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Earth System Dynamics Discussions

Interactive comment on "Storylines of the 2018 Northern Hemisphere heat wave at pre-industrial and higher global warming levels" *by* Kathrin Wehrli et al.

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We thank the reviewer for the positive and thoughtful evaluation of the manuscript. We appreciate the comments on the selection of the study regions and the bias correction of absolute maximum daily temperatures. We have followed the recommendations and computed new figures that will be included and discussed in the revised manuscript. We now use quantile-mapping to bias-correct our model simulations. The area affected by maximum daily temperature > 40°C has changed due to the new bias correction method. The new results agree better with observations and are qualitatively still in-line with earlier results. Below we will answer the specific questions of the reviewer.

For readability the questions are shown in black *and answers are shown in* blue*.*

1. Figure 3 shows only temperature anomalies. It would be good to also show absolute temperatures (e.g. in the maps), so that the reader can see the extent of the temperature bias of the model.

A1: We agree with the reviewer that biases of absolute temperature of the model and their correction is important. It is well-known that the majority of CMIP5 models, including CESM, overestimate summer temperatures in Northern Hemisphere midlatitudes (e.g. Mueller and Seneviratne, 2014, GRL; Wehrli et al., 2018, GRL; also shown for TXx in CESM in the latter). In the revised manuscript we add plots of absolute TX (mean over Jul. 13-27 2018) to Appendix Figure A3, which show the bias-corrected (using quantile mapping) CESM historical simulation against different references. Since it is known that model biases are large, we do not think it is necessary to show the magnitude of the bias. It is, however, crucial to discuss the bias correction and check the bias-corrected model against reference data sets. For reference we show in this comment a comparison of TXx > 40°C for the original model output, mean bias correction and quantile mapping (using both Berkeley-Earth and ERA-Interim as reference) against ERA-Interim and Berkeley Earth (see Fig. 1 at the end of the comment).

References:

Mueller, B., and Seneviratne, S. I. (2014), Systematic land climate and evapotranspiration biases in CMIP5 simulations, Geophysical Research Letters, 41, 128-134. https://doi.org/10.1002/2013GL058055.

Wehrli, K., Guillod, B. P., Hauser, M., Leclair, M., Seneviratne, S. I. (2018). Assessing the dynamic versus thermodynamic origin of climate model biases. Geophysical Research Letters, 45, 8471-8479. https://doi.org/10.1029/2018GL079220.

2. In some periods and regions, the differences between the nudged run and ERA-

Interim anomalies in the time series in Figure 3 can exceed 1°C for extended periods. Do you have any idea why this would be the case, given that generally the differences are much smaller?

A2: We can only speculate about the reason for the large differences between the nudged run and ERA-Interim temperature anomalies in Figure 3. The most striking case is NEU and we verified that the difference is largest during two shorter periods in mid- and end of June and the period shown in Figure 3 in the beginning of July. For these periods warm anomalies are overestimated, whereas during the rest of the year the differences are generally smaller. One possibility is that during the NH2018 heatwave soil moisture got depleted even in regions that are usually rich in moisture (so-called wet regime), which causes the land surface to react very sensitive to a further decrease in soil moisture and to incoming radiation (i.e. change from wet to transitional regime). If the model dries faster or transitions to a radiation-sensitive state earlier than ERA-Interim this might result in a more sensitive and more pronounced response in temperature. With decreasing moisture availability, more incoming radiation will contribute to sensible heat flux and hence to increased temperature.

3. Comparing Figure 1 and Figure 3, with the exception of the southern portion of NEU the study areas seem almost to be orthogonal to the areas of maximum temperature anomaly, and one of the most striking AgPop regions where there is a high temperature anomaly, eastern Asia, is not included in the study. Thus the choice of study areas seems quite odd. It would surely be straightforward to include a relevant east Asian SREX region for completeness, which would mitigate the European/North American bias of this study.

A3: We agree with the reviewer that our choice of regions was biased towards Europe and North America. In the revised manuscript we include the Eastern Asian SREX region (EAS) in the figures and analysis. The region of Neufundland/Quebec would also be interesting to examine. However, there is no SREX region that would be suit-

able. The Canada/ Greenland/ Iceland SREX region (CGI) encompasses large areas with temperature anomalies of the opposite sign (e.g. Greenland). We decided to not define a new region specifically for this case. Apart from the just-mentioned region in north-eastern America, we believe that the interesting regions for the 2018 heat wave are addressed in this study. The Mediterranean was not strongly affected by heat waves during summer 2018, which was discussed in other studies (e.g. Toreti et al., 2019). Therefore, we thought it is interesting to include this region in the analysis. Except for the scaling plots (Figure 7) and time series in Figure 3, results always show the entire Northern Hemisphere north of 25°N and the discussion is not limited to the SREX regions.

Reference:
Toreti, A., Belward, A.,Perez-Dominguez, I., Naumann, G., Luterbacher, J., Cronie, O., et al. (2019). The exceptional 2018 European water seesaw calls for action on adaptation. Earth's Future, 7, 652–663. https://doi.org/10.1029/2019EF001170.

4. In all three SREX regions of North America, the difference between the nudged run and either ERA-Interim or Berkeley for the maximum daily temperature anomalies (Figure A4), especially for some of the largest values, can be much larger than the difference of the mean daily temperature anomalies (Figure 3). What is the reason for that? And how does it affect your estimates of extreme temperature? This feature suggests that using the climatological mean TX to bias-correct the TX values may not be adequate.

A4: One reason why differences of maximum temperature are larger than differences of mean daily temperature is that in the latter biases during the night can be balanced out by biases during the day and vice versa (overestimated/underestimated diurnal cycle can still show as correct daily mean). Connected to that, biases of mean daily temperature anomalies can affect biases of extreme temperatures (and vice versa) but they don't have to in a direct, linear way. We agree that the bias-correction of TX should be treated in more details and several methods should be evaluated for their adequacy. In the revised manuscript we apply a quantile-mapping that was tested for two reference data sets (see next answer).

5. The left column of Figure 4 apparently includes a bias correction of the model output.This is only mentioned in the figure caption, not in the methods or anywhere else. Since the bias correction is almost certain to affect the results of the study, which are framed relative to a fixed temperature threshold of 40°C, a much more detailed assessment of its effect, and the potential error incurred thereby, is required. It appears that the bias correction was simply an adjustment of the mean, which assumes that the model TX distribution is perfect. Can you support this assumption with evidence? As noted in the previous comment, the assumption would appear to be contradicted by your own results. Why did you not use quantile mapping or some other more detailed method,which would treat the tails differently from the mean?

A5: We agree with the reviewer that the bias correction was not addressed sufficiently in the manuscript. The presented method was a day-of-year dependent correction of the mean (TX) bias. We tested the presented method against a quantile-mapping bias correction using a 91-day moving window (hence, making it also dependent on the day-of-year). As could be expected, the quantile-mapped results reveal that the bias correction method strongly influences the results and the mean bias correction is less appropriate in our case. We discuss this in the revised manuscript. Figure 4 and the numbers in the manuscript are replaced by the results from the quantile mapping. We verified that the quantile mapping leads to better results: mean TX RMSE for the study period (Jul. 13-27 2018) and all land areas north of 25°N is reduced from 7.48°C in the original model to 1.95°C using mean bias correction and to 1.45°C using quantile-mapping (Berkeley-Earth as reference; qualitatively the same is true for the RMSE of the AgPop region). The area affected by temperatures > 40°C discussed in the conclusion better matches the reference data

sets (Berkeley, ERA-Interim, MERRA-2) when using the quantile mapping. With this comment we included a figure to show the effect of bias correction on TXx (Fig. 1). The values for the AgPop region > 40°C are 9.1% and 8.5% for ERA-Interim and Berkeley-Earth, respectively. The bias corrected model simulates 8.8% and 9.3% area affected (depending on the reference used for the calibration of the quantile mapping), which is more accurate than the 20% we obtain for the mean bias correction.

6. In lines 9-10, you should mention also the percentage value for the actual event, as a reference.

A6: We agree and adjusted the last line of the abstract to include the percentage value for the actual event (now changed to the new value from the quantile-mapped simulations).

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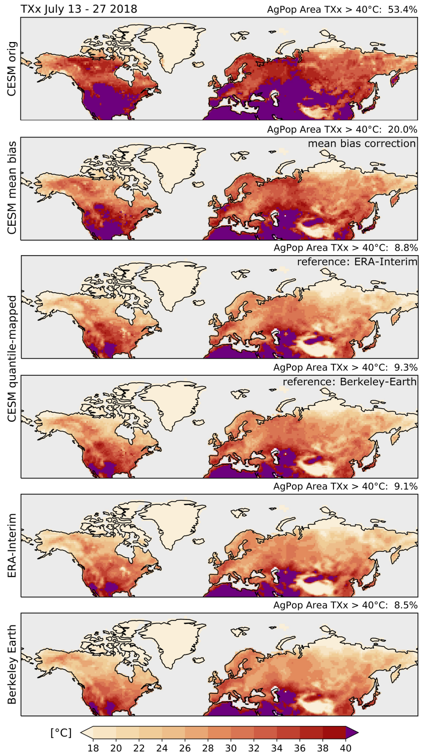

Fig. 1. TXx for 13-27 July 2018 and fraction of the AgPop region experiencing maximum daily temperatures larger than 40°C for the original and bias-corrected model output as well as two reference data sets.