

The role of serial European windstorm clustering for extreme seasonal losses as determined from multi-centennial simulations of high resolution global climate model data

Matthew D. K. Priestley, Helen F. Dacre, Len C. Shaffrey, Kevin I. Hodges, Joaquim G. Pinto

Response to reviewer 1

Dear Reviewer,

We thank you for the comments and suggestions that you have made to our manuscript, which have helped improve its quality. Please find below a response to all of your comments and questions raised. Any page and line numbers refer to the initial NHESD document. The italicised black text are the comments to the manuscript. Our responses are in red with any changes described. An amended version of the manuscript has also been uploaded to highlight the changes. In the marked version, text which has been removed has been struck through, with new additions being in red.

This paper presents an analysis of temporal clustering of extratropical cyclones in the North Atlantic and the associated windstorm losses over central Europe. The studies shows the seasonally aggregated losses are substantially underestimated if temporal clustering is not taken into consideration. Also the relative contribution of the cyclone resulting in the highest losses per season to the overall seasonal losses is investigated. This contribution is very variable and ranges between 25 to 50%. The study makes use of decadal hindcasts to analyze hundreds of years of present day simulations and statistics based on this large sample are very robust. The quality of the text, the figures and the science is high. The only point that should be scrutinized is the GPD fit to the ERA-interim data. This analysis is not convincing and not necessary to support the main points of the paper.

Minor points:

1. Title: Suggest to add that the clustering refers to clustering in time

We have added the word 'serial' and also re-worded the title in accordance with the comments from reviewer 2, comment 1. The title now reads 'The role of serial European windstorm clustering for extreme seasonal losses as determined from multi-centennial simulations of high resolution global climate model data'.

2. P2L7 The most severe seasons in terms of the total windstorm loss

The start of this sentence has been changed from 'The most severe seasons...' to 'The most severe seasons, in terms of total windstorm loss, ...'.

3. P2L31 these events reference unclear

'These events...' has been changed to 'Clustering...' in order to clarify what events are being referred to.

4. *P3L4/5 incomplete sentence*

The words 'spatial coverage' have been added. The sentence start now reads 'With this aim, the historical reanalysis datasets provide a comprehensive spatial coverage...'. This also addresses comment number 11 from reviewer 2.

5. *P3L18 The question is incomplete contributes more than what?*

The question has been rephrased for clarity. It now reads as 'Does windstorm clustering contribute more to losses in Europe for winter seasons with large accumulated losses?'. This is also a point raised by reviewer 2, comment 12.

6. *P5L25 Why is this threshold sensible? Why not set these grid-points to NaN?*

This threshold was chosen based on the results of Karremann (2015). They discuss how wind damage generally occurs for gusts speeds above 21 m/s. This gust speed relates to sustained wind speeds between 8 m/s and 11 m/s. Their analysis then concludes that 9 m/s to be the best minimum threshold for the SSI for all regions across Europe. These grid points are not set to NaN as we want to calculate an SSI values at all European grid-points, therefore setting the threshold to NaN would not allow us to do this.

7. *P6L8 Why a 72 hour threshold?*

The 72-hour threshold is commonly used by re-insurance companies to define the duration of an 'event' (Mitchell-Wallace et al., 2017). This is stated in the text.

8. *P6 L36ff What is the base time for the analysis? Seasons, months?*

The dispersion is calculated using the storm track density in units of storms per month. This value of storms per month is an average for each DJF winter season. The text has been clarified in the text to read 'This relates the variance (σ^2) in storm track density (average number of storms per month in a single DJF season) to the mean (μ) storm track density'. This has also been changed to be in accordance with comment 20 from reviewer 2.

9. *P7L16 How can this proportion become negative? Should it not be always positive?*

Yes, this should always be positive. This should read that the distinction is in values above or below 1 for over/under dispersive behaviour of storms. This has been changed in the text.

10. *P8L15ff How do you decluster the extremes to use only independent values for the GPD estimate, especially as your time-series are clustered in time. See e.g. Ferro and Segers <https://rss.onlinelibrary.wiley.com/doi/abs/10.1111/1467-9868.00401>*

Independent values are used for the GPD estimate by the definition of the AEP and OEP only taking one value per winter season, therefore making them fully independent from the rest of the data. As the AEP and OEP provide one value per winter season, they are not related to the other seasons and hence all values are independent for the GPD estimations.

11. *P8L15 The GPD fit to ERA-interim seems a bit of a coup de main to me, especially considering that you are bias correcting the data beforehand thereby potentially introducing substantial uncertainty. Also the 70th percentile threshold for the fitting seems to be extremely low. Did you test this threshold? I would recommend fitting the GPD only to the model data, the results are convincing enough (even more convincing) without this analysis.*

The reason why we include this figure was to enable a comparison with the GCM data, and display the advantages of the longer dataset. Still, we agree with the reviewer that the GPD is not convincing and thus does not need to be shown and discussed so prominently. Subsequently, we have decided to split figure 5 up, retaining figure 5a in the main text and move

figure 5b to the supplementary material. This has been done for the purpose of continuity in the text with some minor changes made to reflect this. Some of the details regarding the visual details of figure 5b (now figure A2) have been removed from the text to improve the readability of this section. We decided against removing figure 5b altogether from the paper to keep consistency. Moreover, threshold for fitting the GPD to the ERA-Interim data was tested, and using a threshold consistent with that applied to HiGEM (90th percentile) did not result in a good fit due to the very small data sample. We have thus kept the threshold for figure A2 (old 5b)

12. P8L27 well please quantify

The wording has been changed slightly to now read 'agree...' as opposed to the original 'contrast well...' to remove the value judgement. In addition a quantification of the agreement has been added 'agree (anomalies within ± 2 cyclones per month)'. This is also in agreement with comment 24 from reviewer 2.

13. P9L19 Please define clustering for the readers not familiar with Priestley et al 2017

This is discussed in the introduction (paragraph 3) with a definition of clustering provided and the key findings of the Priestley et al. (2017) paper are given. A further quantification has been added to the start of this paragraph that this is '(as discussed in section 1)'.

14. P9L30 slight please quantify

This has been clarified in the text. It now reads 'albeit with a lower frequency of anticyclone RWB on the southern flank of the jet'.

15. P10L18 "this is balanced" be very careful, as soon as the exposure comes into play, the exact location matters a lot and you might introduce substantial artefacts. Are your results qualitatively independent from this bias correction?

We have slightly rephrased the sentence to remove ambiguity, It now reads 'the difference have changed sign and are now positive, there are also some regions that still have negative anomalies, resulting...'. Due to the bias correction being a uniform scaling to the wind data only, all the results examining the SSI are independent from the bias correction. Figure 1 shown at the end of the responses is a version of figure 7 in the main article with no scaling applied, and also no population weighting. You can see how the results are qualitatively very similar to those presented in the article with an average value of AEP/AEP_random of approximately 1.2 at a return period of 200 years.

16. P11L24 increase between what and what?

This is to illustrate the increase in the largest AEP and OEP from ERA-Interim to HiGEM. To improve clarity the text has been reworded to 'For example, the 918 year return period season in HiGEM is approximately twice the magnitude of the 1 in 36 year season in ERA-Interim.'. This change is also in accordance with comment 31 from reviewer 2.

17. P11L33 marginally lower as would be expected... -> I do not understand this sentence

As we are removing a large portion of the events (i.e. setting small events to have a magnitude of 0) that make up each season this results in a reduction of the AEP value compared to when including the full number of events. The sentence has been slightly changed to aid clarification to 'The magnitudes of the reduced event AEPs are marginally lower than the original AEPs, as would be expected...'.

18. P13L2 the 3 year

This has been changed in the text to 'above a return period of 3 years...'.

19. P14l1 suggest: the importance of temporal clustering on seasonal timescales

We have changed the sentence to 'The aim of this study is to investigate the importance of serial clustering on seasonal timescales for high...'.

20. P14l28ff This sentence is unclear

We have removed the sentence 'The absolute difference between the AEP and OEP is increasing with return period.' In order to improve the clarity and readability of this conclusion.

21. Figure 4: what are the units of SSI? What happens in the eastern Mediterranean?

There are no units to the SSI. (V/V_{98}) would be unitless. In addition the population density was normalised in order to reduce the magnitude of the final loss value. Therefore the SSI value is just a magnitude of event or seasonal loss which can be compared with the other events/seasons. With regards to the high SSI values in the eastern Mediterranean, we have found that these grid points have a very long tail in the 10-metre wind speeds compared to all of northern and northwestern Europe (7-8 m/s across E. Med., compared to 6-7m/s across NW Europe). This long tail means that high SSI values will be generated in this region. However, this is not a region for which the SSI is suitable (it is stated in the text that it is a 'loss proxy for European windstorms'), therefore these spurious values can be ignored and are not considered in our analysis.

22. Figure 5a: Please add units

Please see above comment regarding the units of the SSI.

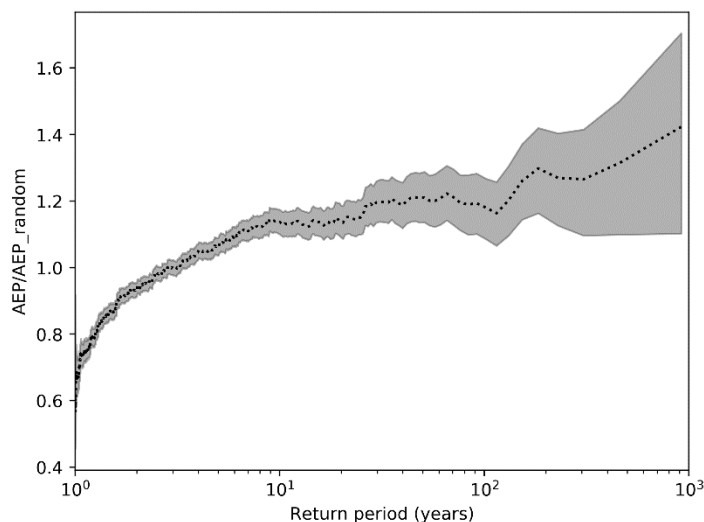


Figure 1. As figure 7 in Priestley et al. (2018), but with no bias correction applied to the 10-metre wind speeds. No population density scaling has been applied either.

References

Karremann, M. K.: Return periods and clustering of potential losses associated with European windstorms in a changing climate, Ph.D. thesis, Universität zu Köln, 2015.

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Response to reviewer 2

Dear Reviewer,

We are very grateful for all of the comments and suggestions you have made to our manuscript, which have greatly helped improve its quality. We hope our revised manuscript addresses the points you have raised. Please find below a response to all of your comments and questions raised. Any page and line numbers refer to the initial NHESSD document. The italicised black text are the comments to the manuscript. Our responses are in red with any changes described. An amended version of the manuscript has also been uploaded to highlight the changes. In the marked version, text which has been removed has been struck through, with new additions being in red.

This study uses a large set of HiGEM present-day climate simulations to estimate extreme seasonal losses due to windstorms and in particular due to the clustering of windstorms. As a main result, it is shown that the clustering of storms leads to peak accumulated seasonal losses that are up to 20% larger than if the storms were randomly occurring. This result is interesting and the methodological approach to use almost 1000 years of simulated data with a fairly high-resolution model is sophisticated. Therefore I recommend the study for publication. I was just somehow disappointed about the quality of the writing. Many sentences are surprisingly fuzzy (surprising, because of the excellent team of co-authors). I therefore ask the authors to carefully revise their paper with the intention to explain things better to the hopefully large future readership. Some clarity issues are mentioned below.

Comments:

1. *title and, e.g., p. 1 line 5: you call your model "high resolution". I understand why, but some colleagues think that high resolution is the km-scale, and in a few years this will be reality. I find the almost 1000 years that you have available for your evaluations more impressive than the HiGEM resolution of about 1 degree. Would it not be worth emphasizing this more in the title?*

We have changed the title based on this comment and comment 1 by reviewer 1. We have decided to keep the reference to 'high resolution' in the title as we agree that as 1km scale regional climate model are planned for the next decade, global coupled climate models will not be run at that resolution for some time. Hence, we have also specified that it is a 'global climate model' to retain that distinction. The title now reads 'The role of serial European windstorm clustering for extreme seasonal losses as determined from multi-centennial simulations of high resolution global climate model data'.

2. p. 1 line 3: "affect one area in a period of time" not sure that this is the best definition of serial clustering?

This has been changed to 'affect one specific geographic region in a short period of time...' in order to improve the definition.

3. p. 1 line 7ff: this is a very long a complicated sentence. Please rephrase. How can a "loss-based metric" be "based on meteorological variables"? Then it is a metric for loss, but not loss-based?

This sentence has been rephrased for clarity. It is now as follows: 'The role of windstorm clustering is investigated using a quantifiable metric (storm severity index (SSI)) that is based on near-surface meteorological variables (10-metre wind speed) and is a good proxy for losses. The SSI is used to convert...'

4. p. 1 line 9: here it is completely unclear that the 918 years do not correspond to one long transient millennium simulation but rather to a large ensemble of present-day climate conditions. Please clarify.

The wording of the abstract has been reworded to clarify this. It now reads '918 years of a present-day ensemble of coupled climate model simulations from...')

5. p. 1 line 13: "return periods" of what?

We have changed the end of this sentence to '...to the seasonal windstorm loss as a function of return period.' to clarify this.

6. p. 1 line 16: it is difficult to understand what you mean by "random realizations of the HiGEM data". This first sounded to me as if you were running HiGEM with randomly perturbed physics. Since this sentence, in my opinion, is the key result of the study, it is important to explain this "random realization" much better in the abstract.

This has been rephrased to add clarity. It now reads '...20% larger than the accumulated seasonal loss from a set of random resamples of the HiGEM data'. Changes have also been made in the text to refer to the raw HiGEM data being 'dynamically consistent' in order to be clarify the difference in the data.

7. p. 1 line 18: usually you give values in %, so why here not 25-50%?

We have changed all references to this result to be in % for the conclusions and abstract to be consistent with the other results in these sections. In the main text results are referred to as decimal to be consistent with the figures.

8. p. 2 line 3: US \$?

Yes, the values do refer to US \$. We have clarified that all values are US \$.

9. p. 2 line 7: "space of time" → "time interval"?

We have changed the wording, however it has been changed to 'in a short period of time'.

10. p. 2 line 26: "amounts of RWB" → maybe "frequency of RWB"?

The sentence has been changed, it has been changed to 'flanked by the presence of anomalous Rossby wave breaking (RWB)...'.

11. p. 3 line 4: word missing after "comprehensive"

This was also mentioned in comment 4 from reviewer 1. The words 'spatial coverage' have been added.

12. p. 3 line 17: *I am lost with this question. Do you mean "Does windstorm clustering contribute more to losses in seasons with large accumulated losses?"*

The question has been changed and now reads as 'Does windstorm clustering contribute more to losses in Europe for winter seasons with large accumulated losses?'. This change was also suggested in comment 5 by reviewer 1.

13. p. 3 line 20: *what is an "increasing return period winter season"?*

This is to refer to an increase in the return period of the total accumulated seasonal windstorm loss. This sentence has been rephrased to the following... 'Finally the importance of clustering for seasons with large accumulated European windstorm losses is addressed'.

14. p. 3: *is it a good idea to mix 4 x 59 years of transient simulations with decadal hindcasts? How can you justify that this leads to a good statistical distribution of present day climate variability? Wouldn't it be better to only use the decadal hindcasts as a more homogeneous dataset?*

The aim through using this mix of data is to utilise a large sample of present day climate. As we are treating each year as independent from the others this is a good approach. We have analysed the number of storms per year for all the data to ensure that there are no trends present. Hence all the data is suitable for the purpose which we are using it for.

15. p. 3 line 28: *I failed in understanding how you get in the end 918 years: $4 \times 59 = 236$ years are from the transient runs; how do the remaining 682 years distribute across the 4 ensemble members initialized between 1960 and 2006?*

The remaining data is structured for the 4-member ensemble decadal hindcasts. The first set of hindcasts is initialised every 5 years from 1960 to 2005 (i.e. 1960, 1965, 1970, ..., 2005) and is run for 10 years. This makes up 400 years of data. The remaining years come an additional set of ensemble hindcasts initialised throughout the 1960-2005 time period.

16. p. 5: *there is unnecessary repetition between lines 9ff and 24ff.*

We agree. The sentence 'Changing the value of $V^{98}_{i,j}$ provides a sensible threshold...' has been moved into the bulleted section of the SSI description. The sentence 'Following the method of...' below the equation has been removed.

17. p. 6 lines 5 and 6: *why are these probabilities? it seems that these are losses.*

These are stated as probabilities as these curves refer to the probability of seeing an event of the specific loss size in a particular year. We have used this naming convention in order to follow the standard that is used in the insurance industry, as is stated in the text.

18. p. 6 line 8: *spelling of SSI*

This has been corrected.

19. p. 6 line 14 and throughout the paper: *most likely also in NHESS "Figure" is written with a capital F.*

We have changed all instances in the text to have a capitalised F.

20. p. 6 line 27: *unclear, "storm track numbers" in what time period?*

The dispersion is calculated using the storm track density in units of the average number of storms per month in a single DJF period. A change has been made to the text so it now reads "This relates the variance (σ^2) in storm track density (average number of storms per month

in a single DJF season) to the mean (μ) storm track density'. This was also made in comment 8 by reviewer 1.

21. p. 7 line 28: why "so"?

The 'so' has been removed from this sentence.

22. p. 8 line 17: "M. and G. (2009)"??

This was an error and the reference has been correctly modified to be that of 'Della-Marta and Pinto (2009)'.

23. p. 8 line 23: not sure that predictability can have skill, maybe "skill in ... predictions"

We agree, the sentence has been rephrased to 'the model has skill in seasonal to decadal predictions...'.

24. p. 8 line 27: "contrast" -> maybe "agree"?

This has been changed in the text to now read 'agree well...'. This was also suggested in comment 12 by reviewer 1.

25. p. 9 lines 14-30: here the link to the rest of the paper is not immediately clear and there seems to be some repetition between the two paragraphs. I suggest to merge and shorten them and to explain the reader why this analysis of RWB is relevant for the main part of this study.

A further clarification has been added to the start of the first paragraph in an attempt to frame this section of analysis better with the rest of the paper. This reads as 'It was shown in Priestley et al. (2017a) that clustering events occurring at different latitudes of western Europe are associated with a specific set of dynamical conditions. The clustering periods identified are characterised by a strong and extended...'. Further on we have also added the following 'This analysis has been repeated for all 918 years of HiGEM data in order to assess how well HiGEM dynamically represents these events (figure 2). The same analysis of ERA-Interim is shown in the supplementary material (figure A1)' in order to add further motivation for this section of analysis.

26. p. 10 line 10: how can 10-m winds be compared/contrasted with 925-hPa winds?

This is to illustrate a common difference in datasets with wind speed biases at the surface (10-metres) and low atmosphere (850, 925 hPa). We have amended the sentence in order to clarify this. It is now as follows 'Similar differences have also been found in the biases of 10-metre and 925 hPa wind speeds in four reanalysis datasets (Hodges et al. 2011)'.

27. p. 10 line 20: here "HiGEM" is used as a symbol for wind speed (if I understand correctly), which is strange. Before you used $v_{i,j}$ - the same could be used again. Instead of " v_{bc} " I suggest to use e.g. \bar{v} . And $\overline{p_{98}}$ is not explained.

The use of p_{98} has been changed to $V_{i,j}$ in order to make equation 3 consistent with equation 1 and also the rest of the text. We prefer to keep the HiGEM_{bc} notation. A clarification of the overbar has been added in the text, which reads '...wind speeds by the spatially averaged offset in the V^{98} field between ERA-Interim (V^{98}_{ERA-i} (overbar)) and HiGEM (V^{98}_{HiGEM} (overbar)) for all land grid points...'.

28. p. 10 line 24: west -> east?

Yes, this has been changed to 'east'.

29. p. 10 line 26: delete "how"o

The 'how' has been removed.

30. p. 11: *I am not an expert in statistics, but is it a good idea to calculate return periods of 50y from a 36-y dataset?*

This is the reasoning for discussing the 50yr return period. We discuss the fact that making estimation of losses of greater than 50 yrs with a reanalysis product is almost an impossibility. Hence, using a model like HiGEM with 918 years of data is worthwhile.

31. p. 11 line 24: *I don't understand "the increase in the largest event is by ... 100%"*

The wording of this sentence has been changed to improve the clarity. The sentence is now 'For example, the 918 year return period season in HiGEM is approximately twice the magnitude of the 1 in 36 year season in ERA-Interim.'. This correction is made with suggestions also from comment 16 from reviewer 1.

32. p. 11 line 33: *what is "very marginally"?*

This sentence has been slightly rephrased in accordance with a similar comment from reviewer 1 in order to improve the clarity of this sentence. Details can be seen in the response to the comment from reviewer 1.

33. p. 12 line 4: *should read "clustering to the ..."*

This has been changed to 'clustering to the...'.

34. p. 12 line 5: *to me the notation "AEP_random" looks a bit like computer code. Why not AEP with subscript r?*

We prefer to keep the initial notation of 'AEP_random'.

35. p. 12 line 29: *spelling of "entire"*

The spelling has been corrected.

36. p. 13 line 1: *"as a result" can be omitted*

The wording 'as a result' has been removed.

37. p. 14 line 17: *not sure that I understand "scaling by 18.75%". I would understand "scaling by a factor of 1.1875" or "uniform increase by 18.75%"*

All mentions of the scaling have been changed to 'uniform increase' in the text.

38. p. 14 line 31: *to me, the 10-20% effect of clustering is surprisingly small. I find it an interesting result that this effect is not larger. Maybe you can discuss this a bit more. I then find the "strong implications" on p. 15 line 2 a bit exaggerated, since 10-20% might be below the general uncertainty level (for instance in the evolution of population density).*

The 10-20% has large implications. If you consider that the average insured loss from European windstorms is ~€1.5 billion then the difference of 10% would be an underestimation of losses by €150 million. This is just the average for years within recent living memory, so for the larger loss seasons which are present in HiGEM, this would equate to a considerably larger value. Hence a misrepresentation by loss modellers would result in a vast underestimation of losses in a monetary sense. The monetary implications have also been included in the text. We have also removed the word 'strong' from 'strong implications'. With regards to the uncertainty of population density we have done additional analysis to show this result is actually rather insensitive to the population density scaling (see figure 1 below) and the same conclusions can be made. With this in mind, we do not

believe any differences in evolution of population density in recent years for central and western Europe over the last 30 years (for which the population density is available) would result in different results to those we have presented.

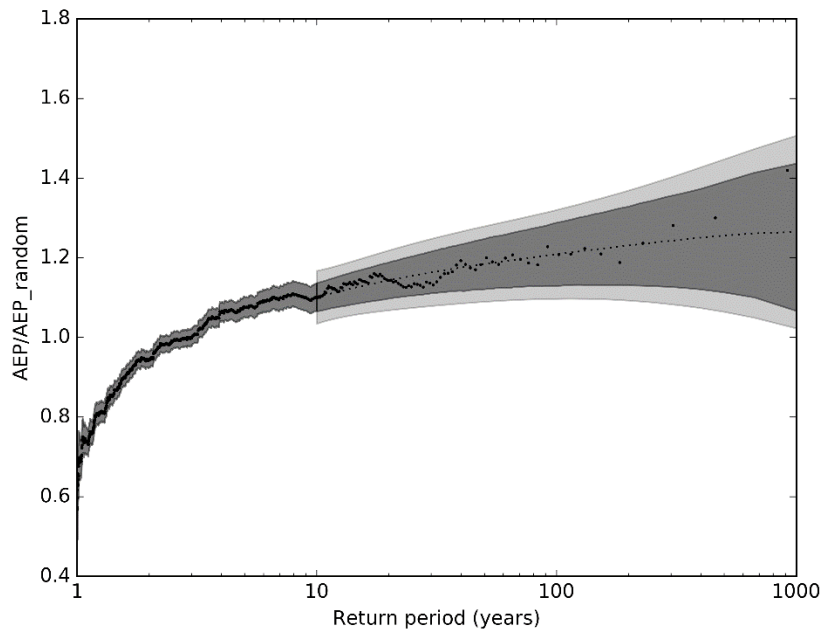


Figure 1. As figure 7 in Priestley et al. (2018), but with no population density scaling applied.

References

- Della-Marta, P. M. and Pinto, J. G.: Statistical uncertainty of changes in winter storms over the North Atlantic and Europe in an ensemble of transient climate simulations, *Geophysical Research Letters*, 36, <https://doi.org/10.1029/2009GL038557>, l14703, 2009.
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~~The role of European windstorm clustering for extreme seasonal losses as determined from a high resolution climate model~~ **The role of serial European windstorm clustering for extreme seasonal losses as determined from multi-centennial simulations of high resolution global climate model data**

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Abstract.

Extratropical cyclones are the most damaging natural hazard to affect western Europe. Serial clustering occurs when many intense cyclones ~~affect one area in a period of time~~ **affect one specific geographic region in a short period of time** which can potentially lead to very large seasonal losses. Previous studies have shown that intense cyclones may be more likely to cluster than less intense cyclones. We revisit this topic using a high resolution climate model with the aim to determine how important clustering is for windstorm related losses.

~~The role of windstorm clustering is investigated using a quantifiable loss-based metric (storm severity index (SSI)) based on near-surface meteorological variables (10-metre wind speed) that is used to convert~~ **The role of windstorm clustering is investigated using a quantifiable metric (storm severity index, SSI) that is based on near-surface meteorological variables (10-metre wind speed) and is a good proxy for losses. The SSI is used to convert** a wind footprint into losses for individual windstorms or seasons. ~~918 years of high resolution coupled climate model data~~ **918 years of a present-day ensemble of coupled climate model simulations** from the High-Resolution Global Environment Model (HiGEM) are compared to ERA-Interim re-analysis. HiGEM is able to successfully reproduce the wintertime North Atlantic/European circulation, and represent the large-scale circulation associated with the serial clustering of European windstorms. We use two measures to identify any changes in the contribution of clustering to ~~the overall seasonal losses for increasing return periods~~ **the seasonal windstorm loss as a function of return period.**

Above a return period of 3 years, the accumulated seasonal loss from HiGEM is up to 20% larger than the accumulated seasonal loss ~~from a set of random realisations of the HiGEM data~~ **from a set of random resamples of the HiGEM data.** Seasonal losses are increased by 10-20% relative to randomised seasonal losses at a return period of 200 years. The contribution

of the single largest event in a season to the accumulated seasonal loss does not change with return period, generally ranging between ~ 0.25 - 0.5 **25-50%**.

Given the realistic dynamical representation of cyclone clustering in HiGEM, and comparable statistics to ERA-Interim, we
5 conclude that our estimation of clustering and its dependence on the return period will be useful for informing the development of risk models for European windstorms, particularly for longer return periods.

1 Introduction

Extratropical cyclones are the dominant weather hazard that affects western Europe. On average extratropical cyclones cause over \$2 billion (US \$) of losses to the insurance industry per year in Europe (Schwierz et al., 2010) as a result of building damage and business interruption from severe wind gusts and large amounts of precipitation. The most severe individual storms can have much greater impacts than what may be observed in an average year, for example storms Daria (25/01/1990), Kyrill (18/01/2007), and Lothar (26/12/1999) caused \$5.1, \$5.8, and \$6.2 billion of insured losses respectively (Munich Re, 2015). The most severe seasons, **in terms of total windstorm loss**, are often characterised by the recurrent influence of multiple cyclone events occurring in a short ~~space~~ **period** of time, e.g. such as the winter of 2013/2014 (Matthews et al., 2014; Priestley et al.,
15 2017b).

There have been several attempts to quantify losses associated with severe extratropical cyclones in re-analysis data and with data from General Circulation Models (GCMs) (e.g., Pinto et al., 2007; Leckebusch et al., 2007; Donat et al., 2011). These studies have primarily focussed on assessments of current climate loss potentials, and how these may alter under future climate
20 conditions. These analyses commonly use loss proxies based on gridded meteorological data, such as the Storm Severity Index (SSI) (Klawa and Ulbrich, 2003). The SSI has been found to reproduce the inter-annual variability of windstorm losses in Germany with a correlation of $r=0.96$ (Klawa and Ulbrich, 2003). This analysis can be performed on a seasonal basis (Pinto et al., 2007; Leckebusch et al., 2007), but also for individual events (Della-Marta et al., 2009; Karremann et al., 2014b, 2016).

North Atlantic winter cyclones have a tendency to occur in groups that affect specific geographical regions within a given period of time. This process is known as serial clustering (Mailier et al., 2006). Serial clustering has been observed in re-analysis data sets in multiple studies (Mailier et al., 2006; Pinto et al., 2013), and is a prominent feature of the cyclones that affect western Europe. Vitolo et al. (2009), Pinto et al. (2013), and Cusack (2016) provided evidence that the magnitude of serial clustering occurring over western and northwestern Europe may increase for more intense cyclones. Furthermore, a strong
30 connection was found between the number of cyclones in a season and their intensities, particularly over the European sector (Hunter et al., 2016). Recent studies (Pinto et al., 2014; Priestley et al., 2017a) have been able to associate specific dynamical conditions with North Atlantic cyclone clustering events. Periods of clustering are associated with a strong and straight North Atlantic jet stream flanked by ~~anomalous amounts of Rossby wave breaking (RWB)~~ **the presence of anomalous Rossby wave**

breaking (RWB) on one or both sides of the jet. The amount of RWB on each side of the jet determines the angle of the jet and hence the location of clustering. More RWB to the south (north) drives the jet and storms further north (south), whereas RWB on both sides keeps the jet and storms constrained to a more central latitude. When these dynamical conditions persist for an extended period of time, it drives many cyclones towards the same location in western Europe. Often these cyclones are members of a 'cyclone family', where cyclones form on the trailing cold fronts of mature cyclones further downstream (Bjerknes and Solberg, 1922). These events **Clustering** can have huge socio-economic impacts, for example the seasons of 1990, 1999 and 2013/14 were all characterised by this behaviour and resulted in insured losses of €20, €16, and €3.3 billion respectively, as well as numerous fatalities across Europe (Munich Re, 2015).

Despite previous studies assessing the return periods of European windstorm losses (Pinto et al., 2007; Leckebusch et al., 2007; Donat et al., 2011; Pinto et al., 2012) the importance of clustering to severe windstorm loss seasons across the whole of Europe has received less attention (notably Karremann et al., 2014b, a). In this study, we will further explore how clustering is associated with windstorm losses for Europe. With this aim, the historical reanalysis datasets provide a comprehensive **spatial coverage** and are typically around 40-100 years in length. Due to the temporal limitations of reanalysis, accurate estimations of high return period storms (1 in 200 year events) are therefore not possible. Assessments of European wind storm losses for longer return periods using general circulation models (GCMs) have been performed (Pinto et al., 2012; Karremann et al., 2014b, a). However, the aforementioned studies were mainly interested in investigating changes to windstorm losses under future climate conditions and all were performed with models with coarse horizontal resolution (ECHAM5/MPI-OM1, T63, ~180 km in Europe (Roeckner et al., 2006)). In this study the High-Resolution Global Environment Model (HiGEM, Shaffrey et al. (2009)) is used since it has higher horizontal resolution compared to the GCMs used in previous studies. In addition, particular focus is placed on evaluating HiGEM's ability to represent the behaviour of clustering as identified in Priestley et al. (2017a).

The main science questions that will be addressed in this study are as follows:

1. Is HiGEM able to capture the upper-tropospheric large-scale dynamics associated with European cyclone clustering?
2. Does the SSI calculated using HiGEM output provide comparable results for individual windstorms and seasonal accumulations, to those obtained from the ERA-Interim re-analysis?
3. ~~Does windstorm clustering contribute more to seasonal losses for more severe European wintertime seasons?~~ **Does windstorm clustering contribute more to losses in Europe for winter seasons with large accumulated losses?**

The paper continues as follows. The data and methods used are described in section 2. The results follow in section 3, which starts with an evaluation of HiGEM, then an analysis of the SSI as a suitable metric for comparing windstorms in HiGEM and ERA-Interim. ~~Finally the importance of clustering is addressed for increasing return period winter seasons~~ **Finally the importance of clustering for seasons with large accumulated European windstorm losses is addressed.** The conclusions are presented in section 4.

2 Data & Methods

2.1 Datasets

The main data source for this work are simulations performed using HiGEM (Shaffrey et al., 2009), a fully coupled high resolution climate model based on the HadGEM1 configuration of the Met Office Unified Model (Johns et al., 2006). The horizontal resolution of the HiGEM atmospheric component is 0.83° latitude \times 1.25° longitude (N144) (~ 90 km in mid-latitudes) with 38 vertical levels up to 39 km. The horizontal resolution of the ocean component is $\frac{1}{3}^\circ \times \frac{1}{3}^\circ$ (~ 30 km) and is considered to be eddy-permitting. A total of 918 years of HiGEM data are available with a 6-hourly temporal resolution. This data comes from a series of 4-member ensemble decadal hindcasts initialised between 1960 and 2006, and also four 59 year transient experiments initialised in 1957. Full details of the data used are described in Shaffrey et al. (2017). HiGEM has been shown to have a good representation of the North Atlantic storm tracks, and also in the representation and distribution of extratropical cyclones (Catto et al., 2010, 2011).

For comparison, the re-analysis from the European Centre for Medium Range Weather Forecasts (ECMWF) ERA-Interim dataset (Dee et al., 2011) is used. ERA-Interim data is available at a 6-hourly resolution, starting from January 1979 and has a T255 spectral horizontal resolution (~ 80 km) with 60 vertical eta levels up to 0.1 hPa. Therefore, the resolution of ERA-Interim is comparable to that of HiGEM. In total 36 years of ERA-Interim data are used, from 1979 to 2015. As the focus of this study is on wintertime losses resulting from extratropical cyclones our analysis will be constrained to the months of December, January, and February (DJF).

20

2.2 Cyclone identification and tracking

To identify extratropical cyclones in both datasets we use the tracking algorithm of Hodges (1994, 1995) applied in the same way as Hoskins and Hodges (2002). This method tracks features using maxima in the 850 hPa relative vorticity field in the Northern Hemisphere. Prior to tracking the vorticity field is spectrally truncated to T42, which reduces the noise in the vorticity field. The large-scale background is also removed by removing total wavenumbers ≤ 5 in the spectral representation (Hoskins and Hodges, 2002). Maxima in the vorticity field (i.e. cyclonic features) are identified every 6 hours and formed into tracks. This is initially done by using a nearest neighbour approach to initialise the tracks, which are then refined by minimizing a cost function for track smoothness that is subject to adaptive constraints on the smoothness and displacement in a time step (Hodges, 1999). Pressure minima are also associated with the tracks using a minimization technique (Bengtsson et al., 2009) within a 5° radial cap. In order to exclude very small scale, noisy tracks, only tracks that travel at least 500 km and have a lifetime greater than 24 hours are retained. In previous dynamical clustering studies (Pinto et al., 2014; Priestley et al., 2017a) the method of Murray and Simmonds (1991) has been applied. Both cyclone tracking methods perform similarly for the tracking and clustering of North Atlantic cyclones, though the Hodges (1994) method generally tends to produce lower clustering

values over the North Atlantic/European sector (Pinto et al., 2016).

We follow the method of Priestley et al. (2017a) to calculate composite fields of RWB and the upper-level jet on clustered days. RWB is calculated using the 2-D Blocking Index method from Masato et al. (2013), which identifies overturning of potential temperature countours on the 2 PVU surface (dynamical tropopause; $1 \text{ PVU} = 1 \times 10^{-6} \text{ K m}^2 \text{ kg}^{-1} \text{ s}^{-1}$). The upper-level jet is identified as regions of high wind speed on the 250 hPa surface. These fields are composited for cyclones passing through three 700 km radii at different latitudes centred on 5°W ; 45°N , 55°N , and 65°N , to focus on the impact for various locations in western Europe.

2.3 SSI metric

The metric developed by Klawns and Ulbrich (2003) is used as a loss proxy for European windstorms. The SSI has been used in numerous other studies for similar purposes (Leckebusch et al., 2007; Pinto et al., 2007, 2012; Karremann et al., 2014b, a). It uses 10-metre wind speeds in its calculation of storm severity. We follow the approach of the population weighted SSI as used by Pinto et al. (2012) and Karremann et al. (2014b). The formulation of the SSI is defined in equation 1 and is constructed as follows:

- Losses due to wind occur on approximately 2% of all days (Palutikof and Skellern, 1991), therefore, for any losses to be produced the wind speed ($V_{i,j}$) must exceed the 98th percentile of the wind speed distribution.
- Buildings are generally constructed in such a way that they can sustain gusts that are expected locally. Hence, the 98th percentile is the local value ($V_{i,j}^{98}$). Following the method of Karremann (2015), if the 98th percentile is less than 9 m s^{-1} , the 98th percentile value is fixed at 9 m s^{-1} . **Changing the value of $V_{i,j}^{98}$ provides a sensible threshold for regions where the actual $V_{i,j}^{98}$ is not a realistic threshold for the onset of damage, such as Southern Europe and Iberia.**
- Losses do not occur if the wind speed does not exceed the local threshold ($I_{i,j}$).
- The value of $\frac{V_{i,j}}{V_{i,j}^{98}}$ is cubed as this is proportional to the kinetic energy flux (Palutikof and Skellern, 1991; Lamb, 1991) and this introduces a realistic, strongly non-linear wind-loss relationship (Klawns and Ulbrich, 2003).
- Winds exceeding the 98th percentile that do not occur over land are ignored as they will not contribute to losses ($L_{i,j}$).
- Insured losses from windstorms are dependent on the location of insured property, which are proportional to the local population density. The SSI is scaled by the 2015 global population density at the corresponding grid-box ($pop_{i,j}$, (Center for International Earth Science Information Network - CIESIN - Columbia University, 2017)).

$$SSI = \sum_{i=1}^{N_i} \sum_{j=1}^{N_j} \left(\frac{V_{i,j}}{V_{i,j}^{98}} - 1 \right)^3 \cdot I_{i,j} \cdot L_{i,j} \cdot pop_{i,j} \quad (1)$$

$$V_{i,j} = \begin{cases} \max(V_{i,j,t}) & \text{if } V_{i,j} \geq 9 \text{ m s}^{-1} \\ 9 \text{ m s}^{-1} & \text{if } V_{i,j} < 9 \text{ m s}^{-1} \end{cases}, t = \text{time period}$$

$$I_{i,j} = \begin{cases} 0 & \text{if } V_{i,j} < V_{i,j}^{98} \\ 1 & \text{if } V_{i,j} \geq V_{i,j}^{98} \end{cases}$$

$$L_{i,j} = \begin{cases} 0 & \text{over seas} \\ 1 & \text{over land} \end{cases}$$

5 $pop_{i,j}$ = Population density per grid-box

Following the method of Karremann (2015) we have applied a $V_{i,j}^{98}$ of 9 m s^{-1} to regions where the $V_{i,j}^{98}$ value is less than 9 m s^{-1} . Changing the value of $V_{i,j}^{98}$ provides a sensible threshold for regions where the actual $V_{i,j}^{98}$ is not a realistic threshold for the onset of damage, such as Southern Europe and Iberia.

- 10 The SSI is calculated at every land grid point and is used in two different forms for the main analysis in this study. Following insurance industry naming conventions, the first approach will be to calculate the maximum loss event in a year (herein referred to as the Occurrence Exceedance Probability (OEP)), and the second will calculate the total loss for an entire DJF season (herein referred to as the Annual Exceedance Probability (AEP)).
- 15 The OEP is calculated as the spatial sum of the maximum SSI **SSI** within a 72-hour period (i.e. the maximum SSI calculated from the 6-hourly windspeeds in a 72-hour period, per grid point). The 72-hour time window is consistent with that used by re-insurance companies for defining a particular event (Mitchell-Wallace et al., 2017). The region used to calculate the OEP is an adapted version of the Meteorological Index (MI) box applied by Pinto et al. (2012). Our OEP region extends from $10^\circ W - 20^\circ E, 35^\circ N - 60^\circ N$ and covers all of western Europe and most of central Europe. Our region differs from that of
- 20 Pinto et al. (2012) as it extends further south to $35^\circ N$, in order to encompass the Iberian peninsula and also all of Italy (shown by the black box in **figure Figure 4b**).

The AEP is calculated in the same way as the OEP, except that instead of using the single 72-hour maximum wind footprint, it sums all the individual 72-hour maximum wind speed footprints in the 90-day winter period. In the calculation of the

- 25 AEP all events are retained. The sensitivity to retaining all events is tested later.

2.4 Clustering measures

There are several ways to assess the clustering of windstorms, which give different information and perspectives. Described below are the three methods which will be used in this study.

5 2.4.1 Dispersion statistic

The first measure is the dispersion statistic (ψ). This is a measure of the regularity of cyclone passages at a particular gridpoint (equation 2) (Mailier et al., 2006). This relates the variance (σ^2) in storm track ~~numbers~~ **density (average number of storms per month in a single DJF season)** to the mean (μ) **storm track density**, with positive (negative) values indicating that cyclones are more likely to occur in groups (regularly). Near-zero values indicate a more random occurrence of cyclones (corresponding to a Poisson distribution).

$$\psi = \left(\frac{\sigma^2}{\mu} \right) - 1 \quad (2)$$

This statistical measure is the base quantification of where the dynamical clustering of cyclones is occurring. When done on a grid-point by grid-point basis it illustrates where cyclone passages are more regular, or more clustered and has been applied in numerous studies for this purpose (Mailier et al., 2006; Vitolo et al., 2009; Pinto et al., 2013). Moreover, Karremann et al. (2014b, a) estimated clustering of European storm series of different intensities and frequencies by approximating the data with a negative binomial distribution, thus estimating the deviation from a random Poisson distribution.

2.4.2 AEP/AEP_random

Another measure for assessing the impact of the clustering of cyclones is to examine the ratio of the AEP to a ~~randomised version of itself~~ **an AEP that is calculated when all the storms have been randomised in time** (this will herein be referred to as AEP_random). The randomisation re-orders all of the 72-hour SSI periods in the 918 DJF periods from HiGEM. Artificial DJF seasons are constructed by randomly sampling thirty 72-hour periods into a new order to remove any **dynamical** clustering between events that may be present in the HiGEM climate model. The AEP/AEP_random measure of clustering is particularly important for re-insurers as it provides information on how having dynamically consistent years (e.g. from the HiGEM model) provides different AEPs relative to a set of random (stochastic) model year.

A **positive** value of AEP/AEP_random **larger than 1** suggests that the dynamically consistent clustering and the severity of cyclones in HiGEM result in a larger AEP, relative to that expected from a randomly sampled set of events. Similarly, a **negative** value **less than 1** suggests that the consistent grouping of cyclones gives a lower AEP than would be expected at that

particular return period.

2.4.3 OEP/AEP

- The final measure used to assess clustering is the ratio of the OEP to the AEP. If the total loss in a season were characterised by just one single 72-hour cyclone event then, by definition, the AEP and OEP would be identical. However, if the OEP were much smaller than the AEP then this would suggest there are many cyclone events contributing to the AEP. The OEP/AEP ratio therefore quantifies the dominance of a single loss event in a season. The OEP/AEP ratio is calculated using the OEP and AEP in the same season.
- It should be noted that all the above measures provide different interpretations of the occurrence of clustering. The dispersion statistic is a measure of how grouped storms are in time relative to a Poisson distribution. This can be so physically interpreted as measuring the seriality of clustering. The ratio of AEP to AEP_random provides information on the dynamically consistent grouping of cyclones affects the accumulated seasonal losses (e.g. that produced from a climate model) compared to a completely random series of cyclones. The OEP to AEP ratio gives information on the dominance of the largest loss event in the overall seasonal losses. One of the additional objectives of this study is to ascertain how consistent the different measures of clustering are for seasonal losses.

2.5 Return periods and statistical methods

- A majority of the results in this paper will be expressed in terms of return period. The return period provides a period of time in which an event of a certain magnitude is expected to occur. Return periods have been allocated in a way such that the maximum AEP year is assigned a return period of the length of the dataset divided by its rank (for the maximum event the rank is 1). Therefore the maximum AEP year from ERA-Interim has a return period of 36 years, the highest AEP year in HiGEM has a return period of 918 years, as they both occur once in their total time period respectively. The second largest events then have return periods of 18 years and 459 years for ERA-Interim and HiGEM respectively. This continues until the lowest ranked year, which has a return period of 1 year. For a majority of our analysis we rank the OEP in the order of descending AEP. This ensures we maintain a temporal connection between the OEP and AEP at all return periods and means that the largest OEP may not necessarily occur in the highest AEP year. Some analysis is performed on independently ordered AEP and OEP, which removes the connection between maximum events and the years in which they occur.

The return periods of the most extreme events are estimated using a generalized Pareto distribution (GPD) that is fitted to the AEP and OEP data above a specified threshold ('peak over threshold' method). The GPD is fit using the maximum-likelihood

method, following Della-Marta and Pinto (2009), and Pinto et al. (2012). Uncertainties at the 95% level are calculated using the delta method (Coles, 2001).

3 Results

3.1 Evaluation of cyclone clustering in HiGEM

5 HiGEM has a good representation of the large-scale tropospheric circulation (Shaffrey et al., 2009; Woollings, 2010) and also extratropical cyclone shape, structure, and distribution (Catto et al., 2010, 2011). Several other studies have demonstrated that the model has skill in seasonal to decadal predictability predictions, particularly in the North Atlantic (Shaffrey et al., 2017; Robson et al., 2017). HiGEM provides a good representation of both the structure and amplitude of the DJF North Atlantic storm track (figure Figures 1a, c, e). The characteristic tilt of the North Atlantic storm track is evident as cyclones in HiGEM
10 (figure Figure1c) follow the SW-NE path found in ERA-Interim (figure Figure1a). In addition the maxima in storm numbers off the coast of Newfoundland and also over the Irminger Sea contrast well agree (anomalies within ± 2 cyclones per month) with ERA-Interim (figure Figure1e). There is an anomalous extension of the storm track in its exit region in HiGEM across Denmark and northern Germany, however the amplitude of the anomaly is small (< 2 cyclones per month). On the larger scale there are minimal biases present across the entire basin and the European continent. There are localised errors that are mostly
15 below 2 cyclones per month when compared to 36 years of ERA-Interim re-analysis (consistent with Catto et al. (2011)). The structure and amplitude of the Mediterranean storm track is also well captured. Stippling in figure Figure 1e indicates where HiGEM and ERA-Interim are different at the 95% level (performed using a two-tailed Student's t-test). These differences are only present around the coast of Greenland and are associated with the minima in the Labrador Sea and Davis Strait, and also the maxima across the east coast of Greenland. None of the anomalies across the rest of the North Atlantic or Europe are
20 statistically significant.

The dispersion of cyclones in the North Atlantic for ERA-Interim and HiGEM is shown in figure Figures 1b and 1d respectively. The pattern of the dispersion is consistent for the two datasets with both being characterised by a more regular behaviour in the entrance of the storm track (western North Atlantic) where storms have their main genesis region (Hoskins
25 and Hodges, 2002) and baroclinic processes are dominant. Both datasets show overdispersive (clustered) behaviour in the exit of the storm track, e.g. the UK and Iceland. The pattern of under/overdispersion in the exit/entrance region of the storm track is comparable with the studies of Mailier et al. (2006); Pinto et al. (2013). There are discrepancies in the magnitude of the dispersion (figure Figure 1f), however, the large-scale pattern and sign of the dispersion is consistent between the two datasets.

30 It was shown in Priestley et al. (2017a) that clustering events occurring at different latitudes of western Europe were associated with It was shown in Priestley et al. (2017a) that clustering events occurring at different latitudes of western Europe are associated with a specific set of dynamical conditions (as discussed in section 1). The clustering periods identified are characterised by a strong and extended upper-level jet that was associated with anomalous RWB on one or both flanks, which acts to drive the

jet further north or further south and then anchor it in position. These persistent conditions allow the cyclones to track in similar directions and leads to clustering over different regions of western Europe. This analysis has been repeated for all 918 years of HiGEM data in order to assess how well HiGEM dynamically represents these events (figure Figure 2). The same analysis of ERA-Interim is shown in the supplementary material (Figure A1). with the same analysis of ERA-Interim being shown in the supplementary material (figure Figure A1). Figure 2a shows that for cyclones clustering at 65°N, the jet is extended toward the northern United Kingdom with speeds in excess of 40 m s⁻¹. The jet is associated with large amounts of RWB on its southern flank. For clustered days at 55°N (figure Figure 2b), the extended jet is more zonal than for events at 65°N. The strong jet has anomalous RWB on the northern and southern flanks, however the RWB on the southern flank is of a smaller magnitude than that seen in ERA-Interim (figure Figure A1b). The clustered events at 45°N show a very zonal upper-level jet with a dominance of RWB on the northern flank.

All of the composites of clustered days (figure Figure 2a-c) show a marked departure from the climatology (figure Figure 2d). The jet is stronger and more zonally extended than the climatology for all three cases, and each features anomalous amounts of RWB on one or both flanks of the upper-level jet, all of which are comparable to ERA-Interim. The climatological state of the jet and RWB in HiGEM (figure Figure 2d) is comparable with ERA-Interim (figure Figure A1d), with a slightly reduced amount of RWB across central Europe. Hence, clustering events in HiGEM appear dynamically consistent with those in ERA-Interim, albeit with a slight under-representation of the albeit with a lower frequency of anticyclonic RWB on the southern flank of the jet.

HiGEM has been found to have a good representation of North Atlantic extratropical cyclones and cyclone clustering, as well as the large-scale circulation driving this behaviour. This demonstrates the suitability of using HiGEM to investigate clustered windstorm related losses.

3.2 Comparison of SSI in ERA-Interim and HiGEM

The SSI is widely used for quantifying losses related to windstorms. We now compare the SSI for both HiGEM and ERA-Interim. The characteristic of the SSI is that it is calculated above a set threshold, the 98th percentile of the local distribution of 10-metre wind speed ($V_{i,j}^{98}$). The structure of $V_{i,j}^{98}$ for ERA-Interim, HiGEM, and the difference between the two datasets is shown in figure Figure 3. Both datasets show a similar large scale structure with maxima over the North Atlantic ocean and minima over the high orography of the Alps and Pyrenees. However, HiGEM values are systematically lower than ERA-Interim across almost all of Europe by 1-3 m s⁻¹ (figure Figure 3c), whereas across the North Atlantic ocean the bias is smaller and slightly positive. This systematic difference suggests there may be differences in the boundary layer scheme of HiGEM compared to ERA-Interim as this bias is not present for wind speed at 850 hPa or higher (not shown). Similar differences have also been found for in the biases of 10-metre winds when contrasted with and 925 hPa winds between wind speeds in four reanalysis datasets (Hodges et al., 2011).

To address the lower European windspeeds, a simple bias correction is applied to the 10-metre wind speeds in HiGEM. This is done by correcting the 10-metre wind speeds by the spatially averaged offset in the $V_{i,j}^{98}$ field **between ERA-Interim** ($\overline{V_{i,j}^{98 ERA-I}}$) **and HiGEM** ($\overline{V_{i,j}^{98 HiGEM}}$) for all land grid points within our area of interest (black box in **figure Figure 4b**). As a result all HiGEM wind speeds are **uniformly** increased by 18.75% over land. The resulting bias-corrected HiGEM 10-metre wind speeds will be called HiGEM_bc herein and its formulation is shown in equation 3. The corrected $V_{i,j}^{98}$ wind field (difference relative to ERA-Interim) is shown in **figure Figure 3d** and shows much reduced differences across our core European region. In some regions (northern Germany, Benelux, northern and northwestern France) the differences have changed sign and are now positive, ~~however this is balanced by the slightly negative regions,~~ there are also some regions that still have negative anomalies, resulting in an overall neutral anomaly compared to ERA-Interim.

$$10 \quad \text{HiGEM_bc} = \text{HiGEM} * \frac{\overline{p_{98}^{ERA-I}}}{\overline{p_{98}^{HiGEM}}}$$

$$\text{HiGEM_bc} = \text{HiGEM} * \frac{\overline{V_{i,j}^{98 ERA-I}}}{\overline{V_{i,j}^{98 HiGEM}}} \quad (3)$$

Spatial maps of the DJF average SSI are shown in **figure Figure 4** and are consistent between ERA-Interim and HiGEM across large parts of northern and northwestern Europe. Both datasets show a peak in SSI across northwestern Europe from London across to northern and northwestern Germany, as would be expected from the population weighting. Other densely populated regions are also identifiable. There are further regions of noticeable SSI across Germany and extending **west east** toward Russia. There are also peaks in SSI across the Iberian peninsula and Italy.

~~Figure 5a~~ **Figure 5** shows how the AEP from ERA-Interim and HiGEM as a function of return period, up to a maximum return period of 36 years. Also shown in ~~figure 5a~~ **Figure 5** are 10,000 bootstrap samples of the 918 years of HiGEM_bc AEP data in 36 year samples, and the associated 95% confidence intervals. The AEP from ERA-Interim is within the confidence intervals of the HiGEM_bc samples at all return periods, with ERA-Interim being at the upper-end of the spread at the lowest return periods of 1-2 years, and in the middle of the spread for the remaining return periods. ~~Figure 5a~~ **Figure 5** suggests that HiGEM_bc can capture the variation of AEP as a function of return period that is found in ERA-Interim.

In ~~figure 5b~~ **Figure A2** we have ordered the AEP and OEP independently **by return period** in order to assess how the SSI from ERA-Interim and HiGEM directly compare in magnitude at varying return periods. ~~Figure 5b~~ **Figure A2** shows how the AEP and OEP change with return period for ERA-Interim, with the dots representing the raw data. Also shown in ~~figure 5b~~ **Figure A2** are the ~~ERA-Interim~~ GPD fits of the ERA-Interim AEP and OEP, and associated confidence intervals (non-filled). Confidence intervals are only displayed above the threshold used to fit the GPD. The GPD provides a good estimation of the data above a 5 year return period, however due to the small amount of data used to fit the distribution, uncertainties start to become very large above a return period of 20 years. By a return period of 50 years they have diverged greatly.

Also shown in figure 5b Figure A2 are the 95% confidence intervals for the GPD fits (shaded regions) of the HiGEM_bc AEP and OEP (ordered independently). These are shown above a return period of 10 years. The confidence intervals for HiGEM_bc are much narrower than ERA-Interim, which is to be expected as there is considerably more data being used in the GPD fit (consistent with Karremann et al. (2014b)). For return periods for which both datasets have data (< 36 years) the GPD fit of the HiGEM_bc AEP and OEP are within the confidence intervals of the ERA-Interim AEP and OEP. This is also the case for return periods greater than 36 years for the AEP and the OEP, although the confidence intervals for the GPD fit for ERA-Interim become extremely large for return periods greater than 50 years. HiGEM_bc is therefore consistent with the accumulated seasonal losses and the individual events found in ERA-Interim. This suggests HiGEM is a useful climate model for investigating AEP and OEP for large return periods.

3.3 Large return Periods losses in HiGEM_bc

Figure 6 shows the AEP and OEP for HiGEM_bc. Both the AEP and OEP curves of HiGEM_bc extend beyond the respective maxima from ERA-Interim, suggesting that more severe windstorm seasons and also single cyclone events may be possible than those seen in the ERA-Interim period. For both the AEP and OEP, the increase in the largest event is by approximately 100%. For example, the 918 year return period season in HiGEM is approximately twice the magnitude of the 1 in 36 year season in ERA-Interim. There is more noise in the ERA-Interim curves compared to their HiGEM_bc counterparts due to the smaller number of years. The OEP and AEP of HiGEM_bc are sorted by AEP magnitude in figure Figure 6. Consequently, there is substantially more spread in the OEP values than seen in figure 5b Figure A2. However, a general increase in OEP with return period is still found, with low AEP years generally having a lower OEP and high AEP years having a higher OEP, but there are some specific deviations from this (for example, note the four very high OEP years between return periods 40 and 100).

To test the sensitivity of figure 5b Figure A2 and figure Figure 6 to the default definition of AEP as the sum of all events, we repeated the analysis, but only retaining on average the top 3 events of each year. This equates to an order of magnitude reduction in the number of events (see figure Figure A3). The magnitudes of the AEP are very marginally lower as would be expected with the filtering of events. The magnitudes of the reduced event AEPs are marginally lower than the original AEPs, as would be expected with the filtering of events, but the main features of the curves in figure Figure A3 are very similar.

(Hunter et al., 2016) previously showed how the number of cyclones within a winter is strongly related to their intensities. Similarly, earlier results (Fig. 1e) showed that cyclones in HiGEM tend to occur in groups. To quantify the contribution of windstorm clustering to the large AEP values we compare the HiGEM AEPs to randomised series of loss events. The ratio between the AEP and the AEP_random may be particularly important for the insurance industry as it characterises the importance of the clustering of cyclones in seasonal losses.

We have performed a non-replacement randomisation of the 72-hour periods that make up the HiGEM_bc AEP with 10,000 samples and this randomisation ensures that each random sample contains the exact same data as the original 918 years. This randomisation allows us to assess how the intensity of losses and the associated number of cyclones acts to influence the AEP in HiGEM_bc, compared to a timeseries where windstorms are occurring randomly. The mean of these random samples is shown by the black line in figure Figure 6, with the grey shading indicating the 95% confidence interval of these samples. Below a return period of ~ 3 years the AEP_random is greater than that from the HiGEM_bc AEP and above the 3 year return period the AEP_random is consistently less than the AEP. Therefore, low (high) return period loss years tend to have a lower (higher) AEP than random.

The ratio of AEP to AEP_random is shown in figure Figure 7. Values >1 (<1) indicate a higher (lower) AEP in the actual HiGEM_bc years compared to the AEP_random years. Above a return period of 3 years the realistic, dynamically consistent, representation of the grouping of events in HiGEM_bc tends to generate more losses and a greater AEP than the random grouping of events. The median contribution above the 3 year return period is generally in the range of 1.1 to 1.2 times the random AEP. At a return period of 200 years the 95% confidence intervals range from 1 to 1.3. For low return periods (< 3 years) the occurrence of events in HiGEM_bc leads to a lower AEP than in the random realisations, with HiGEM_bc AEP values in the range of 0.6 to 1. This suggests that during low loss winters, there are a smaller number of windstorms and weather loss events occurring in HiGEM_bc than would be expected from considering a randomised series of events.

The difference can be interpreted physically by considering two recent DJF periods in the UK. Firstly, the winter of 2009/2010 was characterized by a strongly negative NAO and an absence of extratropical cyclones influencing the UK for this period (Osborn, 2011). Secondly, the winter of 2013/2014 was almost the complete opposite and was associated with the continuous presence of deep cyclones, occurring in groups, for almost the entire DJF period (Matthews et al., 2014; Priestley et al., 2017b). The nature of these two seasons would result in 2009/2010 having a very low AEP, and 2013/2014 having a very high AEP. Randomising these two seasons the result would be two synthetic seasons with AEP values between these two extremes. Hence the clustering of cyclones in 2013/2014 results in a higher AEP than expected from random and 2009/2010 having a lower AEP than expected.

In figure Figure 7 it appears that the realistic, dynamically consistent, representation of clustering in HiGEM_bc causes higher losses above a 3 year return period with losses being 10-20% higher than random as a result at all return periods. Despite the nearly constant value of AEP/AEP_random above 3-year return period a return period of 3 years, the absolute difference between the two values is increasing with return period (the AEP is more than 4 times larger at 918 year return period compared to a 3 year return period). Hence the physically consistent representation of clustering in HiGEM_bc is causing larger increases to the AEP with increasing return period.

A different view of clustering can be gained by examining how a single event can affect the accumulated seasonal losses

through the ratio of the OEP to AEP. A high value implies that the single largest event is causing most of the losses in a season, and a lower value implies a contribution to the overall seasonal losses from many cyclones in that particular season. The results from ERA-Interim and HiGEM are compared in figure Figure 8a. This shows 10,000 random samples of 36 years of the HiGEM_bc OEP/AEP with associated confidence intervals as well as the ERA-Interim OEP/AEP. The values are sorted into return periods by order of descending AEP. There is considerable spread in the ERA-Interim OEP/AEP values, with minima of ~ 0.2 at a return period of 1-2 years, and a maxima of ~ 0.8 at a return period of 10 years. There is no clear systematic increase or decrease in the value of OEP/AEP in the ERA-Interim data, which is consistent with the median values and confidence intervals from the HiGEM_bc samples. The 95% confidence intervals range from 0.15-0.65 at a return period of 1 year, and from 0.2-0.8 at a return period of 36 years. This suggests that there is a wide range of OEP/AEP values that may characterise a high or a low AEP season.

Figure 8b shows the OEP/AEP values for HiGEM_bc. As in figure Figure 8a there is considerable spread variation in the value of OEP/AEP at all return periods, with no clear systematic increase or decrease with return period. All return periods have a majority of the data with values of ~ 0.25 -0.5, with the extremes ranging from 0.15 to 0.9. This indicates that in terms of the contribution of a single event to the overall seasonal loss, there is no direct relationship with return period. At any return period it appears that 25-50% of losses will come from the largest event.

As with the ratio of AEP/AEP_random in figure Figure 7, the ratio of OEP/AEP in figure Figure 8b has a relatively constant value at all return periods and this suggests a constant relationship between the OEP and AEP. However, as the return period is increasing the OEP and AEP are also increasing, so despite the AEP/AEP_random ratio being constant at a return period of 5 years and 200 years, the absolute difference between OEP and AEP at the two return periods would be very different. The higher return periods have a higher absolute difference between the AEP and OEP, hence the additional losses that are not the OEP are increasing with return period. Hence the relative difference between the OEP and AEP is consistent with return period, but the absolute difference is continuing to increase with return period. This absolute increase is likely a result of more severe events in the high return period AEP years.

4 Discussion & Conclusions

The aim of this study is to investigate the importance of clustering for high return period loss events caused by European windstorms. This is achieved using a GCM that is able to adequately capture the large-scale dynamics controlling cyclone clustering. This work has been performed using HiGEM, a high resolution fully coupled climate model. The performance of HiGEM has been evaluated using the ERA-Interim reanalysis. Losses from European windstorms have been estimated using a version of the SSI (Storm Severity Index) applied to European land grid points. The main conclusions of this work are as follows:

- HiGEM can successfully reproduce the large-scale dynamics associated with clustering of European cyclones that are seen in ERA-Interim. The biases in DJF storm track activity in HiGEM are small, with the tilt and intensity of the North Atlantic storm track being well represented. The pattern of dispersion in the North Atlantic is also consistent with ERA-Interim, with cyclones clustering more near the exit of the storm track, and an underdispersive and regular nature in the entrance region. The large scale circulation associated with clustering is also similar in HiGEM and ERA-Interim. Both show how clustering in different locations of western Europe is associated with a strong and extended upper-level jet that is flanked on one or both sides by anomalous RWB. Hence, extratropical cyclone clustering in HiGEM is occurring for the right dynamical reasons.
 - SSI is used as a proxy to assess losses occurring from intense European windstorms. The SSI is applied to land points only and for an area than encompasses all of western and most of central Europe. It is found that HiGEM systematically underestimates 10-metre wind speed over European land regions. A simple bias correction (~~scaling by 18.75%~~) (**uniform increase by 18.75%**) leads to a structure of the DJF SSI average that is consistent between the bias corrected HiGEM (HiGEM_bc) and ERA-Interim. The return periods of AEP and OEP are found to be consistent between HiGEM_bc and ERA-Interim for return periods less than 36 years. Therefore, HiGEM_bc appears to be a suitable model for assessing long return period losses from European windstorms.
 - Compared to a random season of cyclones, the AEP from HiGEM_bc is larger at return periods greater than 3 years. The dynamically consistent representation of cyclone severity and clustering in HiGEM_bc results in values of AEP that are approximately 10-20% larger than AEP_random at a return period of 200 years. Therefore, not having a dynamically consistent representation of cyclone clustering appears to result in an underestimation of losses above a 3 year return period.
 - The relative portion of the AEP that comes from the OEP is very variable across all return periods and there is no strong relationship between the two values. The contribution of the OEP to the AEP is found to be approximately ~ 0.25 to ~ 0.5 **25-50%** in HiGEM_bc. ~~The absolute difference between the AEP and OEP is increasing with return period.~~ Therefore, the relative influence of the largest loss event in a season does not change with return period.
- In this study we have shown that having a dynamically consistent representation of cyclone clustering and storm intensity causes the AEP to be approximately 10-20% higher (for return periods greater than three years) than that expected from a random selection of cyclones. Despite the near constant values of AEP/AEP_random above a 3 year return period, the absolute magnitude of the AEP relative to AEP_random is increasing with return period. This absolute increase suggests an increase in cyclone severity for higher return period loss seasons for cyclones of all magnitudes. This result has strong implications for loss modelling in the insurance industry and demonstrates that if a model does not adequately represent the clustering behaviour of cyclones then losses will be underestimated for larger return periods. **Furthermore, as the wintertime average loss from windstorms in Europe is over \$2 billion (Schwierz et al., 2010), this could result in an underestimation of losses by \$200-400 million.** In addition we have shown how the relative contribution of the largest event in contributing to the AEP does not change

with return period and that the measure of OEP/AEP can be very variable from year to year. The measure of OEP/AEP is not a good measure for assessing any potential changes in the relative importance of a single storm, and hence any changes in clustering, with an increasing return period of a seasons AEP. It should also be noted that as these results come from just one single climate model more robust conclusions could be made from applying our methods to a greater number of climate models.

5

It has been shown in several studies (Leckebusch et al., 2007; Pinto et al., 2012) that loss potentials associated with European windstorms would increase under future climate conditions. Based on low resolution ECHAM5 simulations, Karremann et al. (2014a) provided evidence that the combination of higher single losses and clustering in a warmer climate would lead to significantly shorter return periods for storm series affecting Europe. As in the present study we only focussed on wind-
10 storms under current climate conditions, it would be pertinent as a next step to evaluate if the tendency towards an increase in clustering holds true for the new high resolution CMIP6 climate projections.

Competing interests. There are no competing interests at present.

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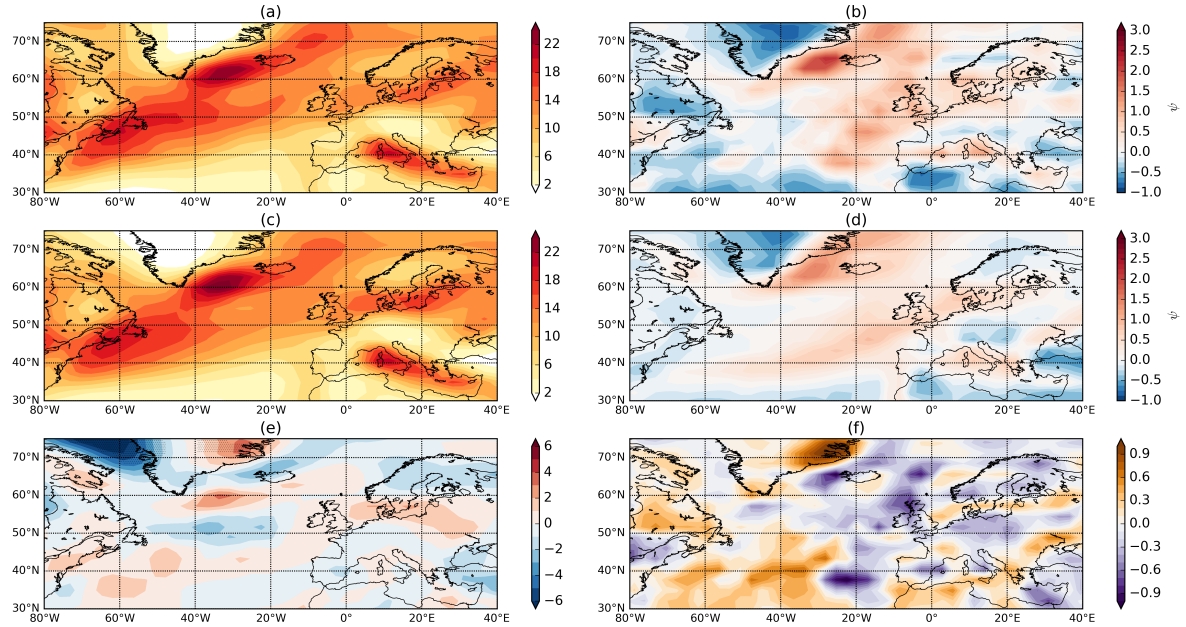


Figure 1. Track density (a) and associated dispersion (b) for ERA-Interim DJF storm track.(c), (d) same as (a), (b) but for HiGEM. (e) is the difference in track density (HiGEM-ERA-Interim), stippling indicates where the two datasets are different at the 95% level. (f) is the difference in dispersion (HiGEM-ERA-Interim). Units for (a), (c), and (e) are cyclones per month per 5° spherical cap.

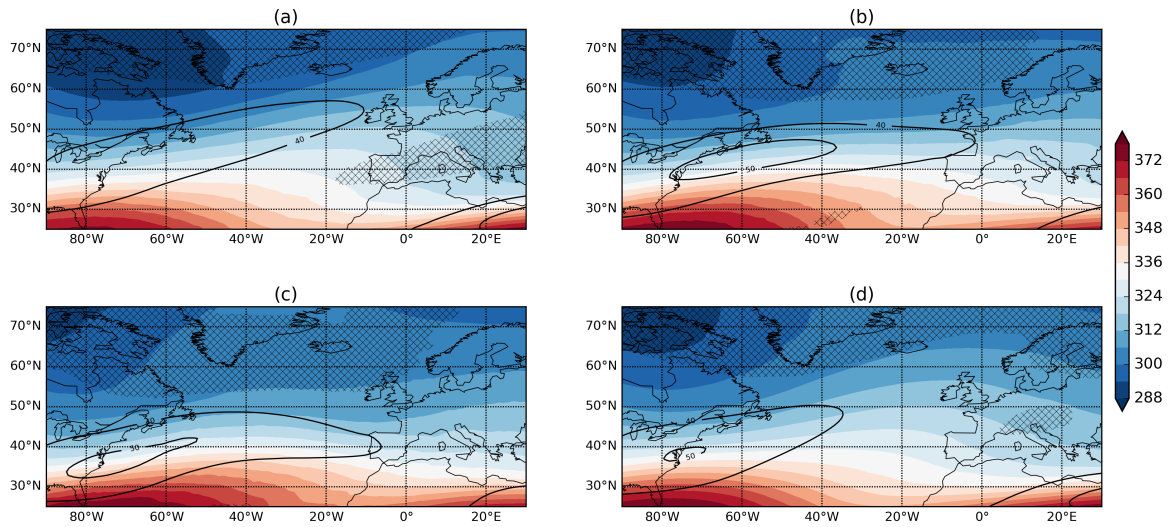


Figure 2. Dynamical composites of clustered days at (a) 65°N, (b) 55°N, and (c) 45°N. (d) Climatology. For all panels the colored contours are θ on the 2 PVU surface (K). Black contours are the 250 hPa wind speed, starting at 40 m s^{-1} and increasing by 10 m s^{-1} . The crossed hatchings are where RWB was occurring on at least 30% of days.

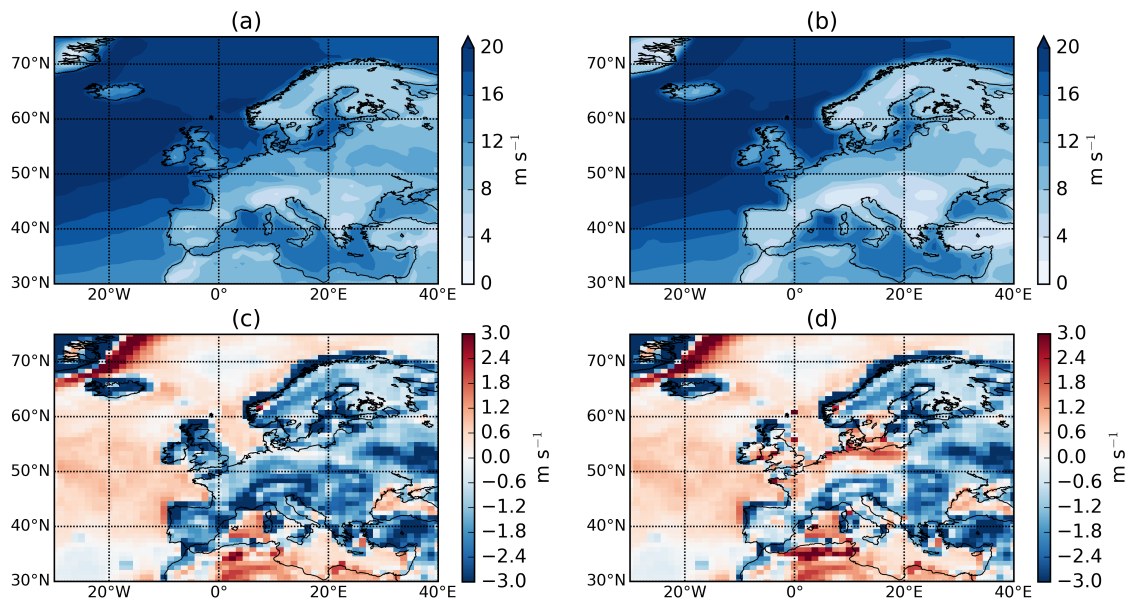


Figure 3. 98th percentile of 10-metre wind speed (m s^{-1}) for the DJF climatology of ERA-Interim (a) and HiGEM (b). (c) is HiGEM-ERA-Interim using the raw HiGEM wind speeds. (d) is HiGEM-ERA-Interim using the HiGEM winds that have been scaled by 18.75%.

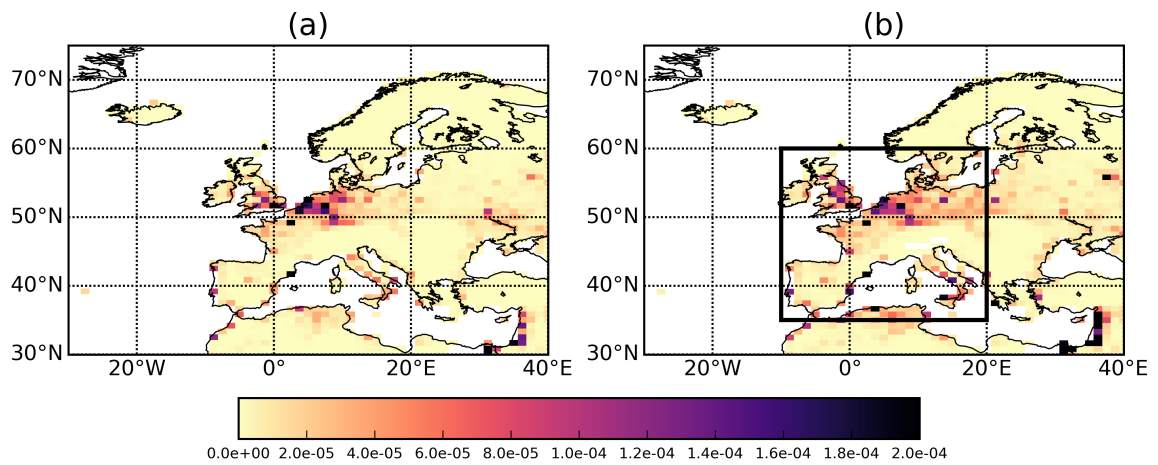


Figure 4. DJF average of 6-hourly SSI for ERA-Interim (a) and HiGEM (b). The black box region in (b) is our SSI calculation region.

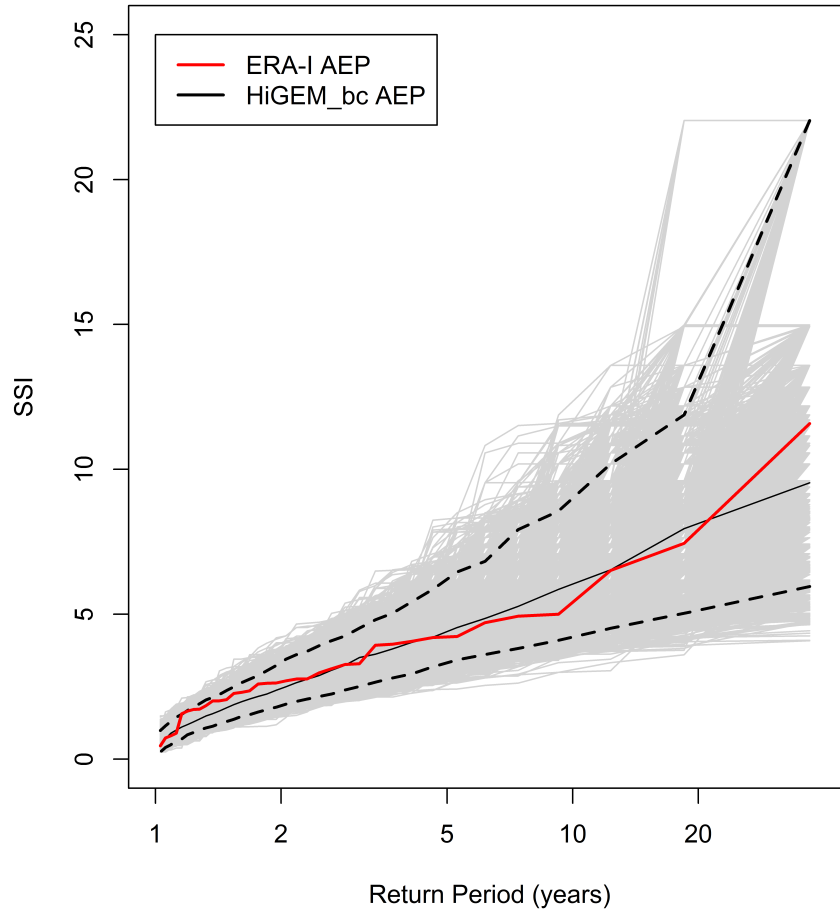


Figure 5. Return periods of AEP for ERA-Interim (red line). The light grey lines are the 10,000 bootstrap samples of the HiGEM_bc AEP. The black dashed lines are the associated 95% confidence intervals of the HiGEM_bc AEP and the black solid line is the median.

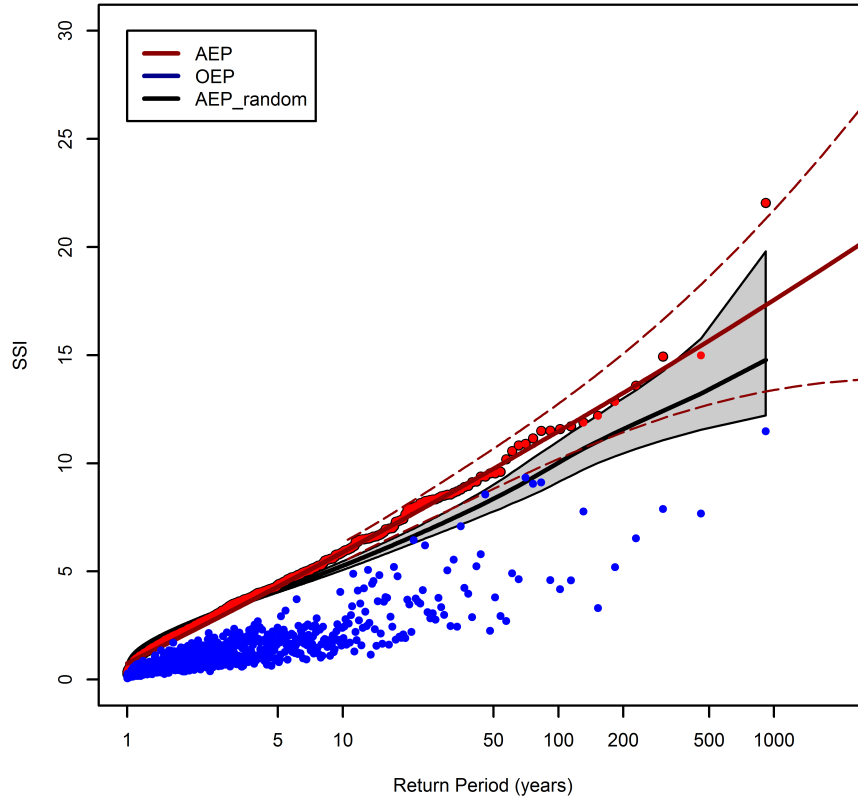


Figure 6. Return periods of the AEP (red points) and OEP (blue points) for HiGEM_bc. The OEP and AEP are sorted according to AEP magnitude. The solid red line is the GPD fit applied to the AEP using a 90th percentile threshold. The dashed red lines are the associated 95% confidence intervals. The black line represents the mean of 10,000 non-replacement random samples of the HiGEM_bc AEP data. The surrounding shaded grey region represents the 95% confidence interval of these 10,000 samples. The GPD fit and confidence intervals are only plotted above the GPD threshold.

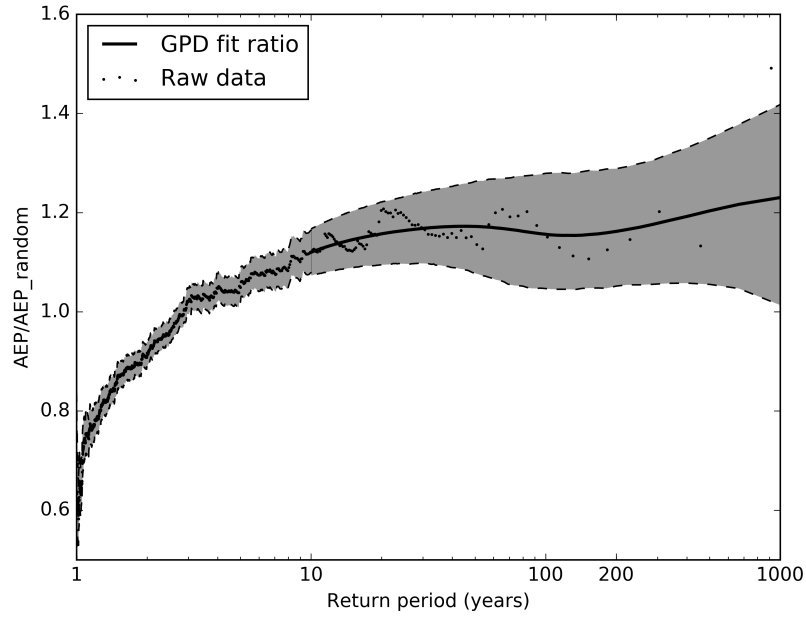


Figure 7. The ratio of the model AEP to the 10,000 random samples of the AEP for increasing return period. Black dots are the raw data points. The dark grey region below 10 year return period indicates the 95% confidence interval of the raw AEP/AEP_random. Above 10 year return period the dark grey shaded region bounded by the black dashed lines is the 95% confidence interval using the fitted AEP (red line in figure 6) in the calculation and the black solid line is the median of the spread. Confidence intervals from the GPD fits are only shown above the GPD threshold.

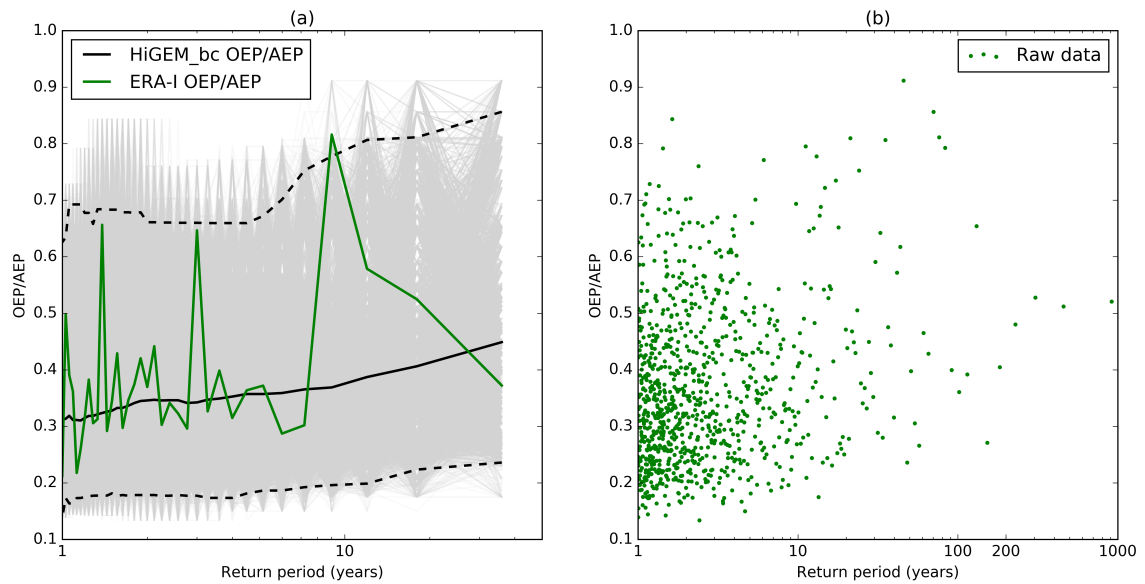


Figure 8. (a) Return periods of OEP/AEP for ERA-Interim (green line). The light grey lines are the 10,000 bootstrap samples of the HiGEM_bc OEP/AEP. The black dashed lines are the associated 95% confidence intervals of the HiGEM AEP and the black solid line is the median. (b) Return periods of the OEP/AEP ratio for HiGEM_bc (green points).

Appendix A

A1

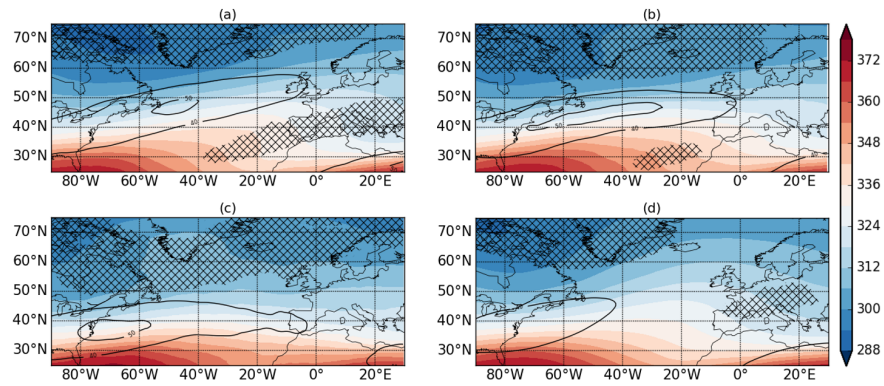


Figure A1. Composites of clustered days from ERA-Interim at (a) 65°N, (b) 55°N, (c) 45°N and (d) Climatology. Contours and hatchings are the same as figure 2.

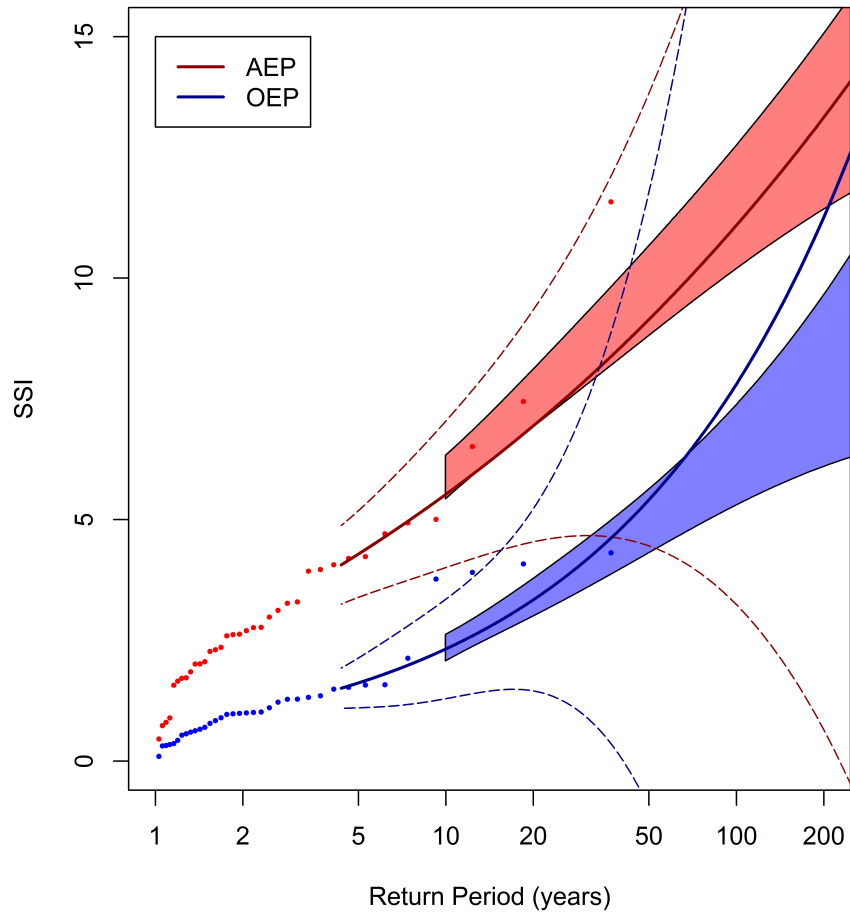


Figure A2. Return periods of the AEP (red points) and OEP (blue points) of ERA-Interim. The solid red and blue lines are GPD fits applied to the AEP and OEP using an 70th percentile threshold. The dashed red and blue regions are the associated 95% confidence intervals. The shaded red and blue regions are the 95% confidence intervals of the HiGEM_bc AEP and OEP GPD fits. The OEP and AEP are sorted independently for both ERA-Interim and HiGEM. The GPD fits and confidence intervals are only plotted only above the GPD threshold of the 90th percentile.

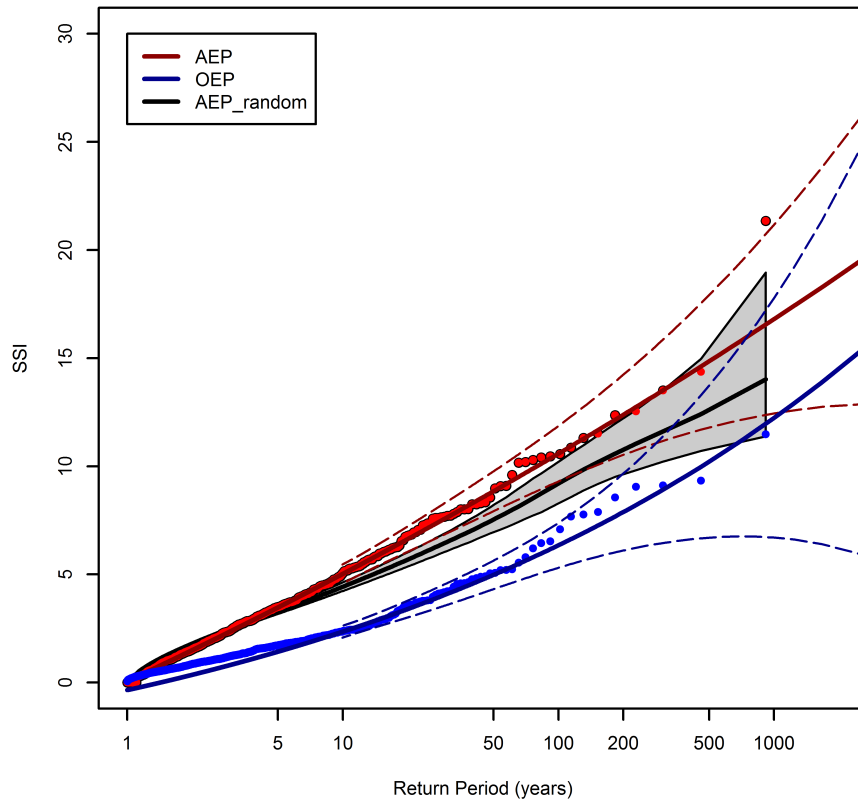


Figure A3. As figure 4, but only retaining the top three events of every year.