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Recent summer soil moisture drying in Switzerland based on measurements from the SwissSMEX network

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Abstract. Notably drier summers and more frequent droughts were reported in Switzerland in the last decades. Here, we present curated timeseries of in situ soil moisture measurements from the Swiss Soil Moisture Experiment (SwissSMEX) network, which as of now cover 15 years. We demonstrate the potential of this comprehensive network for analysing the documented drying trends. At 12 grassland stations, SwissSMEX provides data on the volumetric soil water content at various depths in the soil profile, which can be used to calculate integrated soil water content down to 50 cm depth as an indicator of root zone water. We document recent measures that have been taken to secure the SwissSMEX network and to ensure the continuity of its long-term soil moisture timeseries. These timeseries are used to analyse trends in summer and summer half-year anomalies of integrated soil water content, and to investigate the robustness of the recent drying based on different sets of Swiss Plateau stations. Furthermore, the SwissSMEX-based trends are compared with those from soil moisture of a widely used land reanalysis product (ERA5-Land) and of a merged passive microwave remote sensing product (European Space Agency Climate Change Initiative ESA CCI).

There is good agreement between the temporal evolution and the drying tendency of SwissSMEX in situ soil moisture based on different sets of Swiss Plateau stations, which vary in their temporal coverage due to sensor failures. Comparing the in situ timeseries from stations with best temporal coverage with ERA5-Land and ESA CCI PASSIVE soil moisture from the corresponding grid cells also reveals a good agreement between these three independent data sources, with correlations of 0.85 or higher for the median timeseries calculated across stations. Based on these stations, the drying over the common 2010–2023 period amounts to -2.0 mm yr^{-1} for the absolute summer soil moisture anomalies of SwissSMEX and ERA5-Land (or -1.2 % yr^{-1} for the percentage anomalies), and to -0.9 mm yr^{-1} (or -0.6 % yr^{-1}) for ESA CCI PASSIVE. The summer half-year trends are about half of those from the summer values for SwissSMEX (-1.0 mm yr^{-1}, $p < 0.05$ in this case) and ERA5-Land (-1.1 mm yr^{-1}), while ESA CCI PASSIVE shows similar summer and summer half-year trends. Although most of the trends are not significant over the short 2010–2023 period, trends in summer half-year soil moisture anomalies from ERA5-Land become significant for certain time frames when the period for the trend test calculation is extended to years before 2010. Although the SwissSMEX network indicates that summer soil drying has increased in recent years, the 15 years of in situ data

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currently available are in many cases not yet sufficient to robustly estimate a significant trend. This highlights the importance of sustaining ongoing measurements to ensure a seamless continuation of soil moisture monitoring in Switzerland.

1 Introduction

Droughts in Switzerland have become a significant concern due to their impacts on agriculture, water resources management, energy production, shipping and ecology. Historically, occasional summer droughts have been reported for Central Europe and Switzerland, e.g. in the years 1911, 1947, 1949, 1962, and 1976 in the 20th century (Calanca, 2007; Pfister and Rutishauser, 2000; Van Der Schrier et al., 2007). Following a prolonged period without severe droughts, Switzerland has experienced increasingly frequent drought events in the last two decades, namely in the 2003, 2015, 2018, and 2022 summers, and in the 2011 and 2020 springs/early summers (Calanca, 2007; Brunner et al., 2019; Orth et al., 2016; Schumacher et al., 2024; MeteoSchweiz, 2018, 2012; BAFU, 2016). As a result, notable trends towards drier summer half-years were observed in Switzerland from 1981 to 2020 based on the climatic water balance calculated from meteorological station observations and the soil water content from reanalyses (Scherrer et al., 2022; hereafter referred to as S22). This drying trend is primarily driven by two factors: a non-significant decrease in precipitation and an increase in evapotranspiration due to rising temperatures. This observed drying trend is consistent with the recent assessment of the 6th assessment report of the Intergovernmental Panel on Climate Change (IPCC), which identified an observed drying trend in agricultural and ecological drought (based on soil moisture and/or water-balance metrics) for West-Central Europe (Seneviratne et al., 2021). The dominant role of evapotranspiration for the observed drying tendences in several land regions is also consistent with the conclusions of past publications (e.g. Seneviratne et al., 2021; Padron et al., 2020). S22 showed, however, that the available reanalysis data (ERA5-Land and ERA5) differ considerably in their representation of summer half-year soil moisture and evapotranspiration in Switzerland. ERA5 and ERA5-Land evapotranspiration both significantly increase from 1980 to 2020, but the trend is about twice as strong in ERA5-Land as in ERA5. The latter product already indicates a moisture limitation of evapotranspiration in dry years, while the former shows an evapotranspiration surplus in these years. The associated dry anomalies and drying trend in soil moisture are more pronounced in ERA5 than in ERA5-Land. Overall, compared to ERA5, the behaviour of ERA5-Land is more consistent with results from lysimeter and eddy covariance flux measurements of evapotranspiration in north-eastern Switzerland (Seneviratne et al., 2012; Michel and Seneviratne, 2022), and it agrees better with a limited set of stations from the Swiss Soil Moisture Experiment (SwissSMEX) soil moisture measurement network (Mittelbach and Seneviratne, 2012).

Given these existing uncertainties in the reanalysis data, we present curated in situ timeseries from all Swiss Plateau stations in the SwissSMEX network. The data are then used to extend the analysis of S22 by focusing on the in situ soil moisture trends. Although in situ soil moisture measurements have their own inherent problems and challenges (e.g. due to soil heterogeneity, representativeness of point measurements, sensor calibration issues), they are still the only available ground information to contrast with land reanalysis or remotely sensed soil moisture.

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The SwissSMEX soil moisture network was installed between 2008 and 2010 as a research network and since then measures volumetric water content (VWC, in $m^3 m^{-3}$) and soil temperature in profiles from 5 cm down to a maximum of 150 cm depth using time domain reflectometry (TDR) and capacitance sensors (Mittelbach and Seneviratne, 2012; Mittelbach, 2011). The number of depth levels available varies across the network, and redundant profiles of the same sensor type are available at some stations. The VWC measurements are also used to calculate the integrated soil water content (IWC, in mm) down to 50 cm depth as an indicator of root zone water, which is relevant for plant growth in agriculture and natural vegetation, and is directly related to the fluxes of the land water balance. While root depths are highly variable in space and depend on the plant species, the choice of 50 cm depth covers shallow-rooted plants such as, e.g. lettuce, onions, potatoes, various vegetables and most native grass species (Brouwer et al., 1989). Also, this depth is covered by all stations of the network.

Twelve SwissSMEX grassland sites are still operational, but in recent years sensor have failed more frequently, leading to temporal interruptions or the complete termination of the measurement series (Michel et al., 2022b). This prompted an intervention to preserve the measurement network for the coming years. These sensor failures are particularly problematic for the derivation of IWC, which relies on the simultaneous availability of VWC from sensors at multiple depths. They also affect the capacity of the network for real-time monitoring and long-term trend detection. This is particularly relevant as the increasing frequency of droughts in recent years has prompted the Swiss Federal Council to initiate a programme in May 2022 to establish and expand a national early detection and warning system for droughts, including a national in situ soil moisture network (BAFU, 2024). The implementation of the national network at existing SwissSMEX sites will benefit from the secured long-term records.

This paper documents the recent measures that have been taken to secure the SwissSMEX network and its long-term soil moisture timeseries. It revisits the documented summer drying trends in Switzerland as a use case of the presented in situ measurements and compares the SwissSMEX-based trends with those derived from land reanalysis and remote sensing soil moisture. The in situ timeseries presented here also contribute to the CH2025 national climate scenarios.

2 Data and methods

2.1 SwissSMEX

2.1.1 Status of the network and new installations

The standard instrumentation of SwissSMEX, initiated in 2008, consisted of capacitance soil moisture sensors (Decagon 10HS) at all measurement depths of 5, 10, 30, 50, 80, and 120 cm, and of TDR soil moisture sensors (IMKO TRIME-PICO) at 10 and 80 cm depth (Mittelbach, 2011). In the follow-up project SwissSMEX-*Veg*, selected stations were additionally equipped

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with TDR sensors at 5, 30 and 50 cm depth in 2010. As part of the regular processing of the SwissSMEX measurement data, automatic range and outlier checks, as well as visual controls of individual sensor series, are undertaken. A comprehensive quality assessment and intercomparison of the existing soil moisture time series of the SwissSMEX network has revealed a degradation of data availability due to sensor failures over time, compromising the long-term continuity of the time series (Michel et al., 2022b). This analysis showed that as of 2022, more than a third of all sensors had stopped working since the beginning of the installation in 2008 (Fig. 1). This sensor failure rate is higher for the 10HS capacitance sensors (43 %) than for the TDR sensors (36 %; cf. Appendix A of Michel et al., 2022b).

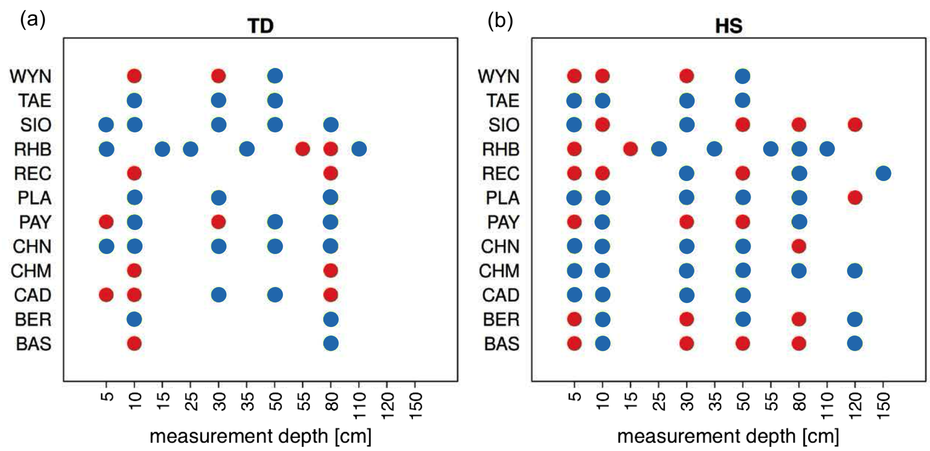

Figure 1 Status overview of sensor availability at the SwissSMEX grassland stations as of spring 2022, i.e. before the intervention during summer 2022 (adapted from Michel et al., 2022b). (a) IMKO TRIME-PICO TDR (TD) sensors, (b) Decagon 10HS (HS) sensors. Abbreviations for station names are given in Table 1. Blue dots indicate functioning sensors; red dots indicate sensors that have had an error rate of more than 20% in the last 30 days and are therefore considered out of order. This is a condensed view incorporating all redundant sensor profiles per sensor type.

In view of this degrading data availability, and in order to secure the network for the coming years, defective TDR sensors at 10 and 30 cm soil depth were replaced with new IMKO TRIME-PICO64 TDR sensors at the SwissSMEX grassland stations during summer 2022, or, if not already present, additional TDR sensors were installed at these depths in the existing profiles (Michel et al., 2022a). This intervention at easily accessible depths, without disturbing the ongoing operation, ensured the continuity of the measurement series at these depths.

2.1.2 Processing

The degradation of the sensor availability is particularly relevant for deriving 0–0.5 m depth integrated soil water content (IWC, in mm). This integration is carried out using the trapezoidal method (e.g. Hupet et al., 2004) and relies on the simultaneous availability of the volumetric water content (VWC, in m^3 m^{-3}) of the sensors at multiple depths. Historically, the integration was performed based on the VWC measurements at 5, 10, 30 and 50 cm depth (Mittelbach and Seneviratne, 2012), plus an additional value of VWC at the surface, which is set equal to the measurement at 5 cm depth. These depths were

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originally fully covered with 10HS sensors, while TDR sensors were predominantly available at 10 and 80 cm depth (Mittelbach et al., 2011; see also Fig. 1). Over time, at some stations, already available TDR sensors were included in the integration to replace defective 10HS sensors (e.g. see station Changins in Fig. 2), or the number of sensors (i.e., depths) entering the integration had to be reduced while ensuring the representativeness of the remaining sensor data (e.g. see station Chamau in Fig. 2). This set of sensors used for the historical IWC timeseries is referred to as original sensor configuration (see also Table S1).

With the increasing number of sensor failures in recent years (Fig. 1), the 0–0.5 m integration based on the original sensor configurations has become impossible at an increasing number of sites. With the upgrade of the network in 2022, all grassland stations are now equipped with at least two TDR sensors in the 0–0.5 m soil column, i.e. at 10 and 30 cm depth. These can be used as alternative for the 0–0.5 m integration when coverage with the original sensor configuration is lacking.

We use the following procedure to secure the long-term 0–0.5 m depth IWC timeseries: The historical timeseries are largely based on the original configurations of 10HS and already available TDR sensors. If the integration based on these sensors is no longer possible due to sensor failures, the long-term IWC timeseries are supplemented by basing the IWC on the 10 and 30 cm TDR sensors that were replaced or newly installed in 2022. For this TDR-only based integration, the 10 cm measurement is used to reflect the 5 cm and 10 cm depths, and the 30 cm measurement is used to reflect the 30 cm and 50 cm depths. The historical hourly IWC timeseries and the 10 and 30 cm TDR-only based series are then merged by correcting the mean and standard deviation of the latter with respect to the former to account for the difference in the representative depth. The offset and relative standard deviation between the two series (see Fig. 2) are calculated based on the overlapping hourly time steps (except for BAS and WYN, where there is no overlap and all time steps are used to calculate the scaling parameters). This procedure allows us to significantly increase the recent station coverage of IWC. In some cases, historical gaps can also be filled in this way for stations that already had TDR sensors at 10 and 30 cm depths prior to 2022.

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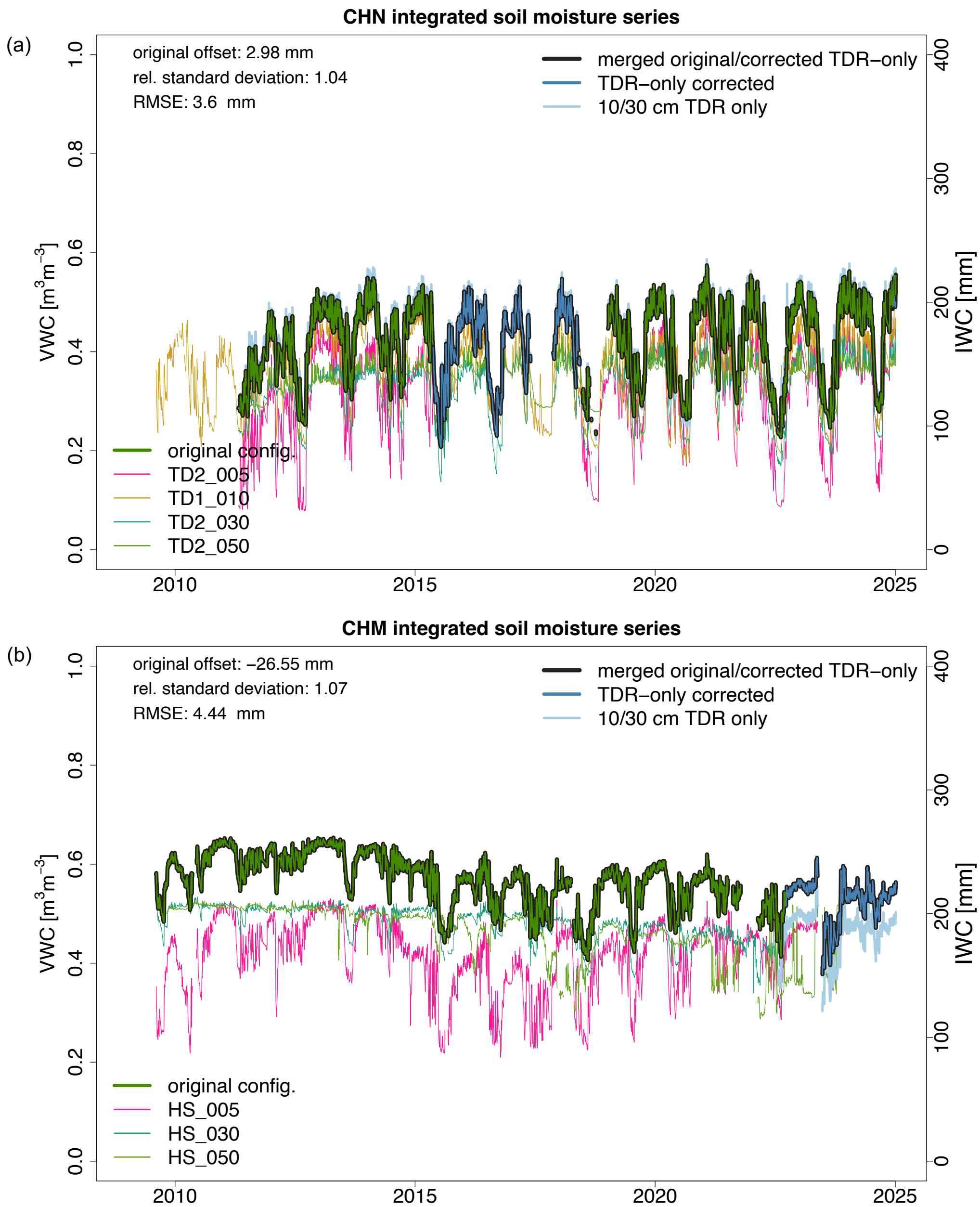

Figure 2 Two examples illustrating the merging of the historical 0–0.5 m integrated soil water content (IWC in mm, daily means) based on the original sensor configuration (displayed as thick dark green line), and the 10 and 30 cm TDR-only based IWC (thick light and dark blue lines represent the TDR-only timeseries before and after correction, respectively). (a) Changins (CHN) where historical gaps could be filled with the corrected TDR-only based IWC, (b) Chamau (CHM) where the IWC timeseries could be extended to near present. Note that the corrected TDR-only based IWC (thick dark blue line) is not displayed when the original configuration (thick dark green line) is present in the merged timeseries (underlying thick black line). Also shown is the volumetric water content (VWC in m^3 m^{-3}) from the 10HS and TDR sensors of the original configuration (see also Table S1). The original offset of the 10 and 30 cm TDR-only based IWC data is also noted, as well as its relative standard deviation and RMSD compared with the IWC calculated from the original sensor configuration (all metrics are based on the overlapping hourly time steps and are calculated before correction of the TDR-only series).

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To illustrate the merging of the historical 0–0.5 m IWC and the 10 and 30 cm TDR-only based IWC timeseries, Fig. 2 shows the temporal evolution of daily mean 0–0.5 m IWC of the station Changins (CHN) as an example for filling historical gaps, and of Chamau (CHM) as an example for extending the historical timeseries to present.

For the following analysis, we focus on mean summer (i.e. June to August, JJA) and summer half-year (i.e. April to September, AMJJAS) soil moisture anomalies, which are expressed as the absolute or percentage deviation from the respective average of the 2010–2020 period, and calculated based on the daily 0–0.5 m (merged) IWC timeseries (cf. underlying thick black lines in Fig. 2). A maximum fraction of 35 % missing days is allowed for the calculation of the respective mean anomalies. This yields the temporal coverage of stations displayed in Table 1. We then test different combinations of stations to investigate the median evolution of summer and summer half-year soil moisture of the Swiss Plateau: "Best coverage" includes stations with maximum one summer/summer half-year missing in the 2010–2023 period, "S22" includes the stations used in S22 (which are representative for an average elevation on the Swiss Plateau), "S22 + best coverage" combines both sets, and we also consider "all stations" listed (ten in total).

Table 1 Overview of the ten SwissSMEX stations of the Swiss Plateau used for the different station combinations.

Station	Full name	Coordinates (lat, lon)	Best coverage[1]	S22	S22 + best coverage	Missing JJA	Missing AMJJAS
BAS	Basel	47.54, 7.58		X	X	2014–2022	2014–2022
BER	Bern	46.99, 7.46	X	X	X	2011	none
CHM	Chamau	47.21, 8.41	X		X	2021	none
CHN	Changins	46.40, 6.23		X	X	2010, 2017, 2018, 2020	2010, 2017, 2018
PAY	Payerne	46.81, 6.94				2021, 2022	2021, 2022
PLA	Plaffeien	46.75, 7.27	X		X	none	none
REC	Reckenholz	47.43, 8.52	X	X	X	2021, 2024	2021, 2024
RHB	Rietholzbach	47.38, 8.99				2014, 2015	2014, 2015
TAE	Tänikon	47.48, 8.90	X		X	2023, 2024	2023, 2024
WYN	Wynau	47.26, 7.79				2010–2012, 2014, 2015, 2021, 2022	2010–2012, 2014, 2021, 2022

[1] maximum one summer/summer half-year missing in the 2010–2023 period

2.2 ERA5-Land

The land component of the ERA5 reanalysis (Hersbach et al., 2020) 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 (Hydrology-Tiled ECMWF Scheme for Surface Exchanges over Land,

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Balsamo et al., 2009) forced by ERA5 near-surface atmospheric reanalysis fields, with additional lapse-rate correction of temperature. HTESSEL 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. ERA5-Land soil moisture is regularly used in the analyses of the Copernicus European State of the Climate Reports. The data has been extracted on a regular latitude/longitude grid of 0.1° x 0.1° spatial resolution and monthly temporal resolution from the Copernicus Climate Data Store (CDS; C3S, 2022). For the comparison with SwissSMEX, the closest grid cells were used for each station location (see Table 1).

The IWC in the 0–0.5 m soil layer, as available from SwissSMEX, has been calculated based on VWC of the soil layers 1–3:

$IWC_{0\text{-}0.5m}$ (in mm) = ($VWC_{0\text{-}7cm} \cdot 0.07$ m + $VWC_{7\text{-}28cm} \cdot 0.21$ m + $VWC_{28\text{-}100cm} \cdot 0.22$ m) · 1000

The assumption is that the VWC of layer 3 (28-100 cm) is representative for the 22 cm between 28 and 50 cm.

2.3 ESA CCI PASSIVE

The European Space Agency (ESA) Climate Change Initiative (CCI) soil moisture (ESA CCI soil moisture, v09.1; Dorigo et al., 2024) provides satellite-retrieved surface soil moisture (penetration depths of ~2–5 cm) over the globe from a large set of active and passive microwave sensors (Dorigo et al., 2017; Gruber et al., 2019). The ESA CCI PASSIVE product was created by merging 14 individual radiometer soil moisture products. Data for v09.1 is available until end of 2023. In addition to the standard product, a gap-filled version of the product, which adapts a 3D-smoothing algorithm (Garcia, 2010) and does not rely on ancillary data, is being produced as a research product of ESA CCI (Preimesberger et al., 2025a).

Here we use root-zone soil moisture estimates based on a gap-filled version of ESA CCI PASSIVE, which is derived by extrapolating gap-filled surface soil moisture to deeper soil layers. This data is also being used in the Copernicus European State of the Climate Reports (C3S and WMO, 2025). The extrapolation is based on an exponential filter (Wagner et al., 1999; Albergel et al., 2008), which is applied to the surface soil moisture timeseries and uses optimal values for the temporal length of the filter (T-parameter) determined from a large number of in situ timeseries (Pasik et al., 2023). The estimates are available for four soil layers: layer 1 at 0–10 cm; layer 2 at 10–40 cm; layer 3 at 40–100 cm; and layer 4 at 100–200 cm. The data is available on a regular latitude/longitude grid of 0.25° x 0.25° spatial resolution and daily temporal sampling. The closest grid cells for each station location (see Table 1) were used for comparison with SwissSMEX, and we restrict the usage of ESA CCI PASSIVE to data from 1991 onwards due to larger data gaps prior to this date in the non-gap-filled product, and the thereby caused high uncertainties associated with the interpolated values (Preimesberger et al., 2025a).

The IWC in the 0–0.5 m soil layer has been calculated as based on VWC of the soil layers 1–3:

$IWC_{0\text{-}0.5m}$ (in mm) = ($VWC_{0\text{-}10cm} \cdot 0.1$ m + $VWC_{10\text{-}40cm} \cdot 0.3$ m + $VWC_{40\text{-}100cm} \cdot 0.1$ m) · 1000

The assumption is that the VWC of level 3 (40-100 cm) is representative for the 10 cm between 40 and 50 cm.

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3 Results

3.1 Station combinations

Figure 3 shows the individual soil moisture anomaly timeseries of the summer 0–0.5 m IWC for the different SwissSMEX stations and the median evolution based on the respective station sets. While the timeseries of SwissSMEX are displayed for the 2010–2024 period in the following, we focus the analysis on the 2010–2023 period, which is common to all datasets (see above). While there is some spread in the anomalies between the individual stations, the station medians of the four station combinations show a consistent temporal evolution.

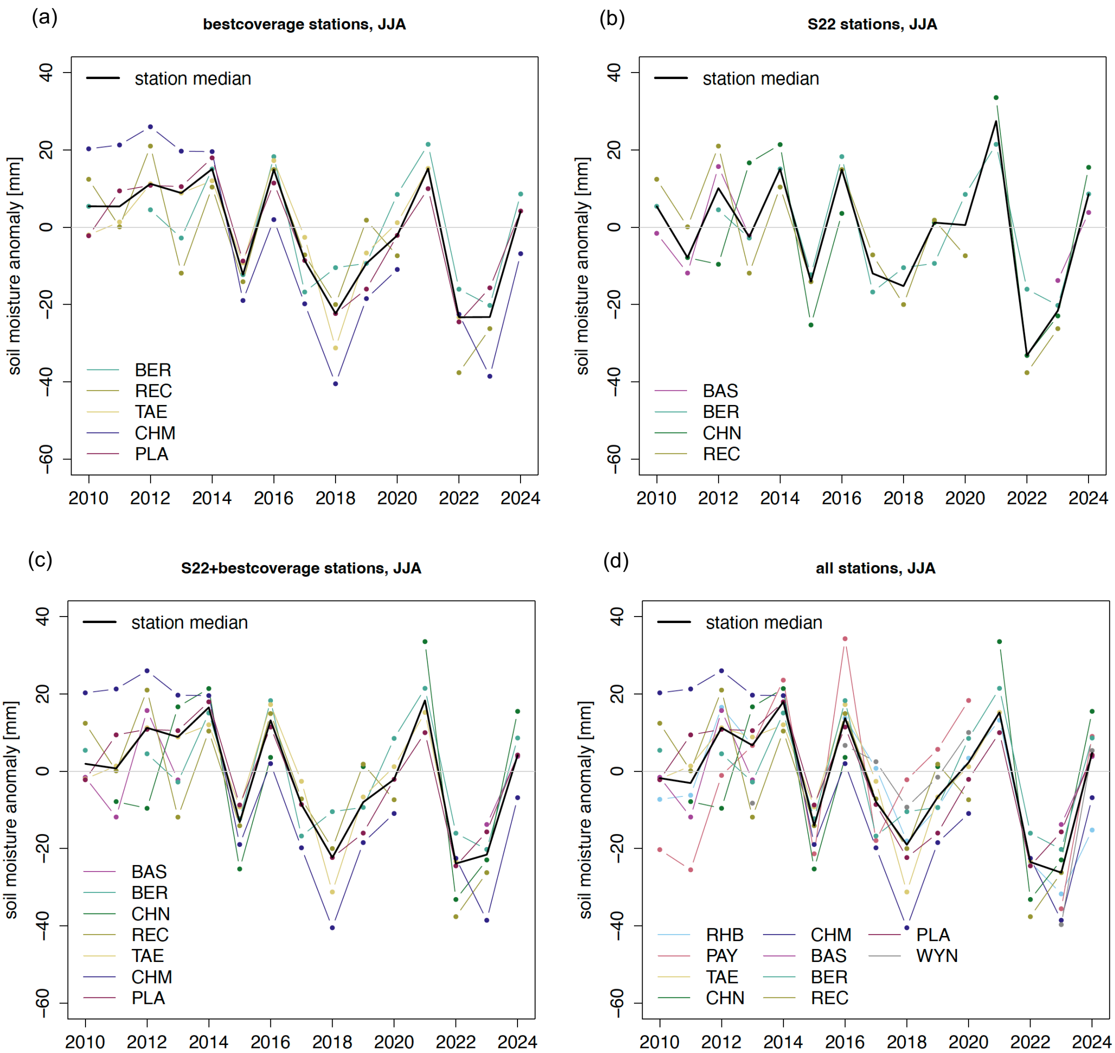

Figure 3 Soil moisture anomaly timeseries of summer 0–0.5 m IWC of different SwissSMEX station combinations (see Table 1) and respective station medians. (a) Stations with best temporal coverage in the 2010–2023 period (i.e. maximum one summer missing), (b) station selection as in S22, (c) S22 and best coverage stations combined, (d) all Swiss Plateau stations. Anomalies are expressed as the absolute deviation from the summer average of the 2010–2020 period.

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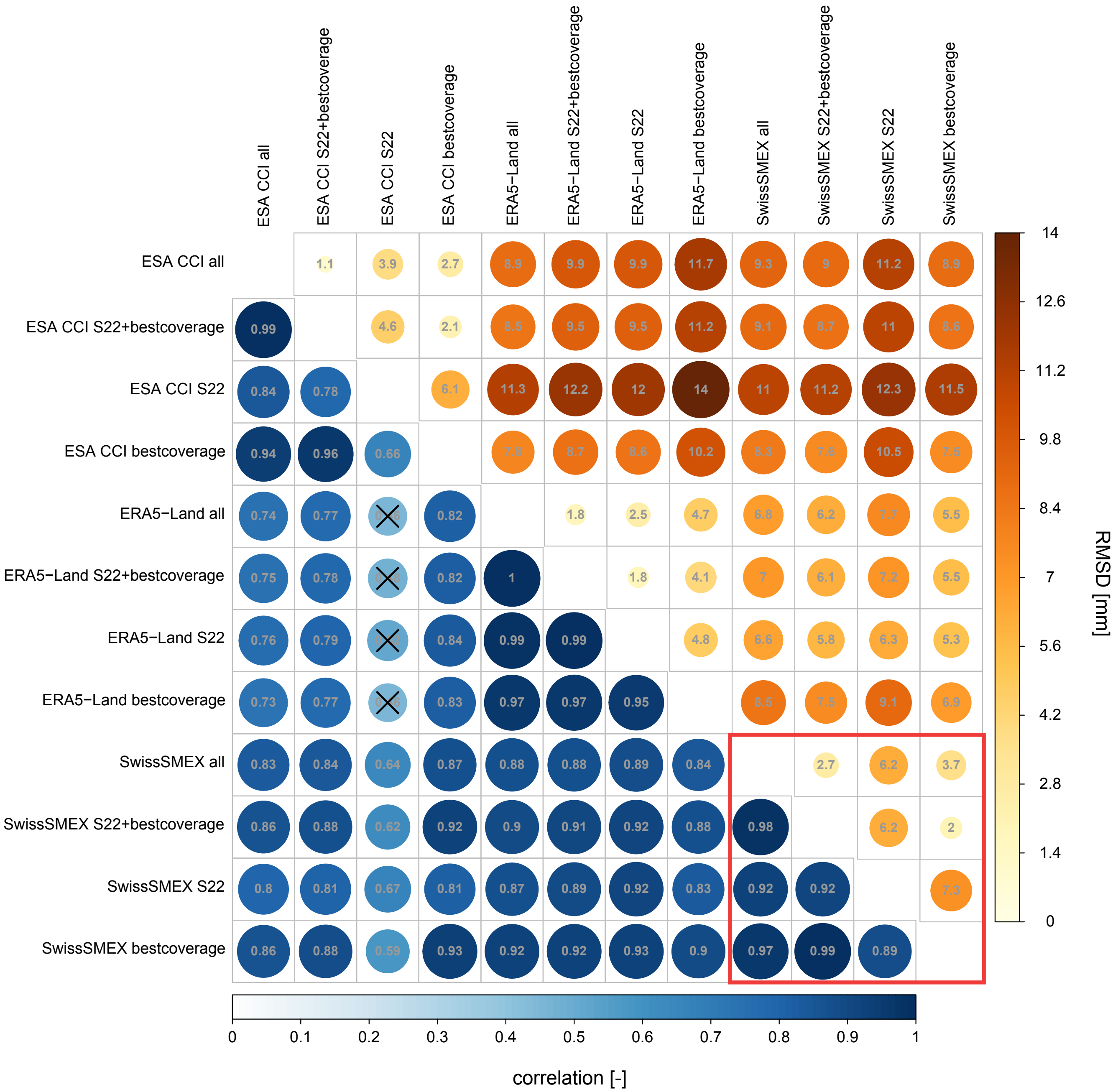

225 **Figure 4 Pearson correlation and RMSD matrices of the pairwise comparison between the SwissSMEX, ERA5-Land and ESA CCI PASSIVE datasets and considering the different station combinations for the Swiss Plateau median timeseries of summer soil moisture anomalies (expressed as the absolute deviation from the 2010–2020 summer average). Values are calculated based on the common 2010–2023 period. Non-significant correlations are crossed out, the rest of the values are significant ($p < 0.05$). The red rectangle highlights the comparison of the different station combinations based on SwissSMEX. See Fig. S1 for the corresponding summer half-year correlations and RMSDs.**

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The pairwise Pearson correlations between these station median timeseries are all greater than 0.89, and the corresponding root mean square deviations (RMSD) amount to a maximum of 7.3 mm (Fig. 4, values in the red rectangle). Similar values of agreement are obtained when summer half-year instead of summer soil moisture is considered (Fig. S1).

All SwissSMEX station combinations also show a tendency towards drying. The respective Theil-Sen trend slopes based on the 2010–2023 period range from -2.0 mm yr^{-1} to -1.3 mm yr^{-1} for summer, and from -1.1 mm yr^{-1} to -0.7 mm yr^{-1} for summer half-year, when trends tend to be lower (Table 2). The respective trends for the percentage anomalies amount to -1.2 % yr^{-1} to -0.7 % yr^{-1} for summer, and to -0.6 % yr^{-1} to -0.4 % yr^{-1} for summer half-year. Note that the drying trend based on the 2010–2024 period is lower (denoted for the best coverage stations in Table 2) since 2024 exhibited a slight positive summer and summer half-year soil moisture anomaly. Thus, the recent soil drying tendency on the Swiss Plateau is independent of the selection of SwissSMEX stations used for the median timeseries, although the trend is only significant ($p < 0.05$) for the absolute anomalies of the best coverage stations during summer half-year of the 2010–2023 period (see also Section 4.1).

Table 2 Theil-Sen trend slopes of summer and summer half-year 0–0.5 m IWC anomalies based on the median of different station combinations (i.e. best coverage, S22, S22 + best coverage, all stations). Anomalies are expressed as the absolute deviation from the summer resp. summer half-year average of the 2010–2020 period, and as percentage deviations from this average. Trend slopes are based on the 2010–2023 period, and trend significance is determined using the non-parametric Mann-Kendall trend test. In addition, for SwissSMEX the 2010–2024 trends for the best coverage stations are given in parentheses.

	Dataset	Best coverage		S22		S22 + best coverage		All stations	
		mm yr^{-1}	% yr^{-1}	mm yr^{-1}	% yr^{-1}	mm yr^{-1}	% yr^{-1}	mm yr^{-1}	% yr^{-1}
summer	SwissSMEX	-2.0 (-1.4)	-1.2 (-0.8)	-1.3	-0.7	-1.7	-1.0	-1.6	-1.0
	ERA5-Land	-2.0	-1.2	-1.9$^{(.)}$	-1.1$^{(.)}$	-1.9	-1.2	-1.8	-1.0
	ESA CCI PASSIVE	-0.9	-0.6	-0.1	0.0	-0.7	-0.6	-0.8	-0.6
summer half-year	SwissSMEX	-1.0$^{(*)}$ (-0.7$^{(.)}$)	-0.6 (-0.4$^{(.)}$)	-1.1	-0.6	-1.0	-0.5	-0.7	-0.4
	ERA5-Land	-1.1$^{(.)}$	-0.7$^{(.)}$	-1.3$^{(.)}$	-0.8$^{(.)}$	-1.2$^{(.)}$	-0.7$^{(.)}$	-1.1$^{(.)}$	-0.6$^{(.)}$
	ESA CCI PASSIVE	-0.8	-0.5	-0.4	0.3	-0.6	-0.3	-0.6	-0.3

$^{(.)}$ denotes $p < 0.1$, and $^{(*)}$ $p < 0.05$

3.2 Comparison with long-term reanalysis and remote sensing soil moisture

The agreement between the different station combinations with respect to the temporal evolution of the Swiss Plateau median soil moisture can also be seen in Fig. 5, which includes in addition to SwissSMEX also the ERA5-Land and the ESA CCI PASSIVE soil moisture. The three independent data sources show good agreement in the inter-annual variations of the summer and summer half-year soil moisture anomalies over the 2010–2023 period, with correlations of 0.85 or higher between the gridded products and SwissSMEX based on the median of the best coverage stations (see also Fig. 4 and Fig. S1). This is the

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case for both the absolute soil moisture anomalies, as well as the percentage anomalies (Fig. S2). The root-mean square deviation (RMSD) from SwissSMEX amounts to 7.5 mm (or 4.3 %) for ESA CCI PASSIVE, and to 6.9 mm (or 4.0 %) for ERA5-Land in summer (Fig. 5, Fig. S2). For the summer half-year, these values are lower due to the lower year-to-year variability (5.1 mm or 3.1 % for ESA CCI PASSIVE, and 5.5 mm or 3.3 % for ERA5-Land).

The pairwise correlations between the three data sources are also mostly significant for the other station combinations, except for the median of the S22 stations based on ESA CCI PASSIVE, which shows non-significant correlations and comparably large RMSDs (11.3 mm to 14 mm) compared with ERA5-Land in summer (Fig. 4). The same applies for the summer half-year, when in addition also the correlations between the ESA CCI PASSIVE-based S22 station combination and SwissSMEX become partly non-significant (Fig. S1).

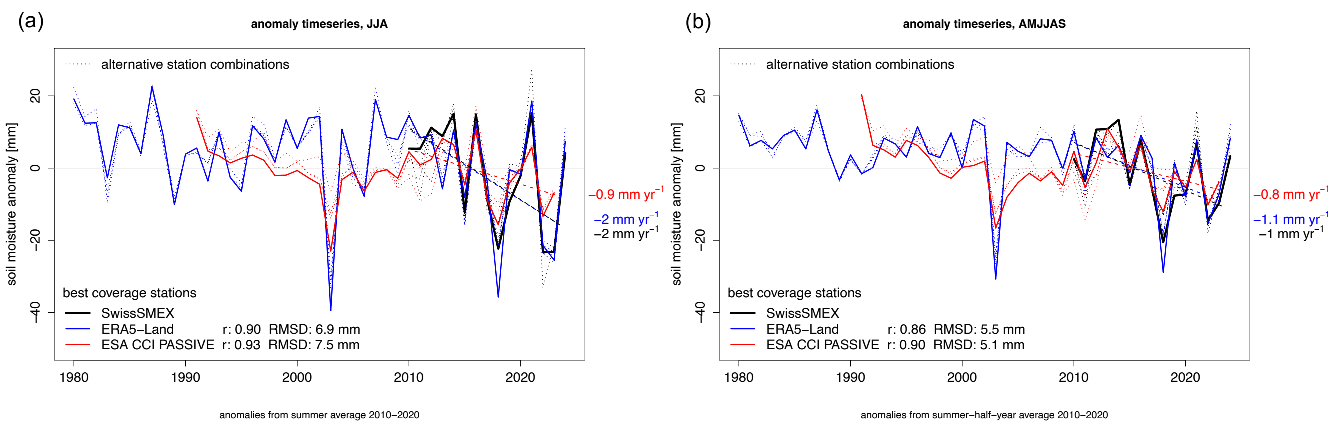

Figure 5 Long-term evolution of (a) summer and (b) summer half-year soil moisture anomalies based on SwissSMEX, ERA5-Land and ESA CCI PASSIVE. Anomalies are expressed as the absolute deviation from the summer resp. summer half-year average of 0–0.5 m IWC of the 2010–2020 period (see Fig. S2 for corresponding anomalies as percentage deviations from this average). Shown are the median timeseries based on the best coverage stations (full lines), as well as the ones based on the alternative station combinations presented in Section 3.1 (dotted lines). For the gridded products, the nearest grid cells from the stations are considered as basis for the median. The dashed lines indicate the linear trend of the 2010–2023 period, with Theil-Sen trend slopes indicated to the right of the plots (based on the best coverage stations timeseries). Also given are the Pearson correlation r and RMSD of the gridded products with respect to SwissSMEX. Note that ESA CCI PASSIVE ends in 2023, while SwissSMEX and ERA5-Land extend to 2024.

The Theil-Sen trend slopes for the median of the best coverage stations amount to -2.0 mm yr^{-1} (or -1.2 % yr^{-1}) for SwissSMEX and ERA5-Land, and to -0.9 mm yr^{-1} (or -0.6 % yr^{-1}) for ESA CCI PASSIVE for summer (Fig. 5 and Fig. S2, Table 2). The summer half-year trends based on the best coverage stations are about half of the summer values for SwissSMEX (-1.0 mm yr^{-1}, $p < 0.05$ in this case) and ERA5-Land (-1.1 mm yr^{-1}), while ESA CCI PASSIVE shows similar trends for summer and the summer half-year (-0.8 mm yr^{-1} for the latter). Overall, ESA CCI PASSIVE shows less pronounced (or partly non-existent) drying tendencies compared to the SwissSMEX and ERA5-Land for all station combinations (Table 2). This is also due to less pronounced negative summer and summer half-year anomalies of ESA CCI PASSIVE compared to SwissSMEX and ERA5-Land (Fig. 5).

The two gridded datasets ERA5-Land and ESA CCI PASSIVE also show reasonable agreement in the inter-annual variations of the Swiss Plateau soil moisture over the longer term since 1991 (Fig. 5), with correlations of 0.70 for summer and 0.57 for summer half-year ($p < 0.05$ for both) based on the median of the best coverage stations. Even though the sign of the anomalies does not agree in some cases, the dry anomalies of 2003, 2015, 2018, 2022 and 2023 are apparent in both products, with ERA5-Land displaying more negative anomalies compared to ESA CCI PASSIVE. This is in line with recently reported product differences in the drought detection capacity of these gridded products (Hirschi et al., 2025b). As for the recent SwissSMEX period, the different station combinations also show largely consistent temporal evolutions since 1991.

4 Discussion

4.1 Robustness of trend

To investigate the impact of the shortness of the SwissSMEX timeseries on the significance of the trend, Fig. 6 displays the p-value of the Mann-Kendall trend test based on ERA5-Land soil moisture as a function of the starting year for calculating the test (i.e. the length of the timeseries). The trend tests are calculated based on the median timeseries of the absolute soil moisture anomalies from the best coverage stations (full lines in Fig. 5), and in addition to the summer and summer half-year trends, also trends based on annual anomalies are considered. Starting year 2010 refers to the 2010–2023 trend (or 14 years of data, i.e. the SwissSMEX period), starting year 1980 refers to the 1980–2023 trend (44 years of data).

Due to the larger inter-annual variations, trends in summer tend to be overall less significant (i.e. higher p-values) than trends based on annual and summer half-year soil moisture anomalies, even though the absolute trend magnitude is larger for summer than for summer half-year (see Table 2). For the short 2010–2023 period, trends in SwissSMEX summer and annual soil moisture anomalies are not significant, but they are significant ($p < 0.05$) for the summer half-year anomalies (circles in Fig. 6, see also Table 2). For the same period, p-values for ERA5-Land trends in annual and summer half-year soil moisture anomalies range between 0.05 and 0.1 and are larger than 0.1 for summer anomalies. Trends in both summer half-year and annual soil moisture anomalies become significant for certain periods when extending the starting year of the trend test calculation. Particularly trends starting from 1992 to 2001 are significant for the summer half-year anomalies (and often significant for annual anomalies). Also, summer half-year trends starting before 1985 become significant again, which is consistent with the results of S22. Trends in summer anomalies are, however, non-significant ($p > 0.05$) for all starting years except 2007. It is also apparent that trends tend to be less significant when the starting year has a comparably dry summer compared to surrounding years (e.g. as 2003, 1989).

This analysis shows that the significance of the trend depends both on the temporal frame of the anomalies (annual, summer half-year or summer) and on the period used for the trend calculation. Thus, while the SwissSMEX network indicates that soils

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have become drier in recent years, the 15 years of in situ data currently available are in many cases not yet sufficient to robustly estimate significant trends. Extending the period for calculating the trend yields significant results, particularly for summer half-year soil moisture anomalies, although the significance of the trend may still be impacted by anomalous soil moisture conditions in the starting year.

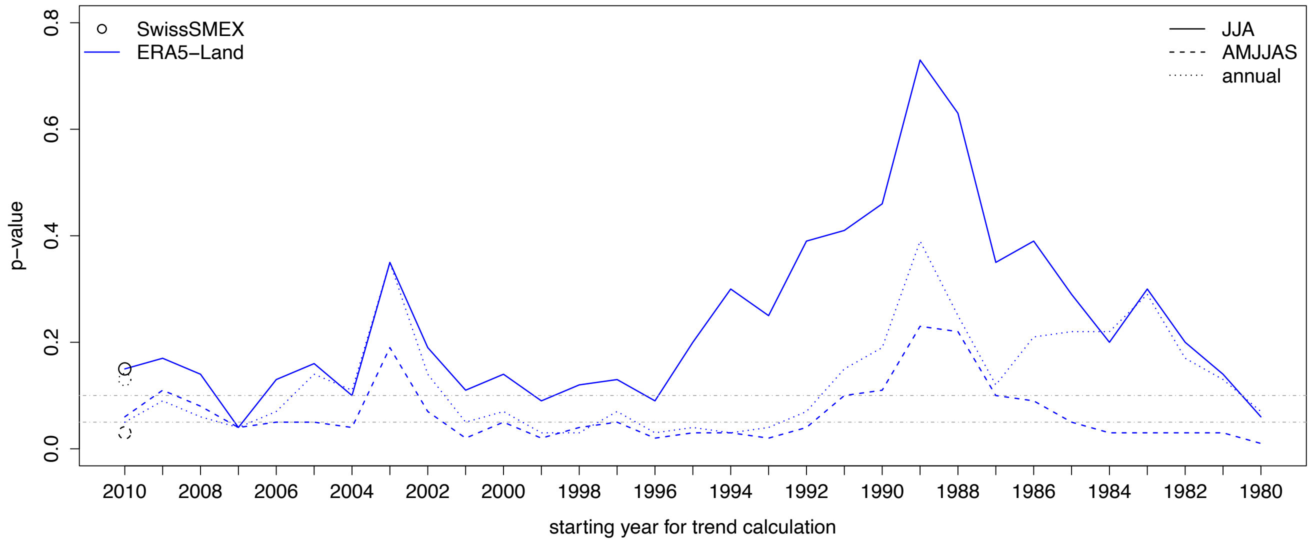

Figure 6 Significance of the Theil-Sen trend slope (p-value of the Mann-Kendall trend test) based on ERA5-Land soil moisture as a function of the starting year for calculating the trend (i.e. the length of the timeseries). The trends are calculated based on the median timeseries of the absolute soil moisture anomalies from the best coverage stations (full lines in Fig. 5). In addition to the summer and summer half-year trends, annual trends are also considered. Starting year 2010 refers to the 2010–2023 trend (or 14 years of data), starting year 1980 refers to the 1980–2023 trend (44 years of data). The p-values for SwissSMEX based on the 14-year timeseries are shown as circles at starting year 2010. The horizontal lines indicate the p=0.05 and p=0.1 thresholds.

4.2 Comparison with S22

Compared to S22, the 0–0.5 m IWC of SwissSMEX presented here is more strongly based on TDR sensors, which have proven to be more robust in operation, and which have been partly renewed or additionally installed in 2022 (see Section 2.1.1). The temporal variability of the TDR sensors tends to be larger than for 10HS sensors, since the latter exhibit a decreasing measurement sensitivity with increasing VWC, and tend to become insensitive to VWC variations above 0.4 m^3 m^{-3} (Mittelbach et al., 2011; Mittelbach et al., 2012). This may explain part of the larger temporal variability and stronger anomalies seen in the presented SwissSMEX timeseries of the Swiss Plateau compared with S22 (cf. Fig. S3 therein). In particular, the IWC of the station CHN was based on 10HS sensors in S22, while it is now based on TDR sensors and extended with 10 and 30 cm TDR-based integration (see Fig. 2). Also, the station BER now includes a 10 cm TDR sensor in the integration, as a replacement of the 10HS sensor at the same depth, which stopped working in 2021 (see Table S1 for an overview of the sensors used). Given the limited number of stations in S22, these changes in the sensor configuration result in the observed differences in the temporal variability of the 0–0.5 m IWC timeseries of SwissSMEX. Consequently, the agreement between SwissSMEX

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and ERA5-Land considerably improves compared to S22, where SwissSMEX showed lower year-to-year variations in IWC than ERA5-Land.

4 Conclusions

We presented a curated, comprehensive set of in situ soil moisture timeseries from the Swiss Plateau stations in the SwissSMEX network. We documented the steps that have recently been taken to secure the network and its long-term soil moisture timeseries. By extending the analysis of S22 and revisiting summer drying trends in Switzerland, we demonstrated the potential of SwissSMEX for analysing the documented drying trends. We further investigated the robustness of the recent drying based on different sets of Swiss Plateau stations and compared these with widely used land reanalysis and remote sensing data on soil moisture. We focussed on summer and summer half-year 0–0.5 m IWC for the analysis as an estimate for root zone soil moisture.

We find good agreement between the temporal evolution of SwissSMEX in situ soil moisture based on different sets of stations. All station combinations share the drying tendency over the 2010–2023 period. Comparing the in situ timeseries with ERA5-Land reanalysis and ESA CCI PASSIVE remote sensing soil moisture also revealed a good agreement between the three independent data sources, with correlations of 0.85 or higher for the median timeseries of the stations with best temporal coverage. The drying over the 2010–2023 period based on these best coverage stations amounts to -2.0 mm yr^{-1} for the absolute summer soil moisture anomalies of SwissSMEX and ERA5-Land (or -1.2 % yr^{-1} for the percentage anomalies), and to -0.9 mm yr^{-1} (or -0.6 % yr^{-1}) for ESA CCI PASSIVE. The summer half-year trends based on the best coverage stations are about half of those from the summer values for SwissSMEX (-1.0 mm yr^{-1}, $p < 0.05$ in this case) and ERA5-Land (-1.1 mm yr^{-1}), while ESA CCI PASSIVE shows similar trends for summer and the summer half-year (-0.8 mm yr^{-1} for the latter). Overall, ESA CCI PASSIVE shows less pronounced drying tendencies compared to SwissSMEX and ERA5-Land.

The analysis also shows that the significance of the trends based on the Mann-Kendall trend test is dependent on the period length (or the starting year) used to calculate the trend. While most of the trends are not significant for the short 2010–2023 period, trends in summer half-year (and annual) soil moisture anomalies of ERA5-Land become significant for certain time frames when the period for the trend test calculation is extended to years before 2010. Trends starting from 1992 to 2001, as well as the ones starting before 1985, are significant for the summer half-year anomalies. Due to the larger inter-annual variations, trends in summer tend to be overall less significant than trends based on summer half-year soil moisture anomalies.

Thus, although the SwissSMEX network indicates that summer soil drying has increased in recent years, the 15 years of in situ data currently available are in many cases not yet sufficient to robustly estimate a significant trend. The projected increase in air temperature and evaporative demand combined with a decline in summer precipitation are expected to lead to further summer drying in Switzerland in the coming years (CH2018, 2018). In this respect, the continuation of the measurements and the current efforts at the federal level to implement a national soil moisture measurement network are important directions for a seamless continuation of soil moisture monitoring in Switzerland.

Data availability

The hourly and daily 0–0.5 m IWC timeseries of SwissSMEX (Swiss Plateau stations), i.e. the historical IWC based on the original sensor configuration, the 10 and 30 cm TDR-only based IWC, and the merged IWC will be made available from the ETH Research Collection at https://doi.org/10.3929/ethz-b-000743711 (Hirschi et al., 2025a) (for the review, data is available at https://polybox.ethz.ch/index.php/s/Xt4Zr9sN5PePyKM). Additionally, the VWC of the individual sensors and depths is available from the same location. ERA5-Land is available from the CDS at https://doi.org/10.24381/cds.68d2bb30 (Muñoz-Sabater et al., 2021). The ESA CCI PASSIVE gap-filled root-zone soil moisture (v09.1) is available at https://doi.org/10.48436/8dda4-xne96 (Preimesberger et al., 2025b).

Author contribution

MH, DM, DLS and SIS: Conceptualization; MH, DM: Formal analysis, Investigation, Methodology, Visualisation; MH, DM, WP: Data curation; MH: Writing – original draft preparation; all authors: Writing – review & editing

Competing interests

The authors declare that they have no conflict of interest.

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