nature portfolio

Peer Review File

Winter stratospheric extreme events impact European storm damage

Corresponding Author: Dr Hilla Afargan-Gerstman

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Version 0:

Decision Letter:

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Dear Dr Afargan-Gerstman,

Your manuscript titled "Stratospheric extreme events impact European storm damage" has now been seen by 3 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication. The revised manuscript must address the robustness and statistical significance of the results by analyzing longer datasets and using various datasets to demonstrate that the signals are statistically significant and are robust to cross-dataset differences.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

Please submit your point-by-point responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and the completed checklist:
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We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

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Communications Earth & Environment

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Alireza Bahadori, PhD
Associate Editor
Communications Earth & Environment

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Please refer to our data policies at http://www.nature.com/authors/policies/availability.html.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

This manuscript investigates the relationship between extreme stratospheric polar vortex events and storm damage in

Europe. Using composite analysis, the authors start by investigating the well-known relationship between strong and weak polar vortex events and storm frequency, precipitation, and surface wind anomalies using 23 years of ERA5 data. Subsequently, the authors investigate the variability of the surface response over selected areas.
The authors continue the analysis by examining the impacts associated with storm and flood events within a period of 28 days following the stratospheric "extreme events." To this end, the authors utilized the EM-DAT and HANZE datasets. The authors find an increase in storm-related impacts over Northern Europe, Scandinavia, and the UK following strong vortex events compared to SSWs. The study builds on well-established relationships between stratospheric and tropospheric variability during the winter season. Its novelty lies in providing a quantitative and regionalized description of storm and flood damage following extreme (weak and strong) vortex events.

Major comments

The authors do not explain why they limited their analysis to the 2000-2023 period when both ERA5 and EM-DAT datasets extend further back in time. Extending the analysis period could enhance the robustness of the relationships found in this study. Furthermore, a longer dataset might reveal whether the relationship is modulated over longer timescales by other potential drivers, such as North Atlantic SSTs.

Minor comments

1. The authors refer to the "Annular Oscillation (AO) in the troposphere." Although I do not see any problem with this terminology, "Arctic Oscillation" or "Northern Annular Mode" are more commonly used in the literature and may be preferable for clarity.

2. The sentence, "It can be seen that SSW events are associated with in northern Europe compared to the same region following strong vortex events," contains an error and should be revised for clarity and grammar.

Reviewer #2 (Remarks to the Author):

I attached the comments for Authors in a separate PDF file.

Reviewer #3 (Remarks to the Author):

Review of "Stratospheric extreme events impact European storm damage" by Afargan-Gerstman and Domeisen

The paper addresses an important outstanding issue: how are extreme stratospheric states translate to surface high-impact weather, all the way to realized disasters and economic damage. While the influence of stratospheric states on the occurrence of extratropical cyclones has been studied before, here the authors aim to systematically establish a link directly to the damage caused by these storm, using two impact datasets for Europe. The aim is indeed important for understanding the predictability of storm-related disasters on subseasonal-to-seasonal timescales, and potentially also in a future climate. The methodology is novel in its combination of the damage datasets with established ERA5 reanalysis diagnostics for 1998-2023. I therefore find the study highly valuable.
However, there are a number of critical aspects that the authors should consider before the paper can be reconsidered for publication. I detail these in general below, and with more specific examples later on.

General comments:

1. Statistical significance of the resulting anomalies. The limited number of years and the low number of extreme stratospheric states raises a key concern with regard to the statistical significance of the results presented in all figures. Some hatching is shown in the first figure, but never explained or discussed. Specifically, are the anomalies in Fig. 2 significant compared to climatology? The climatological distribution should be added to Fig. 2 for reference. In Figure 3 it is also unclear how anomalous the results are compared to a random chance of obtaining the numbers for any 19 or 23 28-day periods in winter. Thus, the figure should have this information and show how different are the results from a random sampling (akin to a bootstrap significance test). For example, for SSW, the relevant 19 months following SSWs comprise 15% of all 130 months in the analysis (winter months of 1998-2023). This is indeed the fraction of storm events in Europe (line 231), suggesting that SSWs do not significantly influence storm counts overall – but perhaps regional differences are still significant. Therefore, this information is critical to evaluate and interpret the overall stratospheric impact. Similarly for floods: do the low fractions noted in lines 239-240 suggest that following extreme stratospheric states there is reduced chance for floods altogether (compared to climatology)? The same arguments apply also the analysis of disaster damage, comparing stratospheric events with climatology in Fig. 4, and to data shown in Figs. 5 and 6. Naturally, the abstract, results and discussion/conclusions sections should reflect this key information.

2. There is missing motivation for the regional analysis of the current study given that stratospheric events are defined using a zonal mean. Do you find anomalies over the Pacific storm track?

3. There are many uncareful and over-statements throughout the text, which should be avoided. I highlight some in the specific comments.

4. Fig. 2: the choice of boxes is not explained. It can be more meaningful to choose a set definition of boxes and quantify the changes of all variables in the same boxes. Perhaps even by country, to be able to relate these to the results in the following figures.

5. Storm track and impact in the Mediterranean: the text mostly describes the Atlantic storm track, but large impact anomalies are also seen in the Mediterranean, which are likely related to the response of local Mediterranean cyclones. The authors should refer to changes in Mediterranean storms/cyclones more directly, taking into account the recent surge in studies connecting Mediterranean cyclones to surface hazards (including compounds).

6. Appendix B: the results from this check should be communicated into Fig. 4 (e.g., masking out of countries with insufficient data), so that more reliable conclusions can be drawn. It is currently unclear if the lack of data is the reason for discrepancies across datasets or countries.

Specific comments:

7. Line 75: seems unclear why have one subsection title in the middle of the Introduction section.

8. Lines 76-80 seem to largely repeat the previous paragraphs and could be deleted.

9. Line 84 "extreme stratospheric variability": elaborate which extreme variability occurred. Later in the paragraph it is mentioned that a major SSW occurred in February, but I was left wondering what occurred earlier that winter, especially considering the long timescale for which impact can be expected (line 65).

10. Line 95 "anomalously cold surface temperatures and precipitation anomalies": are these caused by individual extreme storms or do they occur on longer/larger scales?

11. Line 132: why only until 2020 when other datasets are analyzed until 2023?

12. Lines 136-137: it is unclear if the conditioning by an extratropical cyclone is imposed by the analysis in this study, or already built in the dataset.

13. Line 149: explain what final warming events are for readers not familiar with stratospheric regimes.

14. Fig. 1 / Methods: are the anomalies of the precipitation and wind normalized? The Methods text implies that they should have units. Please clarify.

15. Fig. 1 / Methods: It is not mentioned what the dots represent and if/how statistical significance is computed.

16. Fig. 1 caption: I assume the shadings are the anomalies and the black contours the climatology? Need to clarify in the caption, with units.

17. Line 174: why only the zonal component (also this is not mentioned in the caption)? For damage the total 10-m wind speed is more meaningful, and taking only the zonal component can introduce biases.

18. Line 178: unclear which zonal gradient is referred to. There seems to be a more complex structure in the domain, which partially follows the cyclone anomaly and precipitation patterns. Actually, a more clear zonal gradient is found for the more relaxed criteria in Appendix A.

19. Lines 180-181: these definitions come as a surprise. The sensitivity test can be mentioned and motivated already in the Methods section.

20. Fig. 2 caption and text: clarify units/normalization of the anomalies.

21. Fig. 2: are the data showing the variability across stratospheric events (i.e., box averages), or do they include the variability across all grid points too? which percentiles do the box whiskers mark? Are the anomalies significant compared to climatology? (see also major comment).

22. Line 195 "tend to increase" – although this is true along the coastline, the median is ~0, so not so much.

23. Line 197 "remains unchanged": rather, there seems to be a clear divide between northwestern and southeastern Mediterranean, which compensate each other.

24. Line 197 "larger variability", unclear which variability the authors refer to? The variability as shown in Fig. 2d for north-central Europe is larger than that of the Mediterranean.

25. Line 205: there is less agreement for winds, showing an opposite response for winds, i.e., negative anomalies following strong vortex in the Atlantic.

26. Line 211: add "potentially" before "enhanced"

27. Lines 212-213 "In particular, the downward influence of the stratosphere poses a higher risk of damage over Europe": this sentence is unclear and repeats the previous one – higher risk compared to what?

28. Line 218: replace "with respect to" by "following".

29. Lines 218-220: no need to repeat the selection of cases if they are the same as for Figs 1 and 2.

30. Fig. 3 caption: correct caption and panel references to account for the 6 panels (also correct the reference to specific panels from the main text), replace "i.e." by "e.g."

31. Fig. 3: is the white color always indicating a low value (according to the colorbar) or also countries with no data?

32. Fig. 3 and text: could you explain how 236 storms are not seen in the total count in Fig. 3a, especially given that some storms are counted more than once? Similarly also for the 182 floods and Fig. 3d.

33. Line 227: associated with what?

34. Lines 229-230 "as we have shown…" – actually this is not very consistent. Take France, where more storm counts are clearly shown under strong vortex events compared to SSW (Fig. 3), while the opposite is seen in Fig. 1. Need to evaluate the two datasets more critically, and provide detail on the method for storm counts in the EM-DAT dataset.

35. Fig. 4 caption: I do not understand what is " '00 millions"

36. Does storm damage in Fig. 4 refer only to damage from winds? Please clarify.

37. Lines 277-278 "We show that such disasters tend to occur within a close time frame of a few weeks following the stratospheric events". Be more accurate with regard to what the results indicate: 28 days instead of a few weeks, 'tend to occur' – with higher probability? Compared to what? In response to both SSWs and strong vortex? All kinds of disasters? This sentence is too vague and general and in the end misleading.

38. Lines 284-285: also here the statement is not careful enough. There is large variability among different countries and datasets. The cyclone frequency, disasters and damages across datasets show a more complex picture and this is the place to discuss this. After all, this is the novelty of this work, compared to more simply aligning with previous research with such a general statement.

39. Lines 298-300 " Here, we have shown that changes in the storm track are associated with regional changes in precipitation and surface wind patterns, resulting in a distinct geographical distribution of the impacts following weak or strong vortex forcing". Again, this is a too general and vague statement, which, for specific countries is not true, as they are sensitive to the dataset used. How much of this variability is statistically significant?

40. Lines 305-306: so given Appendix B, which countries are then underestimated and what does it mean for your overall results? The concluding sentence in line 308 is then too strong and misleading, as different datasets show large differences.

Typos and technical corrections:

41. Line 65: add "timescales" after "seasonal"
42. Line 100: "be" -> "been"
43. Line 104: add "by" after "characterized"
44. Line 151: "dates" -> "days"

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Version 1:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Dr Afargan-Gerstman,

Your revised manuscript titled "Stratospheric extreme events impact European storm damage" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment, provided you include a robust assessment of the significance of the "impacts" compared to climatology, and tone down your arguments and conclusions in order to ensure they are fully supported by the presented results, along the lines recommended by our reviewer 3.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewer 3. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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Please review our specific editorial comments and requests regarding your manuscript in the attached "Editorial Requests Table".

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

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Alireza Bahadori, PhD
Associate Editor
Communications Earth & Environment
Consulting Editor
Communications Sustainability

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The authors have incorporated a new dataset and extended their analysis by five years. While this additional period does not significantly enhance the confidence in the results, I acknowledge the authors' point that storm reports become increasingly inconsistent further back in time, and maintaining consistency is crucial for this study. Given these considerations, I recommend the article for publication.

Reviewer #2 (Remarks to the Author):

I accept the changes made.

Reviewer #3 (Remarks to the Author):

2nd review of "Stratospheric extreme events impact European storm damage"

The revised version is much improved following the additional statistical analyses, refinement of datasets and text. Still, not all my concerned were addressed fully, and critical points remain, which I detail more specifically below. Essentially, as the study has statistical methodological approach, rather than mechanistic, it is still unclear for major parts of the results how significant they are compared to climatology. While reanalysis-based cyclone and hazard results are significant, the innovation here is to add more direct impact datasets. However, these are not heavily analyzed for significance compared to climatology. Second, there are still many statements which oversell the results, making them too general and robust, which is not supported by the findings.

Specific comments:

- The introduction ends with the conclusive statement "These patterns are found to be associated with increased damage over Europe and a co-occurrence of precipitation and wind extremes in northwestern Europe and Scandinavia". However, the results are more subtle and region dependent, show contrasting results according to the dataset chosen, and not significant throughout. The statement should be toned down or elaborated.
- Lines 250-252: this is an overstatement, as some regions show contrasting results, e.g., Germany.
- Lines 274-275: "SSW events, on the other hand, are found to be associated with enhanced storm impacts over central and southwestern Europe". In fact, I am not yet convinced. The spatial variability when comparing SSW/strong vortex events is clear, but the significance of having enhanced storm damage following SSWs is not shown, especially when contrasted to climatology – meaning, what is the random probability of having such impact during any 19 months in the climatological period, and is it significantly different? If it is not, then key point #2 is not a major findings. In other words, are the results in Figs. 3-5a,b significant? Or only some of the differences in their panel c?
- Line 275: "as well as storm genesis regions" – this is not shown here, either delete or add a reference to support it.
- Overall, the results are contrasting in terms of storm counts Vs. storm footprints. The first shows reduction over most of Europe during SSW compared to strong vortex, and the second shows enhancement. The damage data show a mixed response. The only agreement is found for Scandinavia. This major contrasting finding is not even discussed, but rather smoothed out with too vague text. In the text, only data availability is mentioned as a limitation, but it is unclear if this is the only reason for any discrepancies in the results, which are not discussed. Relevant aspects such as the influence of storm frequency Vs. intensity are not analyzed or discussed. The concluding sentence in lines 299-300 ("Overall, this analysis indicates that a similar response pattern is found in both datasets following SSW and strong vortex events, supporting the conclusions from the EM-DAT dataset") is therefore not true and even the opposite is the case for most of Europe. Unless there is something I missed, this is a major outstanding issue with the revised manuscript.

Additional comments:

- Line 149 and throughout the text: Events identified above the 20% threshold should not be termed "extreme", but rather moderate strong/weak events, to avoid confusion with the more extreme events as described above.
- Data and Methods section: there is no description of the methodological approach taken to statistically examine the relationship between stratospheric states and surface impacts, and to quantify the significance. Also, justify the usage of the 30-day window following stratospheric anomalies, which appears for the first time in the caption of Fig. 1.
- Figs. 1 and 2: the units of precipitation is likely not meters but mm/day? Actually, the accumulation time is not noted in subsection 2.1.
- Lines 206-207: this sentence is out of context and can be deleted.

- Lines 221-224: this paragraph fits better before the previous one, to first start with the climatological count, and later describe the subset that follows stratospheric events.
- Compound hazards: this fits better in the Result section rather than in the Discussion and Conclusions.

Technical corrections:

Line 28: put reference in parentheses
Line 129: unclear what CDS refers to
Line 160: delete “cyclone frequency” and second “frequency”
Line 176: delete “a”
Line 179: “summarize” seems more appropriate than “evaluate”
Line 228: correct the sentence around “are is”

This paper investigates the connection between extreme stratospheric events and their associated impacts on precipitation and wind speeds caused by extratropical storms making landfall in Europe. The study goes further by quantifying these impacts in terms of economic losses. By integrating both climate and impact datasets, the authors found that strong vortex events are more frequently followed by storm disasters compared to sudden stratospheric warmings, particularly in the UK and northern Europe.

The paper is well-structured, with clear and informative graphics that enhance understanding. I enjoyed reading it, as it addresses a highly relevant and timely topic; linking meteorological extremes to tangible societal impacts. I have some concerns and suggestions:

General Comments:

1. Robustness of impacts results. A major limitation in impact studies, including this one, is the scarcity and variability of reliable datasets for economic loss records. While the authors focus on impact datasets, they rely on just two sources. Although the results from these datasets show some level of consistency, their robustness remains unclear. Notably, the spatial patterns in Figures 4/5 seem to mirror the data scarcity shown in Figure A3/A4. Could the authors incorporate additional datasets, such as those used in [Moemken et al., 1]? This would strengthen the reliability of their findings. If not, I believe stronger clarification on such a caveat is needed specially in the abstract.
2. Limited number of extreme stratospheric events. The analysis is restricted to the period from 2000 to the present. However, EM-DAT includes data extending back to 1900. Expanding the study period to include earlier years could improve the robustness of the findings. In addition; why are you using impacts data from 1998 to 2020 and meteorological data from 2000 to 2023? (please check the description of datasets)
3. How sensitive are the boxplots in Figure 2 to the domain selection? The choice of varying domains for different variables needs to be explained. In addition, how sensitive are those boxplots with respect to the number of SSW and Strong Vortex? Some anomalies appear quite small yet are discussed in the text (e.g., line 196 shows a median of 0.2, but considering more events, as in Figure A2, the median is negative and larger). Consider using a bootstrap test or similar statistical test.

Line-to-line Comments:

1. The authors should clarify what are the dots in Figure 1. If these denote the results of a statistical test, as seems likely, which was the test used?

2. How have the economic losses been adjusted to reflect 2023 values? (Figure 4).
3. The authors use the terms "meteorological hazards" and "impacts" interchangeably (e.g. line 164, line 185), which leads to some confusion. For example, precipitation and wind speed are sometimes referred to as impacts, but I believe these should be categorized as meteorological hazards. Differentiating between meteorological hazards and impacts would improve the clarity and precision of the text.
4. Line 30: where? In general or in certain European regions?
5. Line 57; how is the first sentence different from the previous two paragraphs?
6. Line 100—101: rephrase ("that have be associated")
7. In Section 2.2 and throughout, it is unclear whether storm impacts include both extreme wind and rainfall/snow/hail or only wind (because flooding is treated separately). If only wind is considered, this should be explicitly clarified.
8. Line 145: Add obtained with ERA5 reanalysis
9. Line 153. December or November?
10. Lines 166—168. Section 3.1 is the actual section; is this paragraph misplaced?
11. Line 177. Is the decrease in the North Atlantic, or decrease in southern Europe and a dipole in the North Atlantic?
12. Figure 3. The caption should be rewritten as it appears the letters have been mixed up.
13. Figure 4. "'00" ?
14. Figure 6. Those are only the events that are common in both datasets?
15. Out of curiosity, were the storms in the impact databases explicitly named and categorized (e.g., well-known storms)?

[1] Moemken, Julia, Gabriele Messori, and Joaquim G. Pinto. "Windstorm losses in Europe–What to gain from damage datasets." *Weather and Climate Extremes* 44 (2024): 100661.

Reply to Reviewers: Stratospheric extreme events impact European storm damage

March 16, 2025

Dear Editor,

We would like to thank all three 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.

All changes have been included into the manuscript and are indicated **in bold** in the annotated manuscript. The main changes to the manuscript include:

- We have added extended statistical significance tests of the results (e.g., Figures 3, 4 and 5).
- We now focus on establishing the connection between stratospheric variability and storm impacts, and thus removed the part concerning flood impact.
- We have added a new analysis of storm footprint
- We included an additional dataset (Copernicus Winter windstorm indicators for Europe).

1 Reviewer 1:

This manuscript investigates the relationship between extreme stratospheric polar vortex events and storm damage in Europe. Using composite analysis, the authors start by investigating the well-known relationship between strong and weak polar vortex events and storm frequency, precipitation, and surface wind anomalies using 23 years of ERA5 data. Subsequently, the authors investigate the variability of the surface response over selected areas. The authors continue the analysis by examining the impacts associated with storm and flood events within a period of 28 days following the stratospheric "extreme events." To this end, the authors utilized the EM-DAT and HANZE datasets. The authors find an increase in storm-related impacts over Northern Europe, Scandinavia, and the UK following strong vortex events compared to SSWs. The study builds on well-established relationships between stratospheric and tropospheric variability during the winter season. Its novelty lies in providing a quantitative and regionalized description of storm and flood damage following extreme (weak and strong) vortex events.

1.1 Major comments

The authors do not explain why they limited their analysis to the 2000-2023 period when both ERA5 and EM-DAT datasets extend further back in time. Extending the analysis period could enhance the robustness of the relationships found in this study. Furthermore, a longer dataset might reveal whether the relationship is modulated over longer timescales by other potential drivers, such as North Atlantic SSTs.
We thank the reviewer for their helpful comments. Following the reviewer's comments, we have added another dataset to the analysis. We have adjusted the study period to 1998-2023, during which data from Copernicus, as well as from the EM-DAT database, were available. While it is possible to technically go back to data starting in 1979, Moemken et al. (2024) also focuses on the period October 1999 to March 2022. Even for this period, Moemken et al. (2024) finds that the datasets often disagree on individual storm reports, as well as on storm frequency per winter season. Therefore, we have preferred to focus in this study on shorter period that allows a more careful examination of individual storm events and their impact across datasets, thus ensuring greater reliability.
Regarding the investigation of additional large-scale precursors, while examining the relationship with other potential drivers, such as North Atlantic SSTs, can be useful for understanding the main drivers of storm impacts over Europe, this will require an extensive analysis which is beyond the scope of this paper. Such extensive study would probably exceed the length limitation of the journal. In addition, previous studies have demonstrated the inter-event variability of extreme stratospheric events (e.g., Afargan-Gerstman and Domeisen, 2020). Thus, understanding and quantifying the downward coupling between the tropospheric circulation and the stratosphere requires careful attention on its own, and therefore is the focus of this manuscript.

1.2 Minor comments

1. The authors refer to the "Annular Oscillation (AO) in the troposphere." Although I do not see any problem with this terminology, "Arctic Oscillation" or "Northern Annular Mode" are more commonly used in the literature and may be preferable for clarity.
We have revised the Introduction and removed the sentence concerning the Northern Annular Mode as this terminology is less relevant for the focus of the paper (for instance, more focus has been given to the NAO).

2. The sentence, "It can be seen that SSW events are associated with in northern Europe compared to the same region following strong vortex events," contains an error and should be revised for clarity and grammar.
We have removed this sentence.

2 Reviewer 2:

This paper investigates the connection between extreme stratospheric events and their associated impacts on precipitation and wind speeds caused by extratropical storms making landfall in Europe. The study goes further by quantifying these impacts in terms of economic losses. By integrating both climate and impact datasets, the authors found that strong vortex events are more frequently followed by storm disasters compared to sudden stratospheric warmings, particularly in the UK and northern Europe. The paper is well-structured, with clear and informative graphics that enhance understanding. I enjoyed reading it, as it addresses a highly relevant and timely topic; linking meteorological extremes to tangible societal impacts. I have some concerns and suggestions:

2.1 General Comments:

1. Robustness of impacts results. A major limitation in impact studies, including this one, is the scarcity and variability of reliable datasets for economic loss records. While the authors focus on impact datasets, they rely on just two sources. Although the results from these datasets show some level of consistency, their robustness remains unclear. Notably, the spatial patterns in Figures 4/5 seem to mirror the data scarcity shown in Figure A3/A4. Could the authors incorporate additional datasets, such as those used in [Moemken et al., 1]? This would strengthen the reliability of their findings. If not, I believe stronger clarification on such a caveat is needed specially in the abstract.

First, as noted by the reviewer, the spatial patterns in Figures 4-5 seem to mirror the data scarcity shown in Figure A3-A4. This is not by chance. The data availability map shows only for countries that were used in the preparation of Fig. 3-4. Therefore, the Appendix figures mirror the same map as in Figures 3-4 but shows different values (the availability percentage). We added a sentence in the caption to clarify this.
Moemken et al. provides a comparison of reported and estimated windstorm losses from five datasets belonging to three categories: Indices combining meteorological and insurance aspects, natural hazard databases, and loss reports from insurance companies.
To overcome the scarcity and variability of reliable datasets for economic loss records, we included analysis from an additional dataset in the revised manuscript - the Copernicus Winter windstorm indicators for Europe derived from reanalysis.

2. Limited number of extreme stratospheric events. The analysis is restricted to the period from 2000 to the present. However, EM-DAT includes data extending back to 1900. Expanding the study period to include earlier years could improve the robustness of the findings. In addition; why are you using impacts data from 1998 to 2020 and meteorological data from 2000 to 2023? (please check the description of datasets)

Although EM-DAT provides data back to the year 1900, records on weather-related impacts from that period are not expected to be as reliable as records from recent decade. In addition, to stay consistent with recent windstorm datasets' comparisons, such as Moemken et al. 2024, we have adjusted the study period to 1998 to 2023. Additional datasets, such as Copernicus European windstorms footprint and loss indicators - now included in this manuscript - cover this period as well. While it is possible to technically go back to data starting in 1979, Moemken et al. also focuses on the period October 1999 to March 2022 (to match with the impact datasets, like the Perils Insurance dataset).

In addition, even for this period, Moemken et al. (2024) finds that the datasets often disagree on individual storm reports, as well as on storm frequency per winter season. For example, out of a total of 94 individual windstorms that were documented, only 11 storms were reported in all five datasets. This variability among datasets emphasizes the need to carefully examine and compare individual records in the datasets, which is more difficult to do for extended periods. Thus, we justify using the period 1998-2023 as it allows for a closer look at individual storm records and their connection to stratospheric events, thus minimizing potential errors.

3. How sensitive are the boxplots in Figure 2 to the domain selection? The choice of varying domains for different variables needs to be explained. In addition, how sensitive are those boxplots with respect to the number of SSW and Strong Vortex? Some anomalies appear quite small yet are discussed in the text (e.g.,line 196 shows a median of 0.2, but considering more events, as in Figure A2, the median is negative and larger). Consider using a bootstrap test or similar statistical test.

We have changed the domain selection for the boxplots in Fig.2. Instead of varying domains, we focus on European weather and climate, thus defining the boxes over northern and southern Europe, and analyze the corresponding anomalies for each region of interest. Additionally, to demonstrate the variability of the response to stratospheric forcing, we have added a bootstrap test as part of the statistical significance test in Fig.1 (and Fig.A1).

2.2 Line-to-line Comments:

1. The authors should clarify what are the dots in Figure 1. If these denote the results of a statistical test, as seems likely, which was the test used?

Hatching in Figure 1 indicates values that are statistically significant at a 95% confidence level, estimated for each country using Student's t-test.

2. How have the economic losses been adjusted to reflect 2023 values? (Figure 4).

The economic losses been adjusted for inflation using the Consumer Price Index of the year 2022. For more details, see Economic Adjustment section in the EM-DAT online documentation: https://doc.emdat.be/docs/protocols/economic-adjustment (last accessed: February, 23, 2025).

3. The authors use the terms "meteorological hazards" and "impacts" interchangeably (e.g. line 164, line 185), which leads to some confusion. For example, precipitation and wind speed are sometimes referred to as impacts, but I believe these should be categorized as meteorological hazards. Differentiating between meteorological hazards and impacts would improve the clarity and precision of the text.

We thank the reviewers for this comment. We have corrected the text to distinguish between meteorological hazards and impacts. Particularly, precipitation and wind speed are now categorized in the text as meteorological hazards.

4. Line 30: where? In general or in certain European regions?

Anthropogenic climate change has led to an intensification of weather-related extremes, including more frequent and more intense heat and precipitation extremes in many regions across the world. We have revised this sentence and add more relevant references.

5. Line 57; how is the first sentence different from the previous two paragraphs?

We have revised the Introduction section and merged these paragraphs to avoid repetition.

6. Line 100—101: rephrase ("that have be associated")

Corrected.

7. In Section 2.2 and throughout, it is unclear whether storm impacts include both extreme wind and rainfall/snow/hail or only wind (because flooding is treated separately). If only wind is considered, this should be explicitly clarified.

In the revised manuscript, we refer the extreme wind as storm impacts. The influence

of stratospheric events on precipitation in general is shown in Fig.1 (with precipitation data based on ERA5 reanalysis), however we do not directly evaluate the influence on precipitation-related impacts (e.g., extreme rainfall, snow, hail).

8. Line 145: Add obtained with ERA5 reanalysis

Corrected.

9. Line 153. December or November?

The wind speed threshold for strong vortex events is based on the period December to March, for consistency with previous studies in the field.

10. Lines 166—168. Section 3.1 is the actual section; is this paragraph misplaced?

Corrected.

11. Line 177. Is the decrease in the North Atlantic, or decrease in southern Europe and a dipole in the North Atlantic?

We have revised Figure 1, and removed the part about the dipole pattern.

12. Figure 3. The caption should be rewritten as it appears the letters have been mixed up.

We have corrected Figure 3 caption.

13. Figure 4. "'00" ?

We rephrased to "hundred millions".

14. Figure 6. Those are only the events that are common in both datasets?

The events shown in Fig.6 are based on a combination of records from both datasets, Thus, these events are not necessarily common in both datasets.

15. Out of curiosity, were the storms in the impact databases explicitly named and categorized (e.g., well-known storms)?

The majority of storms analyzed in this study are explicitly named and categorized storms, but not all of them. The full list of all storms that are reported in at least one datasets, including information on storm name, date and affected countries can be found in Moemken et al., 2024 (in the Supplementary material).

[1] Moemken, Julia, Gabriele Messori, and Joaquim G. Pinto. "Windstorm losses in Europe–What to gain from damage datasets." Weather and Climate Extremes 44 (2024): 100661.

3 Reviewer 3:

The paper addresses an important outstanding issue: how are extreme stratospheric states translate to surface high-impact weather, all the way to realized disasters and economic damage. While the influence of stratospheric states on the occurrence of extratropical cyclones has been studied before, here the authors aim to systematically establish a link directly to the damage caused by these storm, using two impact datasets for Europe. The aim is indeed important for understanding the predictability of storm-related disasters on subseasonal-to-seasonal timescales, and potentially also in a future climate. The methodology is novel in its combination of the damage datasets with established ERA5 reanalysis diagnostics for 1998-2023. I therefore find the study highly valuable. However, there are a number of critical aspects that the authors should consider before the paper can be reconsidered for publication. I detail these in general below, and with more specific examples later on.

3.1 General comments:

1. Statistical significance of the resulting anomalies. The limited number of years and the low number of extreme stratospheric states raises a key concern with regard to the statistical significance of the results presented in all figures. Some hatching is shown in the first figure, but never explained or discussed. Specifically, are the anomalies in Fig. 2 significant compared to climatology? The climatological distribution should be added to Fig. 2 for reference. In Figure 3 it is also unclear how anomalous the results are compared to a random chance of obtaining the numbers for any 19 or 23 28-day periods in winter. Thus, the figure should have this information and show how different are the results from a random sampling (akin to a bootstrap significance test). For example, for SSW, the relevant 19 months following SSWs comprise 15% of all 130 months in the analysis (winter months of 1998-2023). This is indeed the fraction of storm events in Europe (line 231), suggesting that SSWs do not significantly influence storm counts overall – but perhaps regional differences are still significant. Therefore, this information is critical to evaluate and interpret the overall stratospheric impact. Similarly for floods: do the low fractions noted in lines 239-240 suggest that following extreme stratospheric states there is reduced chance for floods altogether (compared to climatology)? The same arguments apply also the analysis of disaster damage, comparing stratospheric events with climatology in Fig. 4, and to data shown in Figs. 5 and 6. Naturally, the abstract, results and discussion/conclusions sections should reflect this key information.
We agree with the reviewer's perspective, suggesting that SSWs do not significantly influence storm counts overall – but affect the regional patterns with significant differences (Fig.3 and Fig.5). We have modified Figures 3 and 4 to show the difference in storm counts and storm damage between periods following SSWs and strong vortex events. Additionally, we have added Fig.5 showing the difference in storm footprint after stratospheric events, emphasizing that the main difference is significant along the SW-NE axis of European windstorms (using a bootstrap significance testing).

2. There is missing motivation for the regional analysis of the current study given that stratospheric events are defined using a zonal mean. Do you find anomalies over the Pacific storm track?
Despite its zonally-symmetric nature, the downward influence of stratospheric extremes is concentrated over the North Atlantic and Europe. This zonal asymmetry has been documented in the literature (Baldwin and Dunkerton, 2001; Butler et al., 2017). To clarify this important point in the text, we have included a sentence about it in the Introduction (Line 45).

3. There are many uncareful and over-statements throughout the text, which should be avoided. I highlight some in the specific comments.
We thank the reviewer for bringing this to our attention. We rephrased all the examples that are mentioned in the specific comments below, and revised our statements to be more careful and statistically robust.

4. Fig. 2: the choice of boxes is not explained. It can be more meaningful to choose a set definition of boxes and quantify the changes of all variables in the same boxes. Perhaps even by country, to be able to relate these to the results in the following figures.
We have revised the choice of boxes used in Fig.2, and now use boxes for southern and northern Europe for analysing the variability of precipitation and surface wind. For the cyclone frequency, we have the boxes are defined for the mid-latitude and high-latitude sectors of the North Atlantic. These boxes are centered around the areas with largest average anomalies of cyclone frequency for SSW events. We have added a clarification in the text (Line 175).

5. Storm track and impact in the Mediterranean: the text mostly describes the Atlantic storm track, but large impact anomalies are also seen in the Mediterranean, which are likely related to the response of local Mediterranean cyclones. The authors should refer to changes in Mediterranean storms/cyclones more directly, taking into account the recent surge in studies connecting Mediterranean cyclones to surface hazards (including compounds).
Indeed, while main focus of the study is the North Atlantic storm track (where the signature of stratospheric influence is considered to be the greatest), changes over the Mediterranean are particularly of interest. For this reason, we have included several references in the context of compound wind and precipitation hazards of the Mediterranean (see the Discussion). We also added modified the boxes in Figure 2 to distinguish souther Europe and the Mediterranean from the northern part of Europe, and added additional description of Mediterranean cyclone frequency, precipitation and surface wind anomalies in the text (e.g., from Line 160 and in Section 3.2).

6. Appendix B: the results from this check should be communicated into Fig. 4 (e.g., masking out of countries with insufficient data), so that more reliable conclusions can be drawn. It is currently unclear if the lack of data is the reason for discrepancies across datasets or countries.

To address the issue of statistical significance, we introduced a statistical test for the difference between SSWs and strong vortex events. While not all countries have a 100% coverage in terms of damage data availability per storm events (Figure A3), there is a relatively good coverage (for instance, above 40%) over most European countries. We have examined to what extent would the storm damage maps change for SSWs and strong vortex events if we take into account only countries with damage data percentage of 50% or higher (Fig. 1 below). We show that while some regions of storm impact are missing, the regional impact patterns over western and northern Europe (with the exception of France) are still clearly shown.

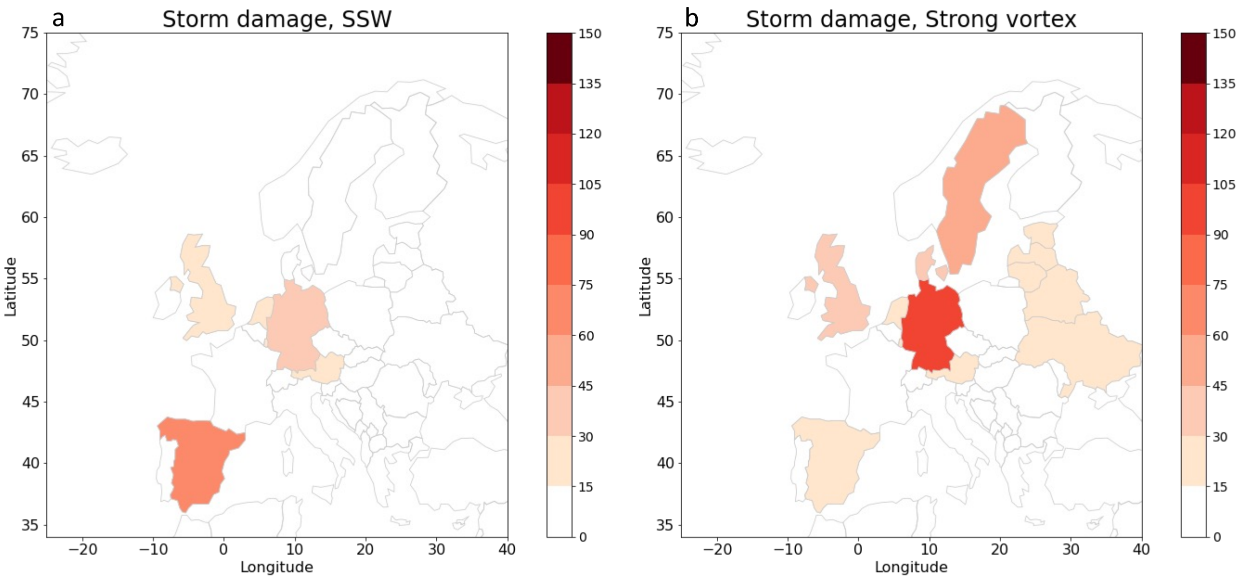

Figure R 1: Storm damage after (a) SSWs and (b) strong vortex events for countries with damage data percentage of 50% or higher.

3.2 Specific comments:

7. Line 75: seems unclear why have one subsection title in the middle of the Introduction section.

We have revised and shortened the Introduction section and removed the additional sub-title.

8. Lines 76-80 seem to largely repeat the previous paragraphs and could be deleted.

We have removed this paragraph and revised this part of the Introduction.

9. Line 84 "extreme stratospheric variability": elaborate which extreme variability occurred. Later in the paragraph it is mentioned that a major SSW occurred in February, but I was left wondering what occurred earlier that winter, especially considering the long timescale for which impact can be expected (line 65).

Sudden stratospheric warnings (SSWs) and strong vortex events represent the extreme states within a broad spectrum of polar stratospheric dynamic variability (Baldwin and Dunkerton, 2001). In the Northern Hemisphere, stratospheric variability peaks from January to March, with early winter extremes being possibly different in terms of their temporal evolution than late winter extremes. This paper primarily focuses on the 30-day period following SSWs and strong vortex states, which represent the weakest and strongest extremes of the polar vortex, respectively. During this period (and up to 60 days), stratospheric variability can influence stratosphere-troposphere coupling (Karpechko et al., 2017). Additionally, an analysis using a wide range of "extreme variability" definitions is further provided in Appendix A.

10. Line 95 "anomalously cold surface temperatures and precipitation anomalies": are these caused by individual extreme storms or do they occur on longer/larger scales?

We revised this paragraph and removed this sentence. Generally, anomalously cold surface temperatures and precipitation anomalies associated with a positive phase of the NAO/NAM are driven by changes in the large-scale atmospheric circulation, including changes to the storm track and their associated precipitation patterns.

11. Line 132: why only until 2020 when other datasets are analyzed until 2023?

We updated to the period between 1998 to 2023.

12. Lines 136-137: it is unclear if the conditioning by an extratropical cyclone is imposed by the analysis in this study, or already built in the dataset.

In the revised manuscript, we analyze disaster data from the EM-DAT and Copernicus datasets. For EM-DAT, we generally examine events classified as extratropical cyclones, but do no exclude winter storms and storms in general. For the Copernicus windstorm data, all events are identified as storms. We added this clarification to the manuscript (Line 210).

13. Line 149: explain what final warming events are for readers not familiar with stratospheric regimes.

We added a short explanation.

14. Fig. 1 / Methods: are the anomalies of the precipitation and wind normalized? The Meth-

ods text implies that they should have units. Please clarify.
The anomalies are not normalized (not unitless). We added unit information to the caption and throughout the manuscript.

15. Fig. 1 / Methods: It is not mentioned what the dots represent and if/how statistical significance is computed.
We added this information to the caption.

16. Fig. 1 caption: I assume the shadings are the anomalies and the black contours the climatology? Need to clarify in the caption, with units.
We added this information to the caption.

17. Line 174: why only the zonal component (also this is not mentioned in the caption)? For damage the total 10-m wind speed is more meaningful, and taking only the zonal component can introduce biases.
We agree. As suggested by the reviewer, we have revised this figure, and replaced the panels of the zonal wind component with the total 10-m wind speed (updated Figures 1-2 and A1-A2).

18. Line 178: unclear which zonal gradient is referred to. There seems to be a more complex structure in the domain, which partially follows the cyclone anomaly and precipitation patterns. Actually, a more clear zonal gradient is found for the more relaxed criteria in Appendix A.
We have modified this figure to show the surface wind speed at 10-m rather than the zonal component of the wind. As a result, we removed the sentence on the zonal gradient.

19. Lines 180-181: these definitions come as a surprise. The sensitivity test can be mentioned and motivated already in the Methods section.
We have moved these definitions (for weak and strong vortex states) to the Methods section, as suggested by the reviewer..

20. Fig. 2 caption and text: clarify units/normalization of the anomalies.
In the revised version, we clarify that anomalies are computed with respect to daily climatology (described in the Methods).

21. Fig. 2: are the data showing the variability across stratospheric events (i.e., box averages), or do they include the variability across all grid points too? which percentiles do the box whiskers mark? Are the anomalies significant compared to climatology? (see also major comment).
The boxes show the variability of spatially-averaged anomalies following stratospheric

events. The whiskers extend to the smallest and largest values within 1.5 times of the inter-quartile range (between the 25th and 75th percentiles) - we have added this information to the caption of Figure 2. To determine if the anomalies are significant, we would have to plot the anomalies over each box during NDJFM. Due to lack of space, we have not included this information in Figure 2, however, significance compared to climatology is shown in Figure 1: the hatching indicates the significance at the 95% level (computed per grid point).

22. Line 195 "tend to increase" – although this is true along the coastline, the median is 0, so not so much.
We have modified the boxes used for Figure 2, and focus on analyzing the variability of precipitation and surface wind anomalies over northern and southern Europe. Using the revised boxes, the median of precipitation values after SSW events is 0.3 m**. We have updated this information in the revised manuscript.**

23. Line 197 "remains unchanged": rather, there seems to be a clear divide between northwestern and southeastern Mediterranean, which compensate each other.
As discussed for the previous comment, we have modified the boxes used for Figure 2, focusing on atmospheric circulation changes over southern Europe and the Mediterranean (right panels in Figure 2) and northern Europe (left panels).

24. Line 197 "larger variability", unclear which variability the authors refer to? The variability as shown in Fig. 2d for north-central Europe is larger than that of the Mediterranean.
The box plots shown in Figure 2 demonstrate the variability of a variable by displaying its distribution, median and spread. Here, we refer to variability based on the range of the distribution. We have corrected this sentence (as the spread is indeed larger over northern Europe) and rephrased it.

25. Line 205: there is less agreement for winds, showing an opposite response for winds, i.e., negative anomalies following strong vortex in the Atlantic.
We rephrased this sentence and corrected it.

26. Line 211: add "potentially" before "enhanced"
Corrected.

27. Lines 212-213 "In particular, the downward influence of the stratosphere poses a higher risk of damage over Europe": this sentence is unclear and repeats the previous one – higher risk compared to what?
We have removed this sentence due to repetition.

28. Line 218: replace "with respect to" by "following".
Corrected.

29. Lines 218-220: no need to repeat the selection of cases if they are the same as for Figs 1 and 2.
Corrected.

30. Fig. 3 caption: correct caption and panel references to account for the 6 panels (also correct the reference to specific panels from the main text), replace "i.e." by "e.g."
We have corrected the caption accordingly.

31. Fig. 3: is the white color always indicating a low value (according to the colorbar) or also countries with no data?
Since the datasets used in this study are event-based, the white color in Figure 3a,b indicates both countries with no data and countries with no relevant records during the examined period. In the revised manuscript, we have an additional panel (Figure 3c) in which the white color indicates no data, and light grey color indicates low values (according to the colorbar). We have added this information to the manuscript (Figure 3 caption).

32. Fig. 3 and text: could you explain how 236 storms are not seen in the total count in Fig. 3a, especially given that some storms are counted more than once? Similarly also for the 182 floods and Fig. 3d.
We have revised Figure 3. The revised figure shows the total count of European storms per country during the extended winter season (November to March). In total, 205 counts have been recorded. Table 1 below shows the distribution of storm counts (as well as availability for damage information) by country.

33. Line 227: associated with what?
We rephrased this sentence.

34. Lines 229-230 "as we have shown..." – actually this is not very consistent. Take France, where more storm counts are clearly shown under strong vortex events compared to SSW (Fig. 3), while the opposite is seen in Fig. 1. Need to evaluate the two datasets more critically, and provide detail on the method for storm counts in the EM-DAT dataset.
The plots shown in Figure 1 and Figure 3 cannot be directly compared to each other, as storm frequency is indeed derived using different methods in Figures 1a,b and Figure 3. More specifically, storm counts in Figure 3 are defined based on the surface

impact of storms rather than the anomalous location of the low-pressure systems, as represented in Figure 1. Furthermore, the EM-DAT storm count is the number of times each country was affected by storms. These events are categorized in EM-DAT as 'extratropical cyclones', but some are 'severe weather' or 'winter storm', however they record events of storm impacts rather then the actual meteorological hazard. This distinction highlights the difference between cyclone occurrence and their associated impacts in countries, which we acknowledge and have now clarified in the manuscript.

35. Fig. 4 caption: I do not understand what is " '00 millions"
We rephrased to hundred millions.

36. Does storm damage in Fig. 4 refer only to damage from winds? Please clarify.
Generally, many windstorm damage indices are based on the cube of wind speed, however the storm damage depends on other factors, such as exposure of buildings to high wind speed. Additionally, insured losses depend on the insurance coverage in the specific region. Therefore, it is difficult to determine without additional information id the storm damage recorded in EM-DAT (which is based on a variety of sources including UN agencies, NGOs, World Bank, research institutes, insurance/reinsurance industry and news agencies) is only due to the wind.

37. Lines 277-278 "We show that such disasters tend to occur within a close time frame of a few weeks following the stratospheric events". Be more accurate with regard to what the results indicate: 28 days instead of a few weeks, 'tend to occur' – with higher probability? Compared to what? In response to both SSWs and strong vortex? All kinds of disasters? This sentence is too vague and general and in the end misleading.
This sentence is part of the "Discussion and conclusions" and therefore meant to be a more general statement. We have rephrased this sentence to be more specific. We have added an additional explanation: "While cyclone frequency tends to be higher over the midlatitude North Atlantic and Europe following SSW events, relative to strong vortex events (Fig.1, Fig.2), fewer European countries are found to be affected by storm-driven disasters under SSW conditions as compared to strong vortex events (Fig.3)".

38. Lines 284-285: also here the statement is not careful enough. There is large variability among different countries and datasets. The cyclone frequency, disasters and damages across datasets show a more complex picture and this is the place to discuss this. After all, this is the novelty of this work, compared to more simply aligning with previous research with such a general statement.

Indeed, this work highlights the large variability among different countries and datasets in their response to stratospheric forcing. We have added another paragraph to the Discussion to further clarify this complex relationship. Additionally, in the revised manuscript we have added an analysis of storm footprint based on the Copernicus European Windstorm data (Figure 5). A storm footprint is useful for assessing the impact and extent of a storm, specifically for surface hazards (e.g., strong winds and risk of damage). The storm footprint in Figure 5 shows that the regions most affected by storms following SSW events are in western and northern Europe, while regions most affected aster strong vortex events extend towards the UK and Scandinavia.

39. Lines 298-300 " Here, we have shown that changes in the storm track are associated with regional changes in precipitation and surface wind patterns, resulting in a distinct geographical distribution of the impacts following weak or strong vortex forcing". Again, this is a too general and vague statement, which, for specific countries is not true, as they are sensitive to the dataset used. How much of this variability is statistically significant?
We have add a new analysis to determine which affected regions have a statistically significant surface response following SSW and strong vortex events (Figures 3 and 4). We have revised this sentence and added more specific details about the statistical significance of the results throughout the paper (Line 270). In addition, we have move the analysis of combine wind and flooding events to Appendix C, and included a discussion about these results (Line 280).

40. Lines 305-306: so given Appendix B, which countries are then underestimated and what does it mean for your overall results? The concluding sentence in line 308 is then too strong and misleading, as different datasets show large differences.
For most European countries, EM-DAT provides information about the estimated damage for at least 50% of the recorded storm events. However, in some countries damage data availability is lower (e.g., Italy, Portugal, and the Balkans). We have added this information to the Discussion. This analysis does not provide an estimation on which countries are then underestimated, in terms of storm counts, but rather suggest that these countries may have underestimated damage costs.

3.3 Typos and technical corrections:

41. Line 65: add "timescales" after "seasonal"
Fixed.
42. Line 100: "be" -¿ "been"
Fixed.

43. Line 104: add "by" after "characterized"
Fixed.
44. Line 151: "dates" -¿ "days"
Fixed.

References

Baldwin, M. P. and Dunkerton, T. J.: Stratospheric harbingers of anomalous weather regimes, Science, 294, 581–584, 2001.

Butler, A. H., Sjoberg, J. P., Seidel, D. J., and Rosenlof, K. H.: A sudden stratospheric warming compendium., Earth System Science Data, 9, 2017.

Karpechko, A. Y., Hitchcock, P., Peters, D. H., and Schneidereit, A.: Predictability of downward propagation of major sudden stratospheric warmings, Quarterly Journal of the Royal Meteorological Society, 143, 1459–1470, 2017.

Moemken, J., Messori, G., and Pinto, J. G.: Windstorm losses in Europe–What to gain from damage datasets, Weather and Climate Extremes, 44, 100 661, 2024.

Country	**Storm counts**	**Availability of damage data**
Albania	2	0
Austria	4	2
Belarus	1	1
Belgium	11	4
Bosnia and Herzegovina	2	2
Bulgaria	2	0
Croatia	1	0
Czechia	7	2
Denmark	6	3
Estonia	1	1
France	25	11
Germany	19	12
Greece	3	1
Hungary	4	0
Ireland	8	3
Italy	8	1
Latvia	3	2
Lithuania	2	2
Luxembourg	1	1
Netherlands (Kingdom of the)	9	6
North Macedonia	1	0
Norway	3	1
Poland	11	4
Portugal	7	1
Republic of Moldova	1	1
Romania	3	0
Serbia Montenegro	1	0
Slovakia	1	1
Slovenia	2	1
Spain	14	7
Sweden	4	2
Switzerland	11	5
Ukraine	2	2
UK and Northern Ireland	21	11
SUM:	**205**	**92**

Table 1: Storm counts and availability of damage data by country during NDJFM, between 1998 to 2023.

Reply to Reviewers: Stratospheric extreme events impact European storm damage

May 13, 2025

Dear Editor,

We would like to thank all three reviewers for their insightful and helpful comments which contribute to improve our manuscript. Please find our detailed responses to the reviewers' comments and suggestions below.

All changes have been included into the manuscript and are indicated **in bold** in the annotated manuscript.

The main changes to the manuscript include:

- We have added statistical analysis for the direct impact datasets and compared to climatology.
- We rephrased some of the arguments, to ensure their support by the findings.
- We have updated the definition to strong vortex events (SPVs) to consider only events that last at least 5 days in the stratosphere. This improvement to the definition of SPVs does not affect the results.

Best regards,
Hilla Afargan-Gerstman (on behalf of the co-authors).

REVIEWERS' COMMENTS:

Reviewer 3 (Remarks to the Author):

The revised version is much improved following the additional statistical analyses, refinement of datasets and text. Still, not all my concerned were addressed fully, and critical points remain, which I detail more specifically below. Essentially, as the study has statistical methodological approach, rather than mechanistic, it is still unclear for major parts of the results how significant they are compared to climatology. While reanalysis-based cyclone and hazard results are significant, the

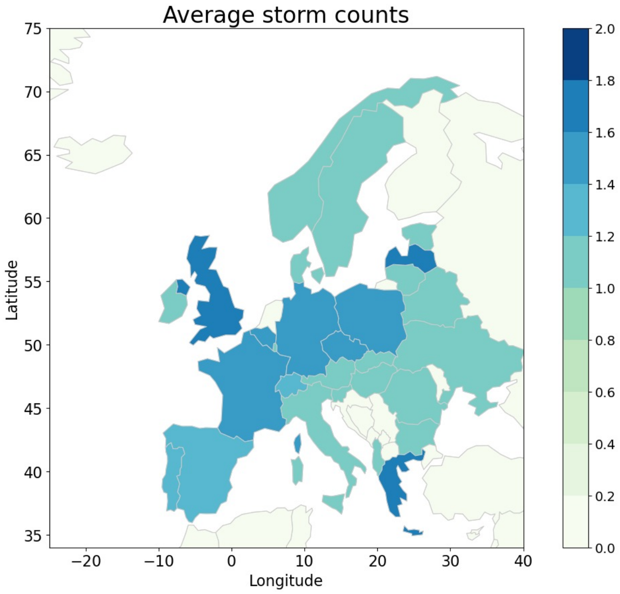

Figure R 1: Average storm count over European countries for 1998 to 2003, based on EM-DAT.

innovation here is to add more direct impact datasets. However, these are not heavily analyzed for significance compared to climatology. Second, there are still many statements which oversell the results, making them too general and robust, which is not supported by the findings.

First, we would like to thank the reviewer for their constructive comments. We would like to clarify that the analysis in this study, obtained from reanalysis or impacts datasets, provide consistent results. In the reply letter below, we have included additional analysis to support the arguments presented in the manuscript. Specifically, we address the significance of the results obtained from impact datasets. We believe these changes improve the clarity of the manuscript and present analysis that further supports the main findings.

Specific comments:

- The introduction ends with the conclusive statement "These patterns are found to be associated with increased damage over Europe and a co-occurrence of precipitation and wind extremes in northwestern Europe and Scandinavia". However, the results are more subtle and region dependent, show contrasting results according to the dataset chosen, and not significant throughout. The statement should be toned down or elaborated.

We have revised this statement, as follows: "in winter, stratosphere-troposphere coupling following stratospheric extreme states is characterized by distinct tropospheric circulation signatures for weak and strong stratospheric vortex conditions. These patterns are associated with shifts in storm frequency and windstorm damage over

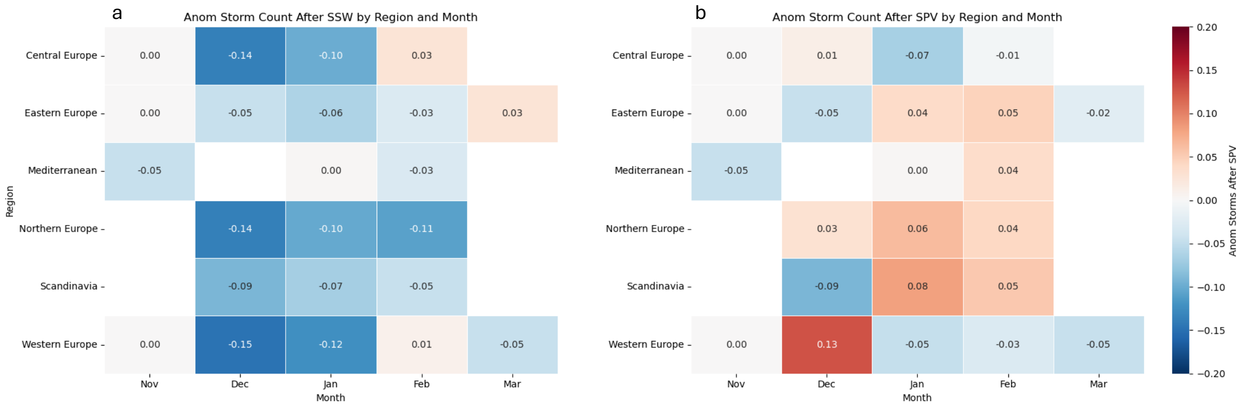

Figure R 2: Anomalies of high-impact storm counts shown by region and month. The anomalies are computed as deviations for the average storm count for 1998 to 2003, for that region and month, for (a) SSW events, and (b) SPV events. All records are obtained from EM-DAT.

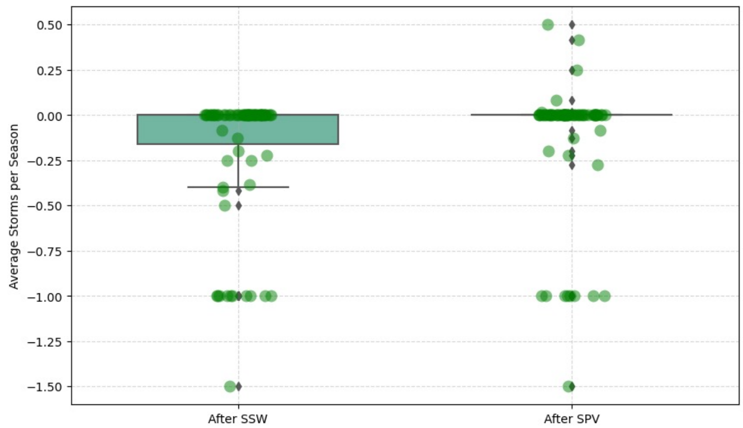

Figure R 3: European storm count per winter based on EM-DAT for SSW and SPV events. Values for different countries are represented by green circles.

Europe". Moreover, we have revised the text throughout the manuscript clarifying that the results are region dependent and that not all regions are statistically significant. Certain cases appear to be contrasting according to the dataset chosen, however, as also discussed in detail in our reply (see reply to Lines 250-252 below), these cases can be often explained as a result of missing data records.

- Lines 250-252: this is an overstatement, as some regions show contrasting results, e.g., Germany.

In the study, we perform a comparison of storm footprint (shown in Fig.5 in the revised manuscript) and storm damage from EM-DAT (in Fig.6) for SSW and SPV events. This comparison demonstrates a consistent difference pattern in the majority of European countries, however exceptions exist in central Europe, and in Germany in

Storm	Month	Economic loss (in hundred millions USD)
Erwin	**01/2005**	**4.04**
Kyrill	**01/2007**	**77.6**
Xaver	12/2013	N/A
Friederike	**01/2018**	**6.85**
Ciara	02/2020	N/A
Malik	01/2022	N/A

Figure R 4: Storms reported in Germany in a 30-day period after strong vortex events. Data is based on EM-DAT.

particular. In the revised version, we have increased the number of storms obtained from the Copernicus dataset (allowing more than one windstorm to be considered for each SSW and strong vortex event). Specifically for Germany, EM-DAT storm damage following strong vortex events is obtained from the accumulated loss records for three storms: Erwin (in winter 2005), Kyrill (2007) and Friederike (2018) (see Table R4). However, windstorm footprint for storm Friederike in 2018 is not available by Copernicus (according to personal communication), making this an exceptional case where the average storm footprint is underestimated. We have added a clarification to the manuscript and remove the statement that was previously included.

- Lines 274-275: "SSW events, on the other hand, are found to be associated with enhanced storm impacts over central and southwestern Europe". In fact, I am not yet convinced. The spatial variability when comparing SSW/strong vortex events is clear, but the significance of having enhanced storm damage following SSWs is not shown, especially when contrasted to climatology – meaning, what is the random probability of having such impact during any 19 months in the climatological period, and is it significantly different? If it is not, then key point #2 is not a major findings. In other words, are the results in Figs. 3-5a,b significant? Or only some of the differences in their panel c?

The probability of having a high-impact storm during the climatological period is shown in Fig. R1 (as well as in Fig. A3 in the revised manuscript). According to EM-DAT, no more than two high-impact storms (per month) are reported in European countries during NDJFM. To further quantify the anomalous response of high-impact storm counts to stratospheric extremes, we follow the reviewer's suggestion and examine the change in EM-DAT storm counts with respect to their climatological frequency (Fig. A3 in the revised manuscript). For this purpose, we define the anomalies in storm events for each month in NDJFM as deviations from the monthly mean.

High-impact storm counts are found to decrease across Europe but increase over the eastern Mediterranean after SSW events (Fig. A3b), while anomalously increasing over the UK and Scandinavia, as well as over southern Europe, after SPV events (Fig. A3c). These results indicate that storm counts over Europe exhibit a response to the stratospheric forcing, with respect to their climatology. However, the results are not significant in most European region (possibly due to the small sample size of storm counts per country).
Additionally, we examine the month-to-month variability if high-impact storm count anomalies as a function of month and region (Fig. R2 below). After SSWs (left panel), there is generally a decrease in storm counts for most regions, except for central and eastern Europe. For comparison, storm counts after SPV events (right panel) exhibit an increase in storm counts in western and northern Europe, as well as in Scandinavia and eastern Europe. This plot demonstrates that the signature of the tropospheric response is thus both region-dependent and month dependent (Fig. R2).

Thus, high-impact storm frequency in Europe are becoming less frequent after SSW events and more frequent after SPVs. We further summarize this comparison for all European countries and all winter months (Fig. R3). We find that the average anomalies of storm counts are centered around zero for both SSWs and SPV events, as expected (i.e., some regions exhibit an increase while others a decrease). Incorporating additional impact datasets in the future can help to further determine the statistical significance of the downward influence of the stratosphere on extreme storm events.

- Line 275: "as well as storm genesis regions" – this is not shown here, either delete or add a reference to support it.
This sentence refers to shifted in extratropical cyclones genesis regions shown in another paper (Rupp et al., 2024). We have rephrased this sentence and added a relevant reference.

- Overall, the results are contrasting in terms of storm counts Vs. storm footprints. The first shows reduction over most of Europe during SSW compared to strong vortex, and the second shows enhancement. The damage data show a mixed response. The only agreement is found for Scandinavia. This major contrasting finding is not even discussed, but rather smoothed out with too vague text. In the text, only data availability is mentioned as a limitation, but it is unclear if this is the only reason for any discrepancies in the results, which are not discussed. Relevant aspects such as the influence of storm frequency Vs. intensity are not analyzed or discussed. The concluding sentence in lines 299-300 ("Overall, this analysis indicates that a similar response pattern is found in both datasets following SSW and strong vortex events, supporting the conclusions from the EM-DAT dataset") is therefore not true and even the opposite is the case for most of Europe.

Unless there is something I missed, this is a major outstanding issue with the revised manuscript.
We would like to clarify that the results, obtained from either reanalysis or impacts datasets, are consistent, although they may appear to be contrasting in a first glace. Here we explain our arguments point by point, as follows:

- **We have updated the definition of SPV events, and revised Fig.1 in the manuscript. The updated figure shows that the spatial pattern of storm frequency shifts significantly compared to reanalysis during SSW and strong vortex winters (in the 30-day period following the events). The shift is known to be significant for the North Atlantic (Fig. 2), but the response over Europe remains unclear.**
- **Counts of high-impact (disaster) events recorded in the context of extratropical cyclones (named here 'storm counts'), shown in Fig.3, indicate the total number of disasters recorded after SSW and strong vortex events, thus this is a measure that is purely impact-based (i.e., a storm without major impact would not be reported).**
- **The difference in disaster counts between SSW and strong vortex events, shown in Fig.3c, suggests that high-impact storms are more frequent over Europe during strong vortex compared to after SSWs.**
- **Individual cyclones may cause most of their impact southward or poleward of their track (determined by the point of minimum pressure). In addition, cyclones can propagate across Europe without being accounted as high-impact.**
- **Thus, while cyclone frequency is significantly enhance over southern Europe after SSWs and over northern Europe after SPVs (Fig.1), anomalous increase in storm impact is more country-specific (Fig. A3) and depends on both the intensity of the storm and the country's socio-economic preparedness, rather than being dependent only on the storm's track.**

Consequently, the economic loss associated with these storm disaster events demonstrate a difference in loss between southern and northern Europe, consistent with the changes in the regional patterns of surface wind speed and the storm's footprint based on reanalysis.

Additional comments:

- Line 149 and throughout the text: Events identified above the 20% threshold should not be termed "extreme", but rather moderate strong/weak events, to avoid confusion with the more extreme events as described above.
We agree, and rephrased this terminology from "extreme" to "moderate" as suggested

by the reviewer.

- Data and Methods section: there is no description of the methodological approach taken to statistically examine the relationship between stratospheric states and surface impacts, and to quantify the significance. Also, justify the usage of the 30-day window following stratospheric anomalies, which appears for the first time in the caption of Fig. 1.

We have added an explanation in the Methods section on why we use a 30-day window to assess stratospheric impacts (stratospheric influence is persistent in the troposphere). As for the methodological approach taken to statistically examine the link between stratospheric states and surface impacts, we have moved from the figure captions to the Methods, as suggested by the reviewer. Using the Mann-Whitney U-test is appropriate for the small sample size, and does not require an assumption that the data follows a normal distribution.

- Figs. 1 and 2: the units of precipitation is likely not meters but mm/day? Actually, the accumulation time is not noted in subsection 2.1.

We use total precipitation from ERA5 converted from hourly values to daily sums. Units are 'mm per day'. We have added this information to the Methods section and corrected the figure caption.

- Lines 206-207: this sentence is out of context and can be deleted.

We have deleted this sentence.

- Lines 221-224: this paragraph fits better before the previous one, to first start with the climatological count, and later describe the subset that follows stratospheric events.

We have re-ordered the paragraphs in this section, as suggested by the reviewer (climatology first, and stratospheric events later).

- Compound hazards: this fits better in the Result section rather than in the Discussion and Conclusions.

We have moved this paragraph from the Discussion to the Results section, as suggested by the reviewer.

Technical corrections:

Line 28: put reference in parentheses

Done.

Line 129: unclear what CDS refers to

We corrected the missing reference.

Line 160: delete “cyclone frequency” and second “frequency”

Done.

Line 176: delete “a”

Done.

Line 179: “summarize” seems more appropriate than “evaluate”

Done.

Line 228: correct the sentence around “are is”

We rephrased this sentence.

References

Rupp, P., Spaeth, J., Afargan-Gerstman, H., Büeler, D., Sprenger, M., and Birner, T.: The impact of synoptic storm likelihood on European subseasonal forecast uncertainty and their modulation by the stratosphere, EGUsphere, 2024, 1–19, 2024.