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

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Abstract. Soil drying has multiple adverse impacts on environment, society, and economy. It is thus crucial to monitor and characterise related drought events and to understand how underlying geophysical trends may affect them. Here, we compare the ability of long-term satellite observations and state-of-the-art reanalysis products for characterising soil drying. We consider the ESA CCI remote-sensing surface soil moisture products (encompassing an ACTIVE, a PASSIVE, and a COMBINED product) as well as surface and root-zone soil moisture from the ERA5, ERA5-Land, and MERRA-2 reanalysis products. In addition, we use a new root-zone soil moisture dataset derived from the ESA CCI COMBINED product.

We analyse soil moisture trends in these products over the 2000–2022 period, with a particular focus on global patterns. Furthermore, we investigate the impact of the soil moisture trend representation of the products on their ability to capture major seasonal soil moisture (or agroecological) drought events as a use case. The latter is based on the analysis of 17 drought events within predefined spatial and temporal bounds documented in scientific literature. Based on standardised daily anomalies of surface and root-zone soil moisture, the drought events are characterised by their severity (the time accumulated standardised anomalies), magnitude (the minimum of the standardised anomalies over time), duration, and spatial extent.

The soil moisture trends are globally diverse and partly contradictory between products. ERA5, ERA5-Land and ESA CCI COMBINED show larger fractions of drying trends, ESA CCI ACTIVE and MERRA-2 more widespread wetting trends. The differences between reanalysis products are related to a positive mean bias in the precipitation trends and regionally negative biases in surface air temperature trends of MERRA-2 compared to ground observational products, which suggests that this reanalysis underestimates drying trends. Given these biases in the MERRA-2 precipitation and temperature trends, but also considering available validation studies and the respective limitations of the included datasets, the ESA CCI COMBINED-based products and ERA5-Land are considered more reliable and are consecutively used for a synthesis on the global surface and root-zone soil moisture trends.

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This synthesis suggests a consistent tendency towards soil drying during the last two decades in these products in 49.3% of the surface and 44.5% of the root zone layers of the covered global land area. The respective fractions of wetting trends amount to 21.1% (surface) respectively 20.6% (root zone), and areas with no trend direction consensus to 29.6% respectively 35.0%, reflecting the considerable uncertainties associated with global soil moisture trends. Geographically, the drying is localized in parts of Europe and the Mediterranean, in the region of the Black Sea/Caspian Sea and Central Asia, in Siberia, in parts of western USA and the Canadian Prairies, as well as larger parts of South America, parts of southern and northern Africa and northwest Australia.

All investigated products mostly capture the considered drought events. Overall, the events tend to be least pronounced in the ACTIVE remote-sensing product across all drought metrics, particularly in the magnitudes. Also, MERRA-2 shows lower drought magnitudes than the other products both in the surface layer and the root zone. The COMBINED remote-sensing products (surface and root-zone soil moisture dataset) display partly stronger drought severities than the other products. In the root zone, the droughts are dampened in magnitude and smaller in spatial extent than in the surface layer, but show a tendency to prolonged durations and stronger severities. The product differences in drought magnitude for individual events are consistent with the differences in soil moisture trends, which demonstrates that the representation of soil moisture trends plays a fundamental role for the drought-detection capacity of the different products.

1 Introduction

Soil drying and related droughts have multiple impacts on environment, society, and economy, including substantial impacts on agriculture, ecosystems, and public water supply (Stahl et al., 2016; Seneviratne et al., 2021). Furthermore, both can act as triggers for other natural hazards at the sub-continental scale, including increased wildfire activity (Gudmundsson et al., 2014). Through feedback with the atmosphere, the prevailing dry conditions may further enhance air temperatures and trigger heat extremes (e.g., Miralles et al., 2014; Hirschi et al., 2011; Mueller and Seneviratne, 2012).

Based on varying data products, regional soil moisture drying trends have been reported, e.g., for East Asia (e.g., Jia et al., 2018; Cheng et al., 2015), Western and Central Europe (e.g., Trnka et al., 2015; Scherrer et al., 2022), and the Mediterranean (e.g., Hanel et al., 2018; Moravec et al., 2019). Also, global studies have documented soil moisture drying during past decades for several regions (Dorigo et al., 2012; Albergel et al., 2013; Gu et al., 2019; Preimesberger et al., 2021). However, the involved products show considerable differences in the global patterns and magnitudes of the soil moisture drying. At the same time, important drought metrics, such as duration and magnitude, rely on the robustness of the applied climatology (Lloyd-Hughes and Saunders, 2002), as demonstrated by the relevance of the baseline period as design choice in drought studies (Champagne et al., 2019). Any trend inherent in the climatology will result in a different distribution of the data,

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potentially affecting the ranking of drought events or even their detection. However, the impact of soil drying and – most importantly – its uncertainty on drought representation is understudied.

The recent IPCC AR6 report assessed three types of droughts (Seneviratne et al., 2021; Douville et al., 2021): meteorological droughts based on precipitation deficits, agricultural and ecological droughts – here referred to as "agroecological droughts" (Zaitchik et al., 2023) – related to deficits in soil moisture and other measures of changes in the land water balance, and hydrological droughts related to streamflow deficits. The most impact-relevant drought types are agroecological and hydrological droughts. The primary driver of these droughts is a lack of precipitation (meteorological drought; see e.g., Seneviratne, 2012; Seneviratne et al., 2021; Liu et al., 2020). Increased evapotranspiration due to enhanced radiation, wind speed, or vapor pressure deficit (itself linked to temperature and relative humidity) can further intensify the water shortage and lead to critical soil moisture values (agroecological drought) inducing e.g., adverse impacts on vegetation development (due to increased water stress) and crop yield reduction/failure (e.g.,Teuling et al., 2013; Seneviratne et al., 2021; Bueechi et al., 2023). Furthermore, pre-conditioning (pre-event soil moisture, surface, snow and/or groundwater storage) can contribute to the emergence of agroecological and hydrological droughts (Koster et al., 2010). Under strong droughts, soil moisture can also become limiting for evapotranspiration, thus reducing the evaporative cooling effect (e.g., Miralles et al., 2014; Seneviratne et al., 2010). The IPCC AR6 report concluded that a number of regions of the world are affected by increases in agroecological droughts (Seneviratne et al., 2021), mostly due to increases in evapotranspiration (Padron et al., 2020). Thus, monitoring and characterising soil moisture droughts is crucial, and will become more important with ongoing global warming.

Since in situ observations of soil moisture are still scarce and not continuously available in space and time over long time periods (Dorigo et al., 2011; Dorigo et al., 2021b), reanalysis and merged remote-sensing products provide an alternative for global long-term timeseries to investigate drying trends and soil moisture droughts on supra-regional scales. Here, we investigate the ability of the long-term remote-sensing dataset ESA CCI soil moisture (encompassing multi-sensor merged ACTIVE, PASSIVE and COMBINED surface soil moisture products, as well as a new root-zone soil moisture product based on COMBINED) and selected state-of-the-art reanalysis products (ERA5, the offline ERA5-Land, and MERRA-2) for characterising soil drying. Soil moisture trends in long-term satellite observations and differences in these trends between measuring approaches are still understudied. Most of the available ESA CCI soil moisture based 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; Jia et al., 2018). Previous analyses indicated that global trend patterns of ESA CCI COMBINED soil moisture may be subject to differences between product versions (Hirschi et al., 2023), due to yet unknown reasons. Even though the patterns have become more stable with latest product versions, potential sources of uncertainty include the different merging steps involved in the ESA CCI processing chain, changes in the sensor composition between versions, and

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characteristics of the underlying ACTIVE and PASSIVE products per se that translate into the COMBINED product. Understanding where confidence in the remote-sensing based soil moisture trends is justified, and where not, is thus fundamental for the use of such products as climate data record. The same applies to (land) reanalysis products, which we use as a comparison. To attribute some of the product differences, potential drivers of the global soil moisture trends in the reanalyses are analysed by considering trends in relevant variables of the land water balance and surface air temperature, and corresponding trends in ground observational data. Additionally, we look at bioclimatic indicators and land-surface characteristics that potentially affect the stability of the soil moisture retrieval and the reanalysis-based soil moisture.

Focussing on agroecological drought as a use case, we further systematically characterise documented major seasonal drought events in the 2000–2022 period and analyse the impact of the soil moisture trend representation of the products on their ability to capture these events. The drought events are selected based on scientific literature and drought reports, providing the temporal and spatial bounds for the analysis. Given the lack of widely available ground data of soil moisture, we rely on well documented drought events and focus on the relative behaviour of the products within the temporal and spatial bounds of the events. Thus, we do not aim for a in situ validation of the products regarding their representation of the soil moisture trends and considered drought events but focus instead on the product ensemble to identify the products with larger deviations from the majority and collect convergence of evidence. The considered products, in particular the ones from the Copernicus Climate Data Store (CDS), also offer new opportunities for monitoring of ongoing droughts and applications like drought index insurances (Vroege et al., 2021), since they are available in near real-time.

2 Data

2.1 Remote sensing and reanalysis soil moisture

Soil moisture from both the near-surface soil layer as well as the root zone is considered. Despite the overall strong correlation of surface soil moisture with deeper soil layers, evapotranspiration and vegetation processes might be more sensitive to variations of root-zone soil moisture, in particular under very dry conditions (Hirschi et al., 2014). The surface layer corresponds to roughly 0–5 cm depth (according to GCOS, 2016) and covers the penetration depth of microwave remote sensing soil moisture products. Note that this upper soil layer depth may slightly vary per product depending on the microwave sensing frequency or the land-surface model. For the root zone, the soil layer of 0–100 cm depth is considered. All data presented in the following has been re-gridded to a common 0.5° x 0.5° spatial resolution using conservative remapping after the retrieval.

2.1.1 ESA CCI soil moisture

The European Space Agency (ESA) Climate Change Initiative (CCI) soil moisture (ESA CCI soil moisture, v08.1) provides satellite-retrieved surface soil moisture over the globe from a large set of active and passive microwave sensors (with soil

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penetration depths of ~2–5 cm). The dataset contains the following sub-products: "ACTIVE", "PASSIVE" and "COMBINED" (denoted ESA-CCI-ACT, ESA-CCI-PAS and ESA-CCI-COM in the following). The ESA-CCI-ACT and ESA-CCI-PAS products were created by using scatterometer (active microwave sensing) and radiometer (passive microwave sensing) soil moisture products, respectively. For ESA-CCI-COM, all active and passive single-sensor products are directly merged based on the signal-to-noise ratio of the input datasets (Gruber et al., 2019). Note that in the merging process for ESA-CCI-COM, the active and passive L2 products are scaled against surface soil moisture from the GLDAS-Noah v2.1 land surface model (Rodell et al., 2004) from which the dynamic range is inherited (Dorigo et al., 2017; Gruber et al., 2019). As of v08.1, a break-adjustment is implemented for ESA-CCI-COM, which corrects for breaks in mean and variance (Preimesberger et al., 2021; Su et al., 2016).

Microwave retrievals are impossible under snow and ice or when the soil is frozen, and complex topography, surface water, and urban structures have negative impacts on the retrieval quality (Dorigo et al., 2017; Dorigo et al., 2015). In addition, dense vegetation attenuates the microwave emission and backscatter from the soil surface and may (partly) mask the soil moisture signal. Altogether, these limitations result in spatial and temporal data gaps of remote sensing-based soil moisture estimates, with main affected areas in the high latitudes during winter and the tropical rainforests with very dense vegetation.

The product is provided on a 0.25° x 0.25° spatial grid and in daily temporal resolution from November 1978 onwards (in case of ESA-CCI-PAS and ESA-CCI-COM) or from August 1991 onwards, respectively (in case of ESA-CCI-ACT), and data is available until 2022. Data coverage is limited in the early years of ESA-CCI-COM (and -PAS) when only few passive sensors are available (e.g., Loew et al., 2013). The inclusion of active sensors from July 1991 (Gruber et al., 2019) and the availability of multiple passive and active sensors after 2000 increased the spatio-temporal coverage (Hirschi et al., 2023). The ESA CCI soil moisture product has been extensively validated (Dorigo et al., 2015; Beck et al., 2021; Hirschi et al., 2023) and used in various research applications (see Dorigo et al., 2017 for an overview).

In addition to these ESA CCI surface soil moisture products, an ESA-CCI-COM-based root-zone soil moisture dataset is included in the analysis, which is derived by extrapolating surface soil moisture to deeper soil layers (denoted ESA-CCI-COM-RZSM). The extrapolation is based on an exponential filter (Wagner et al., 1999; Albergel et al., 2008), which is applied to ESA-CCI-COM soil moisture (v08.1) and uses optimal values for the temporal length of the filter (T parameter) determined from a large number of in situ time series (Pasik et al., 2023). The data represents the root zone down to one meter soil depth and will be released with the ESA CCI soil moisture products as of v09.1.

2.1.2 ERA5

ERA5 is the fifth generation ECMWF reanalysis of the global climate and weather for the past decades (Hersbach et al., 2020). Data is available from 1940 onwards until present and updated daily with a latency of about 5 days. ERA5 is

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The remote sensing dataset "Soil moisture gridded data from 1978 to present" (v202012.0.0 and v202012.0.1; Dorigo et al., 2021a) from the Copernicus Climate Data Store (CDS) provides estimates of surface soil moisture over the globe. This operational dataset uses a processing algorithm based on ESA CCI soil moisture version v05.2 for the product generation and the subsequent merging into the combined product (C3S, 2021), and considers near real-time L1 and L2 input datasets. Similar as for ESA CCI soil moisture, data based on ACTIVE and PASSIVE microwave remote sensing, as well as a COMBINED product are available (denoted C3S-SM-ACT, C3S-SM-PAS and C3S-SM-COM in the following). Compared to ESA CCI soil moisture, C3S soil moisture is based on fewer sensors (and associated lower spatio-temporal coverage) and uses a consolidated processing algorithm that does not include the most recent developments of ESA CCI soil moisture v08.1 (e.g., no frozen ground cross-flagging, no seasonal rescaling, or no seasonal uncertainty estimation; Dorigo et al., 2023a). Also, for C3S-SM-ACT, the near real-time L2 dataset distributed by EUMETSAT is used instead of the H SAF product used by ESA CCI soil moisture (C3S, 2021).¶
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The product is updated every ten days with a maximum latency of ten days. It is provided in 0.25° x 0.25° spatial and daily temporal resolution from November 1978 onwards (in case of C3S-SM-PAS and C3S-SM-COM) or from August 1991 onwards, respectively (in case of C3S-SM-ACT). The same limitations on coverage as for ESA CCI soil moisture apply in high latitudes during winter and the densely vegetated tropical regions.¶

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produced using 4D-Var data assimilation in CY41R2 of ECMWF's Integrated Forecast System (IFS). ERA5 provides hourly data with a spatial resolution of 31 km.

The land-surface scheme of ERA5, HTESSEL (Hydrology-Tiled ECMWF Scheme for Surface Exchanges over Land, Balsamo et al., 2009) distinguishes between four different soil layers with the following layer depths: layer 1 at 0–7 cm; layer 2 at 7–28 cm; layer 3 at 28–100 cm; and layer 4 at 100–289 cm. Apart from the assimilation of 2 m temperature and relative humidity pseudo-observations (e.g., De Rosnay et al., 2013), ERA5 is the first ECMWF reanalysis that includes remotely-sensed observations in a soil moisture analysis. Remote-sensing soil moisture from scatterometers (ERS-1,-2; MetOp-A,-B ASCAT) are assimilated in the land data assimilation from 1991 onward using a Simplified Extended Kalman Filter for the three soil moisture layers of the top first meter of the soil (Hersbach et al., 2020; De Rosnay et al., 2014).

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On the one hand, we focus on layer 1 (0–7 cm), i.e., (near-)surface soil moisture to allow comparison with the ESA CCI remote sensing soil moisture products (see above). On the other hand, average soil moisture from layers 1–3 (i.e., 0–100 cm; layer-depth weighted) is considered as a representation of root-zone soil moisture. The ERA5 data has been retrieved on a regular latitude/longitude grid of 0.25° x 0.25° spatial resolution and hourly temporal resolution from the CDS. We have further aggregated the retrieved hourly data to daily means.

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2.1.3 ERA5-Land

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The land component of the ERA5 reanalysis provides global, hourly, high-resolution information of the water and energy cycles over land in a consistent representation (Muñoz-Sabater et al., 2021). ERA5-Land is a single simulation based on the land-surface model HTESSEL (Balsamo et al., 2009) forced by ERA5 near-surface atmospheric fields, with additional lapse-rate correction of temperature. Compared to ERA5, near-surface quantities are available in higher spatial resolution, and the soil parameters are more homogeneous between ERA5 production streams (Hersbach et al., 2020). There is no feedback from the land surface model to the atmospheric parameters, and atmospheric observations only influence the land surface simulations indirectly through the ERA5 forcing. Unlike ERA5, ERA5-Land does not assimilate remote sensing soil moisture or other land variables. ERA5-Land is available from 1950 onwards and updated monthly with a latency of about three months. It provides hourly data with a spatial resolution of 9 km, thus allowing more spatial detail compared to ERA5.

The representation of the soil compartments in ERA5-Land is consistent with ERA5 since both products consider the same land-surface model HTESSEL (see Sect. 2.1.2). Consequently, as for ERA5, soil moisture from layer 1 (surface soil moisture) and from layers 1–3 (root-zone soil moisture, layer-depth weighted average) are considered in the analyses. Evaluation against in situ observations and other reference datasets shows the added value of ERA5-Land in the description of the hydrological cycle when compared to ERA5, with enhanced soil moisture and lake representation, and better agreement of river discharge with observations (Muñoz-Sabater et al., 2021).

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The ERA5-Land data has been extracted on a regular latitude/longitude grid of 0.25° x 0.25° spatial resolution and hourly temporal resolution from the CDS. We have further aggregated the retrieved hourly data to daily means.

2.1.4 MERRA-2

The Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2), is the latest atmospheric reanalysis of the modern satellite era produced by NASA's Global Modeling and Assimilation Office (GMAO; Gelaro et al., 2017). It was introduced to replace the original MERRA dataset because of the advances made in the assimilation system that enables assimilation of modern hyperspectral radiance and microwave observations, along with GPS-Radio Occultation datasets. Among the advances in MERRA-2 are the assimilation of aerosol observations, several improvements to the representation of the stratosphere including ozone, and improved representations of cryospheric processes. Other improvements in the quality of MERRA-2 compared with MERRA include the reduction of some spurious trends and breaks related to changes in the observing system and reduced biases and imbalances in aspects of the water cycle. MERRA-2 provides data beginning in 1980, at 0.625° x 0.5° spatial resolution and hourly temporal resolution. For an overview on the dataset, see Gelaro et al. (2017).

The land surface model used in MERRA-2 is the Catchment model (CLSM; Koster et al., 2000). It explicitly addresses subgrid-scale soil moisture variability and its effect on runoff and evaporation, using the basic computational element of a hydrological catchment. The land hydrology of MERRA-2 has been assessed against GRACE terrestrial water storage data as well as against in situ soil moisture data (Reichle et al., 2017b). MERRA-2 is produced using four separate streams, initialised in 1979, 1991, 2000, and 2010. The first year of each stream is designated as spinup (Bosilovich et al., 2015). The land surface restart files for each MERRA-2 stream were themselves spun up for at least 20 years, using the offline (land only) version of the MERRA-2 land model forced with MERRA surface meteorological fields (Reichle et al., 2017a). Despite this allowance for a spinup, it has been documented that discontinuities remain in the high latitudes for root-zone soil moisture (cf. Fig. 13 of Reichle et al., 2017a).

The variables SFMC (water surface layer, 0–5 cm depth) and RZMC (water root zone, 0–100 cm depth) have been retrieved from the Goddard Earth Sciences Data and Information Services Center (GES DISC) as daily aggregated data (GMAO, 2015).

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Table 1 Product summary of the considered soil moisture products. The column 'horizontal grid spacing' lists the resolution of the data retrieved, if applicable the native resolution of the dataset is listed in brackets. Similarly, for 'temporal resolution', values between brackets indicate the underlying temporal resolution when this differs from the retrieved resolution.

Dataset	Institution	Type of product	Time range	Horizontal grid spacing	Soil layer depth	Variable name	Temporal resolution	Main reference
ESA-CCI-COM/-ACT/-PAS v08.1	ESA	Active and passive microwave remote sensing	Nov 1978 / Aug 1991–2022	0.25°x0.25°	~2–5 cm	sm	Daily	Gruber et al. (2019); Dorigo et al. (2017); Dorigo et al. (2023)
ESA-CCI-COM-RZSM v08.1	TU Wien	Exponential filter-based root-zone soil moisture	2000–2022	0.25°x0.25°	0–100 cm	rzsm_1m	Daily	Pasik et al. (2023)
ERA5	ECMWF	Atmospheric reanalysis	1940–present	0.25°x0.25° (~31 km)	0–7 cm, 0–100 cm	swvl1, swvl1–3	Hourly	Hersbach et al. (2020)
ERA5-Land	ECMWF	Land-surface reanalysis	1950–present	0.25°x0.25° (~9 km)	0–7 cm, 0–100 cm	swvl1, swvl1–3	Hourly	Muñoz-Sabater et al. (2021)
MERRA-2	NASA	Atmospheric reanalysis	1980–present	0.625°x0.5°	0–5 cm, 0–100 cm	SFMC, RZMC	Daily (hourly)	Bosilovich et al. (2015)

2.2 Other meteorological variables from reanalyses and ground observations

Apart from soil moisture, the following variables are used from the ERA5, ERA5-Land and MERRA-2 reanalysis products: total precipitation, evapotranspiration, runoff and surface air temperature. Note that ERA5 and ERA5-Land share the same precipitation data, except for the higher spatial resolution of the latter.

Observed global land-surface precipitation and air temperature are taken from CRU TS (Climatic Research Unit gridded Time Series, v4.07). The dataset is derived by the interpolation of monthly climate anomalies from extensive networks of weather station observations (Harris et al., 2020) and is available at 0.5° x 0.5° spatial resolution and monthly temporal resolution, spanning the 1901–2022 period. The choice of this monthly product is driven by the fact that daily gridded observations for both temperature and precipitation were not readily available up to 2022 at the time of the analysis.

2.3 Land-surface characteristics and bioclimatic indicators

ESA CCI provides a set of ancillary datasets that were used in the generation of the products (Dorigo et al., 2021a). The ESA CCI soil porosity map has been used to convert ESA-CCI-ACT from the original units "percentage of saturation" to volumetric soil moisture in $m^3\ m^{-3}$ as provided by the other considered products. The porosity map has been derived according to Saxton and Rawls (2006) taking clay, sand, silt, and organic matter of the Harmonized World Soil Database as input.

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¶
Daily global gridded temperature anomaly fields (w.r.t. 1951–1980 climate) based on various sources of station observations are taken from Berkeley Earth (Rohde et al., 2013). Data is available at a regular spatial resolution of 1° x 1° latitude/longitude grid, covering the period 1880-present.¶

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For investigating impacts of land-surface and bioclimatic variables on the soil moisture trends in the various products (see Sect. 5.3), the latter are compared globally to those calculated using the maximum data availability over the 2000–2022 period for Vegetation Optical Depth (VOD; Zotta et al., 2024), ERA5-derived aridity (2000–2018 only; Wouters, 2021), and fractional covers of urban area, of bare soil and of tree cover (C3S, 2019).

3 Methods

3.1 Trend estimation

The analysis of trends is based on the yearly averages of the daily soil moisture data. For this, the daily soil moisture of the reanalysis products is masked for frozen soil conditions (based on the surface layer soil temperatures of the respective products), while ESA CCI soil moisture is already masked for this (Dorigo et al., 2017). Then, a mutual masking of all products is applied yielding in a consistent coverage. Trends are derived using the Theil-Sen trend estimator. Significance of the trends is determined with the Mann-Kendall test with a false rejection rate (or alpha value) of 0.05, and non-significant trends are masked for display of the trend maps when indicated.

Apart from surface and root-zone soil moisture, also trends in other relevant variables of the land water balance (i.e., total precipitation, evapotranspiration, runoff), as well as in surface air temperature are considered. For an easier comparison to these variables, we focus on trends in absolute soil moisture. These trends are based on yearly means of monthly data (see Section 2.2). In addition, we also look at trends in various land-surface characteristics and bioclimatic indicators (see Section 2.3).

3.2 Drought events characterisation

3.2.1 Event definitions

Based on guidance from the WMO (2016), extreme weather and climate events can be described quantitatively by a combination of the following metrics and information:

- An Index describing the anomaly from normal conditions (based on observations)
- A Threshold (above or below which conditions become 'extreme')
- Temporal information (records of the start date, end date, and duration)
- Spatial information (geographic area affected)

Here we focus on documented major drought events of the past two decades, with regions and periods that are predefined based on scientific literature and drought reports. From 2011 onward, in particular the Bulletin of the American

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Meteorological Society (BAMS) “Explaining Extreme Events from a Climate Perspective” report series is considered for this purpose. These event definitions serve as spatial and temporal bounds for the characterisation of the individual drought events. An overview on the considered events and their predefined event regions and event periods is given in Supplementary Table 1. This analysis extends on the extreme event catalogue and event metrics developed within the C3S_511 (Crezee et al., 2019; Yang et al., 2022).

3.2.2 Index and drought metrics calculation

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The soil moisture products considered here are given in volumetric moisture content (i.e., in units of m^3 m^{-3}), except for ESA-CCI-ACT which are originally in percent of saturation and converted to volumetric moisture content using the ESA CCI soil porosity map (see above). However, care needs to be taken when comparing absolute soil moisture from different sources since the absolute values are known to be dependent on underlying assumptions of the land-surface models and related soil property datasets (e.g., differing soil depths and soil properties like porosity) as well as on varying penetration depths of the remote-sensing products. We apply a standardization (Z–transformation) to remove differences in absolute levels and variability of the soil moisture values between the products, but also between locations, and focus on the temporal anomalies (see e.g., Koster et al., 2009; Orlowsky and Seneviratne, 2013).

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These unitless standardised soil moisture anomalies (e.g., Orlowsky and Seneviratne, 2013) are based on daily input data and are calculated per individual grid point with respect to the climatology of the 2000–2022 reference period:

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$$SMA_{y,d} = \frac{SM_{y,d} - \mu_\mathrm{d}}{\sigma_\mathrm{d}} \qquad (1)$$

In Eq.1, $SM_{y,d}$ denotes soil moisture at any year y and day d, while μ_d and σ_d denote the climatological mean and inter-annual standard deviation of soil moisture of day d calculated over the reference period. To enhance the sample size, calculation of μ_d and σ_d for each day of the year is based on the days in a 11-day window around d, i.e., by applying a 11-day moving average on the original soil moisture time series. Note that a reference period identical to the analysis period is chosen in order to keep the calculation of the standardised anomalies independent of temporal fluctuations in the original time series prior to that, and also to avoid reduced data coverage in the remote sensing products in earlier periods (e.g., Hirschi et al., 2023). A 3-day running mean is applied in addition on the resulting daily standardised anomalies with the purpose to fill daily gaps in the remote-sensing products.

For the definition of a drought, a threshold value of –1.5 standardised anomaly is chosen and any value below this is considered being in an abnormal dry state (i.e., $SMA_{y,d} < -1.5$). This threshold is inspired by the SPI-based categorization of droughts, where values below –1.5 represent severe to extreme drought (Mckee et al., 1993).

Four different metrics are defined for characterizing each drought event within the predefined event region and event period (see Supplementary Table 1). The *magnitude* of the event is the minimum standardised anomaly over time. The *duration* of the event is the total number of days (not necessarily consecutive) during the event for which the standardised anomaly is below the threshold value of –1.5. The *severity* is defined as the time accumulated standardised anomalies over the days (i.e., consecutive, and non-consecutive) for which the standardised anomaly is below the threshold value and is given in units of days times unitless standard deviations (i.e., days*1). These metrics are all calculated on the grid point scale. In addition, the temporally varying *spatial extent* of the event is defined as the area in which the standardised anomaly is below the threshold of –1.5.

Note that the application of the 3-day running mean smoothing of the standardised anomalies helps to fill temporal gaps in the remote sensing products, while still being as close as possible to the original data. For the remote sensing products, a larger smoothing window size (i.e., 5-day window) mainly impacts the calculation of the magnitude, while duration and severity only slightly change. Also, sensitivity tests showed that there is not much impact of varying smoothing windows on the results for the reanalysis products (not shown).

Since the severity captures both the duration and the amplitude of the event, it is suitable for defining the most affected *core* of the event region as represented by the products. This core region is defined as all grid points for which the severity is larger than the median of all non-zero severity grid points of the event and is used to spatially aggregate the drought metrics for summarising the events.

4 Results

4.1 Trends in soil moisture

Among the remote-sensing products, ESA-CCI-COM and its root-zone estimate ESA-CCI-COM-RZSM show more widespread significant soil moisture drying trends, in particular in Siberia, the Black Sea/Caspian Sea region, southern Africa, parts of South America and Australia (Fig. 1 d–f and i, cf. also Table 2). In contrast, ESA-CCI-ACT and to a lesser extent -PAS display larger fractions and more pronounced wetting trends. Partly consistent drying trends in the ESA CCI products (considering the trend direction, see Supplementary Fig. 1 a) can be observed in small parts of Siberia, the Black Sea/Caspian Sea region, parts of central Europe, southern South America and northern Australia, consistent wetting trends mainly in Asia, North America, northwest Brazil and southeast Australia. Overall, the agreement in the trend direction is limited among the ESA CCI products.

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The reanalysis products ERA5 and ERA5-Land show mostly significant drying trends, particularly for surface soil moisture (Fig. 1 a–b and g–h, Table 2). Strong and widespread drying can be observed in the northern mid- to high latitudes, in South America, and central Africa, and in addition for the root zone also in southern Africa and parts of Australia. MERRA-2 in contrast displays widespread significant wetting trends in both surface and root-zone soil moisture, except for South America, Australia, as well as parts of Siberia and Europe (Fig. 1 c and i). For the latter, consistent drying trends are observable in all reanalysis products (see also Supplementary Fig. 1 b). Consistent wetting trends in the reanalyses (Supplementary Fig. 1 b) can be observed in east Asia, parts of central Africa and North America, and in southeast Australia, but these appear less widespread in ERA5/ERA5-Land compared to MERRA-2. Significant drying trends in ESA-CCI-COM, as well as ESA-CCI-COM-RZSM mostly agree with ERA5/ERA5-Land, wetting trends in Asia tend to agree more with MERRA-2.

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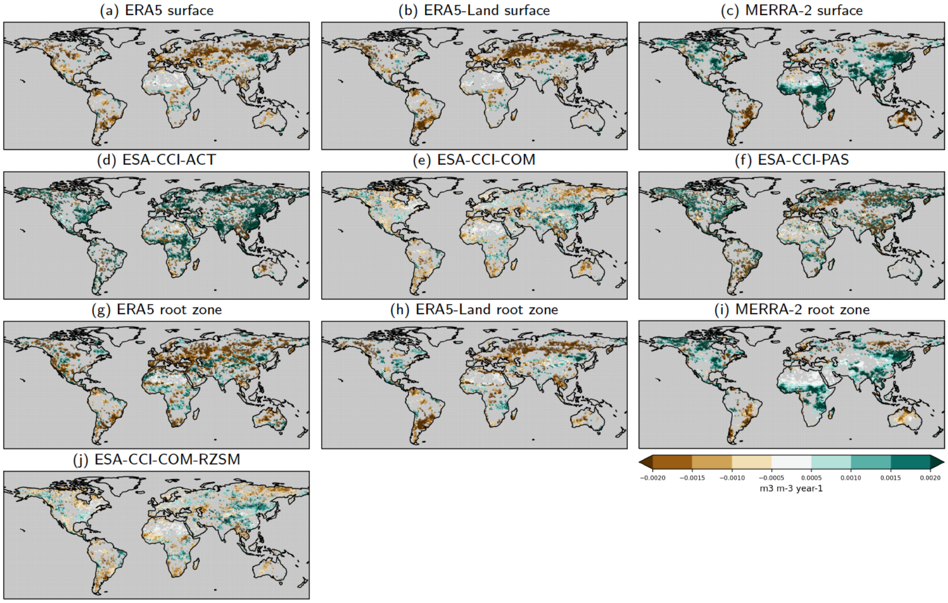

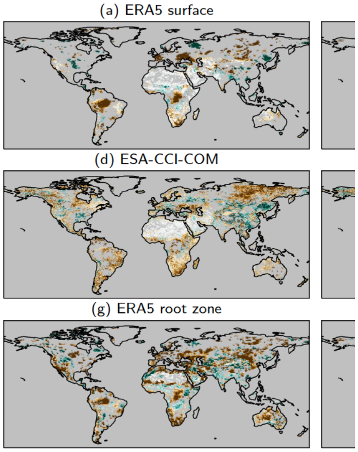

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Figure 1. Theil-Sen trend estimate (m^3 m^{-3} yr^{-1}) on yearly mean soil moisture (based on daily data mutually masked for ESA CCI data availability and non-frozen soil conditions of the reanalysis products) in (a–f) the surface and (g–i) the root zone layer, 2000–2022 period. A Mann-Kendall test with a false rejection rate (or alpha value) of 0.05 was performed to mask out regions where no significant trend is present.

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Of all products, ERA5-Land, ERA5 and ESA-CCI-COM, show largest area fractions of surface soil moisture drying trends (65.2, 65.2 and 59.1 % respectively, trends not masked for significance), while ESA-CCI-ACT and MERRA-2 show largest fractions of wetting trends (63.8 and 59.0 % respectively; Table 2). Similarly, largest area fractions of root-zone soil moisture drying trends are present in ERA5, ERA5-Land and ESA-CCI-COM-RZSM (58.7, 57.8 and 58.3 %), and largest fractions of wetting trends in MERRA-2 (62.1 %). Nevertheless, some regions with largely consistent drying trends (considering the trend direction, see also Supplementary Fig. 1 c) are apparent in parts of central Europe, in a region north of the Black Sea/Caspian Sea, in southern Africa, and in parts of Australia, Siberia and South America.

Table 2 Area fractions (in %) of positive and negative trends within each product. 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.

	Dataset	% area wetting trends	% area drying trends
Surface soil moisture	ESA-CCI-ACT	**63.8**	33.9
	ESA-CCI-COM	40.9	**59.1**
	ESA-CCI-PAS	50.9	49.0
	ERA5	34.8	**65.2**
	ERA5-Land	34.8	**65.2**
	MERRA-2	**59.0**	41.0
	Best-estimate products	***21.1***	***49.3***
Root-zone soil moisture	ESA-CCI-COM-RZSM	41.7	**58.3**
	ERA5	41.3	**58.7**
	ERA5-Land	42.2	**57.8**
	MERRA-2	**62.1**	37.9
	Best estimate products	***20.6***	***44.5***

4.2 Drivers of soil moisture trends in the reanalysis products

To shed light on possible reasons for the observed differences in soil moisture trends between ERA5/ERA5-Land and MERRA-2, Fig. 2 displays the Theil-Sen trend estimates on yearly means of monthly precipitation, runoff, evapotranspiration and 2 m temperature (in addition to the trends in root-zone soil moisture) for these products as well as for two gridded stations-based datasets of precipitation and temperature (both CRU). The patterns in precipitation trends (Fig. 2 a–b) of ERA5 and MERRA-2 show positive values in parts of east Asia and India, western USA, parts of east Africa, northeast South America, and southeast Australia. Negative trends in both products are present in large parts of South America and in northeast Australia. However, precipitation trends disagree in central Africa (trends negative in ERA5, but positive in MERRA-2), as well as southeast Asia (more widespread positive trends in MERRA-2). In addition, the positive trends in precipitation of MERRA-2 are often more pronounced and widespread compared to ERA5. While the pattern

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correlations with the observed precipitation trends (Fig. 2 c) are similar for ERA5 and MERRA-2, precipitation trends of MERRA-2 display a positive mean bias (0.0086 mm/d yr^{-1}) and a larger RMSD (0.042 mm/d yr^{-1}) compared to ERA5, which has a slight negative bias (−0.0002 mm/d yr^{-1}) and a lower RMSD (0.025 mm/d yr^{-1}, see Supplementary Table 2). This results in larger differences between the reanalyses for trends in runoff and particularly for evapotranspiration (Fig. 2 d–i). In large parts of Asia, Africa and north America, trends in evapotranspiration are strongly and widespread positive in MERRA-2 while ERA5/ERA5-Land show more mixed or negative trends in these regions. These differences in evapotranspiration trends are reflected in the described differences in the soil moisture trends (Fig. 2 j–l, cf. Sect. 4.1).

The regional product differences in evapotranspiration and soil moisture trends also show a link to regional differences in 2 m temperature trends (Fig. 2 m–o). In the mentioned regions, the temperature trends for MERRA-2 are (more) negative, while ERA5/ERA5-Land show positive or only weak negative temperature trends. As for the precipitation trends, the temperature trends based on gridded observations (Fig. 2 p) in fact agree better with ERA5/ERA5-Land, while MERRA-2 overestimates the negative trends in Asia, Africa, and North America compared to the observations, resulting in a larger RMSD of 0.031 K yr^{-1} of MERRA-2 compared to 0.027 K yr^{-1} of ERA5 respectively 0.026 K yr^{-1} of ERA5-Land. Corresponding pattern correlations with the observed temperature trends amount to 0.65 for MERRA-2 and ERA5, and to 0.7 for ERA5-Land, with a negative mean bias of –0.011 K yr^{-1} for MERRA-2 compared to a positive bias for ERA5 (ERA5-Land) of 0.011 K yr^{-1} (0.012 K yr^{-1}).

Overall, the lower biases in precipitation trends of ERA5 and the stronger constraint with observed regional temperature trends results in more widespread soil drying and evapotranspiration decreases of both ERA5 and ERA5-Land. In contrast, in MERRA-2 the biased positive trends in precipitation translate into enhanced soil moisture and evapotranspiration and a resulting stronger regional cooling, which is less in line with the observed temperature trends.

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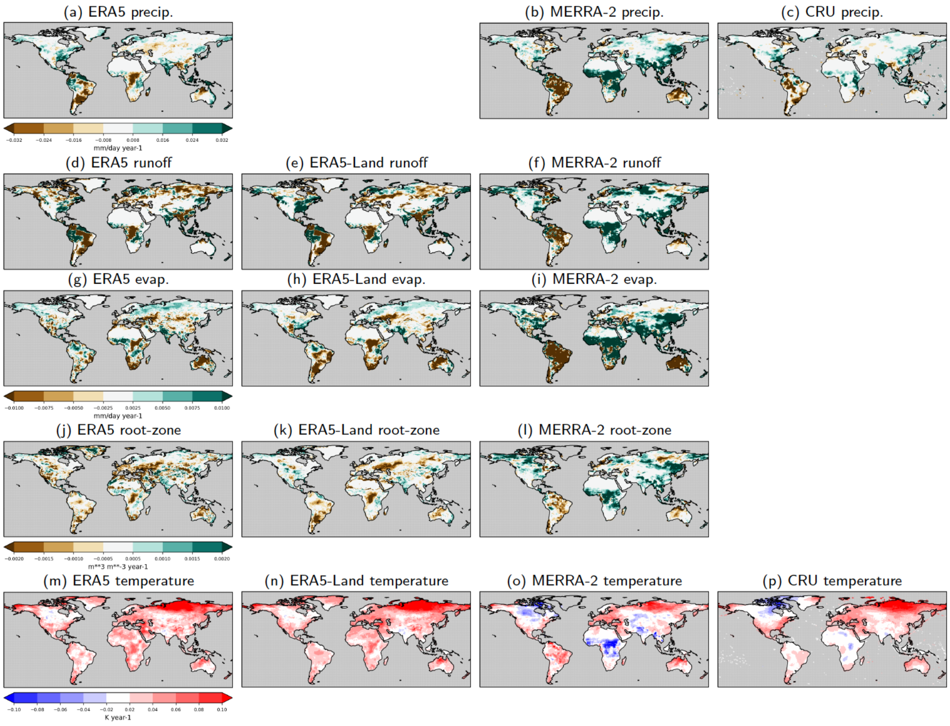
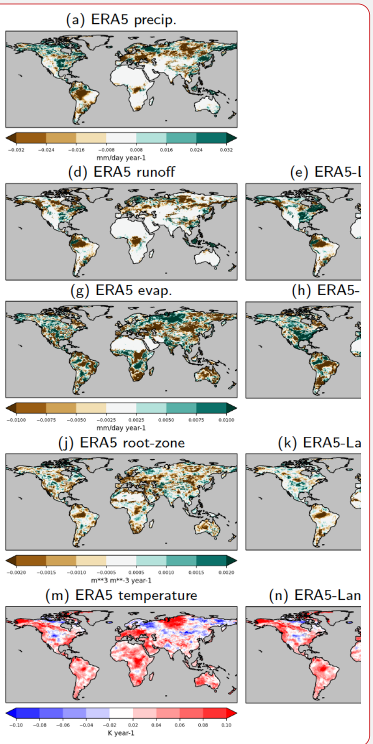


Figure 2 Theil-Sen trend estimate (2000–2022 period) on yearly means of monthly precipitation (a–c), runoff (d–f), evapotranspiration (g–i), root-zone soil moisture (j–l) and surface air temperature (m–p) from the reanalysis products as well as two gridded stations-based datasets for precipitation and temperature. Values are in mm/d yr^{-1} for the fluxes, respectively m^3 m^{-3} yr^{-1} for soil moisture and K yr^{-1} for temperature. Regions with non-significant trends are not masked out for easier comparison with the trends in soil moisture. Note that ERA5-Land is forced by ERA5 precipitation and is thus not shown for the former.

4.3 Drought Europe 2022

Detailed results are presented for the recent 2022 drought in Western-Central Europe (Schumacher et al., 2022; Schumacher et al., 2024) as an example. This is followed by the characterization of multiple recent major drought events worldwide considering all products (Sect. 4.4) and the product intercomparison based on these events (Sect. 4.5).



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The severity of the 2022 drought event appears largest in central and western Europe, with highest values based on surface soil moisture in Germany, Switzerland, France, Italy as well as parts of eastern Europe (Fig. 3 a–f). This core of the event region (see Sect. 3.2.2) is captured by all products, but the region appears less coherent in the ESA-CCI-ACT (and partly -PAS) remote sensing product. Due to the strong correlation of surface soil moisture with deeper soil layers (e.g., Hirschi et al., 2014), the location of the event in the root-zone is very similar compared to the surface layer (Fig. 3 g–i). However, the core region is less coherent and widespread in the root zone (cf. also horizontal line segments of Fig. 6 b, which indicate the spatial extent of the core region).

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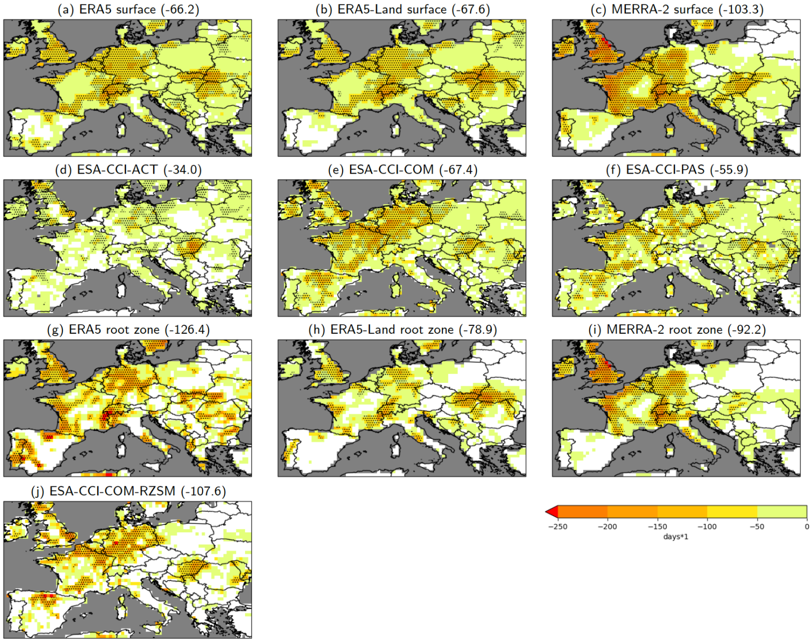

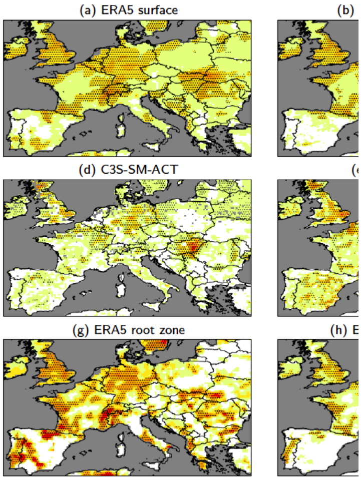

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Figure 3 Severity of the 2022 Europe drought event (in days*1) based on the time accumulated soil moisture anomalies in (a–f) the surface and (g–j) the root zone layer. The core of the event region is stippled, and the area mean of the severity over the respective core of the event region is denoted in brackets.

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For surface layer soil moisture, the event appears most severe in MERRA-2 (though within a smaller extent of the core region than the other reanalyses), followed by ERA5-Land, ESA-CCI-COM, and ERA5 (Fig. 3, see also Supplementary Table 3 for an overview on all drought metrics of the 2022 Europe event). In particular ESA-CCI-ACT shows weaker severities for this event. The magnitude of the 2022 European drought based on ESA-CCI-COM and -PAS is over large parts

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comparable to the reanalysis products, with standardised anomalies of –3 and less in parts of the core region of the event (Fig. 4). ESA-CCI-ACT shows weaker magnitudes. The event shows the longest durations in MERRA-2, with over 90 days in parts of the core region and over 50 days on the average over it (Fig. 5). ERA5/ERA5-Land and ESA-CCI-COM and -PAS display average durations of around 30 days, and ESA-CCI-ACT the shortest with 18 days.

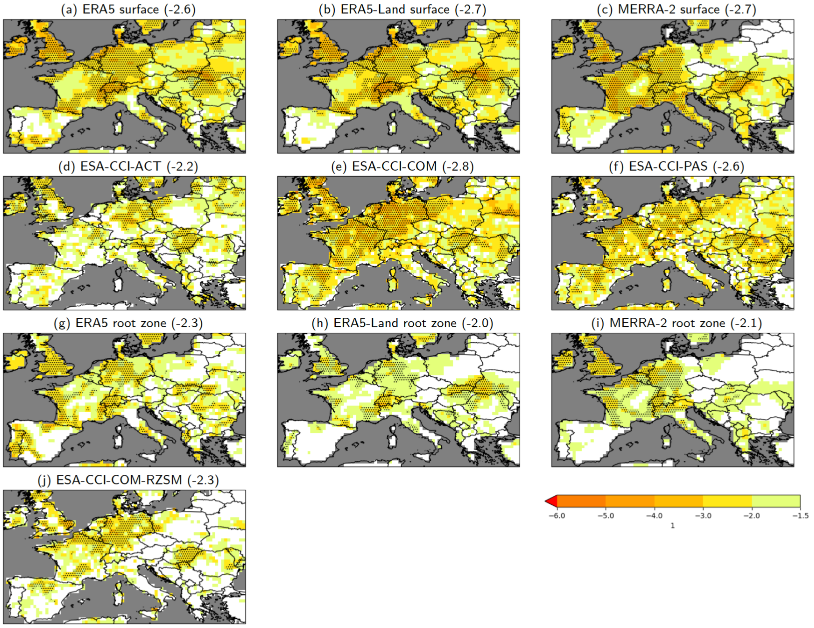

Figure 4. Magnitude of the 2022 Europe drought event (in standard deviations) based on the temporal minimum of the standardised soil moisture anomalies in (a–f) the surface and (g–j) the root zone layer. The core of the event region is stippled, and the area mean of the magnitude over the respective core of the event region is denoted in brackets.

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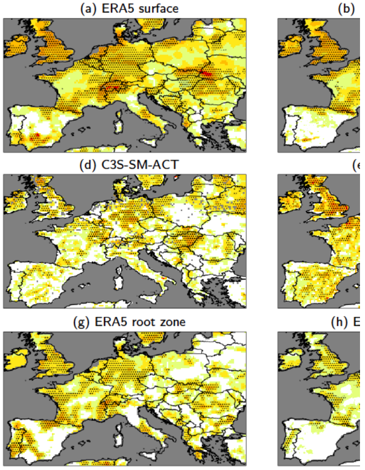

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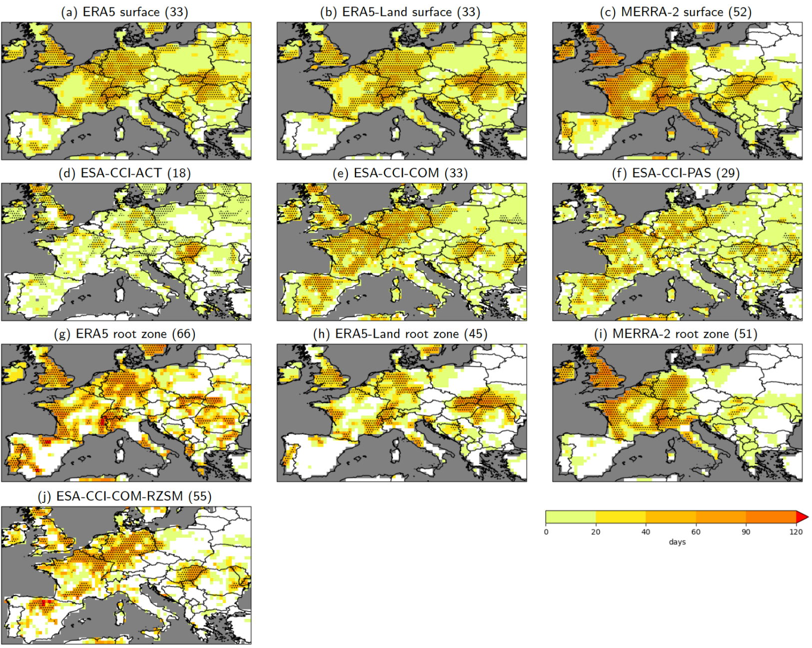


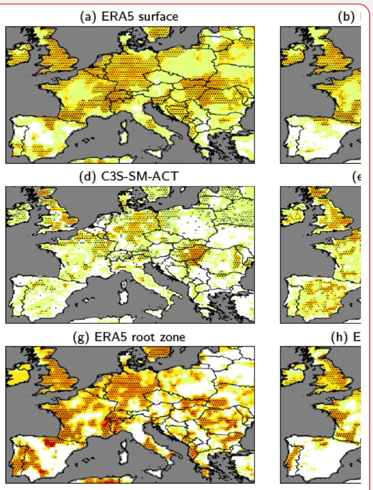
(a) ERA5 surface (33) (b) ERA5-Land surface (33) (c) MERRA-2 surface (52)

(d) ESA-CCI-ACT (18) (e) ESA-CCI-COM (33) (f) ESA-CCI-PAS (29)

(g) ERA5 root zone (66) (h) ERA5-Land root zone (45) (i) MERRA-2 root zone (51)

(j) ESA-CCI-COM-RZSM (55)

Figure 5 Duration of the 2022 Europe drought event (in days) based on the number of days within the event period with standardised soil moisture anomalies below –1.5 in (a–f) the surface and (g–j) the root zone layer. The core of the event region is stippled, and the area mean of the duration over the respective core of the event region is denoted in brackets.



(a) ERA5 surface (b)

(d) C3S-SM-ACT (e

(g) ERA5 root zone (h) E

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In the root-zone of ERA5-Land and particularly of ERA5 and ESA-CCI-COM-RZSM, the 2022 European drought appears more severe as compared to the surface layer (Fig. 3, see also Supplementary Table 3), mostly due to longer durations (Fig. 5), while the magnitudes are weaker (Fig. 4). MERRA-2 shows a similarly reduced drought magnitude in the root zone as ERA5/ERA5-Land, but in contrast, the duration is similar as in the surface layer (where it is however already substantially longer than in ERA5/ERA5-Land). Together with partly weaker negative anomalies (cf. Fig. 6 a), the severity in the root zone of MERRA-2 as a result becomes reduced compared to the surface layer.

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The temporal evolution of the standardised surface soil moisture anomalies averaged over the core of the event region shows two strongest phases of the event in the second half of July and first half of August 2022 (Fig. 6 a), with average standardised anomalies based on the reanalysis products reaching –1.5. Anomalies are most pronounced (i.e., close to –2) and prolonged for MERRA-2 compared to the other products. ERA5 and ERA5-Land show weaker negative anomalies and a

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quicker return to normal conditions. Among the remote-sensing products, ESA-CCI-COM and -PAS show the most negative anomalies, however with the minimum in the second half of July. Over the whole period, ESA-CCI-ACT show overall weakest standardised anomalies, which are on average only shortly below normal conditions.

Root-zone soil moisture anomalies from the reanalysis products display less temporal variation, with longer-lasting minimum values in July and August (dashed lines in Fig. 6 a). In the root zone, the dryer than normal conditions persist during late summer and early autumn, with values still below –1 standardised anomaly. Strongest and most prolonged root-zone soil moisture anomalies are displayed by ERA5 and ESA-CCI-COM-RZSM, while ERA5-Land and MERRA-2 show weaker negative anomalies.

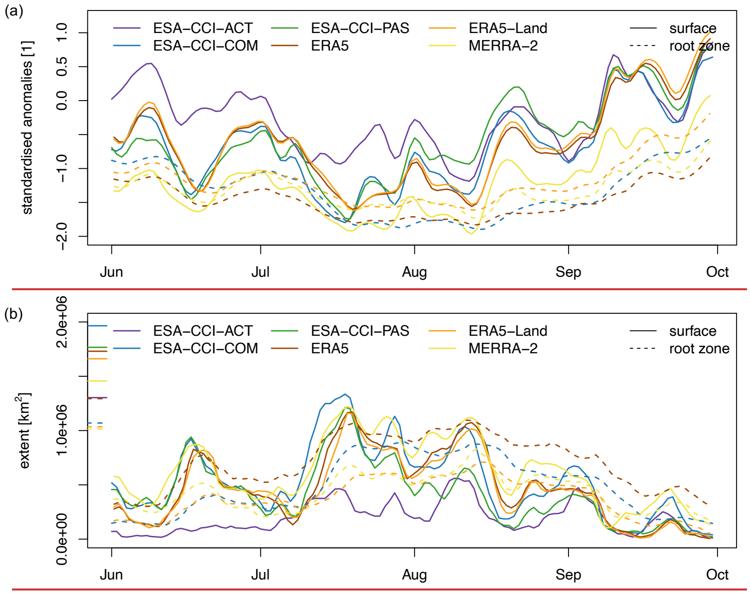

Figure 6. (a) Average of the standardised surface (full lines) and root-zone (dashed lines) soil moisture anomalies within the respective core of the event regions (cf. stippled regions in Figs. 1–3) during the 2022 Europe drought event period. (b) Spatial extent of the standardised surface (full lines) and root-zone (dashed lines) soil moisture anomalies below –1.5 within the core of the event region during the 2022 Europe drought event (full lines). Line segments at the left border of the figure indicate the extent of the core region for each dataset (i.e., corresponding to the extents of the stippled areas of Figs. 1–3 where the severity is larger than the median of all non-zero severity grid points).

The temporal evolution of the spatial extent of the drought (i.e., the area of standardised soil moisture anomalies below –1.5 within the core of the event region) shows highest values during July, reaching over 1.3 Mio. km^2 for surface soil moisture of

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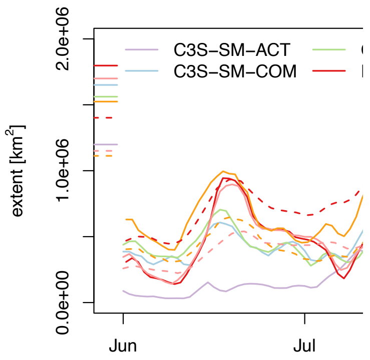

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ESA-CCI-COM (Fig. 6 b, Supplementary Table 3) followed by 1.2 Mio. km^2 of MERRA-2 and ESA-CCI-PAS. The maximum spatial extent of the event in the root-zone is clearly lower compared to the respective surface layer in ERA5-Land, MERRA-2 and ESA-CCI-COM-RZSM, while it is less reduced in ERA5. Correspondingly, ERA5 shows the largest spatial extent of the drought in the root zone with a maximum of 1.09 Mio. km^2, followed by ESA-CCI-COM-RZSM with 0.90 Mio. km^2 (Supplementary Table 3).

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4.4 Recent major drought events

An overview on the characteristics of major drought events in the 2000–2022 period as represented in the various products is given in Fig. 7 (based on surface and root-zone soil moisture).

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The Iberian Peninsula 2011–2012 drought and the Texas 2011 and Great Plains 2012 droughts appear most severe and longest in most of the products and both surface and root zone layer. The East Africa drought of 2015 shows overall strongest magnitudes (except in MERRA-2), followed by Iberian Peninsula 2011–2012 drought. The spatial extents of the drought reach highest values for the Europe 2020 and the South Africa 2015–2016 droughts, though with large differences between the products.

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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. MERRA-2 tend to show weaker magnitudes compared to the other products particularly in the root zone, while the durations are partly prolonged in the surface layer (e.g., Texas 2011, Iberian Peninsula 2011–2012).

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In the root zone, the drought events appear weaker in terms of magnitudes, often prolonged and partly more severe. Compared to the reanalysis products, ESA-CCI-COM-RZSM shows partly stronger drought severities and corresponding longer event durations (e.g., Iberian Peninsula 2011–2012, South Africa 2015–2016, Texas 2011), as well as often stronger magnitudes. Also, the spatial extents of the droughts appear larger in some cases in ESA-CCI-COM-RZSM (e.g., Southeast Europe 2007, South Africa 2015–2016, Great Plains 2012).

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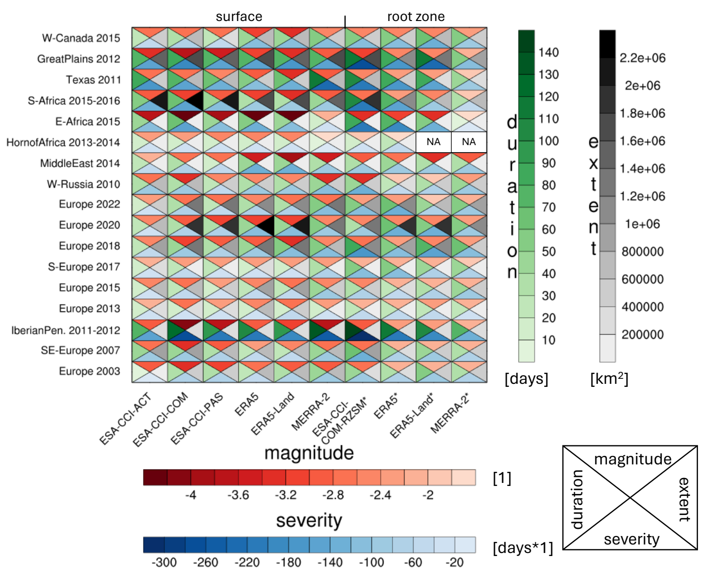
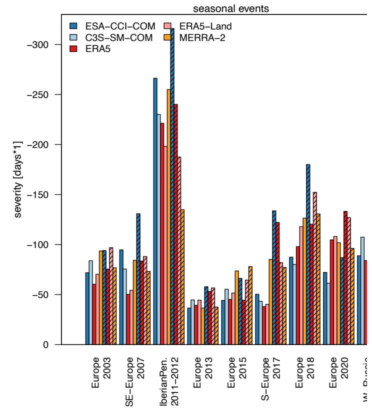


Figure 7 Drought metrics of recent major drought events. The values are based on surface soil moisture and root-zone soil moisture (products denoted with *) and represent the area mean over the respective core of the event region in case of severity, magnitude, and duration, and the temporal maximum in case of the spatial extent. NA is displayed when products do not exhibit standardized anomalies below –1.5 for a specific event.

4.5 Product intercomparison

The overall product behaviour during the analysed drought events is summarised in Fig. 8. In line with the results of the previous section, the dampened drought magnitudes and smaller spatial extents in the root zone compared to the surface layer are again visible in the respective products. Also, a tendency to prolonged durations and stronger severities of the droughts in the root zone is observable (except for MERRA-2, which already shows partly longer durations in the surface layer compared to the other products). ESA-CCI-COM-RZSM displays partly stronger representation of the drought severities and particularly magnitudes compared to the reanalysis products, while MERRA-2 shows weaker drought magnitudes and partly shorter durations and lower severities.



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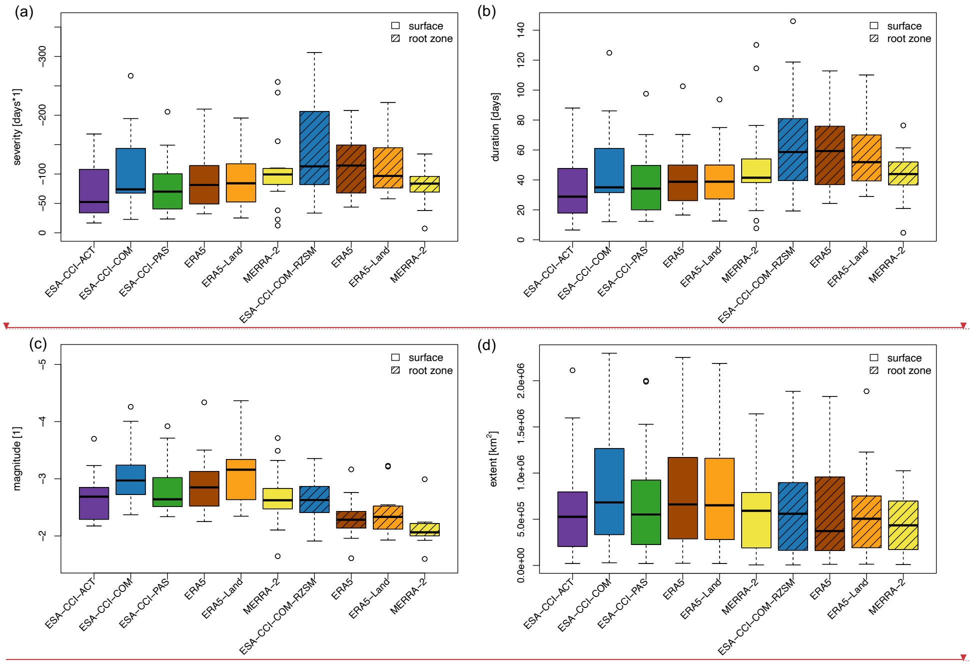
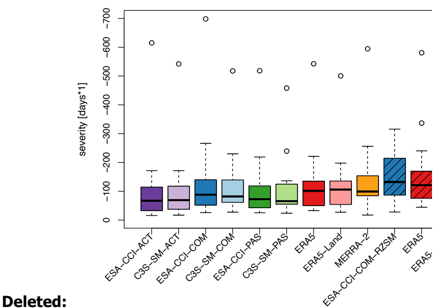


Figure 8 Product intercomparison based on the drought metrics (a) severity, (b) duration, (c) magnitude, and (d) spatial extent. The box-whisker plots represent the distributions of the drought metrics for the analysed 17 drought events.

For surface soil moisture, the ESA-CCI-ACT and to a lesser extent the ESA-CCI-PAS products, tend to show partly weaker drought signals in all presented metrics compared to ESA-CCI-COM and ERA5/ERA5-Land. This is most pronounced for the drought magnitudes of ESA-CCI-ACT. Similar as for the root zone, ESA-CCI-COM displays partly stronger drought severities (cf. ESA-CCI-COM-RZSM) and longer durations. Also as for the root zone, MERRA-2 displays weaker drought magnitudes compared to the other products, while particularly shorter droughts appear partly prolonged (and more severe) in its surface layer (cf. also the 2022 Europe drought above and corresponding Figs. 5–6, and Supplementary Table 3, as well as Fig. 7 for all events).

The spatial extents of the droughts based on surface soil moisture tend to be larger for ESA-CCI-COM and ERA5/ERA-Land, particularly for larger droughts. In the root zone, the spatial extents of larger droughts tend to be smaller.



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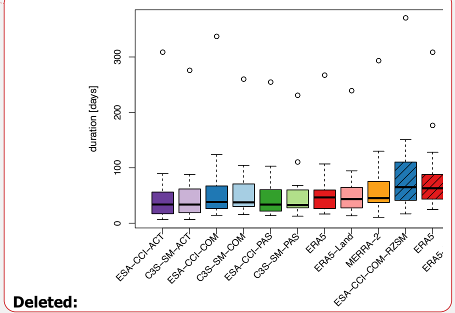

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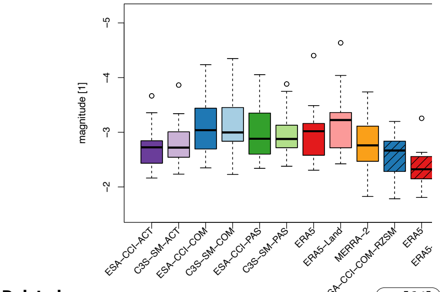

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5 Discussion

5.1 Synthesis of soil moisture trends

Section 4.2 has shown that ERA5/ERA5-Land appear more consistent with observed precipitation and temperature trends. The resulting more widespread soil drying and evapotranspiration decreases can thus be assumed to be more realistic in these products than in MERRA-2. In contrast to ERA5, MERRA-2 does not benefit from an analysis of synoptic surface air temperature observations (Simmons et al., 2017), and is thus less constrained by ground observations. This could explain the identified regional negative biases in 2 m temperature trends of MERRA-2 compared to ERA5. The latter includes an assimilation of these ground-based surface air temperature measurements, from which also ERA5-Land indirectly benefits. In addition, the assimilation of 2 m temperature and relative humidity pseudo-observations in the soil moisture analysis of ERA5 tend to have an important impact on root-zone soil moisture and latent/sensible heat fluxes (Fairbairn et al., 2019), which could contribute to the increased sensitivity of ERA5 to drought events.

Apart from the impact of differences in the forcing and in the data assimilation strategies on the observed soil moisture trends of the reanalyses, differing land-surface model parametrisations may further contribute to product-specific drought representation and trends of the reanalyses. In particular, MERRA-2 has been shown to exhibit a prolonged surface soil moisture memory (Dirmeyer et al., 2016; cf. Fig. 6 therein), which contributes to the observed partly prolonged durations (and stronger severities) of shorter droughts in the surface layer of this product. Also, He et al. (2023) report that in water-limited evapotranspiration regimes, MERRA-2 shows a larger overestimation of soil moisture memory times compared to estimates from SMAP, while the bias in ERA5 is lower. It is noted that soil moisture thresholds (i.e., wilting point and critical point; see e.g., Seneviratne et al., 2010) in the land-surface model parametrisations contribute to the observed differences in the soil moisture memory times. Comparing these soil moisture thresholds between ERA5 (based on HTESSEL) and MERRA-2 (based on the CLSM) reveals that both the wilting point and particularly the critical point tend to be higher for ERA5 than for MERRA-2 (cf. also Schwingshackl et al., 2017, Fig. 14 therein). This may translate into the observed stronger drought representation of ERA5 since it more quickly enters a soil moisture limited evapotranspiration regime during dry downs.

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Previously, ERA5/ERA5-Land and MERRA-2 soil moisture were jointly evaluated with other reanalyses against in situ observations from various networks (Li et al., 2020; Beck et al., 2021; Zheng et al., 2023). On the network scale, ERA5 showed higher consistency with observed soil moisture compared to MERRA-2 based on temporal correlation coefficients and standard deviations, as well as when considering the correlations of the seasonal trend decomposed time series (Li et al., 2020). Furthermore, ERA5-Land soil moisture shows a consistent improvement compared to ERA5 based on a large set of in situ observations (Beck et al., 2021; Muñoz-Sabater et al., 2021). The improvement is more marked for root zone soil moisture than for surface soil moisture. Also, compared to Cosmic Ray Neutron Sensor observations, ERA5-Land outperforms MERRA-2 (Zheng et al., 2023). Within the remote-sensing products, available validation studies indicate that ESA-CCI-COM outperforms the individual ESA-CCI-ACT and ESA-CCI-PAS products when compared to in situ soil moisture measurements (Gruber et al., 2019; Beck et al., 2021; Hirschi et al., 2023). Also, previous studies point to artificial wetting trends in ASCAT soil moisture in areas of widespread deforestation or urban growth (Hahn et al., 2023). This is reflected in the observed larger fractions of wetting trends of ESA-CCI-ACT, which since 2007 is solely based on ASCAT observations. Given these available evaluation studies and the identified biases in MERRA-2 precipitation and temperature trends (Sect. 4.2), in the following we only consider the ESA-CCI-COM-based products and ERA5-Land for a synthesis on the global surface and root-zone soil moisture trends based on these best-estimate products. It should be noted that ESA-CCI-COM-RZSM is unlikely to show surface to root-zone de-coupling in trends given the exponential filter derivation.

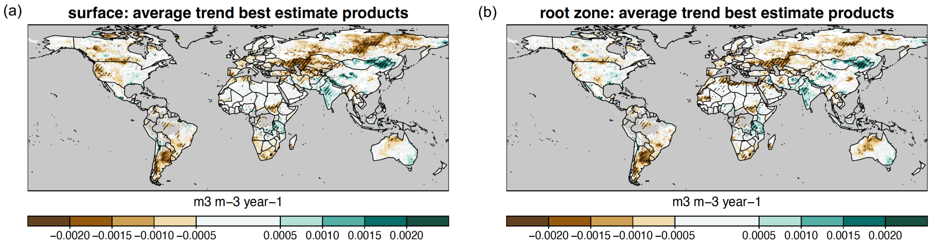

Figure 9 Best-estimate products average of 2000–2022 Theil-Sen trends (m^3 m^{-3} yr^{-1}) on yearly mean (a) surface and (b) root-zone soil moisture. Underlying daily data is masked based on the ESA-CCI-COM (a) (and -RZSM, b) data availability, and non-frozen soil conditions of ERA5-Land (a, b). The mean trends are only shown in areas with trend direction agreement of both respective best-estimate products, while white colour denotes no consensus in the trend direction. Additionally, areas of common significant trends are hatched.

Based on the average of the respective two best-estimate products' trends (Fig. 9), common soil moisture drying can be observed in Siberia, in the region of the Black Sea/Caspian Sea and Central Asia, in parts of Europe and the Mediterranean, parts of western USA and the Canadian Prairies, as well as larger parts of South America, parts of southern and northern Africa and northwest Australia. These drying trends are often significant in both products ($p < 0.05$; cf. hatched areas in Fig. 9), and the regions are mostly consistent with previous studies on trends in water availability (e.g., Padron et al., 2020). Common wetting trends are present in East Asia and India, southeast Australia, and in eastern Africa. Common significant wetting trends appear less widespread than drying trends and are mostly refined to parts of Asia and central and eastern Africa.

The corresponding global area fractions of common soil moisture drying trends amount to 49.3% for the surface soil layer, and to about 44.5% for the root zone (Table 2). The respective wetting trends amount to 21.1% (surface) respectively 20.6% (root zone), and areas with no trend direction consensus to 29.6% respectively 35.0%, reflecting the considerable uncertainties associated with global soil moisture trends.

5.2 Relation of drought representation and soil moisture trends

In the following, we investigate the effect of the diverse and partly contradictory soil moisture trends of the products on their representation of the investigated drought events. For each event and product, Fig. 10 shows the product deviation in the representation of these events in terms of magnitude versus the deviation in the 2000–2022 trend. The analysis is stratified by separating the drought regions in areas with drying trend agreement and in those without trend direction agreement (cf. Supplementary Figure 1 c, brown respectively white areas). Trends and magnitudes are averaged over these respective areas, and the respective deviations are calculated with respect to the product median. The chronology of the events within the 2000–2022 period is indicated with increasing circle sizes.

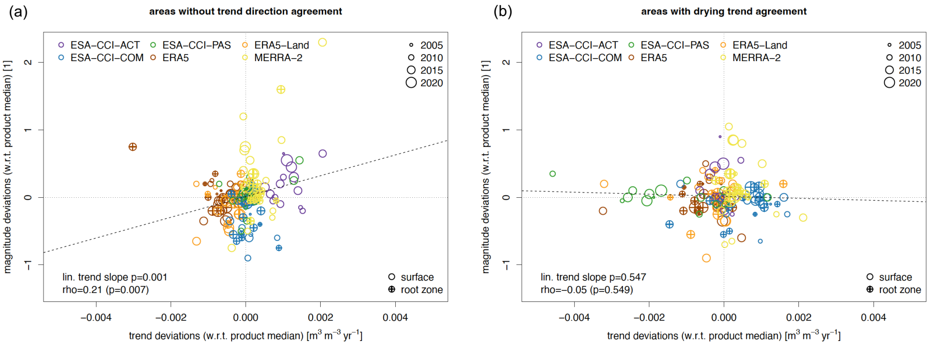

Figure 10 Product deviations in drought magnitude as a function of product deviations in the 2000–2022 soil moisture trends, with circle sizes depending on the chronology of the events within the investigated period (i.e., later events are displayed with larger circles). (a) Relation in areas without trend direction agreement of the products, (b) relation in areas with drying trend agreement. 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 "+"). The trends and drought magnitudes are averaged over the respective areas of drying trend agreement and trend direction disagreement within the 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.

The scatter plots reveal that in areas without trend direction agreement (Fig. 10 a), a significant relation between deviations in drought magnitude and deviations in the trend is present. Thus, as expected, products with negative (positive) deviations in the trends are connected with stronger (respectively weaker) drought magnitudes (i.e., corresponding to negative respectively positive deviations in the magnitude). The scatter plot of Fig. 10 a also indicates a temporal dependency of the deviations, as the largest deviations tend to relate to events occurring after around 2010, which further shows the importance of the trend representation on the drought response of the products. However, in areas with drying trend agreement of the products (Fig. 10 b), such a relation between product deviations in the drought magnitude and the corresponding deviations in the trend is not present. Thus, consensus in the soil moisture drying results in more consistent drought signals of the

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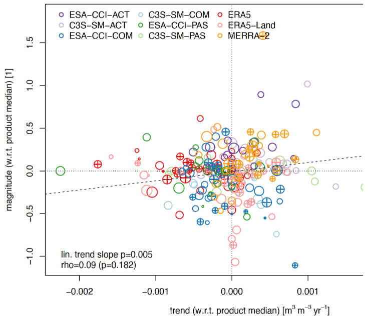

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products. Overall, this analysis highlights that the trend representation has a significant influence on the drought-detection capacity of the products.

For the ESA-CCI-ACT and MERRA-2, the positive deviations in the trends and the reduced drought magnitudes are visible in the location of several events in the respective upper right quadrant (Fig. 10 a). These are the products that show larger area fractions of positive than negative trends (cf. Table 2). ESA-CCI-ACT also exhibits an intensification and extension of the wetting trends in the later part of the analysis period (compared to the 2000–2022 period, not shown), which further contributes to the reduced drought magnitudes of later events. An additional contribution may come from sensing issues of active microwave remote sensing during dry spells, which lead to an increase in the backscatter of the signal due to subsurface scattering, resulting in an erroneous increase in soil moisture (Wagner et al., 2022).

5.3 Impact of land-surface/bioclimatic variables on satellite soil moisture retrieval and modelling uncertainties

The detected differences in trend (and consequent drought) representation of reanalysis and remote-sensing products (Fig. 1) have partly been reported previously (e.g., Dorigo et al., 2012; Preimesberger et al., 2021). Past studies have linked them to fundamental modelling simplifications in the description of human impacts, which may explain differences regionally (Qiu et al., 2016). However, differences result also from the intrinsic trend representation error of the satellite products. The evidence of locally contradicting trends between the considered ESA-CCI-ACT, -PAS, and -COM (Fig. 1) suggests that the differences in the observation system and retrieval algorithm used in the various products have a non-negligible effect on their trend- and drought-detection capacity.

The presented trend analysis is bound to deal with the heterogeneities in the true spatial support and sampling frequency of the products, which can explain part of the observed deviations if accounted for explicitly (Wen et al., 2022). In this respect, the satellite products are set apart by the lower observational density that results from ingesting (in the 2000–2022 analysis period) four sensors in the ACTIVE products against more than double that amount in PASSIVE and COMBINED. This affects the noise levels and – remarkably – their rate of change over time (Hirschi et al., 2023), which leads to biased trends. On top of this, the individual sensors are subject to their own performance drift (Fennig et al., 2020), that propagates to the merged products but is virtually impossible to isolate in the merged soil moisture signal. Generally, spurious trends are also attributed to non-resolved inter-sensor biases in the merging process (Yang et al., 2013). However, this was not found to be the case in antecedent product versions of the considered ESA CCI products (Preimesberger et al., 2021; Su et al., 2016).

Dynamic processes on the land-surface present an additional potential impediment to the stability of the soil moisture retrieval and the reanalysis-based soil moisture (and thus trends and anomalies representation). Retrieval algorithms as well as the land-surface models underlying the reanalyses may in fact be grounded on stationarity assumptions that are challenged by evolving land-surface characteristics. For instance, the vegetation correction of the H SAF ASCAT soil moisture record

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ingested in the ESA-CCI-ACT and -COM products is parametrised on a seasonal basis in the TU Wien model (Naeimi et al., 2009; H SAF, 2021), thus not accounting for inter-annual differences and trends in vegetation (Vreugdenhil et al., 2016). This may introduce biases over time, leading to an inconsistent representation of the anomalies and to spurious trends in certain areas. The same effect would be caused by temporal variations of the statically calibrated dry- and wet-reference, following soil porosity variations. Abrupt land cover changes are also not automatically parametrised and cause artificial trends which should be visible for instance in areas of widespread deforestation or urban growth (Hahn et al., 2023).

Based on the above, trends in the remote sensing and the reanalysis products – or at least differences between them – might be explained by considering the underlying trends of relevant land-surface characteristics and bioclimatic indicators. Hence, trends in soil moisture are compared globally to those calculated using the maximum data availability over the 2000–2022 period for VOD, ERA5-derived aridity (2000–2018 only), and fractional covers of urban area, of bare soil and of tree cover, and the results are included in Appendix A. The VOD data is masked consistently as for the soil moisture trends; this was not possible for the other variables as they were already aggregated above the daily level in the original products. In case of aridity, there appears to be a strong explanatory capacity for the soil moisture trends in all considered reanalyses – not just ERA5/ERA5-Land, for which this is expected due the model internal consistency – and in most of the satellite-based products (Fig. A1 of the Appendix A). On the contrary, the soil moisture trends in ESA-CCI-ACT are mixed for all aridity trend regimes, consistently with the weaker drought representation found for this product (Fig. 8). As argued, trends in vegetation cover or density may reflect in the soil moisture signal of the remote sensing products for the role they play in the uncertainty budget, but should also reflect the soil moisture signal as a result of changes in water availability in both satellite and model data. In the case of tree cover (Fig. A2), ESA-CCI-ACT shows a relation with (dry) wet trends in areas of (de-)forestation, while ESA-CCI-PAS shows the opposite relation. A positive relation is to a lesser extent also visible in ERA5/ERA5-Land (more pronounced in the root zone) and ESA-CCI-COM-RZSM (when considering q75 of the trend distributions) as well as in MERRA-2 (when considering q25). Conversely, global VOD (Fig. A3) only explains trends in the ESA-CCI-ACT product and to a lesser extent in ESA-CCI-COM and -RZSM, but does not relate to the modelled trends, either in the surface nor in the root zone. The physical relation between VOD and water availability shows more clearly when water limited areas only are considered (below the 25th percentile of the mean ERA5 100–289 cm depth layer soil moisture for the 2000–2020 period, Fig. B4). In this case, soil moisture emerges more distinctly as a vegetation control in the remote sensing products (Lyons et al., 2021), and is better captured by the satellite-based products. No distinct relations emerge with bare soil trends for either of the products (if not a mild negative relation to ERA5/ERA5-Land trends), although a subsurface scattering effect (Wagner et al., 2022) might explain remarkably wetter trends in the higher bare ground quantiles for ESA-CCI-ACT (Fig. A5). ESA-CCI-ACT also displays an evident increase in soil moisture trends with trends of urban area fraction (Fig. A6). This is consistent with similar observations made for the ASCAT-derived products (Hahn et al., 2023), and visible also in ESA-CCI-COM (which also ingest ASCAT).

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In synthesis, several controls can be identified for the soil moisture trends in the various products, although no one variable explains all trends coherently. In some cases (e.g., for urban area), these may be artifacts of the L0 signal that should be decoupled in the retrieval of soil moisture through an update in the model parametrisation. In other cases, it is reasonable to assume some form of relationship (e.g., for the aridity indicator or for VOD in water-limited regions), which, however, a few products fail to render.

6 Conclusions

We investigated the potential of long-term remote-sensing and selected state-of-the-art reanalysis products for characterising soil drying by analysing their 2000–2022 Theil-Sen soil moisture trends and their representation of major agroecological drought events of this period. The product differences in the representation of the drought events as a use case were confronted with the soil moisture trends and their drivers, and a synthesis of the global trends was provided based on the best-estimate products. We focused on the relative behaviour of the products to circumvent the lack of widely available ground data of soil moisture. Thus, we did not aim for a in situ validation of the products regarding their representation of the soil moisture trends and considered drought events but focused on the product ensemble and identify the products with larger deviations from the majority to collect convergence of evidence.

Global distributions of the soil moisture trends are diverse and partly contradictory among the products. ERA5-Land, ERA5 and ESA-CCI-COM show larger area fractions of drying trends in surface soil moisture, while ESA-CCI-ACT and MERRA-2 show larger fractions of wetting trends. The different global patterns of soil moisture trends of the reanalysis products ERA5/ERA5-Land and MERRA-2 are reflected in regional differences in their runoff and particular evapotranspiration trends. These differences are driven by a positive mean bias in the precipitation trends of MERRA-2 and a larger RMSD compared to ERA5, which has a slight negative bias and a lower RMSD compared to observed precipitation trends. The diverse soil moisture and evapotranspiration trends also show a clear link to regional differences in 2 m temperature trends in parts of Asia, Africa, and North America, where MERRA-2 shows a negative bias compared to observed temperature trends. The lower bias in precipitation trends of ERA5 and its stronger constraint with observed regional temperature trends results in more widespread soil moisture drying and evapotranspiration decreases of ERA5/ERA5-Land. In MERRA-2, the too strong positive trends in precipitation translate into more widespread wetting trends in soil moisture and enhanced evapotranspiration, and an unrealistic regional cooling.

Given these biases in MERRA-2 precipitation and temperature trends, but also based on available validation studies, ESA-CCI-COM and -RZSM, as well as ERA5-Land were considered for a synthesis on the global surface and root-zone soil moisture trends. Based on these best-estimate products, common soil moisture drying trends can be observed in 49.3% of the surface and 44.5% of the root zone layers of the covered global area. The common drying trends are localized in Siberia, in

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the region of the Black Sea/Caspian Sea and Central Asia, in parts of Europe and the Mediterranean, parts of western USA and the Canadian Prairies, as well as larger parts of South America, parts of southern and northern Africa and northwest Australia.

We also analysed the product representation of drought events as a use case based on their severity, magnitude, duration, and spatial extent, which are calculated from standardised daily anomalies of surface and root-zone soil moisture. We considered well documented drought events selected based on scientific literature and drought reports. The investigated products mostly capture the considered 17 drought events. The ESA-CCI-ACT microwave remote-sensing and to a lesser extent the ESA-CCI-PAS products, tend to show partly weaker drought signals based on surface soil moisture in all metrics compared to the combined ESA-CCI-COM product and ERA5/ERA5-Land. This is most pronounced for the drought magnitudes of ESA-CCI-ACT. The magnitudes are also reduced in MERRA-2 both in the surface layer and the root zone. ESA-CCI-COM displays partly stronger drought severities and prolonged durations. In the root zone (based on the reanalysis products and ESA-CCI-COM-RZSM), the drought events appear dampened in magnitude and smaller in spatial extent, while a tendency to prolonged durations and stronger severities of the droughts is observable (except for MERRA-2). ESA-CCI-COM-RZSM displays partly stronger representation of the droughts in severity and magnitude compared to the reanalysis products.

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The product deviations in drought magnitude further showed a significant relation with deviations in the soil moisture trends in areas without trend direction agreement. This is most visible in the reduced drought magnitudes of MERRA-2 and the ESA-CCI-ACT remote sensing product compared to the other products, which is linked to their larger global fractions of strong positive trends in soil moisture. In areas with drying trend agreement of the products, however, such a relation between product deviations in the drought magnitude and the corresponding deviations in the trend was not present, and magnitudes were more consistent. This study demonstrates that soil moisture trends play a fundamental role for the drought-detection capacity of different products. Uncertainties in the representation and global distribution of soil moisture trends, as reflected in the large area fractions of lack of consensus in trend direction, both between and among remote sensing and reanalysis products, contribute to product-specific representations of droughts, particularly affecting the drought magnitude.

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We also identified several land-surface characteristics and bioclimatic indicators (i.e., aridity, VOD, fractional coverage of urban area, of tree cover and of bare soil) that control soil moisture trends in the various products, although none of these explains all trends coherently. The analysis of trends in these land-surface and bioclimatic variables qualitatively showed that the soil moisture trends are affected by retrieval or modelling artifacts, e.g., due to non-valid stationarity assumptions in the land-surface variables. Conversely, trends in these variables may show valid physical relationships to trends in soil moisture (e.g., in case of aridity, VOD in water-limited regions), which are however not represented by some products. As a future step, the exact sources of such artifacts should be identified to reconcile the different – and partially diverging – trends representations and advance the drought assessment capacity of the remote sensing observations and reanalysis systems.

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Appendix A

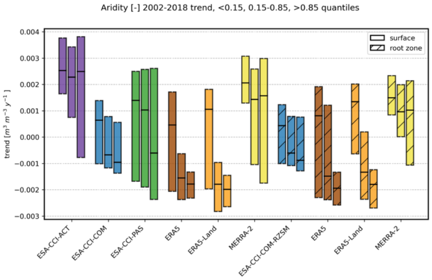

Figure A1 Distributions (median, inter-quartile range) of global soil moisture trends in the different products in relation to different quantile bins of trends in aridity (i.e., <0.15, 0.15-0.85, >0.85). Note that trends are not masked for significance.

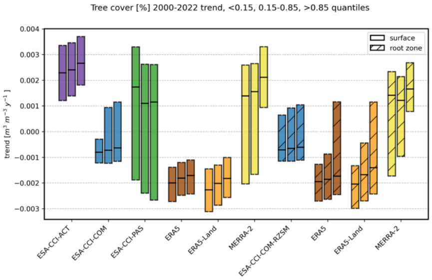

Figure A2 As Fig. B1, but for trends in tree cover fraction.

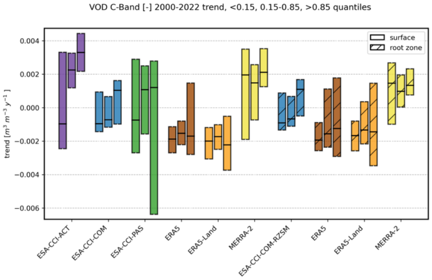

Figure A3 As Fig. B1, but for trends in global VOD.

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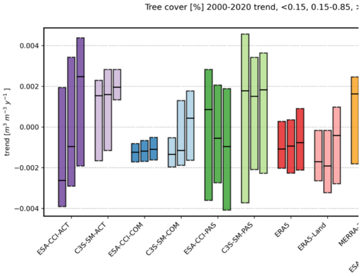

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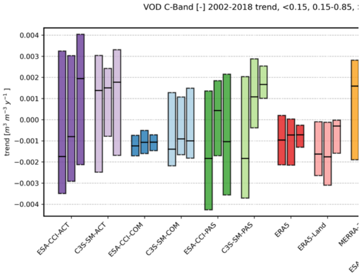

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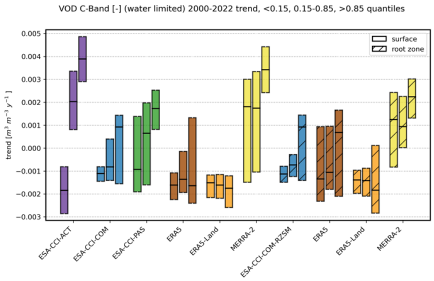

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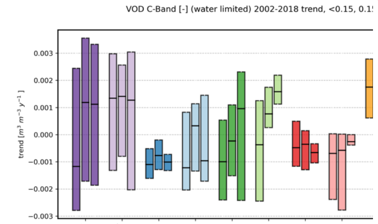

Figure A4 As Fig. B1, but for trends VOD in water-limited regions.

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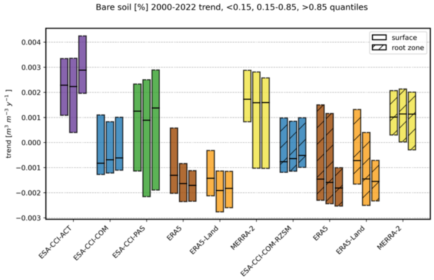

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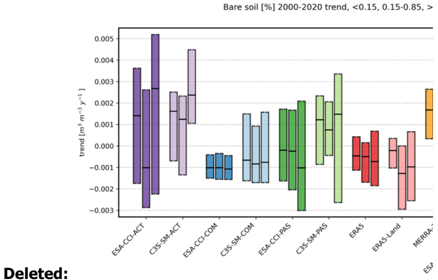

Figure A5 As Fig. B1, but for trends in bare soil fraction.

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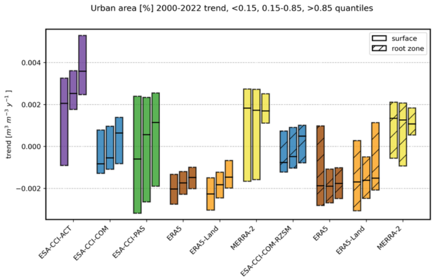

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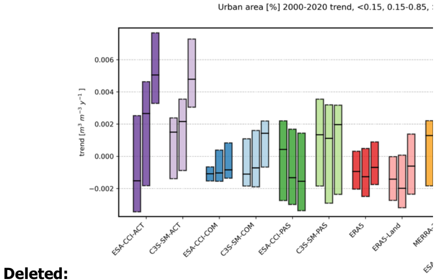

Figure A6 As Fig. B1, but for trends in urban area fraction.

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Author contribution

MH, PS, BC, WD and SIS: Conceptualization; MH, BC, PS: Formal analysis, Investigation, Methodology, Visualization; MH: Writing – original draft preparation; all authors: Writing – review & editing.

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Competing interests

The authors declare that they have no conflict of interest.

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