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Statistical uncertainty of changes in winter storms over the North Atlantic and Europe in an ensemble of transient climate simulations

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[1] Winter storms are among the most important natural hazards affecting Europe. We quantify changes in storm frequency and intensity over the North Atlantic and Europe under future climate scenarios in terms of return periods (RPs) considering uncertainties due to both sampling and methodology. RPs of North Atlantic storms' minimum central pressure (CP) and maximum vorticity (VOR) remain unchanged by 2100 for both the A1B and A2 scenarios compared to the present climate. Whereas shortened RPs for VOR of all intensities are detected for the area between British Isles/North-Sea/western Europe as early as 2040. However, the changes in storm VOR RP may be unrealistically large: a present day 50 (20) year event becomes approximately a 9 (5.5) year event in both A1B and A2 scenarios by 2100. The detected shortened RPs of storms implies a higher risk of occurrence of damaging wind events over Europe. **Citation:** Della-Marta, P. M., and J. G. Pinto (2009), Statistical uncertainty of changes in winter storms over the North Atlantic and Europe in an ensemble of transient climate simulations, *Geophys. Res. Lett.*, *36*, L14703, doi:10.1029/2009GL038557.

1. Introduction

[2] The European continent is often affected by extra-tropical winter storms. Such systems typically originate over the North American east coast, develop over the North Atlantic along its mid-latitude baroclinic zone, propagate eastward and reach Europe further downstream, where they may create severe weather conditions. Cyclone activity over the North Atlantic undergoes decadal variability, from periods with high storminess in the late 19th century, a relative minimum around 1960 and a sharp increase and following decline in the recent decades [e.g., *Bärring and von Storch*, 2004]. Possible modification of the mid-latitude storm climate due to increases in greenhouse gases (GHG) has been investigated using general circulation models (GCMs) [cf. *Ulbrich et al.*, 2009, and references therein]. The most important features include an enhanced number of storms for certain regions (e.g., Great Britain, Aleutian Isles) and a reduction of total cyclone counts [e.g., *Bengtsson et al.*, 2006; *Lambert and Fyfe*, 2006; *Leckebusch et al.*, 2006]. However, several differences between these studies are observed, as the results are sensitive to the choice of methodologies, data and scenarios [cf. *Ulbrich et al.*, 2009].

[3] In assessing the likelihood of anthropogenically induced global and regional climate change there are four types of uncertainty that should be considered: 1) Model, 2) Initial condition, 3) Boundary condition, 4) Statistical. In this study we quantify the statistical uncertainty (4) of possible changes in the frequency and intensity of winter storms based on ensemble climate simulations following different forcing scenarios (therefore partly addressing uncertainties of type 2 and 3). Previous studies [e.g., *Pinto et al.*, 2007b] (hereinafter referred to as P07b) have tested the significance of possible changes in the frequency of storms using simple statistical tests, which are not entirely suitable. In contrast to such simple methods, we use robust Extreme Value Analysis (EVA) techniques which fit an extreme value distribution to data above a high threshold. This allows estimates of the frequency of storms well above, e.g., the 95th percentile [e.g., *Leckebusch et al.*, 2006], to be deduced. The methods calculate the uncertainty in both the frequency and intensity of storms due to sampling [cf. *Della-Marta et al.*, 2009; P. M. Della-Marta et al., Improved estimates of the European winter wind storm climate and the risk of reinsurance loss using climate model data, submitted to *Journal of Applied Meteorology and Climatology,* 2008]. We focus here in the extreme tail of high intensity cyclones (storms) in transient GCM simulations. In our study, these data and techniques are applied to infer robust estimates of the statistical uncertainty in possible changes of winter storms RP under future climate scenarios.

2. Data and Methods

[4] All results are derived from 6 hourly mean sea level pressure (MSLP) data for the extended winter season (October–March). The main results of this paper are based on ensemble simulations with a coupled ocean-atmosphere GCM. Reanalysis data is used to help quantify differences between observations and GCM 20th century runs: NCEP/NCAR Reanalysis (1958–2008; hereafter NCEP [*Kistler et al.*, 2001]), with a spectral horizontal resolution of T62; and ECMWF reanalysis (1957–2002, hereafter ERA40 [*Uppala et al.*, 2005]). To allow a better comparison between datasets and to maintain consistency of the cyclone tracking parameters [cf. *Pinto et al.*, 2005], we reduced the spectral resolution of ERA40 to that of NCEP by removing all wave numbers higher than T62.

[5] The coupled GCM used is the ECHAM5/OM1 (European Centre Hamburg Version 5/Max Planck Institute Version/Ocean Model Version 1; abbreviated ECHAM5 [*Roeckner et al.*, 2003]) with T63 resolution. Three ensemble runs for the recent climate (20C) were initialised at

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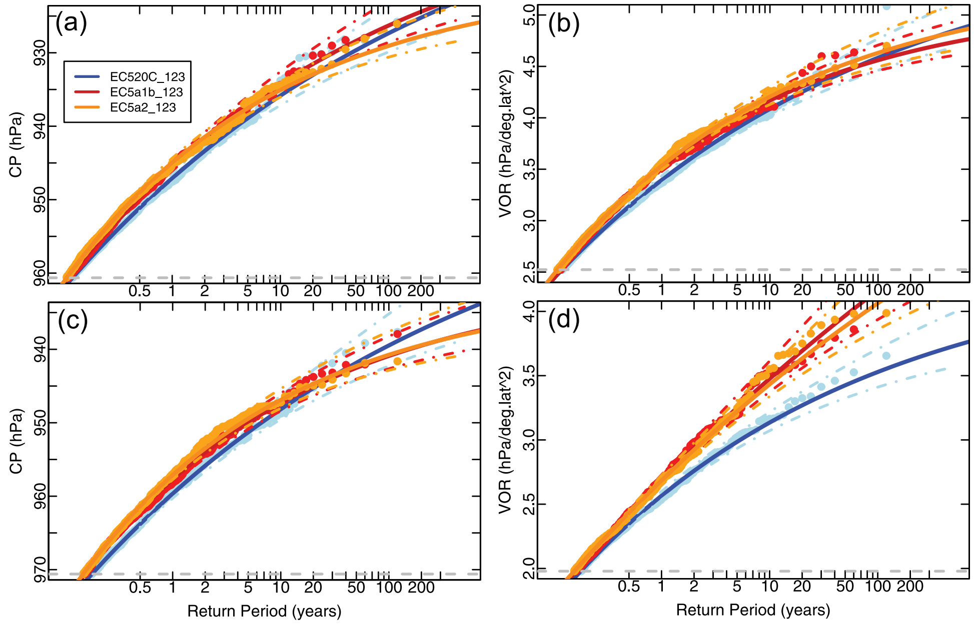

Figure 1. Return periods (RP) of storms from ECHAM5 in terms of (a) CP for Box 2, (b) VOR for Box 2, (c) same as Figure 1a but for Box 3, (d) same as Figure 1b but for Box 3. Blue curve corresponds to ECHAM-20C storms, red curve to A1B storms, and orange curve to A2 storms. Individual values are shown as single dots. Dot-dashed lines indicate the 90% CI limits. The units are hPa and hPa/(deg. lat.)^2 for CP and VOR respectively. Horizontal dashed gray line denotes the GPD threshold. Note the logarithmic x-axis.

different states and forced with historical GHG and aerosol concentrations for the period 1860–2000. The final states of the 20C ensemble members (EM) were used as initial conditions for two climate change experiments using SRES scenarios A1B and A2 [cf. *Nakićenović et al.*, 2000] for the 21st century (2001–2100). Climate signals refer to the changes between end of the 21st century (2060–2100) and recent climate conditions (1960–2000). For some analyses we used continuous data from 1960 to 2100. We either present results based on all EM concatenated together (following *Kharin and Zwiers* [2000, 2005]) or individual EM. Concatenation of ensemble runs assumes that all runs are unbiased, equally probable estimates of the future climate.

[6] Cyclones are identified and tracked using an algorithm originally developed by *Murray and Simmonds* [1991], adapted for Northern Hemisphere cyclone characteristics [*Pinto et al.*, 2005]. The tracking methodology performs well in comparison to other similar methods [*Raible et al.*, 2008]. The method tracks cyclones based on a proxy of their relative geostrophic vorticity (VOR [cf. *Murray and Simmonds*, 1991] approximated by the Laplacian of MSLP). VOR is the mean vorticity of all grid points around the cyclone's core within a fixed 4° radius. We consider both central pressure (CP) and VOR as intensity measures, as the latter is largely independent of the background flow. Cyclone data for NCEP and ECHAM5 are the same used by *Pinto et al.* [2005] and P07b. The inclusion of a second reanalysis dataset (ERA40) aims at dealing with uncertainties inherent with the reanalysis data [cf. *Raible et al.*, 2008].

[7] RPs are estimated using peak over threshold (POT) EVA. For each cyclone track within a given domain, the minimum value of CP and maximum of VOR is retained. Note that as a minimum CP does not necessarily imply a high VOR maxima and vice-versa, the two datasets are partially disjoint. Sensitivity tests show that this has little effect on the results (not shown), moreover, the strongest cyclones in the two datasets are almost identical. A Generalized Pareto Distribution (GPD) is fitted to the maximum intensity series considering only intensities above a high threshold (95th or 97.5th percentile depending on the region, see auxiliary material for sensitivity tests), i.e., extreme cyclones (storms). In all 20C and A1B/A2 comparisons the GPD threshold is taken from 20C data. In the reanalysis and 20C comparisons the threshold is taken from NCEP. The GPD is fitted using maximum likelihood and the GPD fit uncertainty is calculated using the profile log-likelihood method (see *Coles* [2001] and *Della-Marta et al.* [2009] for more details). RP distributions are significantly different (1% level) if the 90% CI of each RP distribution do not overlap [*Kharin and Zwiers*, 2000].

3. Results

[8] Possible climate change signals are assessed entirely within the GCM, i.e., we compare 20C with A1B and A2 scenarios. In order to discuss the GCM results, including possible biases, we first present results of a comparison between reanalysis and 20C storm climates. General characteristics of the North Atlantic storm track, are in close agreement between the GCM and the reanalysis data, even though the GCM displays a more zonal storm track over the Eastern North Atlantic and western Europe (cf. P07b). Here, we compare RP statistics for several selected study areas (cf. Figure S1 of the auxiliary material[1]): Box 1, the whole

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL038557.

Table 1. Comparison of Storm VOR ECHAM5 20C RPs (years) With A1B and A2 Storm VOR Including 90% CI Estimates for Each Region of the North Atlantic (Boxes 1, 2, and 3) for the Extended Winter Season[a]

		ECHAM5-20C			ECHAM5-A1B			ECHAM5-A2		
Regions	VOR hPa (deg.lat^2)	Lower	RP	Upper	Lower	RP	Upper	Lower	RP	Upper
Box 1	3.97	0.91	1.0	1.1	0.92	1.0	1.10	0.94	1.0	1.1
	4.46	3.9	5.0	6.4	4.2	5.3	6.9	4.2	5.5	7.1
	4.65	7.1	10	14	7.8	11	16	7.9	11	17
	4.81	13	20	33	14	23	39	14	24	43
	5.01	26	50	110	30	62	140	31	68	170
	5.14	42	100	300	52	130	440	55	150	590
Box 2	3.40	0.91	1.0	1.1	**0.72**	**0.72**	**0.85**	**0.68**	**0.69**	**0.82**
	3.90	4.0	5.0	6.3	2.8	3.4	4.1	**2.5**	**3.1**	**3.8**
	4.09	7.3	10	14	5.3	6.9	9.1	4.6	6.1	8.1
	4.25	13	20	31	10	15	22	8.3	12	19
	4.45	27	50	94	25	46	94	18	33	71
	4.58	46	100	220	49	120	380	31	73	220
Box 3	2.57	0.9	1.00	1.1	**0.68**	**0.72**	**0.82**	**0.68**	**0.72**	**0.82**
	2.98	3.9	5.0	6.4	**1.9**	**2.3**	**3.1**	**2.0**	**2.4**	**2.9**
	3.13	7.1	10	14	**2.9**	**3.6**	**4.4**	**3.1**	**3.8**	**4.8**
	3.27	12	20	33	**4.1**	**5.3**	**6.9**	**4.5**	**5.8**	**7.7**
	3.42	25	50	110	**6.1**	**8.5**	**12**	**6.9**	**9.7**	**14**
	3.53	40	100	320	**8.0**	**12**	**18**	**9.3**	**14**	**21**

[a]Columns Lower and Upper denote the lower and upper bounds of the 90% CI respectively. Boldface A1B and A2 RPs are significantly different at the 1% level from the corresponding 20C RP.

North Atlantic region (35°N–70°N, 80°W–0°E). Box 2 (45°N–65°N, 30°W–10°E), the area where significant changes of cyclone frequencies and intensities were detected in previous works [P07b; *Pinto et al.*, 2009]. Box 3, the British Isles/North Sea/western Europe region (45°N–60°N, 10°W–30°E). Figure S2 compares the storm climate in Boxes 1, 2 and 3 of NCEP, ERA40 and 20C (concatenated ensemble, three EM, 1960–2000). The GCM is able to reproduce storms with similar CP and VOR to those identified in NCEP and ERA40. However, the GCM consistently underestimates the VOR of storms whose RPs are between approximately 0.5 and 50 years (Figures S2b, S2d, and S2f). There is also a (non-significant) tendency for the CP of storms to be higher (i.e., less intense) in 20C than in reanalysis. This becomes more noticeable at regional scales (Figures S2c and S2e). Note that individual storm RPs (both VOR or CP) are similar using either reanalysis dataset. VOR and CP RP are shorter for ERA40. The largest (significant) discrepancies in RP are found for VOR in Box 2 between 0 and 20 years.

[9] Next, we consider the model simulations with changed boundary conditions (A1B and A2). The climate change signal is defined as the difference in the GPD climatologies of either A1B or A2 (2060–2100) and 20C (1960–2000). In North Atlantic/European area (Box 1), no significant changes in the RP of both CP (not shown) and VOR (Table 1) are found. However, the area near British Isles/North Sea/western Europe (Box 2, 3), shows a significant change in annual RP storms in terms of CP, which become 0.68–0.85 (90% CI, Box 2) and 0.68–0.82 (90% CI, Box 3) year events under A1B and A2 (cf. Figures 1a and 1c). There are also significant CP RP reductions from 5 years to 3.1 years (90% CI 2.5–3.8) for Box 2 A2 (Figure 1c, orange curve). Higher CP RP storms in this area remain unchanged. The British Isles/North Sea/western Europe region (Box 3) shows the most dramatic changes in VOR RP. RPs of VOR for all intensities and both scenarios become significantly shorter (Figure 1d). However, in the same region we only see minor (but significant) changes in annual CP RP of storms (Figure 1c). This suggests changes in circulation intensity. Alternatively, it may also be an indication of changes in size, although latest research indicates that most changes in cyclone characteristics under the A1B scenario of the ECHAM5 model are driven by intensity changes rather than changes in cyclone radii (A. Schneidereit et al., Radius-depth model for midlatitude cyclones in re-analysis data and simulations, submitted to *Quarterly Journal of the Royal Meteorological Society*, 2009).

[10] The changes in RP of VOR in Box 3 may be unrealistically large. For example, storms estimated to have a 50 (20) year RP in 20C have a RP of around 9 (5.5) years in the 2060–2100 period (Table 1). Even taking the most conservative estimate of the upper confidence bound (90% CI) of the A2 scenario, a 50 year 20C event is at most a 14 year event under future climate scenarios. These changes imply that storms like 'Daria' (25–26/01/1990) whose RP of VOR is approximately 18 (90% CI 12–33, Box 3) years will occur on average every 5.5 (90% CI 4.1–7.7) years. Similar conclusions are drawn for shorter and longer RPs of VOR changes in this region (Table 1). The climate change signal is also seen in individual EM (cf. Figure 2 and below).

[11] Results by *Pinto et al.* [2009] suggest that a significant part of the storm frequency change signal over the western European area may be due to changes in rapidly deepening cyclones near the British Isles, named 'British Bombs' (BB, their section 5.4). We have tested this hypothesis and conclude that BB partially contribute to the detectable change in frequency and intensity of storms over Europe. However, the storm RP change still remains significant if BB are removed (auxiliary material).

[12] Table S1 presents changes in annual average frequency of storm occurrence (λ) for each Box and scenario. This frequency represents the mean and variance of the Poisson distribution used to model the exceedence of the percentile based threshold [see *Della-Marta et al.*, 2009]. There are indications of a storm frequency decrease under

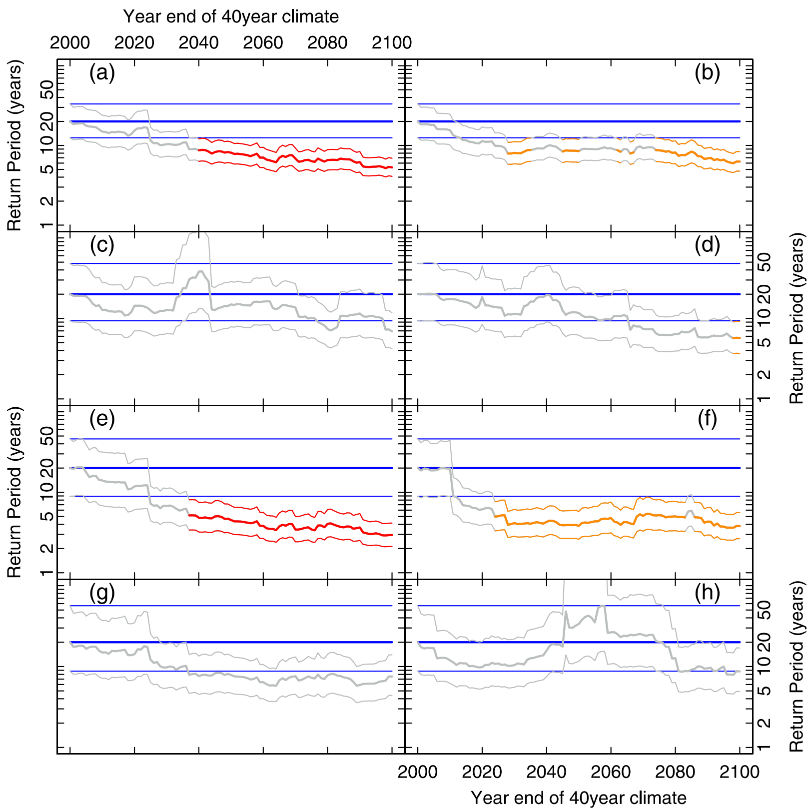

Figure 2. Change in 20C 20 year RP based on moving 40 year climatology for VOR in Box 3. (a and b) For all EM for A1B and A2 respectively. Individual (c, e, and g) A1B and (d, f, and h) A2 EM. Blue lines denote the 20C 20 year RP with 90% CI; grey lines, the estimated RP from the transient runs (and 90% CI) based on the previous 40 years data; colored red and orange lines indicate where RP estimates are significantly different from 20C. Note the logarithmic vertical axis.

A2 scenarios in the North Atlantic region (Box 1, not significant) and increased storm frequencies in Boxes 2 and 3, although only significantly under A2.

[13] To assess when a possible anthropogenically induced change in storm frequency and intensity may occur, a GPD is fitted to each 40 year period ending from 2000–2100 (i.e., year 2060 indicates the period 2021–2060) for VOR in Box 3. Figures 2a and 2b show the change in 20 year RP relative to 20C (120 years for each 40 year period) for A1B and A2 respectively. The resulting changes suggest that a 20 year event will become a 10 year event around 2040 and 2030 for A1B and A2, reducing further to 5.3 and 5.8 year events by 2100, respectively. Figures 2c, 2e, and 2g (Figures 2d, 2f, and 2h) show the change in 20 year RP for each A1B (A2) EM. A1B EM2 and EM3 (Figures 2e and 2g) and A2 EM1 (Figure 2d) demonstrate a more or less steady decline in the 20 year RP to significantly (between 1 and 10% significance) lower RPs, whereas A2 EM2 (Figure 2f) demonstrates an almost discontinuous change to significantly lower RPs around 2025. A1B EM1 and A2 EM3 display a more erratic and non-significant change in 20 year RP over the 21st century. Figure S3 shows the same figure but for Box 2 and CP RPs of 1 year, displaying significant changes by 2040 in A1B and 2080 in A2 (see Table 1 for change in RP by 2100).

4. Conclusion

[14] This study extends previous studies [e.g., P07b; *Pinto et al.*, 2009] by assigning uncertainty estimates to changes in the frequency and intensity of extreme cyclones (storms) in the North Atlantic and Europe under future climate scenarios. The EVA enables the quantification of changes in storms that are more extreme than, e.g., the 95th percentile, which have not been previously documented. The RP of storms of all intensities become significantly shorter under future climate conditions for the British Isles, North Sea, and western Europe region (Box 3) using VOR as a measure of cyclone intensity (cf. Figure 1d). On the other hand, RPs for storm CP in this region become shorter only for low intensity storms (between 0 and 1 year RP, Figure 1c). However, this CP signal may be partially biased by the changes in the MSLP background field identified in this GCM: Changes in average background MSLP using the A1B scenario for the period 2070–2099 minus 1970–1999 [cf. *Fink et al.*, 2009, Figure 9c] are in the order of −1.03 hPa, −1.55 hPa and +0.07 hPa for boxes 1–3 respectively. RP changes become statistically detectable at various times in the future depending on scenario, region and parameter. The strongest changes in VOR RP (Box 3) become detectable around 2030–2040 depending on the scenario (which correspond to the time windows 1991–2030 and 2001–2040, respectively). For the North Atlantic area as a whole no significant changes in storm frequency and intensity are found using either storm intensity measure.

[15] Our threshold exceedence change results (cf. Table S1) are consistent with P07b, who detected no changes in the frequency of storms (VOR > 2,5 hPa/(deg. lat.)^2) over the North Atlantic (P07b, Table 2; CNA) and a

greater number of storms over western Europe region (P07b, Table 2; Box WEU). However, the present study adds many important details (e.g., analysis of different RPs) to the results presented by P07b, which only provided rough estimates of frequency changes of less extreme cyclone intensities. Rapidly intensifying storms near the British Isles are responsible for some but not all of the climate change signal in Box 3 (cf. auxiliary material).

[16] The detected changes (Box 3) are associated with more favourable conditions for the development storms, including: an extension of the polar jet into Europe and an enhanced frequency of zonal flow patterns (P07b). Factors affecting the development of individual cyclones include enhanced values of: latent heat, upper air-divergence, baroclinicity and jet stream [cf. *Pinto et al.*, 2009]. The detected changes are also associated with an enhanced frequency of extreme winds and loss potentials over western and central Europe [e.g., *Pinto et al.*, 2007a].

[17] The magnitude of RP changes in Box 3 seem to be excessively large. The RPs become shorter by between 28% for 1 year RP and 88% for 100 year RP. The example of the storm Daria (which becomes 70% more frequent) gives an indication of how severe these possible changes may be. The comparison of reanalysis datasets show very similar RP for individual storms using either VOR or CP, whereas ECHAM5 20C systematically underestimates the VOR and CP of storms (cf. Figure S2). Even though this could indicate that ECHAM5 may not adequately resolve the physical processes (e.g., diabatic processes), *Bengtsson et al.* [2009] have demonstrated that ECHAM5 can realistically simulate baroclinic life cycles, particularly if higher GCM resolutions are considered. Clearly, a larger and more dedicated ensemble of climate models [e.g., *Lambert and Fyfe*, 2006] is needed to assess any anthropogenic signal (addressing uncertainties of type 1, 2 and 3). This study concludes that the use of EVA is essential for addressing the statistical uncertainty (type 4) which is a major component of any analysis of possible changes in storm intensity and frequency under future climate scenarios.

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