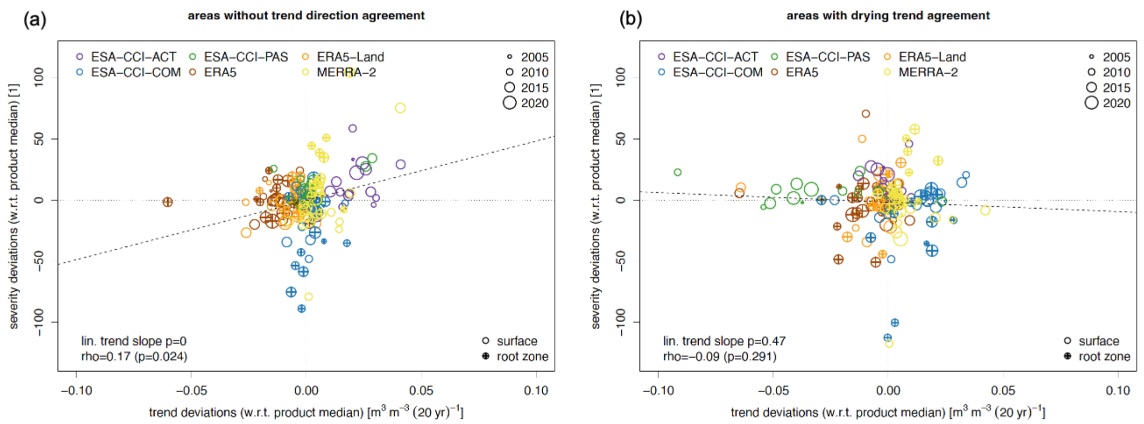
Anonymous Referee #1, 27 Jun 2024 (Report #2)

I thank the author for their efforts in addressing my comments, and I can see that the revised manuscript improves a lot. The aim, innovation, and implication are now clearer. However, I still have some comments as follows, before consideration of its publication.

We thank the reviewer for the positive feedback and for recognising the improvements over the original version. Below are our responses to the remaining comments.

1. The product deviations in drought magnitude showed a significant relation with deviations in the soil moisture trends in areas without trend direction agreement. How about other drought characteristics used in this study (e.g., spatial extent, drought severity, and frequency)? Some discussions are needed at least.

We have included a corresponding figure for drought severity in the supplementary material (Supplementary Fig. 3, also included below) and added a statement on these results in the manuscript. Similar as for the drought magnitude, deviations in drought severity show a significant relation with deviations in the soil moisture trends only in areas with no agreement in trend direction.



Supplementary Figure 3 As Fig. 11 of the main manuscript, but for product deviations in drought severity as a function of product deviations in the 2000–2022 soil moisture trends.

2. The units of label bar in Figure 1, 2, 9 should be revised. For example, “m3 m-3 year-1” should be changed to “m^3 m^{-3} $year^{-1}$”.

All units are now denoted with exponents (e.g., “m^3 m^{-3} yr^{-1}”).

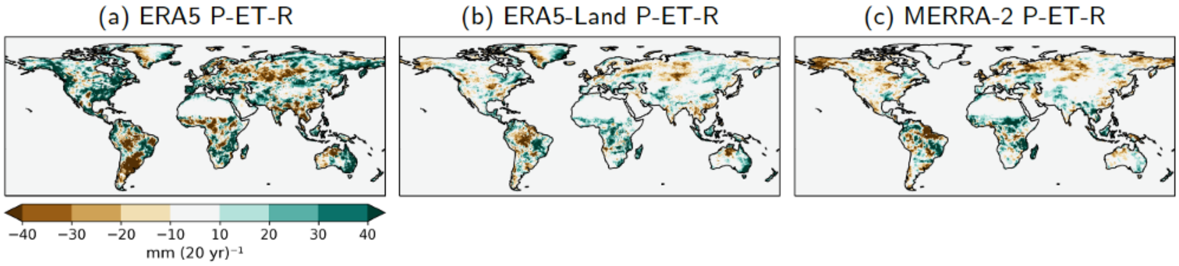
3. Is it accurate to use “days*1” as the unit of drought severity? The severity is the accumulated time accumulated standardised anomalies over the whole drought period. It looks like that using “[1]” is more appropriate. For example, the units for accumulated precipitation deficit is “mm” instead of “mm*days”.

Indeed, this is more appropriate. We have changed the units of severity to “[1]”.

4. Compared to precipitation (P), evapotranspiration (ET), and runoff (RNOF), the P-ET-RNOF is more related to the soil moisture anomaly. So I suggest to add the trend of P-ET-RNOF in the Figure 2.

We thank the referee for this suggestion. Please find below the trends based on the yearly means of cumulated monthly P-ET-R (calculated on annual basis). As can be seen, the trends in the annual terrestrial water balance (or terrestrial water storage) show a relation to the trends seen in soil moisture, but also some differences. ERA5 and ERA5-Land particularly show more widespread wetting in terrestrial water storage than in root-zone soil moisture, while MERRA-2 shows more widespread drying. These differences are due to the fact that components other than root-zone soil moisture (i.e., deeper layer soil moisture and groundwater, snow, ice, biomass water) also contribute to terrestrial water storage and its trends. In addition, during the data assimilation water may be added or removed in the soil moisture analysis of the reanalysis systems, leading to a non-closed water balance. This may explain the differences seen between ERA5 and ERA5-Land, as the former is directly affected by the data assimilation, while the latter is produced in offline mode.

We added these trends in P–ET–R in the supplementary material (Supplementary Fig. 2) in order not to overload Fig. 3 (original Fig. 2).



Supplementary Figure 2 As Fig. 3 of the main manuscript, but for Theil-Sen trends on yearly means of the cumulated monthly terrestrial water balance (i.e., precipitation minus evapotranspiration minus runoff). The terrestrial water balance is cumulated on annual basis.

differences in the soil moisture trends (Fig. 3 j–l, cf. Sect. 4.1). Supplementary Fig. 2 also shows the trends on yearly means of the cumulated monthly terrestrial water balance (i.e., precipitation minus evapotranspiration minus runoff, cumulated on annual basis). These trends in the annual terrestrial water balance (or terrestrial water storage) also show a relation to the trends seen in soil moisture, but also some differences. ERA5 and ERA5-Land particularly show more widespread wetting in terrestrial water storage than in soil moisture, while MERRA-2 shows more widespread drying. These differences are due to the fact that components other than root-zone soil moisture (i.e., deeper layer soil moisture and groundwater, snow, ice, biomass water) also contribute to terrestrial water storage and its trends.

5. The abstract is very long. Please make sure the length of abstract meets the requirement of HESS.

We shortened the abstract by removing unnecessary methodological details.

Anonymous referee #2, 18 Jun 2024 (Report #1)

This study investigates the ability of surface and root-zone soil moisture from multiple reanalysis and remote-sensing products in representing drought events in recent 20 years globally, and compares their differences in describing various drought metrics. Overall, this paper provides a comprehensive reference for selecting datasets for drought study. Although the authors have made a major revision in the whole storyline and figures, but I still suggest a major revision before publication. The main suggestions are as follows.

We thank the reviewer for the re-examination of our manuscript and the additional feedback. Below are our responses to the comments.

General comments:
1. Throughout the whole paper, the quantitative evaluation is still not sufficient, and there are too many qualitative statements, such as Line 395, conclusions and abstract. For the multiple datasets used in the study, such reanalysis is clearly enough to readers.

We extended the quantitative evaluation of the trends by adding a new Fig. 2 that builds upon and expands the original Table 2 with the global mean trends of the products as well as their mean trends in the wetting and drying areas respectively (see below; note that the original Table 2 has been moved to Supplementary Table 2). This additional analysis shows that not only the area fractions of the trend directions diverge between the products, but also their trend magnitudes. ESA-CCI-ACT and MERRA-2 show positive global means of the trends, while all other products show negative global means. The mean trend magnitudes in the wetting areas are largest for surface soil moisture of ESA-CCI-ACT and -PAS, as well as MERRA-2 (0.03–0.04 m^3 m^{-3} $(20\ yr)^{-1}$; cf. Supplementary Table 2). Both ESA-CCI-ACT and -PAS also show largest drying trend magnitudes (around -0.035 m^3 m^{-3} $(20\ yr)^{-1}$). The mean drying is somewhat lower, but largely consistent between the reanalysis products (around -0.03 m^3 m^{-3} $(20\ yr)^{-1}$) for both surface and root-zone soil moisture. The overall lowest trend magnitudes in both directions can be observed for ESA-CCI-COM and -RZSM (less than 0.02 m^3 m^{-3} $(20\ yr)^{-1}$).

In addition (see Point 2 below), we also extended the quantitative evaluation of the drought metrics by comparing the product deviations in the metrics with respect to the product median for the individual events, as well as by evaluating the products based on their spatial drought metrics patterns.

Regarding the statement in line 395, the quantitative numbers (bias, RMSD, correlation) are presented in the sections that proceed this concluding paragraph of Section 4.2.

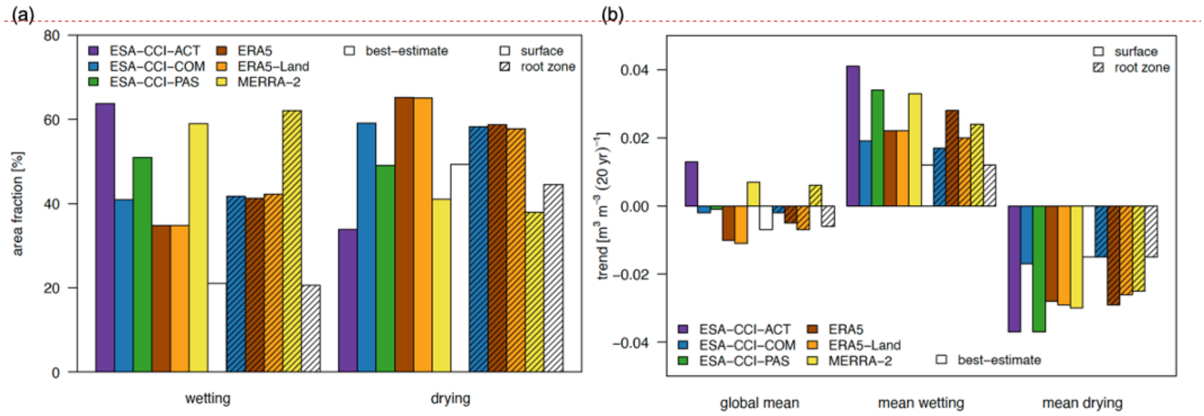


Figure 2 (a) Area fractions (in %) of wetting and drying trends within each product, as well as (b) their global mean trends and the respective mean wetting and drying trends (in m^3 m^{-3} (20 yr)$^{-1}$). Note that trends are not masked for significance, but for common spatial coverage of the datasets. The values for the best-estimate products (cf. Sect. 5.1) are based on the areas with trend direction consensus. Note that the respective numbers that are referred to in the text can be found in Supplementary Table 2.

Not only the area fractions of the trend directions diverge between the products, but also their trend magnitudes (Fig. 2 b). ESA-CCI-ACT and MERRA-2 show positive global means of the trends, while all other products show negative global means. The mean trend magnitudes in the wetting areas are largest for surface soil moisture of ESA-CCI-ACT and -PAS, as well as MERRA-2 (0.03–0.04 m^3 m^{-3} (20 yr)$^{-1}$; Supplementary Table 2). Both ESA-CCI-ACT and -PAS also show largest drying trend magnitudes (around -0.035 m^3 m^{-3} (20 yr)$^{-1}$). The mean drying is somewhat lower, but largely consistent between the reanalysis products (around -0.03 m^3 m^{-3} (20 yr)$^{-1}$) for both surface and root-zone soil moisture. The overall lowest trend magnitudes in both directions can be observed for ESA-CCI-COM and -RZSM (less than 0.02 m^3 m^{-3} (20 yr)$^{-1}$).

2. Figure 7: It is better to show their differences with respect to the baseline dataset, and thus it is easier to capture their abilities. In addition, the statistical results, such as RMSE and pattern correlation coefficients, can also be presented in this way.

We extended Fig. 8 (original Fig. 7; see below) with a table plot of the product deviations in the drought metrics with respect to the product median of each event as a baseline (cf. Fig. 8 b). The weaker drought representation of ESA-CCI-ACT becomes apparent and is particularly pronounced for events in Europe. Similarly, MERRA-2 root-zone soil moisture shows weaker droughts, in this case most evident for events in North America and Africa. The deviations for MERRA-2 surface soil moisture are more mixed, with a weaker representation of the East Africa 2015 drought, but a stronger representation (particularly in terms of duration and severity) of the Texas 2011 and the Iberian Peninsula 2011-2012 droughts. Also, ESA-CCI-COM-RZSM shows stronger drought representation for many events.

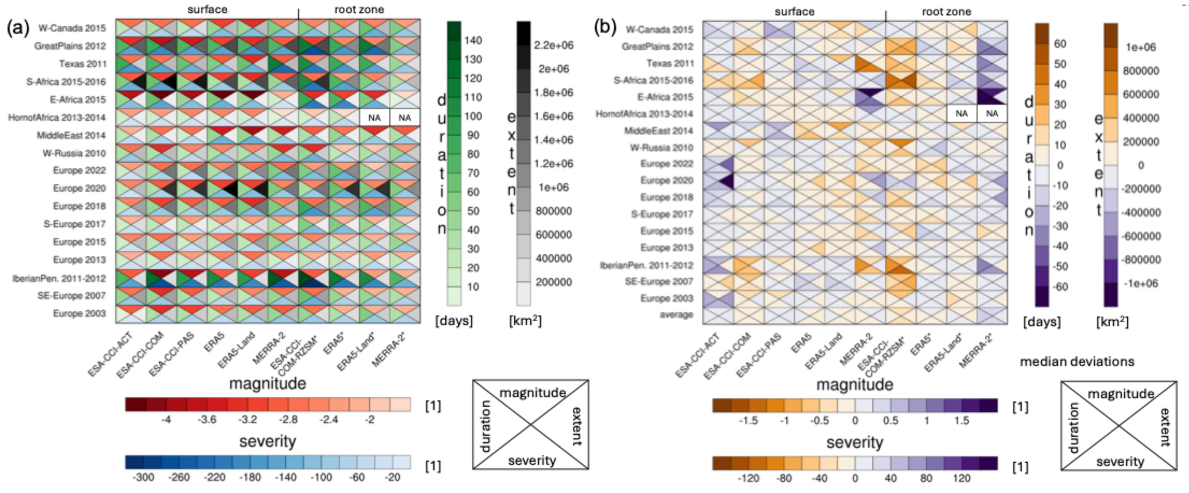
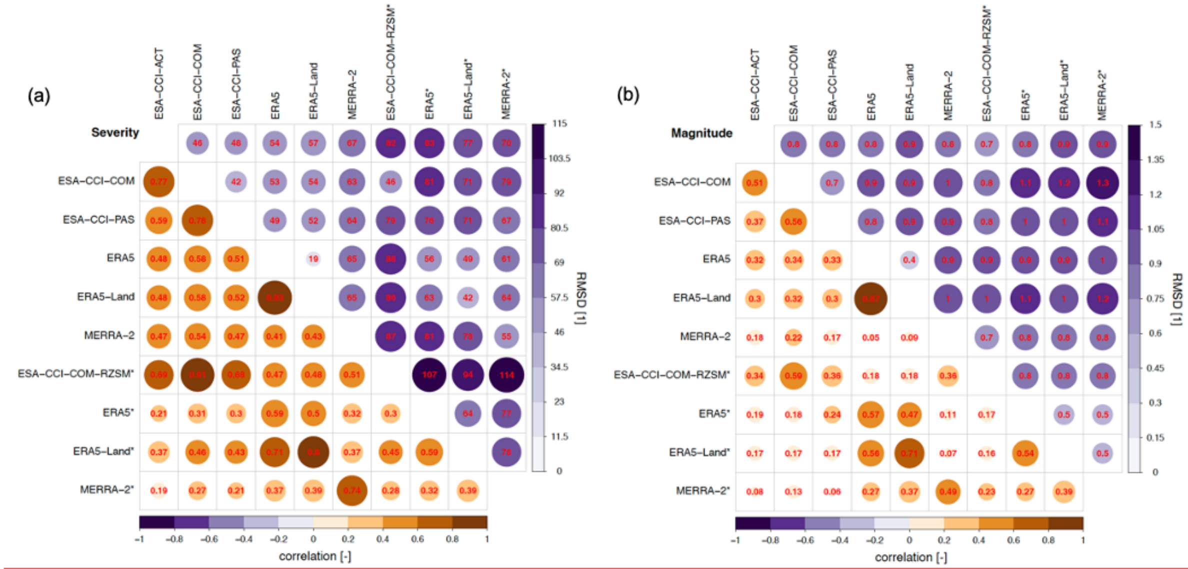


Figure 8 (a) Drought metrics of recent major drought events. The values are based on surface soil moisture and root zone soil moisture (products denoted with *) and represent the area mean over the respective core of the event region in case of severity, magnitude, and duration, and the temporal maximum in case of the spatial extent. (b) Product deviations in these drought metrics with respect to the product median of each event, separately calculated for the surface and the root zone (i.e., comparable to the product deviations that are shown in Fig. 11 and Supplementary Figs. 3 and 4). In this case, also the average of the product median deviations is shown for the individual products. NA is displayed when products do not exhibit standardized anomalies below –1.5 for a specific event.

As for the 2022 drought event in Europe, ESA-CCI-ACT often displays weaker droughts in all metrics compared to the ESA-CCI-COM and the ERA5/ERA5-Land products. This is also visible in Fig. 8 b, which displays the respective product deviations in the drought metrics with respect to the product median of each event as a baseline. The weaker drought representation of ESA-CCI-ACT is particularly pronounced for events in Europe and is evident in all metrics (on average over all events +17 in severity, +0.2 in magnitude, –6 days in duration, and –129’000 km^2 in spatial extent). Also MERRA-2 shows weaker droughts in the root zone compared to the other products, which is most evident for events in North America and Africa (+33 in severity, +0.25 in magnitude, –14 days in duration, and –105’000 km^2 in spatial extent on average over all events). In the surface layer, the deviations of MERRA-2 are more mixed, with a weaker representation of the East Africa 2015 drought, but a stronger representation (particularly in terms of duration and severity) of the Texas 2011 and Iberian Peninsula 2011–2012 droughts. For other events, durations also tend to be prolonged and corresponding severities increased in MERRA-2 surface soil moisture, while the magnitudes are partly weaker and spatial extents smaller.

Furthermore, we provide in Appendix A an evaluation of the products based on their spatial drought metrics patterns and refer to it in Section 4.5. The new Fig. A1 (see below) shows the pairwise pattern correlations and RMSDs of severity, magnitude and duration (cf. Figs. 4–6 for the Europe 2022 drought) as represented by the products. The Pearson correlations between the patterns of the products are overall positive and significant for all metrics, showing the general product agreement of the location and spatial variability of the considered droughts. The correlations between products are similar for severity and duration (which are related by design) but tend to be lower for the drought magnitude. As expected, related products (i.e., ERA5/ERA5-Land, ESA-CCI-COM/-RZSM), as well as surface and corresponding root-zone soil moisture products show closest agreement with correlations ≳0.6 for severity and duration (and ≳0.5 for magnitude). Similarly, correlations between the satellite products also amount to ≳0.6 for severity and duration but tend to be lower for magnitude. The patterns of the RMSD values are less distinct, but ERA5/ERA5-Land and ESA-CCI-COM show comparably lower values for severity and duration, while ESA-CCI-COM-RZSM and MERRA-2 tend to show largest values.



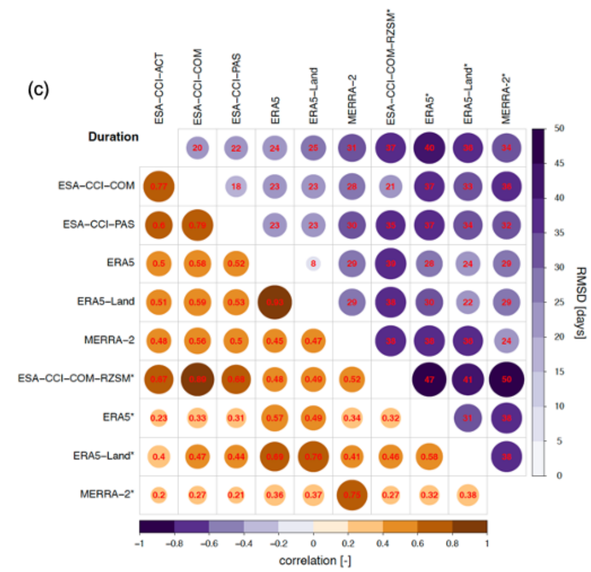


Figure A1 Pairwise pattern correlation (lower left) and RMSD (upper right) of (a) drought severity, (b) magnitude and (c) duration between individual products, calculated over all events. Only significant values are shown for Pearson correlation ($p < 0.05$), and root-zone soil moisture products are denoted with *.

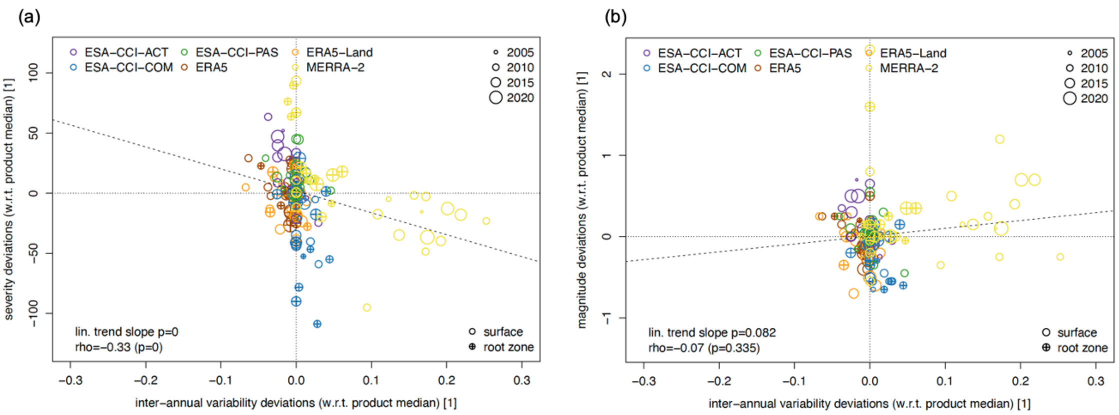
Appendix A furthermore provides an intercomparison of the products based on their spatial drought metrics patterns. Fig. A1 shows the pairwise pattern correlations and RMSDs of severity, magnitude and duration (cf. Figs. 4–6 for the Europe 2022 drought) as represented by the products. The Pearson correlations between the patterns of the products are overall positive and significant for all metrics, showing the general product agreement of the location and spatial variation of the considered droughts. The correlations between products are similar for severity and duration (which are related by design, see Sect. 3.2.2) but tend to be lower for the drought magnitude. As expected, related products (i.e., ERA5/ERA5-Land, ESA-CCI-COM/-RZSM), as well as surface and corresponding root-zone soil moisture products show closest agreement with correlations $\gtrsim 0.6$ for severity and duration (and $\gtrsim 0.5$ for magnitude). Similarly, correlations between the satellite products also amount to $\gtrsim 0.6$ for severity and duration but tend to be lower for magnitude. The patterns of the RMSD values are less distinct, but ERA5/ERA5-Land and ESA-CCI-COM show comparably lower values for severity and duration, while ESA-CCI-COM-RZSM and MERRA-2 tend to show largest values.

3. Figure 8: I think it is more reasonable to intercompare the datasets for each drought events than all events.

Indeed, the intercomparison of the datasets for each drought event is shown in the extended Fig. 8 (original Fig. 7; see above), where the metrics for each event are displayed for all datasets. This is summarised for all events in this Fig. 9 (original Fig. 8).

4. Figure 10: Except for the long-term trend, drought events are also largely affected by the interannual variability. Hence, I suggest the authors add the relevant evaluation for the interannual variability.

We thank the reviewer for this suggestion. Based on this, we evaluated the relation of the product deviations in drought severity and magnitude to the product deviations in the inter-annual variability of the standardised soil moisture anomalies. The inter-annual variability is characterised by the standard deviation of the annual mean standardised soil moisture anomalies of the 2000–2022 period, which are detrended using a LOWESS filter. The new Supplementary Fig. 4 (included below) indeed indicates a significant relation between drought severity and the inter-annual variability of soil moisture (Supplementary Fig. 4 a). Thus, products with larger inter-annual variability in soil moisture display stronger drought severities. However, such a relation is not evident for the drought magnitudes, which show no significant relation with inter-annual soil moisture variability (Supplementary Fig. 4 b). This may be because magnitude represents only one day of each event (i.e., the temporal minimum of the standardised anomalies during the drought period), whereas severity is calculated as the accumulated standardised anomalies over all days below the drought threshold and thus tends to be more related to the annual mean of the anomalies. We added a paragraph on these additional analyses to Section 5.2.



Supplementary Figure 4 Product deviations in (a) drought severity and (b) magnitude as a function of product deviations in the inter-annual variability of the standardised soil moisture anomalies. The inter-annual variability is characterised by the standard deviation of the annual mean standardised soil moisture anomalies of the 2000–2022 period, which are detrended using a LOWESS filter. Deviations are displayed with respect to the product median of the individual events, separately calculated for the surface and the root zone (the latter additionally indicated with a "+"), with circle sizes depending on the chronology of the events within the investigated period (i.e., later events are displayed with larger circles). The inter-annual variability and drought metrics are averaged over the respective drought regions. The p-values of the linear trend slope (dashed line) and the Spearman rank correlation rho between the drought metrics and the soil moisture trends are noted as well.

Apart from the trend representation, also the inter-annual variability of soil moisture may contribute to the drought-detection capacity of the products. This is investigated by relating the product deviations in drought severity and magnitude to the product deviations in the inter-annual variability of the standardised soil moisture anomalies. The inter-annual variability is characterised by the standard deviation of the annual mean standardised soil moisture anomalies of the 2000–2022 period, which are detrended using a LOWESS filter. Supplementary Fig. 4 a indicates a significant relation between drought severity and the inter-annual variability of soil moisture. Thus, products with larger inter-annual variability in soil moisture display stronger drought severities. However, such a relation is not evident for the drought magnitudes, which show no significant relation with inter-annual soil moisture variability (Supplementary Fig. 4 b). This may be because magnitude represents only one day of each event (i.e., the temporal minimum of the standardised anomalies during the drought period), whereas severity is calculated as the accumulated standardised anomalies over all days below the drought threshold and thus tends to be more related to the annual mean of the anomalies.

Specific comments:
The numbers under all colorbars are too small, and it is better for the units of trend to transformed to *** $(20yr)^{-1}$

We have increased the font sizes for the numbers and units under all colorbars. Also, we have scaled the trends to *** $(20\ yr)^{-1}$ to enhance readability and interpretability of the numbers.