Replies to RC1: Anonymous Referee #1, 18 Dec 2023

This work compares the difference among some soil moisture products in representing the soil moisture drought, and discusses the potential factors that cause this difference. Although the research objective sounds important, the current manuscript is not suggested for publication. The knowledge gap and innovation is not clarified, the implication and suitability of the conclusion is unclear, and the interpretation is confuse and should be revisited carefully. Detailed comments are below:

We thank the reviewer for the critical feedback. Based on this, we decided to reframe the study and focus on the potential of long-term satellite observations for characterising soil drying. Soil drying includes i) long-term negative changes in soil moisture, and ii) agricultural drought events.

Soil moisture trends in long-term satellite observations and differences in these trends between measuring approaches are currently understudied. Most of the available trend analyses use the COMBINED product (e.g., Dorigo et al., 2012; Albergel et al., 2013; Feng and Zhang, 2015; Gu et al., 2019; Preimesberger et al., 2021) and many focus on regional trends only (e.g., Li et al., 2015; Rahmani et al., 2016; Wang et al., 2016; Zheng et al., 2016; An et al., 2016).

However, our analysis shows that soil moisture trends from ACTIVE, PASSIVE and COMBINED products are associated with substantial uncertainties (cf. Fig. 14 and Table A1 of the Appendix A in the current manuscript). Documenting these diverse and partly contradicting trend patterns is crucial to understand where confidence in the remote-sensing products is justified, and where not.

Accordingly, based on the ACTIVE, PASSIVE and COMBINED satellite products, we will identify regions with soil moisture trend direction agreement and those with trend disagreement (products deviate) in order to identify the areas where the agreement leads to higher confidence in satellite observed trends (see Fig. 1, top left).

We will confront this with a similar analysis based on the reanalysis products (Figure 1, top right). Based on the analysis of the drivers of the soil moisture trends in the reanalysis products (cf. Section 5.2, Fig. 13 of the current manuscript), and the relation to observed trends in these drivers (i.e., precipitation, temperature), we will identify the reanalysis products with higher confidence regarding the representation of soil moisture trends.

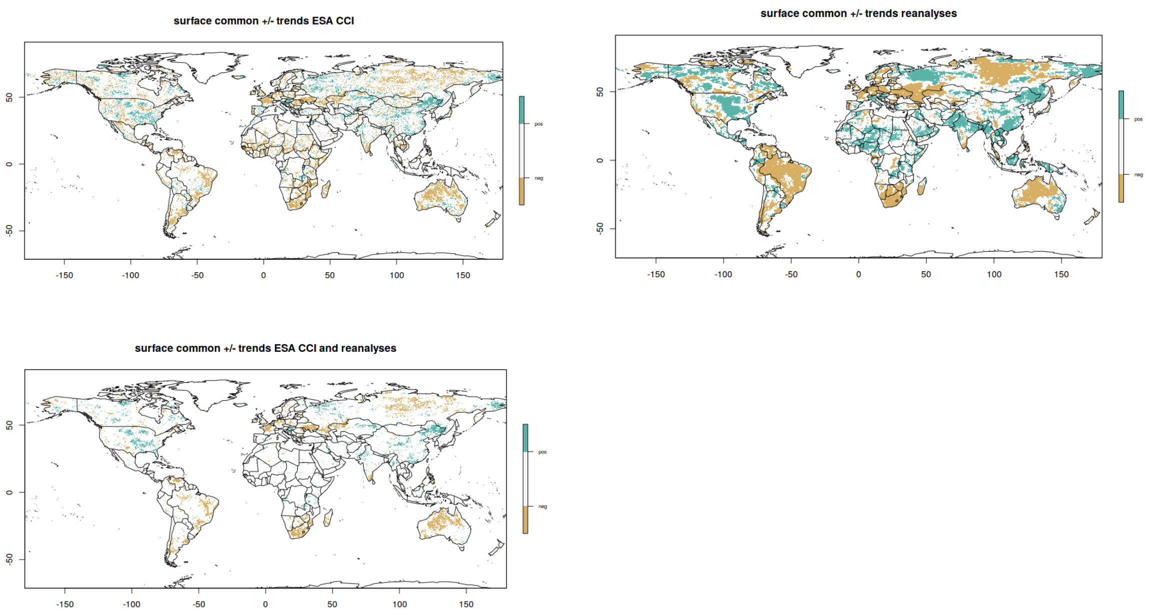

Figure 1: Trends agreement in the sign (i.e., all agree on positive or negative trends respectively) of the ACTIVE, PASSIVE and COMBINED satellite products (top left), of the ERA5, ERA5-Land and MERRA-2 reanalyses (top right), and of all mentioned products (bottom). Trends are based on surface soil moisture and are not masked for significance.

In a new “Discussion and synthesis” section, we will provide a synthesis of the global trends based on the “best-estimate” products from both remote sensing and reanalysis data. This synthesis will consider the analysis of the areas with trend agreement (cf. Fig. 1) and also make use of the adjusted area fractions of positive and negative trends of the products (cf. Table A1 of the current manuscript).

In a second step, we will investigate the agricultural drought events as a use case to quantify how the diverse trend representation also affects the drought detection capabilities of the products – evidence in this sense is already present in the current manuscript and will be made more prominent. For this, we will stratify the product intercomparison of the drought metrics (e.g., magnitude, severity), particularly regarding the relation of product deviations in drought representation and soil moisture trends, by separating the drought regions in areas with trends agreement and in those without agreement. This will allow to generalise the product intercomparison.

1. The innovation. The introduction states the importance of the drought and then states that “involved products show partly considerable differences in the global patterns and magnitudes of the soil moisture drying.”. However, either a comprehensive review on the literature that evaluates the ability of different products in capturing drought, or the current knowledge gap on understanding the differences between different products, is provided. This makes it confuse to the reader on the innovation of the current work.

   As stated above, soil moisture trends in long-term satellite observations and differences in these trends between measuring approaches are currently understudied. Most of the available trend analyses use the COMBINED product and many focus on regional trends only (cf. references above). The COMBINED product, however, is based on the merging of the individual ACTIVE and PASSIVE sensors.

Thus trend disagreement in these underlying products and with the merged product is a clear indication of problems in the data (addressed in Section 5.3 of the current manuscript), and these may also translate into the COMBINED product. On the other hand, trend agreement may indicate regions where confidence in the remote-sensing products is justified. The output of the study is critical feedback on the products to prompt an investigation and reconciliation of (the causes of) such trends in the upcoming versions.

We will extend the literature review on currently available trend assessments to more clearly indicate the innovation of the study.

2. The implication and suitability of the conclusion. The current result is based on the intercomparison between different datasets based on a few drought cases (e.g., 19), so the results only indicate the difference between the chosen products (e.g., ESA-CCI, ERA5, ERA5_Land and MERRA2). Then, what is the implication of the results? Which dataset should we relief on? Or which dataset is more suitable to perform drought analysis? In addition, the drought cases are mainly over the Europe and are not enough for a global perspective.

   We will reframe the study by first investigating the global soil moisture trends based on the considered products and then looking at the impact of the diverse trend patterns on their drought detections capabilities. In a new "Discussion and synthesis" section, we will provide a synthesis of the global soil moisture trends based on the best-estimate products.

   Based on the analysis of the drivers of the soil moisture trends in the reanalysis products (cf. Section 5.2 of the current manuscript), there exists an indication to favour ERA5/ERA5-Land over MERRA-2 when taking into account the negative temperature bias of the latter as discussed in the manuscript. Also, since the drying patterns of the COMBINED products tend to agree more closely with ERA5/ERA5-Land, to favour it over the ACTIVE and PASSIVE products. This is also due to the discussed artefacts of the ACTIVE products in urban areas and its sub-surface scattering effects.

   While the goal is not to provide a definitive indication of a single product to use for trends assessment, a substantiated and reliable indication of regions of confidence will be provided. We will be more clear on this in a revised version and we will use these findings to provide a synthesis of the global soil moisture trends based on the best-estimate products from both remote sensing and reanalysis data. This will be presented in a new "Discussion and synthesis" section and will consider the analysis of the trend agreement areas (cf. Fig. 1 above), as well as the area fractions of positive and negative trends (cf. Table A1 of the current manuscript).

   We will further investigate seasonal drought events as a use case to show how the diverse trend representation also affects the drought detection capabilities of the products. For this, we will stratify the product intercomparison of the drought metrics (e.g., magnitude, severity), particularly regarding the relation of product deviations in drought representation and soil moisture trends, by separating the drought regions in areas with trends agreement and in those without agreement. This will allow to generalise the product intercomparison.

3. The dry-season SM. The dry-season SM in current research is discontinuous, and is different from the usually used concept that is based on a consecutive period with lower SM. Therefore, the meaning of the the linear trend of dry-season SM should be clarified more clearly. In addition, the trend of dry-season SM is used to interpret the difference among different products in representing drought characteristics. This is very confuse to me, because lots of the drought cases happened during the wet seasons (e.g., June-September).

   We agree with the reviewer that some of the events will not be fully covered by the dry season. In order to circumvent this we decided to switch to trends based on the full year, but excluding the frost period in this case (see below). Previous analyses show that trend patterns based on the full year (Fig. 2) are comparable to dry-season only trend patterns.

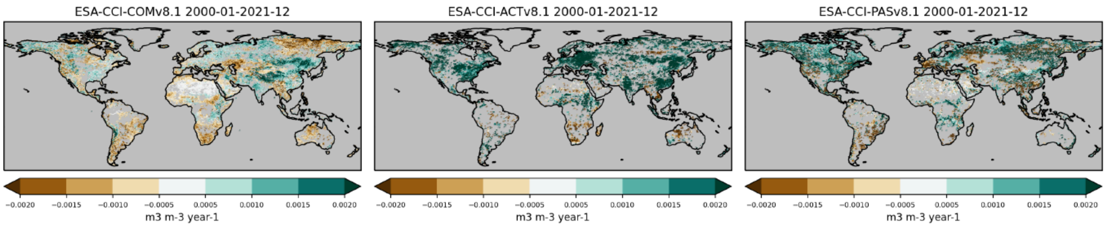

   Figure 2: 2000-2021 trends of ESA CCI v08.1 COMBINED, ACTIVE and PASSIVE. Trends are based on the full year, and a Mann-Kendall test with a false rejection rate of 0.05 was performed to mask out regions where no significant trend is present. Figure taken from Hirschi et al., 2023.

4. The different spatial resolution of products. Was the analysis based on the original spatial resolution of different datasets or a fixed resolution (e.g., aggravate them to 0.25°)? Different spatial resolution would lead to different grid samples in the same drought area, and may influence the result. In addition, the high-resolution products tend to be more heterogeneous and potentially influence the identification of the core zones of drought events.

   The current analysis is based on the original resolution of the products with the idea to also consider the added value of the higher spatial resolution of ERA5-Land with 0.1° vs. ERA5 with 0.25°. Using ERA5-Land resampled to 0.25° instead of 0.1° had only minor effects on the trend patterns and the drought representation.

   However, we will consider switching to a fixed resolution of 0.5° in a revised manuscript to simplify the product intercomparison and the consistent soil frost masking.

5. It seems that, the soil moisture in reanalysis products includes both liquid and solid soil water while the remote sensing products only provide the liquid soil water. I suggest the author to confirm this and pay attention to the frozen period when comparing different products.

   We agree on this fact, even though the analysed events typically do not fall within the soil frost period. However, given reviewer's point 3 on the dry season, we decided to switch to trends based on the full year, but in this case excluding the soil frost period.

   We will apply a frozen soil mask based on the individual soil temperature data for the reanalysis products, and then apply a mutual masking of all products (note that the remote sensing products are already masked for frozen soil conditions).

6. The discussion said that satellite datasets do not consider the dynamic land-surface characteristics and bioclimati and attributes the differences between satellitedataset and reanalyses dataset to the considering of the underlying trends of relevant land-surface characteristics and bioclimatic indicators. However, similar with the satellite dataset, the reanalysis dataset also does not consider these dynamic factors. Therefore, the discussion may be incorrect.

   We agree with the reviewer that both remote sensing and reanalysis products do not directly consider the temporal dynamics of land-surface characteristics (and bioclimatic indicators). We will also note this in the discussion for the reanalysis products. However, unlike the remote sensing products, the reanalyses assimilate a variety of ground data that are at least indirectly affected by potential changes in the land-surface properties.

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