Enhancing cross-disciplinary process understanding and scientific exploitation of soil moisture and land evaporation ECV measurements in Switzerland (SMiLE-ECV-CH)

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FINAL REPORT

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1 Summary

The SMiLE-ECV-CH project has proven the value of collecting in-situ soil moisture and land evaporation measurements across Switzerland as ground-truth reference. The validation of, e.g., remote sensing products of these essential climate variables with direct observations helps developing accurate high-resolution information on the hydrological conditions at any place on the earth's surface. The performance of gridded remote sensing and reanalysis products, i.e., the remote sensing ESA-CCI and ASCAT-SWI and the reanalysis ERA5 soil moisture series as well as LAS SAF land evaporation are assessed with our SwissSMEX data set. Moreover, we highlight the importance of continuous long-term time series by detecting and quantifying recent droughts in Switzerland based on soil conditions. All gridded products are able to detect drought events, such as the summer 2015 (and 2018, if data is available). The correlation of the time series between gridded datasets and in-situ measurements at all compared sites is high, albeit owed to some degree to the pronounced seasonality of the variables. Overall, the results indicate a good performance of model-based soil moisture and land evaporation, which are representative of the hydrological dynamics across Switzerland. When it comes to the accuracy within smaller areas with above-average temperature and dryness, such as in Valais and Ticino, for example, the algorithms seem to overestimate water limitation for evaporation. At the site Rietholzbach we found a strong resilience of evapotranspiration even under very dry conditions in the lysimeter measurements, highlighting the ample water availability at this humid station. Also at this site, the actual land evaporation from the remote sensing appears slightly underestimated. This too tight coupling (or limitation) of land evaporation from soil water content is assumed to be particularly responsible for the underestimation of remote sensing evaporation at dry sites.

At the same time, the SMiLE-ECV-CH project points out the impact on degrading sensor functionality over the course of time. Even though the SwissSMEX soil moisture network is equipped with redundant measurement profiles at each of the 12 grassland stations, we have lost a third of all sensors and three entire stations (when considering depth-integrated profile soil moisture) since 2009. The project already got the attention of GCOS Switzerland for a follow-up, one-off support project, aiming at securing the continuity of the existing infrastructure. A strategy for consistent long-term monitoring of soil moisture in Switzerland, including the Alpine region, is currently being planned with different institutions, under the coordination of MeteoSwiss and BAFU.

2 Scientific report

2.1 Introduction

Climate projections indicate an increasing risk of dry and hot episodes in Central Europe, including in Switzerland (Seneviratne et al., 2010, 2013; Vogel et al. 2017, Seneviratne et al. 2012). However, models display a large spread in projections of changes in summer drying (Vogel et al. 2017, Orlowsky and Seneviratne 2013, Greve and Seneviratne 2015, Vogel et al. 2018), highlighting the importance of related observations to evaluate climate models and constrain projections (Vogel et al. 2018, Padron et al. 2019). Land hydrological variables play an essential role for these projections. This is particularly the case for soil moisture and land evaporation, which are directly affecting the exchange of land moisture and energy with the atmosphere, and which play a key role in the development of droughts and heatwaves in summer in both present and future climate (Seneviratne et al., 2010, 2016, Vogel et al., 2017, Hirschi et al. 2011, Miralles et al. 2014). Since 2008, the SwissSMEX project (Mittelbach and Seneviratne, 2012) is monitoring soil moisture at 19 stations within 17 sites[1] (14 grassland, 1 arable and 4 forest stations). These constitute the main coordinated long-term measurement series for the soil moisture ECV in Switzerland. The SwissSMEX measurements have been used in several applications, for instance for the derivation of European-scale gridded estimates of soil moisture and evaporation (Orth and Seneviratne, 2015). In addition, since 2017 several SwissSMEX stations were complemented with land evaporation measurements from mini-lysimeters (Ruth et al., 2018). The recent 2018 drought in Switzerland has highlighted the importance of monitoring and assessing changes in land hydrology, in particular soil moisture and land evaporation which are strongly related to drought impacts on agriculture, forestry, and ecosystems (Seneviratne et al., 2013). The SMiLE-ECV-CH project is providing an assessment of the monitoring capabilities for the soil moisture and land evaporation ECVs in Switzerland, addressing issues such as quality control of measured data, drought events, related heat waves and changes in land hydrology. The project was focusing on the following four main topics: 1) Quality checks of SwissSMEX measurements, intercomparisons within and between sites; 2) Closing land water budgets in Switzerland; 3) Assessing the suitability of remote sensing estimates of soil moisture and land evaporation; 4) Investigating land-atmosphere interactions during dry and wet periods.

These four objectives are directly aligned on the Priority 3.2 of the GCOS Pillar 3 in the GCOS Switzerland Strategy 2017-2026: "*Enhance process understanding through a more integrative monitoring approach".* The work accomplished and insights gained in the SMiLE-ECV-CH project feed into overarching aims of the GCOS Implementation Plan 2016, namely to "*ensure that the climate system continues to be monitored*", that "*regional and local long-term climate forecas*t" and "*the provision of useful information to users*" is improved.

The quality assessment and intercomparison of the existing soil moisture data series of the SwissSMEX network has pointed out a degradation of data availability due to sensor failures over time, compromising the long-term continuity of the data series. This encouraged the submission of a project proposal aiming at upgrading the soil moisture observation network and securing the continuity of the measurements. A corresponding GCOS Switzerland follow-up, one-off support project has been granted in April 2021, which adds directly to topic 1 of this project and thus to the GCOS Pillar 3 in the GCOS Switzerland Strategy. Preliminary results from this follow-up project are also presented briefly in this report. Based on in-situ data from one specific SwissSMEX site, the land water budget in dry periods was investigated. Collaborations between ETH and MeteoSwiss mainly focused on land-atmosphere interactions during dry and wet periods across Switzerland, the analysis

[1] One site (Oensingen), including 3 stations, was discontinued in 2013.

of recent drought events and the assessment of remote sensing techniques to estimate and monitor soil moisture and land evaporation.

The analyses have been performed by members of the land-climate dynamics group with Dr. Dominik Michel, Dr. Martin Hirschi, and Prof. Sonia I. Seneviratne as main investigators. Additionally, significant contributions to this project resulted from scientific collaborations with MeteoSwiss (Annkatrin Burgstall, Dr. Anke Duguay-Tetzlaff and Dr. Simon Scherrer). Dr. Michael Rösch supported the technical field work. Ms. Barbara Wittneben (formerly) and Ms. Rahel Buri are the administrative assistants on the project.

2.2 Methods and activities

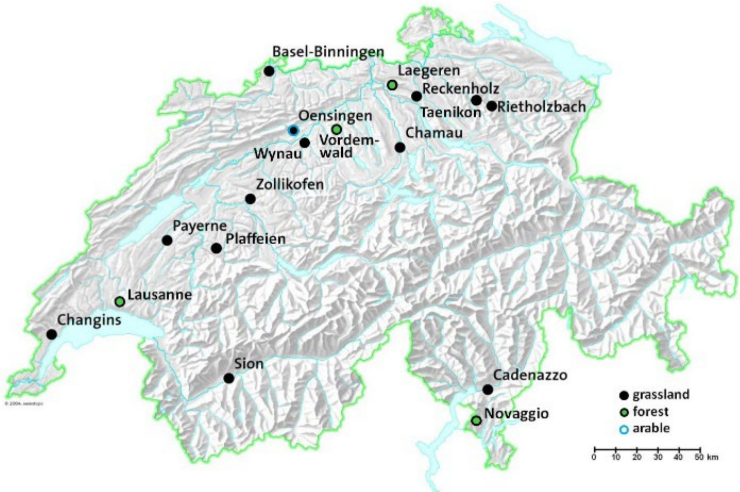


Figure 1: Location of the SwissSMEX soil moisture sites. The current SMiLE-ECV-CH projects focuses on the available 12 grassland sites.

Over the course of the period 2019-2022 we focused on the structural condition, data quality and representativeness of the Swiss-wide soil moisture network SwissSMEX (Mittelbach and Seneviratne, 2012). The analyses considered the available 12 available grassland sites, which encompass the main data base of SwissSMEX (all-black dots in Figure 1). The four forest stations differ substantially from the grassland stations, not only in terms of vegetation and thus response of the measured hydrological variables, but also in terms of instrumentation and status of the data processing.

The grassland stations are all equipped with at least two volumetric water content (VWC) profiles: One using IMKO TRIME TDR sensors, and one using Decagon 10HS capacitance sensors. The number of available depth levels from 5 cm to a maximum of 120 cm varies across the network. At some stations, there are redundant profiles of the same sensor type available. At the RHB site a third profile is in place, using Campbell Scientific CS616 water content reflectometers. Figure A1 gives an overview of the installed sensors at each site. One application of the VWC data is the calculation of depth-integrated water content in mm, which represents the soil water content in an area down to a certain depth. Here we use a depth of 50 cm, which is reached with sensors at all sites. The presented lysimeter data have been measured with mini lysimeters (cf. Figure 5) at seven SwissSMEX stations, as well with a large weighable lysimeter at the Rietholzbach site (Ruth et al., 2018).

For the data quality assessment and availability checks, we mostly relied on absolute long-term time series and visual inspection. For the intercomparison of gridded products of soil moisture with in-situ data, as well as the response of soil water content to dry events, we looked at seasonal patterns, anomalies and correlations. In August 2021, in the context of securing the continuation of the soil

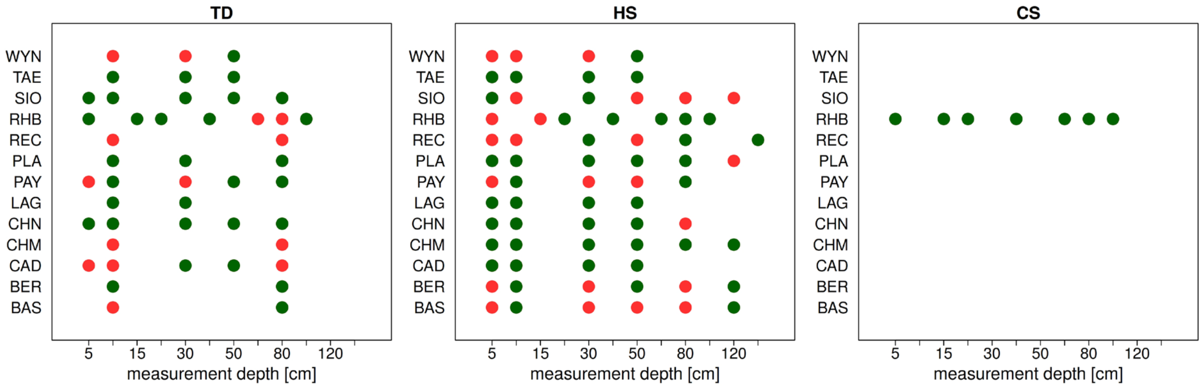


Figure 2: Status overview of sensor availability at the SwissSMEX grassland stations. Green dots indicate functioning sensors, red dots indicate sensors with an error quote of more than 20% in the last 30 days, i.e., are considered out of order. This is a condensed view incorporating all redundant sensor profiles per sensor type: TRIME TDR (TD), Campbell Scientific CS616 (CS), Decagon 10HS (HS).

moisture time series, we started installing new TDR sensors (SoilVUE10) at every grassland SwissSMEX station as well as replacing broken sensors.

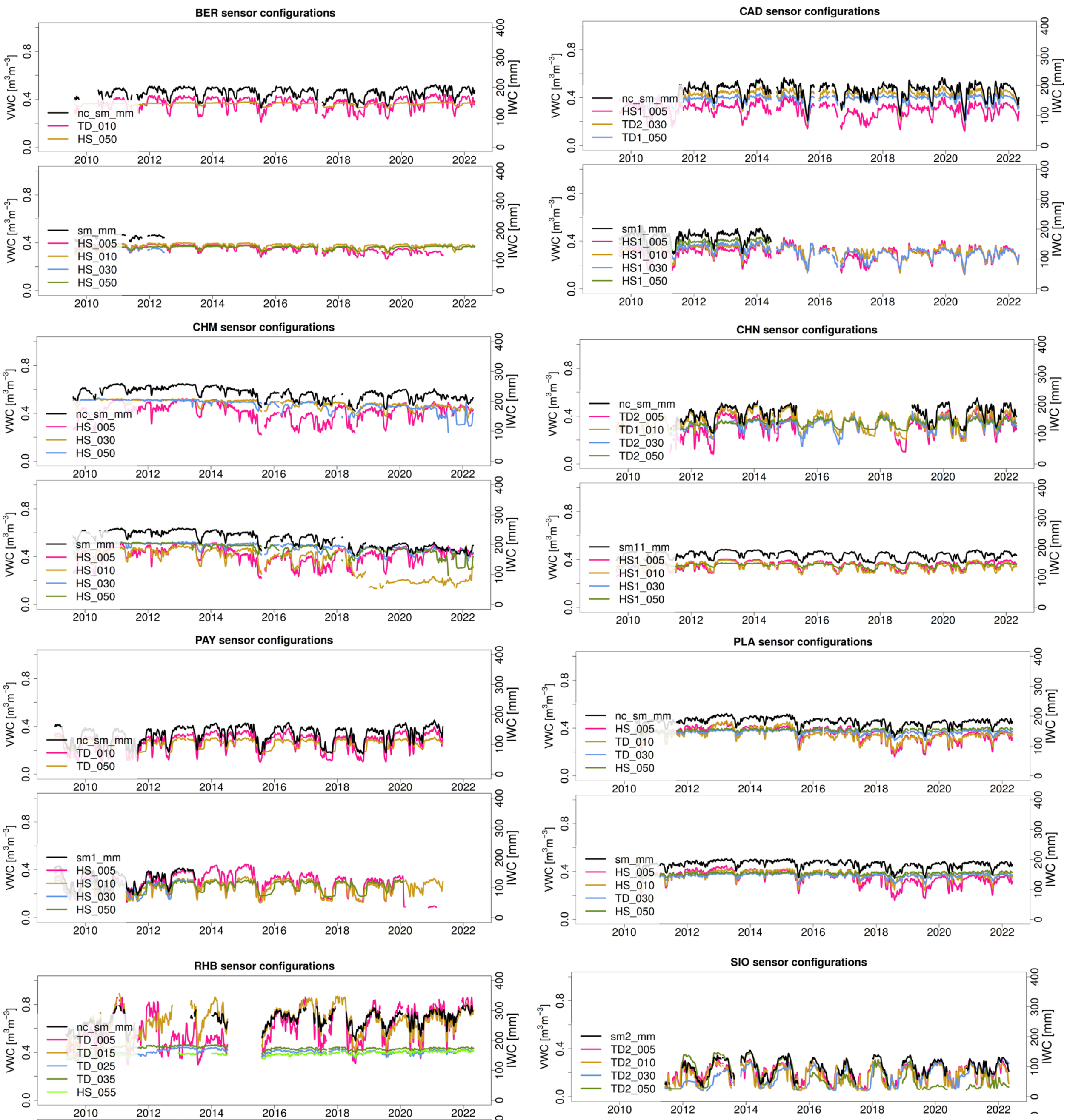
2.3 Results

This section gives an overview of the main results of the project and is structured as follows: In the first part, the findings of the data quality assessment (topic 1) are reported. In the second part, we present results from three studies, which made use of the SMiLE-ECV-CH framework and datasets, and are related to topics 2-4 of the project: Scherrer et al. (2022) on “Trends and drivers of recent summer drying in Switzerland”; Burgstall et al. (in preparation) on “Climatological drought monitoring in Switzerland using EUMETSAT SAF satellite products”; Michel and Seneviratne (2022) on “Multi-year eddy-covariance measurements at a pre-alpine humid grassland site: Dataset overview, drought responses, and effects of land management”.

2.3.1 Quality checks of SwissSMEX measurements and outlook to SoilVUE10 sensor evaluation

We assessed the data quality of the SwissSMEX soil moisture observations at the grassland stations based on inspecting the data availability, the levels of absolute volumetric soil water content as well as its seasonal patterns. It became apparent that sensors failing over the course of time are a major problem, leading to data gaps or implausible data (which are discarded). Figure 2 indicates, which soil depths are currently still represented properly per sensor type. Up to date, more than a third (36 %) of all sensors have stopped working (see also Figure A1 for a profile-specific overview). Missing depth information of soil moisture renders the calculation of depth-integrated soil water content (IWC) unreliable to impossible. Therefore, in the light of the degrading data availability, we tested different sensor configurations to produce the best estimate of IWC with available sensor as of today, which differs from the original configuration used since the installation in 2008. The resulting configurations and time series are shown in Figure 3. Note that for Basel, Reckenholz and Wynau, degradation was so advanced, that no configuration enabled the calculation of IWC for the current sensor availability (not shown). In Sion, no adaption of the sensor configuration was necessary.

The deteriorating state of the SwissSMEX network highlighted the urgent need for the planning of a new operational soil moisture measurement network in Switzerland to satisfactorily monitor the soil moisture ECV in the mid- to long-term. The GCOS follow-up project “*Updating the SwissSMEX soil moisture monitoring network infrastructure to secure the continuity of the long-term data series and ensure the data quality”* has been submitted February and granted in April 2021, which aims at securing the mid- and long-term continuity of the SwissSMEX grassland stations. An additional new



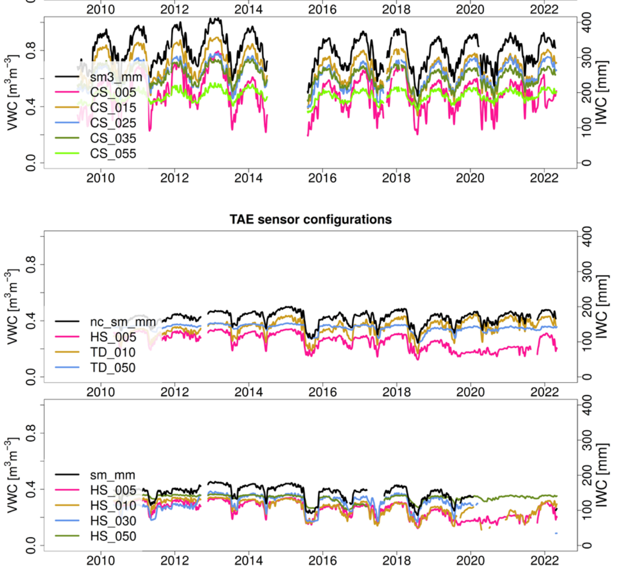


Figure 3: Comparison of the old sensor configuration used since the beginning of the SwissSMEX project and the currently used new configuration at nine (of 12) grassland stations. The top panel at each station shows the new configuration, the bottom panel shows the original configuration (note that for SIO, the original sensor configuration is still working - thus no adaption was necessary). The black line denotes the depth-integrated water content (IWC) in mm calculated with all sensor readings of the volumetric water content (VWC) down to 50 cm soil depth. In the legend, HS denotes capacitance sensors (Decagon HS10), TD denotes TDR sensors (IMKO TRIME), CS denotes soil water reflectometers (Campbell Sci. CS616); the numbers denote the depth in cm.

sensor type will allow for a consistent and more sustainable infrastructure that will be easier to maintain over a long period of time. Figure 4 shows preliminary data from one of currently three sites (CAD, RHB, TAE), where the new infrastructure (SoilVUE10, Campbell Scientific) is being used. While the soil water content dynamic of the new sensor agrees very well to the original SwissSMEX sensors, it generally reads significantly lower levels of soil moisture. We are currently investigating the performance of the sensor at different sites under different hydrological conditions.

Apart from the quality assessment of soil moisture data, land evaporation data from mini lysimeters at 7 SwissSMEX stations in Switzerland have been processed or re-processed and tested in 2021 (Figure 5). The main finding is, unfortunately, that substantial data gaps are present at several stations due to technical difficulties, above all flooding of the systems. A substantial amount of time was and still is invested to fix these problems by adding new equipment, improving the situation for the future to some extent. These sensors (SMARTFIELD-lysimeter, Meter GmbH; denoted SFL) have been off the market by the end of 2021, mainly due to the very same technical difficulties we also experienced. The technical difficulties strongly limited the use of the in-situ land evaporation from these sensors in this project.

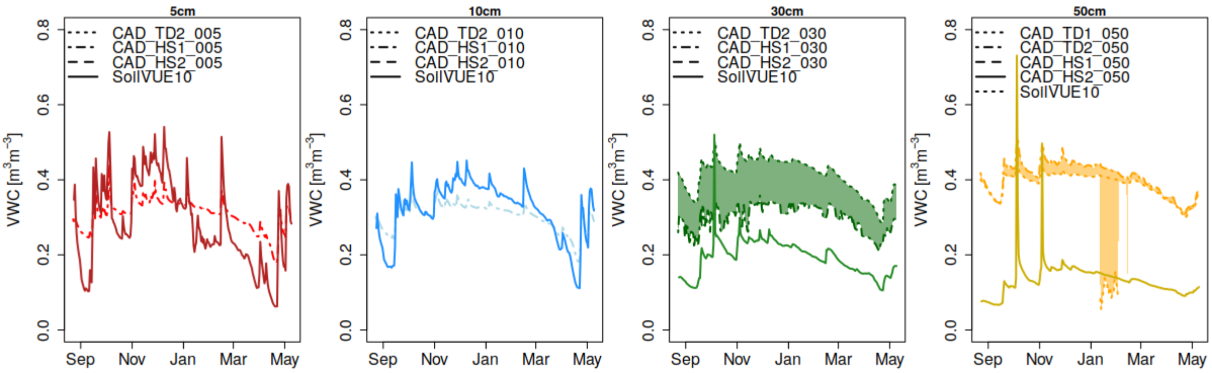


Figure 4: Preliminary evaluation of the newly installed SoilVUE10 sensors with existing SwissSMEX sensors at the site CAD from August 2021 to May 2022.

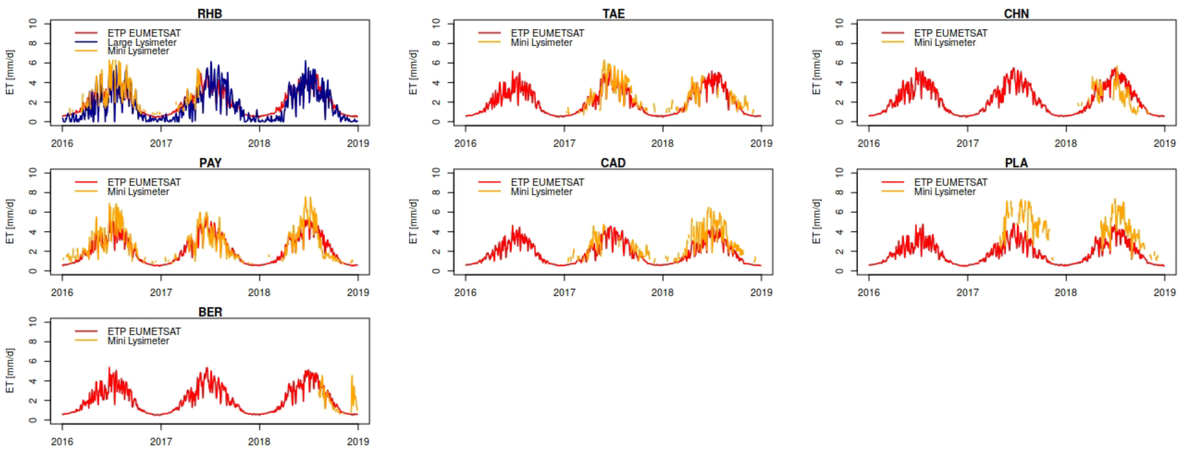


Figure 5: Time series of in-situ lysimeter land evaporation and remote sensing LSA SAF potential land evaporation observed at seven SwissSMEX stations. RHB and PAY started in 2016, TAE, CHN, CAD and PLA in 2017 and BER in 2018.

2.3.2 Climatological drought monitoring in Switzerland using satellite products

This study assesses the quality and suitability of remote sensing products for monitoring soil moisture and evaporation in Switzerland. In addition, new ECMWF reanalysis products are considered.

The intercomparisons of SwissSMEX in-situ soil moisture measurements with gridded remote sensing and reanalysis products, i.e., the European Space Agency (ESA) Climate Change Initiative (CCI) surface soil moisture product (ESA CCI soil moisture; Dorigo et al. 2017) as well as the ECMWF reanalysis ERA5 (Hersbach et al. 2020) have been extended to date. In addition to the ESA CCI surface soil moisture product, two different remote sensing products have been added to the SMiLE-ECV-CH data frame, namely the preliminary (unpublished) high-resolution Copernicus ASCAT-SWI soil moisture product covering the period 2011-2018 and the EUMETSAT LSA SAF land evaporation product, covering the period 2006-2015 for ET and 2006-2018 for ETP. The response of different products (LAS SAF ET, ASCAT-SWI and in-situ SwissSMEX) to droughts in Switzerland is currently being analysed and prepared for a joint publication with MeteoSwiss (Annkatrin Burgstall and Dr. Anke Duguay-Tetzlaff).

Figure 6 shows the correlation between in-situ soil moisture measurements and ASCAT-SWI at 10 SwissSMEX grassland stations. The correlation of the deseasonalized anomalies is generally high at most stations. The low correlation at the Sion station is partly a result of the large data gaps for the remote sensing product during winter (due to snow cover). Another explanation is the topography at this station, which makes it difficult for the remote sensing system (1 km resolution) to capture the signal at the point scale.

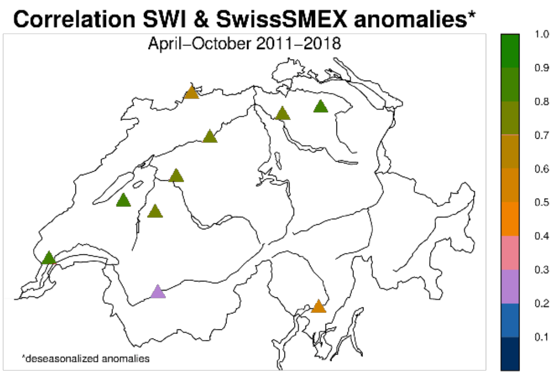


Figure 6: Correlations of the ASCAT soil water index (SWI) and the SwissSMEX soil moisture measurements at the ten considered grassland sites during April to October from 2011 to 2018 based on deseasonalized anomalies.

The seasonal evolution of the averaged soil moisture anomalies across Switzerland (wrt. the long-term mean) is shown in Figure 7 for the SwissSMEX in-situ data (depth-integrated soil moisture down to 50 cm soil depth), and for the ASCAT-SWI. The known drought summers (cf. Scherrer et al., 2022) are clearly visible in the SwissSMEX data, and also depicted in the remote sensing product. Pronounced phases of dryness beginning mid-June are visible in 2018 and 2015. These are consistently represented in SwissSMEX and ASCAT-SWI. Also, the distinct dry period in April/May 2018 with low soil moisture values according to the in-situ data is captured by the ASCAT-SWI (though just within the 5-95% percentile of the climatology), indicating an overall good performance of the remote sensing product. For 2011, the particularly dry spring is represented in both data sets. Also 2020 shows a pronounced dry phase in spring and later in July/August in the SwissSMEX data (no temporal coverage with ASCAT-SWI).

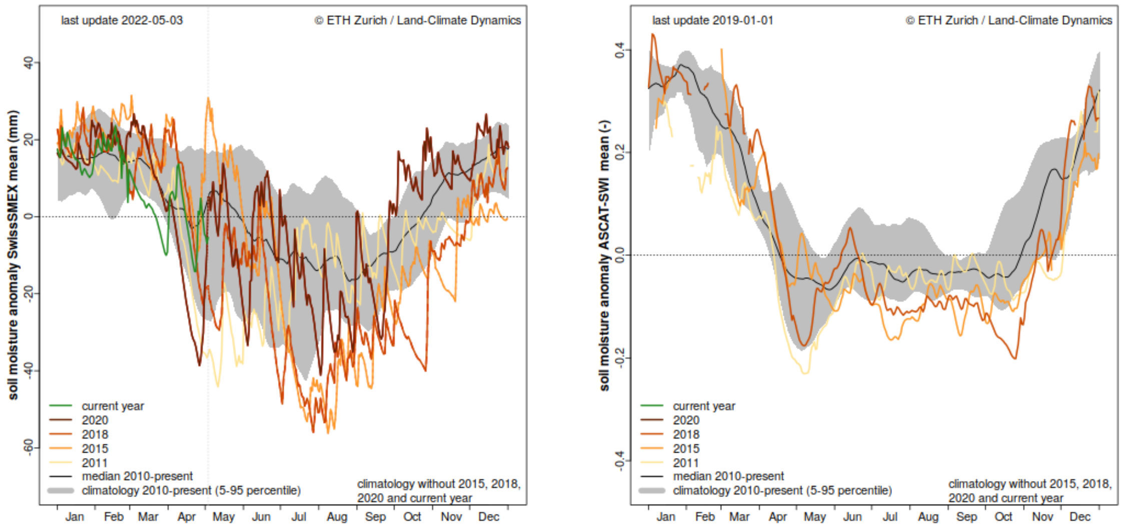


Figure 7: Seasonal evolution of the averaged soil moisture anomalies at SwissSMEX grassland stations. The climatology is based on the years 2010 to present (without the recent *dry years 2015, 2018*, and 2020, *and without data from the current year). The evolution of the current year (green), as well as that of the years* 2011, *2015*, 2018 *and* 2020 (yellow to red colors) are *shown. (left)* SwissSMEX *in-situ data, new configuration of soil moisture sensors* used for integration; *(*right*) ASCAT-SWI (T=10, data until 31.12.2018).*

In Figure 8 (left), the seasonal cycle of LSA SAF actual and potential land evaporation are compared to the in-situ large lysimeter observations at the Rietholzbach site. The Pearson correlation r between the in-situ measurements and actual ET is 0.86, while it is 0.74 for potential ET (ETP). The lower correlation between the lysimeter measurements is mainly due to the influence of snow on the in-situ data, when liquid water availability is substantially reduced. During the snow-free period April – October, both time series ET and ETP are consistent with the measured data, with ETP being slightly closer to the in-situ reference. We interpret the minor underestimation of actual land evaporation during the summer half-year as a marginal overestimation of soil water limitation at Rietholzbach in the ET algorithm. The small difference between in-situ land evaporation and ETP indicates that this site is characterized with ample water availability.

The performance of the LSA SAF products under differing hydrological conditions, i.e., soil water availability, at the considered ten grassland sites, is demonstrated in Figure 8 (middle). The medians of spatially aggregated satellite-based ET and ETP for the period 2006-2014 as well as for the dry year 2015 differ considerably throughout the seasonal cycle. This difference, however, is by large a result of three stations out of ten, where the actual land evaporation rate is substantially smaller than the potential rate: Basel, Sion and Cadenazzo (not shown). All three locations are characterized by dry and warm climatological conditions. We thus consider it plausible that the modelled actual ET is significantly influenced by overestimated water limitation at these locations. In order to test this assumption, we compared the available mini-lysimeter measurements in Cadenazzo from 2018 with the LSA SAF ETP from the same year and the LSA SAF climatologies (see Figure 5, right). The in-situ readings of land evaporation indicate in 2018 a land evaporation rate, which is considerably higher than the remote-sensing-based ETP, which is close to its climatology. Invoking the Penman-Montheith equation of land evaporation based on MeteoSwiss meteorological measurements (temperature, relative humidity, wind velocity) at the site indicates, that this estimate is very close to the lysimeter observations. This underlines the fact, that, at least for dry and warm climatological conditions, the SAF products might generally underestimate the water availability, and, consequently, land evaporation.

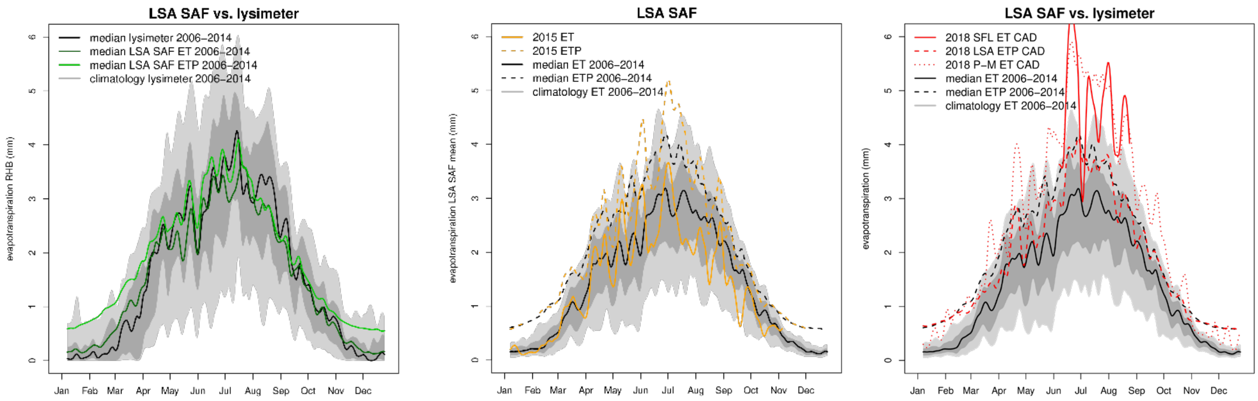


Figure 8: Seasonal evolution of daily land evaporation from (left): lysimeter measurements and LSA SAF satellite-based data at the site Rietholzbach from 2006 to 2014, (middle): spatially aggregated satellite-based data from 2006 to 2014 (based on the grid cells closest to the ten considered grassland stations), and (right): mini-lysimeter measurements (SFL), satellite-based data and Penman-Monteith potential evaporation at the site Cadenazzo. ET denotes actual land evaporation, ETP denotes potential land evaporation. The dark grey shading shows the 25%-75% range of the respective common background climatology of 2006-2014 (i.e., without the dry year 2015); the light grey shading the 5-95% range. The evolution of the respective median as well as of the covered dry years is highlighted.

2.3.3. Trends and drivers of recent summer drying in Switzerland

In another joint publication with MeteoSwiss (Scherrer et al., 2022), summer half-year droughts of 1981-2020 in Switzerland have been identified and analyzed using MeteoSwiss station observations of precipitation (P), potential land evaporation (PET) and the climatic water balance (P-PET), as well as using ERA5/ERA5-Land reanalysis-based land evaporation and soil water content. The reanalysis data was used due to their long-term availability, while measurements from SwissSMEX only start to become available with the year 2008 (Mittelbach and Seneviratne, 2012).

The drought indicators from station observations and the ERA5/ERA5-Land reanalyses show a tendency towards drier summer half-years with a drying in most months from March to October. Increasing land evaporation and a non-significant precipitation decrease of are identified as roughly equivalent drivers.

However, the considered ERA5 and ERA5-Land reanalyses show considerable differences for soil water and actual land evaporation, especially in drought summers, with the ERA5 soil being clearly drier than the one of ERA5-Land. The comparison of the two reanalysis data sets with SwissSMEX data reveals that ERA5-Land seems to better match the in-situ measurements (Figure 9). The correlation between reanalysis and SwissSMEX is high (r ~ 0.86 (0.88) for ERA5 (ERA5-Land)). The SwissSMEX anomalies are smaller than those of the reanalyses in most years. ERA5 shows the most negative anomalies in drought years. Both, the mean bias (-3.9 mm in ERA5- Land, -8.3 mm in ERA5) and the MAE (5.5 mm in ERA5-Land, 10.5 mm in ERA5) are smaller for ERA5-Land than ERA5.

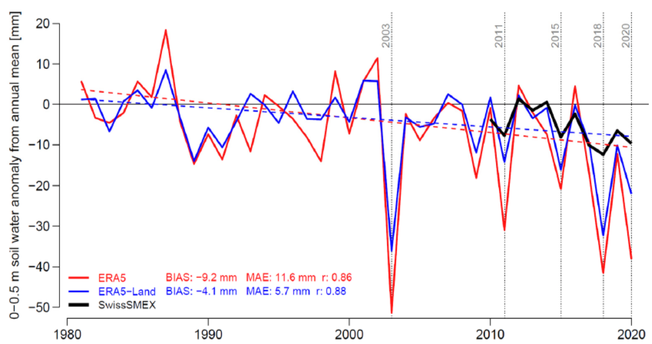


Figure 9: Evolution of summer-half year 0-0.5m depth-integrated water content anomalies (in mm) with respect to the 2010-2020 annual mean soil water content for ERA5 (red), ERA5-Land (blue) for the 1981-2020 period and for SwissSMEX (black) for the period 2010-2020. The bias (reanalysis minus SwissSMEX), the mean absolute error (MAE) and the Pearson coefficient r for the 2010-2020 period are also given. The straight lines show the 1981-2020 linear trends.

2.3.4 Multi-year eddy-covariance measurements at a pre-alpine humid grassland site: Dataset overview, drought responses, and effects of land management

The multi-year measurements of Rietholzbach are further analyzed in a third study (Michel and Seneviratne, 2022) The severity of the European summer heat and drought events in 2015 and 2018 as observed at the Rietholzbach research site is clearly visible with regard to the long-term records, as shown in Figure 10. The discussed dry years stand out as the driest years since 2003 in terms of the precipitation and soil water content (θ) as well as storage change (ΔS). In the records of air temperature (not shown), a general warming trend over the last 45 years is noticeable, while the records of precipitation and soil moisture indicate an increase in frequency of dry years in the last decade.

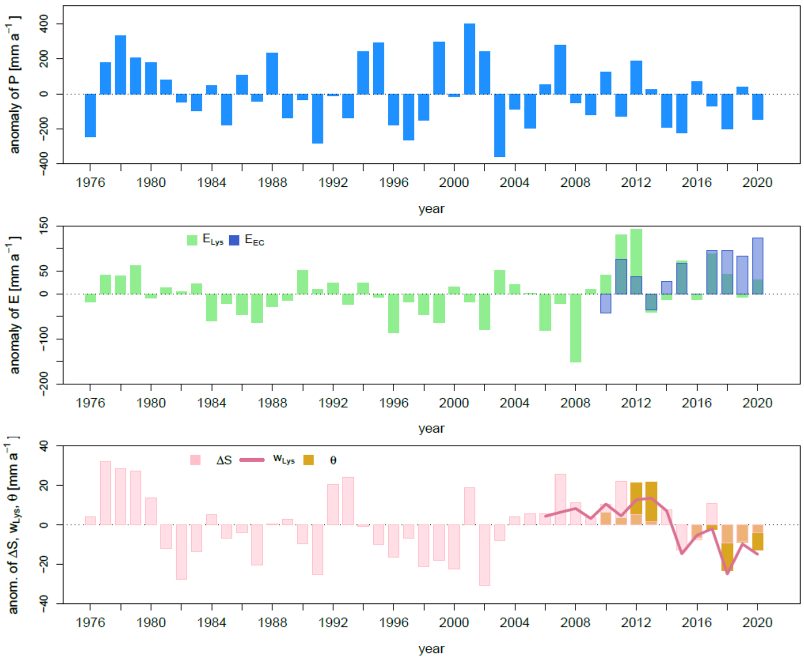


Figure 10: Annual anomalies of precipitation (P, top), land evaporation (E, middle) and soil water content (θ, bottom), with respect to the long-term mean of the available data series. The subscripts Lys and EC denote lysimeter and eddy covariance measurements, respectively. The pink line in the bottom panel refers to the annual anomalies of lysimeter weight-based water storage changes. The brown bars in the same panel denote SwissSMEX water content measurements since 2010.

The impact of the drought in 2015 and 2018 on the hydrological conditions on a seasonal scale at the site Rietholzbach with regard to the climatological situation is analyzed on the basis of soil water content and precipitation, as well as the turbulent heat fluxes (Figure 11). Apart from precipitation, the seasonal cycle of soil moisture (θ) at the site Rietholzbach is controlled by atmospheric conditions with high soil evaporation and transpiration in summer. The use of soil water for ET results in a minimum of soil water storage during June until late August, even when the average amount of daily precipitation is highest. The annual evolution of θ is characterized by wet periods in winter, when there can also be snow, i.e., January-February and November-December. In between, a drying phase starts mid-March, which is paused from April to beginning of May and then is followed by further drying to a minimum soil water content in July/August. The ample amount of precipitation in summer is thus mostly evaporated rather than put into soil storage. Land evaporation is driven by available energy and does not seem to be constrained by water availability. This is reflected in the seasonal cycle of the latent heat flux, which reaches its maximum in summer, when the soil water content is at its lowest level. The response of soil water content to the precipitation deficit during the dry spells in 2015 and 2018 is very distinct. Both dry years stick out with below-average precipitation and soil water content even below the 5th percentile in July/August.

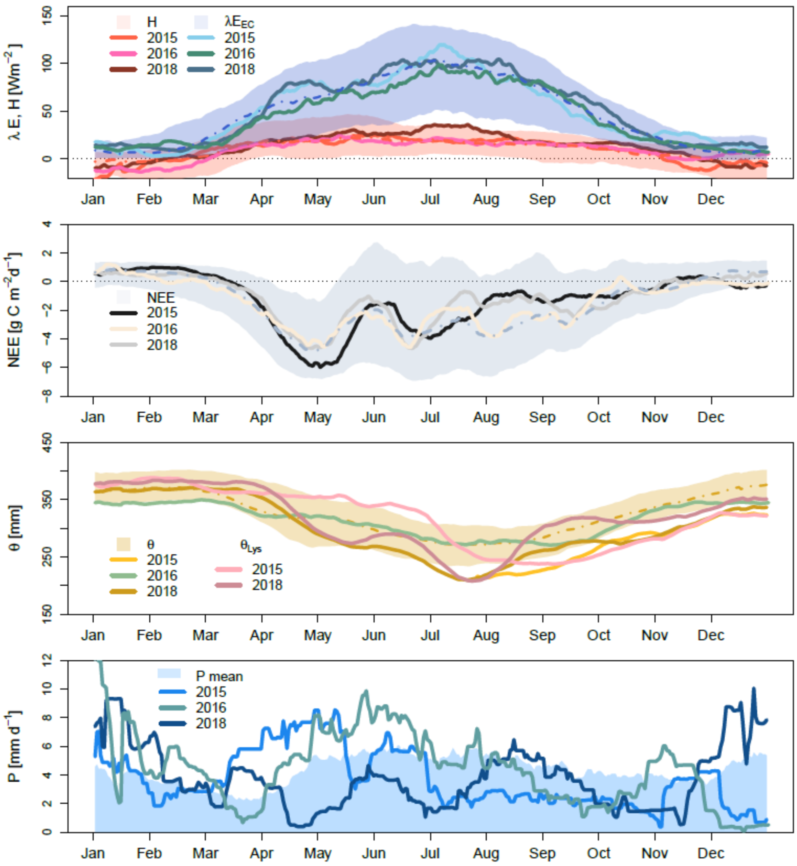


Figure 11: Seasonal pattern of daily sensible heat H and latent heat flux λE_{EC} (top), net ecosystem exchange N EE (second to top) and soil water content θ (second to bottom) from 2010 to 2020 without DH1518. The shaded area denotes the 5% to 95% range, the dashed lines represent the median. In the bottom panel the shaded area is the average daily precipitation. The dry years 2015 and 2018 are shown separately (solid lines). For θ in DH1518 apart from the CS616-measured data also the lysimeter-based soil moisture data (θ_{Lys}) are shown. The shaded are in the three topmost panels denotes the 5-95% range.

2.4 Conclusions and limitations

The assessment of the data quality of the soil moisture and land evaporation measurements have revealed issues with data availability due to technical problems in the first place. The insights gained in this project as well as the granted GCOS Switzerland follow-up project will contribute to resolve these problems within the current year 2022. The planned actions secure the availability of depth-integrated soil moisture at all grassland stations and seamless continuation of soil water dynamic monitoring. We hope that the technical interventions at the mini lysimeter stations will improve the data availability of land evaporation in the mid- to long-term. The comparison of reanalysis and remote sensing data with in-situ observations indicates a great potential of monitoring droughts in Switzerland with gridded products, above all for qualitative estimation of wet vs. dry anomaly periods. Uncertainties of these methods in absolute values can be evaluated and compensated to some extent with the help of the SwissSMEX in-situ measurements in the respective region. In terms of quantitative soil water content, we found that the variability of the readings among different in-situ sensor types as well as the local spatial soil variability is substantial, requiring proper user guidance when providing such data. This is again underlined with the deployment of the new SoilVUE10 TDR sensors, which yet yields different estimates of soil moisture. We thus recommend to focus on the seasonal dynamic of soil water content, as well as anomalies, such as droughts and wet periods and not necessarily to absolute values, when cross-examining in-situ and gridded products.

2.5 Outreach work, publication of results and data

The analyses conducted within the framework of the GCOS project have been presented or have been addressed in the following media:

Website
https://iac.ethz.ch/group/land-climate-dynamics/research/swisssmex.html

Conference talks
- ZHydro Seminar, November 2019: In-situ measurements of soil moisture and land evaporation in Europe (Michel, D.)
- EGU General Assembly, April 2021: Integrative soil moisture monitoring in Switzerland for a better preparedness for projected drying trends (Michel, M., Hirschi, M., and Seneviratne, S.I.)
- EMS Annual Meeting, September 2021: Summer drought in Switzerland 1981-2020: Events, trends and drivers (Scherrer, S., Spirig, C., Hirschi, M., Maurer, F., and Kotlarski, S.)
- EUMETSAT Meteorological Satellite Conference, September 2021: Climatological drought monitoring in Switzerland using SAF satellite products (Burgstall, A., Duguay-Tetzlaff, A., Michel, D., Hirschi, M. et al.)
- Swiss Remote Sensing Days, April 2022: Climatological drought monitoring in Switzerland using SAF satellite products (Burgstall, A., Duguay-Tetzlaff, A., Hirschi, M., Seneviratne, S.I., Stöckli, R., Bourgeois, Q., and Michel, D.)
- EGU General Assembly, May 2022: Assessing the suitability of remote sensing estimates of soil moisture and land evaporation in Switzerland for a better preparedness for projected drying trends (Michel, M., Burgstall, A., Hirschi, M., Duguay-Tetzlaff, A., and Seneviratne, S.I.)

Publication of data and results
The current status of the seasonal evolution of averaged soil moisture anomalies at active SwissSMEX grassland stations is published and daily updated on https://iac.ethz.ch/group/land-climate-dynamics/research/swisssmex/current_status.html. Since 2021, deseasonalized and standardized anomalies are also available. SwissSMEX data can currently be obtained upon formal request.

Publications (peer-reviewed):

- Burgstall, A., Michel, D., Hirschi, M., Duguay-Tetzlaff, A., Seneviratne, S.I., and Stöckli, R.: Climatological drought monitoring in Switzerland using SAF satellite products, in preparation.
- Michel, D., Seneviratne, S.I. (2022): Multi-year eddy-covariance measurements at a pre-alpine humid grassland site: Dataset overview, drought responses, and effects of land management, submitted, in revision, doi:10.2139/ssrn.3997592.
- Scherrer, S.C., Hirschi, M., Spirig, C, Maurer, F., and Kotlarski, S. (2022): Trends and drivers of recent summer drying in Switzerland. Environmental Research Communications, doi:10.1088/2515-7620/ac4fb9.

News reports
MeteoSwiss Blog | Trockenere Sommer | 03.03 2022
Tages-Anzeiger | Es müsste jetzt einen Monat lang durchregnen | 09.06.2020
Die Zeit, Schweizer Split | Der April macht, was er will | 23.04.2020
NZZ am Sonntag | So trocken wie noch nie | 19.04.2020
SonntagsZeitung | Spanischer Frühling in der Schweiz | 19.04.2020
RTS Couleur 3 | Un printemps très sec en Suisse | 17.04.2020
Spektrum der Wissenschaft | Trockenheit in Deutschland: April, April | 22.04.2020
Tages-Anzeiger | So trocken wie seit 2010 nicht mehr | 16.04.2020
watson.ch | Getreideproduzenten und Bauern hoffen auf Regen – doch es sieht vorerst nicht gut aus | 17.04.2020

2.6 Outlook

Until August 2022, the functionality of TDR soil moisture sensors to a depth of at least 30 cm at all SwissSMEX grassland stations will be secured with repairs and replacements. Additionally, every grassland station will be equipped with a SoilVUE10 sensor.

In an upcoming MSc thesis at the IAC, the preliminary evaluation of the SoilVUE10 sensors and of replaced traditional TDR sensors will be continued.

The presented results of the SMiLE-ECV-CH project and the gained experience with the new sensor options, as well as results of the mentioned MSc thesis also feed into the "Arbeitsgruppe Bodenfeuchte". This group currently discusses a potential nation-wide soil moisture network under the coordination of MeteoSwiss and BAFU.

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2.8 References

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Appendix A

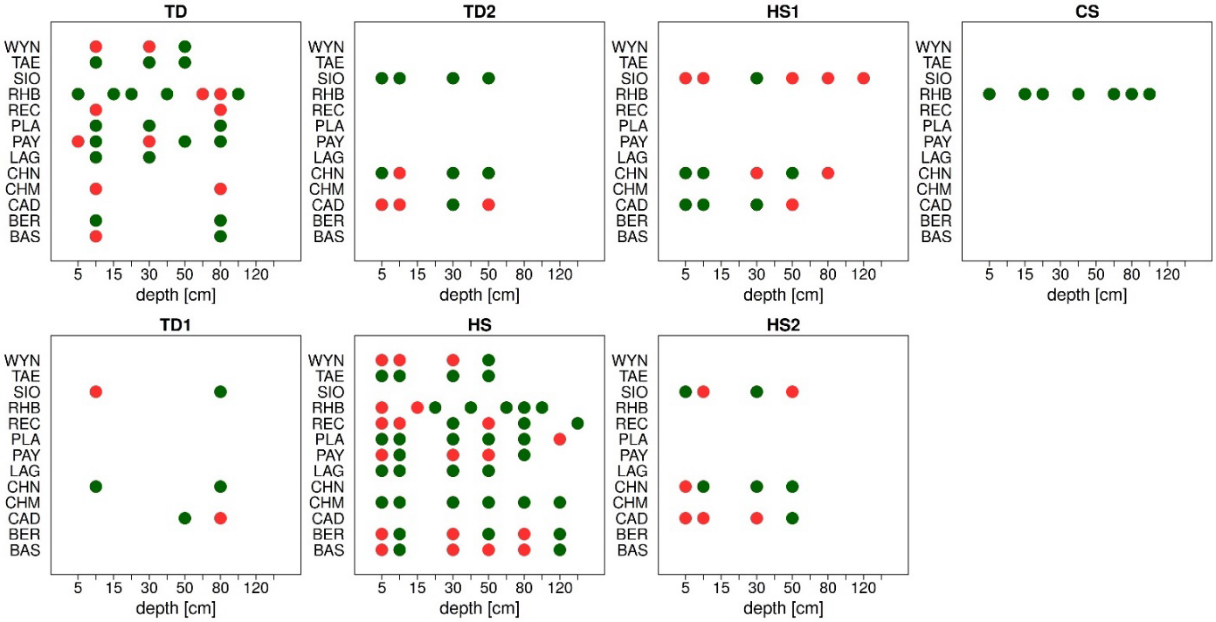

Figure A1: Status overview of sensor availability at the SwissSMEX grassland stations. Green dots indicate functioning sensors, red dots indicate sensors with an error quote of more than 20% in the last 30 days, i.e., are considered out of order. TRIME TDR (TD), Campbell Scientific CS616 (CS), Decagon 10HS (HS). Numbers behind the sensor types denote redundant profiles, e.g., HS1 and HS2.