Response to Referee Comment 2: "Concurrent modes of climate variability linked to spatially compounding wind and precipitation extremes in the Northern Hemisphere"

Comments to the authors

Overall impression of article

I think it is an important study on compounding extreme events, especially when linking this to potential impact (e.g. through the population metric used in this study). I also value the link to global drivers and teleconnections, as this can benefit short term predictions but also long term projections. Generally, I think this paper needs a bit more restructuring, notably the result and discussion sections. Furthermore, it needs another careful read through because it was difficult at times to understand the sentences. Below I mention more details in some major and some minor suggestions.

Response:

We would like to thank the referee for their positive comments and the detailed feedback. We took action and rephrased sentences that were too long or complex when needed. All the comments and our point-by-point responses are given below.

Comments:

Major points of discussion

1. The motivation for this study is not so clear to me. Why look at compound wind&precip?

Response:

Thanks for this comment. In this study, we looked at compound wind and precipitation (CWP) extremes and associated spatially compounding events due to the potential widespread impacts it could have on many sectors of the economy (such as damages to agricultural crops, energy infrastructure and buildings). As suggested by the referee later in the review, CWP events are not the only impactful compound events. Droughts and heatwaves or floods are indeed other examples of potentially impactful spatially compounding events that need to be taken into account for risk assessments. However, to our knowledge, spatially compounding wind and precipitation extremes and their drivers have been little investigated, representing a research gap in the literature.

We add in the Abstract some sentences (in blue) to clarify the motivation of the study:

L1: "Compound wind and precipitation (CWP) extremes often cause severe impacts on human society and ecosystems, such as damage to crops and infrastructure. ~~High regional frequencies of CWP extremes across multiple regions in the same winter, referred to as spatially compounding events, can further impact the global economy and the reinsurance industry.~~ **Spatially compounding events with multiple regions affected by CWP extremes in the same winter can impact the global economy and reinsurance industry, however our understanding of these events is limited. While climate variability modes such as El Niño Southern Oscillation (ENSO) can influence the frequency of precipitation and wind extremes, their individual and combined effects on spatial co-occurrences of CWP extremes across the Northern Hemisphere have not been systematically examined.**"

Link to this comment, the referee later questions why CWP should be prioritized over other multi-hazard events. Therefore, we also highlight other significant compound events in the Introduction:

L24 of the article initially submitted: "**A highly studied example of an impactful compound event is hot-dry conditions (e.g., Bevacqua et al., 2022), which are enhanced by land-atmopshere feedback (e.g., Zscheischler et al., 2017, Rasmijn et al., 2018, Ridder et al., 2022). Another example is compound wind and precipitation (CWP) extremes that can cause more damage than high winds or precipitation in isolation (e.g., Li et al., 2024)**."

We better motivate the reason why we specifically analyse CWP extremes in the Introduction (instead of another compound events):

L40 of the article initially submitted: "**While the characteristics of spatially compounding events such as droughts (e.g., Kim et al., 2019, Singh et al., 2021) or floods (e.g., Jongman et al., 2014) have already been studied, our understanding of spatially compounding CWP extremes and their drivers is limited.**"

Comments:

2. Similarly, the motivation for these exact modes of variability is a bit lacking in introduction. You do mention the Indian ocean as a potential influence in discussion. What about other modes? Why not include those?

Response:

Thanks for this comment. The four climate modes NAO, PNA, AMV and ENSO are known to strongly influence wintertime storm activity, atmospheric circulation, and moisture transport across the Northern Hemisphere, and are thus chosen in this study to investigate their relationships with occurrences of wintertime CWP extremes over the Northern Hemisphere. In the Introduction, we modified the examples of the already-known influence of climate modes on wintertime weather to specifically focus on the Northern Hemisphere.

L47 of the article initially submitted: "For example, the **North Atlantic Oscillation (NAO)** and Pacific North American (PNA) ~~pattern and the North Atlantic Oscillation (NAO) are two dominant modes of interannual midlatitude climate variability during the Northern Hemisphere winter~~ **are the leading modes of variability affecting wintertime weather in Europe (e.g., Hurrell et al., 1995) and North America (e.g., Wallace et al., 1981).**"

L56 of the article initially submitted: "The AMV, an alternation of warm and cold sea surface temperatures in the North Atlantic on decadal timescales, has been shown to influence ~~the intensity and frequency of Atlantic hurricanes (Trenberth and Shea, 2006; Wang et al., 2022) and~~ **weather in both North America and Europe (e.g., Knight et al., 2006), as well as** the long-term variability of the NAO (e.g., Davini et al., 2015)."

We also specify precisely that the four modes are selected due to their already-known influence on CWP extremes in the Northern Hemisphere:

L67 of the article initially submitted: "We consider these four modes of variability due to their already-known influence on storm activity and moisture transport in the Northern Hemisphere."

We recognize that adding other climate modes, such as the Indian Ocean Dipole, that are also known to have an influence on wind and precipitation extremes would have been interesting. However, a choice on the number of modes has to be made, and here we selected four modes of variability that are known for having large effects on storm activity in winter across the Northern Hemisphere. We also note the addition of extra conditioning would result in a reduced sample size when quantifying conditional statistics, potentially reducing the robustness of the results of some statistical analyses, particularly those based on reanalysis data.

Comments:

3. Why do you choose to average the daily wind and precipitation values instead of taking the maximum wind speed and the sum of total precipitation of the day? Especially when it comes to wind, I'm worried that averaging is not the best choice to catch wind-extreme events.

Response:

We thank the referee as clarifications and corrections in the Manuscript are indeed required. First, regarding precipitation, we used daily data of total precipitation and not daily means, as indicated in the article. It should be noted, however, that as our methodology uses a quantile-based approach, the choice of daily average or daily total for precipitation does not affect our analysis by construction. Secondly, with regard to the wind values, the reviewer is right, and it would have been preferable to take into account the maximum wind speed rather than the daily averages to examine the wind extremes. This choice has been made due to data availability: for the CESM simulations, only daily averages were available.

We suggest to provide the following corrections to the text:

L91 of the article initially submitted: "~~For daily wind and precipitation data,~~ **Daily total precipitation and daily mean of wind speed are extracted for** the historical period ~~simulations~~ (1950–2005)~~are extracted and~~. **Simulated data are then** extended until 2019 using the emission scenario associated with a radiative forcing of +8.5W.m−2 (RCP 8.5 scenario), resulting in a total of 70 × 40 = 2800 years of data. **We choose daily averages rather than maxima for wind due to data availability for the CESM simulations.**"

For ERA5, we directly downloaded daily means of wind speed and daily total precipitation, and did not get daily means from sub-daily data, as initially indicated in the article. Daily means were selected for consistency with the CESM data. We suggest the following correction:

L95 of the article initially submitted: "To evaluate the CESM model, we employ ERA5 reanalysis data (Hersbach et al., 2020) (spatial resolution of 0.25 ◦) for the period 1959-2019 (Singh et al., 2021), from which we ~~derive~~ **also extract** daily means of wind speed and **daily total** precipitation~~ via averaging sub-daily data~~**for consistency**."

Comments:
4. Why are you considering seasonal mean indices? Why not look at weekly/monthly data? I think there is an issue with the different timelags here, since ENSO is clearly a yearly oscillation, but the NAO can also be defined on weekly/monthly timescales. I think this has to be motivated from a physical point of view.

Response:
We thank the reviewer for raising this important point regarding the choice of seasonal mean indices for modes of variability. The choice of the seasonal time scale was made based on the modes considered in the study. The NAO has variability that differs in a physical way depending on the timescale (e.g. between interannual/decadal and multidecadal time scales, see e.g. Woollings et al., 2014, https://link.springer.com/article/10.1007/s00382-014-2237-y). As noted by the reviewer, ENSO operates primarily on seasonal timescales (e.g., Schmidt et al., 2001; Camberlin et al., 2001). Given one of the main focus areas of this study is on ENSO, it makes sense to consider this timescale in our study. Using the same timescale for all indices allows for a consistent comparison of their influences on CWP extremes. Considering shorter timescales (e.g., weekly or monthly indices) would have not allowed us to assess the influence of important modes such as ENSO and its interactions with other variability modes occurring at seasonal timescales.

We suggest to add in the Introduction:
"**We consider these four modes of variability due to their already-known influence on storm activity and moisture transport in the Northern Hemisphere. As ENSO operates primarily on seasonal timescales (e.g., Schmidt et al., 2001; Camberlin et al., 2001), seasonal mean indices are considered.**"

References:

- Schmidt, N., E. K. Lipp, J. B. Rose, and M. E. Luther, 2001: ENSO Influences on Seasonal Rainfall and River Discharge in Florida. *J. Climate*, **14**, 615–628.
- Camberlin, P., Janicot, S. and Poccard, I. (2001), Seasonality and atmospheric dynamics of the teleconnection between African rainfall and tropical sea-surface temperature: Atlantic vs. ENSO. Int. J. Climatol., 21: 973-1005. https://doi.org/10.1002/joc.673

Comments:
5. Which threshold do you end up choosing? It is a bit unclear, you take 95th in ERA5 and 98th in CESM? How do these two compare to each other (I believe you compare 95th in both era and CESM in the supplementary)? Did you do sensitivity experiments to determine these two thresholds are the same?

Response:
We thank the reviewer for this comment, as some clarifications are needed. In the study, we consider two percentile-based thresholds to determine CWP extremes: (1) 98th percentile of wind and precipitation for the main analysis based on the CESM model, and (2) the 95th percentile for model evaluation based on ERA5 and CESM model (Figs. S1-S5 of the Supplement). With respect to point 2, thus, contrary to what is initially understood by the reviewer, we use identical thresholds to compare occurrences of CWP extremes in CESM

simulations and ERA5 data. Therefore, no sensitivity experiments are required to determine if these thresholds are the same. We suggest to provide the following clarifications (in blue) to the text:

L110 of the article initially submitted: "We use the 98th percentile of wind and precipitation over the 1950–2019 period for the main analysis based on data from the CESM model. **Percentile-based thresholds are frequently used to investigate climate extremes (e.g., Zhang et al., 2011, Martius et al., 2016). Following Klawa and Ulbrich (2003) and Martius et al (2016), we chose the 98th percentile, which is a compromise to capture the most extreme events in the CESM simulations while ensuring a sufficiently large sample size for robust statistical analysis.** For model evaluation, **which involves both the CESM model and ERA5 reanalyses (Figs. S1-S5 of the Supplement only)**, we use the 95th percentiles over the 1950-2019 period -- such a lower threshold allows for a more robust evaluation. **The reason for this is that,** given the ERA5's limited period, **extremes in the reanalysis data set are more scarce and associated statistics for very extreme events are largely affected by sampling uncertainty (Bevacqua et al., 2021b). Selecting a slightly lower threshold allows us to reduce this sampling uncertainty and thus improve confidence in assessing the model's ability to simulate extremes (e.g., Bevacqua et al., 2021b, Kelder et al., 2022, Fischer et al., 2023)**."

Comments:

6. I think the result & discussion sections should be re-structured: you already discuss the findings with respect to other literature in the results, I believe this should be moved to the discussion. In the results only mention your own findings. This will also make your paper easier to read.

Response:

We agree with this comment. We removed aspects related to the discussion of the findings from the Results section to the Discussion.

Comments:

Minor suggestions

Abstract

1. I miss the motivation for these specific SST-modes of variability in the abstract.

Response:

As previously mentioned, the motivation for these specific SST modes of variability is now provided in the Introduction. To maintain a concise Abstract, we have opted not to include this motivation there.

Comments:

2. In the abstract I had to read the following sentence a few times before I understood: "we identify dependencies enabling extreme spatially compounding events with many regions experiencing CWP extremes in the same winter" L9/10.

Response:

Thanks for this comment. We simplified the sentence as:

L9/10: "By examining the relationships between **frequencies of wintertime** CWP extremes across regions, we identify dependencies enabling extreme spatially compounding events ~~with many regions experiencing CWP extremes in the same winter~~**, that is winters with many regions experiencing CWP extremes.**"

Comments:
3. "mitigation of spatially compounding CWP extremes." L15 how could these CWP extremes be mitigated ?

Response:
We suggest to modify the sentence as follows:
L15: "Our analysis highlights the importance of considering the interplay between variability modes to improve risk management and **adapt to the impacts of** spatially compounding CWP extremes."

Comments:
Introduction
4. L24: "co-occurring compound wind and precipitation (CWP) extremes" co-occurring and compound is that not the same?

Response:
Thanks for noticing this. We removed "co-occurring".

Comments:
5. Introduction: are there any examples of spatially compounding CWP events that lead to extreme damages? You mention the flooding as an example. But it is not entirely clear to me why CWP should specifically be investigated over other multi-hazard events (hot-dry, no wind-cold, etc.)

Response:
Thanks for this comment. Examining the drivers of spatially compounding of CWP events addresses a gap in the existing literature, compared to other compound events such as floods or droughts, which have been already investigated.

Comments:
6. L46: "cyclones are particularly exposed to CWP extremes" are cyclones not considered a CWP extreme? How is a CWP defined actually?

Response:
The referee refers to the sentence "regions prone to cyclones are particularly exposed to CWP extremes". Following the proposed typology for compound events (see Table 1 in Zscheischler et al., 2020), cyclones are considered a driver of CWP extremes. Thus, cyclones are not a CWP extreme. Furthermore, not all CWPs arise from cyclones, as explained in the Introduction (L43 of the article initially submitted). For instance, CWPs can occur in non-cyclonic systems, such as atmospheric rivers or frontal systems.

Reference:

- Zscheischler, Jakob & Martius, Olivia & Westra, Seth & Bevacqua, Emanuele & Raymond, Colin & Horton, Radley & Hurk, Bart & AghaKouchak, Amir & Jézéquel, Aglaé & Mahecha, Miguel & Maraun, Douglas & Ramos, Alexandre & Ridder, Nina & Thiery, Wim & Vignotto, Edoardo. (2020). A typology of compound weather and climate events. Nature Reviews Earth & Environment. 1. 1-15. 10.1038/s43017-020-0060-z.

Comments:
7. Why do you focus on wintertime CWP only? Aren't summer storms especially damaging (due to trees being in full leaves).

Response:
Thanks for raising this point. The occurrence of CWP extremes are known to be most frequent in the winter season, hence the choice of this season for our study.

We add the following sentence in the Introduction:
"Such compound extremes are most frequent in coastal regions of the Pacific and Atlantic oceans (e.g., Maraun et al., 2016) and tend to be more frequent and intense in the winter season (e.g., Greeves et al., 2007, Hansen et al., 2019)."

Still, we acknowledge that summer storms can be particularly damaging due to trees being in full leaf, and thus, it is interesting to analyse. Future research could address these differences and explore the vulnerabilities associated with summer storms. For example, summer storms are known to be more localized (e.g., convective storms) than winter storms, potentially resulting in different conclusions. We now also mention that summer storms are interesting to analyse in the discussion section.

Comments:
8. L156 how do you calculate significance?

Response:
Thanks for this comment. All the details are provided in subsection 2.2.4, as already specified. We suggest modifying the following sentence (in blue) to point to the text explaining the calculation of significance:

L156 of the article initially submitted: "When presenting the results in Sect. 3, we focus our analysis on individual and concurrent variability modes having a *significant and positive* effect on the different metrics using permutation tests (see subsection 2.2.4 **for more details on calculating the significance**)."

Comments:
Methods
9. Metric 1: if you average the count per grid point do you still need the latitude weight?

Response:
Thanks for this question. As indicated in the text for Metric 1 of the original manuscript, "CWP counts are averaged by region over land-masses, weighted by the cosine of latitude". The reason for using latitude weighting when averaging over regions is to account for the

potential uneven distribution of grid points across latitudes in the different regions. Without weighting, grid cells closer to the poles would be disproportionately represented in our calculations, potentially distorting regional averages for regions including such grid cells, for example Greenland/Iceland or Northeastern North America. Thus, we still need the latitude weighting for Metric 1.

Comments:
10. Metric 2: why 80th percentile?

Response:
Thanks for this comment. Choosing a higher threshold would allow us to focus on regions that are more severely affected. However, it would also limit the number of regions being reported as affected and, thus, the statistical robustness of our results regarding spatially compounding extremes. We suggest to add the following sentence:

L125 of the article initially submitted: **"Although choosing a higher percentile (>80th percentile) would enable us to focus on cases where regions are more severely affected, it would considerably limit the number of regions reported as affected and, consequently, the statistical robustness of our results."**

Comments:
11. Why do you only look at positive cases, e.g. when a mode has a positive effect? L151

Response:
We decided to look at positive cases, i.e., when anomalous phases of variability modes lead to an increase in the means of the different metrics compared to neutral conditions because of the greater potential impact of these events, and therefore their societal relevance. Indeed, looking at positive cases means looking at cases for which modes increase the frequency of CWP extremes (Metric 1) or the number of regions affected by CWP extremes (Metric 2). We added the following words to the text:

L151 of the article initially submitted: "For both regional and spatially compounding cases, we focus on the modes of variability influences leading to an **enhancement** in the means of the different metrics compared to neutral conditions (hereafter referred to as *positive effects*) **– we focus on the increase, rather than the decrease, as this is of relevance for potential impact to society.**"

Comments:
12. Have you tried any kind of regression analysis? Maybe this also can take away the effect of 'neutral' states not really being neutral, as mentioned L139-140

Response:
Thanks for this comment. It is a very good point from the reviewer, as using regression techniques could help better controlling the effect of modes varying within the range of neutral conditions. We did not try any kind of regression analysis and represents a nice perspective for future research. We modified a sentence in the Discussion section to mention it as a possible perspective for future studies.

Comments:
13. Why not take the significance level of 0.05? L 180: significance level α = 0.10

Response:
Thanks for this comment. The choice of the significance level is always subjective. Here, the 10% significance level was intentionally chosen to balance the detection of meaningful effects while avoiding false negatives. Indeed, with a limited sample size (which is the case in our study when we compare distributions), a lower significance level might be too stringent to detect significant effects, especially at a 5% or 1% significance level. Choosing a larger significance level is aligned with the exploratory nature of our work, allowing us to shed light on potential effects of modes on CWP extremes.

We suggest to add the following sentence:
L180 of the article initially submitted: "Specifically, for a given CWP metric, we test whether the ratio of the average of the metric associated with a given set of phases of interest (e.g., NAO+ENSO-, set as the numerator) to the average of the metric under neutral conditions (set a denominator) is larger than one at significance level α = 0.10 based on one-sided tests. **Compared to a lower significance level, our chosen level allows the detection of significant effects of modes of variability while reducing false negatives in the context of small sample sizes.**"

Comments:
Results

14. Your maps would be easier to interpret if you mask out the non-land areas.

Response:
Thanks for your comment. Although we agree that such masking would allow a more direct focus on regional CWP extremes, it is interest to some readers to have an overview of the occurrences of CWP extremes over the oceans, which also allows for having spatial continuation in the visualisation of the effects across the earth surface and facilitate interpretation. Consequently, we decided not to mask the non-land areas as suggested by the referee and let the maps be as they are.

Comments:
15. What's the difference between the following two statements in section 3.2 L250 and L259: "Model simulations (CESM) show that not only individual variability modes can have effects on regional wintertime frequencies of CWP extremes, but also combinations of modes." vs "Model simulations (CESM) show that concurrent anomalies in variability modes amplify the effects of individual modes in many regions." I think this section needs more attention. There are so many details in the figure, and the text is not complimenting this enough. It is very difficult to understand the main results at the moment, also because you weave discussion in here.

Response:
We want to thank the referee for this comment. First, we removed L259 as it is redundant with L250, as identified by the referee. Second, we simplified Section 3.2 and reduced its size by focusing on the main results. We also removed the elements of discussion. As noted

by the reviewer, a lot of information is provided by Figures 3 and 4, and is not possible to fully describe in the text. We suggest to better precise this point in the following sentence:

L258 of the article originally submitted: “**In the following, we** ~~move to discussing~~ **focus on describing the effects of a selection of mode combinations and regions in Figs. 3-5. To maintain clarity and conciseness, we do not discuss all regions and mode combinations in the text, and readers can explore specific regional effects directly in the figures.**”

Comments:
16. L118-119: “in general agreement with existing literature,”; either mention the literature or do not mention this. Generally, I think this should be part of the discussion, not the results.

Response:
Thanks for this comment. We removed all the mentions to the existing literature from Section 3.1 and 3.2 and instead mentioned it in the Discussion section.

Comments:
17. L315-325 suits better in discussion?

Response:
We believe the referee wanted to say “Methods” instead of “Discussion”. We moved and adapted these lines to the Methods section, in agreement with another comment from the first reviewer.

L116 of the article initially submitted: “As Metric 1 is derived for each region individually, the influence of variability modes on the high regional frequencies of CWP extremes across multiple regions in the same winter (i.e., spatially compounding events) cannot be deduced **directly. For example, based on Metric 1, we find that the variability mode phase ENSO+ modulates regionally averaged CWP extreme frequencies for North America and Central Asia. However, a possibility could be that half of the winter seasons with ENSO+ leads to increased CWP extremes for North America only, while the other half affects Central Asia, thus not simultaneously. Examining the dependencies between counts of CWP extremes in different regions can provide preliminary information on spatially compounding events (Bevacqua et al., 2021) because regions connected by positive dependencies tend to experience CWP extremes at the same time. Thus, as a first step for investigating spatially compounding events, we analyse dependencies in Metric 1 computed for different regions, so as to provide preliminary information on groups of regions that may be affected by CWP extremes during the same winters.**

Then, to examine spatially compounding events, we use two additional metrics. We employ these metrics to investigate the effects of variability modes on regional high frequencies of CWP extremes across multiple regions in the same winter (Metric 2) and on the total population of the Northern Hemisphere exposed to CWP extremes in the same winter (Metric 3).”

Comments:

18. L328-331 this is motivation, should maybe go to introduction.

Response:
We agree with the reviewer that this sentence is misplaced. Instead of removing it, we decided to move and adapt this sentence when providing the results for Figure 4 at the beginning of subsection 3.2:

"**The presence of a given mode phase or combination of mode phases that has an effect on CWP extremes in multiple regions suggests the potential for spatially compounding events, which will be examined in subsection 3.3.**"

Comments:
19. L333: "Figure 5a shows Spearman correlations of regionally averaged CWP extreme frequencies (Metric 1) between all pairs of regions" You regionally average CWP extreme frequencies, but I'm thinking this could be slightly problematic. The regions are quite large, whereas these CWP extremes can be very local. What happens when you sum the CWP counts instead? Also, why not perform a spatial-dependency analysis on the original CWP data on high frequency, e.g. monthly?

Response:
Thanks for this comment. As with any dependency analysis, a choice on the spatial or temporal scale has to be taken. First, to avoid a potential misunderstanding, we note that we do not average precipitation and wind across the region but rather the counts of CWP extremes, thereby accounting for the local-scale dependency between precipitation and wind extremes. Generally, we agree that regional averaging of CWP extreme frequencies does not allow for analysis of dependency between local-scale CWP extremes, potentially occurring at the local scale, within different regions.

Here, with our choice of the considered spatial scale, by averaging CWP frequencies across a region within a winter, we aim to define an indicator of conditions that can generally be detrimental for the considered region within a winter. Then, we study spatial dependencies between such regional-scale detrimental conditions. Although we recognize that the considered spatial scale does not allow us to investigate CWP extremes at local scale, we note that our study complements the work carried out using the SREX regions adopted by the Intergovernmental Panel on Climate Change (IPCC). We clarified in the text this by adding:

L83: "We examine the influence of four variability modes on CWP extremes across 25 selected regions in the Northern Hemisphere defined in the SREX (see Fig. 1, Iturbide et al., 2020). **We chose these regions as they are standard reference in IPCC reports, as they encompass areas with relatively homogeneous climatic characteristics (Iturbide et al., 2020). While using these regions does not enable an explicit analysis of dependencies between local-scale CWP extremes and modes of variability, it allows for complementing IPCC assessments.**"

We also mention in the Discussion that the influence of variables on more local CWP extremes can be investigated in future research:

“In addition, the selected SREX regions may not reflect the natural spatial patterns of variation of CWP extremes**, potentially occurring at a more localized scale or span across multiple regions.”**

Regarding the choice for the timescale, we already mentioned earlier that shorter timescales (e.g., weekly or monthly indices) could have allowed us to capture the variability of extremes more precisely. However, the choice of the seasonal scale in this study allows to account for 1) the integrated influence of some important modes like ENSO, which operates primarily on seasonal to annual timescales (e.g., Schmidt et al., 2001; Camberlin et al., 2001), but also 2) the interactions between variability modes occurring at seasonal timescales. Looking at shorter timescales would be a different study as it leads to different physical connections and mechanisms, and is therefore an interesting question to explore in future research.

Concerning the suggestion of the referee, which is to sum CWP counts over the regions instead of averaging, we note that this would not allow us to examine local CWP extremes. This is for the same reason as for averaging: when summing over a large region, the total count might be dominated by a high number of grid cells with moderate CWP extremes, potentially masking local areas experiencing extreme CWP events. Summing CWP counts instead of averaging them over regions would yield the same results up to a scaling factor, with the scaling factor being the number of grid cells used to compute the average. Thus, Spearman correlations between regions would not be affected, as the rank of the metric for the individual regions would not be modified. Averaging facilitates a more equitable comparison of CWP extremes across regions of different sizes, a distinction that would not be achievable using summed values.

Comments:
20. L374-376: “In particular, variability modes in isolation do not lead to significant effects on the population exposure compared to neutral conditions, indicating the importance of considering combinations of modes to distil the effects of modes of variability on the population affected.” Where do you draw this conclusion from? To me it is unclear how this is related to fig 6a (which you reference the sentence before).

Response:
Thanks for this comment. Indeed, this sentence refers to Fig. 6b. We added a reference to the appropriate panel in the text.

Comments:
21. Fig 7b: but NAO is an index of SLP, so in this sense when you compare NAO- to NAO neutral you will of course find a difference in SLP. Here you go into discussion how a NAO- can physically lead to more CWP extremes as discussed in other literature. This should not be a result in my opinion, unless you have actually shown a physical mechanism in your results (e.g. convection anomalies, wind anomalies, latent heating anomalies,…). I think this last section of the results is mostly repetition from the previous sections and can be taken out. Instead focus on interpreting these physical mechanisms in a discussion section.

Response:
Thanks for this comment. First, we removed the element of discussion regarding NAO- and the links to the literature from subsection 3.4, as indicated by the reviewer. We also removed

another element of discussion regarding the influence of model biases on results, that we now discuss in the Discussion section.

Second, although we agree with the reviewer that Figure 7 and subsection 3.4 can present some repetitions with previous subsections (e.g., regarding the identification of regions affected by the combinations of modes, already done in Figure 3), we still think that linking the affected regions to SLP patterns under combined modes having the most significant effects on spatially compounding events according to Metric 2 and 3 is an interesting results. Note that not all modes are defined based on SLP.

We suggest removing some mentions of results that have been already detailed in Fig. 3, which shorten the subsection. We leave all the explanations regarding SLP patterns and how they are changed depending on the combinations of modes, the main point of this Figure.

Comments:
Discussion
22. It is important to mention you use a climate model in the first sentence already

Response:
Thanks for this comment. We now mention the use of a climate model in the first sentence.

Comments:
23. Some sentences are unclear, e.g. L 428: "Simulations show that extreme spatially compounding events with many regions under CWP extremes in the same winter are enabled by positive dependencies between CWP extremes across different regions"

Response:
Thanks for this comment. This sentence is not part of the Manuscript anymore. We also worked on reformulating other sentences to improve the readability.

Comments:
24. L339: "Our model evaluation against ERA5 reanalysis data indicates that the simulated anomalies in CWP extremes associated with modes of variability are well suited for the purpose of our analysis (Figs. S2-S5)". In my opinion there's some differences between the ERA5 and CESM figures; notably, ERA5 seems more pronounced. There are also regions where ERA5 does not agree with CESM: e.g. S2 shows that parts of North America have a negative ratio in ERA5 under NAO+ whereas this is positive in CESM, or S3 shows parts of North Africa have differences for ENSO+. I think it is important to highlight this, because that means that for some regions we can not make strong statements.

Response:
Thanks for this comment. We now highlight in the Discussion the fact that ERA5 does not agree with CESM for some modes and regions (ENSO+ and Northern Africa, Fig. S3), and that, consequently, conclusions should be made with care.

Comments:

25. Why didn’t you include IOD if you mention this has an influence on CWP extremes? To me this comes back to the general motivation for this study; the choice for these exact modes need to be motivated clearly.

Response:

Thanks for this comment. This is already addressed in our response to the referee’s second comment.