Reply on referee comment 1

Projections and uncertainties of winter windstorm damage in a changing climate

We would like to thank all reviewers for taking the time to review our work. We appreciate the insightful and helpful comments which contribute to improve our manuscript. Please find our detailed responses to the reviewers' comments and suggestions below.

The changes have been included into the manuscript and are indicated in blue here and in the annotated manuscript. In cases of corrections, phrases from the former version of the manuscript are indicated in red for reference.

The main changes to the manuscript are listed in the following. Our responses to each referee's comment are given next.

1. To account for the assumption of stationary exposure and vulnerability taken in this study, the term "future" referring to storm damage has been systematically changed to "in a changing climate", or "future-climate", or "under future climate conditions". We also replaced the term "future change", with "Delta Climate change", to clarify that the projected changes in risk refer to the changes due to future climate conditions. The title of the manuscript has also been changed accordingly to: "Projections and uncertainties of winter windstorm damage in Europe in a changing climate". Please see our reply to comment 1 of Reviewer 2 for more details.

2. Also related to point 1, clearer explanations regarding our assumptions on the modelling of the exposure and vulnerability, and their importance for the risk modelling have been included, in the description of the exposure, and vulnerability in the method section, and in the "Summary, discussion and conclusion" section. Please see our reply to comment 1 of Reviewer 2 for more details.

3. We extended our analysis by explicitly studying the effects of considering different future climate scenarios on the outcome of the damage projection. This extension has been included as an additional subsection in the results section of the manuscript. Please refer to comment 1 of Reviewer 1 for further details.

4. We found that some results in the previous version of the manuscript were erroneous as the results of the projections of the Average Annual Damage got interchanged with the results of the projections of damage events with a return period of 30 years. This modification in our results affects some details in the projections of the regional changes in the damages but does not change the main results and conclusion of the paper. To correct this inconsistency, we updated Figure 5b of the original manuscript and modified the manuscript in the results, and in the Summary, discussion and conclusion sections. The exact changes in the manuscript as well as the updated version of Figure 5b can be found in the erratum section.

Erratum:

Due to a mistake in the production of Fig. 5b and of some of the results presented in the body of the previous version of the manuscript, we updated Fig. 5b (see Fig. R 1 in our response below) as well as the erroneous lines in the manuscript:

(Lines 378-391 in the previous version of the manuscript): Disregarding the important spread, the multi-model medians of the ensemble show positive changes in the average annual damage in five regions: British Isles (BI, +20%), Western Europe (WEU, +34%), Central Europe (CEU, +9%), the Mediterranean and Balkan region (MED, +1%), and Scandinavia (SC, +8%); and negative changes in two regions: the Iberian Peninsula (IP,-7%), and Eastern Europe (EEU, -14%). When considering median changes in the damages aggregated to the entire domain, we observe a tendency for the damage amounts with longer return periods to increase more relatively to damages amounts with shorter return periods, as damage amounts with return periods of 15 years increase by +24%, while damage amounts with return periods of one year only increase by +13%. We recall that even small changes in the average annual damage might result in significant damage amounts, as the damages accumulate over the years. As an illustration, we show in absolute terms the future-minus-historical difference of the accumulated damages, resulting from the accumulation of 20 years of average annual damage over the historical and the future SSP585 period. The differences between the damages accumulated over 20 years of the historical period and the damages accumulated over 20 years of the future period yield +3.9 bn USD for the British Isles, +3.4 bn USD for Western Europe, +829 mn USD for Central Europe, +1.1 mn USD for the Mediterranean and Balkan region, +237 mn USD for Scandinavia, -107 mn USD for the Iberian Peninsula, and -29 mn USD for Eastern Europe, for a total of +6.9 bn USD for the entire European domain.

to

(Lines 419-429 in the revised manuscript): Disregarding the important spread, the multi-model medians of the ensemble show positive changes in the average annual damage in three regions: British Isles (BI, +16%), Western Europe (WEU, +17%), and Scandinavia (SC, +13%); and negative changes in four regions: the Iberian Peninsula (IP,−28%), Central Europe (CEU, −3%), the Mediterranean and Balkan region (MED, −15%) and Eastern Europe (EEU, −35%).

We recall that even small changes in the average annual damage might result in significant damage amounts, as the damages accumulate over the years. As an illustration, we show in absolute terms the future-minus-historical difference of the accumulated damages, resulting from the accumulation of 20 years of average annual damage over the historical and the future SSP585 period. The differences between the damages accumulated over 20 years of the historical period and the damages accumulated over 20 years of the future period yield +987 mn USD for the British Isles, +997 mn USD for Western Europe, −164 mn USD for Central Europe, −45 mn USD for the Mediterranean and Balkan region, +175 mn USD for Scandinavia, −186 mn USD for the Iberian Peninsula, and −37 mn USD for Eastern Europe, for a total of +2.7 bn USD for the entire European domain.

and

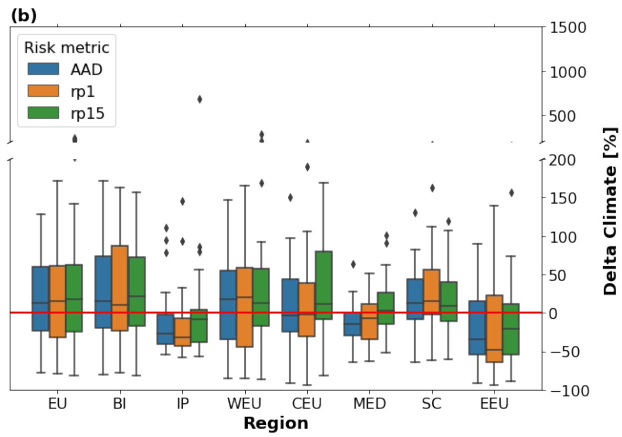

Figure R 1: Updated version of Fig 5b. of the manuscript.

(Lines 436-445 in the previous version of the manuscript): In particular, we highlight the British Isles and Western Europe to be particularly at risk, with the median of the multi-model ensemble projecting increases in average annual winter storm damage of +20% and +34%, respectively. We find more moderate increases in the damages in Central European (+9%), Scandinavian (+8%), and the Mediterranean and Balkan (+1%) regions, and decreases in the Iberian Peninsula (-7%) and Eastern European (-14%) regions. Overall, the climate model agreement on the future changes in winter storm damage is poor over the regions where the damages are expected to increase according to the multi-model median, but the climate model agreement improves over the regions where the damages are expected to decrease according to the multi-model median. We find evidence for the damages associated with long return periods to increase more relatively to damages associated with shorter return periods, with multi-model median European-wide damage amounts associated with return periods of one and 15 years increasing by +13% and +24% respectively.

to

(Lines 520-527 in the revised manuscript): In particular, we find the British Isles, Western Europe, and Scandinavia to be at risk of increased winter windstorm damage under future climate conditions, with the median of the multi-model ensemble projecting increases in average annual damage of +15%, +17%, and +13% respectively. We find a moderate decrease in the damages in Central Europe (-3%), and more marked decreases in the Iberian Peninsula (-28%), the Mediterranean (-15%) and Eastern European (-35%) regions. Overall, the climate model agreement on the Delta Climate changes in winter storm damage is poor over the regions where the damages are expected to increase according to the multi-model median, but the climate model agreement improves over the regions where the damages are expected to decrease according to the multi-model median.

Reviewer 1:

Comment 1

The result that the scenario is not important for the uncertainty of the projections of damages is quite surprising, and as the authors point out, is not consistent with previous studies. The model variability is the largest uncertainty here. However, the use of multi-model ensembles is good because the multi-model mean will give a better representation of observations than any one realisation (e.g. IPCC 2007). There is of course a lot of uncertainty between the models, and this may be larger than the difference shown by using different SSPs. But, given the multi-model mean, it would be very informative to know the variation between the different scenarios. This is especially true given the larger changes in the storm tracks projected for higher emissions scenario (e.g. Priestley and Catto 2022). It would be good if the authors could give more information about and interpretation of this result.

Answer: *We thank the referee for this suggestion, and we share the referee's opinion that a more careful study of the effect of considering different future climate scenario can be insightful. Consequently, we investigate the sensitivity of the results to the future climate scenario by studying both the multi-model distribution at a regional level, and the damage maps of the multi-model median of the future change in Average Annual Damage computed over 14 climate models using SSP126, SSP245, and SSP370, and SSP585. We find our results to be partly sensitive to the choice of the climate scenario, despite the strong model uncertainty. We find this additional analysis to be a valuable complement to our study, and hence incorporated it in the body of the manuscript as new sub-subsection of the results section, entitled "Sensitivity to the future climate scenario". The new section can be found in the manuscript at lines 447-477 and is reproduced below as well as the additional figures (Fig. R 2 and Fig. R 3).*

(Lines 447-477 in the revised manuscript): In addition, we investigate the sensitivity of the results to the future climate scenario by showing the regional boxplots of the multi-model distributions (Fig. R 2) and the damage maps of the multi-model median (Fig. R 3) of the Delta Climate change in average annual damage computed over 14 climate models using SSP126, SSP245, and SSP370, and SSP585. The regional boxplots show that the multi-model distributions are partly sensitive to the future climate scenario in certain regions, as the multi-model distributions derived with scenarios corresponding to stronger future warming (SSP245, SSP370, SSP585) are shifted towards less negative changes in the average annual damage when compared with a scenario of lower future warming (SSP126). This sensitivity to the future climate scenario is visible in four out of the seven regions of the domain (British Isles, Western Europe, Central Europe, and Scandinavia), and for the projections aggregated to the entire domain. In regions where the ensemble of climate models agrees well on a negative future change in the average annual damage (Iberian Peninsula, Mediterranean, and Eastern Europe), there is no marked difference between the different future climate scenarios, except in the Eastern Europe region, where projections obtained using SSP585 are associated with a multi-model distribution indicating less negative future changes. For the projections aggregated over the entire domain, the multi-model distributions gradually shift towards more positive Delta Climate changes in average annual damage, as future climate scenarios corresponding to higher warming are considered. However, this sensitivity to the warming level is less clear when investigating results at a regional level.

Using the damage maps (Fig. R 3), we find the SSP126 scenario to be associated with a marked decrease in storm damage over the entire domain, and a signal for increased future-climate storm damage to emerge as scenarios of higher warming are considered (SSP245, SSP370, SSP585). Our results thus indicate that Delta Climate changes in storm damage partly scale to the future change in temperatures, where more moderate increases in temperature could result in larger decreases in storm damage over Europe. This increase in the damages for future climate scenario of higher warming is consistent with previous studies suggesting an increased number of cyclonic bombs over the British Isles and Western Europe for scenarios of high global warming (e.g. Zappa et al., 2013; Priestley and Catto, 2022). However, we note that the influence of using different future climate scenarios is still limited when compared to the influence of the choice of the climate model used, as is highlighted in our sensitivity analysis (Sect. 3.1). Furthermore, we see some differences between the regional patterns of changes obtained with this set of 14 climate models, and the patterns of changes obtained with the full ensemble of 30 climate models. In particular, the multi-model median computed using 30 climate models indicates stronger regional increases in the damages, and further highlights the choice of the climate model to be the major contributor to the uncertainty in the projections. In this case, some of the climate models projecting the stronger increases in the future damages are missed when the analysis is restricted to this set of 14 climate models.

Comment 2

Line 140: Could the area threshold of 15000km2 be spread over wide regions? Or is there some criterion that says this is a contiguous area? I'm wondering if winds from multiple different storm features could be combined together.

Answer: *First, we would like to mention that the previous threshold area of 15000km2 is a typo, as the actual area threshold used for this study is 150000km2, consistently with Kruschke (2014). Secondly, different storm features at separate geographical locations can indeed be combined to trigger the detection of a storm day as no criterion on the clustering of the storm grid cells was defined. Hence, a storm day is detected as soon as the total area of the different grid cells that is identified as stormy at a particular day exceeds the threshold of 150000km2, regardless of the actual distance between the stormy grid cells. As we acknowledge that the previous formulation might lack of clarity, we incorporate this clarification in the manuscript:*

(Lines 140-142 in the revised manuscript): No clustering criterion is required on the stormy grid-cells to be included in the total stormy area required for a storm day. Hence, different wind features at separate geographical locations can be combined to evaluate whether or not the storm area ex-

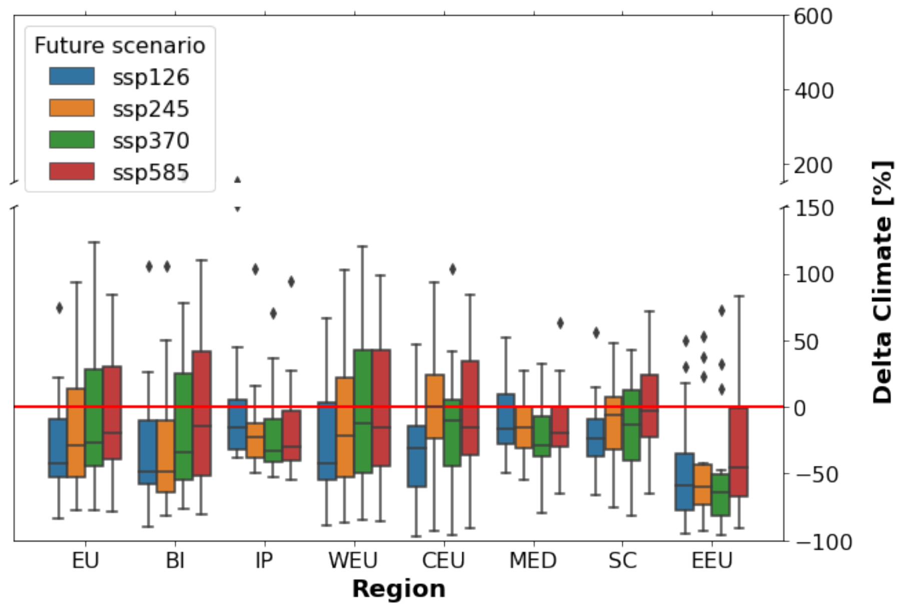

Figure R 2: Boxplots of the multi-model distributions of the regional changes in winter storm damage in Europe, comparing different future (2070-2100) climates to a historical period (1980-2010). The boxplots show the multi-model distributions of the future-minus-historical changes relative to the historical period (Delta Climate; %) in Average Annual Damage (AAD), aggregated over all exposure points in each of the seven regions defined in Fig. 2: British Isles (BI), Iberian Peninsula (IP), Western Europe (WEU), Central Europe (CEU), Mediterranean and Balkan region (MED), Scandinavia (SC), Eastern Europe (EEU), and over the entire European domain (EU), and using four different shared socio-economic pathways (SSP126, SSP245, SSP370, SSP585) to model the future climate. The boxplots' colored boxes represent the 25th and 75th percentile range (inter-quartile range) of the distributions, and the black lines inside the boxes represent the medians. The boxplot whiskers are drawn at distances of 1.5 times the inter-quartile range (IQR) below and above the 25th and 75th percentiles of the distributions or at the minimum and maximum data points when those points fall at a distance of less than 1.5 times the IQR. The diamonds represent outlying data points outside the whiskers. The red line represents the 0-% change line, which corresponds to no change in the future damages with respect to their historical value.

ceeds the minimum threshold to count as a storm day in Europe. A value of 150000 km2 is chosen for A_{min}, which is representative of the typical area of the wind footprint of an extratropical storm (Kruschke, 2014).

Comment 3

The exposure data is interesting, but I'm curious to know how this compares to a simple population density.

Answer: *Thank you for the interesting comment. In general, the distributions of population and asset distributions can vary substantially, and thus the impact distribution would probably also look*

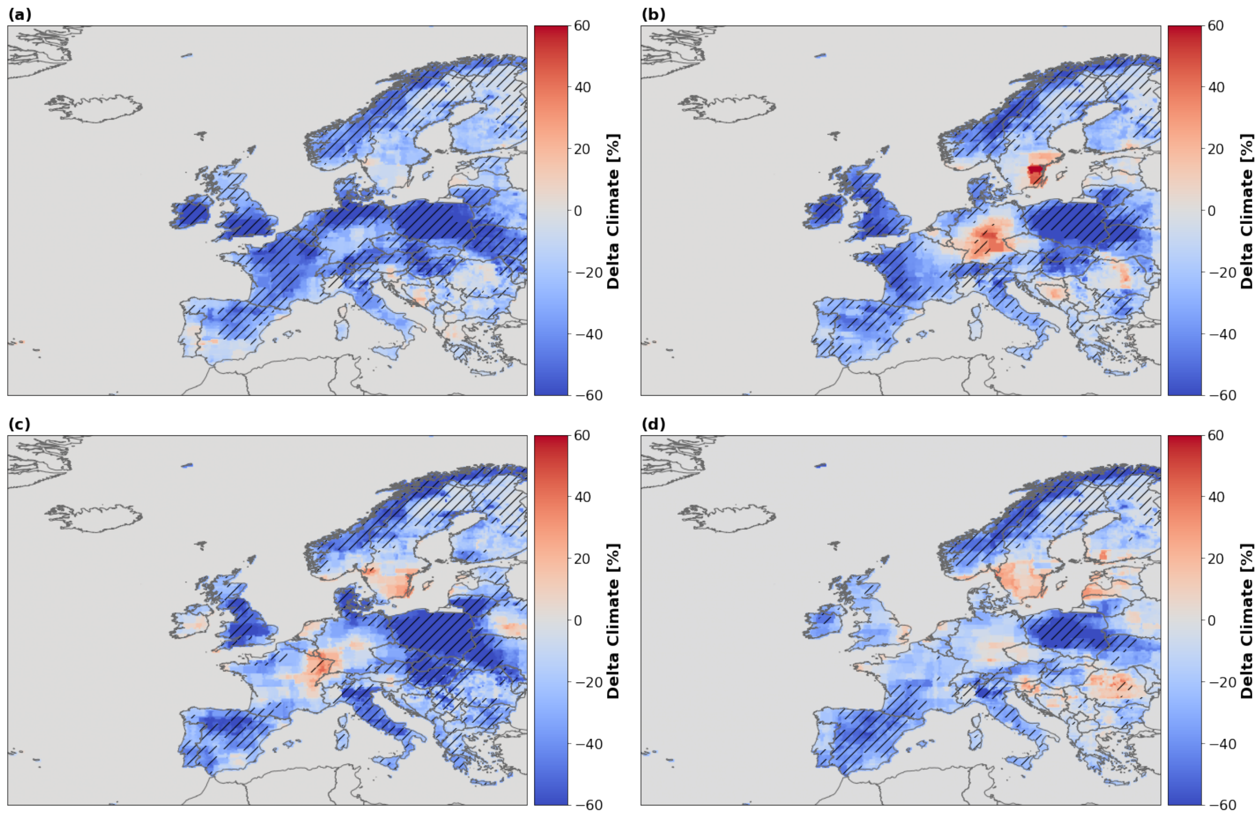

Figure R 3: Regional changes in winter storm damage in Europe, comparing different future (2070-2100) climates to a historical period (1980-2010). Panels **(a), (b), (c),** and **(d)** show spatial maps of the multi-model median of the future-minus-historical change relative to the historical period (Delta Climate; %) in average annual damage, computed at each exposure point and using four different shared socio-economic pathways (SSP126: panel (a), SSP245: panel (b), SSP370: panel (c), SSP585: panel (d)) to model the future climate. The hatching represents regions where more than 75% of the GCMs agree on the sign of the change in average annual damage.

different. It would be interesting to not only study the damages to physical assets but also the number of affected people, however, this is beyond the scope of this manuscript.

Comment 4

Lines 488-490: I wonder if the dynamical downscaling would actually reduce biases. Surely this depends on the large-scale/lower-resolution input? Unless the pattern is correct, but it's only the intensity that is misrepresented.

Answer: *We agree with this comment. What we meant is that dynamical downscaling could be a beneficial addition, especially when investigating damage projections over complex topography. We hence updated the corresponding section in the manuscript as indicated below:*

(Lines 488-490 in the previous version of the manuscript): Using a dynamical downscaling approach should improve the biases in the representation of extreme surface winds, especially over regions with complex topography, and allow to obtain more accurate and spatially refined estimates of the future changes in extreme winds and damages.

(Lines 584-588 in the revised manuscript): Using a dynamical downscaling approach should improve the representation of extreme surface winds over regions with complex topography, and allow to obtain more accurate and spatially refined estimates of the future changes in extreme winds and wind damages.

References

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