Reply to
1st Reviewer
Russo, E., Fallah, B., Ludwig, P., Karremann, M., and Raible, C.C.: The long-standing dilemma of European summer temperatures at the Mid-Holocene and other considerations on learning from the past for the future using a regional climate model

Dear referee,

thank you very much for accepting to review our manuscript and for the time you dedicated to its revision.

Below we go point by point through your technical corrections, presented in *italic*, detailing how we dealt with your concerns reported in **bold**.

Sincerely,

Emmanuele Russo

General Comments

The authors use a regional climate model to investigate the role of spring soil moisture in influencing summer temperatures over Southern Europe and Mediterranean during the mid-Holocene. The authors find that increasing soil moisture generates cooler summer temperatures, identifying a potential source of model bias that may help explain proxy-based paleoclimate reconstructions that show cooler than present mid-Holocene summer temperatures in many parts of the region while models show a uniform warming. The paper is very well written and the project is well designed. I think that it is eminently suitable for publication in Climate of the Past, and I can thoroughly recommend its publication with only minor changes. The paper provides what I think is an interesting and important contribution to both modern and palaeo climate science. I have some questions and general comments, as well as a few minor technical corrections.

- *Q1. What influence could change in soil depth and quality have compared to winter rainfall on soil moisture content? I presume that models use modern soils, but if mid-Holocene soils were better quality and* *depth then presumably they could create a similar effect since it would allow increased retention of winter/spring rainfall. Model soil hydrology is quite crude (especially in GCM's) but there is also quite a considerable body of evidence that suggests the Mediterranean region lost soil in the late Holocene as a result of natural and anthropogenic aridification. This could mean that better soils in the MH could result in more soil moisture being held in the spring, irrespective of any change in winter rainfall. See for instance https://iopscience.iop.org/article/10.1088/1755-1315/9/1/012011. It may be worth adding a comment on this.*

Uncertainty related to changes in soil composition or quality on millennial time scales is something that definitely needs to be better considered when performing and interpreting paleoclimate modeling simulations. Different and better soil would very likely impact the results (as evident also for present-day studies [Guillod et al., 2013, Smiatek et al., 2016]) and is something that deserves to be properly taken into account in future studies for the MH, considering that soil might have plausibly changed on millennial time scales. Our experiments do not allow to exhaustively assess the influence of winter precipitation versus changes in soil composition and quality on soil moisture content available at the beginning of summer. For this task a more comprehensive set of experiments should be performed using a larger ensemble of climate models of different complexity. Nevertheless, following the referee's comment, we will better discuss this point, acknowledging its importance, in the new version of the manuscript.

- *Q2. How does increased soil moisture generate the observed summer cooling? It would be interesting to know to what extent this is a result of, for instance, latent heat, evapotranspiration, clouds or atmospheric circulation changes. Perhaps the authors could add a paragraph on this as it would be interesting to know the degree to which the effects are felt locally (similar to the thermodynamic effect of orbital changes in insolation) or over some distance.*

The summer cooling obtained for the experiments with enhanced spring soil moisture is due mainly to a larger partition of the incoming energy towards latent heat, with a consequent increase in

surface evapotranspiration and near surface temperatures. This is visible from the plots we provide here in Fig. 1. The plots present summer biases in evapotranspiration and latent heat calculated between the simulation with saturated soil (+100%) and the one with 50% relative soil moisture in spring (reference state). The pattern of the two maps is almost the same, and pretty similar to the corresponding map of the bias in near surface temperatures (Fig. 5 of the former version of the manuscript). An excess of latent heat flux (negative sign taken in the upward direction) and evapotranspiration is evident over a large part of the domain, consistent with the pattern of cooler temperatures for the corresponding experiment with enhanced spring soil moisture. Following the referee's comment, we will try to better describe the effect of increased spring soil moisture onto summer temperatures in our experiments, in the new version of the manuscript. However, we would like to avoid having an additional section in the paper, since we think it results already quite lengthy.

- *Q3. The authors mention the debate about summer cooling over southern Europe and the Mediterranean during the mid-Holocene. Their experiments show cooling with increased soil moisture, but is this cooling of sufficient magnitude to override the strong warming in the model and therefore cause the negative temperature anomalies shown in the proxy evidence? As far as I understand it, figure 5 shows the effect of soil moisture on summer temperatures relative to the normal model state at the MH, and not summer temperatures as an anomaly compared to the PI. It would be useful to include a comment or figure (even in the supplementary) on this to see whether it is likely to approach the cooler than present summer temperatures shown in the proxy evidence.*

We want to emphasize here again that the main goal of our study is not to properly quantify the effect of soil moisture on summer temperatures. Rather, we want to show that there is a strong spatial dependency of MH summer temperatures on the soil moisture available in spring over Europe, that needs to be carefully acknowledged when interpreting climate models results. Our experiments are very helpful in this sense: even though the "default" outputs of our model are in agreement with previous modeling works, and also with proxy-based reconstructions such as the one of Samartin

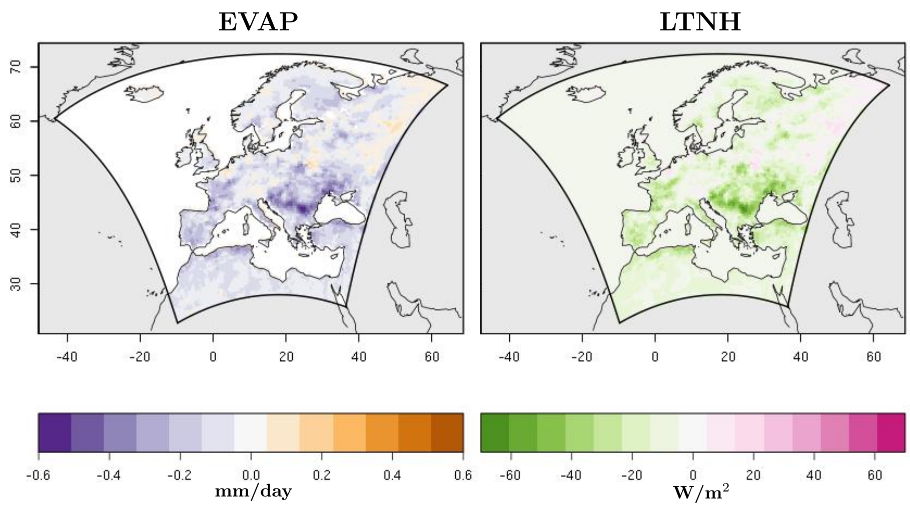

Figure 1: **Differences in summer mean of daily values of evapotranspiration (*left*) and daily mean latent heat flux (*right*), calculated between the simulation with saturated spring soil moisture and the one with 50% relative soil moisture. The sign of the fluxes is taken negative in the upwards direction.**

et al. [2017], its results change remarkably over specific areas when perturbing spring soil moisture. At the same time, following the referee's comment, we want to specify here that figure 5 shows the effect of soil moisture on summer temperatures relative not to the normal model state, but to a state with 50% relative soil moisture in spring. In this case, the summer cooling resulting from increased spring soil moisture seems quite restrained in order to fit the picture drawn from pollen-based reconstructions. However, when considering the differences between the wettest (+100%) and the driest (-75%) of our set of sensitivity tests presented in the former version of the manuscript, we see that very large differences (down to -7°) are evident in particular over the Balkans and the areas North of the Black Sea (Fig. 2 of the current document). This pronounced differences suggest that, over some regions, higher spring soil moisture content could very plausibly help approaching the cooler than present summer temperatures shown in the pollen-based reconstructions. Following the referee's comment, we will review our results and discussion section in the new version of the manuscript, trying to make these evidence clearer to the reader.

- *Q4. P4 10-14; The authors highlight the importance of the GCM in which regional models are embedded (eg Armstrong et al 2019). To what degree could the choice and performance of the GCM impact the result? For instance, we know that GCM's have difficulty simulating the mid-Holocene African Monsoon, and therefore probably the Hadley Cell and sub-tropical high pressure over the Mediterranean in summer. This may be related to my Q2, and particularly to what degree the spatial pattern of cooling caused by soil moisture changes could be dependent on the GCM outside of the regional model (e.g. atmospheric dynamics etc). Maybe a comment would be useful just to say whether this is/is not important, and why.*

The selection of the driving GCM definitely has an important impact on the results of an RCM, especially for Europe [Sørland et al., 2021]. A different spatial sensitivity of European summer temperatures from the soil moisture available in spring/late winter could likely result from the use of a different GCM. This could happen, for example, as a consequence of changes in cloud cover

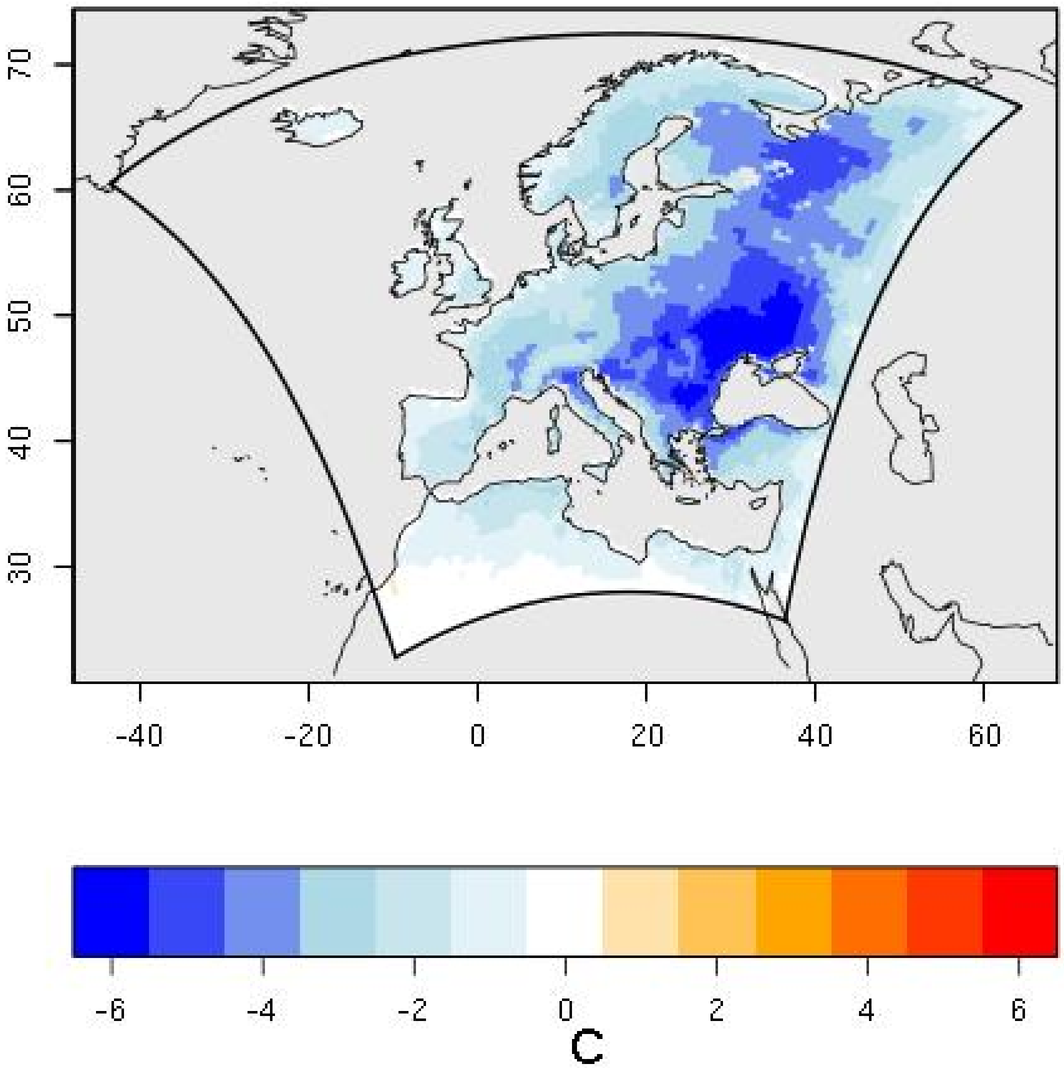

Figure 2: **Differences in summer mean near surface temperatures calculated between the simulation with saturated spring soil moisture and the one with a 75% soil moisture reduction with respect to the reference with half-saturated soil.**

associated with different large-scale features imposed by the driving GCM, affecting the pattern of incoming shortwave radiation at the surface. We agree with the author that this is a point deserving more attention, and we will try to add some comments in this regard in the new version of the manuscript.

- *P5 22-23; The soil in the model is an important part of the story here. Where has the soil data come from that is used in the model? And what are the main variables used? eg carbon content, particle size, permeability etc. There are different sources with different qualities (eg FAO, EU etc)*

We agree with the referee that detailed information on soil characteristics are missing in the former version of the manuscript. Our simulations use a soil map derived from the digital soil map of the World (FAO, 2003). The soil model has 8 different soil types. For each grid box, the soil in the column belongs to the same soil type. Each soil type has constant values prescribed in the model, for different parameters such as pore volume, field capacity, permanent wilting point, heat capacity, etc. A table with the values of the different soil parameters is provided in Doms et al. [2013]. Following the referee's comment, we will provide more detailed information on the soil map used in our study and on TERRA_LM, together with corresponding references, in the new version of the manuscript.

- *P9 18 P11 11-12; See also my earlier comments in Q1 about MH soils in the Mediterranean region being different than the modern soils in the region*

Please refer to our answer to your previous point.

Minor technical corrections

The text has some minor grammatical errors and typos. I highlight some here, but please take time to have another careful read of the text, particularly from section 3 onwards.

- *P2 28 'Despite different studies have used..' Different studies have used climate models for investigating MH summer temperatures, but no thorough..*

Thanks. We will modify this part accordingly.

- *P4 2 'stationarity proper of..' stationarity in calibration (?)*

We refer here to the stationarity of the relationships between model outputs and "reality". We will try to make it clearer in the text.

- *P4 6 'In a first place..' Firstly,*

We will modify the text accordingly.

- *P5 9; 'covering entire Europe' covering the whole of Europe*

Thanks. We will correct this part.

- *P5 9; 'used as boundary' used as a boundary*

We agree and will modify this part of the text accordingly.

- *P9 5; 'to not appreciable..' to no appreciable..*

Correct.

- *P9 15; 'The here presented..' The experiments presented here..'*

We agree and will modify the text accordingly.

- *P9 23; 'different forcing.' different forcings.*

We will modify the text accordingly.

- *P9 27, P10 5, P10 12; 'nature' do you not mean 'natural' state?*

Here we simply wanted to name the simulation that we assume closer to reality as the "nature" state. Therefore, we used a name instead of an adjective. We feel that this can be well regarded as a personal preference.

- *P9 27-28; 'what would normally' that would normally*

We agree and will modify the text accordingly.

- *P11 17; 'maintain its' maintains its..*

This will be corrected following the referee's suggestion.

Figures

- *Fig 1; Scale needs attention, blank above 2500m*

We will remove white from the colorbar.

- *Fig. 3 'subtracting to the climatological. . . ' not sure what is meant here so no suggested replacement text, but the whole sentence needs another look.*

We will revise the caption of Fig. 3, trying to make it easier to read.

- *Fig. 3; Convention would suggest using blue for cooler and red for warmer (use green/brown for drier)*

Agree and we will change the employed colors for this plot, following the referee's suggestion.

- *Fig 4; 'mea'? not sure what this means.*

Here we wanted to refer to the "mean". We will correct this typo in the new version of the manuscript.

- *Fig 6; Can you use a different value on the x axis rather than hours? I have no concept of how long 1000's of hours are (having looked it up, 1000 hours = 42 days). The y axis would also be better scaled in mm rather than in metres, and it would be easier to understand if the labels for each of the 9 levels included their depths, or at least something to give them more meaning if possible.*

We will modify the plots of Fig. 6 following the referee's comments.

References

G. Doms, J. Föster, E. Heise, H.J. Herzog, D. Mironov, M. Raschendorfer, T. Reinhardt, B. Ritter, R. Schrodin, J.P. Schulz, and G. Vogel. A description of the nonhydrostatic regional cosmo-model - part ii: Physical parameterizations. Technical report, COSMO - Consortium for Small-Scale Modelling, 2013.

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