Response to review #2

We thank anonymous referee #2 for the constructive review and helpful comments that have greatly helped us to improve our work in the revised manuscript. The main improvements in the response to reviewer #2 are summarized as follows:

- We have added a robustness test to check the sensitivity of the detected causal links when the time period is changed
- We have improved the visualization of the causal maps by reducing the noise and adding labels to better identify each region when described in the text
- We have expanded the explanation in the Methods section
- We have checked the description of each region in the Results section

We have taken into account all suggestions made by the reviewer and a point-by-point response to each comment is reported below. Please note that in the following text the referee's comments are highlighted in bold font, while our answers are in regular font.

Specific comments

1) Clarification on methodology: - Section 2.2: The choice of MCA is not clear as compared to other methods of dimension reduction.

We choose MCA over other methods of dimension reduction because we are interested to identify those patterns that evolve simultaneously and may be causally related (via e.g. dynamical coupling between multiple variables). Thus, we applied MCA to identify those patterns that can explain shared covariance, which is an objective that cannot be addressed by using EOF analysis alone. We will explain this point explicitly in the revised manuscript: "A*mong the available correlation based methods to highlight strong co-variability and reduce the dimensionality of a spatiotemporal dataset, MCA allows identification of patterns in pair of variables that evolve simultaneously and may be causally related (via e.g. dynamical coupling between multiple climatological fields). MCA detects patterns that can explain shared covariance, which cannot be achieved using other dimensionality reduction methods that consider individual variables separately, such as empirical orthogonal function (EOF) analysis. However, for providing a complete picture we will also discuss the corresponding EOF patterns and the fraction of variance explained for comparison with our MCA results.*"

It would be helpful to describe what will happen with MCA modes after section 2.2.

We now explain in more detail what happens to times series identified by using MCA in section 2.2: "*Here, we select the first two MCA modes representing the dominant patterns of co-variability between tropical convection and mid-latitude circulation, and calculate time series for each MCA mode. These time series will be used as input for the causal discovery algorithm (see sections 2.3 and 2.4).*"

In Figure 2, the legend suggests four time series but one can only recognize two time series.

We agree that in the first version of Fig. 2 it was difficult to recognise two time series. We have changed the colours to represent the two pairs of time series and adopted a different aspect ratio for the axes to better show the four time series. See Fig. R1 in this document.

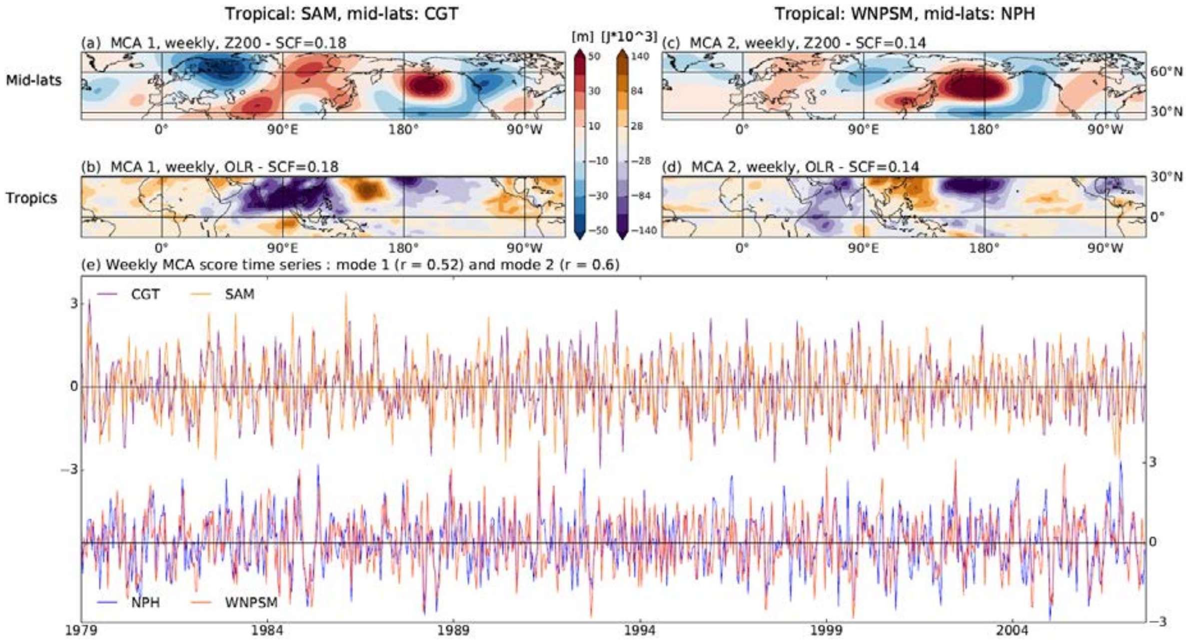

Figure R1. Revised version of Fig. 2.

Section 2.4 is very generic; it would also be useful to know at some point what "A, B, C" are in the current analysis.

We will include this suggestion in the revised manuscript. In the Results section, we will make explicit how the variables used compare to the examples given in the method section. For example: "*Referring to the schematic illustrated in Fig. 1 and following the PCMCI algorithm explanation (section 2.3), here A and B time series are represented by the SAM and CGT time series respectively, while C(lon, lat) is represented by Z200, OLR and T2m fields.*" Moreover, we have also added a more detailed explanation on how these time series are used in the causal discovery algorithm (see reponse to reviewer #1, point 4).

Adding a table describing indexes and abbreviations separated in cause and response actors used for the causal effect analysis would be helpful.

Following the reviewer's suggestion we have added a table (Table R1 in this document) to better identify each time series/field used (see also point 5 in this response).

ABBREVIATION	FULL NAME	DIMENSIONS
BSISO	Boreal summer intraseasonal oscillation	1D time series
SAM	South Asian monsoon - MCA mode 1 OLR	2D spatial pattern + 1D time series
CGT	Circumglobal teleconnection pattern – MCA mode 1 Z200	2D spatial pattern + 1D time series
WNPSM	Western North Pacific summer monsoon – MCA mode 2 OLR	2D spatial pattern + 1D time series
NPH	North Pacific High – MCA mode 2 Z200	2D spatial pattern + 1D time series
Z200	Geopotential height at 200 hPa	2D field + time
OLR	Outgoing longwave radiation	2D field + time
T2M	2m temperature	2D field + time

Table R1.

A discussion on the sensitivity of results to data-length would also be useful.

We address this comment by providing a robustness test by repeated calculation of the causal maps and screening for robust regions in the final results. This step also makes the causal maps less noisy, such that robust patterns emerge better, improving the visual appearance and interpretability of Figures 3, 4 and 5 in the revised version of the manuscript. We describe in detail how this test is performed: "*Finally, to test the robustness of our causal maps to the choice of time period and to reduce non-robust small-scale features, we repeatedly calculate causal maps for reduced time series length. In 10 trials we removed a consecutive time record of ~10% (4 years) of the entire period. For ENSO dependent causal maps, we have shorter time series and we thus remove only one year in each trial, leaving a set of 14 causal maps for La Niña events and 13 causal maps for El Niño events. As a result, we obtain an ensemble of causal maps and apply the false discovery rate correction to their p-values. Then, both for the 1979-2018 period and for El Niño and La Niña years separately, we masked out areas where less than 70% of the trials indicated a significant causal link. This gives an indication of robustness of our findings and suppresses noise.*" The masks obtained in this way and used to produce new Fig. 3,4 and 5 will be inserted in the revised supplementary material and are reported below (Figs. R2-R4 in this document).

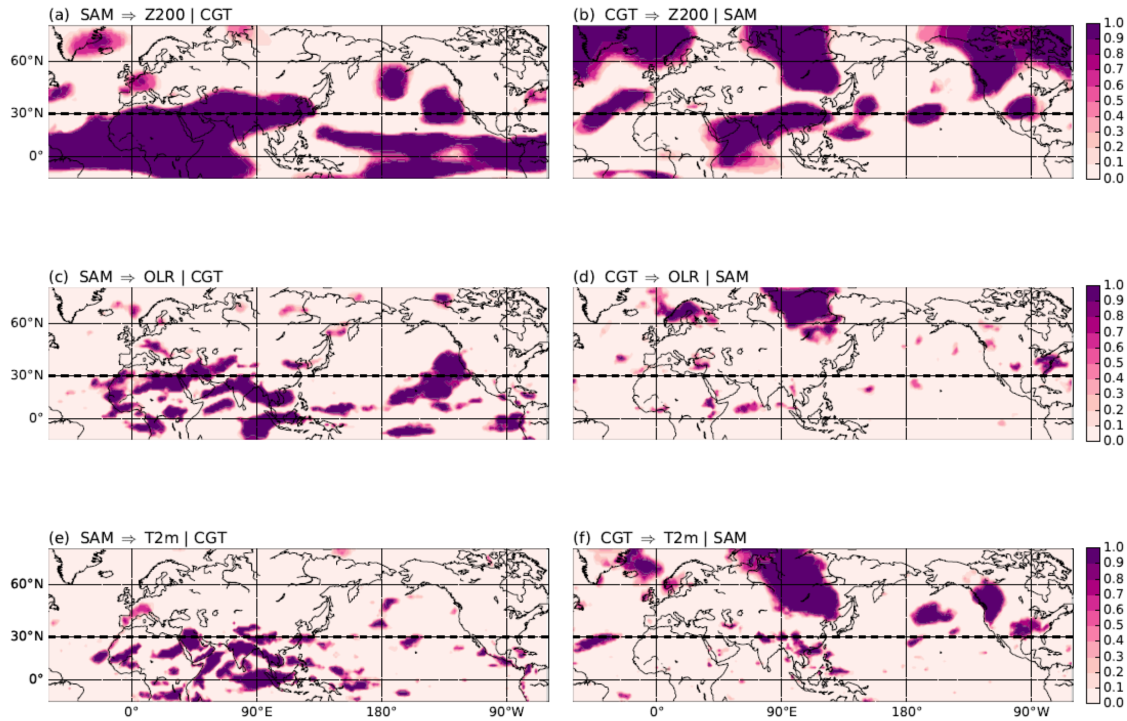

Figure R2. Robustness for Fig. 3 in the main text.

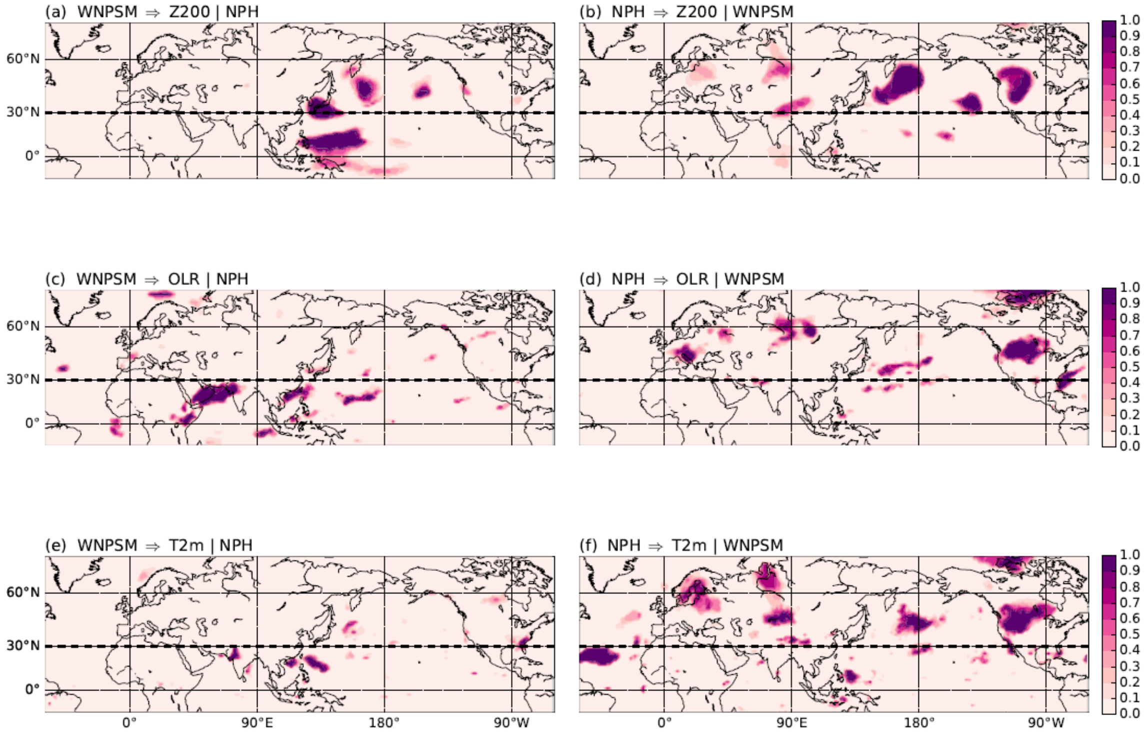

Figure R3. Robustness for Fig. 4 in the main text.

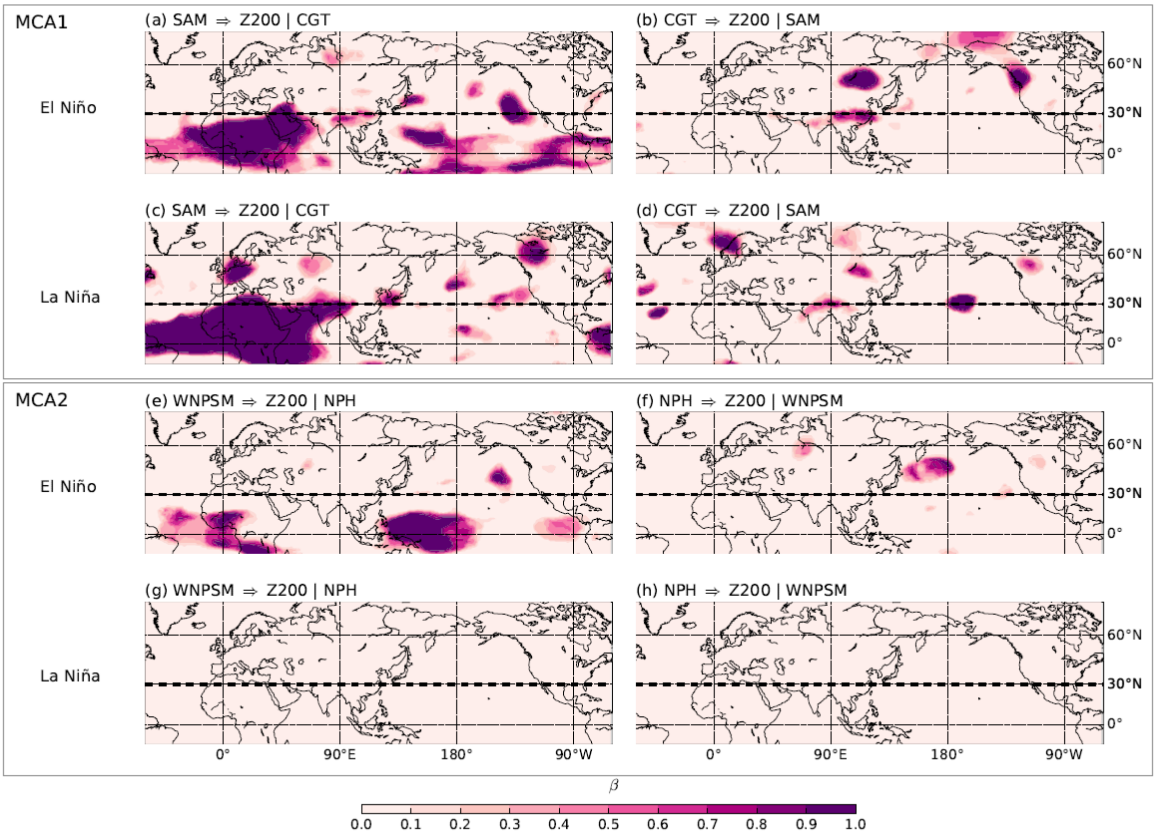

Figure R4. Robustness for Fig. 5 in the main text.

L219-223 and L310-315 should be in Methods because this text describes methodology and not the

results.

We have moved those lines "*To extract the dominant co-variability patterns reflecting interactions between mid-latitude circulation in the Northern Hemisphere and tropical convection at intraseasonal time-scales, we follow Ding et al. (2011) and apply maximum covariance analysis (MCA) to OLR fields (used as a proxy for convective activity) in the tropical belt (15°S-30°N, 0°-360°E) paired with Z200 fields in the northern mid-latitudes (25°N-75°N, 0°-360°E).*" and "*Here, we will derive causal maps using the time series obtained with MCA for modes 1 and 2 and Z200, OLR and T2m fields both for the entire time period (1979-2018) and for two subsets depicting different ENSO phases, to assess how the ENSO background state influences the causal relationships. El Niño (La Niña) summers are defined as summers preceding the El Niño (La Niña) peak in boreal winter. We thus obtain 14 La Niña years and 13 El Niño years (see Table 1 in the Supplementary material for the listing of years and Fig. S1 for the corresponding SST anomaly composites). Although the strongest SST anomalies related to the ENSO phase are found in winter, warm (cold) SST patterns related to El Niño (La Niña) phases are already clearly developed during the preceding summers.*" to the Methods section as suggested.

2) **Clarification on results and discussion: L250-259: It is not clear what the purpose of this paragraph is.**

We agree with anonymous reviewer #2 that a detailed description of BSISO can distract the reader from the main story line. We have moved this explanation into the SI and now refer to it only briefly in the main text: "*Using OLR composites, we explicitly show that the temporal evolution of the SAM convective activity at weekly time-scales resembles the evolution of the Boreal Summer Intraseasonal Oscillation (BSISO) (Goswami and Ajaya Mohan, 2001; Saha et al., 2012) (see Fig. S5-S6 and further discussion in the Supplementary Material).*"

L266-268: Mentioned patterns do not look "similar" at all to me. I would suggest to specify regions where similarities are seen by authors.

We thank the anonymous reviewer for pointing out that it was difficult to recognize in the figures the regions that we are interpreting in the text. We have addressed this comment by adding labels that are referred to in the main text, including the Results section. See Figs. R5-R7 in this document.

Explaining some of the results, authors interpret patches of beta-values on causal maps that look like noise. E.g., L280: "Although the CGT influence is mostly concentrated in the mid-latitude regions, one can see a negative causal effect of the CGT pattern on OLR values over the Bay of Bengal (Fig. 3f)." It looks like the effect that authors describe is a small dash over the Bay of Bengal, I cannot even see the color of the region, just the black contour color. Does the method behind causal maps take care of spatial noise?

We have taken the issue of robustness and potential noise in our causal maps seriously (see also our earlier reply and Figs. R2-R4). The new figures 3, 4 and 5 (Figs. R5-R7 in this document) are now all produced using the robustness test described above (see our response to comment #1). As a result, the specific region described on line 280 (original manuscript) is now indeed masked out and we will update the text correspondingly: "*The CGT influence is mostly concentrated in the mid-latitude regions, and a significant and consistent negative causal effect of the CGT pattern on OLR values in the tropical regions can only be seen in a small area in the western Indian Ocean (Fig. 3f).*" In general, using the robustness test described above noisy patterns have been removed, enabling us to only discuss the main, large-scale patterns of interest.

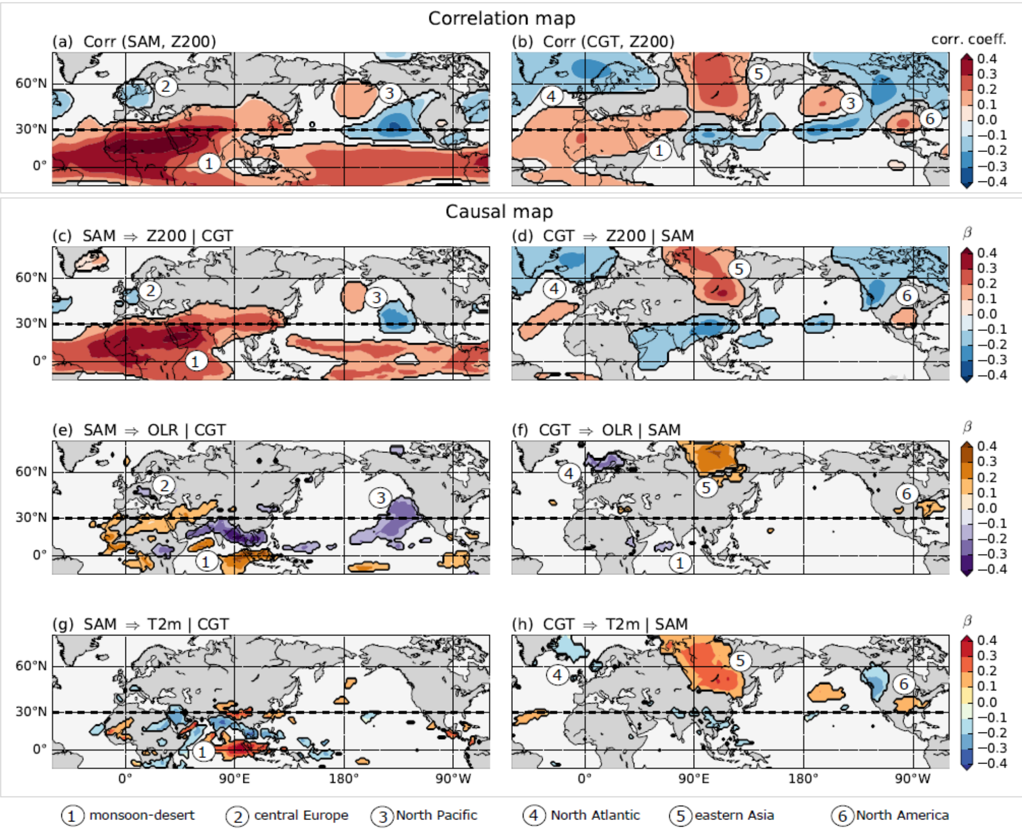

Figure R5. New Fig. 3.

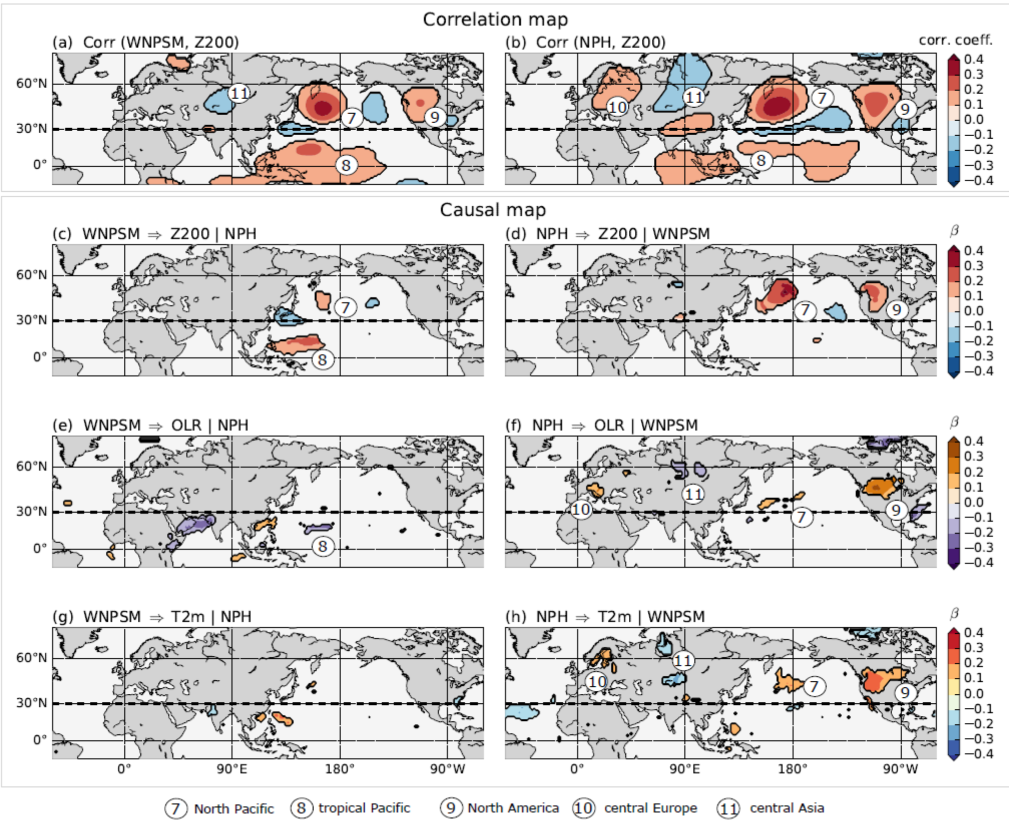

Figure R6. New Fig. 4.

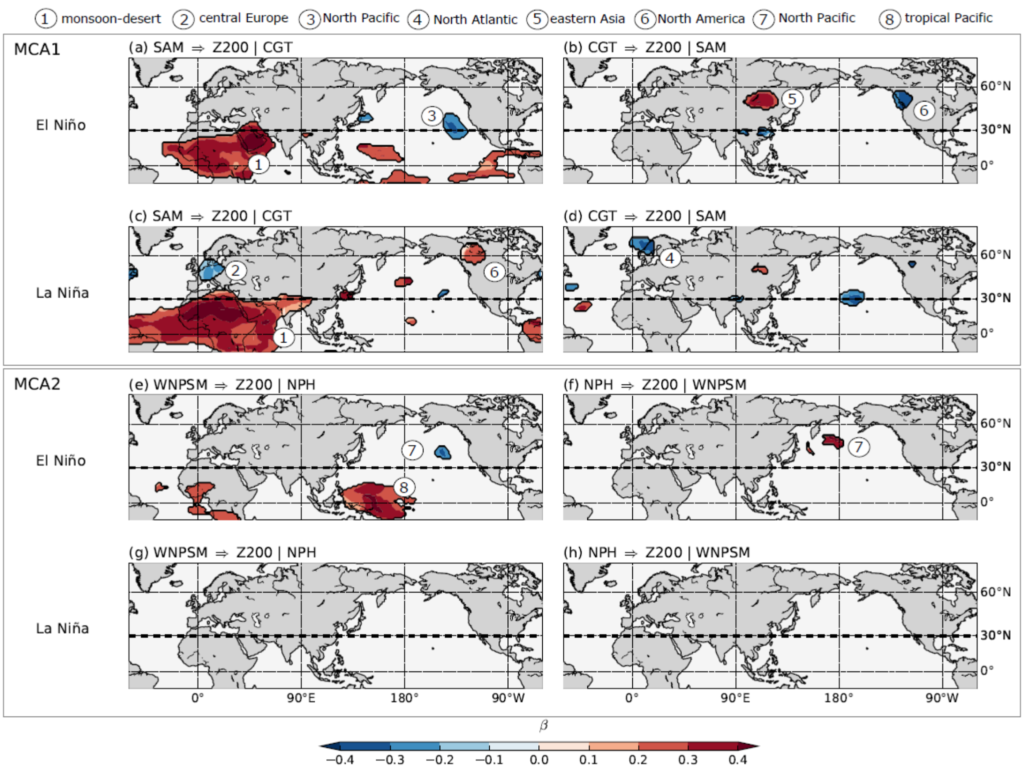

Figure R7. New Fig. 5.

L282: "Asia and North America are strongly affected by the CGT." It would be useful to support the qualitative judgment of the link-strength by providing beta-coefficient values in parentheses for this particular example and throughout the text, where link's strength from causal maps is described.

We thank the anonymous reviewer for this useful suggestion. We will add the values of the beta coefficients throughout the revised text to help the reader in the interpretation of the results.

L455: "apparent paradox": I am not sure there is any paradox. Studies cited by the authors describe a trend in current observations and future climate change projections, which cover two different time periods, thus such comparison is not consistent.

We have removed the sentence referring to the apparent paradox and rephrased the paragraph to make our point more carefully. The revised paragraph will read: "*Future projections describe an increase in monsoon precipitation associated with increasing global mean temperature and thermodynamic arguments (Menon et al., 2013; Turner and Annamalai, 2012). Quantifying teleconnections between the tropics and mid-latitudes is important in order to better understand and constrain future changes in boreal summer circulation, as uncertainty may arise due to changing connections to remote regions. While simulations show great uncertainty in the ENSO response to global warming (Cai et al., 2015; Chen et al., 2017a, 2015, 2017b), observations show a La Niña-like warming trend in central-western Pacific SST (Kohyama et al., 2017; Mujumdar et al., 2012).* "

L435-440: A comparison of teleconnections acting on subseasonal timescales from this study with those from other studies on interannual and decadal timescales is odd.

By comparing interannual and intraseasonal studies, we do not intend to imply that a similarity in the results obtained at different time scales *should* be expected. Nevertheless, a similarity in the pattern *is found* and this represents an outcome of our analysis that we believe needs to be discussed. In the discussion, we elaborate on what possible explanations for these findings there may be. Moreover, the similarity in these patterns between various time scales strongly suggests that there are interactions between the time scales – see for example the arguments of Sperber et al. (2000) who found a common mode of variability on intraseasonal and interannual time scales. Such commonality of patterns is necessary in order for the large scale forcing to be able to perturb the PDF at shorter time scales. See: Sperber et al. (2000) "Predictability and the relationship between subseasonal and interannual variability during the Asian summer monsoon", Quarterly Journal of the Royal Meteorological Society, 126: 2545-2574.

L56 and L496: A statement about paving the way to better predictions without further explanation is a bit bold. The CEN method has a potential to improve our understanding of climate processes but authors need to explain better how exactly this method can improve climate predictions.

We will add more in depth information on how CEN may help improving seasonal forecast in the revised version of the manuscript: "*A better understating of these teleconnections in observation can help to improve S2S forecasts. Verifying the existence and strength of causal teleconnections in forecast models, could help diagnose the origin of model biases. E.g. one could disentangle whether lower forecast skill (such as in the mid-latitude regions in summer) is related to local processes or to a misrepresentation of remote drivers. Beverley et al. (2019) showed that the CGT representation in seasonal forecasts is too weak. The CGT is important for predictability of summer extremes and its relationship with the SAM may provide some information to improve predictability. Therefore, these methods could help answering the question "where do model biases come from?" and help developing a physics-based bias correction. At the same time, CEN provide an encoded predictive model, which can be used for actual forecasting (Di Capua et al., 2019; Kretschmer et al., 2017; Lehmann et al., 2020).*"

3) **Inaccurate region description: L295: "Russia/Scandinavia": I would say "northern and eastern Europe" because this where non-zero beta values actually are. On the other hand, what does "non-corrected p values" from the caption mean, I do not find it explained.**
We now show only p-values that are corrected using the false discovery rate correction, to reduce noise and non-robust results. We have also carefully checked the description of each region in the Result section.

L323: "over Kazakhstan" I would say "north of Kazakhstan" if the region enclosed by the contour is meant. Moreover, Kazakhstan is located north-east of the Caspian Sea not north-west of the Caspian Sea.
This region did not pass the new robustness test and was removed.

L319: "a few areas": Indeed these are three regions which can be named.
We have added regional labels in the causal maps and use those references in the text.

L412: "European Russia". I would rather say "northern and eastern Europe".
We will implement this suggestion in the revised manuscript.

4) Figure 5: During El Nino years, there is a link between SAM and Z200 in the tropical Pacific, which is not present during the La Nina years, therefore the concluding statement in the results, conclusions and abstract about strong effect of El-Nino only for the second MCA mode is confusing.
We thank the anonymous reviewer for pointing out this discrepancy. We now mention that both

phases of ENSO affect the relationship between SAM and Z200: "*Thus, the second MCA mode (the WNPSM-NPH pair) has its strongest effect during El Niño summers, whereas the first MCA mode (SAM-CGT pair) is important during both La Niña and El Niño summers but with different characteristics*" and "*Nevertheless, during La Niña summers, the effect of the SAM-CGT mode is reinforced over Europe, North Africa and the Indian subcontinent and reaches northward towards Canada while during El Niño summers the effect of the SAM is mainly confined to the tropical belt. For the WNPSM-NPH pattern, a clear asymmetry between El Niño and La Niña summers is shown, with a stronger signal during El Niño (Fig. 5e,f) that is absent during La Niña years.*"

NPH and mode 2 results are not described in the text.
We now describe the results related to Mode 2: "*In the western North Pacific, the most notable feature is the presence of both the WNPSM and NPH on the North Pacific only during El Niño summers (Figs. 5e,f). During those summers, the positive causal effect of the WNPSM over the western North Pacific (Region 1 and 2 in Fig. 5e) intensifies in magnitude (absolute beta ~ 0.3-0.4) relative to the 1979-2018 mean pattern (Fig. 4c), although the geographical extent of Region 1 shrinks. Over the western tropical Pacific, in correspondence with the La Niña warm pool, a region of positive causal effect is shown (Region 2 in Fig. 5e). These features disappear during La Niña summers.*"

L417: "the pattern identified in Fig 5f with a low over central Europe and high over western Russia". I do not see a low-high dipole, the figure shows beta coefficients not geopotential. We have removed this sentence as this statement in not supported by the stricter robustness test applied in the new causal maps.

L419: ": : :wave-trains initiated by La Nina: : :" I do not follow this explanation.
We have removed this sentence as this statement in not supported by the stricter robustness test applied in the new causal maps.

Figure 5f is about El Nino effects. Similarly, L456-458: ": : : if La Nina conditions would become: : :(Fig. 5f)". Figure 5f is about El Nino effects.
This mistake had been corrected by including the correct panel for Fig. 5c.

5) An extensive use of abbreviations makes the paper a bit difficult to follow. – Adding a table describing CEN actors abbreviations would be very helpful. - Abbreviation is introduced but never used in the manuscript such as EASM (L92) and SRP (L439). - BSISO abbreviation in L138 is not introduced.
Following the suggestion of the anonymous reviewer, we have added a table showing the full name of each abbreviation used throughout the manuscript and, when useful, its dimensions. We have removed abbreviations for EASM and SRP since they are not used later in the text. We now introduce the term BSISO both at its first appearance and in the abbreviation table.