Authors' response to interactive comment of the Referee #2

Black text: Referee comment
Blue text: Authors' response

Here I want to continue the discussion on the use of dominance analysis, and the variables used in the analysis. The authors provide the example of groundwater, where the technique was used to study the relative impacts of monsoon rainfall and pumping on the groundwater table dynamics. This example actually illustrates my point fairly well. In case of rainfall and pumping, nobody would argue against that these are the two main factors that control groundwater table dynamics in a rather direct, predictable and proportional way. This however is not the case when considering impacts of global CO_2 and local soil moisture deficits. The link between global CO_2 is indirect, and opposite to the groundwater example nobody would argue that there is or should be a direct link between global CO_2 levels and HWD at any particular time and location. The same is true for soil moisture. Soil moisture is known to contribute to heatwave temperatures (e.g. Miralles et al., 2014, doi:10.1038/ngeo2141), but much of the local heat actually comes from advection driven by circulation patterns (e.g. Rasmijn et al., 2018, doi:10.1038/s41558-018-0114-0 and Schumacher et al, 2019, doi:10.1038/s41561-019-0431-6). In spite of the strong correlation, the contribution of local soil moisture to heatwave temperatures is important, but by no means dominant. The problem here is the classical pitfall that correlation is not causality. Soil moisture and temperature will be strongly negatively correlated in many regions simply because synoptic conditions leading to high temperatures (clear skies) are the same as those enhancing soil drying. But this does not mean that dry soils cause the high temperatures. In regions that are wet enough for ET not to become limited by soil moisture even during hot extremes, one would not expect soil moisture to impact temperature. By only using simple correlation, these regions will incorrectly be flagged as regions where soil moisture impacts temperature. To circumvent this, more complex coupling metrics have been developed that look for instance at anomalies in the surface energy balance (see Miralles et al. (2012) doi:10.1029/2012GL053703 among many others). The main factors in determining year-to-year variability of HWDs, like circulation indices, are not considered here. By only looking at correlation between variables that only weakly and indirectly impact HWDs, statistically significant results might be found, but that doesn't mean that they also provide new or meaningful insights.

This is an interesting discussion. No doubt that this discussion will help to revise the next version of the manuscript.

We agree with you that synoptic weather systems, related to large-scale atmospheric circulations, play very important roles in influencing the occurrence of hot extremes. But the aim of this study is not looking for the dominant driver among all influencing factors. We aimed to identify the dominant one (more important one) between the two selected influencing factors (global CO_2 concentration and local soil moisture). The use of the word 'dominant' might be the root of your concern. We will replace the word 'dominant'/'dominates' by 'is more important' in next revision.

We have used both deviation of global mean annual temperature and global atmospheric CO_2

to approximate the global warming, resulting in very similar patterns (shown in our last response). CO_2 concentration was finally selected in the manuscript because it is something that human society can take action on. In addition, as we described in the previously submitted manuscript that "The observed global warming is considered extremely likely associated with anthropogenic influences, particularly greenhouse gas emission (IPCC, 2013). An increase in atmospheric CO_2 concentration as a consequence of emissions can cause an increase in extreme temperature (Min et al., 2013; Kim et al., 2016; Seneviratne et al., 2016; Baker et al., 2018).". We think it is reasonable to use CO_2 as one influencing factor in this study. However, if the editor thinks it is better to use global mean annual temperature, we are happy to do so.

The physical connection between soil moisture and hot extremes is becoming clear as Lisa Alexander explains in her article *Extreme heat rooted in dry soils*, (Alexander, 2011, doi: 10.1038/ngeo1045). We agree with you that the correlation between the two does not necessarily always points to a causal relationship in one direction or the other. Nevertheless, in the hottest month (for which the number of hot days is investigated here), the negative correlation between soil moisture and temperature is more likely to reflect the feedback of dry (primarily root-zone) soil to the atmosphere. Such feedback is expected to enhance the occurrence of hot extremes. Based on the mechanism that low soil moisture availability reduces evaporative cooling and increases atmospheric heating from sensible heat flux (Alexander, 2011), Mueller and Seneviratne (2012) (doi: 10.1073/pnas.1204330109) used correlation between hot days in the hottest month and 3-month SPI (a proxy for soil moisture) as coupling diagnostic to identify hot spots at a global scale. Those hot spots agree well with transitional climate regions (Koster et al., 2004 (doi: 10.1126/science.1100217); Seneviratne et al, 2010 (doi: 10.1016/j.earscirev.2010.02.004)) where soil moisture strongly constrains evapotranspiration variability and thus result in feedbacks to the atmosphere.

In our previous work, we did examine the other direction of coupling (i.e., hot temperature dries soil), similar as what you suggested. We investigated the correlation between temperature anomaly and remote sensed surface soil moisture and found very low correlations (see figure shown below). For some spots, the correlation is even positive, which is counterintuitive.

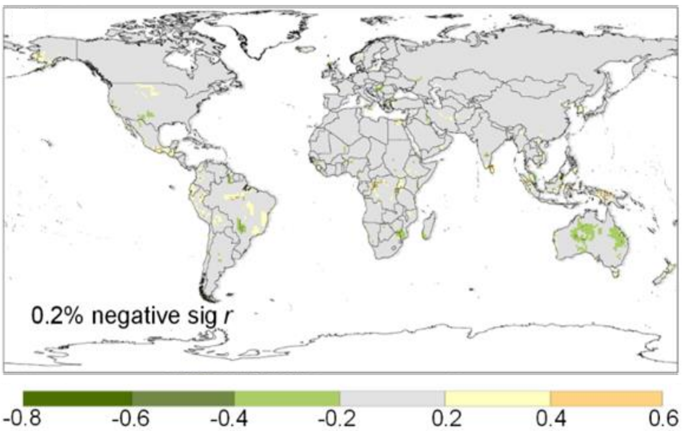

Figure R2.1. Correlation coefficients (*r*) between air temperature and surface soil moisture. Dots indicate that the corresponding *r* has passed the significance test at 0.05 significance level.

It appears that although we have discussed the causal relationship between hot extremes and soil moisture deficit in the previously submitted manuscript, it is likely not clear enough. We will improve the relevant explanation in next revision.

We hope the above discussion will convince you that it is meaningful to investigate the *relative* importance of the two selected variables, global CO_2 concentration (or average temperature deviations) and soil moisture, to hot extremes. This does not at all mean that the circulation pattern is not important in the occurrence of specific hot extremes. Since the process of atmospheric circulation is beyond the control of human society, we selected two influencing factors (global warming and soil moisture deficit) that are more likely affected by human activities so that the corresponding results are expected to provide practical advice for society in mitigating heatwaves. We acknowledge that some descriptions in our previously submitted manuscript may not be clear, we will revise the relevant text to avoid misunderstanding.