L. Samaniego (Referee #2)

General comments

a) In this manuscript. the authors use a high resolution 6-member ensemble of the general circulation model EC-Earth to get a better and more realistic position of the storm track, which in turn leads to improved representation of the soil moisture (SM) conditions in the future and characterization of SM droughts. The study domain is the central-western Europe under the RCP4.5 emission scenario. One of the major claims of the authors is that high resolution CMIP5 GCMs leads to an underestimation of soil droughts characteristics.
The subject covered by this paper is a highly relevant research topic for practitioners and researchers in hydro-climatology and climate change impacts. I wellcome this study because I am convinced that high resolution GCMs will improve the estimates of future precipitation and temperature patterns because of better parameterization of convective precipitation and land-atmosphere feedbacks.
In the present state of the manuscript, nevertheless, there are many shortcomings that have to be clarified before publication.

We thank L. Samaniego for his positive evaluation and the constructive and valuable comments concerning our manuscript, which helped to considerably improve the quality of the paper. We have studied the comments carefully and made major corrections. Our detailed responses to the comments are presented below.

Specific comments

The following technical shortcomings should be addressed in the revised manuscript:

b) The literature of future soil moisture drought projections should be updated and the insights of these studies should be put in context of this interesting study. I recommend to include:

- Samaniego, L., S. Thober, R. Kumar, N. Wanders, O. Rakovec, M. Pan, M. Zink, J. Sheffield, E. F. Wood, and A. Marx (2018), Anthropogenic warming exacerbates European soil moisture droughts, Nature Climate Change, 5, 111721, doi:10.1038/s41558- 018-0138-5.
- Hanel, M., O. X. I. Rakovec, Y. Markonis, P. M. X. ca, L. Samaniego, J. Kysely, and R. Kumar (2018), Revisiting the recent European droughts from a long-term perspective, Scientific Reports, 8(1), 111, doi:10.1038/s41598-018-27464-4.
- Hirschi, M. et al. Observational evidence for soil-moisture impact on hot extremes in southeastern Europe. Nat. Geosci. 4, 1721 (2010).
- Huang, J., Yu, H., Guan, X., Wang, G. & Guo, R. Accelerated dryland expansion underclimate change. Nat. Clim. Change 316, 847171 (2015).

- Berg, A., Sheield, J.& Milly, P. C. D. Divergent surface and total soil moisture projections under global warming. Geophys. Res. Lett. 44, 236244 (2017).
- ... and references therein.

Thank you for these recommendations. We will update and revise the introduction with these relevant recent insights and add the suggested references in the text.

c) L7, P4. Parametric uncertainty plays a very strong role in soil moisture predictions and corresponding drought characteristics (see Samaniego et al, JHM, 2013). For this reason, I consider that a ensemble of 6 members and a single land surface model is too small an ensemble to provide conclusive evidence.

We agree that a larger ensemble of different models should be used to obtain robust answers about the impact of model resolution. The use of a single model allowed us to put emphasis on mechanistic explantations for the differences between model resolutions. Certainly, these results should be verified with a larger systematic ensemble of high resolution model simulatons such as the CMIP6-endorsed HighResMIP, which are currently not available. Therefore, we will add notes in the manuscript to emphasize that a larger ensemble is required to obtain conclusive evidence.

d) L17 ff P2: Please clarify in the revised manuscript that the PDSI should not be used for climate impact studies because it does not perform well un non-stationary climate. See the explanation provided in the methods section of Samaniego et al. NCC 2018 and in its supplementary information (Fig S8, S9). Contrary to what Sheffield et al. stated in his Nature paper, the reason of the poor performance of PDSI is more likely related to the autoregressive formulation of this index rather than in the temperature-based PET formulation used in the original formulation of PDSI. The text as it written, put in context with these recent insights, is misleading or at least incomplete.

Thank you for this insightful suggestion. We will add the explanation provided by Samaniego et al. NCC 2018 in the introduction. In addition, we will strongly reduce the paragraph that discusses the PDSI results and will shift the focus to soil moisture projections instead.

e) L30 ff P2: I strongly sugest to avoid comparisons with the PDSI index (see last point) in future projections. EDgE results (http://edge.climate.copernicus.eu), which are based on downscaled CMIP5 forcings and a multi model ensemble, may be more interesting and realistic than the PDSI estimates. Data is available in nc format upon request (contact L. Samaniego if required).

We clearly understand your point. We will remove the paragraph in which a comparison of PDSI results is made and we will revise the introduction to shift the focus to actual soil moisture projections instead of drought metrics.

f) L35 ff P2: More recent insights on the future soil moisture droughts can be found in Samaniego et al, NCC 2018, e.g., an increase drought area by 40 $\pm$ 24% by an increase of 3 K. This study also offers a regional perspective that can be put in contrast with the present study.

We will add a regional comparison with this study in the conclusions section.

g) L9 P4 Why only the RCP4.5 is used in this study? In my opinion RCP6.0 or 8.5 would be more interesting in the context of future impacts.

Although we would have liked to include other RCPs, we did not have the resources to repeat the runs at this very high resolution for other RCPs as well. Therefore, RCP4.5 was chosen since it is one of the middle scenarios. If changes are significant in RCP4.5, they are very likely also significant in the higher RCPs. Our aim is to demonstrate the impact of spatial resolution on future soil drying and to provide a mechanistic explanation. For this goal, one RCP was considered sufficient.

h) L9, P5 I strongly sugest to use the soil moisture index (see Samaniego et al. JHM 2013, code written in Fortran, it is open source) instead of a soil moisture anomaly. The advantage of SMI is that the SM is mapped to a 0-1 space that allows comparison over time and space. It facilitates the calculation of drought area, duration and magnitude as presented in Samaniego et al. JHM 2013, Vidal et al. HESS 2010, Andreadis et al. JHM 2005, Sheffield et al. JGR, 2004). The index used in eq.3 is difficult to put in context with past studies.

Thank you for this suggestion. We understand your point and agree that SMI (as calculated in Samaniego et. al. JHM 2013) is a good measure for multi-model and regional intercomparison studies. In our study, however, we mainly focus on mean changes in soil drying (aridity) rather than on soil moisture droughts (extremes). In addition, we do not focus on regional patterns but on a regional average value over central-western Europe. From your comment, we have realized that this main focus was not clear enough from the paper as written. Therefore, we will revise the paper accordingly by changing the title and structure of the paper. We will remove the term 'drought' from the title and replace it with 'soil moisture changes'. Furthermore, we will include more specifically the study region 'central-western Europe' rather than 'Europe' in the title. We will also restructure the paper by moving the section on droughts towards the impact section at the end of the paper. The main body of the paper will be clearly

focused on regional average soil moisture changes and its underlying mechanisms. The absolute drying measure (expressed in soil moisture changes) facilitates the quantitative comparison of different water balance components (precipitation, evapotranspiration, runoff, soil moisture storage) in terms of magnitude.

i) L10 P7. Please estimate the severity as used in literature (see previous references). Very interesting will be the changes of the curve area-severity relationship with the resolution of the GCM. The code to estimate this curve as presented in Samaniego et al. JHM 2013 is open source.

Thank you for this suggestion. We have computed the severity based on percentile thresholds of the soil moisture anomaly distribution, as is done in for example Burke (2007, JHM) and Zhao (2015, J. Clim.) for CMIP5 models. The results show that broad change pattern in EC-Earth is similar to other CMIP5 simulations. We will add this in the text. Considering the area-severity relationship, we believe this would be very interesting. However, we did not concentrate on drought area in our study since we focus on a regional average value over the Rhine-Meuse drainage basin and not on the entire European continent. We believe that your suggestion would be an excellent idea for a study focusing on the continental scale changes, but in our current study we only focus on a relatively small region in central-western Europe. Therefore, we will take your suggestion into account for a future study focussing on the impact of model resolution on future European patterns of droughts with multiple global climate models.

j) L5 P9. The term anomaly as defined in this paragraph is misleading. It is an average change over the domain. I recommend to estimate the change is aridity as defined in Samaniego et al. NCC, 2018 since it is a better estimate of the changes in soil moisture under extreme conditions (droughts). A similar index can be develop to wetter events (just the oposite of the distribution function). I recommend to estimate changes over natural regions to avoid compensation. Some regions experience increases in wetting (Scandinavia), others the oposite (Mediterranean).

We understand that this terminology could be a bit misleading, therefore we will not call future mean changes in soil moisture or other water balance components 'anomalies'. We will change this terminology throughout the text.
As mentioned before, we believe that there was some confusion in the text about 'droughts' (extreme conditions) and 'drying' (mean changes). The main focus of our paper is not on extreme conditions but on mean future changes. Where appropriate, we will clarify this in the text.
Our focus region is roughly over the Rhine-Meuse drainage basin in central-western Europe, which is a natural region. In Figure 2 we show that the changes in aridity over this region are not compensating but have the same sign.

k) L22 P5, the selection of percentiles is a bit ad-hoc. Why not round numbers like 1, 2, 5, 10, 90, 95, 99 percentiles. Remaning analysis should be updated.

We understand that these percentiles could be confusing, since they are indeed not round numbers. This is because we only have 30 years of data. Therefore we can only compute e.g. 1/30, 2/30 or 6/30 year events, which we classified as extreme, severe, and moderate droughts, respectively. To avoid confusion we have rewritten this paragraph to make this clear. In addition, we have moved this subsection to the final part of the paper which focuses on extremes rather than mean changes in soil moisture.

l) L11 P14, This hypothesis is highly interesting and should be done as proposed in the future. In this study, however, authors should compare the results existing CMIP5 models (e.g., based on EDgE data) to see if the hypothesis holds with present insights (see above).

Thank you for this suggestion. Unfortunately, we do not (yet) have future simulations of other high resolution models to test our hypothesis at the moment, since the model runs were performed with only one global climate model. Existing CMIP5 models do not have this high spatial resolution. In fact, EC-Earth in its 'standard' CMIP5 resolution has already a high spatial resolution compared to other CMIP5 models. In a future study, in which we will have systematic model simulations with multiple high resolution GCMs, we will be able to make this comparison.