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Trends and drivers of recent summer drying in Switzerland

S C Scherrer[1], M Hirschi[2], C Spirig[1], F Maurer[1] and S Kotlarski[1]

[1] Federal Office of Meteorology and Climatology MeteoSwiss, Zurich-Airport, Switzerland
[2] Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland

E-mail: simon.scherrer@meteoswiss.ch

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Abstract

The Alpine region recently experienced several dry summers with important and adverse impacts on economy, society and ecology. Here, we analyse drought indicators, evapotranspiration and meteorological data from point observations, reanalyses and regional climate model data to assess trends and drivers of summer drought in Switzerland in the period 1981–2020. The drought indicators from station observations and ERA5-Land and ERA5 reanalyses show a tendency towards drier summer half-years (climatic water balance: -39 mm decade^{-1}, 0–1 m integrated soil water content: -5 to -7 mm decade^{-1}) with a drying in most months from March to October. Both, increasing evapotranspiration (potential evapotranspiration: $+21$ mm decade^{-1} or $+7\%$ K^{-1} warming; actual evapotranspiration: $+8$ to $+15$ mm decade^{-1}) and a non-significant precipitation decrease of 17 mm decade^{-1} are identified as important and roughly equivalent drivers. The reanalyses show considerable differences for soil water and actual evapotranspiration, especially in drought summers. The ERA5 soil is clearly drier than the one in ERA5-Land. ERA5 evapotranspiration is smallest and partly soil moisture-limited in drought years while evapotranspiration in ERA5-Land is highest, still mainly energy-limited and scales well with temperature ($+4\%$ K^{-1} warming). ERA5-Land seems to better match with *in situ* measurements of soil water and evapotranspiration than ERA5, but considerable differences with *in situ* measurements remain. Variability and trends of the drought drivers temperature and precipitation are also investigated in the EURO-CORDEX regional climate model ensemble. Most simulations considerably underestimate the recent warming and the ensemble shows a large possible range of precipitation changes with a mean change near zero. The summer precipitation-temperature scaling and the correlation between summer temperature and precipitation on the interannual time scale are mostly overestimated. Our results highlight that the analysis of Central European summer drought evolution and its drivers remains challenging especially with regional climate model data, but considerable uncertainties also exist in reanalyses.

Introduction

Droughts have large negative impacts on many aspects of life, including agriculture, water resources management, energy production, shipping and ecology (Wilhite 2000; Fuhrer *et al* 2006, Seneviratne *et al* 2013, Pluess *et al* 2016, Lickely and Solomon 2018). While a meteorological drought is caused by a lack of precipitation only, a soil-moisture or agricultural drought is caused by a lack of precipitation and/or excess evapotranspiration (Seneviratne 2012). A hydrological drought refers to a lack of water in the hydrological system, i.e. abnormally low streamflow or lake levels (van Loon, 2015). Historically, central Europe and the European Alps were affected by occasional summer drought events (cf Pfister and Rutishauser 2000, Calanca 2007, van der Schrier *et al* 2007, Haslinger *et al* 2019). After almost three decades without severe summer droughts, the Alpine region and Switzerland experienced several major drought events in the early 21st century, namely in the summers 2003, 2018, 2015 and spring/early summer 2011 and 2020 (Calanca 2007, MeteoSchweiz 2012, Orth *et al* 2016, MeteoSchweiz 2018, Brunner *et al* 2019). While several studies report evidence for increasing trends in summer drought in Central Europe and the Alpine region in recent decades (e.g. Trnka *et al* 2016, Stagge *et al* 2017, Hänsel *et al* 2019), others are inconclusive or point to large uncertainties of the recent evolution (Orlowsky and Seneviratne 2013, Zolina *et al* 2013, Gudmundsson and Seneviratne 2015, 2016, Gudmundsson *et al* 2017, Spinoni *et al* 2017, Hirschi *et al* 2020). Also future drought projections are subject to considerable uncertainties as the Alpine region is located between a strong projected drying in Southern Europe and a wetting in Northern Europe, and the future evolution of evapotranspiration is highly uncertain. However, many simulations show a tendency for increasing summer drought risk in the Alpine region in the second half of the 21st century (Orlowsky and Seneviratne 2013, Cook *et al* 2014, Gobiet *et al* 2014, CH2018 2018, Hirschi *et al* 2020, Spinoni *et al* 2020).

Against this background, the main goals of this study are to revisit the trends and drivers of summer droughts in Switzerland in the last 40 years (1981–2020), to reconcile the observational, reanalysis and regional climate model evidence and to put the results into context with the existing literature for Central Europe. We focus on meteorological and soil-moisture/agricultural drought accumulating over the summer-half year from April to September. Hydrological drought is explicitly not considered. To reach our goals, we tackle the following research questions:

- How has the summer climatic water balance and integrated soil water content changed in Switzerland during the last 40 years?
- Which main drivers were responsible for the observed trends in summer drought?
- To what extent can reanalyses and regional climate model simulations represent the main drivers of Swiss summer drought?

Answering the last question in particular is required to assess the abilities of, and to build up confidence in, model data sets that potentially enable a large-scale drought monitoring and the projection of future change in summer droughts and their respective drivers.

Data and methods

Two main drought indicators are considered in this study: (1) volumetric soil water content (SWC) and (2) climatic water balance (CWB) defined as precipitation (P) minus potential evapotranspiration (PET). They can be seen as complementary measures for drought. While SWC measures the actual water content in the soil column, CWB describes the imbalance between atmospheric water supply and atmospheric demand, which is mainly driven by the meteorological conditions (cf Vicente-Serrano *et al* 2020). In relatively humid regions as in Switzerland, where evapotranspiration is mainly energy limited (Teuling *et al* 2009), summer-half year SWC and CWB are highly correlated on the interannual time scale ($r_{Pearson} > 0.8$ in Switzerland, cf figure S1 (available online at stacks.iop.org/ERC/4/025004/mmedia) in the supporting data file).

SWC is taken from the ERA5-Land (Muñoz Sabater *et al* 2021) and ERA5 reanalyses (Hersbach *et al* 2020) since *in situ* SWC measurements in Switzerland from the SwissSMEX network only start to become available with the year 2008 (Mittelbach and Seneviratne 2012). SWC data from reanalysis products show reasonable agreement with *in situ* SWC measurements (Hirschi and Crezee 2020, Li *et al* 2020) and are one of the few options to analyse the evolution of SWC for several decades. As in other soil moisture products (e.g. MERRA-2, Gelaro *et al* 2017), integrated SWC in the root zone (0–1 m depth), i.e. soil levels level 1, 2 and 3 in ERA5-Land and ERA5 are used.

Monthly CWB values are calculated using homogenised P observations (cf Begert *et al* 2005) and computed PET at meteorological stations. PET is calculated using the Penman-Monteith equation as implemented in FAO-56 (Allen *et al* 1998), which accounts for temperature, radiation, humidity and wind speed as drivers and which models PET on an idealized, well-watered grass surface. The PET values are computed in hourly resolution using quality-checked but not homogenised data and are then temporally aggregated to monthly and summer-half year sums. A comparison with PET calculated with the FAO ETo Calculator (Raes 2012) using homogenised monthly temperature, radiation, humidity and wind speed data showed only small differences in the single digit percentage range for actual values and trends.

Several additional variables from various data sets are used:

- monthly actual evapotranspiration (ET) from the ERA5-Land and ERA5 reanalyses
- monthly P from homogenised station data from MeteoSwiss (OBS) as benchmark, the ensemble mean from the gridded E-OBS data set (v21.0e, cf Cornes *et al* 2018), ERA5 reanalysis (ERA5-Land P is identical to ERA5

apart from differences related to regridding) and 31 simulations from the EURO-CORDEX regional climate model (RCM) ensemble (Jacob *et al* 2014, 2020, details below)

- monthly 2 m air temperature (T) from homogenised station data from MeteoSwiss (OBS) as benchmark, the ensemble mean from the gridded E-OBS data set, ERA5-Land and ERA5 reanalysis and EURO-CORDEX
- monthly 0–0.5 m integrated SWC from four SwissSMEX stations (cf Mittelbach and Seneviratne 2012 and supporting data file)

The 31 EURO-CORDEX RCM simulations considered are the RCP8.5 scenario runs also used in the recent Swiss climate scenario initiative CH2018 (CH2018, 2018). Ten simulations have a horizontal grid resolution of 0.11° (~12 km) and 21 simulations are runs with 0.44° (~50 km) resolution driven by different global climate models at their lateral boundaries (cf table S1 in the supporting data file for details). Until 2005, the observed greenhouse gas forcing is prescribed to all simulations. Up from 2006, the RCP8.5 pathway simulations are used. All RCM simulations employed are driven by free-running GCMs at their lateral boundaries. Individual observed events are therefore not represented, and the RCM data are not considered in the event analyses.

We analyse regional mean time series for the Swiss Plateau, a hilly region of roughly 12,000 km^2 size, inhabited by about 5 million people. The regional mean is constructed using the mean of the four measurement sites Zürich/Fluntern (soil water: Zürich/Reckenholz), Genève/Cointrin (soil water: Nyon/Changins), Basel/Binningen and Bern/Zollikofen or the mean of the four closest grid points using the native resolution for the gridded data sets E-OBS (0.1°), ERA5-Land (0.1°), ERA5 (0.25°) and EURO-CORDEX (0.11°/0.44°) (cf table S2 in the supporting data file for more information). The sites all measure over 'grass' and are representative for a setting at an average elevation on the densely populated Swiss Plateau (Scherrer and Begert 2019).

The time period analysed are the 40 years from 1981 to 2020. The year 1981 marks the start of the automated Swiss measurement network and the start of the ERA5-Land reanalysis at the time of writing. Monthly and summer-half year (April 1st to September 30th, denoted 'summer' in the following) values are presented. Anomalies are computed with respect to the WMO norm period 1981–2010. We report sums (accumulations) for P, PET, ET and CWB and mean values for T and SWC. Trends are computed using the robust Theil-Sen trend estimator (Theil 1950, Sen 1968) and the non-parametric Mann-Kendall trend test is used to determine trend significance (Mann 1945, Kendall 1975). A p-value less than 0.05 is required for statistical significance. Ordinary least square regression is used to scale the water cycle components with T. Statistical significance is determined with a Student's t-test (Student 1908).

Overview of the drought events 1981–2020

The main recent summer drought events have been determined and discussed in detail in the literature (Calanca 2007, MeteoSchweiz 2012, Orth *et al* 2016, MeteoSchweiz 2018, Brunner *et al* 2019). Here we only give a short overview of the TOP5 summer drought events in the analysed data sets (cf table 1). More details on the temporal course of the TOP5 drought events are given in the supporting data file (e.g. figure S2). The driest summer soil conditions in ERA5-Land are found for the years 2003 (0–1 m SWC anomaly: −67 mm) and 2018 (−56 mm). 2020 ranks third (−40 mm), followed at some distance by 2015 (−26 mm) and 2011 (−25 mm). The SWC anomalies correspond to −7 to −19% of the 1981–2010 summer mean. In ERA5, the same TOP5 events are found, albeit with a different ranking and stronger SWC anomalies (−10 to −29%). Also the CWB based on station data identifies the same TOP5 driest summers, again with a slightly different ranking (2018 first, 2003 s). The TOP5 drought summers are all characterised by strong negative P anomalies in the order of −100 to −200 mm or about 20 to 33% of total summer precipitation. They are all also warm summers (temperature ranks 1, 2, 3, 5 and 6). PET is large in drought years with values between 60 and 120 mm or about 10 to 20% above the long term mean summer PET. According to ERA5-Land also ET peaked in drought summers (ranks 1, 2, 5, 7 and 8). In ERA5 on the other hand, ET was strongly reduced during these events (ranks 40, 39, 30, 29 and 23) and at least partly soil water limited. The CWB components suggest that the TOP5 Swiss summer droughts are still dominated by the water supply component (P contributes 54%–68% to the CWB anomaly) but that also the demand side is an important driver (PET contributes 32%–46% of the CWB anomaly), which probably reinforces the drought conditions noticeably.

Drought variability and trends

The ERA5-Land summer SWC values range from 296 mm (minimum in 2003) to 387 mm (maximum in 1987) with a 1981–2010 mean of 363 mm (figure 1(a), maroon). The SWC series shows a negative trend of −4.8 mm decade^{-1} (p = 0.05) or a total decline of 19 mm (~5% of the summer mean SWC). The SWC trends in ERA5 are

Table 1. Key figures for the TOP5 summer-half year drought events on the Swiss Plateau 1981–2020. Shown are the event year, mean 0–1 m SWC anomaly dSWC and actual evapotranspiration anomaly dET from ERA5-Land and ERA5 (in mm, anomaly in percent), as well as the accumulated CWB anomaly dCWB (in mm), accumulated P anomaly dP (in mm, anomaly in percent), accumulated PET anomaly dPET (in mm, anomaly in percent) and mean T anomaly dT (in °C) from station observations (OBS). Ranking according to the parameters given in parentheses (values of ranks 1–5 and 36–40 in bold). Anomalies are computed with respect to the summer-half year 1981–2010 mean and rounded to full mm/percent/0.1 °C.

	ERA5-Land		ERA5		Station observations (OBS)			
event year	dSWC mm/% (rank)	dET mm/% (rank)	dSWC mm/% (rank)	dET mm/% (rank)	dCWB mm (rank)	dP mm/% (rank)	dPET mm/% (rank)	dT °C (rank)
2003	**−67/−19 (1.)**	**+47/+9 (2.)**	**−96/ −29 (1.)**	**−42/−9 (40.)**	**−293 (2.)**	**−188/−32 (2.)**	**+104/+18 (2.)**	**+2.3 (2.)**
2018	**−56/−15 (2.)**	+38/+7 (7.)	**−73/−22 (2.)**	**−29/−6 (39.)**	**−314 (1.)**	**−194/−33 (1.)**	**+120/+21 (1.)**	**+2.6 (1.)**
2020	**−40/−11 (3.)**	**+50/+10 (1.)**	**−73/−22 (2.)**	−9/−2 (30.)	**−221 (3.)**	**−130/−22 (3.)**	**+91/+16 (3.)**	**+1.6 (3.)**
2015	**−26/−7 (4.)**	+37/+7 (8.)	**−32/−10 (5.)**	+1/0 (23.)	**−196 (4.)**	−106/−18 (6.)	**+90/+16 (4.)**	**+1.5 (5.)**
2011	**−25/−7 (5.)**	**+43/+8 (5.)**	**−59/−18 (4.)**	−8/−2 (29.)	**−189 (5.)**	**−128/−22 (5.)**	+60/+10 (7.)	+1.3 (6.)

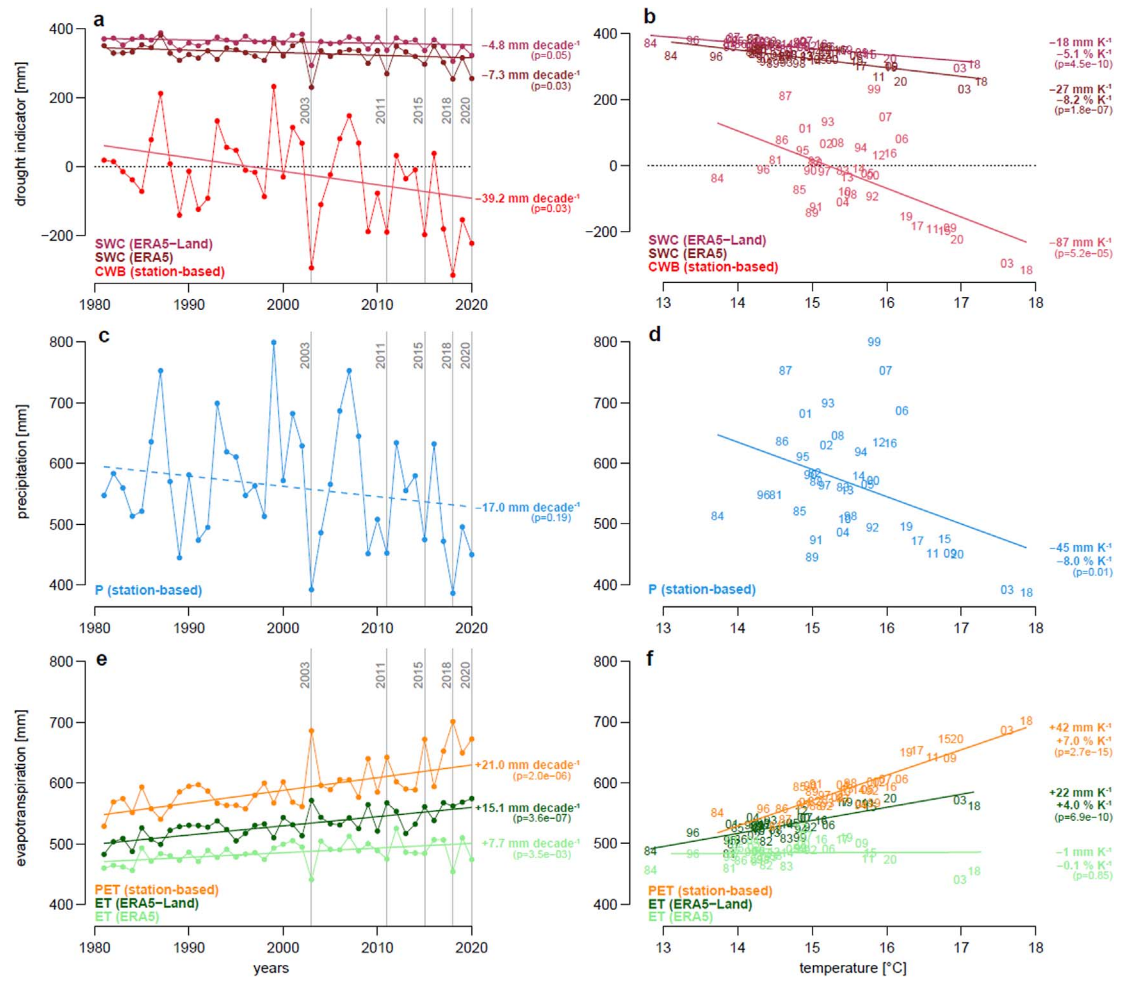

Figure 1. Evolution of 1981–2020 Swiss Plateau summer-half year drought indicators (panel a, station-based (OBS) CWB (red) and 0–1 m integrated SWC in ERA5-Land (maroon) and in ERA5 (brown)), precipitation (panel c, station-based (OBS) P) and evapotranspiration (panel e, station-based (OBS) PET (orange), ET from ERA5-Land (dark green) and ERA5 (light green)). The straight lines show Theil-Sen trends (significant: solid; not significant: dashed; p-limit = 0.05). Units: mm, trends in mm decade^{-1}. Also shown are scatterplots of temperature versus the drought indicators (panel b), precipitation (panel d) and evapotranspiration (panel f). The straight lines show linear regression fits in mm K^{-1} and % K^{-1}.

stronger (−7.3 mm decade^{-1} or roughly −9% of the summer mean SWC; figure 1(a), brown). A comparison with *in situ* measurements from SwissSMEX shows that the ERA5-Land SWC is closer to the *in situ* measurements (higher correlation, smaller bias and mean absolute error) than ERA5 (cf supporting data file, figure S3), which is in agreement with evaluations on larger spatial scales (e.g. Beck *et al* 2021). A tendency for summer drying in Switzerland has recently also been reported by Hirschi *et al* (2020), although uncertainties in the different data sets are large and not all trends were statistically significant. The SWC variability scales very well with the T variability and declines with −18 mm K^{-1} or −5.1% K^{-1} in ERA5-Land and −27 mm K^{-1} or −8.2% K^{-1} in ERA5 (cf figure 1(b)). The values of the second drought indicator CWB from station observations (figure 1(a), red) range from −315 mm (minimum in 2018) to +232 mm (maximum in 1999) with a 1981–2010 mean of −2 mm. CWB variability is dominated by the P variability ($r = 0.97$). The CWB shows a significantly decreasing trend of −39.2 mm decade^{-1} ($p = 0.03$) or a total decline of −153 mm, corresponding to about 26% of the 1981–2010 mean P. Also the CWB variability scales highly significantly with T variability and declines with −87 mm K^{-1} (figure 1(b)).

Drought drivers

Observations and reanalysis

The main drought driver candidates are precipitation and evapotranspiration which both are also related to temperature. Figure 1(c) shows the evolution and variability of P from station observations and in figure 1(e) the same for PET and ET from ERA5-Land and ERA5. P and PET share almost the same 1981–2010 summer mean of 580 and 582 mm respectively. However, P variability (range: 386–799 mm; interquartile-range (IQR): 136 mm) is

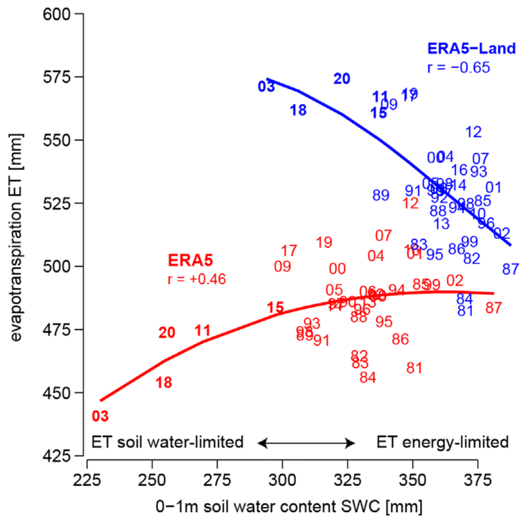

Figure 2. 1981–2020 summer-half year 0–1 m integrated soil water content (SWC in mm) plotted against actual evapotranspiration (ET in mm) for ERA5-Land (blue) and ERA5 (red). Years are abbreviated with two digit numbers. The smoothed lines show a second-order local polynomial regression fit (loess, cf Cleveland *et al* 1992) with smoothing parameter $\alpha = 2$. The Pearson correlation coefficients r between SWC and ET are also given. The TOP5 drought years are shown in bold.

much larger than PET variability (range: 529–701 mm; IQR: 32 mm). P is decreasing by 17.0 mm decade^{-1} (1981–2020 change: −66 mm or −11% of P mean) but the trend is not statistically significant ($p = 0.19$). PET shows a highly significant positive trend of +21.0 mm decade^{-1} (1981–2020 change: +82 mm or +14% of PET mean). This suggests that both, increasing PET and decreasing P are contributing to the strong CWB trend. A substantial contribution of increasing evapotranspiration on the intensification of the dry season in Central Europe has been reported by several recent studies (e.g. Vicente-Serrano *et al* 2014, Trnka *et al* 2016, Hänsel *et al* 2019, Prăvălie *et al* 2019, Padron *et al* 2020, Sjoukje *et al* 2020, Spinoni *et al* 2020).

Also ET is significantly increasing. The ERA5-Land trend (+15.1 mm decade^{-1}) is almost twice the one of ERA5 with +7.7 mm decade^{-1}. Trends reported for Central Europe by recent studies (e.g. Hobeichi *et al* 2020, Pan *et al* 2020) between about 10 and 25 mm decade^{-1} appear to be closer to the ERA5-Land values than those of ERA5. The differences are particularly striking in drought years when ET in ERA5 is generally depressed, while ET in ERA5-Land is highest (cf table 1 and figure 1(e)). In agreement with ERA5-Land, *in situ* ET measurements with a lysimeter and eddy covariance flux measurements in north-eastern Switzerland both show an ET surplus in dry summers (Seneviratne *et al* 2012, Hirschi *et al* 2017, Michel and Seneviratne 2021). The scatterplot of SWC versus ET (figure 2) illustrates the differences between the two data sets in more detail. ERA5-Land ET increases with decreasing SWC, and the curve starts to flatten only for the two driest summers (2003/2018 with SWC $\sim$ 300 mm). For ERA5, ET is reduced in drought years (SWC $<$ 300 mm) and there is no clear relation between SWC and ET in non-drought years. In other words: ET in recent drought years was already partly soil moisture-limited in ERA5, while ET in ERA5-Land (and *in situ* measurements) was still mainly energy-limited. Also note that the SWC trend in ERA5 is stronger than in ERA5-Land (cf figure 1(a)) although the T and P changes are almost identical (cf figure 4(a)). Hence, the ERA5 SWC seems to be considerably more sensitive to P and T changes than the one in ERA5-Land (cf figure 1(b)).

Figures 1(d) and (f) show scatterplots and the linear regression (scaling) of P, PET and ET variability with T variability. P (figure 1(d)) scales significantly with T (−45 mm K^{-1} or −8.0% K^{-1}, $p = 0.01$) but R^2 is only 0.16 and the relation becomes non-significant if the two driest summers 2003 and 2018 are omitted (−27 mm K^{-1} or −4.7% K^{-1}, $p = 0.20$). The eight warmest summers have all been dry summers, but summers not much cooler than the warmest ones (e.g. 1999, 2006, 2007) have been among the wettest in this period. PET on the other hand (figure 1(f)), scales excellently with T (+42 mm K^{-1} or +7.0% K^{-1}, $p{\sim}2.7{\cdot}10^{-15}$, $R^2 = 0.81$). The scaling is somewhat higher than values found by Scheff and Frierson (2014) for Central Europe in CMIP5 climate models and very close to the 6%–7% K^{-1} warming scaling of the saturation vapour pressure of air (Trenberth *et al* 2003, Held and Soden 2006). Also ERA5-Land ET scales significantly with T (+22 mm K^{-1} or +4.0% K^{-1}, $p{\sim}6.9{\cdot}10^{-10}$, $R^2 = 0.64$), while ET in ERA5 is reduced for warm summers, confirming the different behaviour of the two datasets when going towards warmer and drier conditions (cf figure 2).

To better understand the seasonal systematics behind the drought changes and their drivers, figure 3 shows the 1981–2020 changes (Theil-Sen trend slope times period length) of P, PET, CWB, SWC and T for each month of the year. The SWC changes are negative from March to October (monthly changes between −3 and −28 mm) for ERA5-Land and in all months except February (−1 to −62 mm) for ERA5. For ERA5-Land, only the April

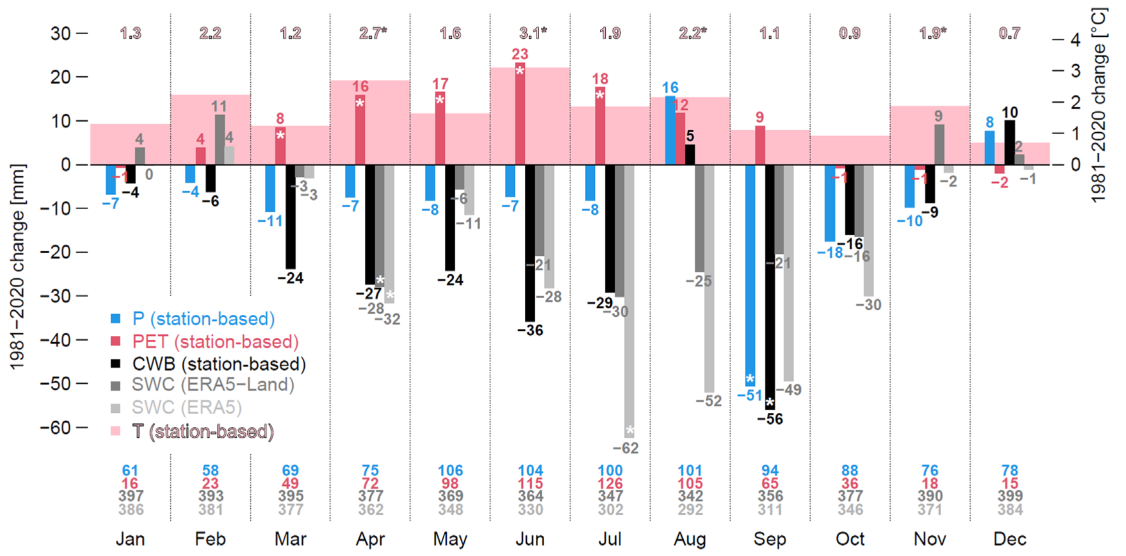

Figure 3. 1981–2020 monthly P (blue bars), PET (red bars), CWB (black bars) changes (all station-based, OBS), 0–1 m SWC changes from ERA5-Land (dark grey bars) and ERA5 (light grey bars). Changes are the Theil-Sen trend slope times 39 years (units: mm). Also shown are the station based T changes (broad pink bars, right axis in °C). The asterisks denote significant trends ($p<0.05$) using a Mann-Kendall trend test. The numbers in the lower part of the plot show the 1981–2010 mean values of P (blue), PET (red) and 0–1 m SWC from ERA5-Land (dark grey) and ERA5 (light grey).

decrease (−28 mm/−7%) is statistically significant, while for ERA5 significant decreases are found for April (−32 mm/−9%) and July (−62 mm/−21%) and close to significant decreases ($p = 0.05$) are found for August (−52 mm/−18%) and September (−49 mm/−16%). The CWB changes are negative (−4 to −56 mm) in all months except August (+5 mm) and December (+10 mm). Again only one month (September, −56 mm) shows a statistically significant decrease. The changes of the drivers P, PET and T are useful to explain most features of the SWC and CWB declines. P changes are non-significant (except for September) but show a small tendency for decreases in all months except August and December. PET is increasing from February to September and the changes are statistically significant for all months from March to July (+8 to 23 mm). T increases substantially in most months, especially strong warming is found for June (+3.1 °C), April (+2.7 °C) and August (+2.2 °C). The SWC and CWB changes show strong similarities in most months with the exception of August and September, where CWB reflects variations in P and SWC does not, indicating the memory effect of SWC. Some features cannot be easily explained such as the small negative SWC trend in May. The strongly negative CWB trend caused by a strong warming and small decrease in P together with an already strongly SWC negative trend in April would suggest an even more negative SWC trend in May. Beside differences in the data sources (P, PET, CWB from station data, SWC from reanalysis), additional water from increased snow melt could be a potential explanation for this behaviour.

EURO-CORDEX regional climate model simulations

As illustrated above, summer drought in Switzerland is mainly driven by P and PET/ET which are strongly linked to T (cf figure 1). In this respect, the ability to correctly represent the variability and trends of the drivers T and P is a prerequisite for a good representation of drought variability. Here we compare the T and P changes and the interannual P-T relation in EURO-CORDEX RCM simulations with observations (MeteoSwiss OBS and E-OBS) and reanalyses (ERA5-Land and ERA5) in the 40 year period 1981–2020.

Homogenised station observations (OBS) show a summer warming of 2.2 °C, E-OBS warmed by 2.0 °C and ERA5-Land and ERA5 by about 1.9 °C (cf figure 4(a), change: Theil-Sen trend slope times period length). The 31 member EURO-CORDEX ensemble shows a large warming range of +0.3 to +2.3 °C with a mean warming of only +1.2 °C. This is 0.7 °C–1 °C less than the observational and reanalysis estimates. The faster warming in nature than in climate models is a long-standing and well-documented feature (van Oldenborgh *et al* 2009, Bhend and Whetton 2013, van Oldenborgh *et al* 2013). Observations and model experiments indicate that decreasing aerosol forcing and less cloud cover may have strongly enhanced the summer warming in the last decades (Ruckstuhl *et al* 2008, Dong *et al* 2017, Rottler *et al* 2019), factors not particularly well represented or even discarded in RCMs (e.g. Nabat *et al* 2014, Bartók *et al* 2017, Boé *et al* 2020). The observational and reanalysis data sets point to non-significant decreases in summer P (OBS: −12%; E-OBS: −8%; ERA5-Land/ERA5: −15%). The EURO-CORDEX ensemble shows a large range of P changes between −14 and +40% and a mean change near zero (+2%). The observed P declines are at the lower bound of the model values. Two simulations

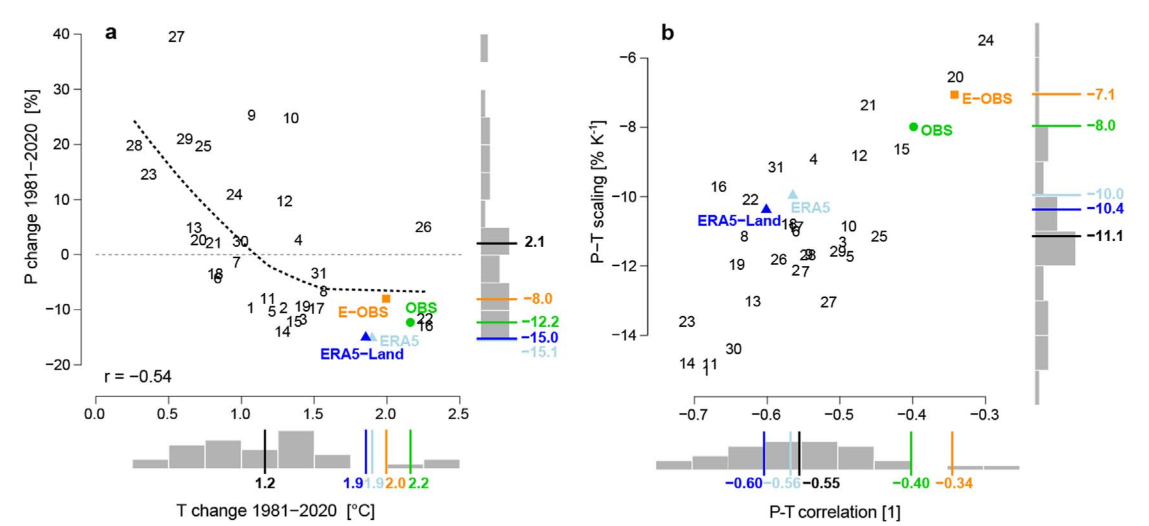

Figure 4. Panel a (left): Scatterplot and univariate histograms of 1981–2020 summer-half year T change (x-axis, °C) versus P change (y-axis, percentage deviation from 1981–2010 mean) on the Swiss Plateau for station-based observations from MeteoSwiss OBS (green), E-OBS v21.0e (orange), ERA5-Land (blue) and ERA5 (light blue) reanalysis and 31 EURO-CORDEX simulations (numbers, cf table S1 in the supporting data file). Changes are the Theil-Sen trend slope times 39 years. The bold dashed line shows a second-order local polynomial regression fit (loess, cf Cleveland *et al* 1992) with smoothing parameter $\alpha = 1$. The Pearson correlation r of the T and P changes in the simulations is shown in the lower left corner. Panel b (right): Scatterplot and univariate histograms of 1981–2020 summer-half year Pearson correlation of T and P values (x-axis) versus P-T scaling (y-axis, % K^{-1}). The lines and numbers in the histograms show the change, correlation and scaling values for the different data sets (black: EURO-CORDEX ensemble mean).

(#16/#22) show a T-P change combination close to the observations, but the observations/reanalyses are at the very edge of the T-P change space spanned by the model ensemble. The T and P changes in the simulations are negatively correlated ($r_{Pearson} = -0.54$). Most simulations with no or very moderate warming tend to show a summer wetting, while strongly warming models mostly tend to drier conditions (exception: simulation #26).

Figure 4(b) shows the 'tightness' (Pearson correlation coefficient r) and the 'steepness' (regression slope, P-T scaling, expressed in % K^{-1} for easy comparison with the Clausius-Clapeyron scaling) of the linear relationship between summer P and T variability. OBS ($r = -0.40$; P-T scaling: -8.0% K^{-1}) and E-OBS ($r = -0.34$; P-T scaling: -7.1% K^{-1}) show similar correlations and scalings. ERA5-Land ($r = -0.60$; P-T scaling: -10.4% K^{-1}) and ERA5 ($r = -0.56$; P-T scaling: -10.0% K^{-1}) show a somewhat stronger relation and more negative scaling than the *in situ* observations. The correlations of the EURO-CORDEX simulations range between -0.71 and -0.30 (mean: -0.55) and P-T scaling values are all negative and range between -5 and -15% K^{-1} (mean: -11% K^{-1}). A small number of simulations show similar values as the observations but most models overestimate the recent P-T correlation and scaling. Interestingly, the reanalyses values are well inside the 'cloud' of the EURO-CORDEX simulations and quite far away from the *in situ* observations. Also note that the simulations close to the observations are not particularly good in representing the T and P changes in figure 4(a). This indicates that a good representation of trends and a good representation of the interannual P-T relation are not necessarily linked.

Summary and conclusions

We used soil water content and evapotranspiration data from reanalysis, climatic water balance observations at stations and temperature and precipitation data from regional climate models to assess trends and drivers of the summer drying in Switzerland in the last 40 years (1981–2020). The observed climatic water balance and soil water content from reanalysis show a clear tendency towards drying with decreasing trend numbers in most months from spring to autumn. Increasing evapotranspiration and a non-significant decrease in precipitation are identified as main and roughly equivalent drivers. We found considerable differences between ERA5-Land and ERA5 in terms of the representation of soil water and evapotranspiration. ERA5 shows less soil water, a much stronger soil drying in late summer/early autumn and evapotranspiration was already soil moisture-limited in recent drought events. In ERA5-Land on the other hand, evapotranspiration remained high (energy-limited) also in the drought summers and has increased fairly linearly with increasing temperature. Soil water content and evapotranspiration values from ERA5-Land, and its behaviour during drought summers, seem to agree better with *in situ* measurements than those from ERA5. Variability and trends of the drought drivers temperature and precipitation have also been investigated in 31 simulations of the EURO-CORDEX regional climate model ensemble. Most simulations considerably underestimate the recent warming. In addition, the simulations show a large possible range of precipitation changes with a mean change near zero. Also the negative summer precipitation-temperature scaling and the correlation between summer temperature and precipitation on the interannual time scale are mostly overestimated by simulations and the reanalyses. The analysis of the regional summer drought evolution and its drivers remains challenging especially with regional climate model data but considerable uncertainties also exist in reanalysis data sets that should be further analysed. We did not aim at separating effects of natural variability from the climate change signal, and the influence of natural variability on the drying trends remains to be investigated in detail. Also the possible influence of climate model deficiencies especially linked to feedbacks and forcings (e.g. aerosol changes and cloud processes) impacting the recent temperature evolution requires further investigation.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

S C Scherrer https://orcid.org/0000-0002-5040-0470

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