Spatiotemporal patterns of snow depth within the Swiss-Austrian Alps for the past half century (1961 to 2012) and linkages to climate change

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Our current knowledge on multi-decadal to centennial changes of snow in different parts of the world is based largely on observations of snow depth and depth of snowfall from national weather and hydrographic services. Studies analysing these snow observations in the European Alps are predominantly based on national data and are therefore limited by their respective borders in the detection of robust, spatiotemporal snow trends. In order to overcome this limitation, data from Austria and Switzerland, which cover a substantial fraction of the Alps when taken together, are merged for this study (196 station-records). Additionally, it is the first time that such an analysis is based on homogenized data. Our homogenization study shows that, although the detection of breaks in snow depth series works quite well with the existing methods, further research is needed to adequately correct snow depth series at a daily resolution. Roughly, 70% (139 station-records) of the snow depth series could be homogenized and are used for further trend analysis.

The findings concern seven climatologically different areas that are identified by a regionalization (using empirical orthogonal functions) using station records from 1961 to 2012. These regions share a high degree of inner similarity and outer separation, and the temporal trends detected are rather different across the Swiss-Austrian domain. Regions in the south show a clear decrease in the snow depth of up to −12 cm/decade on average, while those in the northeast are characterized by almost no change. The declining trend in the southern regions intensifies as altitude increases. Comparisons of these variations in depth changes with concurrent changes in air temperature and precipitation totals reveal a clear dichotomy with respect to elevation. Snow depths in low elevated areas are highly sensitive to air temperature changes, whereas those at high elevations strongly depend on alterations in precipitation totals.

**KEYWORDS**
Alps, climate change, decadal variability, homogenization, mountain, observational data analysis, snow, statistical methods

### 1 | INTRODUCTION

This study investigates the evolution of snow depth observations in Switzerland and Austria over the past half century to allow for a spatially differentiated picture of what has happened in a substantial part of the European Alps in response to the climate change that has already occurred. In order to increase the robustness of derived changes and trends from
1961 to 2012, we test the snow depth data from the Swiss-Austrian domain for homogeneity and homogenize them at detected breaks.

During the last 30 years, the Alpine region experienced several winters with snow scarcity due to warm and dry atmospheric conditions as well as snow abundant winters. Whereas winters with snow scarcity immediately trigger widespread discussions on problems for winter tourism, which is of substantial importance for Alpine tourism (e.g., Koenig and Abegg, 1997), snow abundant winters are often accompanied by hazards such as, for instance, avalanches, floods in spring or dangerously high snow loads on infrastructure. As for winter tourism, Abegg et al. (2006) showed that many alpine ski resorts require at least 100 days (per season) with snow depths exceeding 30 cm to run cost-effective.

However, snow is not only economically important but also a key factor for the alpine environment. Apart from having a significant influence on regional ecology, snow is a vital natural water storage for both mountainous and lowland regions (Barnett et al., 2005). Runoff, for instance, is delayed when precipitation falls as snow. Alpine river discharges in spring are dominated by the availability of snowpack and snowmelt. Changes in these factors are known to result in a clear shift in the timing and magnitude of maximum spring flow rates. The absence or presence of a snow cover is also an important factor in the vegetation cycle, and changes in the snow cover can result in shifts in the distribution of plant species (Keller et al., 2005).

Considering the relevance of snow, it is surprising that in the past its measurement has not been attributed much importance by the national weather services. In Austria, for example, long-term series of snow observations come almost exclusively from the hydrographic service. In Switzerland, the longest snow time series come from the national weather service, however, they were only recently digitized and analysed (Scherrer et al., 2013). To secure long-term snow series and to establish a reliable snow monitoring network, Wüthrich et al. (2010) objectively defined climatological snow regions for Switzerland. One key finding of this study is related to the detection of regions with homogeneous snow depth records. On this basis, a network of notably important series (and, hence, sites) for monitoring snow, which is an essential climate variable as designated by the Global Climate Observing System (WMO, 2016), may be selected. At least two types of snow measurements are standard practice in the meteorological and hydrographical networks of both countries: the depth of snowfall over the last 24 hours (measured at 7.00 a.m.) and total snow depth of the snow pack (also measured at 7.00 a.m.). Here we use the terms “snow depth” (HS, also height of snowpack) and “depth of snowfall” (HN, also termed as height of new snow) according to their definitions given by the International Association of Cryospheric Sciences (Fierz et al., 2009). HS and HN are the only measures available for studying snow climatology on the multi-decadal to centennial time scale.

Many recent studies on Alpine snow changes have been done for Switzerland alone (e.g., Beniston, 1997; Beniston et al., 2003; lateimers and Schneebeli, 2003; Scherrer et al., 2004; Marty, 2008; Serquet et al., 2011), and there are a far fewer studies for other Alpine countries, although the economical relevance of snow is similar in Austria, for example. Laterms and Schneebeli (2003) provided a first comprehensive analysis of snow climatology based on snow depth and depth of snowfall observations. Later, Marty (2008) demonstrated that snow depth does not decrease linearly with time, but in a rather step-like manner with only small changes since the end of the 1980s.

Studies on the spatiotemporal changes of snow in Austria with respect to climate change are rather sparse or date back many years in time. Fliri (1992a, 1992b), Schöner et al. (2003) and Auer et al. (2008) are more recent studies, with the latter two focusing mainly on data preparation and data quality control based on observations going back as far as World War 2. Unfortunately, most daily climate data in the archives of the Austrian national weather service (Zentralanstalt für Meteorologie und Geodynamik, ZAMG) from before 1945 were lost due to the events of World War 2. This limits the evaluation of centennial trends to data series provided by the Austrian Hydrographic Service, which generally start in 1896. Some studies have focused on the relationship between the number of snow days and air temperature in Austria. They identified the region of highest sensitivity of snow cover days with respect to European air temperature as the elevation range between 500 and 1,500 m.a.s.l. depending on season (Hantel et al., 2000; Hantel et al., 2012). The median snow line (which is by definition the line of highest sensitivity to temperature change) moves upwards by 123 m if temperature increases by 1 K (Hantel et al., 2012). Schöner et al. (2008) used the network of snow depth measurements at Sonnblick (Austrian Central Alps, 3,105 m.a.s.l.), which has data extending back to 1928, to show that stake measurements have been spatially representative to an unexpected extent as well as to demonstrate that snow depths increased during spring but decreased in autumn. Exceptionally, high values of snow depth amounting to about 12 m (i.e., approximately three times the long-term average in May at Sonnblick) were observed in May 1944 and May 1951.

Air temperature and precipitation are primary drivers for changes in snow depth over space and time. Relationships between these climate variables and snow depth or snow water equivalent have been shown in many studies (e.g., Mankin and Diffenbaugh, 2014) and are used for simple snow cover models. A few papers also studied the elevation dependency of the snow depth-air temperature and snow depth-precipitation relationships, respectively. Obviously, there is a clear elevation dependency in the relationship between air temperature and snow day changes (e.g., Scherrer
and Appenzeller, 2006; Morán-Tejeda et al., 2013; Sospedra-Alfonso et al., 2015), between air temperature and snow water equivalent changes (e.g., Sospedra-Alfonso et al., 2015) and between air temperature and snow depth changes (e.g., Morán-Tejeda et al., 2013). On the other hand, the elevation dependency in the relationship between precipitation and snow cover changes is not as clear from different studies (capturing different geographical regions and different snow parameters). However, Morán-Tejeda et al. (2013) showed clear asynchronous behaviour with respect to the elevation dependency of the correlation between snow depth and air temperature (decreasing with altitude) and snow depth and precipitation (increasing with altitude) for the Swiss Alps. They identified a threshold elevation of approximately 1,400 m a.s.l., below and above which the main explanatory variables are temperature and precipitation, respectively.

With respect to underlying atmospheric patterns of snow changes, Scherrer et al. (2004) found that the North Atlantic Oscillation (NAO) does not explain the inter-annual variability of snow days for the northern region of the Swiss Alps but explains a substantial part of inter-annual snow variability for the southern region of the Swiss Alps. For decadal trends, however, the NAO can significantly explain the variability of days with snow cover through its linkage to air temperature for the northern region of the Swiss Alps, and through precipitation and air temperature linkages for the southern region of the Swiss Alps. It is also known that the NAO is related to atmospheric blocking, with negative correlation for Atlantic blocking and positive correlation for blocking over Central and Western Europe (Scherrer and Appenzeller, 2006). Pinto et al. (2007) were also able to show that the extraordinary snow accumulation in parts of central Europe in the winter of 2005/06 was a result of a high frequency of blocking west of Central Europe, which caused below average temperatures and therefore more precipitation as snow and reduced melting of snow cover.

As snow is a specific form of precipitation, snow changes should be related to precipitation changes. However, air temperature is the most important parameter determining the transition from rain to snow, and from freezing to melting on the ground. Other atmospheric conditions like humidity or radiation (Steinacker, 1983; Kuhn, 1987) and surface conditions like evaporation, snow settling or wind erosion alter snow fall and snow depth. These driving forces motivate our hypothesis that spatial patterns of snow (both snowfall and snow on the ground) could be rather spatially and temporally inhomogeneous, even on the climate time scale and not only for a single snowfall event. Consequently, there are very good reasons to study spatiotemporal changes of snow at the scale of subregions of the Alps and put them into the larger context of aggregated regions such as the Swiss-Austrian Alps or the entire Alpine region.

Based on our hypothesis, we present a regionalization of snow depth measurements for the Swiss-Austrian domain. Our analyses are based on homogenized records in order to delineate the climate signal from non-climatic noise. Snow depth trends are calculated for each region using an approach for separating large scale from local-scale variability. In a further step, we show the elevation dependency of the temporal trends of snow depth and their linkages to respective temperature and precipitation changes. This shall help to facilitate a deepened understanding of meteorological processes shaping snow depth distributions in the European Alps.

2 | DATA

Snow depth data used in this study are mean values over the cold half years from November 1 until April 30 in the following year starting in 1961 and ending in 2012. This seasonal mean which covers the major part of the snow period in the Alps, has a strong impact on the water cycle and coincides with many economical activities (e.g., winter tourism starting in November and ending in April in the Alps).

For Switzerland, the data are taken from the networks of the WSL Institute of Snow and Avalanche Research (SLF) and the Federal Office of Meteorology and Climatology (MeteoSwiss), which include 96 stations. The different public mandates of the two institutions are clearly reflected in the spatial distribution of their stations, with SLF having a focus at higher elevation sites. In Austria, snow data are collected by the Zentralanstalt für Meteorologie und Geodynamik (ZAMG) and the Austrian National Hydrographic Service (Hydrographisches Zentralbüro, HZB) with a total of 100 stations. Altogether 196 records are available, but they seldom cover the entire period and are not uniformly distributed over Austria and Switzerland.

Snow depth measurements, which are generally scheduled at 7 a.m., determine the snow depth including sleet and ice on the ground. The records reflect the situation within a representative area around the observing site. Any particular snow depth measurement records the net accumulation, since the preceding observation, for example, the depth of fresh snow, gain or losses by snowdrift and losses by evaporation, melting or settling.

Measurements at the beginning and at the end of the season are particularly prone to errors. For brevity, further details are omitted here but may be found in for example, Gutmann (1948) or Klinger (1986) for Austria, and Schweizerische Meteorologische Anstalt (1932), Thüring-Jenzer and Graf (2012) for Switzerland. It should, however, be kept in mind that the observation of snow depth relies largely on good judgement, on visual averages, on rules of thumb and that records depend strongly on orographic features of observing sites. Time series of snow depth comprising high quality require substantial expertise and care.

Snow depth measurements are prone to inhomogeneities due to random wind occurrences typical of complex terrain (Sevruk, 1985), but many additional uncertainties come from
station relocations, changes in observational guidelines, observer changes etc., referred to as inhomogeneities in climate time series as described by a series of papers (e.g., Auer et al., 2007). Altogether quite a number of obstacles make data selection and quality assessment a decisive work package in any investigation that involves time-series analysis.

Figure 1 shows the recording sites that passed the quality check and homogenization procedure (described in Section 3). Only about 68% of the Austrian and 74% of the Swiss sites originally available were retained as homogeneous in our study (see Table 1). Even before homogenization, the station has to pass several quality checks related to the comparison of 1 day’s snow depth with the previous day’s and with depth of snowfall. Therefore, stations entering the analysis here must not only comprise records that comply with targets set out by statistical analyses, but their histories must not contain significant relocations or any other decisive changes either. This rigorous procedure yielded a plenty of rejections of records containing potentially contaminated observations and only a small fraction of records are used in this study.

The corresponding tests on data quality focused not only on thorough applications of a variety of statistical tools and the evaluation of coherence measures established in quality assurance programmes, but also included visual assessments as well as comprehensive studies of associated metadata. Hence, tests for inner and outer data consistencies are accompanied by evaluations of appendant station histories.

### METHODS

#### 3.1 Homogenization

Although there is plenty of literature available on the topic of homogenization of air temperature and precipitation time series, there is very little available on snow series homogenization (Marcolini et al., 2017). Consequently, we applied the existing methods of time series homogenization developed for air temperature and precipitation for our snow series, thus achieving the aim of homogeneous snow series. Briefly, homogenization can be described as a two-step procedure: (a) multiple break detection and (b) correction of the inhomogeneous part of the series (e.g., Auer et al., 2007). We used the method PRODIGE (Caussinus and Mestre, 2004) for the detection of multiple breaks in the snow depth series and INTERP (Vincent et al., 2002) for the calculation of corrections at detected breaks. Both methods are implemented as part of the software package HOMOP (Nemec et al., 2013).

Generally, homogeneity tests for climate time series assess relative homogeneity by testing differences or ratios between the candidate series and a reference series (neighbouring stations). In our case, reference series were generated from linear combinations of several station series, aiming at higher common variance between the compared series. We only considered stations within a horizontal radius of 100 km and a maximum elevation range of 300 m as reference series. The average number of reference stations used for constructing the
reference series was about 12. However, not all of them were free of gaps over the comparison period, which is a common problem in time series homogenization. For the detection of breakpoints in the snow depth series, we compared seasonal series of snow depth (December to February (DJF) and November to March (NDJFM)) for both the candidate and the reference series. Test cases with break detection for the daily records were not successful because of a number of specifics immanent to snow depth series, in particular the zero snow depth during snow-free periods. Since spatial variations in the seasonal snow depth are expected to be dominated by a multiplicative model (such as for precipitation). Ratio time series that covered less than 5 years or had gaps of more than 1,000 consecutive days were rejected. In order to deal with the increasing likelihood of detection with increasing number of breakpoints (overfitting), the PRODIGE method is based on a penalized log-likelihood criterion (Mestre et al., 2011). We used the criteria of Caussinus and Lyazrhi (1997), Jong et al. (2003) and Lebarbier (2005) for the detection process.

Once breakpoints were identified, they were cross-checked with metadata information in the station protocols. Verified inhomogeneities were corrected by applying a modified version of the INTERP method (Vincent et al., 2002) on the daily snow depth series. Since snow depth measurements are characterized by high spatial and temporal variability resulting from different influences, that is, temperature, wind, radiation that cannot be accounted for by the correction factor, a simple approach was chosen, from which, however, reasonable improvement of the time series can be expected. The formula for the calculation of the seasonal adjustment is as follows:

\[
\text{Correction factor} = \frac{\text{median } \{ C / R \}}{\text{median } \{ C / R \}}
\]

where indices \( a \) and \( b \) mark the period after and before the detected break and \( C \) and \( R \) are the seasonal (NDJFM) snow depths of the candidate (\( C \)) and reference (\( R \)) time series. The same correction applies to the daily snow depth series with no further smoothing or interpolation. Thus, the final step of homogenization involves the multiplication of the inhomogeneous daily scale sub-period before the breakpoint by the respective seasonal correction factor. Due to the multiplicative approach, no additional snow days are added to the corrected time series. In contrast, correction factors smaller than 1 may remove days with observed snow depths from the candidate time series.

### 3.2 Empirical orthogonal function analysis

The goal of this study is to establish a detailed overview of trends in snow depths over the past half century across Switzerland and Austria. This requires the detection of homogeneous groups of stations with regard to snow depth variability. These groups of stations or regions share a large fraction of inner similarity and show, at the same time, substantial separation from other groups.

The approach used here, called empirical orthogonal function analysis (EOF, for example, von Storch and Zwiers, 1999), is a multivariate technique deriving dominant patterns of variability among time series. The technique has already been successfully applied to identify precipitation regions in Austria (Ehrendorfer, 1987; Matulla et al., 2003). In line with von Storch and Zwiers (1999), these patterns and pertaining time series will be hereafter referred to as “EOFs” and “time coefficients” (principal components [PCs]), respectively. The analysis is based on the abovementioned snow depth records (from which two stations had to be excluded) consisting of daily measurements within the winter season from 1st of November to 30th of April. Each time series is centred on its mean and divided by its standard deviation. The EOF analysis is performed by a “singular value decomposition” (see for example, von Storch and Zwiers, 1999), which is closely linked to the eigenvalue decomposition of the data covariance matrix (Bretherton et al., 1992; Wallace et al., 1992). Once all EOFs and time coefficients are on hand, it is essential to decide on how many of them to retain in order to (a) adequately reproduce the signal and (b) filter the noise. Among the various methods supporting this decision, “North’s rule of thumb” (North et al., 1982) and the so called “scree test” (e.g., Cattell, 1966) are most frequently used.

As we expect large common variance in the time domain of the snow series within an identified region, we also used EOF analysis to reduce the number of series for each snow region to describe the dominant time pattern(s). Consequently, if the explained variance of the leading EOF is high, its time coefficient can be used to describe a large fraction of the temporal evolution of snow depth within the region.

### 3.3 Trend analysis

For the detection of trends in the snow depth time series, we used the nonparametric Mann–Kendall (MK) trend test (Mann, 1945; Kendall, 1975; Lettenmaier et al., 1994). The MK trend test is rank-based, so that it can also be applied to time series with outliers. Under a given level of significance (e.g., \( p \)-value<0.05), it can be determined from the \( p \)-values (two-tailed test) of the MK statistics if for example, the null-hypothesis can be rejected and the alternative hypothesis (meaning there is a trend in the time series) can be accepted. Consequently, the higher the \( p \)-values, the higher the probability of there being no trend in the series. In order to account for potential lag-1 autocorrelation in the time series, we used the so-called Trend–Free–Prewhitening procedure of Yue et al. (2002) before testing for a trend. In our study, \( p \)-values <0.01 imply a significant trend in the series, 0.01 < \( p \) < 0.05 a tendency and \( p \) > 0.05 no significant trend.

A trend in a time series strongly depends on the chosen period or the values at the beginning and at the end of the
period. In order to account for any possible trend throughout the investigated time period, we use a running trend approach. For this purpose, the window-width for the trend is iteratively increased and moved along the time axis by 1 year. The central value of the time-window is shown on the x-axis and the window-width on the y-axis. Within the resulting triangle, the sign and significance of the trend are shown. The smallest window-width used is 10 years.

The strength of the trends is estimated by the Theil–Sen method (Sen, 1968), a robust nonparametric slope estimator for linear regression. For this method, all possible pairs of data (date, measurement) are ordered (from smallest to the largest), connected and all slopes of lines through pairs of points are computed. The median of all slopes is then the estimate of the strength of the trend (Sen slope).

4 | RESULTS AND DISCUSSION

4.1 | Homogenization

The results of the homogenization procedure of the snow depth series (196 in total) are summarized in Table 1. Roughly, 60% of the station series were per-se homogeneous, 10% of the inhomogeneous series could be homogenized and 30% had to be excluded from further analysis because of remaining inhomogeneities. For Switzerland, additional problems resulted from too few reference series for some of the stations. Figure 2 shows the impact of the homogenization for the example of station Galtür (1,577 m a.s.l., located in the western part of the Austrian Alps), which has a break in 1989 from station relocation. The calculated seasonal correction factor for the time series of Galtür for the 1989 break is 1.2, which was applied to the original series, as shown in Figure 2. Such corrections can clearly alter or even reverse computed trends in the time series.

Our experience with the homogenization of snow series is varied. On the one hand, information gathered from metadata and break detection for our data set of snow series showed that homogenization is clearly an important issue. On the other hand, the results from homogenization using existing methods mainly developed for air temperature and precipitation are not satisfying, in particular if it comes to homogenization of daily snow data. Days with only small snow amounts and probably also those with high amounts are artificially altered using the existing methods. Consequently, our study is based on mean winter snow depth data as they provide a more robust data base, which is less dependent on the exact homogenization of daily values (but still improved by the homogenization procedure). Further research is clearly needed to enhance homogenization methods for snow series.

4.2 | Homogeneous regions of snow depth for the Swiss-Austrian domain

The clear structuring of the study region with respect to precipitation (e.g., Auer et al., 2007) motivates our approach for identifying snow depth regions using the EOF method. The data matrix to be regionalized contains 138 standardized daily snow depth series (homogenized series only, zero mean and with variance one) covering cold half years from November to April 1961–2012 (one station series was excluded because of a shorter time series). The application of North’s rule of thumb identifies three EOFs to be kept. This finding goes along with the “scree profile” (see Supporting Information Figure S1), displaying breaks in the logarithm of the explained variances between the third and the fourth as well as the fifth and the sixth EOF. Taking into account the uncertainty encased in the logarithms of the explained variances and the absolute differences between the third and fourth as well as between the fifth and sixth values, the first break outweighs the second in size. Hence, only three EOFs and their time coefficients are retained for further analysis.

Common variance of snow depth series for the Swiss-Austrian domain is surprisingly high (Figure 3). The leading EOF explains 49% of the total variance and obviously separates different regions (interpolated fields of the EOFs must be interpreted with care because of the low station density). EOF1 appears to contrast Alpine region from the Pre-Alpine and lowland region(s), whereas EOF2 (13%) more directly describes snow depth variations as a function of elevation. Finally, EOF3 (6%) contains information of the clear north–south gradient over the domain investigated. To overcome high-frequency fluctuations on a small timescale, the PCs are seasonally November, December, January, February, March, April (NDJFMA) averaged and low-pass filtered using a Gaussian filter (Figure 3, right panel). The first three EOFs explain almost 70% of the total variance. With respect to the generally hypothesized high spatial variability of the snow on the ground, this value may appear surprisingly high for Alpine snow practitioners, which predominately work on small spatial scales. The high spatial correlation of snow depth identified here is useful for the future planning of station networks for snow observations in both countries with respect to climate change. However, it is important to mention that our results are valid for mean seasonal snow depth only and other snow measures may show different behaviour and regionalization. Interestingly, the EOF patterns as well as the explained variance of the first EOF remain rather similar after rotation of the EOFs (not shown here).

The PC 1 is characterized by a strong year to year variability describing the alteration between snow abundant and snow scarce winters. Furthermore, the low-frequency variations show lower snow depths at the beginning of the 1970s, followed by an increase around the 1980s and a strong decrease during the latter period. In contrast, the variations of PC2 and PC3 are less pronounced. Nevertheless, a weak increase within the reference period is
present, which implies that the altitudinal gradient of the snow variations as well as the characteristic of the north–south dipole varies through time. A closer look at PC2 and PC3 reveals a slight increase since the 1970s. In contrast, the temporal variation of PC1 is characterized by the prominent shift towards lower values at the end of the 1980s. A decrease of PC1 starting from the winter season of 1983 is also apparent.
In order to investigate the common variability of each snow depth series (station series) with each PC, Kendall’s tau[b] rank correlation coefficients (which account for outliers, Kendall, 1975) are calculated and shown as maps in Figure 4 to investigate spatial coherence of the station series. The correlation map for the PC1 and the snow depth series shows positive correlations over the entire domain, with correlations that are all significantly different from zero at the 95% confidence level. A stronger relationship can be observed in higher elevated regions of Switzerland and Austria, thereby distinguishing high elevation regions from low elevation regions. On the other hand, PC2 shows a positive relationship with time series of stations in lower elevated areas, and a strong negative relationship in mountainous regions, mainly north of the main Alpine ridge. There is only poor or no correlation in the south and to some extent in regions north of the main Alpine ridge. This indicates that the relationship between snow depth and elevation in southern regions is less significant. The correlation map associated with PC3 clearly highlights the pronounced north–south gradient. However, no correlation could be found in low elevation regions in the north of Switzerland and Austria.

In order to understand the potential sub-regional elevation dependency of snow depth in the Swiss-Austrian domain,
Kendall's tau correlation coefficients as a function of elevation are shown in Figure 4 for the first three PCs. The pattern for PC1 is characterized by a clear increase of correlation from low elevations to up to about 1,200 m a.s.l. followed by a decreasing correlation for elevations above. The decrease could result from the variable frequency of cold fronts reaching the Alpine main ridge. In winter seasons with less frontal precipitation spread over alpine foothill and flatland areas, mountainous regions may still receive solid precipitation from evolving local-scale convective systems due to orographic effects. The modification of the air flow over the complex terrain probably also yields high-frequency fluctuations of the precipitation pattern on a local scale. For PC2, the correlation coefficients show a clear picture of low-high contrast, with positive correlation values below 600 m a.s.l., negative values above 1,200 m a.s.l. and values close to zero in between. This pattern indicates orographic enhancement of precipitation, which is particularly relevant in winter in cases when cold fronts and associated air masses approach the Alps from the north (Wastl, 2008). Interestingly, the correlation between PC3 and snow depth data reveals a pronounced North–South gradient but no elevation dependency (Figure 4), which indicates that PC3 describes high snow amounts either in the north or in the south of the Alpine region. This spatial north–south structuring is also supported by the well-known inner-alpine dry regions described by, for example, Frei and Schär (1998). Clearly, our abovementioned interpretation is based on the hypothesis that snow precipitation is the dominant factor for spatial variability of snow depth, which is not entirely true as ablation may also play a significant role for snow depth within the study region. Our result for the first three PCs is very similar (in regard to the spatial pattern and in regard to the absolute amount of explained variance) to what was found by Scherrer and Appenzeller (2006) for Switzerland.

We used the correlation maps from Figure 4 to define homogeneous regions with similar inter-annual snow depth variability and thus assigned each snow station to a region. Generally speaking, one could expect that regions derived from EOF patterns should also display regions with homogeneous trend evolution, as both inter-annual variability and temporal trends should be related to prevailing weather patterns. However, as the EOF analysis removes the temporal trend from all series, the assignment and borders of the regions could also be different. To investigate this, we computed MK trends for snow depth over the period 1961–2012 for each station (Figure 5), also taking different seasonal averages into consideration. If the spatial patterns of the trends from Figure 5 are compared with the patterns of

![Figure 5](https://wileyonlinelibrary.com)
correlation of each station with the three PCs in Figure 4, it appears reasonable to come up with not only three regions for Switzerland and Austria respectively, but also a fourth region for Austria covering the transition area of clear west–east contrast from negative to no trends (called region AT4 below). Our final regionalization is shown in Figure 5. We also compared the snow depth regions identified here for Austria with previous studies with similar objectives. The sub-regions of snow depth climatology in Austria, derived by our semi-objective approach, agree well with the more subjective approach used by Spreitzhofer (2000), which in fact was adopted from the previous works of Schalko (1949) and Steinhauser (1970).

4.3 Regional snow depth trends

After assigning each snow station to a sub-region as described in Section 4.2, we performed a PC analysis (PCA) using station series from each respective region only. Figure 6 shows the time series of the leading PC for each of the seven regions identified. The first component explains between 58 and 77% of the sub-regional total variance. Qualitative comparison of the leading PCs reveals obvious different temporal evolution, indicating that the regions derived here exhibit different temporal behaviour and are probably affected by the prevailing weather patterns over the Alps in different manners. However, similarities in the time series are also visible. For example, several regional PCs show a decline in their interannual amplitude at the end of the 1980s. AT1 and CH1, which represent the regions south of the Alpine main ridge in Austria and Switzerland, are characterized by distinct gradual decreases until 2005 and a slight increase since then. In contrast, the leading PCs of AT3 and CH3 remain generally constant between 1975 and today.

In order to make temporal snow depth trends more visible and to account for all possible trends in the time series as well as their significance, we used a running trend technique (see Section 3). This method was applied to the leading PC of all the sub-regions. Results of the trend analysis are shown in Figure 7 for the seven sub-regions in Austria and Switzerland.

In view of the inter-comparison between regions in Switzerland and Austria, CH1 and CH2 show similar temporal variations as observed in AT1 and AT2. It should be mentioned that a year-to-year correspondence cannot be expected due to local effects as well as different levels of orographic barriers and features. Since the amplitude of the PCs is related to the snow depth, the higher amplitude in CH2 can be explained by higher snow depths at higher

**FIGURE 6** Leading PCs for regions in Switzerland (left panel) and Austria (right panel). The PCs were seasonally averaged (NDJFMA), the solid black lines indicate a Gaussian filter with a window size of 11 years. Regions are shown in the lower left panel.
elevations compared to AT2. CH3 and AT3 represent flatland areas and are characterized by low variability. Figure 7 shows the trends of the leading regional PCs over decadal time scales. The results imply that regions south of the main Alpine ridge (AT1, CH1) in particular are characterized by stronger negative trends (significant at a 99% confidence level) compared to other regions. Interestingly, almost no significant negative trends are observed in the Austrian flatland-region AT3 (and also in AT4).

In Figure 4, the elevation is shown to be a relevant factor for determining snow depth regionalization. A similar impact could also be expected for the strength of the temporal trend of snow depth in the Alpine region. As air temperature has high dependency on altitude, certain elevation zones are closer to the threshold temperature of 0°C that roughly defines not only the phase of precipitation but also generally if melt occurs or not. In particular, the impact of air temperature should be largest on duration of snow cover (snow cover days). In order to test this hypothesis, we computed the Theil–Sen slope for the number of days with snow depth \( \geq 1 \) cm (which are snow cover days as defined for Austria and Switzerland) and mean NDJFMA snow depth for each station for the period 1961–2012. Each value was plotted as a function of the corresponding station elevation in Figure 8. Interestingly, a clear picture of non-linear elevation dependency can be seen for snow cover days and a slight linear elevation dependency for mean snow depth. Hantel et al. (2012) investigated the median snow line (snow cover duration \( \geq 5 \) cm for DJF) for about 139 stations in the Swiss-Austrian domain for the period 1961–2010. They found the altitude of highest temperature sensitivity of snow cover duration (which is the altitude of the median snow line) at 793 m.a.s.l., which fits quite well with our elevation range with the highest values of the trend strength, even though the data base is not exactly the same. Similarly, Scherrer et al. (2004) found the maximum trend in snow days to be at about 600 m for the Swiss Alps. Obviously, the strong decrease in the Alpine snow covers duration for elevations between 500 and 1,000 m.a.s.l. (up to roughly –1 day per year which is 1.5 month over the entire study period) largely arise from increasing temperature changes (see also Klein et al., 2016, who found a similar value for Switzerland). It should be mentioned here that snow cover duration at high elevation stations (ca. above 1,500 m.a.s.l.) is usually shortened in May, which is not covered by our NDJFMA period. Klein et al. (2016) demonstrated that snow cover duration also significantly decreases above 1900 m.

The findings for the mean snow depth trends, which show a distinct linear elevation dependency rather than the clear non-linear elevation dependency for snow cover days, come as some surprise. One would expect a similar relevance of air temperature and thus also elevation for snow depth trends as for snow cover duration trends. Two reasons could be crucial for the different behaviour:

1. Obviously, snow cover duration trends are particularly heterogeneous at elevations with the strongest negative trends (ca. 500-1,000 m.a.s.l.). These negative trends are mainly seen in stations from the southern regions, which are characterized by specific weather patterns for snow accumulation.
2. The temporal reference of mean snow depth and snow cover duration can be quite different. Although it is fixed to NDJFMA period for snow depth, the period is defined by the start and end of the period of days with \( \geq 1 \)-cm snow depth for snow cover duration.
Sensitivity of Alpine snow depth changes to temperature and precipitation changes

In this section, we will investigate the relationship of snow depth trends with changes in air temperature and precipitation in the Alps. Such analysis should answer the question as to which degree snow depth trends are caused by either precipitation or temperature changes or both. In this context, one should keep in mind that changes in snow depth are related to both snow accumulation and ablation processes (while neglecting snow density here). Precipitation and air temperature together define the gain in snow (accumulation), but air temperature, as a proper proxy of surface energy balance, is a relevant measure for loss of snow (ablation). Thus, we argue that snow depth is more strongly linked to temperature than depth of snowfall.

Although air temperature trends are rather spatially homogeneous for the Alpine region, precipitation trends are quite different (see for example, Auer et al., 2007). Consequently, it could be expected that trends of snow depth for the Alpine domain are spatially heterogeneous, too. In order to quantify the relationship of snow depth changes with regards to precipitation and air temperature, we used the monthly precipitation and air temperature data of the HISTALP data set (Auer et al., 2007). The HISTALP data set is a good choice as it provides homogeneous multi-centennial climate data series covering the entire Greater Alpine Region. To carry out the analysis, we computed Kendall’s tau rank correlation for all station series. Clearly, the correlation is a good measure of high frequency coincidence in temporal changes and is less indicative for long-term changes.

In Figure 9, the correlation coefficients are shown as a function of the altitude of each station. This figure highlights a clear pattern of air temperature dependency with snow depth for low elevation stations (and no dependency on precipitation changes), whereas high elevation stations show...
increasing precipitation sensitivity with altitude (and no dependency on air temperature changes). Snow depth changes for stations at the transition zone of altitudes are impacted by both air temperature and precipitation. This finding becomes clear if one considers that all precipitation falls as snow at temperatures below 0°C, which means at higher elevations if averaged over the year. For elevations above a certain level, this could also hold true after the temperature has increased. Consequently, in this case, the amount of precipitation also defines the snow depth. On the other hand, at low elevations, the impact of air temperature on the type of precipitation (solid or liquid) and on snow melt is high. Although not surprising, this finding is fundamental in order to understand not only past changes of snow depth but also to predict potential future changes.

Our results confirm previous studies investigating the elevation dependency of snow cover changes and air temperature/precipitation for either other snow parameters or other regions (e.g., Scherrer and Appenzeller, 2006; Morán-Tejeda et al., 2013; Sospedra-Alfonso et al., 2015). In particular, Morán-Tejeda et al. (2013) also showed a clear asynchronous pattern in the correlation between snow depth and air temperature (decreasing with altitude) and snow depth and precipitation (increasing with altitude) for the Swiss Alps.

5 | CONCLUSIONS

This is the first study of spatiotemporal snow depth changes covering a larger part of the European Alps, in particular its west–east extent. We used data from 139 stations in Switzerland and Austria to characterize the spatial and temporal patterns of mean snow depth between November and April over the period since 1961. This period showed a robust ratio between series length and spatial density of stations, which enabled us to homogenize our data. Although the statistical testing for breaks in the snow series was carried out successfully, the adjustment of the snow series at detected break points is still an open issue and could not be solved to a sufficient degree using the existing methods. This is particularly true if homogenization is applied to daily data series and not monthly or seasonal means. The results for snow series homogenization motivated us to work with seasonal mean values of snow depth throughout this study to come up with robust findings. Clearly, future work on homogenization methods is needed for snow depth data in order to enable adjustment of series at higher time resolutions. For obvious reasons, future studies of snow climatology should be based on homogenized series, using the existing standard homogenization tools as a minimum requirement.

We used EOFs to define regions with common variance in the time dependent evolution of snow series. Three regions for Switzerland and four regions for Austria are shown to be useful in describing regional patterns of mean snow depth evolution in the study region. Elevation could be used as additional factor defining temporal changes. Our EOF-derived snow depth regions are in agreement with subjectively identified regions from previous studies. The temporal evolution of snow depth for each region can be well described by the first PC of the PCA from all station series within the region, thus filtering out station-specific local-scale features in the series. The temporal trends are rather different across the Swiss-Austrian domain. Most strikingly, the southern regions in both Austria and Switzerland are characterized by a clear decrease in mean snow depth (up to –12 cm/decade on the mean at elevations of about 2000 m a.s.l.), whereas the northeastern part of Austria shows no trend for the same period. This finding is robust and independent of the length, start and end of the trend-period. Interestingly, the strength of mean snow depth trends increases with altitude (probably explained partly by the elevation-dependent snowmelt potential), whereas the number of snow cover days has a clear maximum of trend strength for elevations between about 500 and 1,000 m a.s.l.

Relating snow depth series with concurrent mean air temperatures and precipitation sums in the Alps shows a clear dichotomy with respect to elevation and underpins previous studies for other snow variables or other
geographical domains. Low elevation regions (below 1,000 m.a.s.l.) show a high correlation with air temperature and accordingly also temperature sensitivity of snow depth, which decreases with increasing altitude. High elevation sites (above 1,000 m.a.s.l.) show increasing correlation between snow depth and precipitation with altitude, indicating that snow depth changes are forced by precipitation. This is plausible, as high elevation regions are cold enough that, despite increasing temperatures, precipitation still falls as snow and melt remains rather low. Our findings are useful with respect to assessing the uncertainty of future changes of snow depth in the Alps from regional climate model simulations. As future climate model scenarios of Alpine air temperature will be much more robust than those for precipitation, we can expect more reliable scenarios for snow depth changes at low elevations regions (where also larger changes have been observed in the past) than for snow depth changes at high elevation regions. However, as result of the future temperature increase, the altitudinal zone of temperature sensitivity will move towards higher elevations, while the region of precipitation sensitivity will decrease in the future.

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