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The Cryosphere Discussions

Observed snow depth trends in the European Alps 1971 to 2019

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Abstract.

The European Alps stretch over a range of climate zones, which affect the spatial distribution of snow. Previous analyses of station observations of snow were confined to regional analyses. Here, we present an Alpine wide analysis of snow depth from six Alpine countries: Austria, France, Germany, Italy, Slovenia, and Switzerland; including altogether more than 2000 stations. Using a principal component analysis and k-means clustering, we identified five main modes of variability and five regions, which match the climatic forcing zones: north and high Alpine, northeast, northwest, southeast and southwest. Linear trends of mean monthly snow depth between 1971 to 2019 showed decreases in snow depth for 87% of the stations. December to February trends were on average -1.1 cm decade^{-1} (min, max: -10.8, 4.4; elevation range 0–1000 m), -2.5 (-25.1, 4.4; 1000–2000 m) and -0.1 (-23.3, 9.9; 2000–3000 m), with stronger trends in March to May: -0.6 (-10.9, 1.0; 0–1000 m), -4.6 (-28.1, 4.1; 1000–2000 m) and -7.6 (-28.3, 10.5; 2000–3000 m). However, regional trends differed substantially, which challenges the notion of generalizing results from one Alpine region to another or to the whole Alps. This study presents an analysis of station snow depth series with the most comprehensive spatial coverage in the European Alps to date.

1 Introduction

In the European Alps, snow is pervasive throughout nature and human society. Snow is a major driver of Alpine hydrology by storing water during the winter season, which gets released in spring and summer and which is used for water supply, agriculture, and hydropower generation. Water stored in the snow cover also feeds alpine aquifers through the network of fault and fracture systems. Ecologically, the mountain flora and fauna depend on the timing and abundance of snow cover (Esposito et al., 2016; Keller et al., 2005; Lencioni et al., 2011). Snow is tightly linked to human culture in the European Alps and has brought wealth to previously remote regions through tourism (Beniston, 2012a; Steiger and Stötter, 2013). Since snow cover depends on temperature and precipitation, ongoing climate change in the Alps and especially rising temperatures and changing precipitation patterns affect the abundance of snow (Beniston and Stoffel, 2014; Gobiet et al., 2014; Steger et al., 2013). Snow cover extent decreased globally, while for snow mass some regions experienced increases (Pulliainen et al., 2020). Decreases are expected for the future, especially at low elevations, with more uncertain trends in observations and future projections at higher elevation (Beniston et al., 2018; Hock et al., 2019; IPCC, 2019).

To assess changes in snow cover, observations of the snow cover are required. The most widespread snow cover measurements are snow depth (HS), depth of snowfall (HN, also denoted fresh snow or snowfall), snow water equivalent (SWE), snow cover area (SCA), and snow cover duration (SCD). Snow depth and fresh snow measurements have been scientifically documented in the European Alps since the late 18th century (Leporati and Luca, 1994). Such measurements indicate the height of the snow cover relative to the ground (snow depth) or a reference surface (depth of snowfall), are performed by observers, and only require a graduated stake or rod. While automatic sensors have been developed in the recent decades, most European weather and hydrological services continue with manual observations. Although there is a trend towards automatization, missing standards on the processing of the data (even at national level) impedes their uptake (Haberkorn, 2019; Nitu et al., 2018). The

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main limitation of snow depth and fresh snow measurements is that their number decreases sharply with elevation, and only few stations are available above 3000 m in the European Alps. SWE is the mass of snow per unit surface area, which corresponds to the amount of water stored in the snow cover and thus is a hydrological key variable. However, its measurement is far more complicated than snow depth, and thus not as widely observed and available with lower temporal frequency. SCA and SCD identify the spatial extent and temporal duration of snow on the ground. SCD can be inferred from snow depth measurements using a threshold, or more recently from satellite observations, which also allow SCA retrieval at different spatial scales from tens of metres to several kilometres. The main benefit of satellite observations is that they cover the whole elevational gradient and are also available in data-scarcer regions. Satellite observations can identify SCA and SCD at high spatial resolutions (1 to 5 km for decadal length time periods), and less accurately SWE at coarser resolution (~25km) (Schwaizer et al., 2020), though they typically cover a relatively short time period and are hampered by cloud cover and rugged topography (Bormann et al., 2018), and the satellite orbit might not provide a worldwide cover. An application of global satellite imagery for 2000-2018 has shown snow declines for 78% of global mountain areas with significant changes and only a few regions with increasing SCD (Notarnicola, 2020), although the short time span of 19 years is a limiting factor in interpreting these trends.

The European Alps are densely populated and have a long history of manual snow depth and depth of snowfall observations, which makes them ideal to study long-term trends over a large spatial domain with complex topography and strong climate gradients. Not surprisingly, a vast array of literature exists; however, most studies are limited in their spatial extent to regions or nations, restricted by a lack of data sharing, harmonized data portals, and joint projects or initiatives fostering such analyses (Beniston et al., 2018). Exceptions include an Alpine wide analysis of SWE trends showing stronger and more significant decrease in spring than winter (Marty et al., 2017), which, however, considered a relatively limited number of locations since SWE measurements are rare and unevenly distributed; a pan-European study showing accelerating negative trends for mean winter snow depth (Bach et al., 2018), which, however, does not cover France and Italy, and covers only sparsely Austria and Slovenia, thus missing large parts of the European Alps; and finally an Austrian-Swiss study, identifying seven snow regions, strongest trends at high elevation, and a regional dependence of the trends (Schöner et al., 2019).

Most of the published literature is on Switzerland. Results include a regime shift in snow days at the end of the 1980s and no clear trend until 2008 (Marty, 2008); differences between north and south Switzerland, more pronounced trends at low and mid elevation, and a shorter SCD mainly because of earlier snow melt (Laternser and Schneebeli, 2003); an analysis of extreme values that shows significant decreases in 44% of the cases for maximum snow depth (Marty and Blanchet, 2012); a long term (1864–2009) seasonal analysis of depth of snowfall that shows strong decadal variability with high values 1900–1920 and 1960–1980 (Scherrer et al., 2013); a mean December to February snow depth decline between -10 to -50% with differences between the moist north and the dry south (Beniston, 2012b); and a study based on 11 stations over the time period 1970–2015, which has shown significant reduction in SCD, on average by 8.9 days decade^{-1}, largely driven by earlier snowmelt (on average 5.8 days decade^{-1}) (Klein et al., 2016).

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In Italy, literature on snow mostly confined to regional analyses or comparisons between the eastern and western Italian Alps. For the provinces of Bolzano and Trento, different dynamics were observed above and below 1650 m, larger reductions at lower elevations, and strong changes in the late 1980s (Marcolini et al., 2017b). An analysis of stations in Veneto and Aosta Valley showed a breakpoint around 1990, stronger negative trends below 1500 m and in spring, and negative trends related to precipitation decreases (Valt and Cianfarra, 2010), as well as decreases in snow cover of 14 days when comparing the period 1991–2007 to 1960–1990 (Valt et al., 2008). In Piedmont, the analysis of six long-term snow depth stations located between 960 and 2177 m showed a significant decrease of snow depth in the period 1951–2010, with the main contribution coming from spring months (Terzago et al., 2013). Another study comparing monthly snow depth at middle elevations (960-1589 m) in the decade 2000–2009 with respect to 1971–2000 showed increased snow depth in November and December, decreased snow depth in January to April, and almost no residual snow in May (Terzago et al., 2010). In the case of Friuli Venezia Giulia, positive anomalies were observed in the 1980s, shifts to low snow amounts until the beginning of the 2000s, and some recovery afterwards (Micheletti, 2008).

For France, an analysis at Col de Porte showed a decrease of mean seasonal (December to April) snow depth between 1960 to 1990 and 1990 to 2017 of 39 cm, which corresponds to 40% of the mean snow depth 1960–1990. (Lejeune et al., 2019).

Other studies have focused on a reanalysis driven snow model (Crocus), instead of directly analysing station observations. For the French Alps, results indicated no trends in December to February snow depth above 2700 m during 1959 to 2005, and decreases below, as well as decreases in snow days at all elevations (Durand et al., 2009).

The high elevation snow network close to the observatory at Sonnblick in Austria, a research station at 3100 m in the vicinity of several glaciers, showed outstanding large snow depths in the 1940s and 1950s, strong decreases afterwards, and clear links between winter precipitation and snow depth (Schöner et al., 2009).

Quantitatively synthesizing all these studies into a common Alpine view is challenging and hampers the provision of quality-ensured information on snow cover climatology and trends at the regional scale (Hock et al., 2019). This starts from the different definitions of the studied seasons, which range from December–February to October–May, and thus sometimes include start, middle, and end of the season. Difficulties also arise in the selection of existing snow variables and indices, such as mean snow depth, maximum snow depth, snow days (based on thresholds from 1 to 50 cm), 3 day cumulative values, etc. Naturally, the station series are of different lengths, and the studied periods get longer for the more recent studies. And finally, the statistical methods differ from one study to another: linear regressions, Mann-Kendall tests, Sen slopes, moving window approaches (windows ranging from 5 to 20 years), breakpoint analysis, principal component analysis / empirical orthogonal function analysis (PCA/EOF) and more.

To overcome these limitations, we embarked on the effort to collect and analyse an Alpine wide data set of snow measurements from stations covering Austria, France, Germany, Italy, Slovenia, and Switzerland. The main aim is to understand how changes in snow cover vary over space and time by applying the same methods to an as homogenous as possible Alpine wide data set. This approach avoids sub-regional perspectives, inconsistencies from single data sources and different methods, and influences

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of artificial boundaries such as national borders. Since we wanted the data collection effort to be of use for the scientific community, we provide as much as possible of the data openly accessible (as far as data policies allow us to). The remainder of the paper is structured as follows: Section 2 introduces the data and the statistical methods, Section 3 presents results and discusses them, while Section 4 concludes.

2 Data and methods

2.1 Study region

The European Alps extend, with their typical arc-shaped structure, over more than 1000 km from the French and Italian Mediterranean coasts to the lowlands east of Vienna, covering Switzerland, northern Italy, southern Germany, Austria, and Slovenia (see Fig. 1 (a)). The Alpine chain is characterized by a very complex physiography including sectors with strong elevation gradients that contrast with deep, tectonically controlled valleys. These elongated depressions etch elevated rough ridges with different orientation shaping numerous mountain massifs.

Regarding their climatic setting, the European Alps are located in a transitional area influenced by the intersection of three main climates: The zone impacted by the Atlantic Ocean with moderate wet climate, the zone linked to the Mediterranean Sea characterized by dry summers and wet and mild winters, and the zone characterized by European continental climate with dry and cold winters and warm summers. Elevational effects and very small-scale climatic features originating from the complex Alpine topography are superimposed on this large-scale climatic setting (Auer et al., 2005; Isotta et al., 2014).

The interaction of the three climate forcing zones can be characterized by four main climate regions for the Alps as shown by Auer et al. (2007). The first and sharpest climatic border is along the central main ridge separating the temperate westerly from the Mediterranean subtropical climate. The second climatic border separates the western oceanic form the eastern continental influences.

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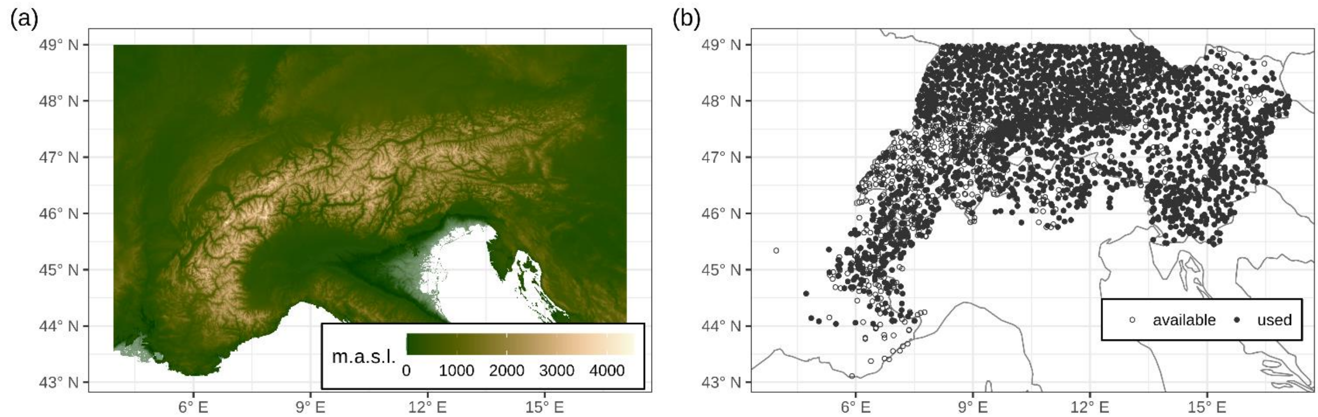

Figure 1: Topography of the European Alps (a) and overview of station locations (b). (a) shows the SRTM30 DEM (Shuttle Radar Topography Mission Digital Elevation Model) with ~1 km resolution. (b) shows the location of snow depth measurement locations that were available (provided) and used in the analysis (see Appendix A for quality checks and Sec. 2.4 for selection criteria).

2.2 Data sources

Acquisition of snow observation data was performed by using open data portals and by directly contacting data providers (see Table 1 for an overview). For Austria, the Austrian Hydrographical Service (HZB, Hydrographisches Zentralbüro) offers free download of their data for the recent decades, and additional historical data at the seasonal scale was kindly provided by the HZB. For France, data was kindly provided by the national weather service Météo-France. This includes data collected as part of the collaborative network (réseau nivo-météorologique) between Météo-France and mountain stakeholders (in particular Domaines Skiables de France, Association Nationale des Maires de Stations de Montagne, Association Nationale des Directeurs de Pistes et de la Sécurité de Stations de Sports d'Hiver). For Germany, data was downloaded from the national weather service's (DWD, Deutscher Wetterdienst) open data portal using the R-package rdwd. For Germany, only stations below 49° N were downloaded. For Italy the data was kindly provided by many regional authorities: for the province of Bolzano from the hydrographical office of Bolzano (BZ); for Friuli Venezia Giulia (FVG) from the regional weather observatory (OSMER, Osservatorio meteorologico regionale), which is part of the ARPA (Agenzia regionale per la protezione dell'ambiente) FVG, and where the data was collected and cleaned by the Servizio foreste e corpo forestale struttura stabile centrale per l'attivita' di prevenzione del rischio da valanga; for Lombardy from the ARPA Lombardia; for Piedmont from the ARPA Piemonte; for the province of Trento from Meteotrentino (TN), and some additional long-term series previously analysed (TN_TUM, Marcolini et al., 2017a); for the Aosta Valley from the civil protection office (CF: Centro funzionale, Regione Valle d'Aosta) and from the avalanche office (AIBM: Assetto idrogeologico dei bacini montani, Regione Valle d'Aosta); for Veneto from the avalanche office (Centro valanghe di Arabba), which is part of the ARPA Veneto; and, finally, additional data for Piedmont and Aosta Valley was provided by the Italian meteorological society (SMI, Società Meteorologica

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Italiana). For Slovenia, data was kindly provided by the Slovenian Environmental Agency (ARSO, Agencija Republike Slovenije za okolje). For Switzerland, data was downloaded from the IDAWEB portal of the national weather service MeteoSwiss, and additional data kindly provided by the WSL Institute for Snow and Avalanche Research SLF. This dataset comprises the entire geographical range of the European Alps, yet we are aware of the existence of additional data sets (such as in the private sector, or public but not yet digitized), which unfortunately were not included in this analysis, and whose inclusion would be beneficial for even more robust results.

The data consists of daily measurements of snow depth (HS) and depth of snowfall (HN), with a few exceptions of monthly/seasonal data from the HZB and SMI. The largest part of the data are manual measurements; some automatic measurements were also included only for France or, thanks to a close communication with the operating office, they were merged with manual series for a few sites in Aosta Valley, in order to extend up to the present some records that were dismissed at the beginning of the last decade. While the observers follow slightly different guidelines in each country or network, the observation modalities are remarkably similar, thus allowing a combination of the different sources. For more detailed information on the measuring modalities, we refer to the European Snow Booklet (Haberkorn, 2019). Values of HS and HN were rounded to full centimetres. The further processing, quality checking, and gap filling are described in Appendix A.

The fraction of stations used for the MeteoSwiss data is very low compared to the other networks. The MeteoSwiss data contains a large number of stations from the manual precipitation network which is not dedicated to snow. Many stations display a strong gap of digitally available snow data in the period 1981–1997 (see also Fig. 2b). This long data break renders a large fraction of the stations unusable for this study.

Table 1: Overview of the number of stations with daily data provided by the different data sources. The data source consists of a country abbreviation, followed by the data source. Country abbreviations are AT for Austria, CH for Switzerland, DE for Germany, FR for France, IT for Italy, and SI for Slovenia. For source abbreviations, please see Sec. 2.2. The numbers in the table are for fresh snow (HN) and snow depth (HS) series provided. See Appendix A and Sec 2.4 for more details on station selection procedure for the number of HS stations used in the analysis. HN was not analysed but only used for checking HS.

Data source	HN	HS	HS used in analysis
AT_HZB	653	652	588
CH_METEOSWISS	505	501	157
CH_SLF	96	96	94
DE_DWD	956	964	850
FR_METEOFRANCE	239	286	152
IT_BZ	60	64	48
IT_FVG	30	30	18
IT_LOMBARDIA	11	11	11
IT_PIEMONTE	34	34	24
IT_SMI	6	8	8
IT_TN	52	52	30
IT_TN_TUM	0	5	2
IT_VDA_AIBM	57	57	17
IT_VDA_CF	0	17	14
IT_VENETO	10	11	11
SI_ARSO	130	172	172
Total sum	2,839	2,960	2,196

2.3 Data overview

The locations of the stations are shown in Fig. 1 (b), the elevational distribution in absolute terms in Fig. 2 (a) and relative in Fig. 2 (b), and the availability of stations in time in Fig. 2 (c). The stations cover the whole Alpine arc, but they are distributed with different station densities arising from the different national and regional networks. As expected, most stations are found at lower elevations, the maximum number is at ~500 m, and sharply declining for higher elevations. Above 2000 m, the number is low, and no stations above 3200 m are available. The longest series date back to the late 18th century for HN (Torino in Italy, starting 1787), and late 19th century for HS (Passau_Maierhof in Germany, starting 1879). The total number of available HS stations depends on the availability of digitized data. It slowly starts increasing around ~1900, with significant jumps in the 1960s and 1970s, when the French, Slovenian and Austria series start, and in the 1980s, when Germany has a large network increase. The highest number of stations is available after the 1980s with approximately 2000 stations. The total number of

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stations drops significantly after 2017, because the data for Austria was only available until 2016, and the data collection was performed between 2019 and 2020, thus some sources ended sometime in between. The main period studied for HS spans from 1961/1971 to 2019, in order to have a complete Alpine view including all sources, some of which start only in the 1960s and 1970s.

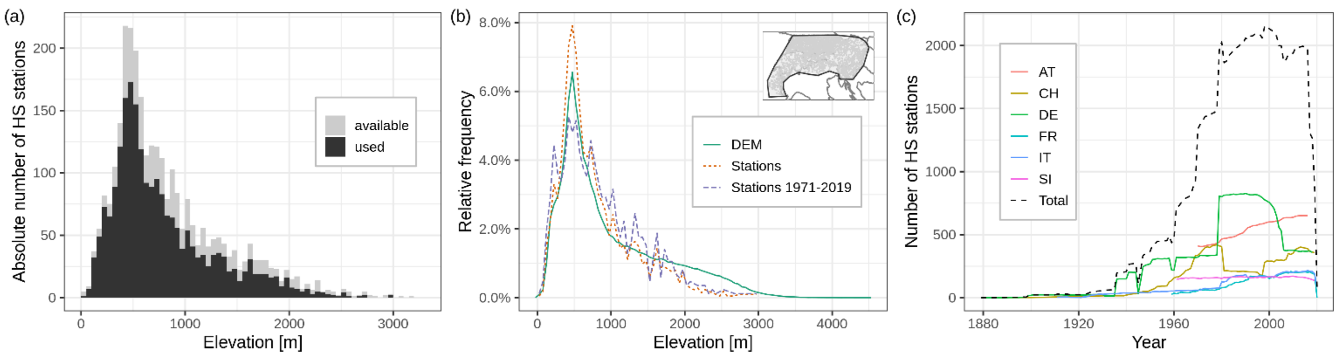

Figure 2: Overview of station elevations and temporal data availability. (a) The elevational distribution of snow depth (HS) stations in absolute numbers, both that were available and used. For the histogram 50 m bins were used. (b) Comparison of the relative elevational distribution of the station locations versus a digital elevation model (DEM). The frequency by elevation (50 m bins were used to calculate to proportion) is shown for the SRTM30 DEM (Shuttle Radar Topography Mission, ~1 km resolution) for the area spanned by the stations (see polygon in inset map). This is compared to the elevation frequency of the stations, both for all stations included in the analysis and for the subset used in the 1971 to 2019 analysis. (c) The number of stations with daily data (before gap filling) is shown per year and country, and a total sum for the whole Alpine region. Stations are included in the count only, if they have at least one non-missing observation in the respective calendar year. Thus, this gives only a rough indication of the network abundance and not the effective usability. Country abbreviations are as in Table 1.

2.4 Regionalization and trends

An empirical orthogonal function (EOF) analysis, also called principal component analysis (PCA), was conducted to determine the common modes of spatial variability. PCAs are widely employed in climatological studies to study spatial modes of variability (Storch and Zwiers, 1999). They have been employed for meteorological records in the European Alps (Auer et al., 2007) and also for snow variables (López-Moreno et al., 2020; Scherrer and Appenzeller, 2006; Schöner et al., 2019; Valt and Cianfarra, 2010). We used a modification that allows using data with gaps to estimate the principal components (PCs) (Taylor et al., 2013). This was done using the daily data from December to April for the hydrological years 1981 to 2010. A hydrological year is defined here as starting in October, and it is designated as the calendar year of the ending month (e.g. December 1998 to April 1999 have the hydrological year 1999). Stations were selected which had at least 70% of daily data available in this period. Each series was scaled to zero mean and unit variance before applying the PCA. We retained the first five PCs as additional PCs explained only less than 2.6% of the variance and the regions became noisy.

In order to identify spatially homogeneous regions within the Alpine domain, we performed a k-means clustering on the estimated PCA matrix. We tested using 2 to 8 clusters on the PCA matrix with 2 to 8 PCs, as well as clustering directly on the daily observations. The best results were obtained using the PCA matrix for clustering and with the same number of clusters as PCs. Five clusters were chosen, because they showed the best results in terms of silhouette values and visual interpretability. Trend analysis was performed using linear regression (OLS, ordinary least squares) with two approaches. The first was to determine the long-term changes in the longest period with the densest station coverage, which is 1971 to 2019. Linear trends were computed separately for each month from November to May. Only stations with complete 49 years were considered. The predicted variable was the mean monthly HS and the only predictor the year (shifted to 0).

The second approach was a moving window approach that aims at identifying the short-term changes in trends. For this, linear trends were computed on all 30 year windows from 1961 to 2019. A 30 year time was identified optimal in the sense that it is short enough to appreciate the changes of trends over time and, at the same time, it is long enough to filter out natural cyclic fluctuations of hydrometeorological variables in the Alps (Mallucci et al., 2019). Again, trends were calculated separately by month (November to May) and station, and only if no year was missing in each window.

Both approaches resulted in different numbers of analysed stations per month (and per moving window), because low elevation stations have no snow early or late in the season, not all stations record the complete winter season, and, in the case of the moving window approach, the network density changes over time. The significance of trends was assessed using assessed using a 95% confidence level.

Some of the previous studies used the Theil-Sen estimator to identify trends in snow cover variables (Marty et al., 2017; Schöner et al., 2019). The Theil-Sen estimator is a robust estimator of trends, which works better than OLS for heteroscedastic data and in the presence of outliers. However, for the monthly snow depth series we did not detect any heteroscedasticity, significant outliers, or other evidence against the assumptions of OLS.

2.5 Air temperature and precipitation data

In order to study the relationship of snow depth with temperature and precipitation, we extracted temperature and precipitation series for each station from available gridded products. While gridded data sets clearly have some shortcomings, e.g. comparisons to point observations need a cautious interpretation (Salzmann and Mearns, 2011), their strength is the spatial and temporal coverage as well as their homogeneity with respect to interpolation methods.

Two types of products were considered, the first is a reanalysis and the second is an observation-based spatial analysis. For the reanalysis, we used temperature and precipitation from the MESCAN-SURFEX data set (Bazile et al., 2017), which was produced during the UERRA (Uncertainties in ensembles of regional reanalyses) project and which is available via the Copernicus data store (CDS). It covers the period from January 1961 to July 2019 on a 5.5 km grid. Precipitation is available as total daily sum and temperature at 6-hour intervals (00, 06, 12, 18 UTC). For the observational based data, we chose E-OBS v20.0e for mean daily temperature (Cornes et al., 2018), and the Alpine precipitation grid dataset (EURO4M-APGD) for total daily precipitation (Isotta et al., 2014; Isotta and Frei, 2013). E-OBS v20.0e spans the period from January 1950 to July 2019 on a 0.1° grid. APGD covers the period January 1971 to December 2008 on a 5 km grid. It should be noted that the observation-based precipitation grids do not account for undercatch, which can lead to uncertainties at high elevations and in winter (Prein and Gobiet, 2017).

In order to assign grid cells to stations for temperature and precipitation, we selected those grid cells which contain the stations. Consequently, some nearby stations could have the same series of temperature and precipitation. The daily (or 6-hour for temperature MESCAN-SURFEX) series were aggregated to monthly means for temperature and monthly sums for precipitation.

The gridded products have a reference orography that, in complex mountain terrain, can differ significantly to the elevation of the point observation, thus e.g. introducing biases in temperature. Thus, temperatures were adjusted using a constant lapse rate of 6.4 °C km^{-1}.

Monthly temperature and precipitation can be considered largely independent from one month to the next, while snow cover is a cumulative process across the snow season. Because of this, seasonal comparisons were performed with average seasonal temperature and precipitation for winter (December to February), spring (March to May), or the whole snow season (November to May). The time period 1981 to 2010 was used, which had the densest station coverage. Climatological averages were computed for all seasons. Since EURO4M-APGD ends 2008, the time period 1981 to 2008 was used for the observation-based products.

2.6 Code and data

All computations were performed with R statistical software version 4.0.2 (RCoreTeam, 2008). Colors for the figures were taken from scientific color scales (Crameri, 2019) and colorbrewer. Code is available at Matiu et al. (2020), which includes scripts to read in the different data sources, perform all data pre-processing, quality checks, gap filling, and do all statistical analyses (i.e. all of Sections 2.3 to 2.5).

Most data providers agreed to share their data: see Table C1 for the availability of daily and monthly values. For the full data set, please contact the main authors (MM or AC); the usage is generally free for research purposes, though explicit consent is required from some data providers, which want to keep track of the usage of the data. The data is available at an open repository (Matiu et al., 2020).

3 Results and discussion

3.1 Regionalization

The PCA of daily snow depth series yielded five main modes of spatial variability, which explained in total 84% of the variance in the period December to April from 1981 to 2010 (Fig. 3). The first PC explains 54.3% of variance and distinguishes between high to middle and low elevation stations (approximate threshold 500–1000 m, Fig. B1), and is probably also partly linked to the permanence (or permanent absence) of snow cover, which is why also some low elevation sites have similar loading as the high sites (a PC loading can be considered the correlation of the original series with the principal component). The second PC

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explains 11.9% of variance and is highly correlated to elevation up to 1000–1500 m, and mostly constant above. The third PC explains 8.1% of variance and separates the stations into north and south of the main ridge. The fourth PC explains 6.0% of variance and separates east from west. The fifth PC explains 3.7% of variance and separates the south–eastern and north–western stations from the rest. See also Fig. B1 for scatterplots of the PCs by elevation and region (from clustering below).

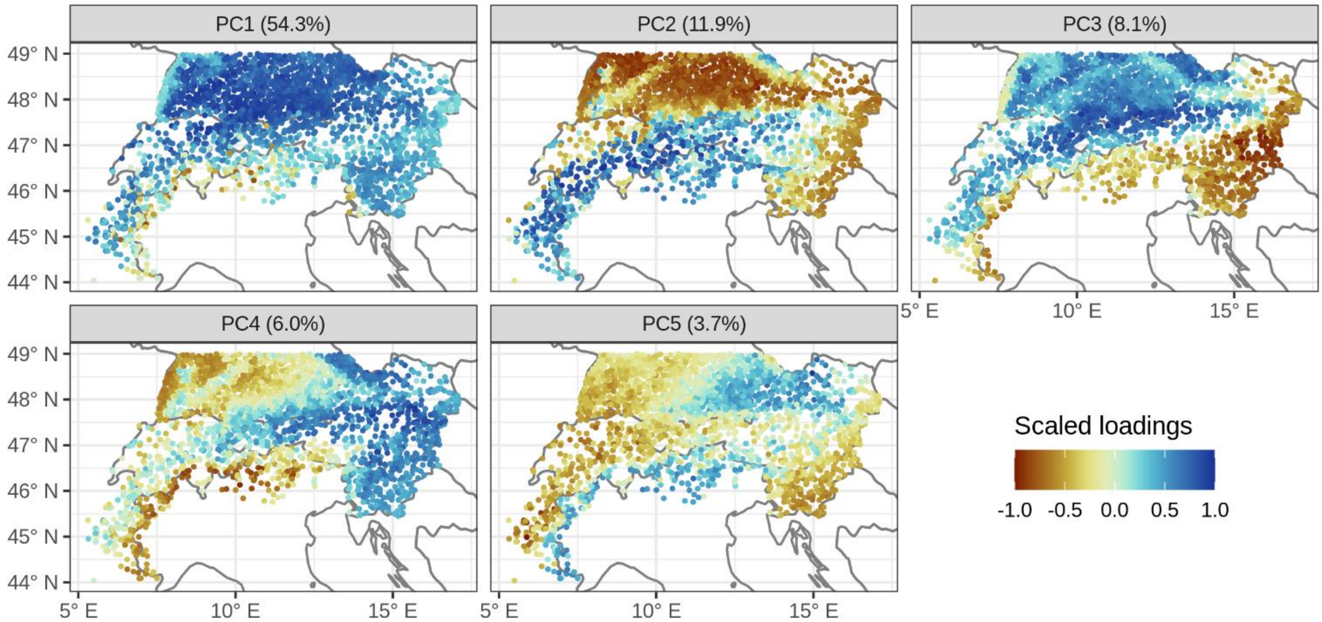

Figure 3: Main modes of variability in daily snow depth series. The plots show scaled loadings for the first five principal components (PCs), which can be considered the correlation of the original series with the respective PC. The title in each panel contains the amount of variance explained by the respective PC. The principal component analysis was applied on daily snow depth data from December to April for the hydrological years 1981 to 2010, for stations that had at least 70% of available data.

Based on the PCA loadings, the stations were clustered into five regions using a k-means clustering (Fig. 4). There were three regions in the north: northwest (NW) with a median elevation of 472 m (min–max: 30–1510 m), which contains stations from southwest Germany, northwest Switzerland, few from France, and a few from eastern Austria; northeast (NE) with a median elevation of 515 m (215–1188 m), which contains stations from southeast Germany and north Austria; North & high Alpine with a median elevation of 1050 m (482–2970 m), which contains stations mainly located in France, Switzerland, and Austria, but also includes the high-elevation sites in Germany, such as in the Black forest and Bavarian forest. South of the main ridge, there were two regions: southwest (SW) with a median elevation of 1530 m (588–2735 m), which contains stations from the southern French Alps, almost all of Italy, few of southern Switzerland, and some of south Austria and east Slovenia; and finally southeast (SE) with a median elevation of 420 m (55–1300 m), which contains almost all stations from Slovenia and parts of eastern Austria.

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Consequently, clusters NW, NE, and SE contain lower elevation sites, while North & high Alpine and SW the higher elevations. The spatial coverage of the stations in this study includes the low elevations sites for Switzerland, Germany, Austria, and Slovenia, but not in France and Italy, where the available stations are mostly high elevation sites. For a future analysis, it would be interesting to include more low elevation sites from France and Italy, and see whether a third cluster would emerge south as has in the north, because as of now, the division into SW and SE is surely also caused by the different station elevations.

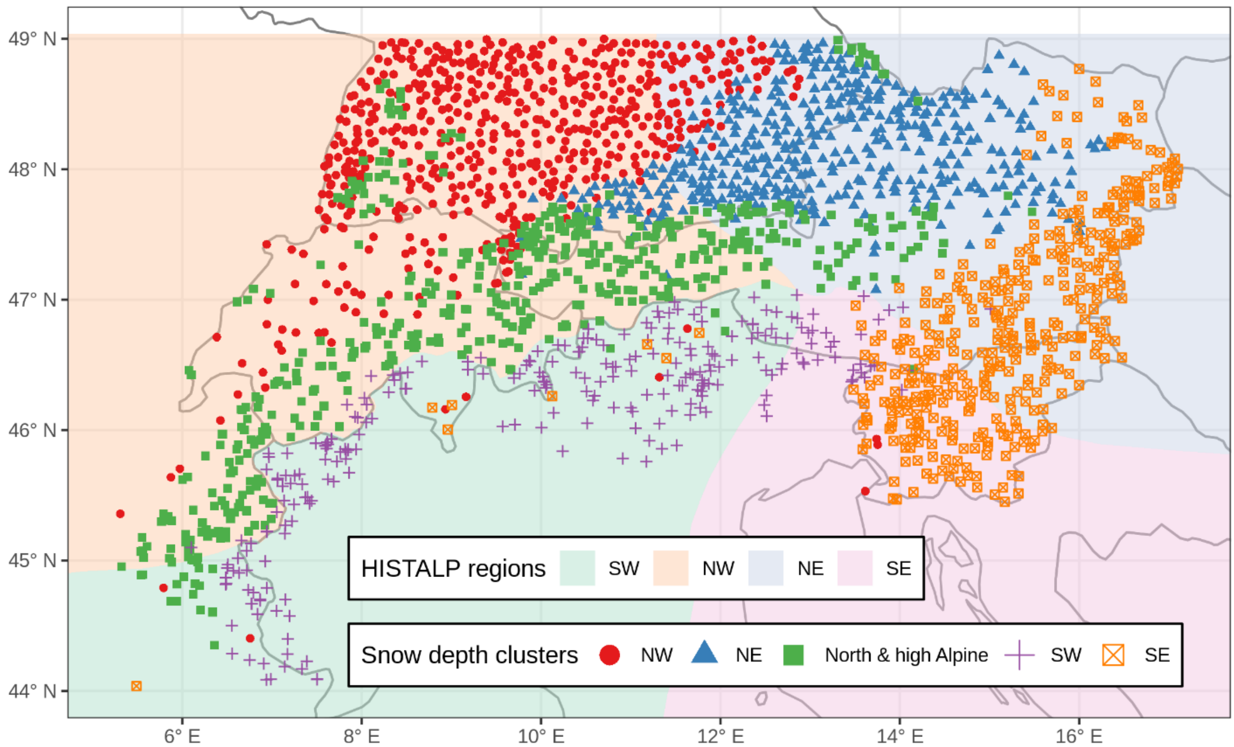

Figure 4: Clustering of stations based on daily snow depth data. Map of regions from applying a k-means clustering on the first five principal components. Underlaid are the HISTALP coarse resolution subregions, which were derived using a semi–automatic principal component analysis of climate variables (temperature, precipitation, air pressure, sunshine, and cloudiness).

The PCA and clustering were estimated data-driven and based solely on snow depth series; no information on location or elevation entered the input matrices. Given this absence of location information in the clustering process, the estimated modes of variability and the resulting regions are very homogenous in space. However, in the clustering, some stations seem off, such as e.g. the few "northwest" stations around Lugano in Switzerland, northern Italy, and at the Adriatic coast in Slovenia, as well as the SE stations in France, Switzerland, and northern Italy. This is not related to the used PCA algorithm that allows gaps in data, since the results look almost identical to a standard PCA (see Fig. B2 and B3), where the clustering agrees in 98.5% of

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the stations in common, and the same common stations seem mis-clustered. Instead, this might be related to special local climatic conditions affecting the snow cover or unique stations in the estimated clusters. For example, the five stations in Ticino, located in Switzerland south of the main ridge, are low elevation stations, which have no correspondence in the SW cluster, which contains middle to high elevations. Thus, the next best clusters were SE and NW, which, however, do not fit well: These sites and all other seemingly mis-clustered stations have low silhouette values (Fig. B4), which is a measure of how well a point matches its cluster compared to the others. Low silhouette values were also found along the borders of the different clusters, especially between NW and NE, which implies a smoother transition between NW and NE compared to the north–south boundary.

The estimated modes of variability of snow match previous estimates on climatic subregions in the Alps, as identified in the HISTALP project (Auer et al., 2007), and which are underlaid in Figure 4. The HISTALP regions were based on temperature, precipitation, air pressure, sunshine and cloudiness, and the division into north, south, east and west matches what we found for snow depth. Since the four regions were a comprise between all variables, they do not match perfectly to what we found for snow depth, because the individual atmospheric variables exert different controls on surface snow cover. While the north–south boundary is almost identical in the central–western part, the eastern part has large mismatches. However, if the single element boundary for precipitation were considered as main factor (cf. Fig. 8 from Auer et al., 2007), then the agreement with snow depth would be almost perfect. This finding confirms a consistent picture of the Alpine climate, in which snow depth is highly related to precipitation and air temperature patterns.

The amount of variance explained in the PCA with five PCs (84%) might seem surprisingly high, given that snow cover is hypothesized to have a high spatial and temporal variability. The value is higher than recent estimates for the Swiss Alps, where the first three PCs explained 78% (Scherrer and Appenzeller, 2006), or for Austria and Switzerland, where the first three PCs explained 70% (Schöner et al., 2019). However, since here we included more stations and also stations from regions with different climatic influences, such as south of the main ridge, an increase in the amount of explained variance could be expected.

3.2 Long-term trends for the period 1971 to 2019

Trends were mainly negative with some exceptions (Fig. 5 and Table 2). Over all stations and all months, 87% of the trends were negative and 13% positive; 18% significantly negative and 0% (only 3 station month combinations) significantly positive. The percentage of significant negative trends was substantially higher in the spring months (March to May) and at lower elevations, irrespective of region, and it could reach 40–80% (see also Table 2).

In the low elevation regions (NE, NW, SE), snow depth was decreasing much stronger in SE than in NE or NW. The mean trend of December snow depth below 1000 m was -0.6 cm decade^{-1} (all further trends in the same unit) in SE and NE, while in January it was -0.7 in NW and NE, but -1.7 in SE (Table 2). In February, NE stations even had increasing snow depth with +0.8, while NW and SE decreased. In the middle elevation (1000 to 2000 m), differences between north and south were even stronger and variable in amplitude during the snow season: While in December the negative trend was stronger in mean North

& high Alpine (N&hA) (-2.1) compared to SW (-0.8), for January and February we observe the opposite behaviour, with a less pronounced negative trend in N&hA (-1.7 and -2.3) compared to SW (-3.9 and -5.1).

In the spring months March and April, trends in snow depth were again more negative south than north. For example, in the middle elevations (1000 to 2000 m), the mean March snow depth trend was -3.9 in N&hA compared to -6.9 in SW, in April -5.9 compared to -7.7, and in May -1.8 compared to -4.0. Notably, stations in SW above 2000 m exhibited strong variability in trends, and there were stations with increasing snow depth in all months (November to May). While mean trends were positive until January (November 1.5, December 4.2, January 0.1), mean trends were negative otherwise (February -2.9, March -5.6, April -8.7, May -10.8).

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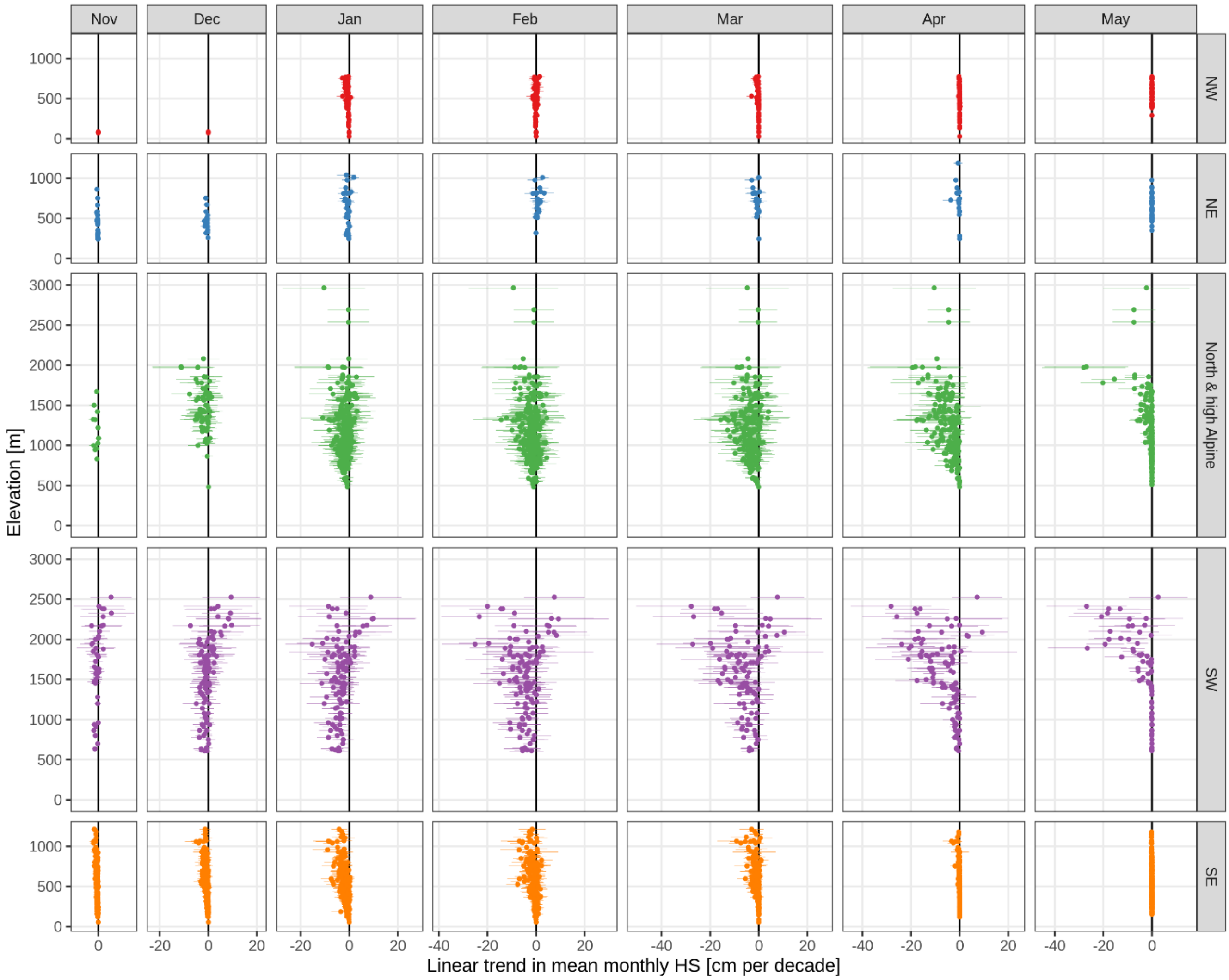

Figure 5: Long-term (1971 to 2019) linear trends in mean monthly snow depth (HS). Trends are shown separately by month (columns) and region (rows). Each point is one station. Points with lines indicate the trend and the associated 95% confidence interval.

Table 2: Overview of long-term (1971 to 2019) trends in mean monthly snow depth. Summaries are shown by month, region, and 1000 m elevation bands (0 to 1000, 1000 to 2000, and 2000 to 3000 m). Cell values are the number of stations (#), the mean trend (mean, in cm decade^{-1}), and percentages of significant negative (sig-) and positive (sig+) trends; the remaining percentage (not shown) corresponds to the total of non-significant negative and positive trends. Empty cells denote no station available (for # and mean), and no stations with significant negative or positive trends (sig- and sig+). Trends were considered significant if $p < 0.05$. See also Fig. 5. A version of the table with 500 m bands instead of 1000 m is available as auxiliary material (Matiu et al., 2020).

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Month	Region	(0,1000] m				(1000,2000] m				(2000,3000] m			
		#	mean	sig-	sig+	#	mean	sig-	sig+	#	mean	sig-	sig+
Nov	NW	2	-0.01	50.0%									
	NE	34	-0.25	8.8%									
	N&hA	4	-1.05	25.0%		9	-0.67	22.2%					
	SW	7	-1.03	57.1%		23	-0.80			12	1.52		
	SE	218	-0.45	11.9%		8	-1.34	50.0%					
Dec	NW	2	-0.00										
	NE	24	-0.62	8.3%									
	N&hA	3	-1.54	33.3%		67	-2.06	4.5%		1	-2.02		
	SW	17	-1.47	11.8%		67	-0.85	1.5%		17	4.21		
	SE	221	-0.61	7.7%		9	-2.27	22.2%					
Jan	NW	81	-0.72	27.2%									
	NE	32	-0.70			2	0.32						
	N&hA	83	-1.98	9.6%		154	-1.72	5.2%		4	-2.83		
	SW	19	-5.03	73.7%		76	-3.91	22.4%		17	0.08		
	SE	243	-1.66	32.1%		10	-4.58	70.0%					
Feb	NW	78	-0.07										
	NE	24	0.77		4.2%	1	2.67		100.0%				
	N&hA	84	-1.35	3.6%		153	-2.30	9.2%		4	-4.09		
	SW	19	-4.76	15.8%		78	-5.09	16.7%		17	-2.91	23.5%	
	SE	228	-0.66	4.8%		12	-2.73	8.3%					
Mar	NW	65	-0.30	1.5%									
	NE	20	-0.90			1	-0.01						
	N&hA	75	-2.82	21.3%		151	-3.94	21.2%		4	-2.44		
	SW	18	-3.68	38.9%		73	-6.90	41.1%		17	-5.55	29.4%	5.9%
	SE	212	-0.61	3.8%		12	-3.25	16.7%					
Apr	NW	64	-0.06	35.9%									
	NE	19	-0.58	63.2%		1	-0.64						
	N&hA	70	-1.99	84.3%		133	-5.93	61.7%		4	-7.22	25.0%	
	SW	15	-1.25	46.7%		66	-7.73	68.2%		17	-8.66	47.1%	
	SE	218	-0.10	6.9%		7	-1.39	14.3%					
May	NW	46	-0.00										
	NE	47	-0.01										
	N&hA	80	-0.05	5.0%		117	-1.77	42.7%		3	-5.70		
	SW	13	-0.03			43	-3.97	55.8%		15	-10.80	46.7%	
	SE	171	-0.02	0.6%		7	-0.14	14.3%					

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3.3 Short-term trend variability from 1961 to 2019

Complementing the analysis over the entire time period from 1971 to 2019 in the previous section, this section analyses the trends within thirty year time periods in order to show the short term variability of trends over a slightly longer time period starting 10 years earlier (1961–2019 compared to 1971–2019 before). Between 1961 and 2019, mean monthly snow depth exhibited strong temporal variability, as evidenced by the variability in 30 year trends (Fig. 6). In general, the winter months December to February showed negative snow depth trends across all regions in the periods 1961–1990 to 1976–2005, and positive trends in the periods 1981–2010 to 1990–2019. However, there were regional deviations from this general picture. High elevation stations in SW showed strong increases already in the period 1981–2010, while North & high Alpine stations were decreasing. The periods 1976–2005 and 1981–2010 showed increasing snow depth in NW, but no change in NE and decreases in SE.

In March, high variability of trends was observed for the SW stations. Similar to before, trends were mostly negative in the periods from 1961–1990 to 1976–2005, both positive and negative in the period 1981–2010, and mostly positive in the periods 1986–2015 and 1990–2019. While North & high Alpine stations exhibited the same pattern, the magnitude of the positive and negative trends was smaller. This implies much stronger short-term variability in the southern Alps compared to the north.

In April and May, the pattern across the 30 year periods remains similar, however, all trends are more negative. Trends are negative across all periods for almost all stations in the three northern regions. Only some high-elevation SW stations show positive trends in April and May in the periods 1961–1990 and 1981–2010 to 1990–2019.

All these patterns fit the previous studies, which showed high snow amounts in the 1960s and 1970s and negative anomalies in the 1980s and 1990s, i.e. snow scarce winters, regime shifts or breakpoints in that period in France, Switzerland, Italy, and the western and southern part of Austria, and a recovery afterwards (Durand et al., 2009; Laternser and Schneebeli, 2003; Mallucci et al., 2019, 2019; Marcolini et al., 2017b; Marty, 2008; Micheletti, 2008; Scherrer et al., 2013; Schöner et al., 2019; Valt and Cianfarra, 2010). In an Alpine wide view, this temporal variability is accompanied by a strong spatial variability, especially comparing stations north versus south of the main ridge.

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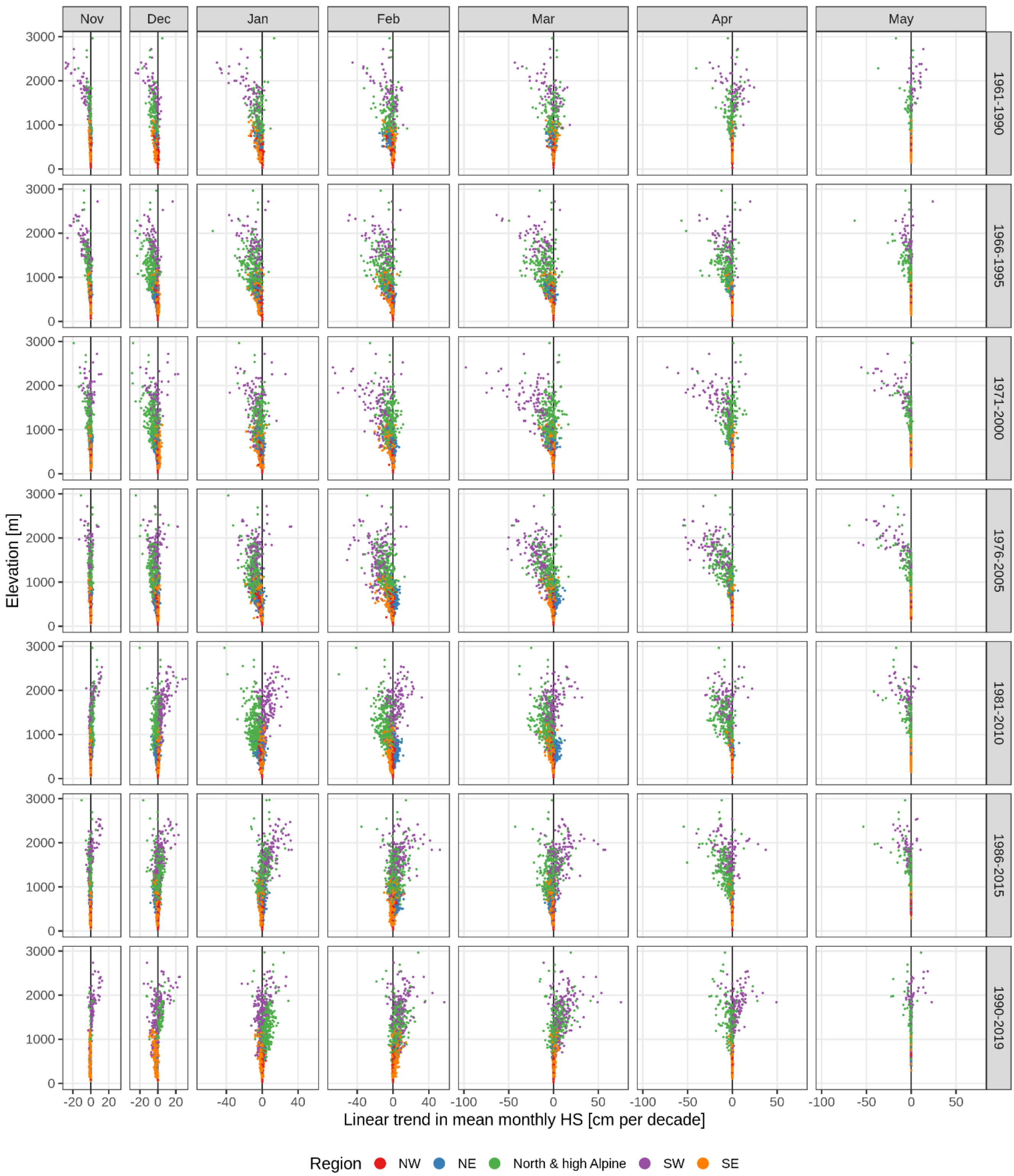

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Figure 6: Thirty year linear trends in mean monthly snow depth (HS) from 1961 to 2019. Each point represents one station, the rows denote the 30 year period used to calculate the trend, and the columns the months. Larger plots and all intermediate windows are available as auxiliary material (Matiu et al., 2020).

3.4 Representativeness of the stations in an Alpine wide context

Most of the analysis was performed with the aim to maximize the number of available observations per month. While this results in unbalanced station sets across months, it should provide better areal estimates than significantly reducing the station set to complete seasonal series only. Moreover, we assume that most of this seasonal imbalance is because there is no or no significant snow cover in that month, and not because the stations have missing observations.

Station observations generally do not cover the full elevational gradient and are supposed to be more densely located at lower elevations. Since we aimed to give an Alpine wide assessment, the elevational representation of the station observations is crucial in determining the confidence in the results. For this, we compared the elevation distribution of our station set with a digital elevation model (DEM) at 1 km resolution for the area spanned by the stations (Fig. 2(b)). In relative terms, the elevations of the stations used in this study oversample the elevations up to 1000 m, are similar from 1000 to 2000 m, significantly underrepresent 2000 to 3000 m, and do not cover elevations above 3000 m.

If the absolute number of stations used in this study is deemed sufficient to describe the spatial coverage, then the confidence of statements would be high for elevations up to 2000 m, while between 2000 and 3000 m, the results should be taken more cautiously. The elevations above 3000 m are only local features, but in an Alpine wide view they only cover a minimal area (0.7% of the area studied here, see Fig. 2(b)), and thus their significance is limited for hydrological applications, yet they remain relevant for mountain ecosystems, glacier dynamics and mountain (ski) tourism.

Spatial variability of snow increases with elevation (see also Fig. 7), and thus the absolute number of stations required for comparative assessments would be even higher for high elevations compared to low elevations. This limitation could be tackled with automatic snow depth sensors, which better sample high elevations; however, their historical time series are yet too short for assessing long-term trends, besides their issue of harmonized data processing (see also Sec. 1).

3.5 Snow depth climatology and links to temperature and precipitation

Besides differences in trends, the regions also demonstrate different snow depth climatologies (Fig. 7). Looking at average winter (December to February) snow depth 1981–2010, the northern regions had higher snow depths than their southern counterparts. These differences became larger with increasing elevation: While below 750 m no substantial differences were observed, southern stations had ~30% less snow than northern station until 1750 m, and ~20% less until 2250 m; above the number of stations is too low (Table C2).

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Average winter temperatures were higher in NW compared to NE and SE, and the latter two were similar. In North & high Alpine and SW temperatures were also comparable, although northern stations were colder in 1500–2000 m. However, precipitation amounts were significantly lower south than north, and SW stations received ~100m less winter precipitation that North & high Alpine stations up to 2000 m, which amounts to ~1/3 of the precipitation north. These results suggest that the difference in December to February snow amounts north versus south are driven by precipitation differences and not temperature.

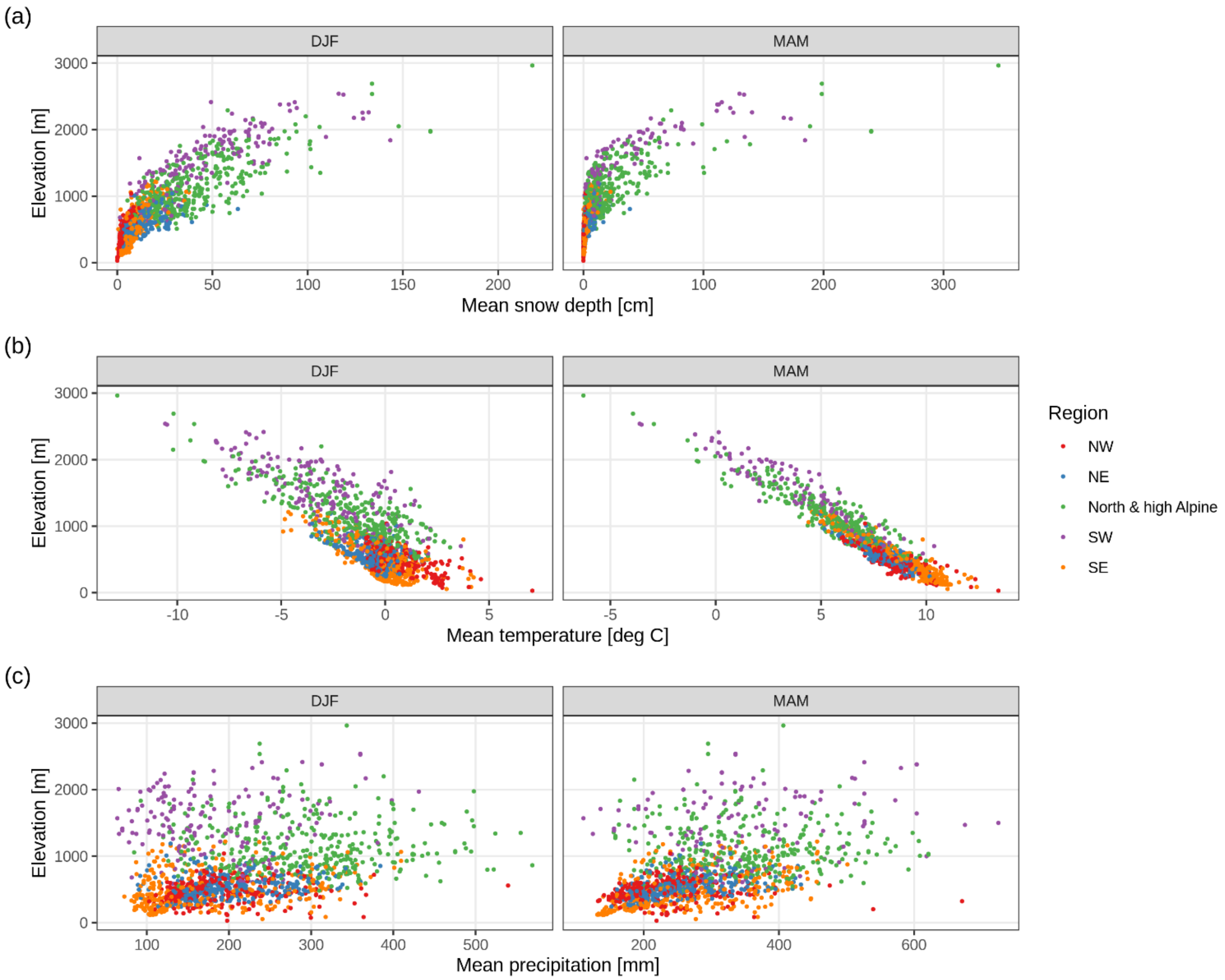

Figure 7: Climatology of (a) snow depth, (b) temperature, and (c) precipitation across regions and elevations for the winter season (December to February, DJF) and spring season (March to May, MAM). Average values are for the period 1981–2010. Each point represents one station. The temperature and precipitation values were extracted from MESCAN–SURFEX reanalysis, while the snow depths are based on station data. See also Table C2 and C3 for summary values.

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Seasonal snow depth was correlated to temperature and precipitation extracted from a gridded reanalysis (MESCAN–SURFEX). Results indicate negative correlations with temperature, decreasing strongly with elevation, and positive correlations with precipitation, mildly increasing with elevation (Fig. B5). The magnitude of temperature correlations was between -0.8 and -0.5 below 1000 m, and the correlation decreased to about -0.2 up to 2000 m. For precipitation, correlations were between -0.2 and 0.7, with much higher variability than temperature. Correlations of snow depth with temperature did not differ by region. However, the stations in SE exhibited stronger (more negative) correlations with precipitation than the NE and NW regions.

The findings on the correlations agree with previous estimates for Swiss and Austrian stations (Schöner et al., 2019) in terms of signs and elevation patterns. However, our estimates are of higher magnitude for both temperature and precipitation. While the climatological and correlational results do not suffice to formally attribute changes in snow cover to temperature and precipitation, they highlight temperature and precipitation as likely drivers of variability and change, consistent with the physical understanding of snow processes (Hock et al., 2019). The lower precipitation amounts south of the main ridge and higher correlations (at least for SE) could be causing the higher variability of snow depth trends in the southern regions, because this implies less chances that precipitation falls at the “right” time.

As sensitivity analysis, we repeated the climatology and correlational analysis using observation based spatial analyses instead of reanalysis for extracting temperature and precipitation (Fig. B6, Table C4, Fig. B7), but results did not differ qualitatively from above.

3.6 Outlook

The scope of this study was primarily the detection of snow depth trends, thereby contributing to better understanding and quantification of the state and evolution of the mountain cryosphere in the European Alps (Beniston et al., 2018; Hock et al., 2019). The formal attribution of the trends to climatic drivers, such as temperature and precipitation, as well as the influence of anthropogenic climate change on snow trends (Najafi et al., 2017; Pierce et al., 2008) is not explicitly addressed, although the collation of this unique dataset allows such studies to develop in the future.

The homogenization of series, which is the removal of non-climatic parts in the time series, such as e.g. caused by instrumentation changes or station relocations, is standard practice in long-term temperature and precipitation records (Auer et al., 2007). Applying the same tools to snow depth is not straightforward. There is discussion ongoing on the appropriate homogeneity tests and suitable observation frequency, such as daily, monthly, or seasonal (Marcolini et al., 2017a; Schöner et al., 2019). Current research tries extending existing approaches with new innovations (Resch et al., 2020). Homogenization could improve the robustness of estimated trends, and be especially useful for areas with sparse observations, such as for elevations above 2000 m. However, the use of such an extended dataset based on several thousands of individuals observation stations reduces the impact of non-climatic changes in some stations, hence the explicit need of homogenization here.

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4 Conclusions

We presented the first Alpine wide assessment of snow depth trends based on in-situ measurements in the European Alps. This enabled the identification of five distinct snow regions, whose spatial gradients are related to the known diverse climatic influences for the Alps.

The trend analysis, based on measurements from 1971 to 2019, highlights the overall reduction in snow cover. Decreases in snow depth were observed for 82% of the stations from December to February (15% of these significant) and 90% for March to April (27% significant), while only 18% and 10% showed increases, respectively (0.6% of the increases significant, in both cases).

The magnitude of trends differed by region and the number of stations analysed here gives high confidence to the changes up to elevations of 2000 m, while above 2000 m the changes have to be interpreted more carefully, especially in the north, where only ~10 stations were available. The decreases in the south were on average stronger than north (Table 3). Combined with the lower snow depths south than north (Fig. 7, Table C2 and C3), this results in even stronger relative decreases south than north.

Table 3: Summary of monthly snow depth trends. The five regions were collapsed into two (north and south) and the months into seasons. Trends are given in cm decade^{-1} for winter (December to February, DJF) and spring (March to May, MAM), along with the number of stations (#) in the respective spatial and temporal subset.

Elevation	Region	DJF mean (min, max)	DJF #	MAM mean (min, max)	MAM #
(0,1000]	North	-0.9 (-7.3, 4.4)	411	-0.8 (-10.9, 0.4)	486
	South	-1.2 (-10.8, 2.3)	747	-0.4 (-8.7, 1.0)	647
(1000,2000]	North	-2.0 (-14.3, 4.4)	377	-4.0 (-28.1, 4.0)	403
	South	-3.4 (-25.1, 3.3)	252	-5.9 (-27.2, 4.1)	208
(2000,3000]	North	-3.3 (-10.4, -0.2)	9	-5.1 (-10.5, -0.3)	11
	South	0.5 (-23.3, 9.9)	51	-8.2 (-28.3, 10.5)	49

The orography of the Alps clearly manifests as a main impact on snow climatology thus defining boundaries for subregions in north versus south, followed by west versus east. The location of a stations with respect to the climatic forcing zones defines the snow depth climatology, impacts the variability of snow depth at daily scale, and can result not only in different trend strength but also trend signs. Besides these larger scale features, substantial variability exists at higher elevations within the estimated snow depth clusters. In summary, the assumption that results from one region are valid in another or for the whole European Alps needs to be evaluated cautiously.

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This study provides a clear and harmonized picture relevant to the detection of observed snow depth trends across the European Alps, thereby contributes to bridging a scientific gap, which exists for many mountain areas in the world (Hock et al., 2019). We anticipate that the dataset developed for this study, and from which a large part is made available to the broader scientific community, will provide support for further studies and in particular formal attribution studies, to physical drivers of changes as well as the quantification of their anthropogenic component, which remain extremely limited regarding snow cover trends (Najafi et al., 2017; Pierce et al., 2008).

A large community effort and open data sharing for research purposes has made this study possible. We hope to have shown the benefits of having such a data set that spans many nations and institutions and expect this dataset to be used, and perhaps expanded thanks to additional contributing organizations, in further studies addressing various sectoral applications or for the evaluation of remote sensing or reanalysis products. However, we currently lack the opportunity to have a continuously updated version. With ECA&D (European Climate Assessment & Dataset), a harmonized station data collection portal exists at the European scale for many meteorological variables. But while the coverage of e.g. temperature and precipitation is balanced across Europe, snow depth is only limited or not at all available for many European mountain regions, such as the European Alps, Carpathians, Balkan Mountains, or Dinaric Alps. It would be desirable to have an updated harmonized station dataset for the snow cover, given its importance in mountains and further downstream. This would enable to better monitor the changes, their consequences and impacts, and contribute more quantitatively than at the present to regional and global climate change, ecosystems and environmental assessments. However, such an endeavour requires a more formal umbrella and long-term commitment, e.g. in the framework of the Copernicus Earth monitoring programme of the European Commission.

Appendices

Appendix A: Data Processing

After collecting the data, the series from different data providers were harmonized and put into a common data format. This included converting all station coordinates into latitude and longitude. In a few cases, where only station name and elevation were available but no coordinates, the missing coordinates were extracted from Google Maps using the approximate location (with correct elevation) based on the station name. Most data providers use station identifiers along with station names. We chose to have unique identifiers for all stations based on the station name. Station names were standardized by replacing blanks and apostrophes with underscores, and by removing accents. If multiple stations had the same name within one network, the names were suffixed with the data provider station identifier. If multiple stations had the same name across networks, the names were suffixed with the data provider identifier.

A.1 Merging of records

The final database included several cases in which snow measurements for the same location were stored as separate records since they covered different periods and/or a slight relocation of the same station site occurred. In some cases, different records were available at very close locations where snow data were collected at the same time or over partially overlapping periods for different operative or research purposes. In order to maximize the temporal continuity and extent of available HS and HN series, the records referring to the same site or to very close locations were merged: One series was created from the multiple series by replacing missing values or missing periods. In particular, the merging was performed only if the sites were closer than 3 km and their vertical distance was less than 200 m. In the case of overlapping periods, the data from the series with the fewest gaps was retained. The merging was evaluated and performed on HS series first. In case HN series for the same sites were also available, the data were merged by following the same criteria used for HS in order to preserve consistency between HS and HN measurements. The metadata of the most recent series included in the merging was assigned to the resulting record. About 60 merged series were obtained in total and the duplicated records for the same site were discarded.

A.2 Quality control

The series were quality checked in order to remove recording errors. First, below zero HS or HN values were replaced with missing values. Then a temporal consistency check was applied to HS to identify recording errors. Series were screened for jumps larger than 50 cm (up and down in two consecutive days; or vice versa). This criterion identified 680 values from the daily observations from all series, which were checked manually, and recording errors were replaced with missing values. Another issue with HS series is that missing observations might falsely be recorded as 0 cm. To identify suspicious series, mean winter (December to February) HS and the fraction of 0 cm values were calculated per station. Then, looking at a surrounding elevation band per station (200 to 500 m, depending on the elevation and station availability), series were marked

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if the mean HS was less than the 5th percentile or the fraction of 0 cm values was higher than the 95th percentile of all stations in the elevation band. This resulted in 181 suspicious series, which were checked manually. For 32 stations, there were periods where 0 cm were obviously missing values, and in these periods the 0 cm values were replaced with missing values; the remaining 149 stations had no missing values denoted as 0 cm. Finally, during all previous manual checks, series that showed "dubious" behavior were marked, which were in total 48 series. Dubious behavior was e.g. inconsistency between HN and HS, unlikely values, improbable temporal variability, multiple seasons with no snow, or excessive gaps. From these 48 series, 29 were considered usable, 11 had some periods removed, and 8 were completely removed.

These procedures could identify some errors, but definitively not all. Because of the large number of series, it was not feasible to manually quality check all of them, and fully automatic checks are often not feasible. Instead a spatial consistency check was applied (see Appendix A.4), and the rest of remaining errors could be considered noise given the large amount of data.

A.3 Gap filling

Most series contained gaps ranging from some days up to whole seasons. In order to conduct climatological or trend analyses, gaps in the series needed to be filled. For this we employed a spatial interpolation approach, similar to the one used for temperature and precipitation records (see e.g. Brunetti et al., 2006; Crespi et al., 2018; Golzio et al., 2018). The approach is based on correlations between the series, and because snow strongly depends on elevation, we first performed a spatial analysis to identify which correlations can be expected depending on horizontal and vertical distances between stations. For this, pairwise correlations (Pearson) between the daily HS series were performed for December to April from 1981 to 2010, only if series had at least 70% valid data, and only if each pair had at least 50% of data in common. As expected, correlations decreased with both horizontal and vertical distance (Fig. A1). But correlations remained high even for large distances, e.g. correlations higher than 0.7 were found up to vertical distances of 500 m (with less than 100 km horizontal distance) or up to horizontal distances of 200 km (with less than 250 m vertical distance). It should be noted that correlations can be high even if there are large differences in amounts or ratios between the series, as long as the differences and ratios are constant across the range of values.

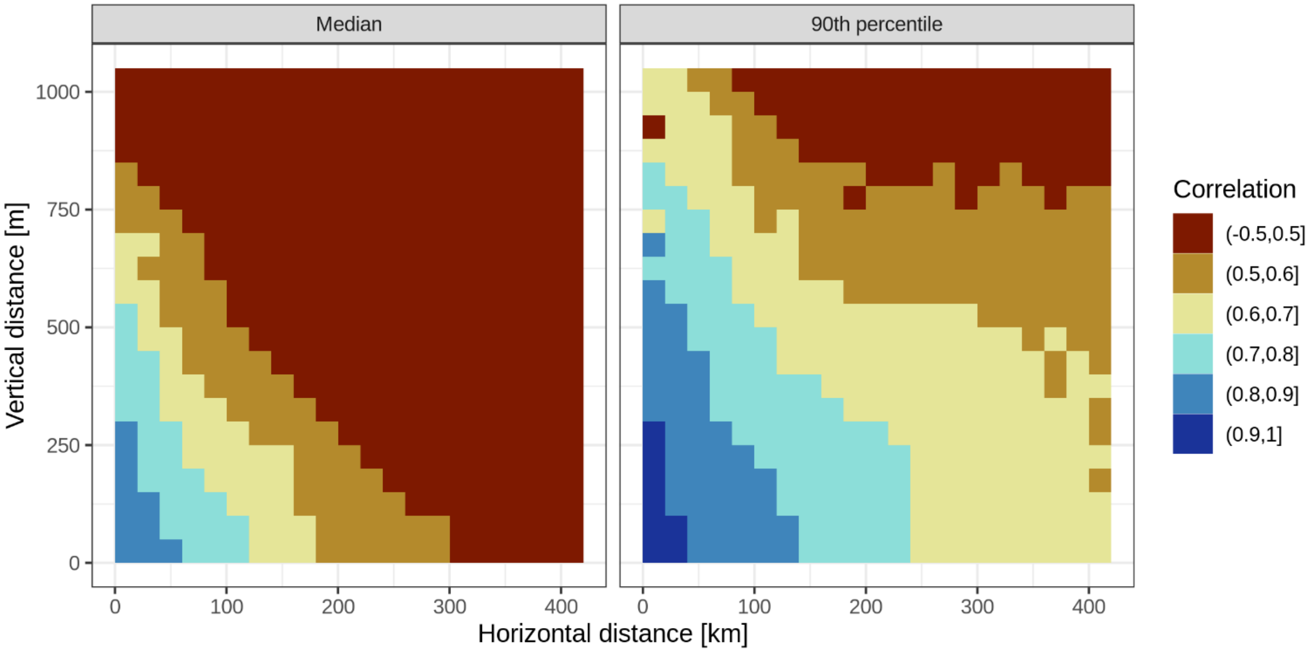

Figure A1: Summary of pairwise correlations between HS series for December to April, 1981 to 2010. Shown is the average (median, left) and 90th percentile (right) of all pairwise correlations in bins of 20 km horizontal distance by bins of 50 m vertical distance.

The chosen approach fills a gap based on finding highly correlated neighboring series to the one with gaps. The correlation is calculated on temporally surrounding data, by crossing a calendar day window with a year window. Specifically, for each gap, 15 days before and after are considered, and the same calendar days are taken 10 years before and 10 years after the gap. Thus, in total, including the gap day/year, this results in a window of 31 days by 21 years (651 potential values). The day window is increased up to 91 days, until sufficient non-missing values are available in common (threshold used here was 150 values). Based on the previous spatial analysis, reference stations were searched for in a 200 km horizontal radius with less than 500 m vertical distance. The threshold for minimum correlation was set to 0.7, as it is used e.g. in the homogenization of snow depth (Marcolini et al., 2017a). One to five reference stations were selected if they passed all of these criteria (within spatial distance, minimum correlation, enough common data in window, and no missing value on gap day); if more than five stations were available, then the five with the highest correlation were selected. Based on the same window as above, the ratio between candidate and each reference series was calculated by dividing the mean of the daily values from the candidate series with the mean of each reference series. The final filled value is a weighted average of the reference series values at the gap date multiplied with the ratios, and the weights were based on the vertical distance between candidate and reference station. The filled value was rounded to the nearest integer value in cm. Since the method requires finding suitable references stations, it was only performed for the period 1961 to 2020, because the station density was too low before. The gap filling was applied

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to all gaps in all series considering all available data; afterwards thresholds were applied to select usable series (see end of this section).

The chosen limits of 200 km horizontal distance and 500 m vertical distance might seem very high in the Alpine context with the complex topography. Since we were interested in larger scale snow pattern and not local snow peculiarities, such large distances were useful. Moreover, the correlation threshold should exert control on selecting only stations that share the same snow cover evolution, and high correlations were found up to these horizontal and vertical limits (Fig. A1). On the other hand, a nearby station might also be a worse predictor than a more distant one, if, e.g., it differs in its local climate.

Since this gap filling approach has not been yet used for snow depth, we performed a cross-validation analysis to identify the gap filling errors. For this, we used data from November to May in the period 1981 to 2010. For each station and each year, one month at a time was held out, but only if at least 10 days were available. Thus, for each month, a maximum potential of ~900 values were cross-validated; however, the effective number was lower, because of missing values, and because not all gaps could be filled, if no suitable reference stations were available. In order to test the effect of shorter period gaps, we also applied the cross-validation on subsets (to reduce computation time): 1) 100 random samples of 1 day and 2) 20 random samples of 5 consecutive days. Then, the held-out values were filled using the above approach, and metrics calculated based on the filled and held-out values. Metrics include the bias, the MAE (mean absolute error), the MAE for non-zero true values only, and a modified version of relative MAE. The relative MAE is based on the MAE for non-zero values only, and this non-zero MAE is divided by the average of true non-zero values. This is then not a "true" relative error, which would divide each error by the true value. This was done to remove the large influence of errors close to zero, which are not that relevant in this case. The metrics were only calculated if more than 50 values were available per month and station (out of potentially ~900 for the month long gaps, and 100 for the 1 and 5 day gaps), in order to provide robust estimates.

The cross-validation showed that the gap filling is unbiased (Table A1) with the overall average daily bias for the month long gaps being -0.04 cm. Average daily MAE for filling whole months was 1.6 cm (averaged over stations located in 0–1000 m), 7.7 cm (1000–2000 m), and 22.0 cm (2000–3000 m). MAE was lower for 1 and 5 day long gaps compared to month long gaps, but almost no differences were observed comparing 1 day or 5 days, e.g. for the 1000–2000 m band, MAE for 1 day gaps was 6.2 cm, for 5 day gaps 6.4 cm, compared to 7.7 cm for 1 month gaps. The relative MAE of month long gaps decreased with elevation from 39.4% (0–1000 m) to 32.7% (1000–2000 m) to 22.8% (2000–3000 m). Additionally, there was also a seasonal dependence of MAE, while bias remained largely constant across the season (Fig. A2). MAE below 2000 m peaked in February, while above 2000 m MAE increased throughout the season. Relative MAE decreased with higher snow depths, both temporally and with elevation, that is, relative MAE was lowest in February and at high elevations. It is to be expected that errors at the end of the season are related to the ablation scheme of the different stations; however, at this stage we did not check this issue further.

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Table A1: Cross-validation (CV) metrics for the gap filling approach: Bias (the difference between gap filled and observed values), the mean absolute error (MAE), mean absolute error only for non–zero observed values (MAE no zero), and MAE no zero divided by the average of all true non–zero values (Rel. MAE no zero).

Elevation band [m]	CV period	Bias [cm]	MAE [cm]	MAE no zero [cm]	Rel. MAE no zero
(0,1000]	1 day	-0.0	1.3	3.1	30.1%
	5 days	-0.0	1.4	3.3	34.0%
	1 month	-0.0	1.6	3.9	39.4%
(1000,2000]	1 day	-0.1	6.2	7.9	26.1%
	5 days	-0.1	6.4	8.2	28.5%
	1 month	-0.1	7.7	9.7	32.7%
(2000,3000]	1 day	-0.6	18.2	18.6	18.9%
	5 days	-0.8	18.3	18.7	19.2%
	1 month	-0.4	22.0	22.5	22.8%

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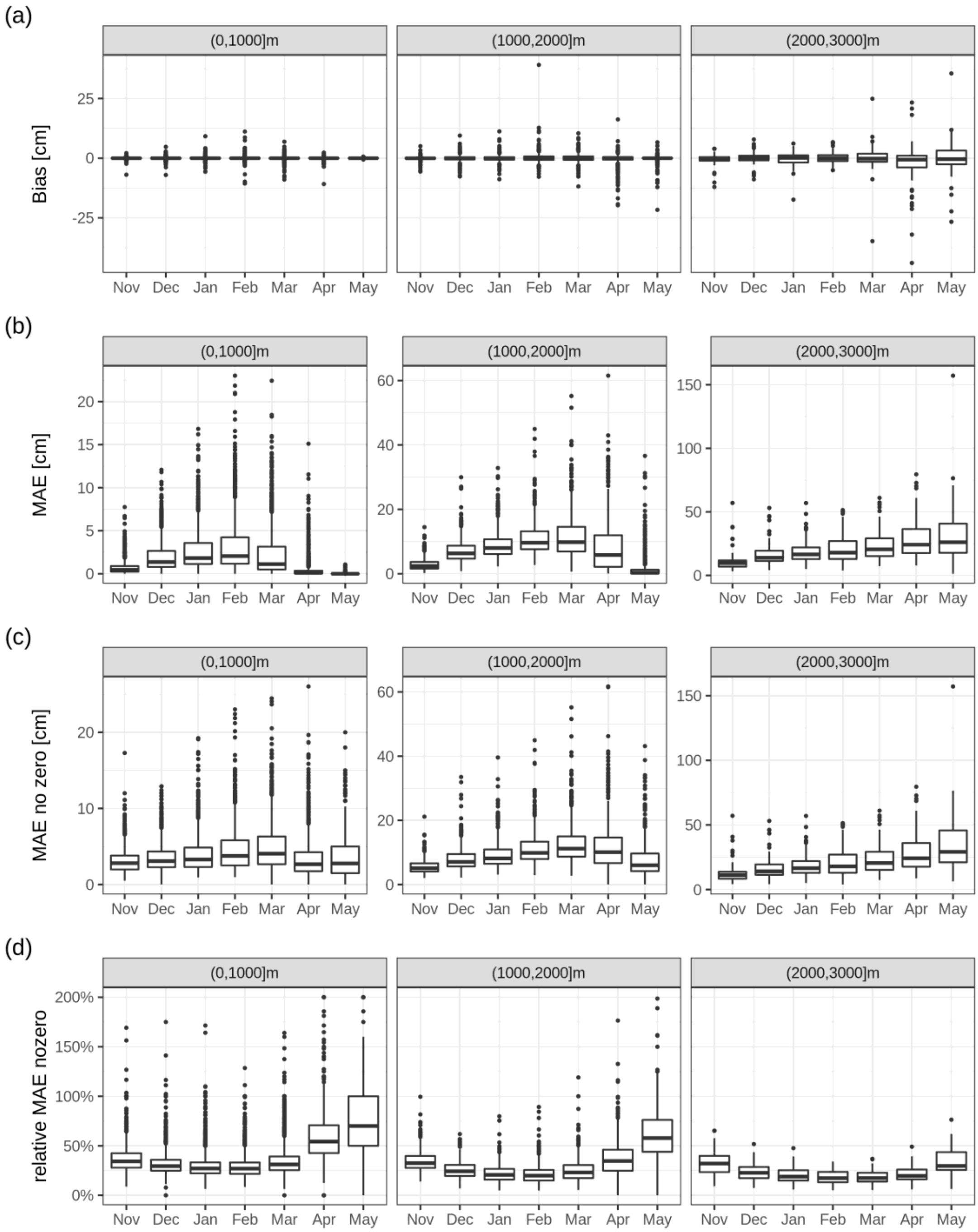

Figure A2: Cross-validation metrics for the gap filling approach: (a) bias, (b) mean absolute error (MAE), (c) mean absolute error for non-zero values (MAE no zero), (d) non-zero MAE divided by the true non-zero mean (relative MAE no zero). Panels show the 1000 m elevation bands indicated in the title.

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Moreover, we compared our proposed gap filling approach to results from gap filling snow depth series using simulations of the Crocus snow model for the French Alps. The observed snow depths with gaps were assimilated into the Crocus modelling scheme, using SAFRAN reanalysis data as forcing (López-Moreno et al., 2020). The two gap filling approaches were compared only for existing gaps in the French Alps. This was intended as a preliminary companion evaluation, and no cross-validation was performed. Thus, there was no ground truth to evaluate the two gap filling approaches with formal metrics, and we only performed a visual assessment (figures for comparison available at Matiu et al., 2020). Time series of both gap filling procedures looked remarkably similar, even for reconstructions of complete missing seasons: the different snowfall events were visible in both and snow depths averaged over multiple days were comparable. Differences emerged in the snow settling behavior and for the spring snow melting periods. More information on this exercise is available from the authors on request.
For Switzerland, a comparison of gap filling methods for HS was performed, which aimed at reconstructing complete missing seasons, and which included regression based methods and snow models (Aschauer et al., 2020). While our proposed method was not explicitly used in that comparison, it can be assumed to be similar to the regression-based and distance weighted methods used there. The errors reported in their study (root mean squared error less than 20 cm) are in the same order of magnitude as those found in our cross-validation.
Altogether, the abovementioned (the cross-validation results, the comparison to Crocus, and the preliminary findings of the Swiss study) convinced us that the gap filling procedure is also suitable for reconstructing whole seasons, and not only some intermediate gaps, considering the fact that we only used it to derive monthly means (see below) and have not used the daily values directly. Further research would be required to check the suitability of the daily reconstructions, in our opinion, also considering the temporal distance to the last existing observations. For the final analysis, all gap filled data within the recording period was used, and we also allowed extending the period up to five years before the start or after the end of the recordings – but only if the total number of gap filled observations was less than the total number of original observations. The main reason for this extension was to have series covering the complete period until 2019, because some series stopped just a few years earlier. As sensitivity analysis, we repeated the statistical analysis also for the original data without gap filling and provide results as auxiliary material (Matiu et al., 2020). The gap filling was able to significantly increase the temporal availability, but its aim was not to fill all gaps. Gaps were not filled, for example, if no suitable reference station was found or if not enough common data was available.

A.4 Aggregation and spatial consistency

The daily snow depth (HS) values were aggregate to mean monthly HS, if at least 90% of the daily values were available in the respective months after the gap filling (monthly time series plots available at Matiu et al., 2020).
Based on the monthly series, a consistency check was performed (Crespi et al., 2018), which identifies dubious values/series, (but can also identify series with strong local influences on snow depth). Each monthly HS series of the tested station was reconstructed from up to five reference stations by a spatial interpolation approach. The reference series were selected if the monthly record was available and if at least 10 monthly records were in common with the tested station. If more than five

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neighbors were available, the ones with the highest weights were selected with weights being derived from the horizontal distance and elevation difference, similar to the gap filling procedure described above. Each reference station value was rescaled by the ratio between tested and reference mean HS for the month under reconstruction. Finally, the monthly simulation of the tested series was defined as the median of the up to five rescaled neighboring values. The comparison between simulated and observed monthly HS series for each station was evaluated by computing bias, MAE, and R^2 (squared correlation) from December to February in order to avoid unreliable low error values due to zeros in HS records outside of winter.

The mean bias over all stations was -0.3 (min, max: -8.0, 10.9) cm, average MAE was 4.8 (0.1, 61.3) cm, and average R^2 was 0.83 (0.0, 0.98). However, there was a strong elevational dependency, and station metrics deteriorated with elevation (Fig. A3). A semi-automatic approach was considered to look for suspicious series. The following criteria were used to screen stations: bias outside the 95% confidence interval per elevation bands (250 m bands up to 1500 m, then 1500 to 2000 m, and 2000 to 3000 m) or MAE above a manually defined threshold line (see Fig. A3 (b)) or R^2 below 0.5 or simulation not successful because of too many gaps. This yielded 225 stations, which were checked manually by looking at monthly simulated and observed series, and daily series. Only 14 stations were found suspicious and 18 partly suspicious; all 32 series were removed from the following statistical analyses. More detailed results and time series comparing simulated with observed snow depths are available as auxiliary material (Matiu et al., 2020).

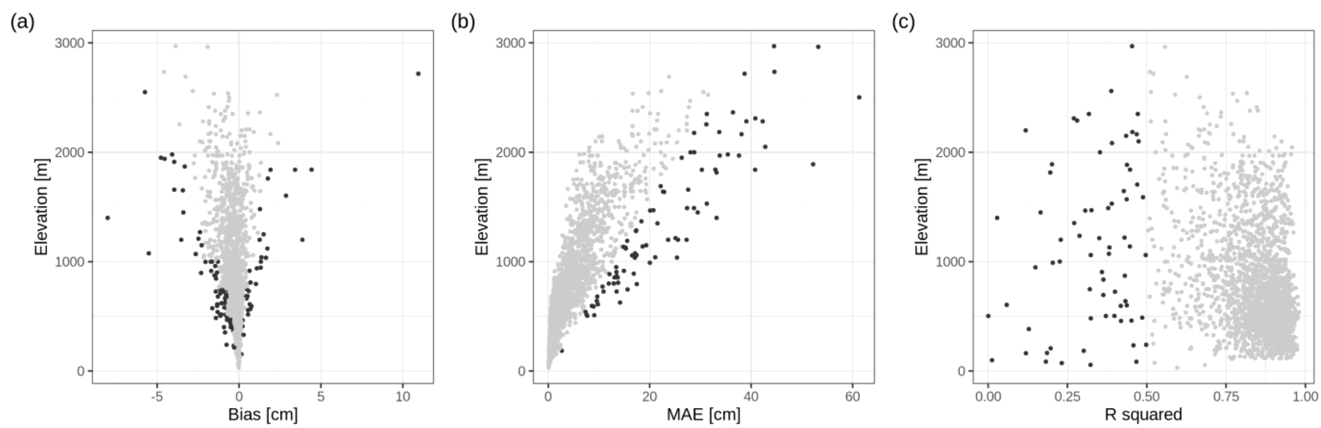

Figure A3: Metrics for spatial consistency: (a) bias, (b) mean absolute error (MAE), and (c) R squared (squared correlation). Metrics were derived from statistical simulations of the monthly series from December to February using spatial neighbours. Black points indicate stations which were further analysed with manual checks.

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755 **Appendix B: Additional figures**

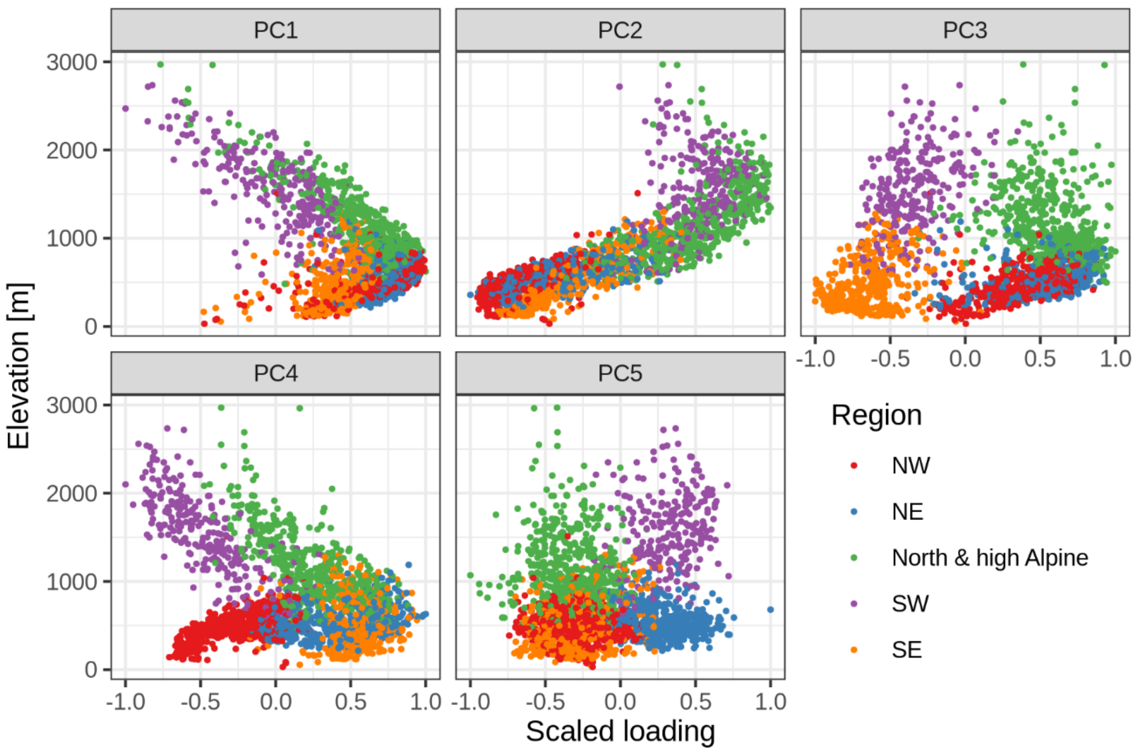

Figure B1: Scatterplots of principal component (PC) loading versus elevation and region. The PC loading can be considered the correlation of the original series with the respective PC. See Fig. 3 for a map of the PC loadings, and Fig. 4 for a map of the regions.

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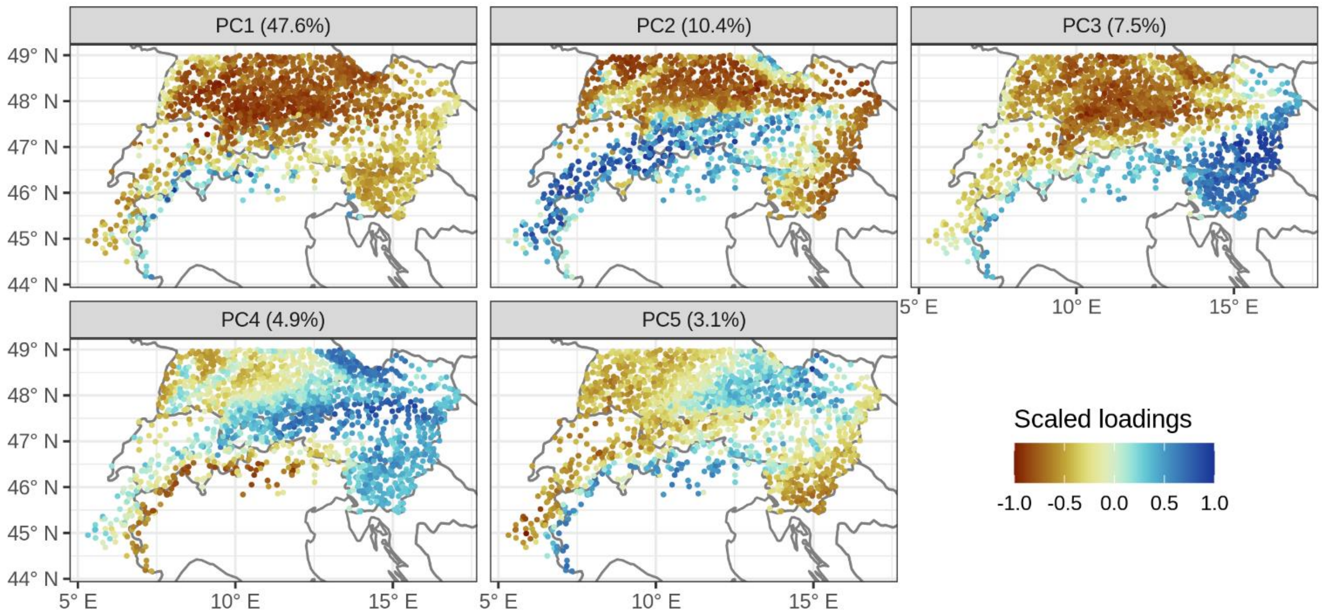

Figure B2: Same as Fig. 3 but using a standard principal component analysis (PCA) and only stations which had complete data. Main modes of variability in daily snow depth series. The plots show scaled loadings for the first five principal components (PCs). The title in each panel contains the amount of variance explained by the respective PC. The principal component analysis was applied on daily snow depth data from December to April for the hydrological years from 1981 to 2010, for stations that had no missing observations.

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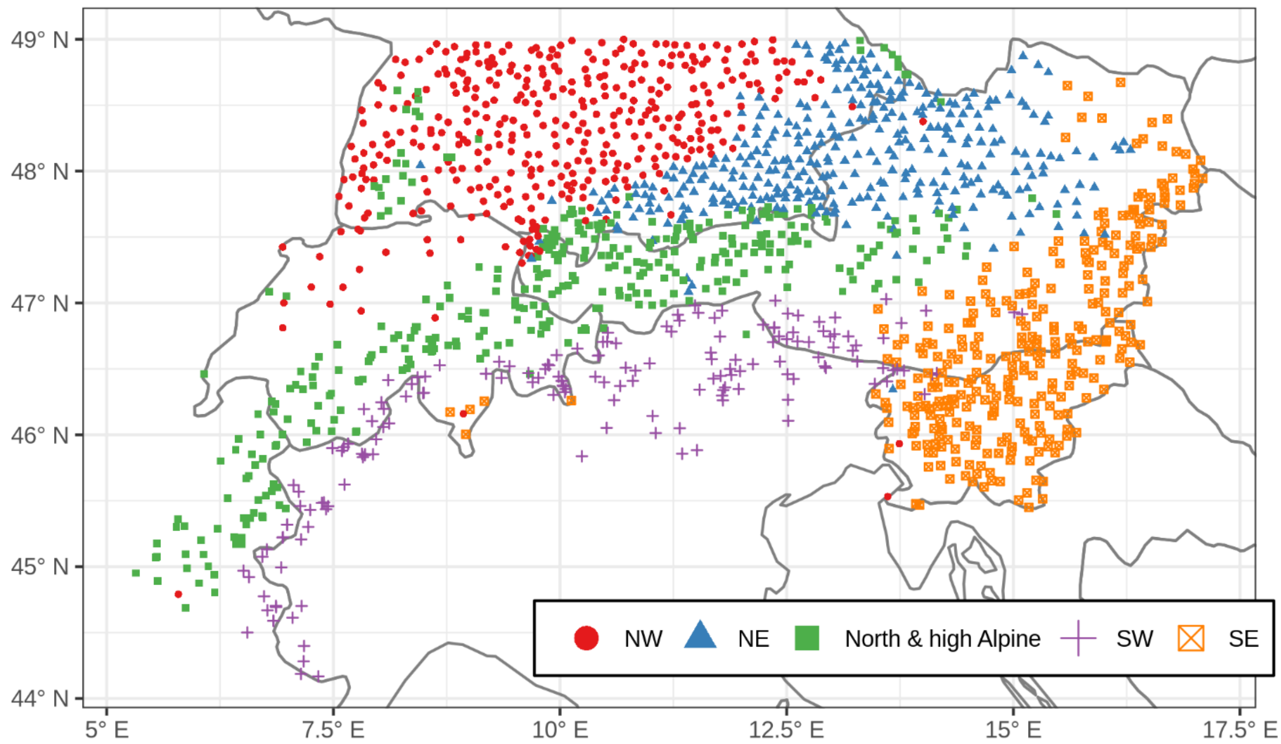

Figure B3: Same as Fig. 4, but based on the PCA from Fig. B2, which is for stations with no missing observations. Clustering of stations based on daily snow depth data. Map of regions from k-means clustering on the first five principal components. See Fig. B2
775 **for the values of the clustering matrix (loadings of the stations).**

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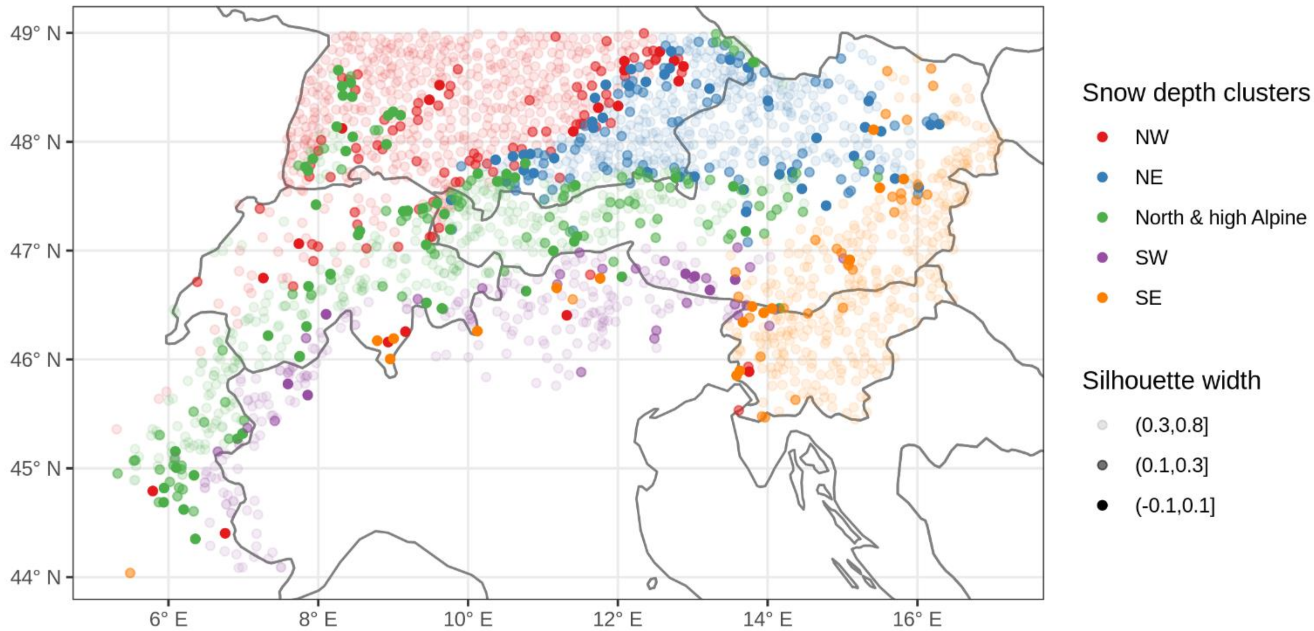

780 **Figure B4: Silhouette values of the stations, which show consistency of clustering. The silhouette is a measure of how similar the station is to its own cluster compared to the other clusters. High values indicate a good match, while low and negative values indicate a poor match.**

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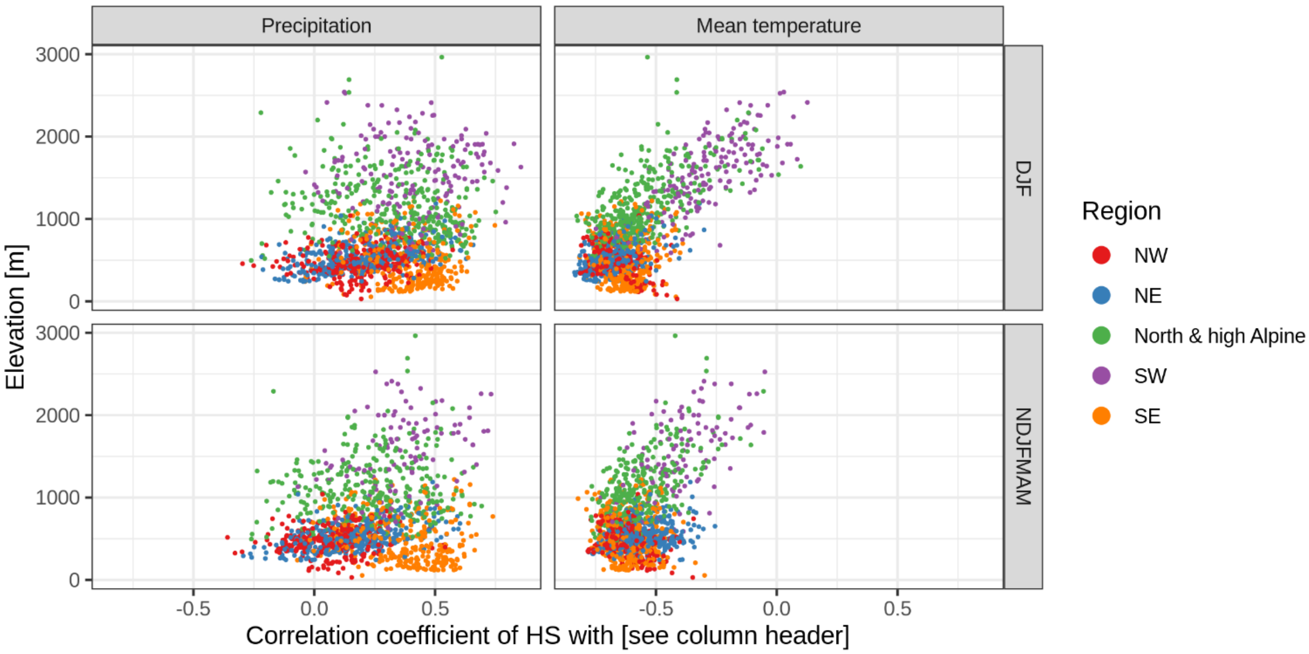

790 **Figure B5: Correlation of station snow depth (HS) with precipitation and temperature extracted from gridded products. Each point shows the Pearson correlation coefficient of seasonal HS with the seasonal sum of precipitation (left column) and with the seasonal mean temperature (right column) for one station. The top row shows the season December to February (DJF), and the bottom row the season November to May (NDJFMAM). The temperature values used in the correlations are extracted from the reanalysis MESCAN-SURFEX.**

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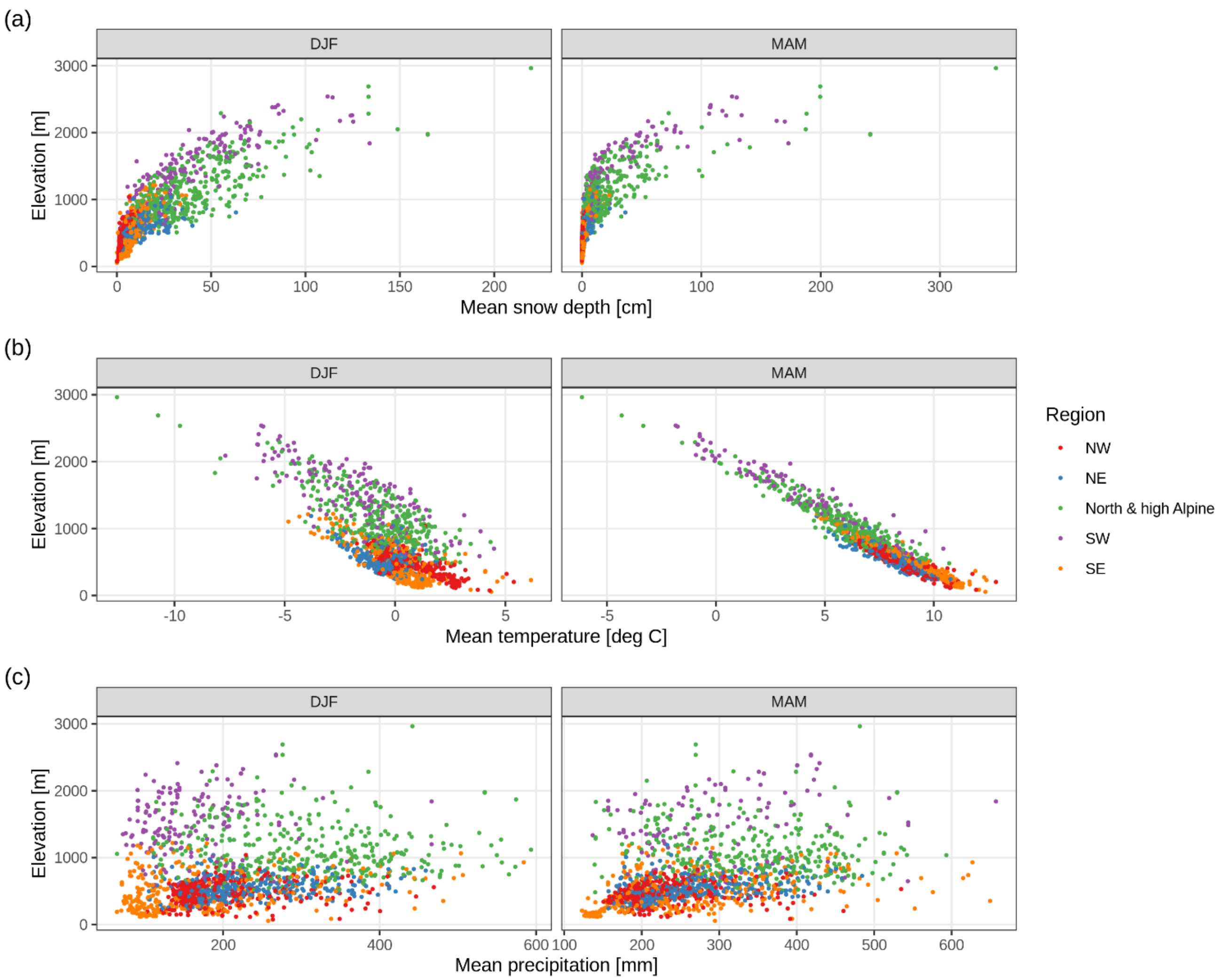

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Figure B6: Same as Fig. 7 but using observation based spatial analysis data for temperature and precipitation and the period 1981–2008. Instead of MESCAN-SURFEX reanalysis, here the temperature and precipitation values were extracted from E-OBS and EURO4M-APGD, and the period slightly shortened form 1981–2010 to 1981–2008, because of the shorter availability of EURO4M-APGD.

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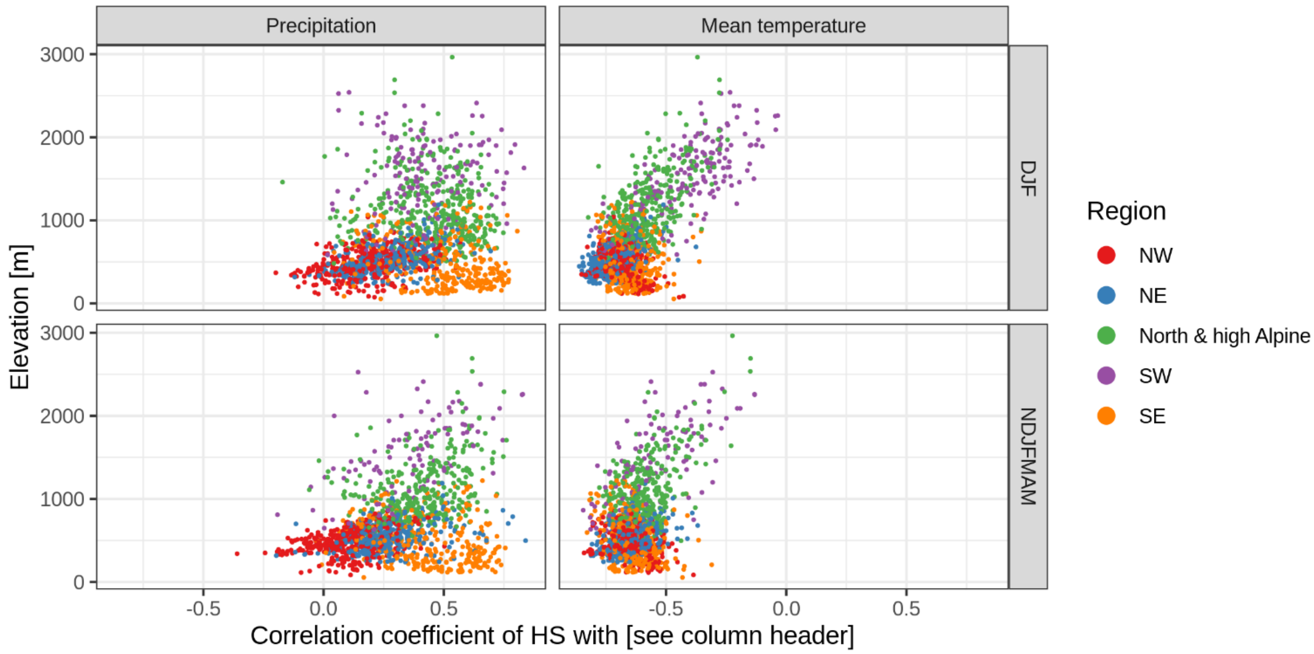

Figure B7: Same as Fig. B5 but using observation based spatial analysis data for temperature and precipitation and the period 1981–2008. Instead of MESCAN-SURFEX reanalysis, here the temperature and precipitation values were extracted from E-OBS and EURO4M-APGD

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Appendix C: Additional tables

810 **Table C1: Overview of shareable data. Column daily indicates if the original daily data can be shared, and monthly if the derived monthly data can be shared.**

Code	Country	Data provider	Daily	Monthly
AT_HZB	Austria	HZB	no	yes
CH_METEOSWISS	Switzerland	MeteoSwiss	no	yes
CH_SLF	Switzerland	SLF	no	no
DE_DWD	Germany	DWD	yes	yes
FR_METEOFRANCE	France	MeteoFrance	yes	yes
IT_BZ	Italy	Bolzano	yes	yes
IT_FVG	Italy	Friuli Venezia Giulia	yes	yes
IT_LOMBARDIA	Italy	Lombardia	yes	yes
IT_PIEMONTE	Italy	Piemonte	no	no
IT_SMI	Italy	SMI	no	no
IT_TN	Italy	Trentino	yes	yes
IT_TN_TUM	Italy	Trentino (TUM)	no	no
IT_VDA_AIBM	Italy	Valle D'Aosta (AIBM)	no	no
IT_VDA_CF	Italy	Valle D'Aosta (CF)	yes	yes
IT_VENETO	Italy	Veneto	no	yes
SI_ARSO	Slovenia	ARSO	no	yes

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Table C2: Climatology of snow depth (HS), air temperature and precipitation for the period 1981–2010 for winter (December to February). The temperature and precipitation values were extracted from MESCAN–SURFEX reanalysis, while the snow depths are based on station data. See also Fig. 7.

Elevation	Region	HS [cm]	Temperature [deg C]	Precipitation [mm]	Number
(0,250]	NW	1.0	2.7	202	27
	NE	3.3	-0.2	135	5
	SE	3.5	0.8	145	73
(250,500]	NW	2.6	0.5	175	165
	NE	5.7	-0.3	184	148
	North & high Alpine	4.3	1.5	249	2
	SE	6.0	0.3	166	111
(500,750]	NW	4.8	0.0	189	123
	NE	11.9	-0.7	220	142
	North & high Alpine	20.8	0.3	284	48
	SW	14.9	0.6	188	12
	SE	9.1	-0.3	207	69
(750,1000]	NW	8.0	-0.5	199	9
	NE	19.9	-1.6	229	31
	North & high Alpine	26.7	-0.4	288	108
	SW	22.5	-0.6	215	16
	SE	14.3	-1.5	208	44
(1000,1250]	NW	7.4	0.1	194	1
	NE	21.3	-1.9	169	3
	North & high Alpine	35.4	-1.0	309	84
	SW	22.5	-1.5	176	21
	SE	20.1	-3.4	189	16
(1250,1500]	North & high Alpine	48.9	-2.4	284	66
	SW	34.6	-2.3	168	36
(1500,1750]	North & high Alpine	56.8	-3.9	287	35
	SW	47.0	-3.3	177	34
(1750,2000]	North & high Alpine	81.1	-5.5	279	21
	SW	65.5	-4.2	191	33
(2000,2250]	North & high Alpine	103.6	-6.7	290	5
	SW	77.2	-6.4	165	13
(2250,2500]	North & high Alpine	58.0	-9.4	270	1
	SW	95.5	-7.0	235	8

Elevation	Region	HS [cm]	Temperature [deg C]	Precipitation [mm]	Number
(2500,2750]	North & high Alpine	133.8	-9.7	237	2
	SW	117.5	-10.5	360	2
(2750,3000]	North & high Alpine	218.0	-12.9	343	1

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Table C3: Same as Table C2 but for spring (March to May).

Elevation	Region	HS [cm]	Temperature [deg C]	Precipitation [mm]	Number
(0,250]	NW	0.1	10.3	251	25
	NE	0.4	9.3	177	5
	SE	0.4	10.5	203	72
(250,500]	NW	0.4	8.7	214	156
	NE	1.1	8.8	226	147
	North & high Alpine	0.4	9.6	251	2
	SE	1.1	9.7	253	111
(500,750]	NW	1.0	7.8	241	117
	NE	3.4	7.8	276	143
	North & high Alpine	6.8	8.0	342	49
	SW	3.9	8.7	329	8
	SE	2.2	8.3	302	71
(750,1000]	NW	2.1	6.5	260	10
	NE	7.4	6.7	292	30
	North & high Alpine	11.2	6.8	339	101
	SW	9.6	7.1	371	13
	SE	4.9	6.9	320	44
(1000,1250]	NW	1.7	7.1	239	1
	NE	8.0	5.7	289	3
	North & high Alpine	16.8	5.9	385	81
	SW	5.7	6.0	321	16

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Elevation	Region	HS [cm]	Temperature [deg C]	Precipitation [mm]	Number
	SE	8.1	5.3	338	18
(1250,1500]	North & high Alpine	32.0	4.5	343	57
	SW	14.5	4.7	340	26
(1500,1750]	North & high Alpine	38.6	2.8	333	26
	SW	27.9	3.2	315	18
(1750,2000]	North & high Alpine	93.7	1.5	335	13
	SW	60.6	2.4	372	24
(2000,2250]	North & high Alpine	118.1	-0.1	318	3
	SW	94.0	0.6	392	9
(2250,2500]	North & high Alpine	73.1	-1.3	376	1
	SW	119.8	-0.3	459	7
(2500,2750]	North & high Alpine	198.7	-3.4	295	2
	SW	131.9	-3.6	336	2
(2750,3000]	North & high Alpine	345.8	-6.3	407	1

Table C4: Same as Table C2 but using observation based spatial analysis data for temperature and precipitation and the period 1981–2008. Instead of MESCAN-SURFEX reanalysis, here the temperature and precipitation values were extracted from E-OBS and EURO4M-APGD, and the period slightly shortened form 1981–2010 to 1981–2008, because of the shorter availability of EURO4M-APGD.

Elevation	Region	HS [cm]	Temperature [deg C]	Precipitation [mm]	Number
(0,250]	NW	1.0	2.8	194	37
	NE	3.1	0.4	152	5
	SE	3.5	1.2	139	73
(250,500]	NW	2.5	0.8	189	192
	NE	5.6	-0.2	208	153
	North & high Alpine	4.3	2.8	196	2
	SE	5.9	0.5	169	109
(500,750]	NW	4.8	-0.1	204	157

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Elevation	Region	HS [cm]	Temperature [deg C]	Precipitation [mm]	Number
	NE	11.8	-0.5	246	149
	North & high Alpine	21.0	0.5	311	50
	SW	14.7	1.6	189	11
	SE	8.9	-0.0	212	69
(750,1000]	NW	7.6	-1.0	208	10
	NE	19.4	-1.2	268	34
	North & high Alpine	26.3	-0.1	313	116
	SW	20.0	0.5	193	15
	SE	13.9	-1.4	218	44
(1000,1250]	NW	6.4	1.4	229	1
	NE	21.1	-1.2	141	3
	North & high Alpine	35.0	-0.3	315	84
	SW	20.2	-0.6	145	21
	SE	19.6	-2.8	187	16
(1250,1500]	North & high Alpine	47.6	-1.2	296	64
	SW	31.6	-1.0	146	37
(1500,1750]	North & high Alpine	56.3	-2.2	242	34
	SW	43.5	-1.9	159	32
(1750,2000]	North & high Alpine	80.7	-3.9	311	21
	SW	62.1	-2.8	177	31
(2000,2250]	North & high Alpine	103.4	-5.2	276	5
	SW	72.6	-5.1	159	13
(2250,2500]	North & high Alpine	94.3	-5.5	286	2
	SW	96.4	-5.6	195	7
(2500,2750]	North & high Alpine	133.4	-10.2	276	2
	SW	113.0	-6.0	268	2
(2750,3000]	North & high Alpine	219.5	-12.6	442	1

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Code and data availability

Code and most of the data are available as supplementary material at a public repository (Matiu et al., 2020). See also Sec. 2.6 and Table C1 for more details.

Author contribution

Conceptualization: MM, AC, GB, CM, SM, WS; Data curation: MM, AC, GB, CMC, CM, DCB, GC, MV, WB, PC, GM, SCS, AC, RC, AD, MF, MG, LM, JMS, AS, AT, SU, VW; Formal analysis: MM, AC; Funding acquisition: MM; Investigation: MM; Methodology: MM, AC, CM, SM, WS; Resources: MZ; Software: MM, AC, CMC; Supervision: MM, MZ; Validation: MM, AC; Visualization: MM; Writing – original draft preparation: MM, AC; Writing – review & editing: MM, AC, GB, CMC, CM, SM, WS, GC, LDG, SK, BM, GR, ST, MV, PC, IG, GM, CN, SCS, US, MW, LG.

Competing interests

The authors declare that they have no conflict of interest.

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