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ORIGINAL ARTICLE

Reconstruction of snow days based on monthly climate indicators in the Swiss pre-alpine region

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Abstract

Landscape and climate change interactions are considerably interrelated in mountainous area, where unsuitable or discontinuous surface meteorological variables constitute an impediment to the generation of homogeneous ecological and hydrological data, and may hinder long-term environmental studies. We developed a non-linear multivariate regression model (NLMRM) estimating snow days per year (SDY) in a focus area, the northern Swiss pre-alpine region (SPAR). The model was calibrated and assessed by using measured SDY data and other climatic variables in the period 1931–2006, and then used to estimate SDY for a longer period earlier than 1931. The extended series (1836–2017) showed a significant decrease of SDY passing from about 36 days year^{-1} in 1836–1943 to 29.9 days year^{-1} in 1944–2017, on average. This indicates that while warming is the major factor driving the SDY decrease recently observed in the study area, other processes related to local precipitation and large-scale climatic patterns emerge from our century-long perspective as important drivers of SDY variability in the Swiss pre-alpine region.

Keywords Climate patterns · Long-term prediction · Regression model · Snow days

Introduction

Snowfall variability and long-term trends are the result of the combined (direct or indirect) effect of several climate drivers, such as atmospheric circulation, air temperature and precipitation (e.g. Niedźwiedź et al. 2009). Studies on the long-term snowfall patterns are justified by the impact that the snow cover has on local climate and hydrology (Diodato et al. 2018) and, ultimately, on human life conditions (Barnett et al. 2005; Dong 2018). Knowing the interannual snow cover variability provides a baseline information for evaluating shifts in plant phenology (e.g. Lane et al. 2012 on the role of snow depth and melt) and in water resources (e.g. Arheimer et al. 2017 on snow-fed rivers). The presence of snow and seasonal melting water is essential to ensure sustained wetlands at lower-and-distant river basins during prolonged summer dry spells (Haeberli and Beniston 1998). Despite the recent warming trend, heavy snowfall and winter-spring melting still considerably contribute to the water balance in mid- to high-latitude mountain areas (Legates and McCabe Jr 2005).

The focus of our study is the Swiss alpine region, where snow is an important social, ecological and commercial resource (e.g. drinking, water reserves, tourism and hydroelectric power) but also entails considerable risks such as avalanches and road closures (Beniston et al. 2003; Scherrer et al. 2004; Techel et al. 2015; Klein et al. 2016; Marty et al. 2017). Monitoring snow dynamics within the alpine area may assist to determine local vulnerability and provide a regional assessment of the ongoing climate change (Hu et al. 2018). The relationships between snowfall amounts, glacier sizes and environmental changes were observed with great interest during the Little Ice Age (LIA, roughly AD 1300–1900; e.g. Zasadni 2007). In that period, concurrent climatic factors amplified cooling during long periods of reduced solar activity (Steinhilber et al. 2009; Delaygue and Bard 2011) and enhanced volcanic activity (Sigl et al. 2015), combined with atmosphere and ocean influences as reflected in the AMO

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(Atlantic Multidecadal Oscillation) and PDO (Pacific Decadal Oscillation) indices (Diodato et al. 2018). The Alps are an excellent example of the combined effect of landscape and climate change. On the one hand, the alpine range is a quite hostile environment to human activities. On the other hand, the Alps capture the interest and fascinated audiences, as affirmed by numerous scholars, geographers, writers and artists since the eighteenth century (Reichler 2002). However, in years of heavy snowfall, when snow cover persists well until late spring on alpine and pre-alpine pastures, winter landscapes and crops can be heavily damaged by a snow mould, as in 1757, 1770, 1785 and 1789 (Pfister 1978). A climatic fluctuation involving cold winters extending until March occurred in the latest part of the LIA (Grove 2004). However, the interannual variability of snowfall in this period is still unknown for Switzerland. After the end of the LIA, a general decreasing trend in snow cover has been demonstrated in the Northern Hemisphere (Brown and Mote 2009). Also, snow depth decreased in the Italian Alps (Terzago et al. 2012, 2013), while the number of snow days decreased in Switzerland until recent times, i.e. 1961–2008 (Scherrer et al. 2013). A shift from snow- to rain-dominated regimes is currently assumed not to influence the mean streamflow significantly (Beniston 1997; Beniston and Goyette 2007; Serquet et al. 2013).

Our ability to monitor trends in mountain regions remaining still limited today (Bormann et al. 2018), it is desirable to increase knowledge of mountain snowfall trends and their controlling mechanisms through improved observations, quality control, satellite-based remote sensing, model simulations and projections (Rasmussen et al. 2012; Mudryk et al. 2017; Frei et al. 2018; Baronetti et al. 2019; Diodato and Bellocchi 2020). In addition, knowledge of past climate is an essential key to understand aspects of climate extremes, such as excessive and/or deficient snow periods (Marty and Blanchet 2012) characterising the long-term natural variability of climate (Diodato et al. 2018). In this way, access to snow days data is of value to support a wide range of ecological and environmental science research, including studies of the impact on human activities, livestock assets and infrastructures (Dafis et al. 2016), and terrestrial water cycle trends and soil moisture processes (Wang et al. 2018). Our understanding of the snowfall characteristics in several regions of the world is however reduced by the short records available and the poor knowledge of the complex, interacting factors involved in weather and climate modifications (Kunkel et al. 2016). Snow monitoring constituting arduous work for the instrumentation, in situ continuous monitoring systems able to collect snowfall data at high temporal resolution are not well established yet (De Walle and Rango 2008). Despite this, some studies have investigated snow trends and patterns in the European Alps (Laternser and Schneebeli 2003; Marty 2008; Durand et al. 2009; Scherrer et al. 2013), and the possible connection between snowfall and climate patterns (Rebetez 1996; Beniston 1997; Scherrer et al. 2004; Estilow et al. 2015; Irannezhad et al. 2017). However, for the Swiss pre-alpine region (SPAR), there has been no recent progress so far on how a combination of climatic factors has affected snow cover back in time. This motivates our focus on this region. Thanks to Marty (2008), for the SPAR, there is now an accessible accurate long-time series (1931–2006) of snow days per year (SDY), that is, the number of days with snow depth of at least 0.05 m between December and March. In this study, we first developed and evaluated a non-linear multivariate-regression model (hereafter NLMRM), which combines scale concepts and illustrates first-order effects on the estimate of SDY. Then, we estimated the SDY back to the end of the LIA to facilitate an inventory of the changes in the most important snow driving factors, namely air temperature and precipitation, and to assess how the evolution of these factors has influenced snow cover in the Swiss pre-alpine region.

Study area

Switzerland occupies the northern slope of the central-western section of the European Alps (i.e., the Pennine-Lepontine and Rhaetian Alps), with the exception of the valleys of Lei (46° 28′ N, 09° 27′) and Livigno (46° 32′ N, 10° 08′ E), which are part of the same mountain range but belong to Italy (Fig. 1a). Its territory comprises three physical regions, which are structurally and morphologically well differentiated: a large alpine area to the South (which exceeds 60% of the total land area), a pre-alpine region (below 800 m a.s.l.) in the centre (which covers 27% of the total area; Fig. 1b, yellow areas) and an anthropized area to the North. The Swiss Plateau extends over the central pre-alpine area as a continuous succession of hills, deep valleys and small plains, with about 100 to 200 days per year on which temperatures dip below 0 °C (Fig. 1c). It declines gently from the subalpine strip, at approximately 800 m a.s.l., towards the anthropized area.

Even if the territory is limited in surface, there are considerable regional variations due to the different exposure of slopes and the presence of large lakes, which exert some mitigating effects (Joly et al. 2018). Swiss Alps show close parallels with the French Alps, where snow maxima are centred along the first mountain range exposed to predominating north-westerly currents (cold and wet). However, snow patterns are characterized by a marked declining gradient from the north-western foothills to the south-eastern interior regions (Durand et al. 2009). During the year, cyclonic Atlantic air masses alternate with areas of anti-cyclonic airflows from Central and Eastern Europe. One thus has a field of variable winds, with wet masses from southwest, and dry and continental winds from northeast.

The distribution of rainfall is rather uneven and unpredictable, depending on the prevailing winds and the presence of

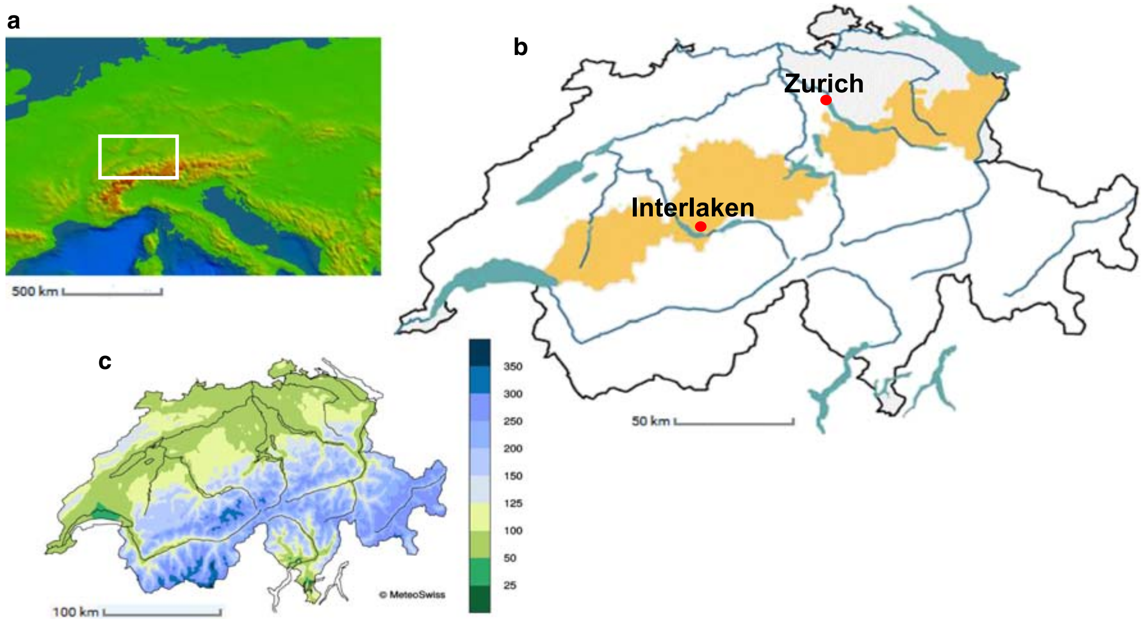

Fig. 1 Geographical setting (**a**), Switzerland territory with pre-alpine areas (SPAR, in yellow) (arranged from goo.gl/VHtfi5) (**b**) and related ice days per year (from MeteoSwiss, https://www.meteoswiss.admin.ch) (**c**)

reliefs. In 3/4 of the territory, rainfall volumes are largely varying around 1000 mm per year. Precipitation increases as approaching the alpine foothills and the Alps (including the Bernese Alps, 46° 25′ N, 07° 45′ E), where peaks of 2000–3000 mm year^{-1} are reached around 2000 m a.s.l. The pre-alpine region is one of the wettest regions of Switzerland (1500–2000 mm year^{-1}). Snowfall increases with elevation until 2000 m a.s.l.

Atmospheric setting of circulation patterns

Alps are located in a pivotal region and often exhibit local snow characteristics, mostly during negative NAO (North Atlantic Oscillation) phases. The fluctuations of snowfall in Switzerland can thus be expected to be sensitive to those of the NAO, in particular the wintertime (December–January–February–March) value. Studies do exist on the links between NAO and alpine climate (Scherrer and Appenzeller 2006; Beniston 2012). One of the most significant findings is that a negative phase of the NAO is related to a strong persistence of low-pressure fields over the Mediterranean region that attract perturbations. They are then forced to cross the Alps from the north, or from the east, in turn positively affecting annual snowfall over the SPAR. Clark et al. (1999) and Bednorz (2002) found that statistically significant negative relationships exist between the NAO index and the number of days with winter snow cover in Poland and Eastern Europe too.

Data and methods

An annual series of SDY data spanning the period between 1931 and 2006 was used for the development of a prediction model based on seasonal temperature and precipitation inputs. The SDY data series was derived by Marty (2008) from 34 Swiss stations between 200 and 1800 m a.s.l. that met quality criteria (homogeneity across data, convenient separation distance among stations and length of observations) out of an initial selection of 41 stations. Quality control on the selected stations included identification and estimation of missing and inconsistent data with the help of neighbouring stations.

For the historical reconstruction of SDY across the SPAR, we used precipitation data from an area included between 07° 11′ and 09° 00′ E, and between 46° 30′ and 47° 30′ N, as derived from the seasonally resolved dataset on a 0.5° grid (eight pixels) from Pauling et al. (2006) and updated by CRU Global Climate Dataset (through https://tinyurl.com/y47nuy4w). Temperatures are instead from the Zurich observatory (47° 22′ N, 08° 32′ E), which provides a long series back to 1836, as derived from the Global Historical Climatology Network, version 3 (Lawrimore et al. 2011). A temperature dataset over the same grid is available from Luterbacher et al. (2004) until 2000 (then updated by CRU Global Climate Dataset). We found that the resulting time series is highly correlated with the readily available Zurich series ($R = 0.99$ for both winter and spring temperatures).

Development and parameterisation of the statistical model

The varied topographic features surrounding the pre-alpine area are modifiers of local precipitation patterns. The large-scale impact of precipitation changes likely depends on the spatial and temporal scales of disturbances, and on the interaction between such disturbances and small-scale structures. It is desirable to quantify the characteristics of winter weather conditions, not just in terms of the changes in temperature or precipitation regimes taken separately, but also in terms of joint quantile distributions (Beniston and Goyette 2007). Joint distributions of temperature and precipitation records have been shown to be closely associated with changes in the underlying atmospheric circulation systems that lead to snow-abundant or snow-sparse winters in the Alps (Beniston 2012). Statistical relationships established between weather records taken at stations ranging from 275 to 2540 m a.s.l. in the period 1958–1999 have shown, however, that the predictability of snow days is low, with determination coefficients (R^2) around 0.4 (Scherrer et al. 2004). Relationships developed at lower-altitude stations (below 1000 m a.s.l.), comprising only temperature as explanatory variables during the period 1931–2006, also resulted in poor performance, with $R^2 = 0.48$ (Marty 2008). This is because cold winters are not always associated with a high number of days with snow on the ground. A winter with a lot of snowfall is also not necessarily associated with a high number of snow days (what makes prediction a difficult task).

To increase the accuracy of predictions and minimize uncertainties in the estimates, we developed an annually resolved model, adopting a non-linear multivariate regression with three input variables and five parameters. The data resource of 76 years (1931–2006) was segregated into two subsets: randomly selected 50 years were used for model calibration, and the remaining 26 years were used for the validation purpose. In this way, a number of monthly climatic explanatory variables was considered during the input selection process according to the following guidance. First, in order to reduce the number of inputs, we investigated the effects of single variables, or sets of variables, on the SDY over some climatologically meaningful periods. For instance, a sequence of seasonal rainfalls can have an additive effect on the SDY and this kind of knowledge can be used to determine the type of dependence (either positive or negative) between SDY and rainfall. This approach helped us to understand the association between the SDY response variable (SDY(SPAR)) and multiple predictors, such as the winter precipitation amount across the gridded Swiss pre-alpine region, *Pw* (GSPAR), and winter (December to February) and spring (March to May) average temperatures at Zurich Observatory, *Tw* (ZOBS) and *Ts* (ZOBS). Then, an iterative process (trial-and-error to compose relevant drivers) enabled us to explain the dynamics of SDY in relatively simple terms. A stepwise approach was used to alternate between adding and removing terms. Afterwards, we included more complex terms, but limiting the number of factors (principle of parsimony). For instance, spring precipitation and autumn temperature were initially introduced in the model, and then removed because they did not allow for improved estimates. The following non-linear multivariate regression model (NLMRM) was thus derived to estimate SDY in the SPAR:

$$\mathrm{SDY(SPAR)} = A\cdot\{\alpha + \ln[Pw(\mathrm{GSPAR})]-\beta + \gamma\cdot Tw(\mathrm{ZOBS})-\vartheta\cdot[Ts(\mathrm{ZOBS})-Tw(\mathrm{ZOBS})]\} \quad (1)$$

where A (day year^{-1}) is a scale parameter; α, β, γ (°C^{-1}) and ϑ (°C^{-1}) are process parameters; *Pw* (GSPAR) is the winter precipitation averaged on a grid across the SPAR (as derived from Pauling et al. 2006 plus updates). Winter and spring temperatures are indicative of the type of air mass present in the atmospheric layers near the SPAR (as derived from the Zurich observatory). The last term of the model represents a jumping factor reflecting the switch occurring from winter to spring temperatures.

The best fit against observations was obtained by maximizing the goodness-of-fit (R^2, optimum = 1) and minimizing the mean absolute error (MAE, optimum = 0). The assessment was completed with the modelling efficiency, using the Nash and Sutcliffe (1970) statistic ($-\infty < \mathrm{EF} \leq 1$, best).

Spreadsheet-based statistical analyses were performed with the support of the STATGRAPHIC (Polhemus 2017) and Wessa (2017) online freeware.

Results and discussion

Model parameterization and evaluation

For Eq. (1), the calibrated parameters are as follows: A = 10.45 day year^{-1}, $\alpha = 4.73$, $\beta = 4.00$, $\gamma = 1.00$ °C^{-1} and ϑ = 0.300 °C^{-1}. The R^2 statistic of the observed versus modelled data (Fig. 2a) indicates that the fitted model explains 67% of the observed variability. Since the ANOVA P value was less than 0.05, the regression was statistically significant. The mean absolute error (MAE), used to quantify the amount of error, was equal to 6.38 days year^{-1}, which is lower than the standard deviation of the residuals (8.1 days yearr^{-1}). The Durbin-Watson (Durbin and Watson 1971) statistic (DW = 1.79308, $P = 0.2696$) revealed no significant serial autocorrelation in the residuals. Figure 2b shows the normal approximation of model residuals (normality test, $P > 0.05$, Jarque

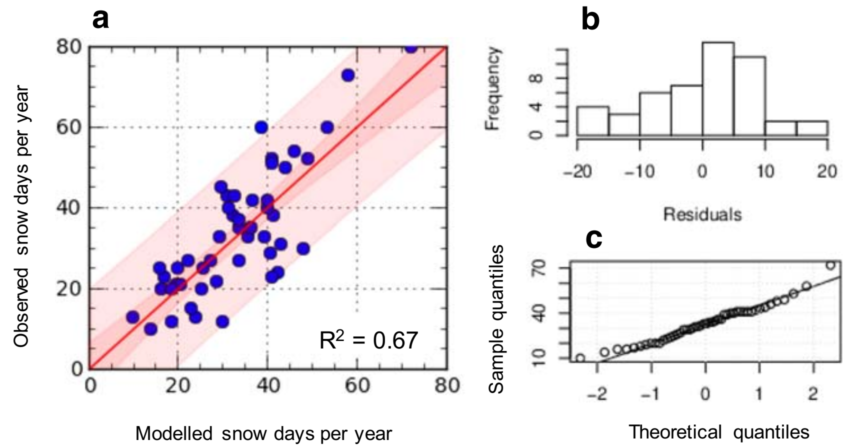

Fig. 2 Scatterplot of observed and modelled snow days per year at calibration stage for a random sub-set of 50 years, with the inner bounds showing 95% confidence limits (pink coloured band), and the outer bounds showing 90% prediction limits for new observations (light pink coloured area) (**a**), histogram of residuals (**b**) and Q-Q plot (theoretical versus sample quantile values) (**c**)

and Bera 1980). The Q-Q plot (Fig. 2c) exhibits a distribution of sample-quantiles around the theoretical line, indicating a model response free from large biases.

At the validation stage, the R^2 statistic indicates that the fitted model explains 60% of the observed variability, while the MAE is equal to 6.4 days year^{-1}. As well, the Durbin-Watson statistic (DW = 1.807, $P = 0.282$) indicates that there is no significant serial autocorrelation in the residuals.

Also at the validation stage (Fig. 3), the distribution of residuals (Fig. 3b) does not deviate significantly from normality ($P > 0.05$), and the experimental Q-Q plot is aligned along the theoretical line (Fig. 3c). The analysis of variance of the regression model gave a P value less than 0.05 for each independent variable, which means that the model cannot be simplified and model results correspond to criteria of stability, interpretability and usefulness (after Royston and Sauerbrei 2008).

Temporal pattern reconstruction of snow days

Figure 4a displays a negative trend of SDY over time, with a correlation coefficient equals to − 0.31. The P value < 0.05 of the ANOVA of the linear regression indicates a statistically significant trend. Three periods are identified in the time series, for which mean SDY differences are maximal and correspond to dissimilar climatic phases: at the end of the LIA (1836–1868), the SDY were, on average, 36.5 ± 9.9 year^{-1}; in a transition interval (1869–1943), this number decreased to 35.6 ± 12.3 days year^{-1}; in the third, warmer phase (1944–2017), the decrease was even larger, with the mean value of SDY equal to 29.9 ± 12.5 year^{-1}. Thus, it can be assumed a substantial absence of a change-point in SDY between the first and second period ($P = 0.7095$), while the difference between the second and third period marks a drastic jump around the year 1943 and a significant trend ($P = 0.00307$). This SDY trend reflects the decreasing trends in snowfall observed in other parts of Europe (Nikolova et al. 2013; Irannezhad et al. 2017). This may extend the plant-growing season length, driving a higher demand for water supply (Wu et al. 2015; Ye et al. 2017). Statistics from Fig. 4a also evidence a P value of the DW statistic less than 0.05 (DW = 1.59665, $P = 0.0031$), then indicating a possible serial autocorrelation at the 95% confidence level in the SDY series. Figure 4b shows two statistically significant autocorrelation coefficients ($P < 0.05$) at 1 and 15 years lag. While lag-1 autocorrelation measures short-term persistence, the 15-year lag mirrors the 5- to 6-

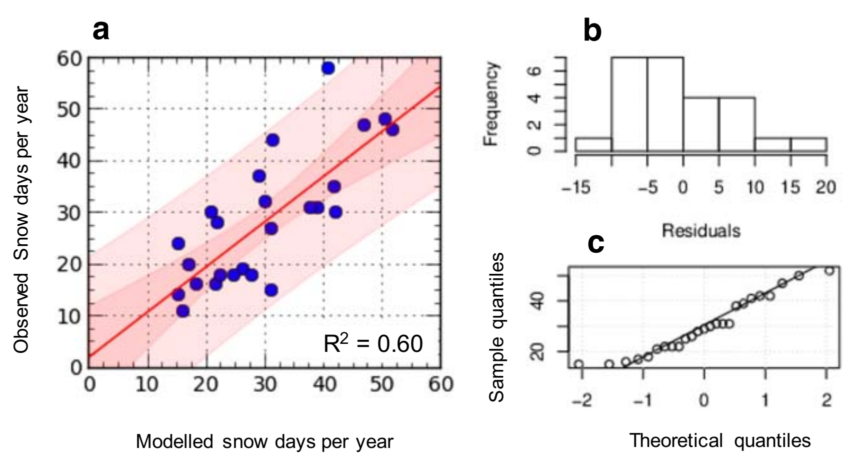

Fig. 3 Scatterplot of observed and modelled snow days per year at validation stage for a random sub-set of 25 years, with the inner bounds showing 95% confidence limits (pink coloured band), and the outer bounds showing 90% prediction limits for new observations (light pink coloured area) (**a**), histogram of residuals (**b**) and Q-Q plot (theoretical versus sample quantile values) (**c**)

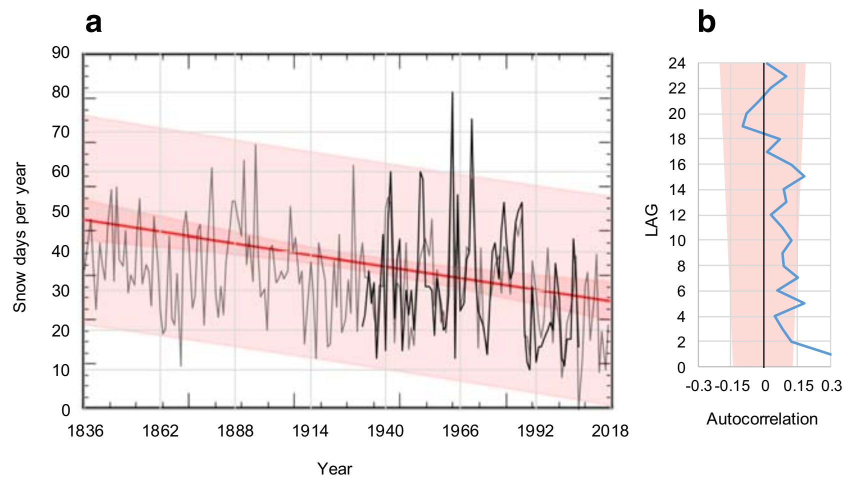

Fig. 4 Temporal evolution of snow days per year in the Swiss pre-alpine region during the period 1836–2017 (in grey reconstructed values, in black the observed ones for the period 1931–2006), with drawn the long-term trend (red line) and related confidence intervals at 90 (large band) and 95% (small band) (**a**). Autocorrelation diagram with 95% confidence limits (pink band) (**b**)

year shift in the bidecadal variability mechanism described by Escudier et al. (2013) that is the lag between the Atlantic Multidecadal Overturning Circulation (AMOC) variability and North Atlantic seas-surface temperature (SST) changes as modulated by volcanic eruptions (Swingedouw et al. 2015).

Positive NAO values force the enhancement of AMOC, and an enhanced AMOC affects ocean heat transport, inducing a SST pattern with a forcing effect delayed by ~ 15 years, possibly due to the inertia associated with slow oceanic processes (Sun et al. 2015). Here, we speculate on the oceanic mechanisms that could reveal the reasons behind the significant 15-year lag autocorrelation because snowfall changes in the Alps tend to reflect Atlantic multidecadal phase shifts (Zampieri et al. 2013).

Influence of atmospheric circulation patterns of snow periods

In order to discover if the three periods identified above are somewhat the result of changes occurred in the continental atmospheric circulation, we grouped the snowiest years according to composite plots of winter geopotential heights. The occurrence of snow events in SPAR is to some extent related to the presence of a low-pressure system over the central Mediterranean area (CMA). At 500-hPa level, a trough, moving from eastern Italy and the Adriatic Sea towards north-eastern Balkans, pushes air masses from central and northern Europe towards Italy, leading to a strong cold advection over the CMA. Empirical orthogonal function (EOF) analysis (Obled and Creutin 1986) was performed on the 500-hPa geopotential height winter (December–January–February) anomalies for three climatic periods. The resulting first two EOFs explain a considerable fraction of the variance (~ 70%). For the first period, 1836–1868, the second function (EOF 2) shows that a strong disturbance in the mid-troposphere is moving from northern Europe to the Balkans, transferring very cold air masses (Fig. 5(a)). Across this period, the prevailing atmospheric circulation favoured a frequent transfer of very cold air masses in the lower troposphere from north-eastern Europe. This situation, named Atlantic blocking, is at the origin of the snow events occurred across SPAR over many days. In the EOF 2 plot of the period 1869–1943 (Fig. 5(b)), a similar deep 500-hPa low stretches from north-east to west with its centre placed over the Balkans, which are invested with continental cold air masses from Russia. Also in this case, conditions are favourable for several snow days over SPAR, although Schwander et al. (2017) observed a decreasing number of cyclonic days after 1870.

In the third period, 1944–2017 (Fig. 5(c)), a cyclonic synoptic system moved on western Mediterranean with high 500-geopotential over northern Europe, thus the flow of cold air from Russian mainland, preventing from prolonged snow events of certain importance, as compared to the period 1836–1868. The differences among the above three composite plots refer to the exact locations, the strength and the trajectories of the synoptic disturbances, and the related cold air masses in the mid troposphere. In turn, it determines the persistence of snow days in the SPAR.

Summary and conclusions

Despite its centrality in ecological and environmental studies, snow is so far a rather unexplored field in climate change studies, for the difficulty in finding sufficiently long instrumental and homogeneous data series. In many regions of the planet, it is not always possible to incorporate snow days into hydrological and ecological dynamic analyses, and in modelling works, owing to the discontinuity of available time series. To reach this objective, it becomes necessary to develop procedures for extrapolating SDY for long time series. The NLMRM approach presented in this paper blends desirable attributes from observations and regional reanalysis to reconstruct data gaps from the end of the LIA in the Swiss pre-

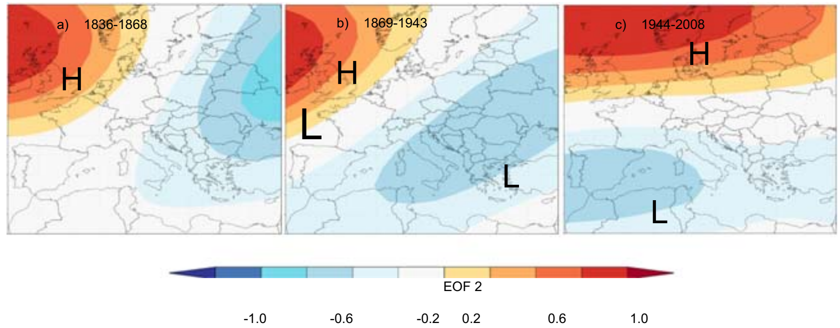

Fig. 5 European monthly 500-hPa geopotential height winter (December–January–February) anomalies during three periods: 1836–1868 (a), 1869–1943 (b) and 1944–2008 (c) (arranged via Climate Explorer, https://climexp.knmi.nl, on data from Luterbacher et al. 2002)

alpine region. The efficiency values obtained (0.7 in the calibration stage and 0.6 in the validation stage) indicate limited model uncertainty (likely associated with narrow parameter uncertainty) because Nash-Sutcliffe efficiency values of 0.6 can discriminate between unsatisfactory and satisfactory performances (e.g. Lim et al. 2006). The model developed for the SPAR is not easily transferable for applications in other alpine areas. In fact, geographical locations have characteristics that require specific model structures and local optimisation. The application of the model to other alpine areas may thus be limited by the ability to provide representative drivers and parameter values. The limitations and the relative uncertainties of our model are those linked to the absence of a physical process that explains the interannual variability of snow days. This uncertainty is mainly dependent on the empirical nature of our model, which could be improved by including features related to the dependence of temperature and precipitation patterns on elevation (e.g. Terzago et al. 2017). In spite of these limitations, this is a distinct improvement over previously published quantitative approaches. In particular, it allowed to identify three periods of significant snow days, which are strictly linked to the changes occurred in the continental atmospheric circulation: 36.5 ± 9.9 days year^{-1} (1836–1868), 35.6 ± 12.3 days year^{-1} (1869–1943) and 29.9 ± 12.5 days year^{-1} (1944–2017). A sharp drop is clearly evident in the most recent period, according to composite plots of winter geopotential heights and the presence of a cyclonic synoptic system centred over Eastern Europe. In a century-long perspective, the increase in temperatures values (and related changes from solid to liquid precipitation) and the impact of large-scale atmospheric patterns emerge as important drivers of the SDY decrease that we have observed in the long-term series reconstructed in this study. In the last decades, snow lines have been moving to higher altitudes, and snow seasons have become progressively shorter, causing accelerated snow and ice melt, and permafrost degradation (Colombo et al. 2018). This affects the seasonality of water availability, with consequences for water storage and management in reservoirs for drinking water, irrigation, tourism and hydropower production. Improvements in numerical modelling and a better understanding of the processes linking variations in snow cover and regional weather patterns are the important fields that, in our view, future climate research should focus on. The contribution of our paper goes in this direction, while seeking to improve the conceptual method of investigation and predict future changes with more confidence.

References

Arheimer B, Donnelly C, Lindström G (2017) Regulation of snow-fed rivers affects flow regimes more than climate change. Nat Commun 8:62. https://doi.org/10.1038/s41467-017-00092-8

Barnett TP, Adam JC, Lettenmaier DP (2005) Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438:303–309. https://doi.org/10.1038/nature04141

Baronetti A, Fratianni S, Acquaotta F, Fortin G (2019) Quality control approach to better characterise the spatial distribution of snow depth over New Brunswick, Canada. Int J Climatol (in press). https://doi.org/10.1002/joc.6166

Bednorz E (2002) Snow cover in western Poland and macro-scale circulation conditions. Int J Climatol 22:533–541. https://doi.org/10.1002/joc.752

Beniston M (1997) Variations of snow depth and duration in the Swiss Alps over the last 50 years: links to changes in large-scale climatic forcings. Clim Chang 36:281–300. https://doi.org/10.1023/A:1005310214361

Beniston M (2012) Is snow in the Alps receding or disappearing? Wiley Interdiscip Rev Clim Chang 3:349–358. https://doi.org/10.1002/wcc.179

Beniston M, Goyette S (2007) Changes in variability and persistence of climate in Switzerland; exploring 20th century observations and 21st century simulations. Glob Planet Chang 57:1–20. https://doi.org/10.1016/j.gloplacha.2006.11.004

Beniston M, Keller F, Koffi B, Goyette S (2003) Estimates of snow accumulation and volume in the Swiss Alps under changing climatic conditions. Theor Appl Climatol 76:125–140. https://doi.org/10.1007/s00704-003-0016-5

Bormann KJ, Brown RD, Derksen C, Painter TH (2018) Estimating snow-cover trends from space. Nat Clim Chang 8:924–928. https://doi.org/10.1038/s41558-018-0318-3

Brown RD, Mote PW (2009) The response of Northern Hemisphere snow cover to a changing climate. J Clim 22:2124–2145. https://doi.org/10.1175/2008JCLI2665.1

Clark MP, Serreze MC, Robinson DA (1999) Atmospheric controls on Eurasian snow extent. Int J Climatol 19:27–40. https://doi.org/10.1002/(SICI)1097-0088(199901)19:1<27::AID-JOC346>3.0.CO;2-N

Colombo N, Gruber S, Martin M, Malandrino M, Magnani A, Godone D, Freppaz M, Fratianni S, Salerno F (2018) Rainfall as primary driver of discharge and solute export from rock glaciers: the Col d'Olen Rock Glacier in the NW Italian Alps. Sci Total Environ 639:316–330. https://doi.org/10.1016/j.scitotenv.2018.05.098

Dafis S, Lolis CJ, Houssos EE, Bartzokas A (2016) The atmospheric circulation characteristics favouring snowfall in an area with complex relief in northwestern Greece. Int J Climatol 36:3561–3577. https://doi.org/10.1002/joc.4576

De Walle D, Rango A (2008) Principles of snow hydrology. Cambridge University Press, Cambridge

Delaygue G, Bard E (2011) An Antarctic view of Beryllium-10 and solar activity for the past millennium. Clim Dyn 36:2201–2218. https://doi.org/10.1007/s00382-010-0795-1

Diodato N, Bellocchi G (2020) Climate control on snowfall days in peninsular Italy. Theor Appl Climatol. https://doi.org/10.1007/s00704-020-03136-0

Diodato N, Büntgen U, Bellocchi G (2018) Mediterranean winter snowfall variability over the past millennium. Int J Climatol 39:384–394. https://doi.org/10.1002/joc.5814

Dong C (2018) Remote sensing, hydrological modeling and in situ observations in snow cover research: a review. J Hydrol 561:573–583. https://doi.org/10.1016/j.jhydrol.2018.04.027

Durand Y, Giraud G, Laternser M, Etchevers P, Mérindol L, Lesaffre B (2009) Reanalysis of 47 years of climate in the French Alps (1958–2005): climatology and trends for snow cover. J Appl Meteorol Climatol 48:2487–2512. https://doi.org/10.1175/2009JAMC1810.1

Durbin J, Watson GS (1971) Testing for serial correlation in least squares regression. III. Biometrika 58:1–19. https://doi.org/10.2307/2334313

Escudier R, Mignot J, Swingedouw D (2013) A 20-year coupled ocean-sea ice-atmosphere variability mode in the North Atlantic in an AOGCM. Clim Dyn 40:619–636. https://doi.org/10.1007/s00382-012-1402-4

Estilow TW, Young AH, Robinson DA (2015) A long-term Northern Hemisphere snow cover extent data record for climate studies and monitoring. Earth Syst Sci Data 7:137–142. https://doi.org/10.5194/essd-7-137-2015

Frei P, Kotlarski S, Liniger MA, Schär C (2018) Future snowfall in the Alps: projections based on the EURO-CORDEX regional climate models. Cryosphere 12:1–24. https://doi.org/10.5194/tc-12-1-2018

Grove JM (2004) Little ice ages: ancient and modern, vol 1. Routledge, London

Haeberli W, Beniston M (1998) Climate change and its impacts on glaciers and permafrost in the Alps. Ambio 27:258–265

Hu Z, Andreas D, Kuenzer C (2018) Snow cover dynamics in the European Alps derived from medium resolution earth Observation imagery. VAO-Symposium, 13-15 March 2018, Grenoble

Irannezhad M, Ronkanen AK, Kiani S, Chen D, Kløve B (2017) Long-term variability and trends in annual snowfall/total precipitation ratio in Finland and the role of atmospheric circulation patterns. Cold Reg Sci Technol 143:23–31. https://doi.org/10.1016/j.coldregions.2017.08.008

Jarque C, Bera A (1980) Efficient tests for normality, heteroskedasticity, and serial independence of regression residuals. Econ Lett 6:255–259. https://doi.org/10.1016/0165-1765(80)90024-5

Joly D, Castel T, Pohl B, Richard Y (2018) Influence of spatial information resolution on the relation between elevation and temperature. Int J Climatol 38:5677–5688. https://doi.org/10.1002/joc.5771

Klein G, Vitasse Y, Rixen C, Marty C, Rebetez M (2016) Shorter snow cover duration since 1970 in the Swiss Alps due to earlier snowmelt more than to later snow onset. Clim Chang 139:637–649. https://doi.org/10.1007/s10584-016-1806-y

Kunkel KE, Robinson DA, Champion S, Yin X, Estilow T, Franksonet RM (2016) Trends and extremes in Northern Hemisphere snow characteristics. Curr Clim Change Rep 2:65–73. https://doi.org/10.1007/s40641-016-0036-8

Lane E, Kruuk LEB, Charmantier A, Murie JO, Dobson FS (2012) Delayed phenology and reduced fitness associated with climate change in a wild hibernator. Nature 489:554–557. https://doi.org/10.1038/nature11335

Laternser M, Schneebeli M (2003) Long-term snow climate trends of the Swiss Alps (1931- 99). Int J Climatol 23:733–750. https://doi.org/10.1002/joc.912

Lawrimore JH, Menne MJ, Gleason BE, Williams CN, Wuertz DB, Vose RS, Rennie J (2011) An overview of the Global Historical Climatology Network monthly mean temperature data set, version 3. J Geophys Res 116:D19121. https://doi.org/10.1029/2011JD016187

Legates DR, McCabe GJ Jr (2005) A re-evaluation of the average annual global water balance. Phys Geogr 26:467–479. https://doi.org/10.2747/0272-3646.26.6.467

Lim KJ, Engel BA, Zang T, Muthukrishnan S, Choi J, Kim K (2006) Effects of calibration on L-THIA GIS runoff and pollutant estimation. J Environ Manag 78:35–43. https://doi.org/10.1016/j.jenvman.2005.03.014

Luterbacher J, Xoplaki E, Dietrich D, Rickli R, Jacobeit J, Beck C, Gyalistras D, Schmutz C, Wanner H (2002) Reconstruction of sea level pressure fields over the eastern North Atlantic and Europe back to 1500. Clim Dyn 18:545–561. https://doi.org/10.1007/s00382-001-0196-6

Luterbacher J, Dietrich D, Xoplaki E, Grosjean M, Heinz Wanner H (2004) European seasonal and annual temperature variability, trends, and extremes since 1500. Science 303:1499–1503. https://doi.org/10.1126/science.1093877

Marty C (2008) Regime shift of snow days in Switzerland. Geophys Res Lett 35:L12501. https://doi.org/10.1029/2008GL033998

Marty C, Blanchet J (2012) Long-term changes in annual maximum snow depth and snowfall in Switzerland based on extreme value statistics. Clim Chang 111:705–721. https://doi.org/10.1007/s10584-011-0159-9

Marty C, Tilg A-M, Jonas T (2017) Recent evidence of large-scale receding snow water equivalents in the European Alps. 18:1021–1031. https://doi.org/10.1175/JHM-D-16-0188.1

Mudryk LR, Kushner PJ, Derksen C, Thackeray C (2017) Snow cover response to temperature in observational and climate model ensembles. Geophys Res Lett 44:919–926. https://doi.org/10.1002/2016GL071789

Nash JE, Sutcliffe JV (1970) River flow forecasting through conceptual models part I - a discussion of principles. J Hydrol 10:282–290. https://doi.org/10.1007/s00704-012-0775-y

Niedźwiedź T, Twardosz R, Walanus A (2009) Long-term variability of precipitation series in east Central Europe in relation to circulation patterns. Theor Appl Climatol 98:337–350. https://doi.org/10.1007/s00704-009-0122-0

Nikolova N, Faško P, Lapin M, Švec M (2013) Changes in snowfall/precipitation-day ratio in Slovakia and their linkages with air temperature and precipitation. Contrib Geophys Geod 43:141–155. https://doi.org/10.2478/congeo-2013-0009

Obled C, Creutin JD (1986) Some developments in the use of empirical orthogonal functions for mapping meteorological fields. J Appl Meteorol 25:1189–1204. https://doi.org/10.1175/1520-0450(1986)025<1189:SDITUO>2.0.CO;2

Pauling A, Luterbacher J, Casty C, Wanner H (2006) Five hundred years of gridded high-resolution precipitation reconstructions over Europe and the connection to large-scale circulation. Clim Dyn 26:387–405. https://doi.org/10.1007/s00382-005-0090-8

Pfister C (1978) Climate and economy in eighteenth-century Switzerland. J Interdiscip Hist 9:223–243. https://doi.org/10.2307/203226

Polhemus NW (2017) Process capability analysis: estimating quality. Chapman and Hall/CRC, London

Rasmussen RM, Baker B, Kochendorfer J, Meyers T, Landolt S, Fischer AP, Black J, Theriault JM, Kucera P, Gochis D, Smith C, Nitu R, Hall M, Ikeda K, Gutmann E (2012) How well are we measuring snow: the NOAA/FAA/NCAR winter precipitation test bed. Bull Am Meteorol Soc 93:811–829. https://doi.org/10.1175/BAMS-D-11-00052.1

Rebetez M (1996) Seasonal relationship between temperature, precipitation and snow cover in a mountainous region. Theor Appl Climatol 54:99–106. https://doi.org/10.1007/BF00865152

Reichler C (2002) La découverte des Alpes et la question du paysage. Georg, Collection « Le Voyage dans les Alpes », Genève. (in French)

Royston P, Sauerbrei W (2008) Multivariate model-building. Wiley, Chichester

Scherrer SC, Appenzeller C (2006) Swiss Alpine snow pack variability: major patterns and links to local climate and large-scale flow. Clim Res 32:187–199. https://doi.org/10.3354/cr032187

Scherrer SC, Appenzeller C, Laternser M (2004) Trends in Swiss Alpine snow days: the role of local- and large-scale climate variability. Geophys Res Lett 31:L13215. https://doi.org/10.1029/2004GL020255

Scherrer SC, Wüthrich C, Croci-Maspoli M, Weingartner R, Appenzeller C (2013) Snow variability in the Swiss Alps 1864-2009. Int J Climatol 33:3162–3173. https://doi.org/10.1002/joc.3653

Schwander M, Brönnimann S, Delaygue G, Rohrer M, Auchmann R, Brugnara Y (2017) Reconstruction of central European daily weather types back to 1763. Int J Climatol 37:30–44. https://doi.org/10.1002/joc.4974

Serquet G, Marty C, Rebetez M (2013) Monthly trends and the corresponding altitudinal shift in the snowfall/precipitation day ratio. Theor Appl Climatol 114:437–444. https://doi.org/10.1007/s00704-013-0847-7

Sigl M, Winstrup M, McConnell JR, Welten KC, Plunkett G, Ludlow F, Büntgen U, Caffee M, Chellman N, Dahl-Jensen D, Fischer H, Kipfstuhl S, Kostick C, Maselli OJ, Mekhaldi F, Mulvaney R, Muscheler R, Pasteris DR, Pilcher JR, Salzer M, Schüpbach S, Steffensen JP, Vinther BM, Woodruff TE (2015) Timing and climate forcing of volcanic eruptions for the past 2,500 years. Nature 523, 543–549. https://doi.org/10.1038/nature14565

Steinhilber F, Beer J, Fröhlich C (2009) Total solar irradiance during the Holocene. Geophys Res Lett 36:L19704. https://doi.org/10.1029/2009GL040142

Sun C, Li J, Jin F-F (2015) A delayed oscillator model for the quasi-periodic multidecadal variability of the NAO. Clim Dyn 45:2083–2099. https://doi.org/10.1007/s00382-014-2459-z

Swingedouw D, Ortega P, Mignot J, Guilyardi E, Masson-Delmotte V, Butler PG, Khodri M, Séférian R (2015) Bidecadal North Atlantic Ocean circulation variability controlled by timing of volcanic eruptions. Nat Commun 6:6545. https://doi.org/10.1038/ncomms7545

Techel F, Zweifel B, Winkler K (2015) Analysis of avalanche risk factors in backcountry terrain based on usage frequency and accident data in Switzerland. Nat Hazards Earth Syst Sci 15:1985–1997. https://doi.org/10.5194/nhess-15-1985-2015

Terzago S, Cremonin R, Cassardo C, Fratianni S (2012) Analysis of snow precipitation during the period 2000-09 and evaluation of a MSG/SEVIRI snow cover algorithm in SW Italian Alps. Supplementi di Geografia Fisica e Dinamica Quaternaria 35:91–99. https://doi.org/10.4461/GFDQ.2012.35.9

Terzago S, Fratianni S, Cremonini R (2013) Winter precipitation in Western Italian Alps (1926–2010): trends and connections with the North Atlantic/Arctic oscillation. Meteorog Atmos Phys 119:125–136. https://doi.org/10.1007/s00703-012-0231-7

Terzago S, von Hardenberg J, Palazzi E, Provenzale A (2017) Snow water equivalent in the Alps as seen by gridded data sets, CMIP5 and CORDEX climate models. Cryosphere 11:1625–1645. https://doi.org/10.5194/tc-11-1625-2017

Wang Y, Yang J, Chen Y, Wang A, De Maeyer P (2018) The spatiotemporal response of soil moisture to precipitation and temperature changes in an arid region, China. Remote Sens 10:468. https://doi.org/10.3390/rs10030468

Wessa P (2017) Linear regression graphical model validation. Free Statistics Software (v1.2.1), Office for Research Development and Education. https://www.wessa.net/rwasp_linear_regression.wasp

Wu W-Y, Lan C-W, Lo M-H, Reager JT, Famiglietti JS (2015) Increases in the annual range of soil water storage at northern middle and high latitudes under global warming. Geophys Res Lett 42:3903–3910. https://doi.org/10.1002/2015GL064110

Ye H, Fetzer EJ, Wong S, Lambrigtsen BH (2017) Rapid decadal convective precipitation increase over Eurasia during the last three decades of the 20th century. Sci Adv 3:1–7. https://doi.org/10.1126/sciadv.1600944

Zampieri M, Scoccimarro E, Gualdi S (2013) Atlantic influence on spring snowfall over the Alps in the past 150 years. Environ Res Lett 8:034026. https://doi.org/10.1088/1748-9326/8/3/034026

Zasadni J (2007) The Little Ice Age in the Alps: its record in glacial deposits and rock glacier formation. Studia Geomorphologica Carpatho-Balcanica 41:117–137