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Potential of long-term satellite observations and reanalysis products for characterising soil drying: trends and drought events

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Supplementary Information

Table S1 Considered major drought events with pre-defined event regions and periods based on the cited references, serving as spatial and temporal bounds for the analysis. Events are ordered chronologically.

Region	Year	Reference(s)	Start time	End time	Latitude extent	Longitude extent
Seasonal, sub-annual events						
Europe	2003	García-Herrera et al. (2010)	10/06/2003	20/08/2003	42° N-53° N	0°-20° E
SE-Europe	2007	Founda and Giannakopoulos (2009)	01/05/2007	01/08/2007	36° N-52° N	20° E-45° E
Western Russia	2010	Barriopedro et al. (2011), Hauser et al. (2016)	10/07/2010	20/08/2010	50° N-60° N	35° E-55° E
Texas	2011	Rupp et al. (2012)	01/03/2011	31/08/2011	25° N-37° N	93° W-107° W
Iberian Peninsula	2011-2012	Trigo et al. (2013)	01/09/2011	31/08/2012	35.9° N-43.9° N	10° W-3.5° E
Great Plains	2012	Hoerling et al. (2014)	01/04/2012	30/09/2012	31° N-46° N	82° W-114° W
Europe	2013	Dong et al. (2014)	01/06/2013	31/08/2013	35° N-60° N	10° W-17° E
Horn of Africa	2013-2014	Marthews et al. (2015)	01/10/2013	30/06/2014	1.75° N-6.5° N	36° E-42.3° E
Middle East	2014	Bergaoui et al. (2015)	01/01/2014	28/02/2014	30.5° N-33.5° N	34° E-36.5° E
East Africa	2015	Funk et al. (2016)	01/06/2015	30/09/2015	7° N-14° N	36.5° E-40.5° E
Western Canada	2015	Szeto et al. (2016)	01/03/2015	30/09/2015	48° N-61° N	113° W-139° W
Europe	2015	Dong et al. (2016)	01/06/2015	31/07/2015	45° N-55° N	0°-35° E
Southern Africa	2015-2016	Yuan et al. (2018)	01/11/2015	30/04/2016	10° S-35° S	10° E-40° E
Southern Europe	2017	Masante et al. (2018b), Kew et al. (2019)	01/06/2017	30/09/2017	36° N-48° N	8° E-24° E
Europe	2018	Masante et al. (2018a), Masante and Vogt (2018)	01/06/2018	30/09/2018	45° N-68° N	10° W-35° E
Europe	2020	Barbosa et al. (2020)	01/03/2020	31/08/2020	40° N-68°N	10° W-35° E
Europe	2022	Schumacher et al. (2022); Schumacher et al. (2024)	01/06/2022	30/09/2022	36° N-58° N	10° W-30° E

Table S2 Area fractions (in %) of wetting and drying trends within each product, as well as the respective area means of wetting and drying trends and the global mean trends (in $m^3\ m^{-3}\ (20\ yr)^{-1}$). Values in bold are referred to in the manuscript text, best-estimate products are underlined (cf. Sect. 5.1). Note that trends are not masked for significance, but for common spatial coverage of the datasets. The values for the best-estimate products are based on the areas with trend direction consensus.

		Wetting trends		**Drying trends**		**All trends**
	Dataset	**area fraction %**	**area mean $m^3\ m^{-3}\ (20\ yr)^{-1}$**	**area fraction %**	**area mean $m^3\ m^{-3}\ (20\ yr)^{-1}$**	**global mean $m^3\ m^{-3}\ (20\ yr)^{-1}$**
Surface soil moisture	ESA-CCI-ACT	**63.8**	0.041	33.9	-0.037	0.013
	ESA-CCI-COM	40.9	0.019	**59.1**	-0.017	-0.002
	ESA-CCI-PAS	50.9	0.034	49.0	-0.037	-0.001
	ERA5	34.8	0.022	**65.2**	-0.028	-0.010
	ERA5-Land	34.8	0.022	**65.2**	-0.029	-0.011
	MERRA-2	**59.0**	0.033	41.0	-0.030	0.007
	Best-estimate products	***21.1***	*0.012*	***49.3***	*-0.015*	*-0.007*
Root-zone soil moisture	ESA-CCI-COM-RZSM	41.7	0.017	**58.3**	-0.015	-0.002
	ERA5	41.3	0.028	**58.7**	-0.029	-0.005
	ERA5-Land	42.2	0.020	**57.8**	-0.026	-0.007
	MERRA-2	**62.1**	0.024	37.9	-0.025	0.006
	Best estimate products	***20.6***	*0.012*	***44.5***	*-0.015*	*-0.006*

Table S3 Validation of global patterns of precipitation and temperature trends. Metrics are based on the comparison to trends in CRU gridded observations (cf. Fig. 2). Note that ERA5-Land is forced by ERA5 precipitation and numbers are thus not shown for the former (denoted NA in the table).

	Metric	**ERA5**	**ERA5-Land**	**MERRA-2**
Precipitation	Correlation	0.33	NA	0.34
	Mean bias ($mm\ d^{-1}\ (20\ yr)^{-1}$)	−0.004	NA	0.171
	RMSD ($mm\ d^{-1}\ (20\ yr)^{-1}$)	0.492	NA	0.847
Temperature	Correlation	0.65	0.7	0.65
	Mean bias ($K\ (20\ yr)^{-1}$)	0.221	0.238	−0.219
	RMSD ($K\ (20\ yr)^{-1}$)	0.536	0.511	0.613

Table S4 Overview of characteristics of the Europe 2022 drought event as represented by surface and root-zone soil moisture of the different products. The metrics represent the area mean over the respective core of the event region for severity, magnitude and duration, and the temporal maximum for the spatial extent of the event. Also noted is the range of these metrics based on all products.

	Dataset	**Severity [1]**	**Magnitude [1]**	**Duration [days]**	**Extent [1e6 km^2]**
Surface soil moisture	ESA-CCI-ACT	–34.0	–2.2	18	0.56
	ESA-CCI-COM	–67.4	–2.8	33	1.34
	ESA-CCI-PAS	–55.9	–2.6	29	1.21
	ERA5	–66.2	–2.6	33	1.17
	ERA5-Land	–67.6	–2.7	33	1.16
	MERRA-2	–103.3	–2.7	52	1.22
	Product range	*[–103.3,–34.0]*	*[–2.8,–2.2]*	*[18,52]*	*[0.6,1.3]*
Root-zone soil moisture	ESA-CCI-COM-RZSM	–107.6	–2.3	55	0.90
	ERA5	–126.4	–2.3	66	1.09
	ERA5-Land	–78.9	–2.0	45	0.71
	MERRA-2	–92.2	–2.1	51	0.83
	Product range	*[–126.4,–78.9]*	*[–2.3,–2.0]*	*[45,66]*	*[0.7,1.1]*

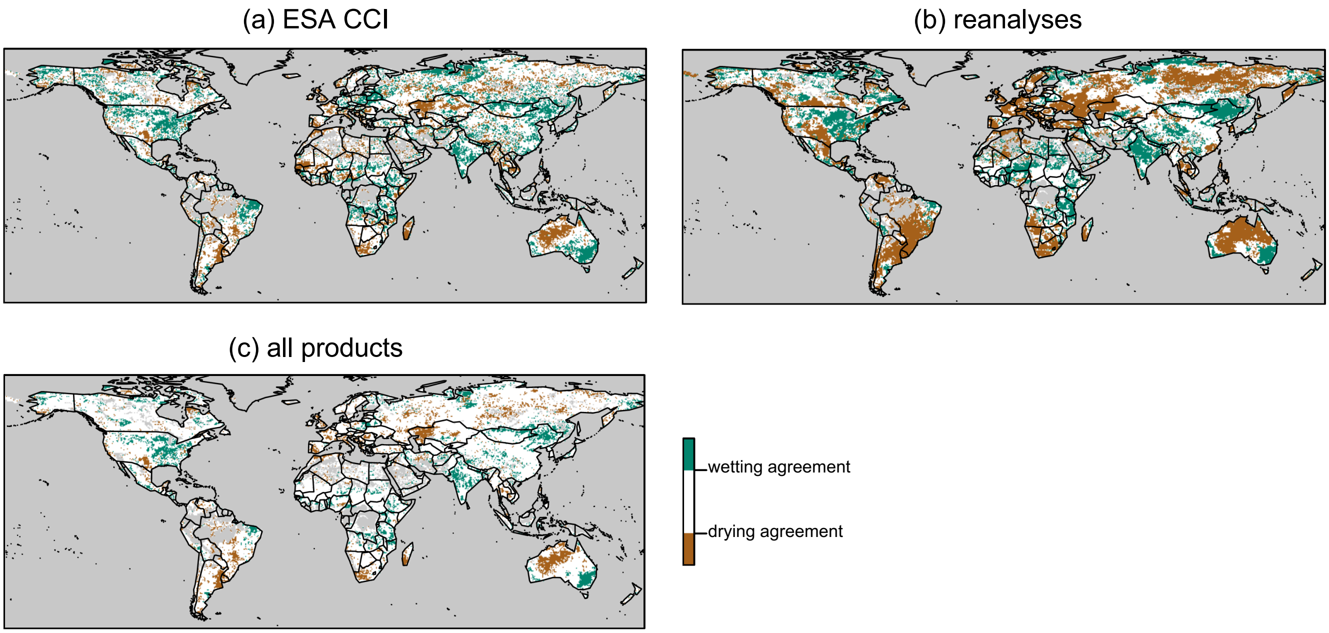

Figure S1 Agreement in the trend direction of surface soil moisture within (a) the ESA CCI soil moisture products, (b) the ERA5, ERA5-Land and MERRA-2 reanalyses, and (c) all considered remote-sensing and reanalysis products. Brown colour denotes areas with drying trend agreement, green colour areas with wetting trend agreement, and white colour areas with no consensus in trend direction. Note that trends are not masked for significance.

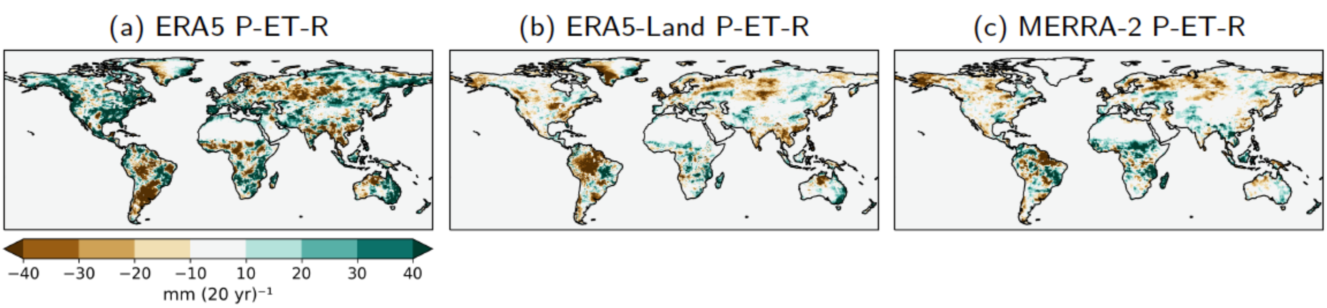

Figure S2 As Fig. 3 of the main manuscript, but for Theil-Sen trends on yearly means of the cumulated monthly terrestrial water balance (i.e., precipitation minus evapotranspiration minus runoff). The terrestrial water balance is cumulated on annual basis.

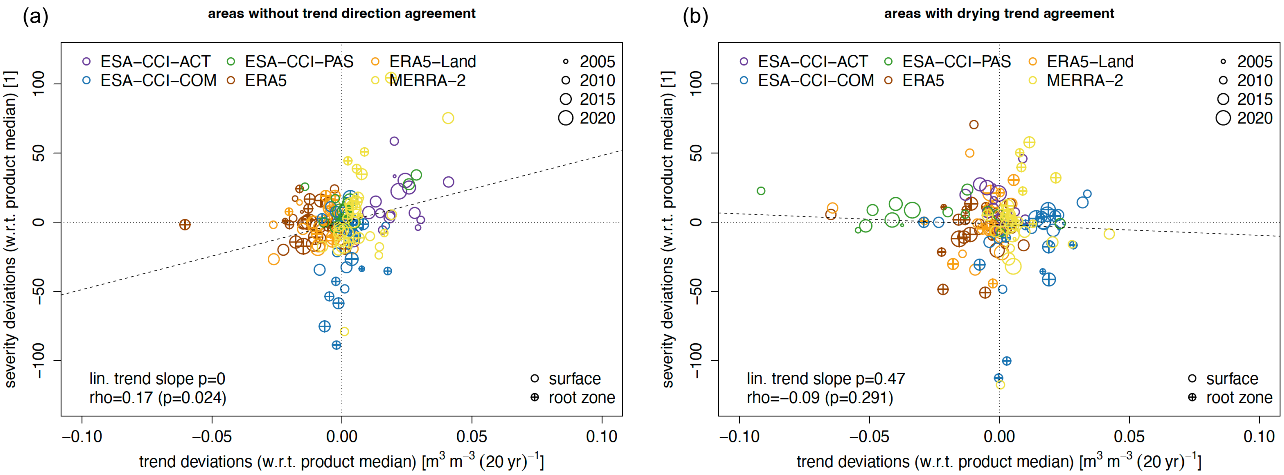

Figure S3 As Fig. 11 of the main manuscript, but for product deviations in drought severity as a function of product deviations in the 2000–2022 soil moisture trends.

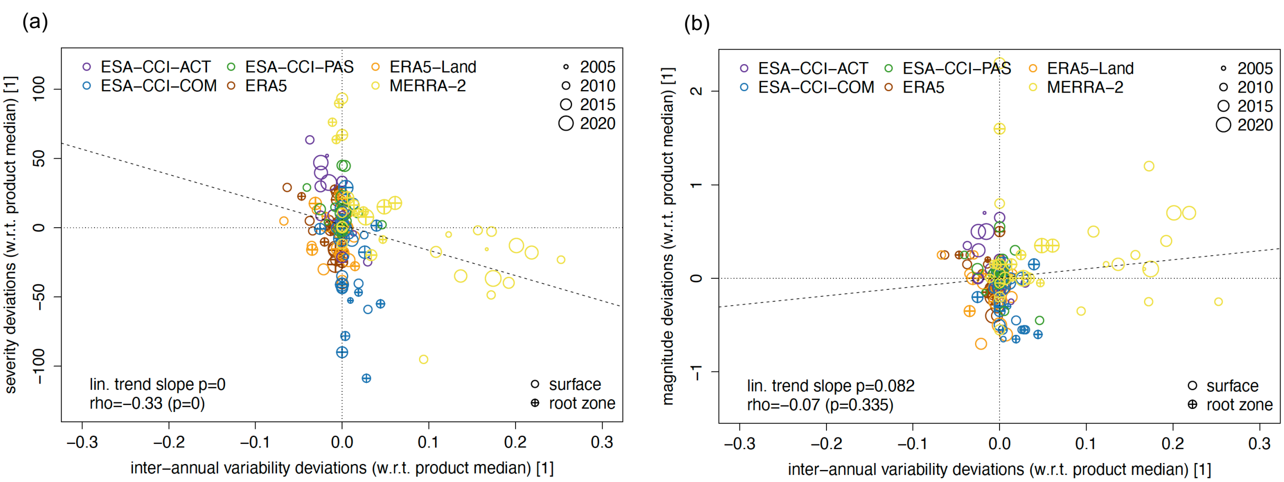

Figure S4 Product deviations in (a) drought severity and (b) magnitude as a function of product deviations in the inter-annual variability of the standardised soil moisture anomalies. The inter-annual variability is characterised by the standard deviation of the annual mean standardised soil moisture 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.

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