROC3.2, MRI-CGCM2.3.2, FGOALS-g1.0, IPSL-CM4, CGCM3.1 (T47), ECHO-G, GISS-AOM, GISS-ER, INM-CM3.0 RCM: -	Change of storm/cyclone track or NAO

Table A1. Cont.

Study	Model(s)	Subregion(s), NAO/Storm Track
Zappa <i>et al.</i> (2013) [51]	GCM: BCC-CSM1.1, CanESM2, CNRM-CM5, CSIRO-Mk3.6.0, EC-EARTH, FGOALS-g2, GFDL-ESM2M, GFDL-ESM2G, HadGEM2-CC, HadGEM2-ES, INM-CM4, IPSL-CM5A-LR, IPSL-CM5A-MR, MPI-ESM-LR, MRI-CGCM3, MIROC5, MIROC-ESM, MIROC-ESM-CHEM, NorESM1-M RCM: -	North Atlantic north of 60°N, Central Europe, Southern Europe, Western Europe, change of storm/cyclone track or NAO

## Appendix B

Table B1. Climate scenarios, variables reported in the reviewed studies and their assignment to the assessed categories frequency, intensity and activity for the subregions evaluated in this review. The listed studies are sorted according to the surname of the lead author.

North Atlantic North of 60°N			
Study	Climate Scenario	Variable(s) Reported	Categories of Aspects of Storminess
Bengtsson <i>et al.</i> (2006) [9]	SRES A1B	Storm track intensity	Cyclone intensity
Geng and Sugi (2003) [52]	IS92a	Density of strong cyclones (central pressure gradient >30 hPa · (1000 km) <sup>-1</sup> )	Frequency of extreme cyclones
Gregow <i>et al.</i> (2012) [53]	SRES A1B, A2, B1	Strength of the 10-year return period extreme wind speed	Wind intensity
Harvey <i>et al.</i> (2012) [50]	RCP4.5	Storm activity	Storm activity
Leckebusch and Ulbrich (2004) [54]	SRES A2, B2	Number of extreme cyclones	Frequency of extreme cyclones
Leckebusch <i>et al.</i> (2006) [13]	SRES A2 (IS92a for ECHAM4/OPYC3)	Cyclone track density of the strongest 5%	Frequency of extreme cyclones
Pinto <i>et al.</i> (2006) [25]	IS92a	Number of intense cyclones, cyclone intensity	Frequency of extreme cyclones, cyclone intensity
Pinto <i>et al.</i> (2007) [37]	SRES A1B, A2	98th wind percentile	Wind intensity
Pinto <i>et al.</i> (2009) [55]	SRES A1B	Track density and intensity of extreme cyclones (10% most severe in term of intensity)	Frequency of extreme cyclones, cyclone intensity
Schwierz <i>et al.</i> (2010) [27]	SRES A2	Strength of extreme storms expressed in gust speed	Storm intensity
Zappa <i>et al.</i> (2013) [51]	RCP4.5, RCP8.5	Wind intensity	Wind intensity
Beersma <i>et al.</i> (1997) [62]	CO <sub>2</sub> -experiment	Number of storm events	Storm frequency
Bengtsson <i>et al.</i> (2006) [9]	SRES A1B	Cyclone track density and intensity, number of stronger storms (>10 × 10 <sup>-5</sup> s <sup>-1</sup> )	Frequency of extreme cyclones, cyclone intensity
Bengtsson <i>et al.</i> (2009) [31]	SRES A1B	99.5th percentile of wind speed in 925 hPa as an aspect of extratropical cyclones	Cyclone intensity
Donat <i>et al.</i> (2010) [2]	SRES A1B	Intensity of storm cyclones and associated wind speed	Cyclone intensity, wind intensity

**Table B1.** *Cont.*

Harvey <i>et al.</i> (2012) [50]	SRES A1B, RCP4.5	Cyclone activity	Cyclone activity
Leckebusch and Ulbrich (2004) [54]	SRES A2, B2	Track density of extreme cyclones (defined by the exceedance of the 95th percentile of the Laplacian of MSLP), cyclone intensity	Frequency of extreme cyclones, cyclone intensity
Geng and Sugi (2003) [52]	IS92a	Density of strong cyclones (central pressure gradient >30 hPa/1000 km)	Frequency of extreme cyclones
Hanson <i>et al.</i> (2003) [45]	SRES A2a, B2a	Number of extreme cyclones (<970 hPa), intensity of cyclones	Frequency of extreme cyclones, cyclone intensity
Leckebusch <i>et al.</i> (2006) [13]	SRES A2 (IS92a for ECHAM4/OPYC3)	Number of extreme cyclones, cyclone track density of the strongest 5%	Frequency of extreme cyclones
Leckebusch <i>et al.</i> (2008) [57]	SRES A1B	Extreme cyclones which are connected to wind storms	Storm frequency
Leckebusch <i>et al.</i> (2008) [58]	SRES A1B, A2	Storm severity defined by its impacts	Storm intensity
Lionello <i>et al.</i> (2008) [59]	SRES A2, B2	Frequency and intensity of extreme cyclones	Frequency of extreme cyclones, cyclone intensity
McDonald (2011) [60]	SRES A2	Ensemble mean number of gale days per winter for storms and stronger events (Bft ≥ 10)	Storm frequency
Pinto <i>et al.</i> (2007) [61]	SRES A1B, A2, B1	Number of intense cyclones (>2.5 hPa/(deg. lat) <sup>2</sup> )	Frequency of extreme cyclones
Semmler <i>et al.</i> (2008) [47]	SRES A2	Maximum wind speed	Wind intensity
Ulbrich <i>et al.</i> (2008) [56]	SRES A1B	Storm track activity	Cyclone activity
<b>Northern Europe</b>			
<b>Study</b>	<b>Climate Scenario</b>	<b>Variable(s) Reported</b>	<b>Categories of Aspects of Storminess</b>
Beersma <i>et al.</i> (1997) [62]	CO <sub>2</sub> -experiment	Number of storm events	Storm frequency
Bengtsson <i>et al.</i> (2009) [31]	SRES A1B	Number of cyclones for winds >45 m/s and 99.5th percentile of wind speed at 925 hPa	Frequency of extreme cyclones, cyclone intensity
Donat <i>et al.</i> (2011) [17]	SRES A1B	Ensemble mean of extreme wind speed (98th percentile of daily maximum wind speed)	Wind intensity
Gastineau and Soden (2009) [64]	SRES A1B	95th-99th percentile of 850 hPa pressure level wind speed	Wind intensity
Giorgi <i>et al.</i> (2004) [63]	SRES A2, B2	Precipitation changes due to changes in storm activity	Storm activity
Gregow <i>et al.</i> (2012) [53]	SRES A1B, A2, B1	Strength of the 10-year return period of extreme wind speed	Wind intensity
Karremann <i>et al.</i> (2014) [30]	SRES A1B	Return period of 1yrl and 2yrl storm events	Storm frequency
Knippertz <i>et al.</i> (2000) [69]	IS92a	Storm track activity, extreme wind speed, deep cyclones with core pressure less than 970 hPa	Frequency of extreme cyclones, cyclone activity, wind intensity
Leckebusch and Ulbrich (2004) [54]	SRES A2, B2	Track density of extreme cyclones	Frequency of extreme cyclones
Löptien <i>et al.</i> (2008) [65]	SRES A1B	Intense cyclones with a central pressure <980 hPa	Frequency of extreme cyclones
Mizuta <i>et al.</i> (2011) [67]	SRES A1B	Number of intense cyclones, frequency of strong wind	Frequency of extreme cyclones, frequency of extreme wind speed



Table B1. Cont.

Nikulin <i>et al.</i> (2011) [66]	SRES A1B	Ensemble mean of the 10 m daily maximum gust wind in terms of the 20 yr return value	Wind intensity
Pinto <i>et al.</i> (2007) [37]	SRES A1B, A2	Value of the 98th wind percentile	Wind intensity
Pinto <i>et al.</i> (2009) [55]	SRES A1B	Track density of very extreme storms which undergo a strong intensification phase close to Europe	Frequency of extreme cyclones
Pinto <i>et al.</i> (2012) [28]	SRES B1, A1B, A2	Intensity of windstorms, return levels for losses due to windstorms	Storm intensity
Pryor <i>et al.</i> (2006) [46]	SRES A2	90th percentile wind speed	Wind intensity
Pryor <i>et al.</i> (2012) [68]	SRES A1B	50-year return period of wind speed, 98th percentile wind gust magnitude	Wind intensity
Schwierz <i>et al.</i> (2010) [27]	SRES A2	Gust events, strength of extreme storms expressed in gust speed	Frequency of extreme wind speed, wind intensity
Walter <i>et al.</i> (2006) [49]	Not mentioned	Mean changes of wind velocities	Wind intensity
<b>Central Europe</b>			
<b>Study</b>	<b>Climate Scenario</b>	<b>Variable(s) Reported</b>	<b>Categories of Aspects of Storminess</b>
Bengtsson <i>et al.</i> (2009) [31]	SRES A1B	Number of cyclones for winds >45 m/s and 99.5th percentile of wind speed at 925 hPa	Frequency of extreme cyclones, cyclone intensity
Beniston <i>et al.</i> (2007) [70]	SRES A2	90th percentile of daily wind speed	Storm intensity
Donat <i>et al.</i> (2010) [2]	SRES A1B	Number of storm days and associated mean daily maximum wind speed	Storm frequency, storm intensity
Donat <i>et al.</i> (2011) [17]	SRES A1B	Ensemble mean of extreme wind speed	Wind intensity
Fink <i>et al.</i> (2009) [38]	SRES A1B	Risk of wind storms	Storm frequency
Gastineau and Soden (2009) [64]	SRES A1B	95th-99th percentile of 850 hPa pressure level wind speed	Wind intensity
Gerstengarbe <i>et al.</i> (2013) [71]	SRES A1B	Winter storm related loss events	Storm frequency
Giorgi <i>et al.</i> (2004) [63]	SRES A2, B2	Precipitation changes due to changes in storm activity	Storm activity
Harvey <i>et al.</i> (2012) [50]	SRES A1B	Storm activity	Storm activity
Karremann <i>et al.</i> (2014) [30]	SRES A1B	Return period of 2yrl storm events	Storm frequency
Klaus <i>et al.</i> (2011) [72]	SRES A1B	Frequency of severe storms	Storm frequency
Leckebusch and Ulbrich (2004) [54]	SRES A2, B2	Track density of extreme cyclones	Frequency of extreme cyclones
Leckebusch <i>et al.</i> (2008) [76]	IS92a	Occurrence of extreme wind speed and storm situations, pressure gradient of cyclones	Storm frequency, cyclone intensity, frequency of extreme wind speed
Pinto <i>et al.</i> (2007) [37]	SRES A1B, A2	98th wind percentile	Wind intensity
Pinto <i>et al.</i> (2007) [61]	SRES A1B, A2, B1	98th percentile of daily maximum 10 m wind	Wind intensity
Pinto <i>et al.</i> (2009) [55]	SRES A1B	Number of windstorms	Storm frequency
Pinto <i>et al.</i> (2010) [73]	SRES A1B, A2	Number of storm events, 98th wind gust percentile	Storm frequency, wind intensity

Table B1. Cont.

Pinto <i>et al.</i> (2012) [28]	SRES B1, A1B, A2	Intensity of storms, return levels for losses due to storms	Storm intensity
Rauthe <i>et al.</i> (2010) [74]	SRES A1B, B1, A2	Wind gust extremes for a 10-year return period	Wind intensity
Rockel and Woth (2007) [75]	SRES A2	Number of storm peaks, 99th percentile of mean wind speed	Frequency of extreme wind speed, wind intensity
Schwierz <i>et al.</i> (2010) [27]	SRES A2	Gust events, strength of storms expressed in gust speed	Frequency of extreme wind speed, wind intensity
Walter <i>et al.</i> (2006) [49]	Not mentioned	Mean change of wind velocities	Wind intensity
Zappa <i>et al.</i> (2013) [51]	RCP4.5, RCP8.5	Number of cyclones, wind speed of cyclones	Frequency of extreme cyclones, cyclone intensity
<b>Southern Europe</b>			
<b>Study</b>	<b>Climate Scenario</b>	<b>Variable(s) Reported</b>	<b>Categories of Aspects of Storminess</b>
Bengtsson <i>et al.</i> (2006) [9]	SRES A1B	Mean intensity of storm track	Cyclone intensity
Bengtsson <i>et al.</i> (2009) [31]	SRES A1B	Number of strong cyclones for winds >35 m/s and 99.5th percentile of wind speed in 925 hPa as an aspect of extra-tropical cyclones	Frequency of extreme cyclones, cyclone intensity
Beniston <i>et al.</i> (2007) [70]	SRES A2	90th percentile of daily wind speed	Storm intensity
Donat <i>et al.</i> (2011) [17]	SRES A1B	Ensemble mean of extreme wind speed, storm loss potential	Wind intensity
Fink <i>et al.</i> (2009) [38]	SRES A1B	Risk of occurrence of wind storms	Storm frequency
Gastineau and Soden (2009) [64]	SRES A1B	95th-99th percentile of 850 hPa pressure level wind speed	Wind intensity
Giorgi <i>et al.</i> (2004) [63]	SRES A2, B2	Precipitation changes due to changes in storm activity	Storm activity
Knippertz <i>et al.</i> (2000) [69]	IS92a	Storm track activity, extreme wind speed, deep cyclones with core pressure less than 970 hPa	Frequency of extreme cyclones, cyclone activity, wind intensity
Muskulus and Jacob (2005) [77]	SRES B2	Number of strong cyclones (<995 hPa)	Frequency of extreme cyclones
Nikulin <i>et al.</i> (2011) [66]	SRES A1B	Ensemble mean of the 10 m daily maximum gust wind speed in terms of 20-year return values	Wind intensity
Pinto <i>et al.</i> (2007) [37]	SRES A1B, A2	Value of the 98th wind percentile	Wind intensity
Pinto <i>et al.</i> (2007) [61]	SRES A1B, A2, B1	98th percentile of daily maximum 10 m wind	Wind intensity
Schwierz <i>et al.</i> (2010) [27]	SRES A2	Strength of extreme storms expressed in gust speed	Wind intensity
Zappa <i>et al.</i> (2013) [51]	RCP4.5, RCP8.5	Wind speed of cyclones	Cyclone intensity

Table B1. Cont.

Western Europe			
Study	Climate Scenario	Variable(s) Reported	Categories of Aspects of Storminess
Barstad <i>et al.</i> (2012) [19]	SRES A1B	Wind speed ( $>27.5 \text{ m} \cdot \text{s}^{-1}$ ) at 100 m height	Wind intensity
Beersma <i>et al.</i> (1997) [62]	CO <sub>2</sub> -experiment	Number of storm events	Storm frequency
Bengtsson <i>et al.</i> (2006) [9]	SRES A1B	Storm track density, number of stronger storms ( $>10 \times 10^{-5} \text{ s}^{-1}$ ), mean intensity of storm track	Frequency of extreme cyclones, cyclone intensity
Beniston <i>et al.</i> (2007) [70]	SRES A2	Number of moderate and strong storms	Storm frequency
Carnell <i>et al.</i> (1996) [80]	CO <sub>2</sub> -experiment	Stronger winds, depth of cyclones	Frequency of extreme wind speed, cyclone intensity
Della-Marta and Pinto (2009) [26]	SRES A1B, A2	Return periods of extreme cyclones of all intensities	Frequency of extreme cyclones
Donat <i>et al.</i> (2010) [2]	SRES A1B	Track density and mean intensity of cyclones	Storm frequency, storm intensity
Donat <i>et al.</i> (2011) [17]	SRES A1B	Ensemble mean of extreme wind speed, loss potential	Wind intensity
Harvey <i>et al.</i> (2012) [50]	SRES A1B	Storm activity	Storm activity
Hanson <i>et al.</i> (2003) [45]	SRES A2a, B2a	Cyclone intensity	Cyclone intensity
Karremann <i>et al.</i> (2014) [30]	SRES A1B	Storm events with a return period of 1 and 2 years	Storm frequency
Leckebusch and Ulbrich (2004) [54]	SRES A2, B2	Influence of windstorms, track density of extreme cyclones, cyclone intensity	Storm frequency, frequency of extreme cyclones, cyclone intensity
Leckebusch <i>et al.</i> (2006) [13]	SRES A2 (IS92a for ECHAM4/OPYC3)	Number of extreme cyclones, cyclone track density, frequency of extreme wind speed, intensity of wind speed	Frequency of extreme cyclones, frequency of extreme wind speed, wind intensity
Leckebusch <i>et al.</i> (2008) [57]	SRES A1B	Extreme cyclones which are connected to wind storms	Storm frequency
Leckebusch <i>et al.</i> (2008) [58]	SRES A1B, A2	Storm severity defined by its impacts	Storm intensity
Leckebusch <i>et al.</i> (2008) [76]	IS92a	Relative frequency of exceedance of the local 98th percentile of the local wind	Frequency of extreme wind speed
Lozano <i>et al.</i> (2004) [5]	IS92a	Number of storms, cyclone intensity	Storm frequency, cyclone intensity
McDonald (2011) [60]	SRES A2	Ensemble mean number of gale days and stronger events	Storm frequency
Mizuta (2012) [78]	RCP4.5	Number of intense cyclones	Frequency of extreme cyclones
Mizuta <i>et al.</i> (2011) [67]	SRES A1B	Number of intense cyclones, frequency of strong wind	Frequency of extreme cyclones, frequency of extreme wind speed
Pinto <i>et al.</i> (2007) [37]	SRES A1B, A2	Frequency of storms, value of the 98th wind percentile, number of extreme cyclones	Storm frequency, frequency of extreme cyclones, wind intensity
Pinto <i>et al.</i> (2007) [61]	SRES A1B, A2, B1	98th percentile of daily maximum 10 m wind, number of intense cyclones	Wind intensity, frequency of extreme cyclones

Table B1. Cont.

Pinto <i>et al.</i> (2009) [55]	SRES A1B	Track density and intensity of extreme cyclones (10% most severe in term of intensity)	Frequency of extreme cyclones, cyclone intensity
Pinto <i>et al.</i> (2012) [28]	SRES B1, A1B, A2	Intensity of windstorms, return levels for losses due to windstorms	Storm intensity
Rauthe <i>et al.</i> (2010) [74]	SRES A1B, B1, A2	Wind gust extremes for a 10-year return period	Wind intensity
Rockel and Woth (2007) [75]	SRES A2	Number of storm peaks (gusts $\geq 8$ Bft), 99th percentile of daily mean wind speed	Frequency of extreme wind speed, wind intensity
Schwierz <i>et al.</i> (2010) [27]	SRES A2	Gust events	Frequency of extreme wind speed
Sterl <i>et al.</i> (2009) [79]	SRES A1B	6-hourly wind speed $>8$ Bf	Wind intensity
Ulbrich and Christoph (1999) [81]	IS92a	Upper air storm track activity	Cyclone activity
Ulbrich <i>et al.</i> (2008) [56]	SRES A1B	Storm track activity	Cyclone activity
Walter <i>et al.</i> (2006) [49]	Not mentioned	Mean changes of wind velocities	Wind intensity
de Winter <i>et al.</i> (2012) [48]	RCP4.5, RCP8.5	Annual maximum wind speed, wind speeds with lower return periods (1:500 year event)	Wind intensity
Zappa <i>et al.</i> (2013) [51]	RCP4.5, RCP8.5	Cyclones associated with strong at 850 hPa wind speed	Frequency of extreme cyclones
<b>Eastern Europe</b>			
<b>Study</b>	<b>Climate Scenario</b>	<b>Variable(s) Reported</b>	<b>Categories of Aspects of Storminess</b>
Donat <i>et al.</i> (2011) [17]	SRES A1B	Ensemble mean of extreme wind speed	Wind intensity
Gregow <i>et al.</i> (2012) [53]	SRES A1B, A2, B1	Strength of the 10-year return period extreme wind speed	Wind intensity
Lionello <i>et al.</i> (2008) [59]	SRES A2, B2	Frequency and intensity of extreme cyclones	Frequency of extreme cyclones, cyclone intensity
Mizuta <i>et al.</i> (2011) [67]	SRES A1B	Number of intense cyclones, frequency of strong wind	Frequency of extreme cyclones, frequency of extreme wind speed
Rockel and Woth (2007) [75]	SRES A2	Number of storm peaks, 99th percentile of daily mean wind speed	Frequency of extreme wind speed, wind intensity

## References

1. Munich, R.E. *Significant Natural Disasters since 1980. Costliest Winter Storms in Europe*; Publication of the Munich Re: Munich, Germany, 2015.
2. Donat, M.G.; Leckebusch, G.C.; Pinto, J.G.; Ulbrich, U. European storminess and associated circulation weather types: Future changes deduced from a multi-model ensemble of GCM simulations. *Clim. Res.* **2010**, *42*, 27–43. [[CrossRef](#)]
3. Schuck, A.; Schelhaas, M.-J. Storm damage in Europe—An overview. In *What Science Can Tell Us. Living with Storm Damage to Forests*; Gardiner, B., Schuck, A., Schelhaas, M.J., Orazio, C., Blennow, K., Nicoll, B., Eds.; European Forest Institute: Barcelona, Spain, 2013; pp. 15–23.
4. Dawson, A.; Elliott, L.; Noone, S.; Hickey, K.; Holt, T.; Wadhams, P.; Foster, I. Historical storminess and climate ‘see-saw’ in the North Atlantic region. *Mar. Geol.* **2004**, *210*, 247–259. [[CrossRef](#)]
5. Lozano, I.; Devoy, R.J.N.; May, W.; Andersen, U. Storminess and vulnerability along the Atlantic coastlines of Europe: Analysis of storm records and of a greenhouse gases induced climate scenario. *Mar. Geol.* **2004**, *210*, 205–225. [[CrossRef](#)]

6. Clarke, M.L.; Rendell, H.M. The impact of North Atlantic storminess on western European coasts: A review. *Quatern. Int.* **2009**, *195*, 31–41. [[CrossRef](#)]
7. Hurrell, J.W.; Kushnir, Y.; Visbeck, M. The North Atlantic Oscillation. *Science* **2001**, *291*, 603–605. [[CrossRef](#)] [[PubMed](#)]
8. Keim, B.D.; Muller, R.A.; Stone, G.W. Spatial and temporal variability of coastal storms in the North Atlantic Basin. *Mar. Geol.* **2004**, *210*, 7–15. [[CrossRef](#)]
9. Bengtsson, L.; Hodges, K.I.; Roeckner, E. Storm tracks and climate change. *J. Clim.* **2006**, *19*, 3518–3543. [[CrossRef](#)]
10. Greeves, C.Z.; Pope, V.D.; Stratton, R.A.; Martin, G.M. Representation of Northern Hemisphere winter storm tracks in climate models. *Clim. Dyn.* **2007**, *28*, 683–702. [[CrossRef](#)]
11. Bader, J.; Mesquita, M.D.S.; Hodges, K.I.; Keenlyside, N.; Østerhus, S.; Miles, M. A review on Northern Hemisphere sea-ice, storminess and the North Atlantic Oscillation: Observations and projected changes. *Atmos. Res.* **2011**, *101*, 809–834. [[CrossRef](#)]
12. Marshall, J.; Kushnir, Y.; Battistic, D.; Chang, P.; Czaja, A.; Dickson, R.; Hurrell, J.; McCartney, M.; Saravanan, R.; Visbeck, M. North atlantic climate variability: Phenomena, impacts and mechanisms, review. *Int. J. Climatol.* **2001**, *21*, 1863–1898. [[CrossRef](#)]
13. Leckebusch, G.C.; Koffi, B.; Ulbrich, U.; Pinto, J.G.; Spanghel, T.; Zacharias, S. Analysis of frequency and intensity of European winter storm events from a multi-model perspective, at synoptic and regional scales. *Clim. Res.* **2006**, *31*, 59–74. [[CrossRef](#)]
14. Pfister, C. Winterstürme. In *Wetternachhersage, 500 Jahre Klimavariationen und Naturkatastrophen*; Haupt-Verlag: Bern, Switzerland, 1999; pp. 246–255. (In German)
15. Fischer, H.; Mieding, B. A 1000-year ice core record of interannual to multidecadal variations on atmospheric circulation over the North Atlantic. *Clim. Dyn.* **2005**, *25*, 65–74. [[CrossRef](#)]
16. Klawa, M.; Ulbrich, U. A model for the estimation of storm losses and the identification of severe winter storms in Germany. *Nat. Hazard Earth Syst. Sci.* **2003**, *3*, 725–732. [[CrossRef](#)]
17. Donat, M.G.; Leckebusch, G.C.; Wild, S.; Ulbrich, U. Future changes in European winter storm losses and extreme wind speeds inferred from GCM and RCM multi-model simulations. *Nat. Hazard Earth Syst. Sci.* **2011**, *11*, 1351–1370. [[CrossRef](#)]
18. Kleemann, M. Stürmische Perspektiven—Nutzungsmöglichkeiten und Grenzen der Windenergie. *Physik in unserer Zeit* **1996**, *27*, 60–68. (In German) [[CrossRef](#)]
19. Barstad, I.; Sorteberg, A.; Mesquita, M.D.S. Present and future offshore wind power potential in northern Europe based on downscaled global climate runs with adjusted SST and sea ice cover. *Renew. Energ.* **2012**, *44*, 398–405. [[CrossRef](#)]
20. Young, G.S.; Kristensen, L. Surface-layer gusts for aircraft operation. *Bound. Lay Meteor.* **1992**, *59*, 231–242. [[CrossRef](#)]
21. Manasseh, R.; Middleton, J.H. The surface wind gust regime and aircraft operations at Sydney Airport. *J. Wind Eng. Ind. Aerod.* **1999**, *79*, 269–288. [[CrossRef](#)]
22. Albrecht, A.; Schindler, D.; Grebhan, K.; Kohnle, U.; Mayer, H. Sturmaktivität über der nordatlantisch-europäischen Region vor dem Hintergrund des Klimawandels: Eine Literaturübersicht. *Allg. Forst Jagdztg.* **2009**, *180*, 109–118. (In German)
23. Ulbrich, U.; Leckebusch, G.C.; Pinto, J.G. Extra-tropical cyclones in the present and future climate: A review. *Theor. Appl. Climatol.* **2009**, *96*, 117–131. [[CrossRef](#)]
24. Feser, F.; Barcikowska, M.; Krueger, O.; Schenk, F.; Weisse, R.; Xia, L. Storminess over the North Atlantic and northwestern Europe—A review. *Q. J. Roy. Meteor. Soc.* **2015**, *141*, 350–382. [[CrossRef](#)]
25. Pinto, J.G.; Spanghel, T.; Ulbrich, U.; Speth, P. Assessment of winter cyclone activity in a transient ECHAM4-OPYC3 GHG experiment. *Meteorol. Z.* **2006**, *15*, 279–291. [[CrossRef](#)]
26. Della-Marta, P.M.; Pinto, J.G. Statistical uncertainty of changes in winter storms over the North Atlantic and Europe in an ensemble of transient climate simulations. *Geophys. Res. Lett.* **2009**, *36*, L14703. [[CrossRef](#)]
27. Schwierz, C.; Köllner-Heck, P.; Zenklusen Mutter, E.; Bresch, D.N.; Vidale, P.-L.; Wild, M.; Schär, C. Modelling European winter wind storm losses in current and future climate. *Clim. Chang.* **2010**, *101*, 485–514. [[CrossRef](#)]
28. Pinto, J.G.; Karremann, M.K.; Born, K.; Della-Marta, P.M.; Klawa, M. Loss potentials associated with European windstorms under future climate conditions. *Clim. Res.* **2012**, *54*, 1–20. [[CrossRef](#)]

29. Outten, S.D.; Esau, I. Extreme winds over Europe in the ENSEMBLES regional climate models. *Atmos. Chem. Phys.* **2013**, *13*, 5163–5172. [[CrossRef](#)]
30. Karremann, M.K.; Pinto, J.G.; Reyers, M.; Klawa, M. Return periods of losses associated with European windstorm series in a changing climate. *Environ. Res. Lett.* **2014**, *9*, 12016. [[CrossRef](#)]
31. Bengtsson, L.; Hodges, K.I.; Keenlyside, N. Will extratropical storms intensify in a warmer climate? *J. Clim.* **2009**, *22*, 2276–2301. [[CrossRef](#)]
32. Wang, X.L.; Swail, V.R.; Zwiers, F.W. Climatology and changes of extratropical cyclone activity: Comparison of ERA-40 with NCEP–NCAR reanalysis for 1958–2001. *J. Clim.* **2006**, *19*, 3145–3166. [[CrossRef](#)]
33. Raible, C.C.; Yoshimori, M.; Stocker, T.F.; Casty, C. Extreme midlatitude cyclones and their implications for precipitation and wind speed extremes in simulations of the Maunder Minimum *versus* present day conditions. *Clim. Dyn.* **2007**, *28*, 409–423. [[CrossRef](#)]
34. Wang, X.L.; Swail, V.R.; Zwiers, F.W. Changes in extratropical storm tracks and cyclone activity as derived from two global reanalyses and the Canadian CGCM2 projections of future climate. In Proceedings of the Eighth International Workshop on Wave Hindcasting and Forecasting, North Shore, Oahu, HI, USA, 14–19 November 2004.
35. Schmith, T.; Kaas, E.; Li, T.-S. Northeast Atlantic winter storminess 1875–1995 re-analysed. *Clim. Dyn.* **1998**, *14*, 529–536. [[CrossRef](#)]
36. Fischer-Bruns, I.; von Storch, H.; Gonzalez-Rouco, J.F.; Zorita, E. Modelling the variability of midlatitude storm activity on decadal to century time scales. *Clim. Dyn.* **2005**, *25*, 461–476. [[CrossRef](#)]
37. Pinto, J.G.; Froehlich, E.L.; Leckebusch, G.C.; Ulbrich, U. Changing European storm loss potentials under modified climate conditions according to ensemble simulations of the ECHAM5/MPI-OM1 GCM. *Nat. Hazard Earth Syst. Sci.* **2007**, *7*, 165–175. [[CrossRef](#)]
38. Fink, A.H.; Brücher, T.; Ermert, V.; Krüger, A.; Pinto, J.G. The European storm Kyrill in January 2007: Synoptic evolution, meteorological impacts and some considerations with respect to climate change. *Nat. Hazard Earth Syst. Sci.* **2009**, *9*, 405–423. [[CrossRef](#)]
39. Leggett, J.; Pepper, W.J.; Swart, R.J. Emissions Scenarios for IPCC: An Update. In *Climate Change 1992. The Supplementary Report to the IPCC Scientific Assessment*; Houghton, J.T., Callander, B.A., Varney, S.K., Eds.; Cambridge University Press: Cambridge, UK, 1992; pp. 69–95.
40. Intergovernmental Panel on Climate Change (IPCC). *Special Report on Emissions Scenarios: A special report of Working Group III of the Intergovernmental Panel on Climate Change*; Nakićenović, N., Swart, R., Eds.; Cambridge University Press: Cambridge, UK, 2000.
41. Van Vuuren, D.P.; Edmonds, J.; Kainuma, M.; Riahi, K.; Thomson, A.; Hibbard, K.; Hurtt, G.C.; Kram, T.; Krey, V.; Lamarque, J.-F.; *et al.* The representative concentration pathways: An overview. *Clim. Chang.* **2011**, *109*, 5–31. [[CrossRef](#)]
42. Leckebusch, G.C.; Ulbrich, U.; Froehlich, L.; Pinto, J.G. Property loss potentials for European midlatitude storms in a changing climate. *Geophys. Res. Lett.* **2007**, *34*, L05703. [[CrossRef](#)]
43. Blennow, K.; Olofsson, E. The probability of wind damage in forestry under a changed wind climate. *Clim. Chang.* **2008**, *87*, 347–360. [[CrossRef](#)]
44. Tebaldi, C.; Knutti, R. The use of the multi-model ensemble in probabilistic climate projections. *Philos. T. R. Soc. A* **2007**, *365*, 2053–2075. [[CrossRef](#)] [[PubMed](#)]
45. Hanson, C.E.; Palutikof, J.P.; Osborn, T.; Davies, T.; Holt, T.; Quine, C. An integrated assessment of the potential for change in storm activity over Europe: Implications for forestry in the UK. In Proceedings of the International Conference Wind Effects on Trees, Karlsruhe, Germany, 16–18 September 2003; pp. 129–136.
46. Pryor, S.C.; Schoof, J.T.; Barthelmie, R.J. Winds of change? Projections of near-surface winds under climate change scenarios. *Geophys. Res. Lett.* **2006**, *33*, L11702. [[CrossRef](#)]
47. Semmler, T.; Varghese, S.; McGrath, R.; Nolan, P.; Wang, S.; Lynch, P.; O'Dowd, C. Regional climate model simulations of North Atlantic cyclones: Frequency and intensity changes. *Clim. Res.* **2008**, *36*, 1–11. [[CrossRef](#)]
48. de Winter, R.C.; Sterl, A.; Ruessink, B.G. Wind extremes in the North Sea Basin under climate change: An ensemble study of 12 CMIP5 GCMs. *J. Geophys. Res. Atmos.* **2012**, *118*, 1601–1612. [[CrossRef](#)]
49. Walter, A.; Keuler, K.; Jacob, D.; Knoche, R.; Block, A.; Kotlarski, S.; Müller-Westermeier, G.; Rechid, D.; Ahrens, W. A high resolution reference data set of German wind velocity 1951–2001 and comparison with regional climate model results. *Meteorol. Z.* **2006**, *15*, 585–596. [[CrossRef](#)]

50. Harvey, B.J.; Shaffrey, L.C.; Woollings, T.J.; Zappa, G.; Hodges, K.I. How large are projected 21st century storm track changes? *Geophys. Res. Lett.* **2012**, *39*, L18707. [[CrossRef](#)]
51. Zappa, G.; Shaffrey, L.C.; Hodges, K.I.; Sansom, P.G.; Stephenson, D.B. A multimodel assessment of future projections of North Atlantic and European extratropical cyclones in the CMIP5 climate models. *J. Clim.* **2013**, *26*, 5846–5862. [[CrossRef](#)]
52. Geng, Q.; Sugi, M. Possible change of extratropical cyclone activity due to enhanced green-house gases and sulfate aerosols—Study with a high-resolution AGCM. *J. Clim.* **2003**, *16*, 2262–2274. [[CrossRef](#)]
53. Gregow, H.; Ruosteenoja, K.; Pimenoff, N.; Jylhä, K. Changes in the mean and extreme geostrophic wind speeds in Northern Europe until 2100 based on nine global climate models. *Int. J. Climatol.* **2012**, *32*, 1834–1846. [[CrossRef](#)]
54. Leckebusch, G.C.; Ulbrich, U. On the relationship between cyclones and extreme windstorm events over Europe under climate change. *Glob. Planet. Chang.* **2004**, *44*, 181–193. [[CrossRef](#)]
55. Pinto, J.G.; Zacharias, S.; Fink, A.H.; Leckebusch, G.C.; Ulbrich, U. Factors contributing to the development of extreme North Atlantic cyclones and their relationship with the NAO. *Clim. Dyn.* **2009**, *32*, 711–737. [[CrossRef](#)]
56. Ulbrich, U.; Pinto, J.G.; Kupfer, H.; Leckebusch, G.C.; Spangehl, T.; Reyers, M. Changing Northern Hemisphere storm tracks in an ensemble of IPCC climate change simulations. *J. Clim.* **2008**, *21*, 1669–1679. [[CrossRef](#)]
57. Leckebusch, G.C.; Donat, M.G.; Ulbrich, U.; Pinto, J.G. Mid-latitude cyclones and storms in an ensemble of European AOGCMs under ACC. *Clivar Exch.* **2008**, *13*, 3–5.
58. Leckebusch, G.C.; Renggli, D.; Ulbrich, U. Development and application of an objective storm severity measure for the Northeast Atlantic region. *Meteorol. Z.* **2008**, *17*, 575–587. [[CrossRef](#)] [[PubMed](#)]
59. Lionello, P.; Boldrin, U.; Giorgi, F. Future changes in cyclone climatology over Europe as inferred from a regional climate simulation. *Clim. Dyn.* **2008**, *30*, 657–671. [[CrossRef](#)]
60. McDonald, R.E. Understanding the impact of climate change on Northern Hemisphere extra-tropical cyclones. *Clim. Dyn.* **2011**, *37*, 1399–1425. [[CrossRef](#)]
61. Pinto, J.G.; Ulbrich, U.; Leckebusch, G.C.; Spangehl, T.; Reyers, M.; Zacharias, S. Changes in storm track and cyclone activity in three SRES ensemble experiments with the ECHAM5/MPI-OM1 GCM. *Clim. Dyn.* **2007**, *29*, 195–210. [[CrossRef](#)]
62. Beersma, J.J.; Rider, K.M.; Komen, G.J.; Kaas, E.; Kharin, V.V. An analysis of extra-tropical storms in the North Atlantic region as simulated in a control and  $2 \times \text{CO}_2$  time-slice experiment with a high-resolution atmospheric model. *Tellus A* **1997**, *49*, 347–361. [[CrossRef](#)]
63. Giorgi, F.; Bi, X.Q.; Pal, J. Mean, interannual variability and trends in a regional climate change experiment over Europe. II: Climate change scenarios (2071–2100). *Clim. Dyn.* **2004**, *23*, 839–858. [[CrossRef](#)]
64. Gastineau, G.; Soden, B.J. Model projected changes of extreme wind events in response to global warming. *Geophys. Res. Lett.* **2009**, *36*, L10810. [[CrossRef](#)]
65. Löptien, U.; Zolina, O.; Gulev, S.; Latif, M.; Soloviev, V. Cyclone life cycle characteristics over the Northern Hemisphere in coupled GCMs. *Clim. Dyn.* **2008**, *31*, 507–532. [[CrossRef](#)]
66. Nikulin, G.; Kjellström, E.; Hansson, U.L.F.; Strandberg, G.; Ullerstig, A. Evaluation and future projections of temperature, precipitation and wind extremes over Europe in an ensemble of regional climate simulations. *Tellus A* **2011**, *63*, 41–55. [[CrossRef](#)]
67. Mizuta, R.; Matsueda, M.; Endo, H.; Yukimoto, S. Future change in extratropical cyclones associated with change in the upper troposphere. *J. Clim.* **2011**, *24*, 6456–6470. [[CrossRef](#)]
68. Pryor, S.C.; Barthelmie, R.J.; Clausen, N.E.; Drews, M.; MacKellar, N.; Kjellström, E. Analyses of possible changes in intense and extreme wind speeds over northern Europe under climate change scenarios. *Clim. Dyn.* **2012**, *38*, 189–208. [[CrossRef](#)]
69. Knippertz, P.; Ulbrich, U.; Speth, P. Changing cyclones and surface wind speeds over the North Atlantic and Europe in a transient GHG experiment. *Clim. Res.* **2000**, *15*, 109–122. [[CrossRef](#)]
70. Beniston, M.; Stephenson, D.B.; Christensen, O.B.; Ferro, C.A.T.; Frei, C.; Goyette, S.; Halsnaes, K.; Holt, T.; Jylhä, K.; Koffi, B.; *et al.* Future extreme events in European climate: An exploration of regional climate model projections. *Clim. Chang.* **2007**, *81*, 71–95. [[CrossRef](#)]
71. Gerstengarbe, F.-W.; Werner, P.C.; Oesterle, H.; Burghoff, O. Winter storm- and summer thunderstorm-related loss events with regard to climate change in Germany. *Theor. Appl. Climatol.* **2013**, *114*, 715–724. [[CrossRef](#)]

72. Klaus, M.; Holsten, A.; Hostert, P.; Kropp, J.P. Integrated methodology to assess windthrow impacts on forest stands under climate change. *For. Ecol. Manag.* **2011**, *261*, 1799–1810. [[CrossRef](#)]
73. Pinto, J.G.; Neuhaus, C.P.; Leckebusch, G.C.; Reyers, M.; Kerschgens, M. Estimation of wind storm impacts over Western Germany under future climate conditions using a statistical-dynamical downscaling approach. *Tellus A* **2010**, *62*, 188–201. [[CrossRef](#)]
74. Rauthe, M.; Kunz, M.; Kottmeier, C. Changes in wind gust extremes over Central Europe derived from a small ensemble of high resolution regional climate models. *Meteorol. Z.* **2010**, *19*, 299–312. [[CrossRef](#)]
75. Rockel, B.; Woth, K. Extremes of near-surface wind speed over Europe and their future changes as estimated from an ensemble of RCM simulations. *Clim. Chang.* **2007**, *81*, 267–280. [[CrossRef](#)]
76. Leckebusch, G.C.; Weimer, A.; Pinto, J.G.; Reyers, M.; Speth, P. Extreme wind storms over Europe in present and future climate: A cluster analysis approach. *Meteorol. Z.* **2008**, *17*, 67–82. [[CrossRef](#)]
77. Muskulus, M.; Jacob, D. Tracking cyclones in regional model data: The future of Mediterranean storms. *Adv. Geosci.* **2005**, *2*, 13–19. [[CrossRef](#)]
78. Mizuta, R. Intensification of extratropical cyclones associated with the polar jet change in the CMIP5 global warming projections. *Geophys. Res. Lett.* **2012**, *39*, L19707. [[CrossRef](#)]
79. Sterl, A.; van den Brink, H.; de Vries, H.; Haarsma, R.; van Meijgaard, E. An ensemble study of extreme storm surge related water levels in the North Sea in a changing climate. *Ocean Sci.* **2009**, *5*, 369–378. [[CrossRef](#)]
80. Carnell, R.E.; Senior, C.A.; Mitchell, J.F.B. An assessment of measures of storminess: Simulated changes in northern hemisphere winter due to increasing CO<sub>2</sub>. *Clim. Dyn.* **1996**, *12*, 467–476. [[CrossRef](#)]
81. Ulbrich, U.; Christoph, M. A shift of the NAO and increasing storm track activity over Europe due to anthropogenic greenhouse gas forcing. *Clim. Dyn.* **1999**, *15*, 551–559. [[CrossRef](#)]
82. Lambert, S.J.; Fyfe, J.C. Changes in winter cyclone frequencies and strengths simulated in enhanced greenhouse warming experiments: Results from the models participating in the IPCC diagnostic exercise. *Clim. Dyn.* **2006**, *26*, 713–728. [[CrossRef](#)]
83. Yin, J.H. A consistent poleward shift of the storm tracks in simulations of 21st century climate. *Geophys. Res. Lett.* **2005**, *32*, L18701. [[CrossRef](#)]
84. Laine, A. An energetics study of wintertime Northern Hemisphere storm tracks under 4 × CO<sub>2</sub> conditions in two ocean-atmosphere coupled models. *J. Clim.* **2009**, *22*, 819–839. [[CrossRef](#)]
85. Catto, J.L.; Shaffrey, L.C.; Hodges, K.I. Northern Hemisphere extratropical cyclones in a warming climate in the HiGEM high-resolution climate model. *J. Clim.* **2011**, *24*, 5336–5352. [[CrossRef](#)]
86. Lambert, S.J. The effect of enhanced greenhouse warming on winter cyclone frequencies and strengths. *J. Clim.* **1995**, *8*, 1447–1452. [[CrossRef](#)]
87. Schubert, M.; Perlwitz, J.; Blender, R.; Fraedrich, K.; Lunkeit, F. North Atlantic cyclones in CO<sub>2</sub>-induced warm climate simulations: Frequency, intensity, and tracks. *Clim. Dyn.* **1998**, *14*, 827–837. [[CrossRef](#)]

