

Response to the reviewer #1:

We highly appreciate and are very thankful for the time and effort that was invested in reviewing our manuscript. The detailed and constructive feedback will help us to improve the manuscript. In the following, we provide an answer to each comment brought up by the editor and reviewers. The original comments are in italic red while our responses are in black.

In this work, the mechanism of sub-decadal climate variability leading to extreme summer temperature events over Europe are investigated by using a Large Ensemble (LE) performed with the MPI-ESM model. The results are relevant in the context of climate prediction, the analyses are robust and well presented, as the quality of the figures is good. However, the language used in this manuscript is not precise and rigorous enough for a scientific article. There are many inaccuracies that make the text difficult to understand. Surprisingly the second part of the article, from section 3.3 is much better written than the first part.

Please, revise your manuscript and improve the precision of the language to make the text clearer. Below some examples and other remarks:

We thank the reviewer for the comments and for sharing our view on relevance of this paper in the context of climate prediction. We would like to apologize for the confusion that has been caused by non-precise wording. In the following, we will go into more detail on how we intend to eliminate these and other sources of ambiguity.

1. Abstract. The abstract is a very important part in the article. It needs to be well written. Please consider to rewrite the abstract to be more precise. Below an example of a rewritten abstract. This precision should be used throughout the text.

The internal variability of European summer temperatures has been linked to various mechanisms from sub-seasonal to multi-decadal timescales. However, the mechanisms controlling sub-decadal (< 10 years) variations remain unexplored. We find that sub-decadal time scales (3-5 years) dominate summer temperature variability over large parts of the European continent. We show that extremely warm summers over Europe, occurring in sub-decadal periods, are related by a strengthening of the Atlantic Ocean subtropical gyre, an increase of meridional heat transport, and an accumulation of ocean heat content over the North Atlantic several years prior to the extreme event episode. The ocean warming affects the ocean-atmosphere heat fluxes, leading to a weakening and northward displacement of the jet stream and increased probability of occurrence of atmospheric blockings over Scandinavia. Thus, our findings link the occurrence of extremely warm European summers to the thermal inertia of the North Atlantic Ocean, whose potential to improve the predictability of extremely warm summers several years ahead is of great societal interest, especially in a warming climate.

We would like to express our appreciation for this very detailed suggestion on how exactly to rewrite the abstract. We will revise the abstract and the whole text regarding the clarity of our wording again.

1. Line 16: "increase in variability" needs to be more precise.

By "increase in variability" we refer to the increase in internal temperature variability, which, together with the general temperature increase, leads to more extreme European summers, as demonstrated by the cited studies. To clarify this, we plan to use "increase in internal temperature variability" instead of just "increase in variability".

2. *Line 21: Remove “as part of the large-scale....”*

We will remove "as part of the large-scale....".

3. *Line 25: “In particular” means what here ???*

"In particular" refers to "long memory mechanisms" at the beginning of the sentence. However, we agree, that this wording could be clearer, therefore we plan to split the sentence into two parts and mention „long-memory mechanisms“ again in the second sentence. We plan to change “...variability, in detail such as...” to “...variability. This means in detail long term mechanisms such as...”.

4. *Different ocean-related quantities: Define*

The different ocean-related quantities refer e.g. to the overturning stream function, ocean heat content, barotropic stream function, and sea surface temperature. In order to specify this term, we plan to change this sentence to “The variability in the North Atlantic region for different ocean-related quantities, such as the overturning stream function, ocean heat content, barotropic stream function, and sea surface temperature, indicate a fully coupled atmosphere-ocean cycle with a period of about 7-10 years”.

5. *Line 28: Please, include all the references at the end of the sentence and not in the middle. This is applicable to the rest of the article.*

We agree with the reviewer that references at the end of sentences enhance the readability and thus contribute to the clarity of the text. We will change this throughout the revised manuscript.

6. *Lines 31-33: Please rewrite, not very understandable.*

We will rewrite this section such as “This research aims to address these inquiries and present a comprehensive explanation for the occurrence of unusually hot European summers attributing it to the heat accumulation that occurs several years in advance. Our investigation concentrates on the exceptionally warm European summers that occur during multi-year periods.”

7. *In the introduction there should be a reference to DCP-C (AMV pace makers experiments) and their findings. I think that the findings of this project are relevant and need to be mentioned in this article.*

Thanks for this suggestion. We agree with the reviewer and plan to add a reference to the Decadal Climate Prediction Project (DCPP) and in particular their AMV pace maker experiments when mentioning the Atlantic multi-decadal variability, such as Boer et al. (2016), Ruprich-Robert et al. (2021), or Qasmi et al. (2021).

Boer, G. J., Smith, D. M., Cassou, C., Doblas-Reyes, F., Danabasoglu, G., Kirtman, B., Kushnir, Y., Kimoto, M., Meehl, G. A., Msadek, R., Mueller, W. A., Taylor, K. E., Zwiers, F., Rixen, M., Ruprich-Robert, Y., and Eade, R.: The Decadal Climate Prediction Project (DCPP) contribution to CMIP6, *Geosci. Model Dev.*, 9, 3751–3777, <https://doi.org/10.5194/gmd-9-3751-2016>, 2016.

Qasmi, S., Sanchez-Gomez, E., Ruprich-Robert, Y., Bo., J., and Cassou, C.: Modulation of the Occurrence of Heatwaves over the Euro-Mediterranean Region by the Intensity of the Atlantic Multidecadal Variability, *Journal of Climate*, 34, 1099–1114, <https://doi.org/10.1175/jcli-d-19-0982.1>, 2021.

Ruprich-Robert, Y., Moreno-Chamarro, E., Levine, X. *et al.* Impacts of Atlantic multidecadal variability on the tropical Pacific: a multi-model study. *npj Clim Atmos Sci* 4, 33 (2021). <https://doi.org/10.1038/s41612-021-00188-5>

8. *The term “Multi-year” is not precise. It is better to use sub-decadal.*

We agree and will change “multi-year” to “sub-decadal” in the revised manuscript.

9. *We use the largest ensemble...are you sure ?? I think that other LE also provide 100 members.*

Sorry for this confusion. To our knowledge there is one additional 100-member large ensemble available with historical and future scenario simulations from a fully coupled climate model, the CESM2-LE. Although this ensemble consists of two sets of 50-members under slightly different forcing conditions and provides only one future scenario, we will clarify this point in the manuscript to “one of the largest” to avoid ambiguities.

10. *What’s a single model initial condition large ensemble?*

Single-model initial condition large ensemble refers to a term widely used in literature to describe a set of simulations from a single climate model under the same forcing conditions but starting from different initial conditions. We will clarify this point in the manuscript.

11. *North Atlantic ocean heat inertia, ocean is missing several times in the text after North Atlantic*

We thank the reviewer for this comment and will add “ocean” throughout the text.

12. *Remove “doing so”, it’s too familiar*

We will remove “doing so” throughout the text.

13. *Line 41: We confirm that the MPI-GE can represent sub-decadal temperature variability well..., where?*

This result can be found in section 3.1, where we analyze whether MPI-GE exhibits good representation of sub-decadal time scales in terms of their dominant time frequency with a cross-spectral analysis (fig. 1a compared to fig. 1b). and check how many extremely warm European summers can generally be found per grid point (fig. 1c).

14. *Remove” by identifying periods that increase....summers”*

We will remove this part of the sentence.

15. *...are done -> are performed*

We will change “are done” to “are performed”.

16. *12-150 km à ??? what does it mean ?*

We will revise and expand the section on the ocean model grid/resolution. The MPI-M ocean model employed in our study (MPI-OM in GR15 resolution, Marsland et al. 2003) is formulated on a C grid and orthogonal curvilinear coordinates. To circumvent grid singularities at the geographical North Pole, the northern grid pole is shifted to Greenland, leading to high resolution in the Arctic and the high-latitude sinking regions. The horizontal resolution is about 1.5° on average and varies from a minimum of 12km close to Greenland to a maximum of 180km in the tropical Pacific. The model has 40

vertical non-equidistant z levels, of which 20 are distributed in the upper 700m. The coupled model does not employ flux adjustment.

Marsland, S. J., Haak, H., Jungclaus, J. H., Latif, M., & Röske, F. (2003). *The Max Planck Institute global ocean/sea ice model with orthogonal curvilinear coordinates*. *Ocean Modelling*, 5, 91– 127.

17. ERA5 reanalysis -> include reference

We already included a reference at the end of the sentence (see Hersbach et al., 2018 line 57).

18. MPI-GE can represent the sub-decadal time scales well -> with respect to ???

We analyze whether MPI-GE exhibits good representation of sub-decadal time scales in terms of their dominant time frequency compared to ERA5. This means whether the model accurately captures the frequency at which significant variations and patterns occur within periods of 5-10 years. We will clarify this sentence in the revised manuscript by adding “dominant time frequency”.

19. Please rewrite sentence *Doing so,*

For more clarity and in order to avoid “doing so, ...”, we plan to combine this sentence with the previous sentence. “We perform the multi-tapering for all 100 ensemble members and each grid point to ascertain the dominant timescale, where the dominant timescale is given by the highest significant peak [Arthun et al., 2018, Ghil et al., 2002].”

20. Remove “around the red noise”

We will remove “around the red noise”.

21. Are you using daily data ? how the summer is defined here ?

We are using monthly data averaged to seasonal summer means over June, July, and August. We plan to add the temporal resolution, as well as the study domain to the method section.

22. The way the temperature extremes are defined in MPI-GE should be explained in the “Methods” section.

We agree and plan to add the following definition “We define extremely warm European summers on sub-decadal timescales, hereafter referred to as extremely warm summers, as those summers which JJA mean temperature anomalies in the region between $\sim 15^{\circ}$ - 35° E and 45° - 60° N exceed their 90th percentile and additionally occur in a positive bandpass-filtered phase (pooled in time and ensemble ($T > 90$ th perc. and $T_{\text{bandpass}} > 0$))” to the method section.

23. I understand that the computations are done separately for each member in MPI-GE ? So what it is presented in the figures ? the ensemble mean of the quantity ?

As the reviewer already mentioned we perform the spectral analysis individually for each ensemble member in MPI-GE. Afterwards we take the mean over all spectra for each grid point. For every grid point at least one peak was significant after a chi-squared 95% interval, if more than one peak for a specific grid point were significant, the more highly significant one was chosen. We hope that this answers the question and we plan to add the fact that we take the mean over all spectra afterwards to the multi-taper method section.

24. Line 81. This is the conclusion of the paper, this is indeed what you want to prove...

We agree that this statement might be misleading in this paragraph. We plan to rewrite this section and to move this sentence to the conclusions.

25. Which variable is used as “temperature” to determine the extremes ? surface temperature, 2m temperature ?

For all of our analyses we used the temperature at 2m height (T2m). We will add this to the revised manuscript.

26. Line 87. In summary, sub-decadal timescales of 5-10....i do not understand the link to MEAN summer temperature since the focus are here the extremes...

Here, we used “mean“ since the cross spectral analysis is performed for the whole time series, not only extremes (a homogenous time series is needed for this kind of analysis). In the first figure only sub-figure 1c refers to extremely warm European summers, which are defined as those with mean summer temperatures above the 90th percentile. We have to apologize for this confusion and will add more text to explain the connection between the dominant time scales (fig. 1b) and number of extremely warm summers (fig. 1c).

27. Lines 90-91, Figure 1.d. I see that there are significant peaks at periods of 15 and 2-4 years. I would not conclude that the sub-decadal is the dominant frequency here...

We agree with the reviewer that the peak at about 15 years is the most dominant one, however, with this figure we want to show that the sub-decadal time scales also have significant peaks over Central Europe and thus we have a good reason to analyze them further. We plan to make this clearer in the text.

28. Line 94. North Atlantic ocean heat content variability

We thank the reviewer for this comment and will add “ocean“ and “content“, not only here, but throughout the text.

29. Figure 1.a and 1.b are not performed at the same spatial resolution, however it is mentioned that ERA5 is regridded on MPI grid, can you clarify ?

We have to apologize for this confusion. We decided to maintain the figure as it is without regridded data and will remove this erroneous statement from the manuscript.

30. Line 98. Please be more accurate and define “years” throughout the text.

We agree, that we haven't used “years“ in an appropriate way in this manuscript. We plan to use “...up to three years prior to an extreme summer“ instead of “...years prior to an extreme summer“. We will change it throughout the manuscript.

31. These high “positive” anomalies...

We will add “positive“ to this sentence.

32. Line 104. Some relation to other long-term climate variability models over the Pacific... can you specify??

In order to be more concrete, we will add the Pacific Decadal Oscillation and Tripolar Pacific Index as examples for possible other modes of ocean variability to this sentence, such as “Although the global anomaly pattern suggests some relation to other long-term

climate variability modes over the Pacific, such as the Pacific Decadal Oscillation and Tripolar Pacific Index ...“.

33. Please, rewrite lines 106-110.

We will change these sentences to “Specifically, this means that no specific ENSO phase (El-Nino, La-Nina, Neutral) can be concretely associated with extremely warm European summers on sub-decadal time scales, meaning that the fraction of extremely warm European summers during the different ENSO phases is consistently low for different lags. Whereas, the fraction of extremely warm European summers strongly relies on the state of the North Atlantic oceanic variables. Whether this relationship is coincidental and caused by an extraneous process (Cane et al., 2017), or whether this response is indicating a causal relationship, is further investigated in the following.“ Further, we will also study the influence of the Tripolar Pacific Index in addition to the influence of ENSO (see comment 34), we will add the results to the sentence above as we proceed.

34. In addition to ENSO, have you consider the TPI (Tripolar Pacific Index) or IPV ? Anomalies shown in fig.2 look very much to TPI spatial structure.

Thanks for this comment, so far we only tested a possible teleconnection with ENSO as one of the most well-known and influential teleconnections for European climate. However, of course it is worth mentioning that the ENSO teleconnection is just one of many factors that can influence European weather patterns, and other climate phenomena, such as the TPI, might also play a role. Therefore we agree with the reviewer and plan to test also the possible influence of TPI on our analysis.

35. Line 120. Please, define the meridional ocean heat transport better.

We will include in the revised manuscript a proper definition (including formulas) of the meridional ocean heat transport computation, both of the total and of the amoc/ gyre heat transport components.

36. Line 145. “During the extreme.” Please be more accurate.

“During the extreme“ refers to the year when the extremely warm European summer occurs, which is lag 0. We will change the old wording to this more precise wording.

37. 149. “temperature anomalies fit...” do you mean spatially fit ??

Indeed we mean “spatially fit“ here. We will add this to the corresponding sentence.

38. Line 150. The heat transfer from the ocean to the atmosphere.

We will rewrite this sentence as suggested by the reviewer: “The transfer of heat from the ocean to the atmosphere is so strong that its signal reaches up to 200 hPa altitude ...“.

39. Line 152. Extremely European warm summers.

As suggested by the reviewer, we plan to use “extremely warm European summers“ instead of “heat extremes“.

40. Line 165: The North Atlantic OCEAN heat inertia...

Thanks again for this comment. As already written, we plan to change “North Atlantic” to “North Atlantic ocean” throughout the text.

41. Line 168. “together with an above average...” of what??

“Together with an above average” refers to the volume transport of the barotropic stream function mentioned later in the sentence. We can see where this confusion comes from and will rewrite the sentence to make it clearer to what this refers to: “Positive anomalies of the ocean heat content, together with an above average horizontal volume transport as well as more northern horizontal volume transport of the barotropic stream function lead to a stronger North Atlantic current and accumulation of heat content.”

42. Lines 170-171. Please, specify where the “released heat” goes...to the atmosphere??

Indeed the reviewer is right and the released heat goes into the atmosphere. We will add “to the atmosphere” in the corresponding sentence.

43. Line 181. Rewrite: We find that the coupled oscillation in the North Atlantic prescribes extremely warm European summers on sub-decadal timescales.

We will rewrite this sentence using more precise wording and tone it also down, such as “We find that the coupled oscillation in the North Atlantic influences the occurrence of very hot summers in Europe on sub-decadal time scales.”

44. Line 182. Other modes of ocean variability? Could you specify?

In order to be more concrete, we will add the North Atlantic Oscillation, El Niño-Southern Oscillation, and Pacific Decadal Oscillation as examples for possible other modes of ocean variability to this sentence. “However, on this timescale other modes of oceanic variability, such as the North Atlantic Oscillation, El Niño-Southern Oscillation, or Pacific Decadal Oscillation may also be influential.”

45. There are other mechanisms leading to the occurrence of extreme events over Europe-Mediterranean, this should be mentioned in the text. Please see Qasmi et al. 2021 and references therein.

We agree that extreme events are often the result of a combination of multiple factors and that also other mechanisms could lead to the occurrence of extreme events over Europe. We will add a paragraph discussing the influence of the NAO and AMV, such as “Additionally, our findings might also be impacted by other mechanisms that interact with each other and possibly lead to the occurrence of extreme events over Europe, e.g. the North Atlantic Oscillation (NAO) and the Atlantic multi-decadal variability (AMV) exert significant influence on the occurrence of extreme events over Europe (Scaife et al., 2008, Qasmi et al., 2021). The NAO plays a crucial role in shaping weather patterns, contributing to the development of heatwaves and droughts, while variations in the AMV can impact atmospheric circulation patterns, influencing the frequency and intensity of extreme events.”

46. The fact that the study was conducted with only one climate model should be discussed in the last section, as the mechanism described in this study could change from one model to another... so there is still uncertainty linked to the model used. We

are not sure that a different Large Ensemble performed with a different model would give the same results.

We agree with the reviewer and plan to add a paragraph along the lines “This study is a single model study which allows us to delve deeper into specific processes and model intricacies, which can contribute to model improvement and process understanding. Replicating this analysis for different climate models would be of great importance to sample potential model uncertainty in these results and help us gain further understanding of this mechanism.”