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Late 1980s abrupt cold season temperature change in Europe consistent with circulation variability and long-term warming

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Abstract
Cold season temperatures in Europe have increased rapidly by about 1.2°C in the late 1980s, followed by relatively modest and regionally flat temperature trends thereafter. The abrupt change affected the entire European continent and coincided regionally with abrupt hydroclimatic changes such as a widespread reduction in snow days in Switzerland. However, the drivers and causes of the event are not well understood. Using a dynamical adjustment method based on statistical learning, we find that the continental-scale late 1980s abrupt winter warming and regional decreases in snow days can be attributed to cold conditions in the mid-1980s followed by a few exceptionally warm seasons. Both are caused by random atmospheric circulation variability superimposed upon a long-term and relatively homogenous warming trend, and do not require an external cause or change of the underlying dynamics of the system. This explanation is consistent with simulations from a 21-member regional climate model ensemble, in which four members display comparable abrupt temperature increases regionally driven by circulation and a long-term externally forced response. Overall, our analysis provides an observation-based interpretation of abrupt temperature change at the continental scale, associated hydroclimatic changes regionally, and its drivers. Furthermore, our method might contribute to improved mechanistic understanding of different observed climate phenomena in many regions of the world that experience high variability.

1. Introduction
Climate variability and change in cold season temperatures and hydroclimatic variables are of high societal interest and relevance. It is therefore crucial to understand and correctly interpret changes in temperature or hydroclimatic characteristics and their underlying drivers on continental but also on regional spatial scales. Average cold season temperatures (Nov.-Mar.) in Europe increased abruptly by about 1.2°C in the late 1980s (figure 1(a)), and the abrupt change affected almost the entire continent (figure 1(c)). After the abrupt change, cold season temperatures increased only relatively modestly in Europe, with flat or even slightly cooling cold season temperature trends over the last three decades in some regions including, for example, Switzerland (figure 1(b)) (Ceppi et al 2012, CH2018 2018, Saffioti et al 2016). Moreover, the abrupt increase in average cold season temperature coincided regionally with abrupt changes in cold season hydroclimate - such as an abrupt decrease in snow days in Switzerland (Marty 2008). The decrease had been particularly pronounced at stations at low or medium elevation that are particularly sensitive to temperature changes (Scherrer et al 2004), and without any clear trends after the change (Marty 2008).

The abrupt temperature and hydroclimatic change has sometimes been interpreted as a ‘climate regime shift’, because the event may be explained statistically by an abrupt, step-wise change (Marty 2008). The event implied substantial physical and hydrological impacts in Switzerland (North et al 2013) and in fact ‘regime shift’ events have been hypothesized at different times in the 1980s across the entire Northern hemisphere (Reid et al 2016). However, the statistical detection and physical interpretation of breakpoints in climate time series is far from
The abrupt late 1980s warming in (a) European and (b) Swiss cold season temperature time series. While a ‘mean change’ breakpoint is detected statistically in 1987 with high significance, it remains unclear whether the event should be interpreted as an abrupt mean change (orange lines in a,b) or rather as a realization of variability superimposed upon a long-term trend (blue lines in a,b). Both interpretations appear plausible from a purely statistical perspective (i.e. small log-likelihood difference between (a) and (b)). (c) Spatial pattern of observed decadal abrupt temperature changes in Europe (i.e. the temperature difference between the decade after and before the abrupt change), and (d) spatial pattern of estimated circulation-induced decadal abrupt temperature changes. Note that panel (a) and (b) shows long-term averages before and after the abrupt change in 1987, whereas panel (c) and (d) shows ‘short-term’ 10-year averages before and after the abrupt 1987 temperature change.

Figure 1. The abrupt late 1980s warming in (a) European and (b) Swiss cold season temperature time series. While a ‘mean change’ breakpoint is detected statistically in 1987 with high significance, it remains unclear whether the event should be interpreted as an abrupt mean change (orange lines in a,b) or rather as a realization of variability superimposed upon a long-term trend (blue lines in a,b). Both interpretations appear plausible from a purely statistical perspective (i.e. small log-likelihood difference between (a) and (b)). (c) Spatial pattern of observed decadal abrupt temperature changes in Europe (i.e. the temperature difference between the decade after and before the abrupt change), and (d) spatial pattern of estimated circulation-induced decadal abrupt temperature changes. Note that panel (a) and (b) shows long-term averages before and after the abrupt change in 1987, whereas panel (c) and (d) shows ‘short-term’ 10-year averages before and after the abrupt 1987 temperature change.

straightforward because of large variability, memory and trends (Beaulieu and Killick 2018). For example, a state-of-the-art breakpoint detection algorithm (Beaulieu and Killick 2018) detects an abrupt ‘mean change’ in 1987 in European and Swiss cold season temperature (ECST and SCST, respectively) averages with high confidence in both records, supporting the interpretation of an ‘abrupt change’ (figures 1(a) and (b)). On the other hand, however, a linear trend over the 1951–2018 period also provides a reasonable fit to the time series (figures 1(a) and (b)), which would support the interpretation of variability superimposed upon a long-term trend (see Text S1 for more details and quantitative comparison). It is therefore not straightforward to generate a convincing argument for or against an abrupt change around the late 1980s, and its underlying causes from the temperature record alone. A lack of agreed terminology may also contribute to the discussion: here, we use the term ‘abrupt change’ for an empirically observed abrupt change in the climate system irrespective of its causes (CCSP 2008), while evidence for a ‘regime shift’ would require an underlying abrupt qualitative change in the system (e.g. in its forcings) and a causal explanation.

Despite a suite of studies (Marty 2008, North et al 2013, Reid et al 2016), the exact drivers and mechanisms of the hypothesized ‘climate regime shift’, and its possible relationship to external forcing or climate variability, is not well understood. While abrupt large-scale warming in the Northern hemisphere in the late 1980s is related to a weakened Pacific Decadal Oscillation and a relative increase in the strength of the North Atlantic and Arctic
Oscillation (Hurrell 1995, Watanabe and Nitta 1999, Lo Hsu 2010), it remains unclear how the observed abrupt change and subsequent trends at continental or regional scales could be interpreted physically. This has led to some confusion and speculation in the public and media about the interpretation of changes in European and Swiss regional snow days in the context of externally forced climate change (1, 7). The lack of process understanding might be related to internal variability in the climate system that may obscure continental or regional climate trends up to multiple decades (Deser et al 2012).

Techniques of dynamical adjustment enable a co-interpretation of climate trends with variability in atmospheric circulation (Wallace et al 1995, Thompson et al 2000, Smoliak et al 2015, Deser et al 2016). These techniques aim to separate a circulation-induced component of a regional climate variable of interest from a residual component (Yiou 2014, Deser et al 2016, Smoliak et al 2015, Saffioti et al 2016, Sippel et al 2019). Apart from random noise, the residual component is assumed to contain thermodynamical components that remain unexplained by atmospheric circulation dynamics (Smoliak et al 2015, Deser et al 2016). Dynamical adjustment techniques have led to important insights into the origins and drivers of recent trends in climatic and hydroclimatic variables. For example, (Deser et al 2016) and (Saffioti et al 2017) found that dynamically adjusted observed temperature trends are often closer to and more consistent with climate models’ thermodynamical responses to external forcing.

Year-to-year variability in Europe’s cold season temperatures is largely driven by synoptic variations in atmospheric circulation (Fraedrich et al 1993) that are linked to atmospheric modes such as Euro-Atlantic blocking or the North Atlantic Oscillation (Scherrer and Appenzeller 2006, Bader and Fukutome 2015). These variations propagate into hydroclimatic regions (Scherrer et al 2004). Hence, internal variability plays an important role in cold season temperature in Europe and regionally. In fact, about half of the Swiss cold season temperature trend is induced by atmospheric circulation (Ceppi et al 2012), and observed cooling trends over the past 30 years can be reconciled with warming climate model simulations if atmospheric circulation effects are accounted for (Saffioti et al 2016).

The objective of the present study is to better understand and explain the late 1980s abrupt climate change over Europe and regionally over Switzerland. The regional analysis serves as a case study to elucidate the impact of the abrupt temperature change on a key hydroclimatic variable (the number of snow days at low elevation). We first separate the observed ECST, SCST, and the Swiss snow day (SD) time series into a circulation-induced component and a residual component using a recently developed dynamical adjustment method (section 3.1). Circulation-induced and residual components are shown to provide a simple yet physically consistent interpretation of the abrupt climate change and subsequent trends. Second, we assess whether regional-scale abrupt temperature changes are consistent with model simulations. We dynamically adjust regional cold season temperature in a 21-member regional climate model ensemble (section 3.2). Finally, we discuss how temperature trends after the abrupt temperature change have evolved in Europe and regionally over Switzerland when circulation is accounted for (section 3.3).

2. Material and methods

2.1. Observational and reanalyses datasets

Temperature data

We analyse European land areas using the E-OBS gridded daily dataset (Version 17.0) in 0.5° spatial resolution and from 1950 up to today (Haylock et al 2008). The gridded dataset is based on interpolation of around 1500 2m temperature observing stations across Europe. To evaluate uncertainties due to dataset choice, we also dynamically adjust European land grid cells in three monthly gridded global datasets (Cowtan and Way 2014), NASA GISS (Version 4) (Lenssen et al 2019), and the Berkeley Earth gridded temperature dataset (Rohde et al 2013)). The regional analysis is based on the homogenized, long-term (1864–2018), ‘Swiss temperature mean’ time series at monthly resolution (Begert and Frei 2018) that integrates data from a small sample (19 stations) of homogenized long-term series and a high resolution (2 km) gridded dataset over a short (20 years) period. This yields a reliable and time-consistent area-mean estimate with uncertainties below 0.1°C (Begert and Frei 2018).

Station-based observations of snow days

We extract the monthly number of snow days that exceed one and five centimeter of snow (SD1 and SD5, respectively) from stations at low elevation (< 1000 m a.s.l.) in Switzerland from the European ECA&D database (Klein Tank et al 2002, Fontrodona Bach et al 2018). Snow measurements are taken at 7.00 am local time, measurements are quality-checked but not homogenized. All stations that contain data before 1960 and through 2015 are included except two stations located in the south of the Alps (Lugano and Locarno), because these stations are subject to a different cold season hydroclimate and snow characteristics (Schöner et al 2019). In total, we are left with ten low elevation stations in northern and western Switzerland with multidecadal snow records available for analysis.

1Tagesanzeiger (Switzerland), 2018/12/10, https://interaktiv.tagesanzeiger.ch/2018/schneetage.
2Süddeutsche Zeitung (Germany), 2018/12/29, https://www.sueddeutsche.de/wissen/klima-schnee-war-s.1.4267240.
Reanalyzed mean sea level pressure

To dynamically adjust the ECST, SCST and SD record, we obtain the surface pressure field from the long-term Twentieth Century Reanalysis Version 2c dataset (Compo et al. 2011). The reanalysis dataset assimilates only surface pressure measurements and monthly sea surface temperatures into an atmosphere and land general circulation model (Compo et al. 2011). The Twentieth Century Reanalysis is available for the period 1850–2012 (and experimentally up to 2014). The reanalysis has been specifically designed to assess climate variability ‘spanning the instrumental record’ and has been demonstrated to largely reproduce observed climate variability (Compo et al. 2011). We concatenate the Twentieth Century Reanalysis with 2015–2018 ERA-Interim sea level pressure (Dee et al. 2011) following earlier dynamical adjustment studies (Lehner et al. 2017, Guo et al. 2019). The results are insensitive as to whether ERA-Interim or Twentieth Century Reanalysis data is used in the overlapping period. Both pressure datasets are regridded to a regular $2^\circ \times 2^\circ$ grid. The geographical domain used for dynamical adjustment of the ECST record is chosen to reflect a $30^\circ \times 30^\circ$ field centered on each European grid cell, and $-8^\circ$ E to $24^\circ$ E and $30^\circ$N to $62^\circ$N for the SCST dynamical adjustment. The choice of domain size reflects a trade-off between capturing all relevant features in the pressure field while avoiding an overly large number of predictors. The dynamical adjustment results do not depend strongly on the domain size as long as the domain is chosen to capture synoptic scales (Sippel et al. 2019).

2.2. Climate model simulations

In addition to the observations-based analysis, we analyze a regional climate model ensemble ('COSMO-IC', Addor et al. (2015), CH2018 (2018)). 21 global model simulations are run with the NCAR-DOE Community Earth System Model CESM 1.0.4 in $2.5^\circ \times 1.875^\circ$ resolution, each forced with the same observed historical radiative forcings from 1950 up to 2005 followed by the Representative Concentration Pathway RCP8.5 (Moss et al. 2010). The simulations each start from slightly different initial conditions, sampling internal variability of the climate system in addition to its response to external forcing. The CESM runs were downscaled using boundary conditions from the 21 global realizations to a $0.44^\circ$ resolution over Europe using COSMO-CLM. To obtain a regional-scale average time series from the model (that is similar to SCST), we extract from each simulation all grid cells in Switzerland and subsequently average these.

2.3. Dynamical adjustment method

We briefly summarize the dynamical adjustment method applied in this study, but refer the reader to (Sippel et al. 2019) for an in-depth technical evaluation. The goal of dynamical adjustment is to separate a climatic target time series (denoted here as a vector $Y$ containing $n$ time steps), such as observed temperature or snow cover, into a circulation-induced and residual component. We use the spatio-temporal pattern of sea level pressure as a proxy for large-scale atmospheric circulation (a $n \times (p + 1)$ matrix $X$, where $p$ is the number of spatial predictors, and a constant column is included in the matrix for the intercept). Next, we train a statistical model based on regularized linear models to obtain a set of regression coefficients ($\hat{\beta}$) that encapsulate the relationship of the concurrent sea level pressure pattern and the target time series:

$$Y = X\beta + \epsilon. \quad (1)$$

The residual time series is assumed to contain thermodynamical components that are not predicted by the atmospheric circulation proxy. Because the spatial pattern of sea level pressure contains many predictors (here: $p \approx 224$), which may be correlated in space, we use a statistical learning framework based on regularization. Regularization is a technique that shrinks regression coefficients based on a given constraint, which avoids overfitting (Hastie et al. 2009, Friedman et al. 2010). We use the elastic-net penalty that is added to the residual sum of squares ($\text{RSS} = \sum_{i=1}^{n} (y_i - (\beta_0 + \sum_{j=1}^{P} x_{ij}\beta_j))^2$) in the objective function, i.e.

$$\beta_{\text{elastic-net}} = \underset{\beta}{\text{argmin}} \{ \text{RSS} + \lambda \sum_{j=1}^{P} ((1 - \alpha) \beta_j^2 + \alpha |\beta_j|) \}. \quad (2)$$

The elastic-net penalty is based on a combination of shrinkage via the $L^2$ and $L^1$ norm (known as ridge regression and the Lasso, respectively (Hastie et al. 2009)), with the value of $\alpha$ balancing between the two (fixed at $\alpha = 0.2$). That is, the ridge penalty dominates, which yields a smooth spatial map of regression coefficients, but the remainder ‘Lasso-type’ shrinkage allows to set some irrelevant predictors exactly to zero (for example, features at the edge of the spatial field used for prediction), performing feature selection (Hastie et al. 2009, Friedman et al. 2010). The parameter $\lambda$ is a tuning parameter that determines the total amount of coefficient shrinkage. The value of $\lambda$ is determined by 10-fold cross-validation. We detrend all time series before dynamical adjustment, but results are virtually identical if no detrending is performed (figures S1, and figure S2 for a comparison of spectral densities of dynamical adjustment for detrended and non-detrended ECST and SCST). Each month in the cold season (Nov.-March) is adjusted separately and subsequently averaged to obtain a cold season mean temperature / snow day estimate. For ECST dynamical adjustment, each grid cell is adjusted separately, and we subsequently average all grid cell estimates from all three European SREX regions (IPCC. 2012). Training is based on the 1950–1960
3. Results and discussion

3.1. Explaining the abrupt change in European and Swiss cold season temperatures and snow days

Dynamical adjustment of cold season (Nov.-March) temperatures reveals that atmospheric circulation accounts for about 76% and 73% of the variance in the detrended cold season temperature series over Europe and Switzerland, respectively (figures 2(a) and (b), blue lines). Hence, our method captures the bulk of temperature variability through its relationship with atmospheric circulation, and some of the peaks are also captured remarkably well as for example the extremely cold winter 1962/63. Importantly, the abrupt temperature increase in the late 1980s is driven to a very large extent by atmospheric circulation both at the continental scale as a European average, and regionally over Switzerland (figures 2(a) and (b)). The estimated circulation-induced component reproduces the spatial pattern over Europe of abrupt temperature changes in the late 1980s remarkably well (compare figures 1(c) and (d)), with slightly more pronounced abrupt cold season temperature changes over Scandinavia, the Baltic region, and some mountain areas such as the Alps, the Pyrenees and the Carpathians (pattern correlation of $R = 0.93$). Larger temperature changes in northerly regions and in mountain regions at higher elevation is consistent with the interpretation of a circulation-induced regime shift. Estimated circulation-induced components of temperature anomalies indicate relatively cold winter seasons in the early and mid 1980s at the continental and regional scale followed by a few unusually warm winter seasons in the late 1980s and early 1990s (figures 2(a) and (b), blue lines). However, in contrast to a persistent ‘regime shift’, the circulation-induced component of ECST and SCST anomalies declined since the mid 1990s back towards their earlier values. This indicates that the abrupt temperature increase was driven by unusual atmospheric circulation anomalies in the short-term (i.e. the first 5–15 years after the abrupt change), consistent with relatively abrupt warming in the entire Northern hemisphere around that time, possibly related to synchronous changes in the Pacific Decadal Oscillation and Arctic Oscillation (Hurrell 1995, Watanabe Nitta 1999, Lo and Hsu 2010). In the longer-term, however, a relatively smooth, upward trend in the residual component that remains unexplained by atmospheric circulation becomes important (figures 2(c) and (d), orange lines; see figure S2 for a spectral density plot), possibly reflecting the imprint of a, possibly externally forced, thermodynamical signal (Saffioti et al 2016).

This residual trend counteracts the recent decline in the circulation-induced component of temperature anomalies. Taken together, these two signals produce an abrupt and sustained change in ECST and SCST that create the impression of a ‘regime shift’, even though there is little if any evidence for a shift in the system’s forcings or behaviour. The abrupt change may thus be interpreted as a combination of internal variability superimposed upon a long-term warming component.

This interpretation requires a discussion of potential caveats of dynamical adjustment. First, potential influences of other variables not captured by sea level pressure may remain (Merrifield et al 2017), and the residual component cannot be interpreted directly as the externally forced component. But it has been shown that the residual component contains the forced thermodynamical component, and hence dynamical adjustment acts as an efficient ‘noise filter’ for circulation-induced variability (Deser et al 2016, Sippel et al 2019). Second, dynamical adjustment results are virtually identical if different temperature datasets and different training periods are used in the training step (Supplementary figure S5). Furthermore, whether dynamical adjustment is based on detrended or original data changes the results only to a minor extent: The long-term detrended version (shown in the main text) reveals slightly larger trends in the residuals as compared to dynamical adjustment based on original data (Supplementary figure S2; see Sippel et al 2019) for more details on detrending prior to dynamical adjustment. Overall, the additional robustness checks indicate that our interpretation of the abrupt change as a combination of circulation-induced short-term variability superimposed upon a long-term warming trend is consistent across various datasets and data pre-processing choices. Third, the question whether the circulation-induced component contains some imprint of externally forced changes is relevant but cannot be answered by dynamical adjustment analysis. Physical mechanisms have been suggested in the literature that may indicate an imprint of forced Arctic warming or reduced sea ice cover on the Northern hemisphere atmospheric circulation (Jaiser et al 2012, Cohen et al 2013), potentially via an intensified ‘warm Arctic, cold continents’ pattern. However, other analysis suggest that this pattern could be attributed to internal variability rather than forced circulation change (Gerber et al 2014, Sun et al 2016), or that (small) forced circulation changes are felt locally in areas of sea ice loss, but not remotely throughout the Northern hemisphere mid-latitudes (Screen et al 2014). We hence conjecture that no consensus on forced mid-latitude winter circulation change has been reached so far (Cohen et al 2019), and that uncertainties in climate projections are dominated by uncertainties in atmospheric circulation (Shepherd 2014, Fereday et al 2018). We therefore refrain from interpreting whether...
the extracted circulation-induced components may reflect only internal variability, or whether some component of forced circulation change may be implicated.

We further discuss the hypothesized abrupt change in regional cold season snow days in Switzerland (Marty 2008). The station average time series of anomalies in the number of snow days (SD) shows an inverse temporal pattern to the regional temperature time series: A few years in the early and mid 1980s, before the abrupt change, showed positive SD anomalies with up to around 20 snow days more than the 1951–1980 average. Simultaneously with the increase in temperature, the number of SDs per cold season dropped in the late 1980s below the average, and has not recovered since (figure 3(a)). Dynamical adjustment of the SD time series performs slightly less well than for the temperature time series (64% of the variance explained), and some of the peaks are underestimated (figure 3(a)). The underestimation may be related to influences not captured by the sea level pressure field such as precipitation, although variability in snow days at low elevation in Switzerland is mainly driven by temperature variability and trends (Scherrer et al 2004). Nonetheless, and similar to the abrupt temperature change, the abrupt decrease in snow days is driven to a very large extent by atmospheric circulation (figure 3(a), blue line). However, in recent years the circulation-induced SD component recovered towards its previous values.

This leaves a negative and relatively smooth trend in the residual SD component (figure 3(b)) that is likely due to a thermodynamical component reflecting an imprint of long-term warming. Hence, a thermodynamical trend has been masked by a short-term circulation change, and both signals together induce the abrupt change towards a lower number of snow days observed in the late 1980s.

Overall, we conclude from the analysis of observed ECST, SCST and SD that late 1980s abrupt shifts is consistent with random short-term changes in atmospheric circulation that have been super-imposed upon a smooth thermodynamical warming trend (causing also a reduction in snow days).

3.2. Is the observed abrupt late 1980s warming consistent with climate model simulations?

In the regional climate model ensemble, atmospheric circulation explains around 82% of the variance in SCST (figure 4(a)). The raw and dynamically adjusted (residual) ensemble mean both show a similar, smooth increase over time (figure 4(b)), indicating that there is no systematic abrupt change over the
Figure 3. Dynamical adjustment of the regional number of snow days (> 1 cm) averaged across eight Swiss plateau locations below 1000 m a.s.l. (a), (b). Predicted circulation-induced components ((a), in blue) show an abrupt change around the late 1980s, and the residual components that contains the external forced response ((b), in orange) shows a relatively smooth downward and long-term trend.

1950–2018 period. However, individual ensemble members show substantial internal variability (CH2018 2018). Four out of the 21 ensemble members show a ‘mean breakpoint’ using a standard breakpoint detection algorithm (see also Text S1) (Beaulieu and Killick 2018). These four members show an abrupt, upward shift either in the 1980s or 1990s up to a mean change of 0.8 °C, slightly lower in magnitude but qualitatively similar to the observed shift. In all four cases, the shift is driven by atmospheric circulation in the years immediately before and after the breakpoint (figures 4(c)–(f), blue lines). In the longer term, however, these abrupt changes in the circulation-induced component of temperature are not sustained (figures 4(c)–(f)), and long-term thermodynamical components driven by external forcing become more important (figure 4(b)).

The role of circulation and the residual thermodynamical component can be understood further as a function of time scale around the abrupt change (figures 5(a) and (c) for observed ECST and SCST, and figure 5(e) for COSMO-IC). A circulation-induced component dominates the mean shift up to 15 years or less before and after the abrupt change in observations (figures 5(a) and (c), e.g. explaining about 1.1 °C of 1.4 °C, and 0.6 °C of 1.1 °C of abrupt change after 10 and 15 years in Switzerland, respectively) and in COSMO-IC simulations that show an abrupt change (figure 5(e)). In contrast, however, on longer timescales before and after the abrupt shift (e.g. 15 years and more) the residual trend becomes gradually more important in maintaining the magnitude of the abrupt change, while the contribution of circulation is reduced (figures 5(a), (c) and (e)). After 30 years, the residual component explains on average around 1.0 °C of 1.2 °C of abrupt change in Europe and 0.7 °C of 1.2 °C in Switzerland.

Overall, we conclude that, firstly, the fact that four out of 21 ensemble members show an abrupt temperature change illustrates that such events are well within the range of simulated outcomes of the model ensemble. Secondly, while historical external
Figure 4. Dynamical adjustment of regional cold season (Nov.-March) temperatures in a 21-member regional model ensemble over Switzerland reveals each member’s circulation-induced component (a) and its residual forced response (b). Four ensemble members display an abrupt temperature change in the 1980s or 1990s ((c)-(f), in black) that appears to be a ‘mean change’ but in reality is driven in the short-term by a circulation-induced component (in blue), in addition to a long-term forced trend (b), comparable to the observations.

Forcing changes only smoothly and the resulting ensemble mean response is smooth as well, simulated abrupt changes in individual realizations may result from random internal variability superimposed upon externally forced changes. Thirdly, this model-based interpretation is consistent with the drivers of the observed abrupt late 1980s warming in Europe and Switzerland.

3.3. Have cold season temperatures increased over the last 30 years in Europe and Switzerland?

After the abrupt late 1980s warming, modestly increasing cold season temperature trends over Europe, and even flat or slightly negative temperature trends regionally, for instance in Switzerland, have been recorded (Ceppi et al 2012, Saffioti et al 2016). These trends created speculation about possible
Figure 5. (a), (c), (e) Contribution of circulation-induced and residual thermodynamic components to the observed late 1980s abrupt change over (a) Europe (transparent lines indicate individual grid cells) and (c) Switzerland, and to (e) simulated abrupt changes in the regional climate model ensemble as a function of averaging time scale before and after the shift. Observed and simulated abrupt temperature shifts contain (in all cases, (a), (c), (e)) a substantial short-term circulation-induced component, and an externally forced component that becomes gradually more important over time. (b), (d), (f) Contribution of circulation-induced and residual thermodynamic components to temperature trends that end in 2018 for (b) Europe, (d) Switzerland, and (f) in the COSMO ensemble. Short-term trends are highly variable and contain substantial circulation-components while longer trends (or if dynamically adjusted) are largely driven by the residual, externally forced, component.
implications in the context of externally forced climate change in the grey literature (Aigner et al. 2018). Here, we briefly reinvestigate this issue using dynamical adjustment. We compute trends of length $L$ from the 2017/18 cold season backwards in observed ECST and SCST (figures 5(b) and (d)) and in the COSMO-IC ensemble (figure 5(f)). At the continental scale and regionally over Switzerland, short-term trends over the last 10–15 years are positive, but smaller and in some cases even slightly cooling if the trend calculation starts around 25–30 years ago (that is, immediately after the abrupt change). However, trends that are calculated over 35 years or more are positive. Dynamical adjustment shows that the flat trends calculated over 25–30 years are due a negative short-term trend induced by circulation after the abrupt shift that is counteracted by an upward thermodynamical component. This result holds both at the continental scale over Europe and regionally over Switzerland, and is consistent with an earlier study focussing on Switzerland specifically (Saffioti et al. 2016). Trends in the residual thermodynamical component are much less variable than the raw trends, and the ‘trend dip’ in the original series at trend lengths of 25–30 years disappears (figure 5).

In COSMO-IC, short-term trends are positive in average (as expected due to external forcing), but trends in individual ensemble members show considerable spread and can be positive or negative (figure 5(f)). The spread between ensemble members reduces with increasing trend length. The spread in residual thermodynamical trends is reduced, and the externally forced thermodynamical trends are exclusively positive beyond a trend length of around 35 years.

Hence, a naive interpretation of raw temperature trends based on only a few decades of data can be misleading due to the important role of internal variability (Deser et al. 2012, Hawkins and Sutton 2012). ECST and SCST display trends of about $0.2–0.3\, {^\circ}\mathrm{C}$ per decade over the last 60 years, and temperature trends with circulation effects accounted for are in fact similar to that number even for shorter time scales (e.g. upwards of only 25 years in trend length). This is consistent COSMO-IC, where short-term trends show large spread and may be positive or negative, but the residual component is consistent with long-term trends.

4. Conclusion

We have shown that the observed late 1980s abrupt cold season warming in Europe, and regionally in Switzerland associated with decreases in the number of snow days, is consistent with a combination of a short-term, possibly random, circulation-induced component (some cold winters in the early 1980s followed by a few unusually warm years in the late 1980s and early 1990s) superimposed upon a slowly evolving warming trend. This explanation and interpretation of the abrupt late 1980s temperature is consistent with regional climate model ensemble simulations, where abrupt changes may arise (in four out of 21 ensemble members) due to a superposition of abrupt short-term circulation variability and an externally forced long-term trend signal. There is neither evidence nor a need for an abrupt forcing nor a qualitative shift in the response (in the sense of a dynamical system switching to a different mode or attractor) in order to explain the abrupt 1980s temperature change in Switzerland and Europe. Our findings imply that dynamical adjustment is a powerful tool for assessing the impact of circulation variability on regional temperature and hydroclimatic trends, and other climate phenomena such as abrupt changes. Hence, a co-interpretation of regional climate trends or abrupt changes with atmospheric circulation variability provides a promising avenue to improve our understanding of such phenomena and their drivers. Beyond only scientific questions, this might also facilitate the communication of such changes in the media or public discussion, where there is often widespread interest in temperature or hydroclimatic changes at the regional level in the context of adaptation policy and planning.

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Data availability statement

The data that support the findings of this study are openly available. We acknowledge the E-OBS dataset from the EU-FP6 project UERRA (http://www.uerra.eu, doi:10.1029/2017JD028200) and the Copernicus Climate Change Service, and the data providers in the ECA&D project (https://www.ecad.eu, doi:10.1002/joc.773). The Switzerland mean temperature time series and individual snow data are publicly available (https://www.meteoswiss.admin.ch/home/climate/swiss-climate-in-detail/Swiss-temperature-mean/Data-on-the-Swiss-temperature-mean.html, doi:10.18751/Climate/Timeseries/CHTM/1.1). The Twentieth Century Reanalysis and the ERA-Interim reanalysis datasets are available from NOAA (https://www.esrl.noaa.gov/psd/data/gridded/data.20thC_ReanV2c.html, doi:10.1175/BAMS-87-2-175) and ECMWF (https://www.ecmwf.int/en/forecasts/datasets/archive-datasets/reanalysis-
datasets/era-interim, doi:10.1002/qj.828), respectively. Support for the Twentieth Century Reanalysis Project Version 2c dataset is provided by the U.S. Department of Energy, Office of Science Biological and Environmental Research (BER), and by the National Oceanic and Atmospheric Administration Climate Program Office.

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