PUBLIZIERBARER ENDBERICHT

A) Projektdaten

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Langtitel:	Snow in Austria during the instrumental period – spatiotemporal patterns and their causes - relevance for future snow scenarios
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KoordinatorIn/ ProjekteinreicherIn:	Univ. Prof. Dr. Wolfgang Schöner
Kontaktperson Name:	Univ. Prof. Dr. Wolfgang Schöner
Kontaktperson Adresse:	Heinrichstrasse 36 8010 Graz
Kontaktperson Telefon:	+43 (0)316 380 8295
Kontaktperson E-Mail:	wolfgang.schoener@uni-graz.at
Projekt- und KooperationspartnerIn (inkl. Bundesland):	Dr. Christoph Marty, WSL-Institut für Schnee- und Lawinenforschung SLF, Davos (Switzerland) Prof. Dr. Ulrich Strasser, Institut für Geographie, Universität Innsbruck (Austria, Tirol)
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Projektübersicht

1 Kurzfassung

Die langen Schneezeitreihen (Gesamtschneehöhe und Neuschneehöhe) für Österreich wurden auf raumzeitlicher Trends und Änderungen, sowie der Untersuchung der zugrundeliegenden Wetterlagen und deren Veränderungen analysiert. In einem ersten Schritt wurden dazu die Schneezeitreihen, sowohl der Zentralanstalt für Meteorologie und Geodynamik als auch der hydrographischen Dienste, einer umfangreichen Datenqualitätskontrolle und Homogenisierung auf Basis der Tageswerte unterzogen. In einem letzten Schritt wurde auch eine Zusammenschau der Zeitreihen mit den Zeitreihen der Schweiz durchgeführt, um die raumzeitlichen Aussagen im Hinblick auf die Alpenregion noch zu erweitern.

Die Homogenisierungsversuche im Rahmen von Snowpat zeigen, dass eine weitere Verbesserung der Methoden in Zukunft notwendig ist. Eine direkte Anwendung bestehender Methode ist nur bedingt möglich. Jedoch zeigen die Ergebnisse aus Snowpat auch, dass die Einflüsse der Inhomogenitäten auf die zeitlichen Trends der Schneezeitreihen deutlich geringer sind als für andere Klimagrößen.

Zirka 70 österreichische Schneezeitreihen konnten endgültig für die Ermittlung von raumzeitlichen Trends verwendet werden. Dabei ist die Anzahl der langen Zeitreihen der Gesamtschneehöhe deutlich größer als die für die Neuschneehöhe. In einem ersten Schritt wurden die Zeitreihen zu homogeneren Regionen zusammengefasst. Die langfristigen Veränderungen des Schnees in Österreich können mit 3-4 Regionen recht gut beschrieben werden. Es zeigt sich, dass für den Süden und Westen Österreichs in den letzten 50 Jahren deutlich abnehmende Trends der Gesamtschneehöhe als auch der Neuschneehöhe, im Nordosten aber keine Veränderung bzw. sogar leicht steigende Trends gemessen wurden. Die negativen Trends sind in einer Seehöhe zwischen ca. 500 und 1000m am stärksten. Während der Rückgang der Schneemengen in tiefen Lagen mit der Temperaturveränderung zu erklären ist, können die Trends in den Hochlagen mittels der Niederschlagsänderungen erklärt werden.

Eine Analyse des Zusammenhanges der Veränderungen der Neuschneehöhen mit Wetterlagen und atmosphärischen Druckmustern zeigt recht klare Ergebnisse. Auffallend sind insbesondere die aufeinander folgenden, hoch positiven NAO–Index Phasen in den 1970ern und speziell gegen Ende der 1980er und in den 1990ern. Dies deutet auf eine Verschärfung der Westwinddrift in diesen Jahren hin. Es kann davon ausgegangen werden, dass die beobachteten negativen Trends in Schneezeitreihen vor allem von Regionen südlich des Alpenhauptkammes in engem Zusammenhang mit diesen außergewöhnlich hohen NAO-Index Phasen stehen.

Regionen innerhalb Österreichs können Neuschneesummen von frontalen Systemen erhalten, welche aus unterschiedlichen Windrichtungssektoren den Alpenraum überqueren. Es wird deutlich, dass innerhalb der Periode 1989–2005 die Häufigkeit von Neuschneesummen speziell aus den Sektoren Süd bis West, teilweise auch Nordwest abgenommen haben. Im Vergleich dazu haben schneebringende, nördliche Wetterlagen zugenommen. Regionen, die Neuschnee aus mehreren Sektoren erhalten (Südwest bis Nord) sind von Änderungen in der Häufigkeit und Intensität bestimmter Wetterlagen weniger stark betroffen, als zum Beispiel Regionen südlich des Alpenhauptkammes, welche bevorzugt den Winterniederschlag aus südlichen Richtungen (Südwest–Wetterlagen) erhalten. Die beobachteten negativen Trends in den Schneezeitreihen südlich des Alpenhauptkammes können somit teilweise mit der Abnahme der Häufigkeit sowie der Abschwächung von Südwest–Wetterlagen (mediterrane Zyklonen) in der Periode 1989–2005 erklärt werden. Darüber hinaus führt aber auch die beobachtete Temperaturerhöhung zu einer Änderung des Anteils festen Niederschlags. Die Untersuchungen haben weiters ergeben, dass ab ca. 2005 die Häufigkeit von Südwest–Wetterlagen wieder zugenommen hat.

2 Executive Summary

The long-term series of snow (snow depth and depth of fresh snow) in Austria were analyzed for spatiotemporal trends and changes, as well as for investigating underlying weather patterns and their changes. In a first step, the snow time series of the Central Institute for Meteorology and Geodynamics and hydrographic services, were quality controlled and homogenized on the basis of daily data. In a final step, a synopsis of the Austrian time series together with the time series of Switzerland was carried out to enhance spatiotemporal patterns and statements with regard to the Alpine region.

It can be concluded from the homogenization as part of Snowpat, that further improvement of methods is necessary in the future. Direct application of existing methods is limited. However, the results from Snowpat also show that the effects of the inhomogeneities on the temporal trends of the snow time series are significantly lower than for other climate variables.

Approximately 70 Austrian snow time series could be finally used for assessing spatio-temporal trends. The number of long-term series of snow depth is significantly greater than that for fresh snow. The time series were clustered into homogeneous sub-regions by cluster analysis and PCA. The long-term changes of the snow in Austria can be described by 3-4 regions quite well. It turns out, trends of snow depth and the snow depth significantly decreased in the south and west, but no change or even slightly increasing trends were measured for the northeastern part of Austria in the last 50 years. The negative trends are strongest in altitudes between 500 and 1000m. While the decline in amounts of snow at low altitudes can be explained by the increasing temperature, trends at high altitudes are correlated to precipitation changes.

Analysis of the relationship of the changes of snow heights with weather patterns and atmospheric pressure patterns show quite clear results. Particularly striking are the successive, high positive NAO index phases in the 1970s, especially in the late 1980s, and in the 1990s. This points to a tightening of the west wind drift during these years. It is quite obvious that the observed negative trends in snow time series, in particular for regions south of the Alps, are closely connected with this exceptionally high NAO index phases.

The various regions within Austria receive fresh snow during passages of frontal systems which cross the Alps at different wind directions. Obviously, during the period 1989-2005 fresh snow has decreased especially in the sectors of south to west, partly also northwest. In comparison, snow-causing weather events from the north have increased during the same period. It can be concluded, that regions which receive snow from several sectors (southwest to north) are less affected by changes in the frequency and intensity of certain weather conditions, as, for example, regions south of the Alps, which preferably receive winter precipitation from the south (southwest weather patterns) almost exclusively. The observed negative trends in the snow series south of the Alps can thus be explained in part by the decrease in the frequency and the weakening of southwest weather patterns (Mediterranean cyclones) in the period 1989-2005. In addition, however, the observed increase in temperature decreases the ratio of solid precipitate on total precipitation. Our investigation further revealed that from approximately 2005 onwards, the frequency of southwest-weather patterns has increased again.

3 Hintergrund und Zielsetzung

Snow is not only an important factor for Alpine economy (e.g. tourism, agriculture) but also a key driver of environmental changes in the Alps. It is a vital natural water storage for both mountainous and lowland regions (Barnett et al., 2005) highly impacting low-flow events and floods (Blöschl et al., 2011). In particular, when precipitation falls as snow runoff peaks can be damped or delayed. In addition, a clear shift in the timing and magnitude of runoff for Alpine streams in spring has been observed as a consequence of climate change for snow dominated catchments (Blöschl et al., 2011). The absence or presence of a snow cover is also an important driver for vegetation growth and thus changes in the snow amount can result in shifts in the species distribution of plants (Keller et al., 2005).

Surprisingly, although snow has been described as highly important for economy and environment in Austria by many studies, research on its spatio-temporal changes based on long-term observational series are rather sparse. First step towards such a study were done by Steinhauser (1974), Fliri (1992a, 1992b) and by the Startclim projects Startclim 1 (Schöner et al., 2003) and Startclim 2007 (Auer et al., 2005) with latter two focusing on data preparation and data quality control based on observational data from ZAMG (Zentralanstalt für Meteorologie und Geodynamik) back to 1948. Due the limited resources of Startclim projects snow data were exploited back to 1948 only and analysis and interpretation of data series are thus rather initial. In Hantel et al. (2000) data on days with snow cover and air temperature from Austria were analyzed for assessing the sensitivity of days with snow-cover on air temperature. Schöner et al. (2009) used the outstanding snow depth measurement at Sonnblick to study the high-alpine snow variability back to 1928. Quite recently, the ACRP project CC.Snow performed an extensive modelling strategy of future snow cover for skiing resorts in Austria based on regional climate model runs (including a transdisciplinary approach of stakeholder involvement). In contrast to Austria, several studies on past snow cover variability and changes were performed for Switzerland (e.g. Beniston, 1997, Beniston 2003, Laternser and Schneebeli, 2003, Scherrer and Appenzeller, 2004, Marty, 2008, Serquet et al., 2011).

Both snow depth and snow duration in the Alps are characterized by their high inter-annual to decadal variability, which indicates a high sensitivity to climatic conditions. The variability is not captured from climate model runs (Steger et al., 2013) and thus of utmost interest for interpretation of future snow scenarios. During the last 20 years the Alpine region experienced several winters with snow scarcity due to warm and dry conditions (e.g. the early 1990s and 2006/2007) but also snow abundant winters as e.g. 1996/1997 and 2008/2009. Whereas winters with snow scarcity immediately opens widespread discussion on problems for winter tourism, which is a fundamental driver of Alpine tourism in general (e.g. Koening and Abegg, 1997), snow abundant winters are often associated with problems of considerable hazards such as avalanches, spring floods or snow loads on infrastructures. In terms of winter tourism, Abegg et al. (2006) showed that many alpine ski resorts need at least 100 days of snow per year above a threshold of 30cm to be cost effective. Beside spatial variability, it is known from observations that snow depth and snow duration in Austria could be also spatial highly variable, as seen for e.g. the winter 2009/2010, when the eastern part of Austria gained relatively long snow duration compared to the western part of Austria. With respect to driving forces, NAO (North Atlantic Oscillation) is known to have major impact on the climate in Europe (Wanner et al., 1997). Scherrer et al. (2004) found that NAO does not explain inter-annual variability of snow days for northern part of Swiss Alps but explain a substantial part of inter-annual variability of snow days for the southern part of Swiss Alps. For decadal trends, however, the NAO significantly explains snow days variability via air temperature for the northern part of the Swiss Alps and via precipitation and air temperature for southern part of Swiss Alps. In addition, NAO is correlated to atmospheric blocking, with negative correlation for Atlantic blocking and positive correlation for blocking over Central and Western Europe (Scherrer et al., 2006). Scherrer and Appenzeller (2006) found high value of explained variance of a uniform new snow sum patterns in Switzerland explained by European blocking (43.5%), whereas a low-high elevation gradient pattern of new snow sum in Switzerland was well explained by the NAO (30.6%).

Homogeneity of observational series of climate variable is known to be essential for deriving robust spatiotemporal trends and changes (e.g. Auer et al., 2007). However, homogenization methods were not applied to snow series so far and experience is missing in particular for homogenizing daily data series. Previous studies either did not use the nowadays tools of data compilation, quality control and homogenisation (e.g. Fliri 1992a, 1992b) or were based on studies from single series only (Schöner at al, 2009). In comparison to other regions worldwide, however, snow observations in Austria have a high potential for studying the snow climatology with respect to series length (back to 1895), spatial density (about 50 long-term series could be expected for Austria) and available knowledge on climate change. Both researchers and practitioners would highly benefit from both the expected database, the analyzed spatiotemporal patterns and derived understanding of mechanisms. Consequently, SNOWPAT aimed at

- providing a comprehensive and homogenised data set of snow characteristics (snow depth, snow duration, depth of fresh snow) covering the entire period of observations in Austria
- analyzing spatiotemporal patterns of snow as well as their changes and trends for Austria back to 1895
- improving the representativeness of derived spatiotemporal patterns by including existing snow series from Switzerland and thus covering a major part of the Alpine longitudinal extent reflecting significant climate gradients
- understanding past changes in snow patterns (including extremes) in Austria from underlying mechanisms, such as weather types and large scale atmospheric circulation patterns and describing to which degree snow relevant weather types are captured by Global Climate Models
- analyzing the influence of the Alpine main divide on spatiotemporal patterns of snow at high elevations from the observational network at Sonnblick
- disseminating the project results to relevant stakeholders

4 Projektinhalt und Ergebnis(se)

The workload of the SNOWPAT project was structured into 7 work packages (see Figure 1 below). The content and results of the project are presented according to the work package structure.

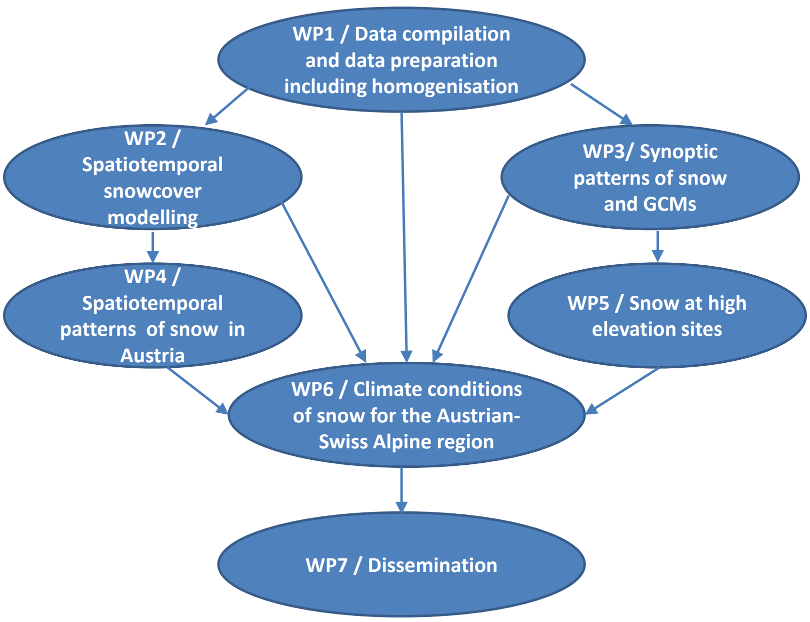


Figure 1: The work-package structure of SNOWPAT

WP1: Data compilation and data preparation including homogenization

The purpose of this chapter is to investigate the question to what extent the homogenization of climate data records of snow depth is suitable. A set of consistent and reliable long-term time series of snow depth on a daily scale from selected meteorological sites across Austria is used. The data records were collected by the Central Institute for Meteorology and Geodynamics (ZAMG) and the Hydrographical Central Bureau of Austria (HZB). The dataset consisted of 41 ZAMG time series and 28 HZB time series on a daily scale. They cover a time period from the late nineteenth century until today. It is well known that the wind induced error may strongly contaminate measurements (Sevruk 1985). Furthermore, long-term climate data records are expected to be affected by non-climatological inhomogeneities, i.e., changes in the measurement conditions. Thus, effective quality controls and homogenization methods are needed to identify erroneous and inhomogeneous snow data.

Time series of the ZAMG network did undergo an extensive quality control and were tested for inner and outer consistency, respectively. Most of the climate data records provided by the HZB network are quality proofed backwards to the beginning of the 1970s. However, it should be noted that in a first step a plausibility check was done for the digitalized HZB raw data before 1970 at low level in order to reject major errors in the time series.

For the ZAMG stations a detailed metadata history exists including information of station relocation and changes in the observing system, i.e., change of the observer and change from analogue to digital measurement. In contrast, the HZB metadata information of station relocation was accessible only. Since uncertainty in observations is a main source of errors in subsequent trend analyses, it is implied that time series of stations which experienced major relocations in the past may poorly represent “true” temporal variability. Regarding the reliability of the snow data, the unknown observational error is expected to be small compared to artificial shifts in snow depth time series due to relocations.

Impact of homogenization on temporal changes

The homogenization process yields seasonal correction factors, which are calculated using the best-correlated reference time series. These correction factors are applied multiplicatively to the inhomogeneous time series of the candidate station. It should be noted, that due to the multiplicative approach no additional snow days are added to the corrected time series. In contrast, the multiplication of correction factors less than 1 may remove days with observed snow depths from the candidate time series.

Figure 2 shows the difference of seasonal (NDJFM) mean snow depths of the best correlated reference time series and the candidate time series of the station Galtür (1577 m a.s.l.), which is located West of the Austrian Alps. The difference is changing before and after the detected break (black vertical line in Figure 3 indicates the computed break date). The calculated seasonal correction factor for the time series of Galtür is 1.2. Applying this factor to the original time series yields an expected increase in seasonal (NDJFM) snow indices (Figures 4 and 5). Clearly, the change in snow cover duration subject to different snow depth thresholds is less pronounced, compared to the corrected seasonal mean snow depth and seasonal maximum snow depth.

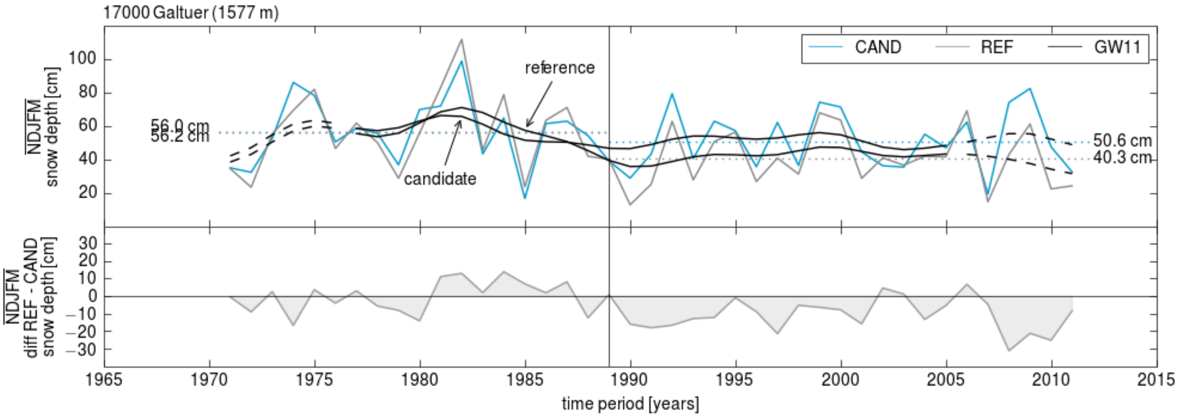


Figure 2: Seasonal (NDJFM) mean snow depth [cm] of the best correlated reference time series (grey) and the candidate time series Galtür (blue). The black vertical line indicates the break date. A Gaussian low pass filter (window length: 11 years) is used for smoothing of time series. The dotted lines indicate the mean snow depth [cm] of the candidate and reference time series before and after the break. The lower panel shows the difference between the reference and candidate time series.

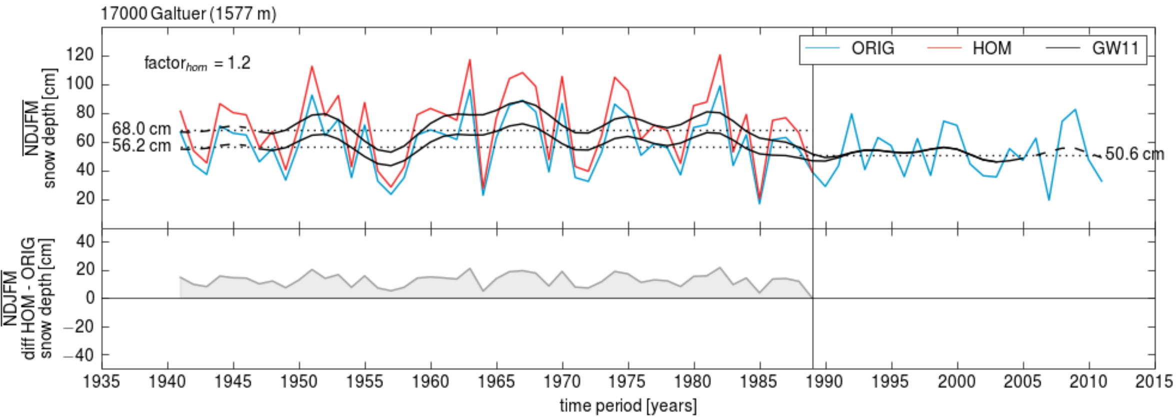


Figure 3: Difference between original and homogenized time series (Galtür) of seasonal (NDJFM) mean snow depth [cm]. The vertical black line indicate the break date, the dotted lines indicate the mean snow depth [cm] before and after the break. The lower panel shows the difference between the corrected and original time series. The seasonal correction factor is also shown.

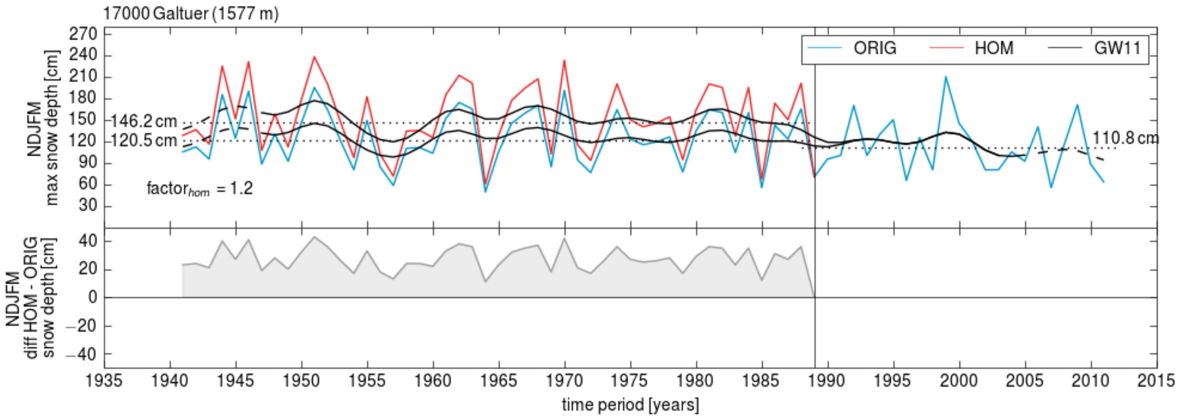


Figure 4: Difference between original and corrected time series (Galtür) of seasonal (NDJFM) maximum snow depth [cm]. The vertical black line indicate the break date, the dotted lines indicate the mean maximum snow over the time window before and after the break.

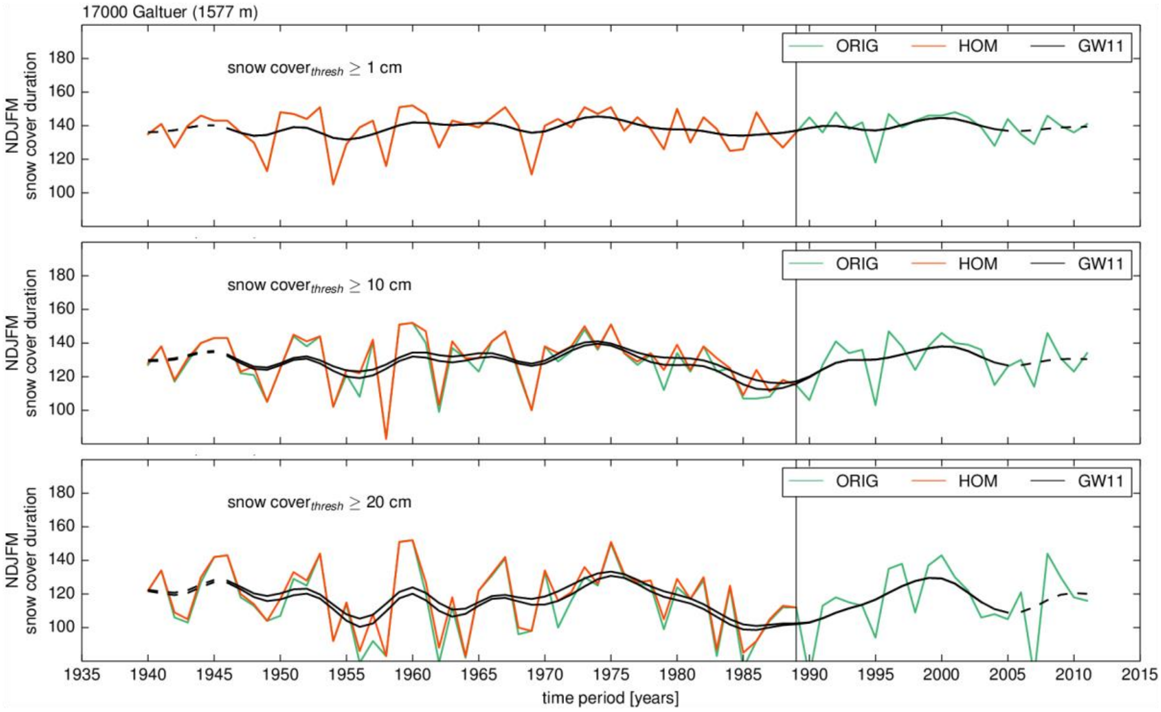


Figure 5: Difference between original and corrected time series (Galtür) of seasonal (NDJFM) snow cover duration [days] for a threshold of snow depth >=1 cm (top), 10 cm (middle) and 20 cm (bottom).

Homogenization results for snow depth and depth of new snow in Austria

Figure 6 summaries the homogenization results. 69 snow depth time series on a daily scale from stations across Austria were tested. 6 time series were corrected by multiplicatively applying a computed seasonal correction factor. The detected breaks have been verified against the available metadata. It turned out, that most of the artificial shifts in the time series can be explained by station relocations (Table 1). In 6 time series breaks were detected close to the observation start or end, which can be attributed to the changed number of reference time series.

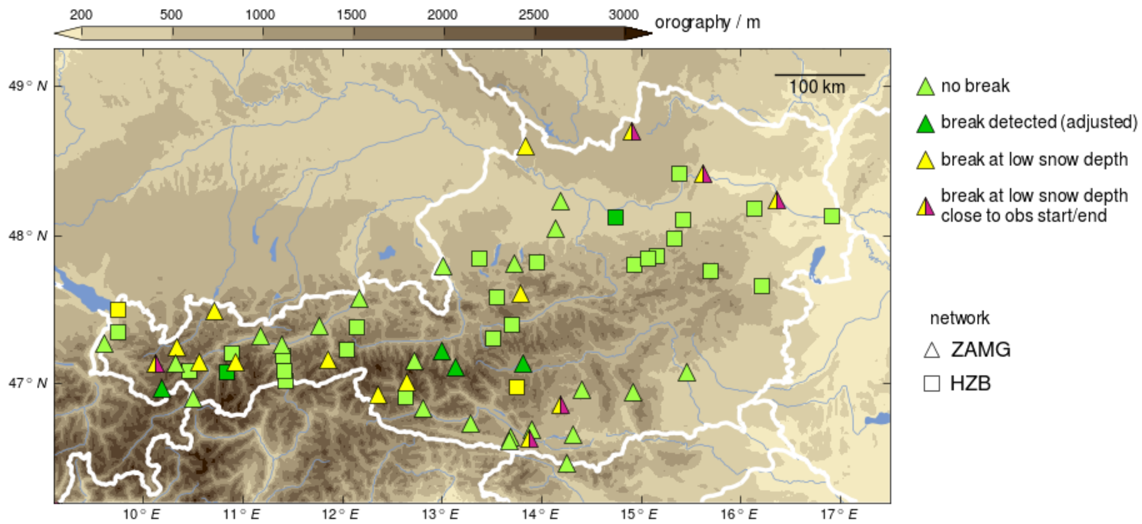


Figure 6: Subset of 69 homogenized long--term time series of snow depth: The dark-green markers indicate corrected time series (6). The Yellow markers indicate suspicious breaks linked to low snow depths and low elevation sites, respectively. The red markers indicate breaks detected close to the observation start (end). The triangles (rectangles) indicate the ZAMG (HZB) station network.

Table 1: Summary of the corrected snow depth time series. The original daily scale time series are multiplied by the seasonal correction factor (adjustment) with respect to the break date.

station name	statnr	elevation / m	break date	adjustment	meta–information
Bad Gastein	15500	1092	19720122	1.38	change of observer
Galtür	17000	1577	19880701	1.22	relocation of station
Rauris	15403	934	19731031	1.57	relocation of station
			19940701	1.64	relocation of station
Tamsweg	15710	1026	19830301	0.83	relocation of station
			19980601	0.73	relocation of station
Oed	106948	400	19960101	1.21	relocation of station
St.Leonhard im Pitztal	102061	1335	19851217	0.95	relocation of station

The distribution of differences between the seasonal means of bootstrap-samples (10000) is shown in Figure 8. It can be seen for Rauris and Galtür that the observed difference in the means is outside the bootstrapped 95% confidence interval. As a consequence, the null hypothesis can be rejected at a 0.05 significance level that the seasonal means of the corrected and original snow depth are the same.

Table 2 summarizes the impact of the homogenization process on the snow depth time series. The impact remains the same whether the winter season NDJFM or DJF is considered. Furthermore, corrected and original time series on a daily scale are almost all significantly different. Through the construction of the correction factor which is based on a seasonal scale, it remains questionable whether these seasonal factors represent important components of the daily scale variation. In order to overcome this uncertainty, it is recommended to use the corrected time series on a seasonal scale.

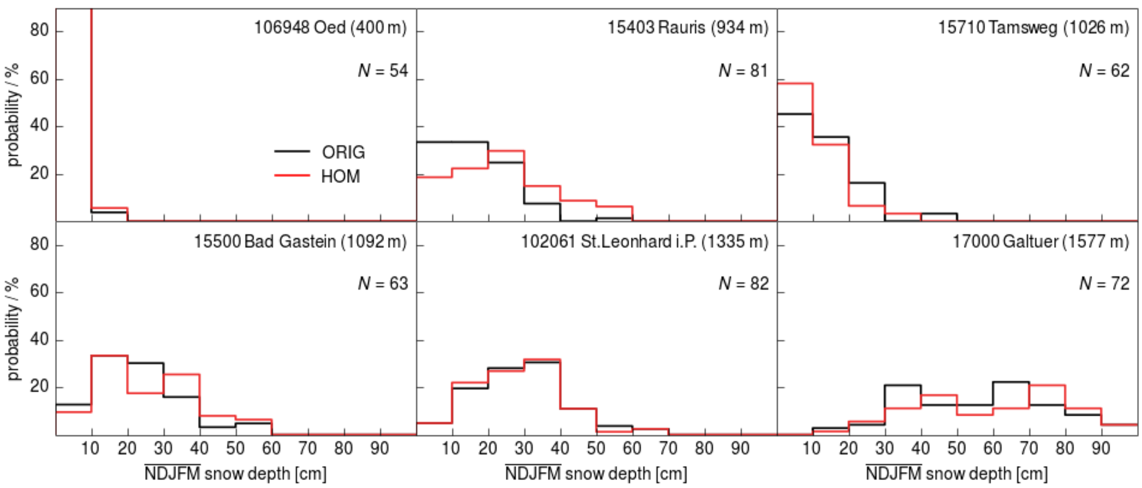


Figure 7: Distribution of the seasonal mean snow depth (NDJFM) of the 6 homogenized time series. Black (Red) indicates the original (homogenized) time series. Top row from left to right: Oed, Rauris and Tamsweg; bottom row from left to right: Bad Gastein, St. Leonhard im Pitztal and Galtür. The black (red) lines indicate the original (homogenized) time series.

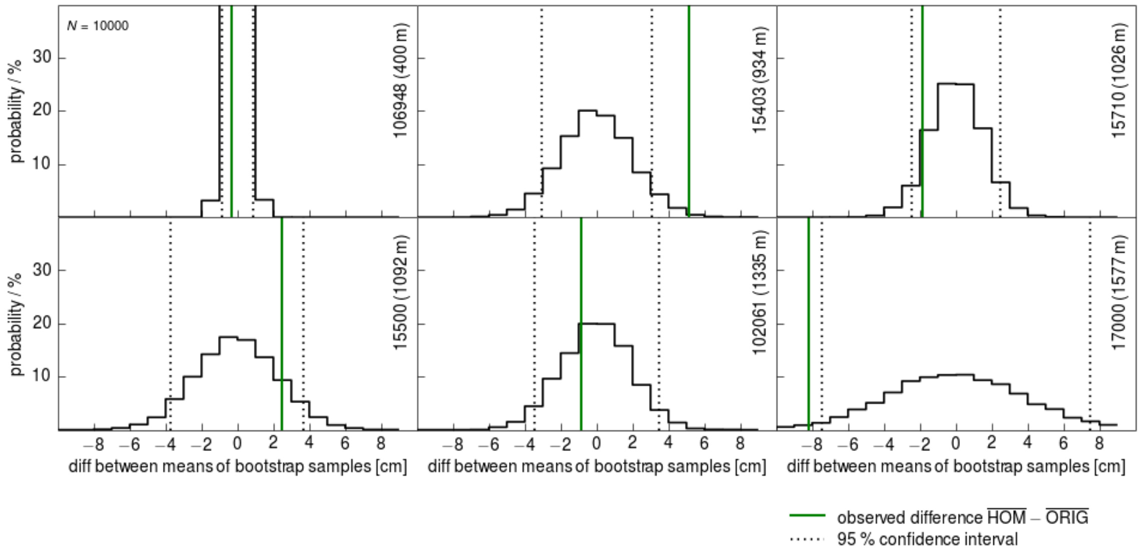


Figure 8: Distribution of differences between the means of bootstrap-samples (10000). The green vertical line indicates the difference between the means of the homogenized and the original NDJFM snow depth time series, the dotted lines indicate the 95% confidence interval. Top row from left to right: Oed, Rauris and Tamsweg; bottom row from left to right: Bad Gastein, St. Leonhard im Pitztal and Galtür.

Table 2: Summary of the significance test for different snow indices and seasons (top: NDJFM; bottom: DJF) of the 6 corrected snow depth time series. The bootstrap approach (10000 samples) was used to assess the statistical significance.

		NDJFM snow depth			NDJFM snow cover duration		
name	elev. / m	daily base	saisonal mean	max SD	SD>=1 cm	SD>=10 cm	SD>=20 cm
Bad Gastein	1092	sig	–	–	–	–	–
Galtür	1577	sig	sig	sig	–	–	–
Rauris	934	sig	sig	sig	–	–	–
Tamsweg	1026	sig	–	sig	–	–	–
Oed	400	sig	–	–	–	–	–
St.Leonhard im P.	1335	sig	–	–	–	–	–

		DJF snow depth			DJF snow cover duration		
name	elev. / m	daily base	saisonal mean	max SD	SD>=1 cm	SD>=10 cm	SD>=20 cm
Bad Gastein	1092	sig	–	–	–	–	–
Galtür	1577	sig	sig	sig	–	–	–
Rauris	934	sig	sig	sig	–	–	–
Tamsweg	1026	sig	–	sig	–	–	–
Oed	400	sig	–	–	–	–	–
St.Leonhard im P.	1335	sig	–	–	–	–	–

WP2: Spatiotemporal snow-cover modelling

The spatially distributed snow model AMUNDSEN (Strasser, 2008, Hanzer et al., 2016) was applied for the snow modelling tasks of Snowpat (see chapter 6). Besides the improvements in model functionality, several performance-crucial model components were optimized for speed, e.g. the interpolation routines were outsourced from IDL to parallelized C code. Along with the reduced model complexity (daily instead of hourly time steps, temperature index melt calculation instead of energy balance) this significantly sped up model run times, allowing to perform a 60-year simulation run for entire Austria in approx. 6 hours

As a sufficiently large number of meteorological stations with homogenized measurements was only available starting from 1948, model runs were performed for the period 1948–2009 (with the number of stations being used as input data ranging between 48 and 71). Although for some stations and/or years partly larger deviations between observed and simulated snow depths occur, the point-based comparison of observed and simulated snow depths for the station locations shows the generally satisfying model performance (Figure 9), which is also underlined by the efficiency criteria shown in Table 3

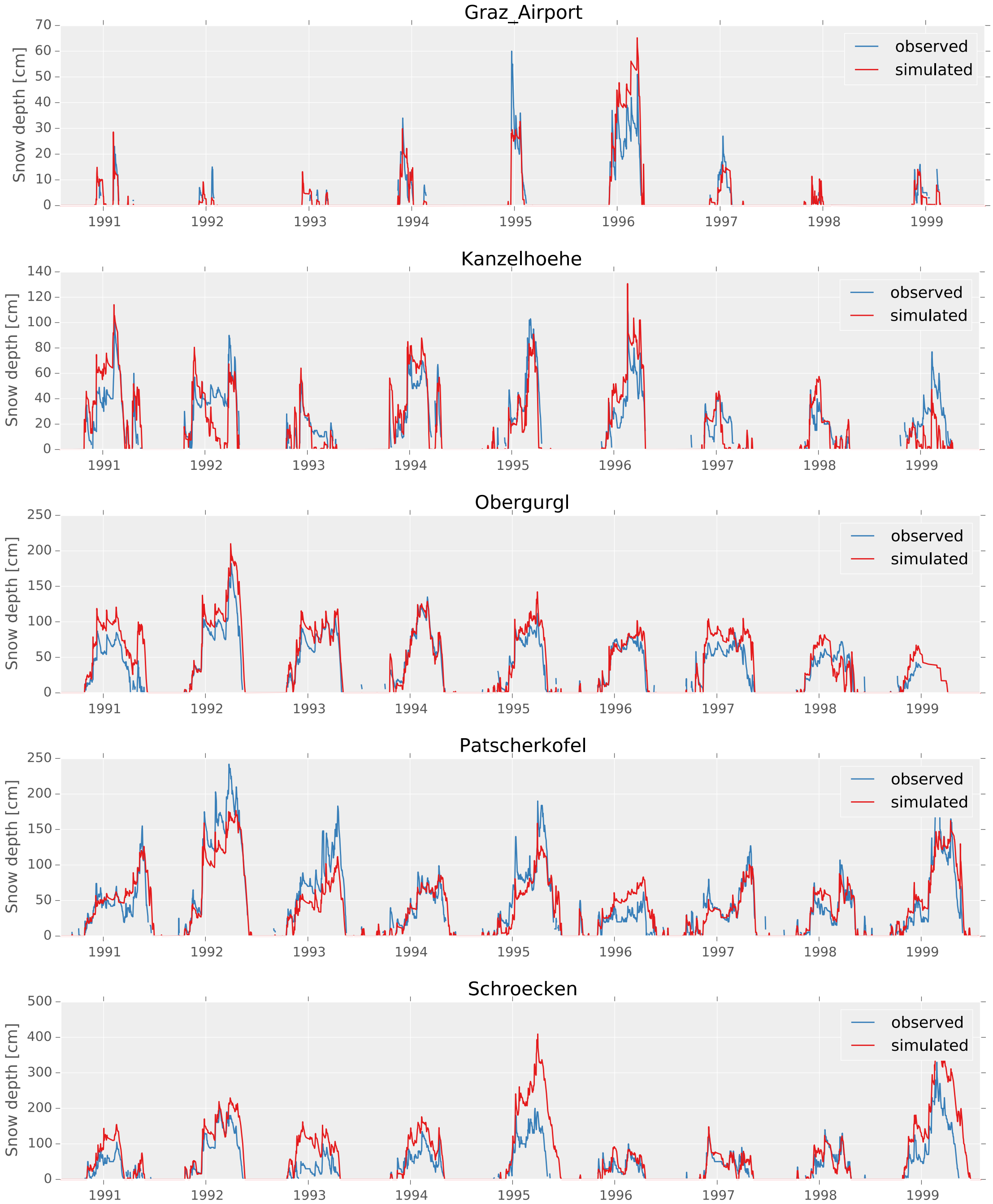


Figure 9: Observed (blue) and simulated (red) snow depths for selected stations and the period 1990–1999.

Table 3: Skill scores (mean absolute error MAE, Nash-Sutcliffe efficiency NSE and percent bias PBIAS) of the comparison of observed and simulated snow depth for selected stations and the period 1990–1999 (winter half year (Nov.–Apr.) only), as well as mean annual observed and simulated snow cover days (number of days with snow depth ≥ 1 cm).

Station	Elevation [m a.s.l.]	MAE [cm]	NSE	PBIAS [%]	Snow cover days (obs)	Snow cover days (sim)
Wien_HoheWarte	203	0.63	0.63	-28.4	36	45
Graz_University	366	0.67	0.68	-8.7	39	44
Kremsmuenster	383	0.71	0.71	-4.9	53	59
Bregenz	424	0.38	0.69	-32.5	31	33
Salzburg_Airport	430	0.63	0.51	-36.9	47	47
Feldkirch	440	0.46	0.65	-23.4	37	35
Klagenfurt	450	1.70	0.41	42.3	67	77
Mondsee	491	1.14	0.46	1.0	51	55
Kufstein	492	1.60	0.73	-14.1	76	67
Jenbach	530	1.22	0.74	-21.3	61	55
Mayrhofen	643	1.76	0.81	1.7	95	85
Lienz	659	1.92	0.78	11.4	80	83
Landeck	798	1.38	0.43	2.4	52	56
Reutte	850	2.96	0.74	-24.4	116	84
Loibl	1098	6.91	0.64	-29.1	131	106
Holzgau	1100	5.14	0.76	-19.6	132	116
StJakob_Def	1400	4.80	0.77	1.1	121	129
Kanzelhoehe	1526	5.82	0.64	-31.9	138	121
Feuerkogel	1618	15.58	0.75	3.1	185	178

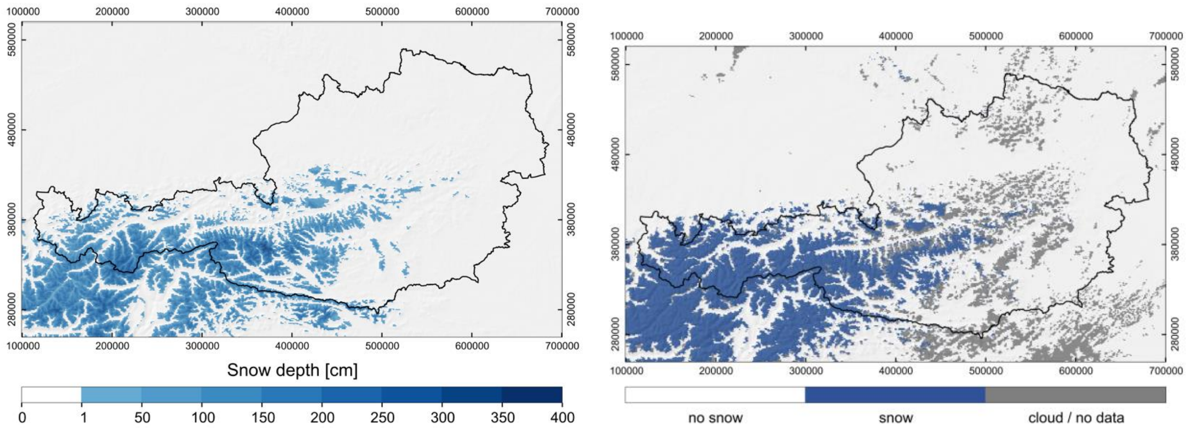


Figure 10: Simulated snow depth (left) and remotely sensed (MODIS) snow-covered area (right) for April 1, 2001.

With regard to the spatial results, a comparison between simulated and observed (i.e., remotely sensed) snow-covered area for selected dates showed that the observed snow patterns in the period with available observations (since 2000) are well reproduced by the model (Figure 10). Using the described model setup, AMUNDSEN runs were performed for the period 1948–2009, producing daily maps of SWE, snow depth, fresh snow, and snowmelt. Figure 11 shows the simulated difference in the number of annual snow cover days (defined as number of days with a snow depth ≥ 1 cm) between the period 1960–1969 and 1990–1999. For most parts of Austria, snow cover days strongly decreased during this period, with more pronounced changes in the low-elevated areas as compared to the mountain regions. Slight increases in snow cover days can at least partly be traced back to issues with the meteorological input data – for example, at the station Obergurgl during the 1960s modifications at the station aiming to prevent the intrusion of blowing snow led to amplified temperature measurements in this period (Kuhn et al. 2013).

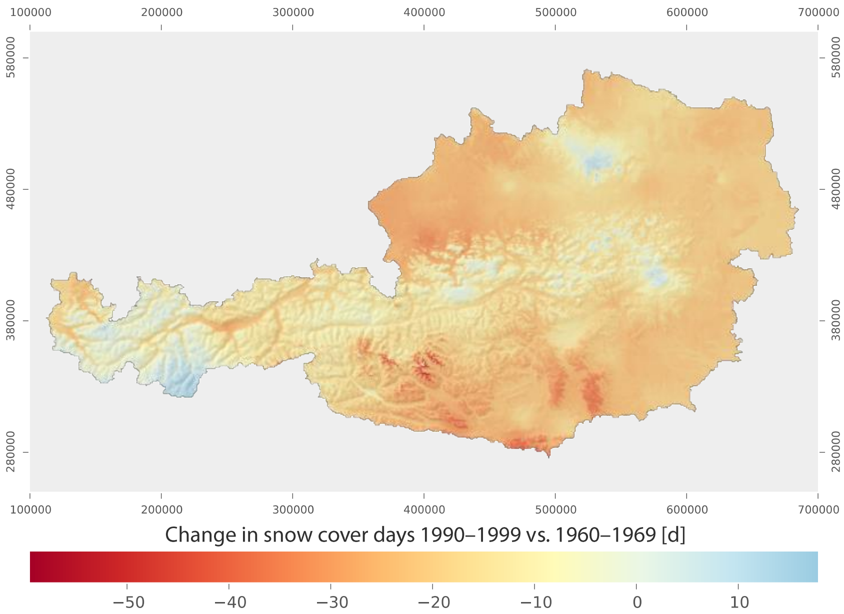


Figure 11: Change in snow cover days between the periods 1960–1969 and 1990–1999 as simulated by AMUNDSEN.

WP3: Synoptic patterns of snow and GCMs

In order to investigate temporal snow variations subject to atmospheric patterns, so-called temperature/precipitation modes (hereafter w-modes) are calculated. The w-modes are derived from the joint 25% and 75% percentiles of winter season HISTALP temperature and precipitation long-term time series on a daily scale within the base period 1951 to 2010 (Table 4). Hereby, the winter season for this analysis is defined as November-December-January-February-March-April (NDJFMA). The percentile-thresholds are finally used to calculate the occurrence of four defined w-modes. Thus, one could expect that the w-modes are strongly linked to atmospheric circulation patterns (Beniston et al., 2011; Moran-Tejeda et al., 2013). Furthermore, this approach allows the quantitative assessment of the sensitivity of the snow pack to different large scale weather situations.

Table 4: Joint percentiles of temperature (txx) and precipitation (pxx) and corresponding w-modes.

w-mode	joint percentile
COLD-DRY (CD)	t25p25
COLD-WET (CW)	t25p75
WARM-DRY (WD)	t75p25
WARM-WET (WW)	t75p75

Table 5 shows the Kendalls tau correlation between seasonal snow indices and w-modes for a selected set of stations across Austria. The strongest correlations can be found for the CW-mode. At the high alpine station, namely Sonnblick, there exists no or only poor correlation. The accuracy of the measured quantities, i.e., temperature, precipitation and snow, is maybe affected by extreme weather situations. As a result, the embedded large uncertainty in these observations may yield poor correlations.

The relationship between the winter time PC-based North Atlantic Oscillation (NAO, Hurrell, 2015) and w-modes is presented in Table 3. The NAO is a dominant pattern of the atmospheric circulation, which affects the climate variability in the Alpine region (Hurrell, 1995; Hurrell, 1996; Hurrell et al., 2003). In the winter season, the impact on temperature and precipitation is strongest. The cold modes show a clear anti-correlation. This is not surprising since during established negative NAO phases the advection of cold air from the Northern Atlantic to the mid-latitudes is increased. In more detail, pressure gradients over the North Atlantic are weakened which favors meridional flow. In contrast, only the WD-mode is closely related to the NAO.

A clear decrease of CW-modes south of the Alpine Ridge can be linked to consecutive extreme positive winter time NAO Phases in the 1990s and in the early years of the 21st century. During these episodes, the frequency of Mediterranean cyclones declined. Since regions south of the Alpine Ridge receives most of the winter precipitation from Genoa cyclones, one can expect that observed low snow depths reflect the shift of CW-modes to lower values.

Table 5: Kendalls tau correlation between selected seasonal (NDJFMA) mean snow depth (snow cover duration) station time series and the seasonal (NDJFMA) mean frequency of w-modes. The base period is 1951-2010. The threshold of snow cover duration for stations above (below) 1500 m a.s.l. is set to 10cm (1cm). Bold values indicate that the Kendalls tau correlation coefficient is significantly different from zero at a 95% confidence level.

		w–mode			
		COLD—DRY	COLD–WET	WARM–DRY	WARM–WET
name	elevation [m]	snow depth / duration	snow depth / duration	snow depth / duration	snow depth / duration
Sonnblick	3109	-0.05 / -0.13	**0.20** / -0.01	-0.10 / 0.01	0.04 / -0.03
Villacher Alpe	2140	0.06 / 0.08	**0.18 / 0.20**	**-0.33 / -0.28**	-0.08 / -0.10
Feuerkogel	1618	0.11 / -0.10	**0.50** / 0.13	**-0.32** / -0.17	**-0.24** / -0.13
Umhausen	1041	**0.25 / 0.24**	**0.33 / 0.25**	**-0.39 / -0.49**	**-0.23 / -0.28**
Landeck	796	**0.26 / 0.33**	**0.60 / 0.57**	**-0.29 / -0.35**	**-0.26 / -0.25**
Innsbruck	578	**0.38 / 0.43**	**0.66 / 0.57**	**-0.37 / -0.38**	**-0.26 / -0.28**
Feldkirch	438	**0.32 / 0.42**	**0.55 / 0.48**	**-0.25 / -0.30**	**-0.29 / -0.28**
Lackenhof	809	0.07 / 0.00	**0.46 / 0.23**	**-0.32 / -0.38**	-0.22 / -0.08
Salzburg	430	**0.44 / 0.54**	**0.72 / 0.62**	**-0.41 / -0.44**	**-0.35 / -0.31**
Kremsmünster	382	**0.40 / 0.47**	**0.62 / 0.58**	**-0.32 / -0.35**	**-0.25 / -0.23**
Graz Univ.	366	**0.46 / 0.52**	**0.63 / 0.69**	**-0.33 / -0.38**	**-0.19 / -0.23**
Wien Hohe Warte	198	**0.48 / 0.57**	**0.63 / 0.62**	**-0.37 / -0.42**	**-0.20 / -0.18**
Preitenegg	1034	**0.32 / 0.28**	**0.49 / 0.38**	**-0.37 / -0.34**	-0.18 / -0.17
Lienz	661	**0.28 / 0.30**	**0.57 / 0.52**	**-0.30 / -0.31**	**-0.29 / -0.31**
Villach	493	**0.32 / 0.32**	**0.51 / 0.42**	**-0.38 / -0.34**	**-0.26 / -0.28**
Klagenfurt	450	**0.44 / 0.40**	**0.51 / 0.49**	**-0.32 / -0.29**	**-0.26 / -0.22**

Table 6: Kendalls tau correlation between the seasonal (NDJFMA) mean NAO index (PC based) and the seasonal (NDJFMA) mean frequency of w-modes. The base period is 1951-2010. Bold values indicate that the Kendalls tau correlation coefficient is significantly different from zero at a 95% confidence level.

		w–mode			
name	elevation [m]	COLD—DRY	COLD–WET	WARM–DRY	WARM–WET
Sonnblick	3109	**-0.32**	-0.09	**0.41**	0.16
Villacher Alpe	2140	**-0.32**	**-0.22**	**0.29**	**0.24**
Feuerkogel	1618	**-0.33**	-0.05	**0.22**	0.15
Umhausen	1041	**-0.24**	**-0.18**	**0.25**	0.15
Landeck	796	**-0.26**	**-0.22**	**0.36**	-0.04
Innsbruck	578	**-0.22**	**-0.20**	**0.24**	0.07
Feldkirch	438	**-0.19**	**-0.35**	**0.25**	0.05
Lackenhof	809	**-0.35**	-0.11	**0.20**	**0.24**
Salzburg	430	**-0.35**	**-0.32**	**0.31**	**0.23**
Kremsmünster	382	**-0.36**	**-0.28**	**0.32**	**0.22**
Graz Univ.	366	**-0.31**	**-0.35**	**0.32**	0.10
Wien Hohe Warte	198	**-0.34**	**-0.24**	**0.30**	0.17
Preitenegg	1034	**-0.30**	**-0.31**	**0.37**	-0.06
Lienz	661	-0.16	**-0.22**	**0.26**	0.09
Villach	493	-0.05	-0.16	**0.30**	0.11
Klagenfurt	450	-0.11	**-0.40**	**0.25**	0.05

Snow and atmospheric circulation - Decadal variations of the upper-level wind field

Besides the computation of temperature/precipitation modes, the investigation of weather types may provide useful information about the variability in the snow pack. Figure 12 shows decadal time slices of seasonal (NDJFMA) upper-level (300hPa) wind speeds for the Northern Hemisphere. The seasonal averaged wind fields are constructed using 6-hourly NCAR/NCEP reanalysis data (Kalnay et al., 1996) of the U- and V-wind component and reflect variations of the large scale flow. Comparing the patterns of the decades, areas of high wind speeds over the Northern Atlantic are spread towards the east and poleward starting from the 1980s. The maximum increase in extent is found in the 1990s, followed by a lateral decline in the 2001 to 2010 time slice.

To investigate the signal of the zonal wind field over the Northern Atlantic and Europe in more detail, one-dimensional time and space-averaged spectral (in terms of spatial wavenumber) energy densities at 300 hPa for different winter seasons were calculated (Figure 13). The kinetic energy mainly dominates this region of the atmosphere. The finite zonal wind data segment was detrended by subtracting the linear least-squares regression from the data. The spectra show a comparable decay towards high wavenumbers. However, the spectral amplitude of the 1991 to 2000 time period is highest for the winter seasons DJF, MA and NDJFMA compared than that of other decades. In the subsequent decade the seasonal spectra are of same characteristics as they are in the 1950s and 1960s. The results are an implication that the kinetic energy of the mean zonal flow was increased during the 1980s and 1990s.

Since dynamically evolving weather systems are embedded in upper-level wind bands, changes in the distribution of wind fields over the Northern Atlantic may affect the intensity and location of winter weather patterns that are relevant for the Alpine area. Regions of high wind speeds, i.e. jet streams, near the top of the troposphere at midlatitudes are created by horizontal temperature gradients (baroclinicity). Hereby, the spatial distribution of wind speed and direction indicates the boundary between warm tropical air and relative cold polar air. One could expect, that the increased extent of the upper-level wind field in the 1980s and especially in the 1990s reflect strong horizontal temperature gradients acting as a barrier for growing perturbations. Within these decades, the enhanced westward drift in the mean flow yields a displacement of the north-south meandering jet stream over the Northern Atlantic, compared to other decades. Baroclinic instability is a major source of evolving synoptic-scale disturbances affecting the Alpine region. This kind of instability is favored in an unstable flow with rapid rotation. The extent of the mean wind field over the Northern Atlantic region in the 1991-2000 decade probably highlight a suppression of these growing disturbances propagating eastward. This also implies a zonal and meridional shift of displacements consisting of warm air moving poleward and cool air moving equatorward (Hilmer and Jung, 2000; Riviere, 2011).

Since, the poleward heat transfer and southward cold air advection presumably affect winter weather conditions north and south of the Alpine ridge, it can be expected that large scale changes of the wavy pattern of the jet stream result in spatiotemporal variations of snow indices, i.e. snow depth, snow cover duration and new snow sums.

As a result, observed warmer and drier winter seasons in the Alpine region at the end of the 1980s and in the 1990s are probably related to the changed distribution of the upper-level wind field over the Northern Atlantic region. Hereby, the location, strengthening and stationary (blocking patterns) of troughs and ridges play an important role for winter time conditions in the Alpine area. Particularly, the variability of winter precipitation is influenced by the orientation of mountain ranges subject to the direction of passing atmospheric circulation patterns (lee versus windward slopes). Besides that, the spatial variations can also be attributed to mountain effects on precipitation (orographic enhancement of precipitation).

For example, Mediterranean cyclones are steered by upper level troughs and the development and strengthening depend on the cold air advection. These cyclones are associated with a strong south-westerly flow and extensive precipitation in regions south of the Alpine ridge. The initial low pressure is located in the lee of the main Alpine ridge, ahead of a cold front which reaches the Alps from directions between west and north. The lee cyclogenesis requires an initial disturbance which interacts with the Alps (Buzzi and Tibaldi, 1978). Clearly, if the seasonal frequency of cold fronts interacting with the Alpine range declines or the interaction is only weak (northerly mean flow associated with North Atlantic blocking), one could expect that regions south of the Alpine ridge receives less winter precipitation yielding lower average snow depths.

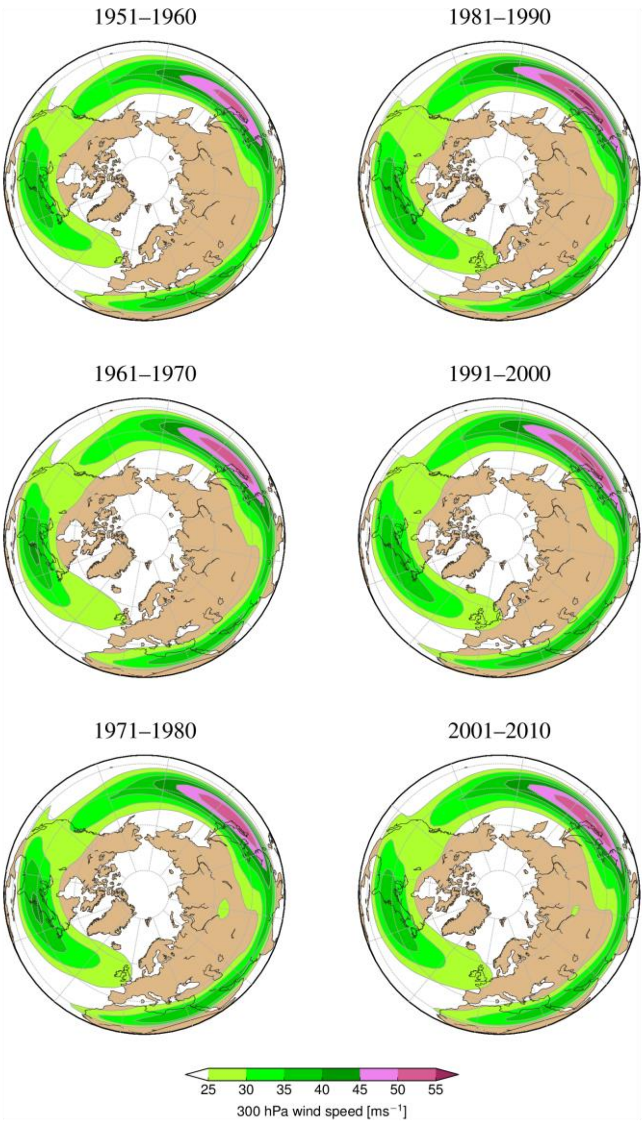


Figure 12: Decadal averaged NCAR/NCEP reanalysis fields of wind speed [m/s] at 300hPa for the winter season NDJFMA.

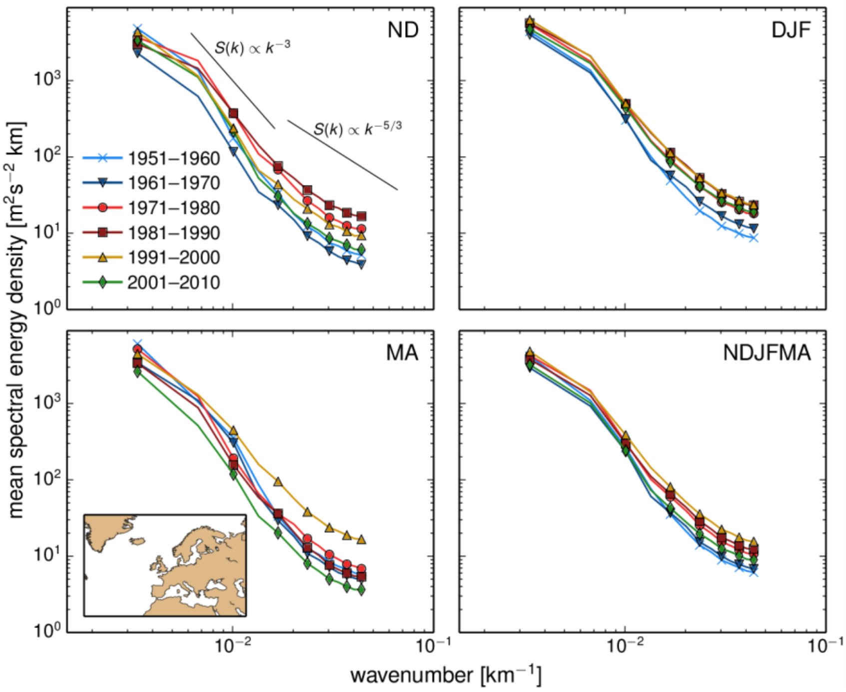


Figure 13: Horizontal decadal mean spectral energy densities at 300 hPa for the zonal velocity field. The mean spectra are calculated for different decades and winter seasons and are valid for the domain 75N/55W-25N/55E (lower left panel). Slopes from theoretical power-laws are shown in the upper left panel. The winter seasons are defined as November-December (ND) for the early winter season, December-January-February (DJF) for the core winter season, March-April (MA) for the late winter season and November-December-January-February-March-April (NDJFMA) for the entire winter season.

The time-varying occurrence of each weather type within the 1951 to 2010 winter seasons is shown in Figure 14. Clearly, the UNC, south-westerly, westerly and north-westerly weather types are most prominent. Thus, it can be expected that variations in the frequency of these types may strongly affect the winter time conditions on a seasonal base. The occurrence of all types is characterized by a distinct year-to-year variation. Besides that, multi-year variations can also be identified. Some shifts in the frequency appear around the second half of the 1960s, the late 1980s and around 2000.

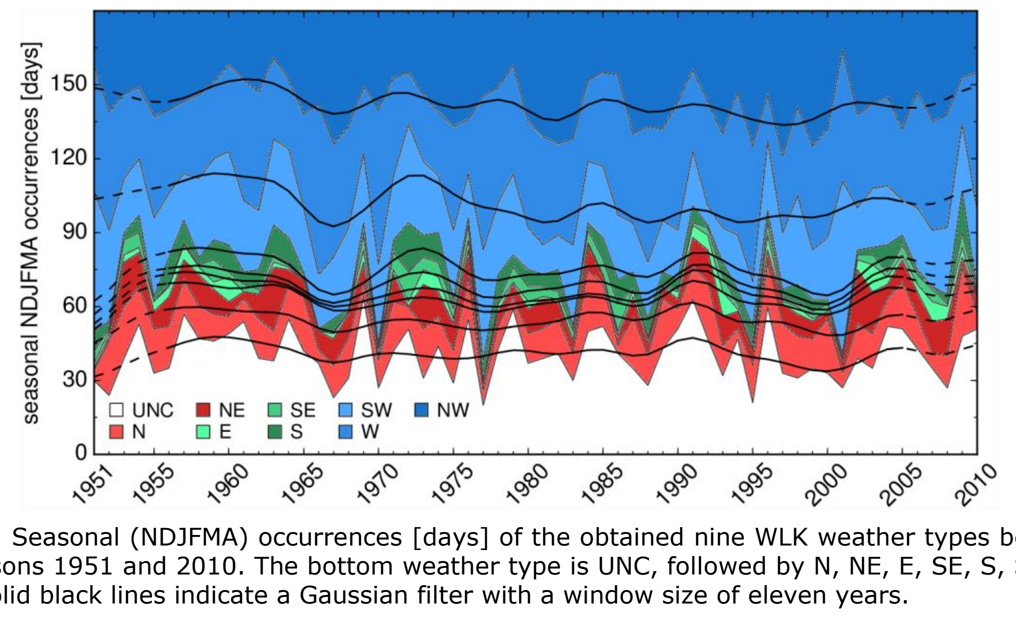


Figure 14: Seasonal (NDJFMA) occurrences [days] of the obtained nine WLK weather types between the winter seasons 1951 and 2010. The bottom weather type is UNC, followed by N, NE, E, SE, S, SW, W and NW. The solid black lines indicate a Gaussian filter with a window size of eleven years.

Decadal distribution of WLK weather types

The WLK- types of classification occur with varying frequency in different winter seasons and decades (Figure 15). The south-westerly, westerly, north-westerly and unclassified weather types show the highest frequency in all seasons considered. The variation from one decade to the next is strongest in the early (ND), late (MA) and core (DJF) winter season. Furthermore, the frequency of the south-westerly weather type in the decade 1991-2000 is lowest in all seasons followed by a remarkable increase during the early and core winter season of 2001-2010. Low values can also be found for the decade 1981-1990 expect that the frequency is higher in the late winter season. Interestingly, in this season the frequencies of the north-westerly and north weather types peak highest during the decade 1991-2000. Since, south-westerly weather types are strongly related to upper-level troughs deepening due to cold air advection, the clear decline in the frequency during 1991-2000 is in accordance with the considerations concerning the changed decadal distribution of the wind field in the latter section (see Figure 12).

Although, the classification scheme cannot capture all possible variations within a certain weather type, it is evident that the findings demonstrate the decadal variation in frequency of dominant synoptic-scale weather patterns.

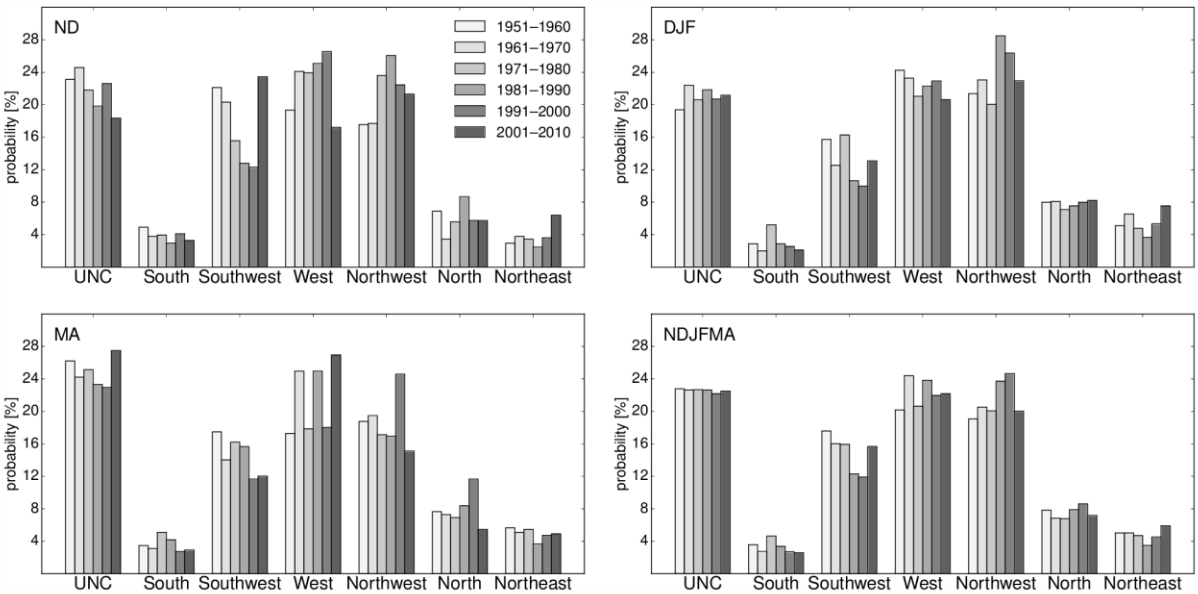


Figure 15: Distribution of particular WLK weather types (UNC, S, SW, W, NW, N and NE) in different winter seasons and decades between 1951 and 2010. The UNC type indicates the unclassified weather type. The winter seasons are defined as November-December (ND) for the early winter season, December-January-February (DJF) for the core winter season, March-April (MA) for the late winter season and November-December-January-February-March-April (NDJFMA) for the entire winter season and are given in the upper left corner.

Relationship between days with new snow and weather types

A subset of 10 stations in Austria and Switzerland (Figure 16) were selected for the following study on the relationship between days with new snow and weather types. For the detection of extreme snow heights the 75%, the 90% and 98% quantiles of daily snowfall totals are used as threshold values for the reference period 1980-2010. Figure 17 shows the seasonal (NDJFMA) occurrence of days with new snow based on the above quantiles as threshold for 5 stations in Switzerland and Austria, respectively. Additionally, for each station the seasonal number of days with new snow are shown in Figure 17. In a next step, the frequency of daily snowfall totals for the nine WLK-weather types are computed (Figure 18). The Figure explains for each station, which weather patterns are relevant for fresh snow events as well as which weather patterns are relevant for low and high snow amounts, e.g. for St. Leonhard i. P (Tyrol) there is high probability for new snow events during West- and Northwest-weather patterns, but also for Southwest-weather patterns, whereas for Bad Bleiburg (Carinthia) the probability for Northwest weather patterns is very low (but West and Southwest is quite probable). From this Figure clear differences in the snow causing weather patterns is obvious for the southern and northern part of Austria and Switzerland. Stations in the south are dependent on lower variety of weather types, which means that reduction in the number of these weather patterns maybe cannot be substituted by other weather patterns.

If changes in the frequency of the weather patterns are correlated with the changes of new snow amounts in Austria and Switzerland is shown by the final Figure 19. It appears quite clear from this Figure, that changes of occurrences of daily new snow between 1989-2005 and 1972-1988 for southwest weather patterns can quite well explain the clear retreat of new snow amount, whereas for St. Leonhard decrease for southwest weather patterns to some part could be substituted by increase for northwest weather patterns.

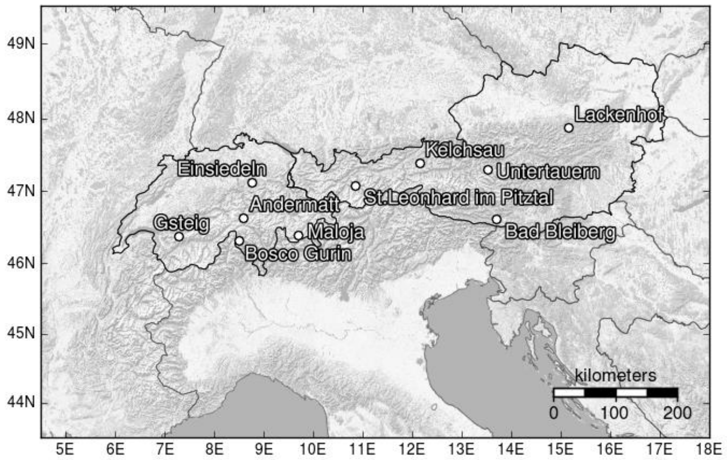


Figure 16: Location of 10 selected stations across Switzerland (Gsteig, Einsiedln, Andermatt, Bosco Gurin and Maloja) and Austria (St. Leonhard im Pitztal, Kelchsau, Untertauern, Bad Bleiberg and Lackenhof).

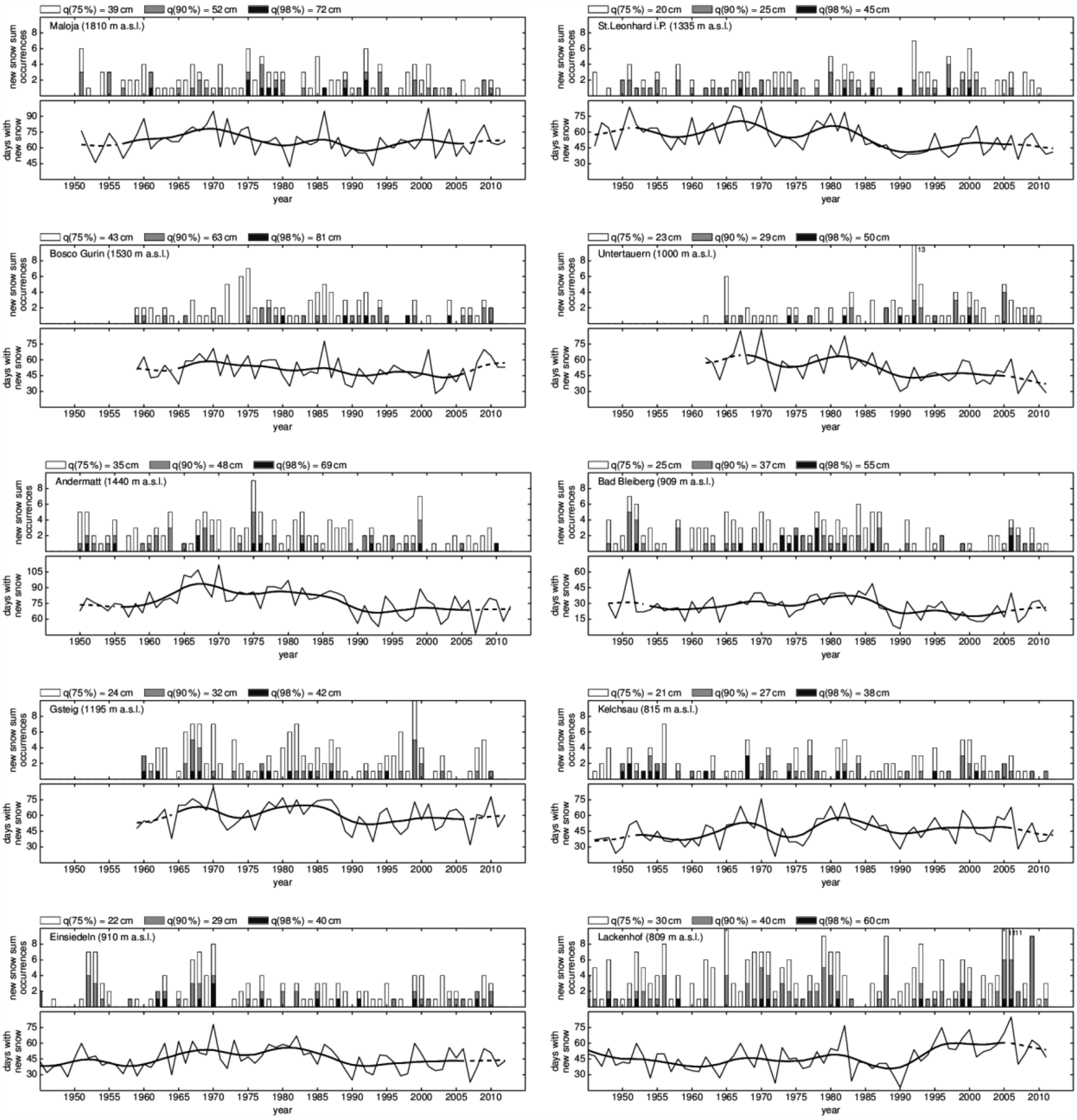


Figure 17: Seasonal (NDJFMA) occurrence of days with new snow for 5 stations in Switzerland (left) and Austria (right). The top panel shows the number of days with extreme new snow sums. The thresholds are calculated using the 75 %, 90 % and 98 % quantiles of the daily new snow sums within the period 1981 to 2010. The lower panel shows the seasonal number of days with new snow. The solid black lines indicate a Gaussian filter with a window size of eleven years.

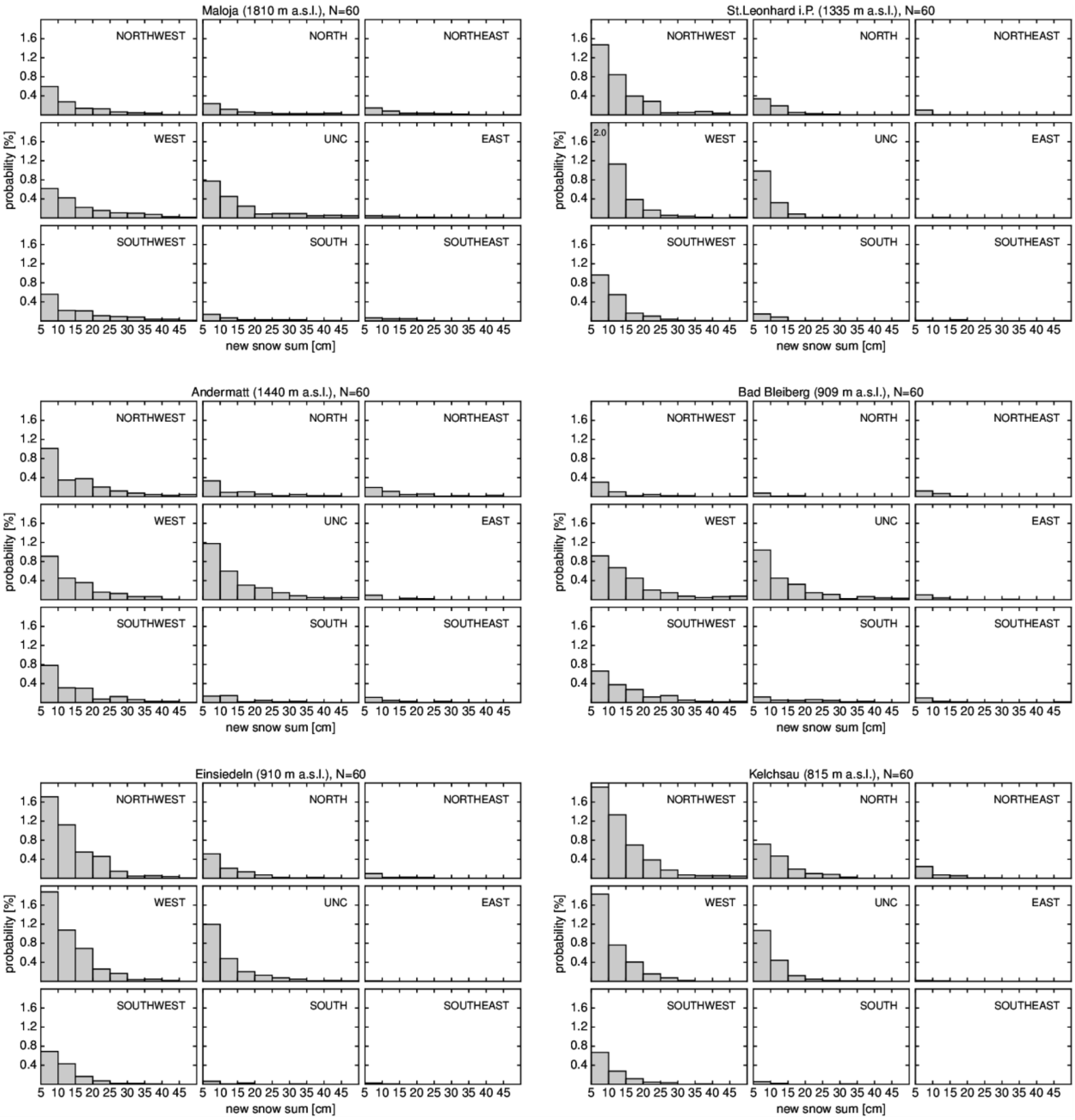


Figure 18: Seasonal (NDJFMA) probability of the daily new snow sums subject to the nine weather types within the period 1951 to 2010. The left (right) column comprises stations in Switzerland (Austria).

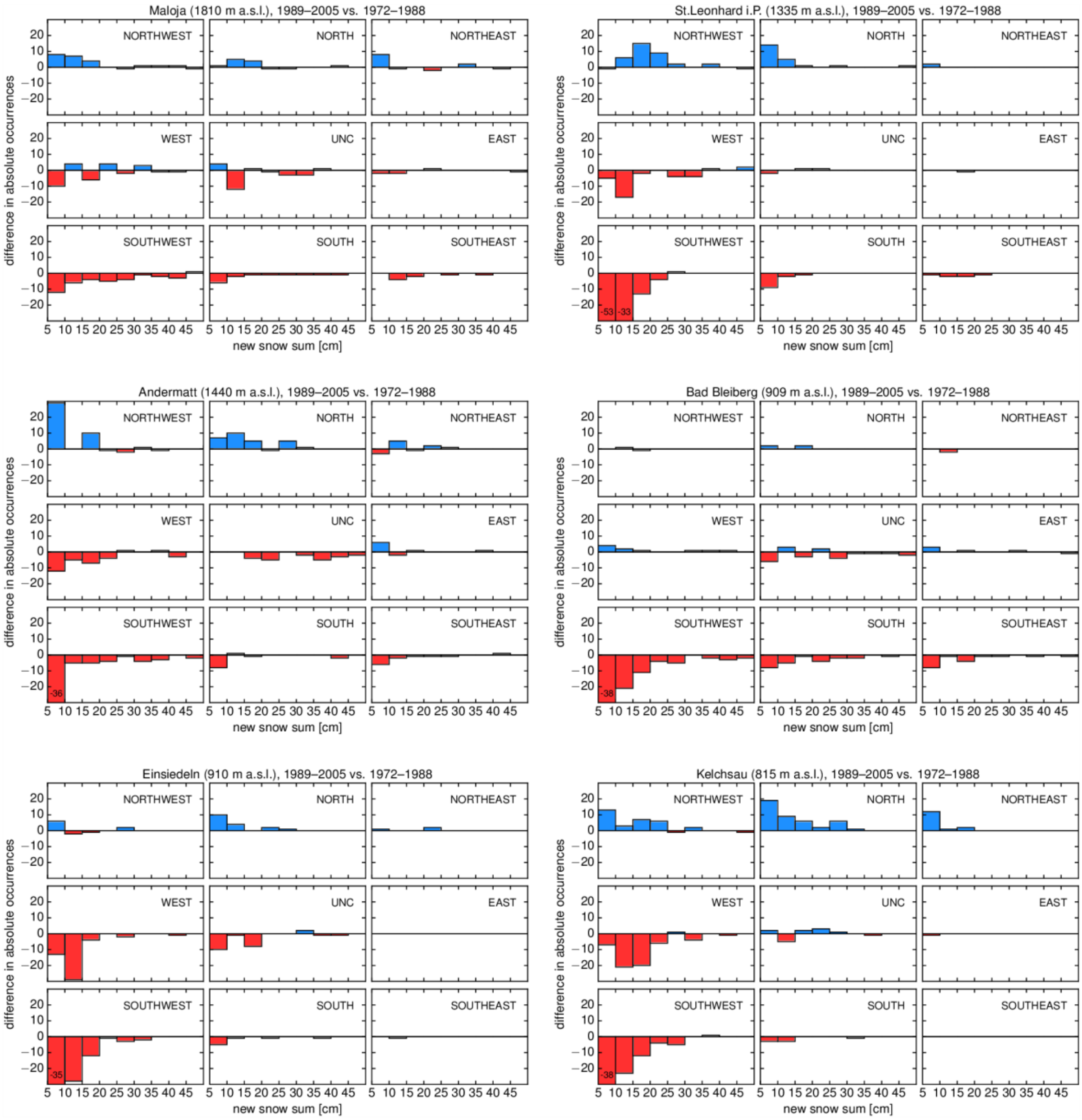


Figure 19: Difference in absolute occurrences of daily new snow sums between winter seasons within the time period 1989 to 2005 and 1972 to 1988. The left (right) column comprises stations in Switzerland (Austria).

WP4: Spatiotemporal patterns of snow in Austria and WP6: climate conditions of snow for the Austrian-Swiss region

Major spatial patterns of snow depth 1962-2010

The analyzed snow depth data matrix contained of 138 mean-centered station time series on a daily scale (Figure 20) for Switzerland and Austria, which had been standardized by dividing each series by its standard deviation. The dataset only consisted of daily measurements within the winter season from 1th of November to 30th of April during the base period. Hereby, the spatial dimension of the dataset is the number of snow time series that are measured on each station location. The technique of PCA is used to reduce the dimension of the original snow dataset to a lower dimension, yielding a subset which contains a large fraction of the variability observed in the original snow data. This is accomplished by finding the projections of the original data samples, i.e., data vectors, on to the directions in the linear space, which maximize the variance. The first derived component is the direction of maximum variance of the dataset.

The second component is orthogonal (independent) to the first and points toward the direction in the phase space which projections define the second largest variance, and so on.

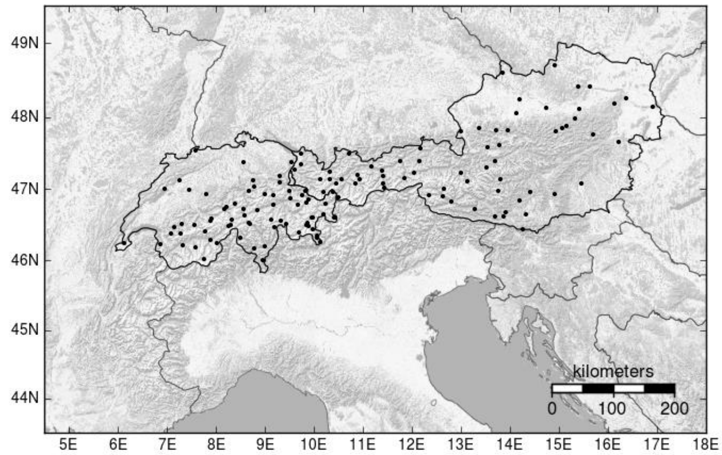


Figure 20: Location of the stations over Switzerland and Austria used in this study.

The first three major spatial patterns of variability (EOFs) and the corresponding time series which describe the time varying evolution of the spatial patterns (PCs) are shown in Figure 21. In order to illustrate the spatial variations, the normalized EOFs were interpolated on a regular latitude-longitude grid using a cubic splines interpolation. Since, the station observations are irregularly spaced, the patterns in data void or data-sparse regions fairly capture regional fine-scale variations. In more detail, the interpolation spreads out the information of the EOFs to surrounding grid-points leading to broader and smoother patterns.

The leading EOF explains 49 % of the total variance and obviously separates different regions. For example, lower elevated areas in Switzerland and Austria can be identified as well as inner alpine areas and regions south of the Alpine Ridge. In contrast, EOF2 (13 %) describes snow depth variations as a function of elevation and EOF3 contains information of the clear North-South gradient over the domain investigated. In order to overcome high frequency fluctuations on a small timescale, the PCs are seasonal (NDJMA) averaged and low pass filtered using a Gaussian filter.

Since the SVD was performed on the standardized snow depth data matrix, the time series of PC1 can be interpreted as the dominant snow depth variability. Clearly, PC1 is characterized by a strong year to year variability. 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 base period is present, which implies that the vertical (altitudinal) gradient of the snow variations as well as the characteristic of the North-South dipole changed in time. Further inspection of PC2 and PC3 reveals a step-like increase in the 1980s. In contrast, the temporal variation of PC1 is characterized by the prominent shift towards lower values at the end of the 1980s. However, a decrease of PC1 starting from the winter season of 1983 is also apparent.

The non-parametric Mann-Kendall statistical test had been used to assess the significance of trends in the PCs at seasonal time scales (NDJFMA). In order to remove the influence of the lag-1 serial correlation from the time series, the trend-free pre-whitening approach (Yue et al., 2002) was applied. Clearly, the seasonal PC1 shows significant trends over decadal time scales (Figure 22). As a matter of fact, the major shift beginning from the late 1980s is predominantly responsible for the observed negative trends. Positive trends in the time series of PC2 and PC3 are statistically significant at the 95 % confidence level for the time period from around 1975 to 2005.

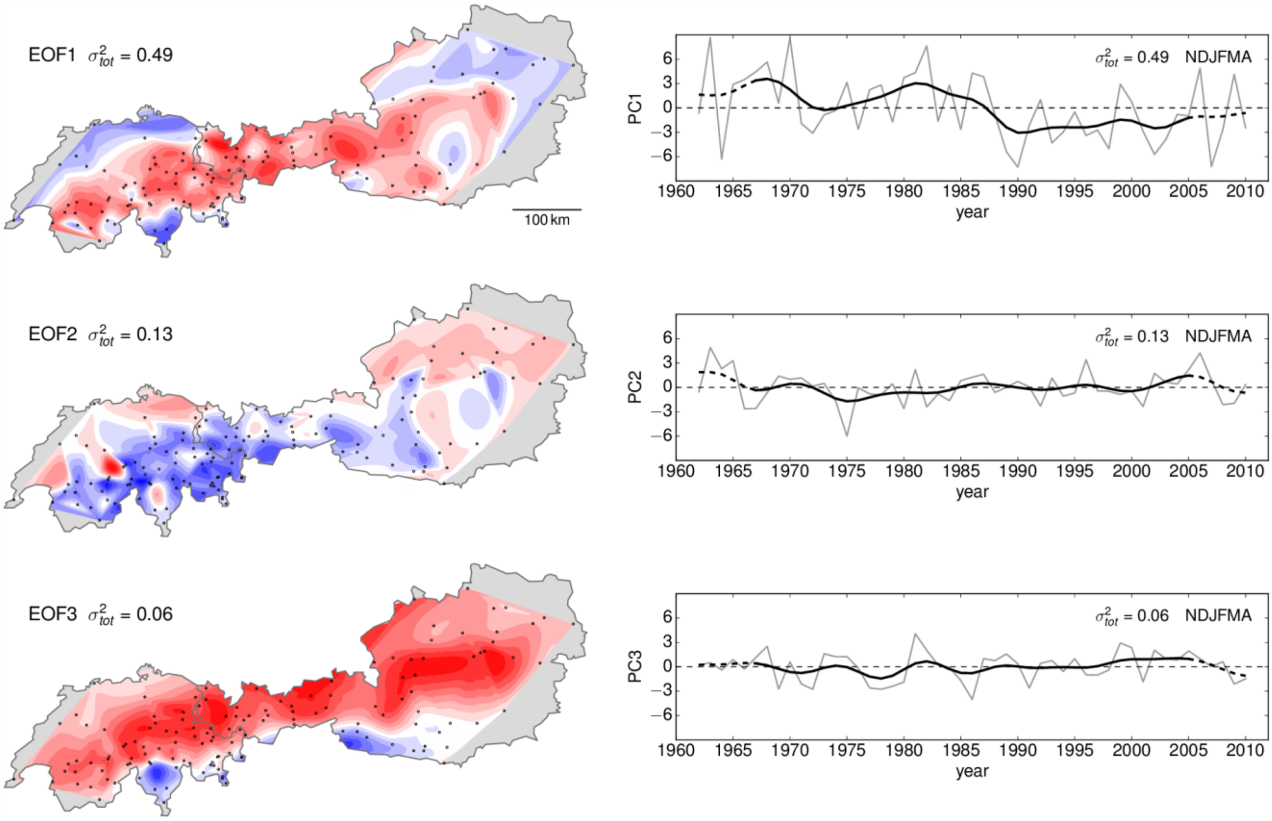


Figure 11: Spatiotemporal variability of mean-centered and standardized winter time (NDJFMA) snow depth time series during the base period 1962-2010. The first three EOF patterns and the time series of the corresponding PCs (right, solid grey lines). The PCs were seasonal averaged (NDJFMA), the solid black lines indicate a Gaussian filter with a window size of eleven years. The EOFs are normalized from zero (Blue) to one (Red) and the variance explained for each EOF is also shown. The black dots in the left panel indicate the station distribution.

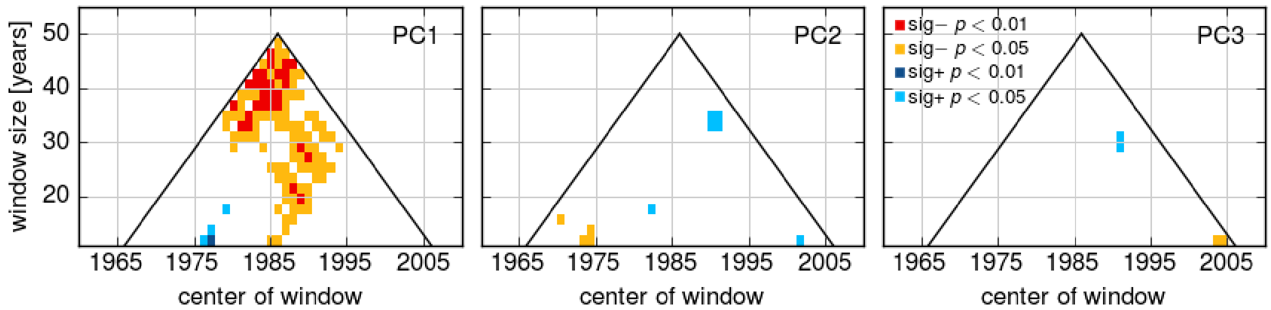


Figure 22: Running trend analysis of the seasonal (NDJFMA) averaged time series of the first three PCs during the base period 1962-2010. The x-axis represents the center of the time window over which the trend is evaluated, and the y-axis represents the size of the time window [years]. The assessed significance of trends is lying inside the black triangle. Negative (positive) trends in the time series of the PCs which are significant at the 95 % (99 %) confidence level are plotted red (blue). White areas indicate the absence of significant trends.

In order to investigate the variability in the snow depth associated with the variations in its own PCs, so-called homogeneous correlation maps are calculated. Since the snow depth time series are highly variable in time, outliers may have adverse effects upon computed correlations. Thus, the assessment of the relationship between the time series of the PCs and the standardized snow depth data (Figure 23) is achieved by using the nonparametric Kendalls tau(b) rank correlation, which is less sensitive to outliers.

The homogenous correlation map for PC1 and the snow depth data shows positive correlations over the whole domain. The correlation coefficients are almost all significantly different from zero at the 95 % confidence level. In addition, a stronger relationship can be observed in higher elevated regions of Switzerland and Austria. 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 (solid) precipitation and elevation in southern regions is less significant. The correlation map associated with PC3 clearly highlights the pronounced North-South gradient. However, no correlation can be found in low elevated regions in the North of Switzerland and Austria.

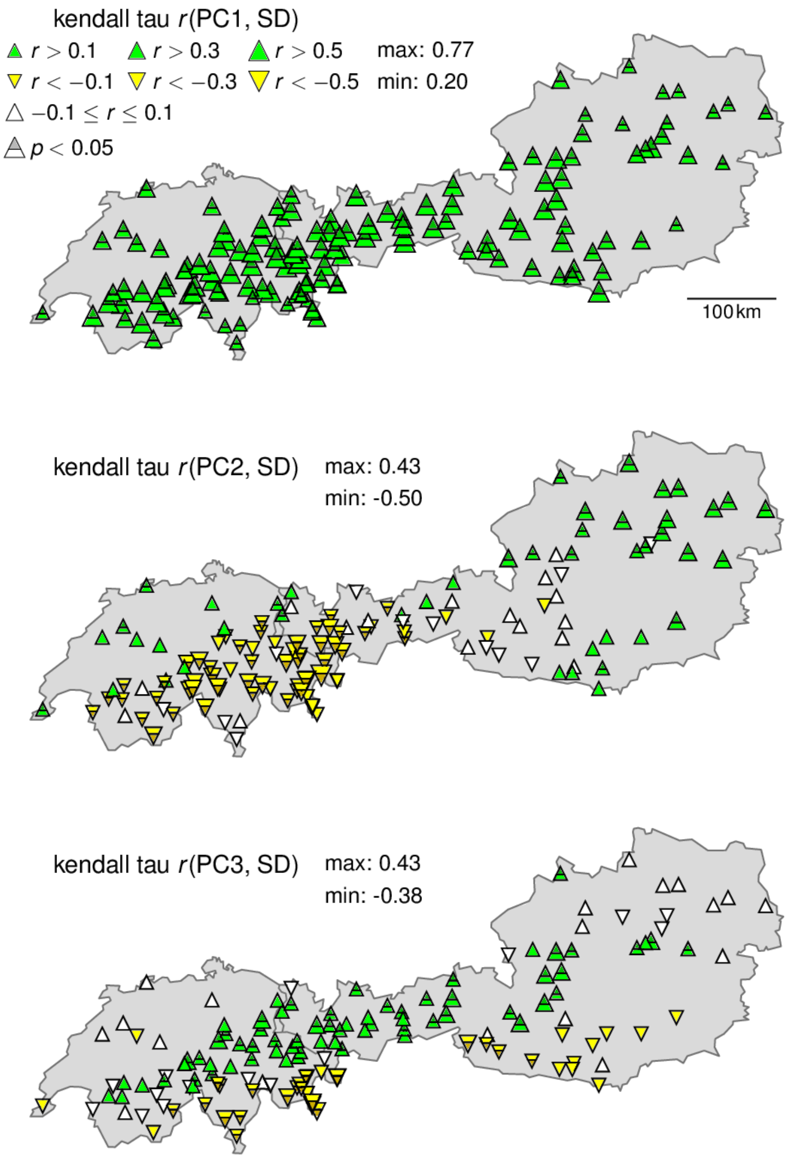


Figure 23: Homogeneous correlation maps presenting Kendalls tau(b) correlation coefficients between the first three PCs and the standardized snow depth time series (SD) from top to bottom. The PCs and snow depth time series were seasonal (NDJFMA) averaged. Positive (negative) correlations are plotted green (yellow). The alternating color of the symbols indicate, that the correlation coefficient is significantly different from zero at a 95% confidence level. White symbols indicate no correlation. The maximum (minimum) value of all correlation coefficients is shown in the top center of each panel.

In view of the altitudinal dependence of the snow depth variations and the findings in the correlation maps, the temporal variability of PC2 implies a weak strength reduction of the elevational snow depth gradient within the base period. Further, it can be assumed that precipitation is the main driver of seasonal snow depth variations at high elevated regions, where effects of temperature changes are expected to be minor. Thus, one could expect that PC2 probably highlight the change in intensity and location of winter precipitation around the end of the 1980s and in the 1990s. In addition, the weak increase of PC3 indicates a strengthening of the North-South gradient over the base period.

It might be attempted to interpret this result that regions south of the main Alpine Ridge received less winter precipitation, compared to regions in the North. Since Southwest precipitation is initially associated with dynamically evolving areas over the Northern Atlantic, it can be expected that temporal variations in the large-scale weather patterns are predominantly responsible for the observed variability in the snow depth data. Besides changes in precipitation patterns, it is evident that the PCs also reflect the influence of variations in the wintertime temperature on the snow depth.

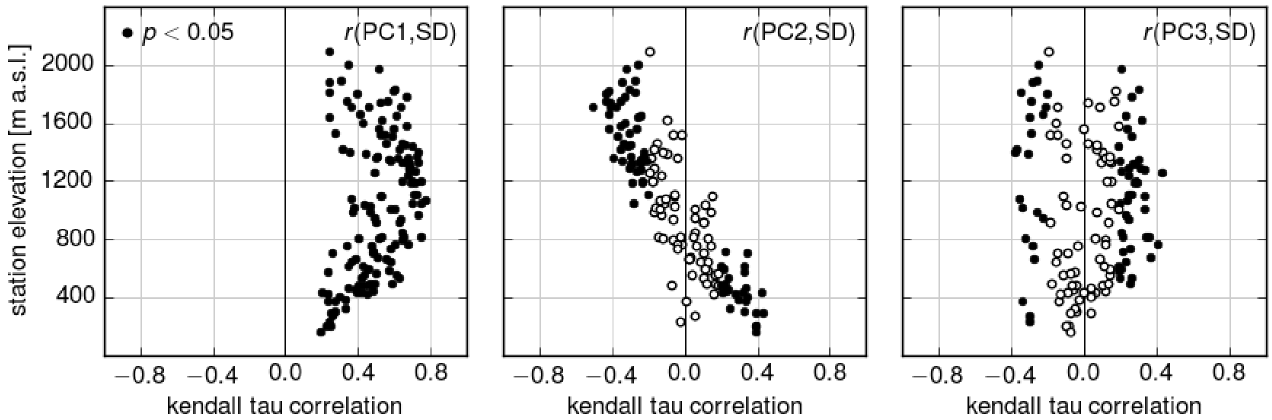


Figure 24: Kendalls tau(b) correlation coefficient between the first three PCs and the standardized snow depth time series (from left to right) subject to the station elevation [m a.s.l.]. The black filled symbols indicate, that the correlation coefficient is significantly different from zero at a 95 % confidence level.

Figure 24 shows the vertical distribution of the Kendalls tau(b) correlation coefficient presented in the homogenous correlation maps. The vertical distribution for PC1 is characterized by a clear increase from lower elevations to 1200 m a.s.l., followed by a decline towards higher elevated stations. One reason for the observed decrease along the elevational gradient could be the variation in the frequency of cold fronts reaching the alpine main ridge. In winter seasons with less frontal precipitation spread over alpine and flatland areas, mountainous regions may still receive solid precipitation from evolving local scale convective systems due to orographic effects. The modification of the wind field over the complex terrain probably also yields high frequency fluctuations of the precipitation pattern on a local scale. For PC2, the correlation coefficients follow a backward tilted vertical distribution with positive values below 600 m a.s.l., negative values above 1200 m a.s.l. and values close to zero in between. One could expect, that the frequency and strength of inversion layers are partly responsible for poor correlations as well as variations in the snow line due to temperature changes. The correlation between PC3 and snow depth observations reveal the pronounced North-South gradient. Hereby, there is no or only a poor correlation in the flatlands and in regions located in the transition zone.

The weak or absence of correlations between the PCs and observations might indicate that fine-scale variations (precipitation and temperature distribution, wind, melting, orographic effects, radiation balance) of the snow depth are embedded or hidden in the large-scale variability.

In order to investigate regional snow depth variations in more detail, the spatial patterns of variability as well as theoretical considerations have been used for a coarse regionalization, identifying major regions with similar conditions during the base period 1962-2010. However, it should be noted that these major regions include various sub-regions, which are characterized by distinct variations of the snow depth. For every region a so-called regional PCA was performed using only the station data within the region considered. Figure 25 shows the 7 major regions (3 in CH and 4 in AT) and corresponding leading PCs. These components explain between 58 % and 77 % of the total variance. Clearly, the leading regional PCs show different temporal variations indicating that these regions exhibit different sensitivity to climate variability and are probably influenced by weather patterns of different characteristics. However, qualitative similarities can be found. For example, at the end of the 1980s all regional PCs show a decline in amplitude. AT1, which represents a region south of the alpine main ridge is characterized by a gradual decrease until 2005. In contrast, the leading PC of AT2 remains low until 1995 followed by a slight increase in subsequent years. Furthermore, all PCs have a minimum around the early 1970s.

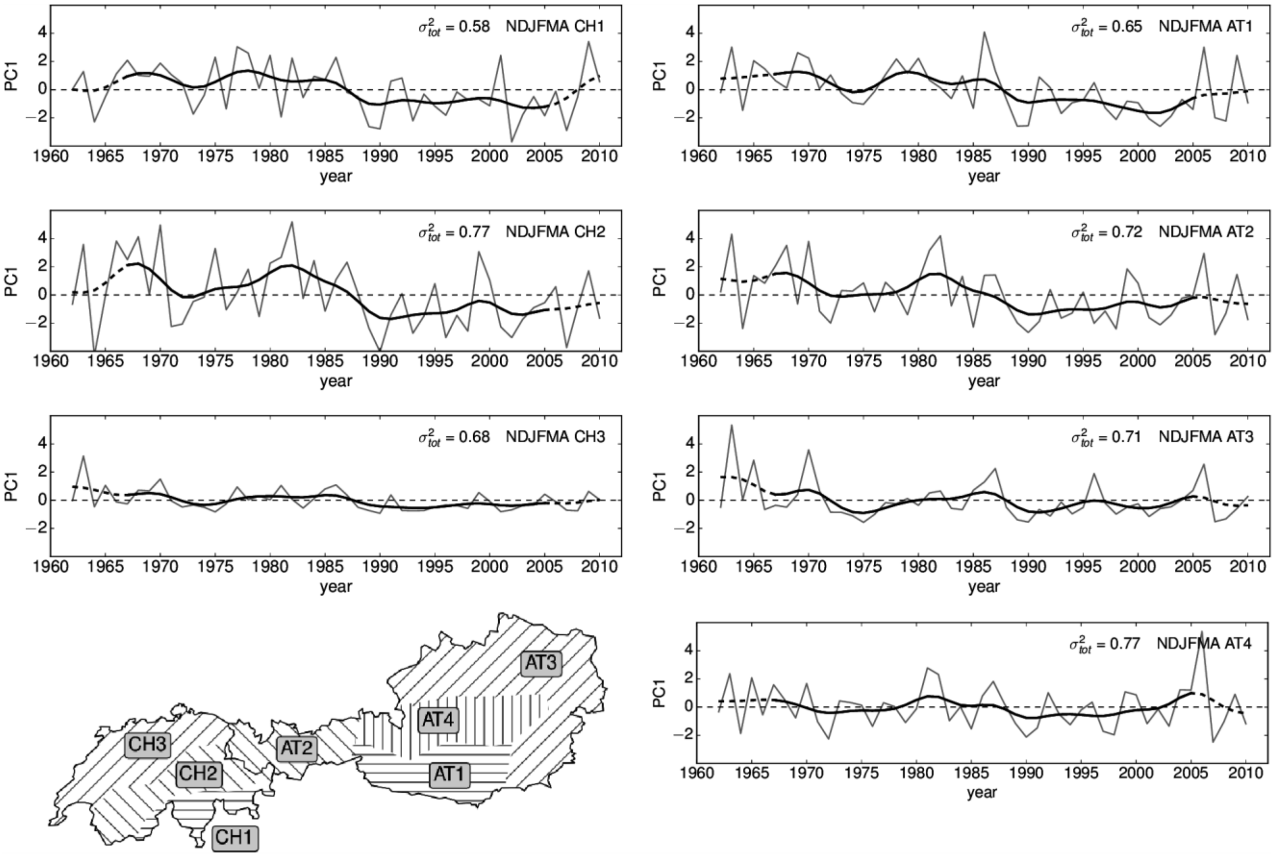


Figure 25: Leading PCs for regions in Switzerland (left panel) and Austria (right panel). The PCs were seasonal averaged (NDJFMA), the solid black lines indicate a Gaussian filter with a window size of eleven years. Regions are shown in the lower left panel.

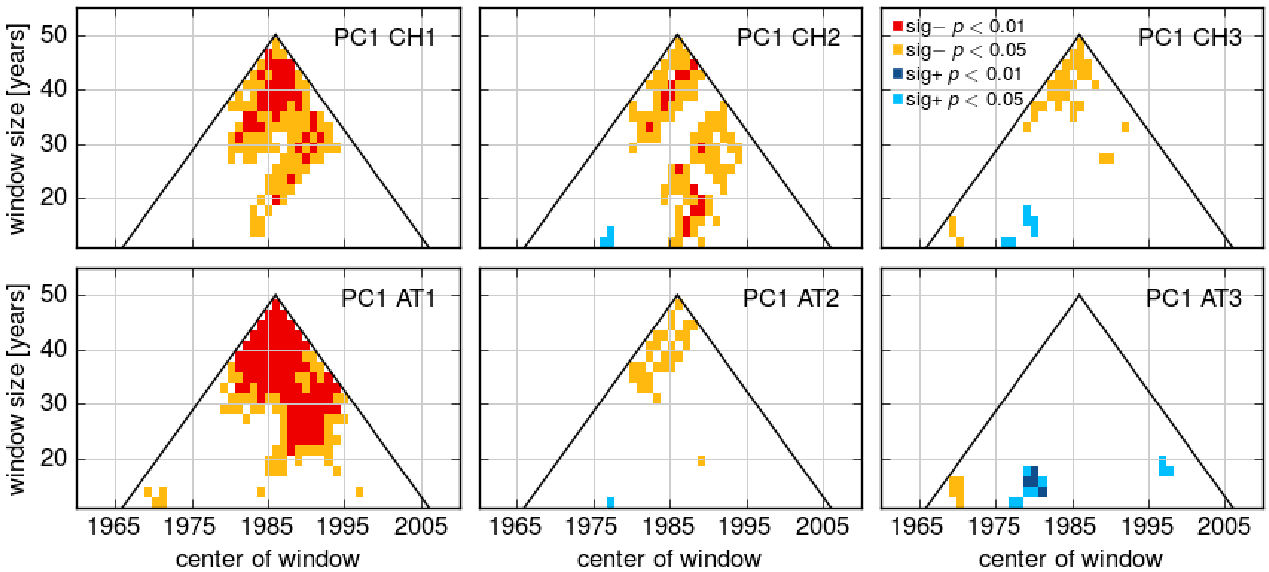


Figure 26: Running trend analysis of the seasonal (NDJFMA) averaged time series of the first leading regional PCs during the base period 1962-2010. The top (bottom) row shows trends for regions in

Switzerland (Austria). The x-axis represents the center of the time window over which the trend is evaluated, and the y-axis represents the size of the time window [years]. The assessed significance of trends is lying inside the black triangle. Negative (positive) trends in the time series of the PCs which are significant at the 95 % (99 %) confidence level are plotted red (blue). White areas indicate the absence of significant trends.

In view of the intercomparison between regions in CH and AT, 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 extent 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 elevations compared to AT2. CH3 and AT3 represent flatland-regions and are characterized by low variability. In contrast, the leading PC of the region AT4 fluctuates more or less around the zero level and clearly can be separated from all other regions investigated.

WP5: Snow at high elevation sites

Temporal changes of snow at high elevation sites of Austria were studied by means of the snow stake network at Sonnblick (Hohe Tauern, Austrian Alps). The network at Sonnblick stands out with respect to its series length back to 1928. The network of stakes and the length of measurements for each stake are shown in Figure 27. All stakes are with monthly readings, with exception of the stake closest to the Sonnblick Observatory (Fleißscharte), which is with daily observations.

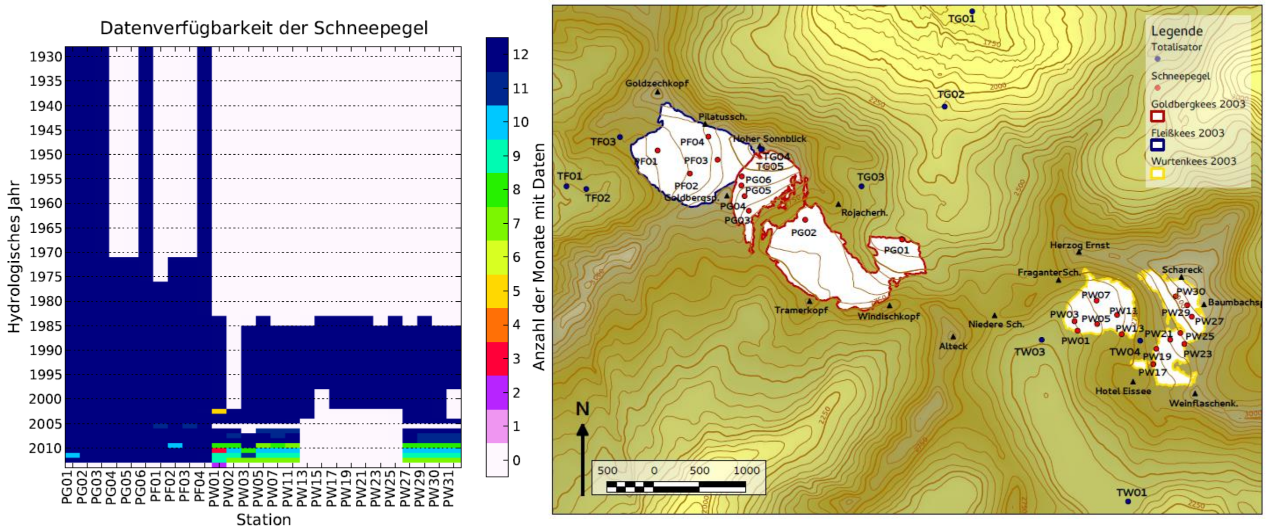


Figure 27: Data availability from the snow stake network at Sonnblick with monthy readings (left) and location map of stakes (right9. (from Leidinger, 2013)

Time series of snow depth at 1 May for each year since 1928 are shown in Figure 28. The snow depth at 1 May represents quite well the maximum snow depth during each year. A large variability of the snow depth is visible from this Figure. Highest values of snow depth were measured in 1944 and 1951, reaching almost 11m of snow for both years. Year-to-year variability clearly decreased during the period ca. 1975 – 1995. Since 2000 maximum snow depth at 1 May decreased significantly.

Interestingly, all stakes in the Sonnblick region agree for the years with highest snow depth in 1944 and 1951, respectively. Nevertheless, this extremely outstanding snow records were crosschecked by a simple snow cover model, which simulates snow depth from daily air temperatures and precipitation. The model not only simulates snow accumulation but also includes a simple snow settling approach and snow ablation based on positive degree-days. Additionally, a snow density module transfers snow water equivalent to snow depth. Figure 29 compares the simulated snow depth with the observed snow depth at Sonnblick for the 1944 event. Using this approach the observed snow maximum in 1944 is rather probable. Similarly, the 1951 event were shown to be realistic, but there are also other indications for this extreme event from e.g. reports on outstanding avalanche events in the Alps.

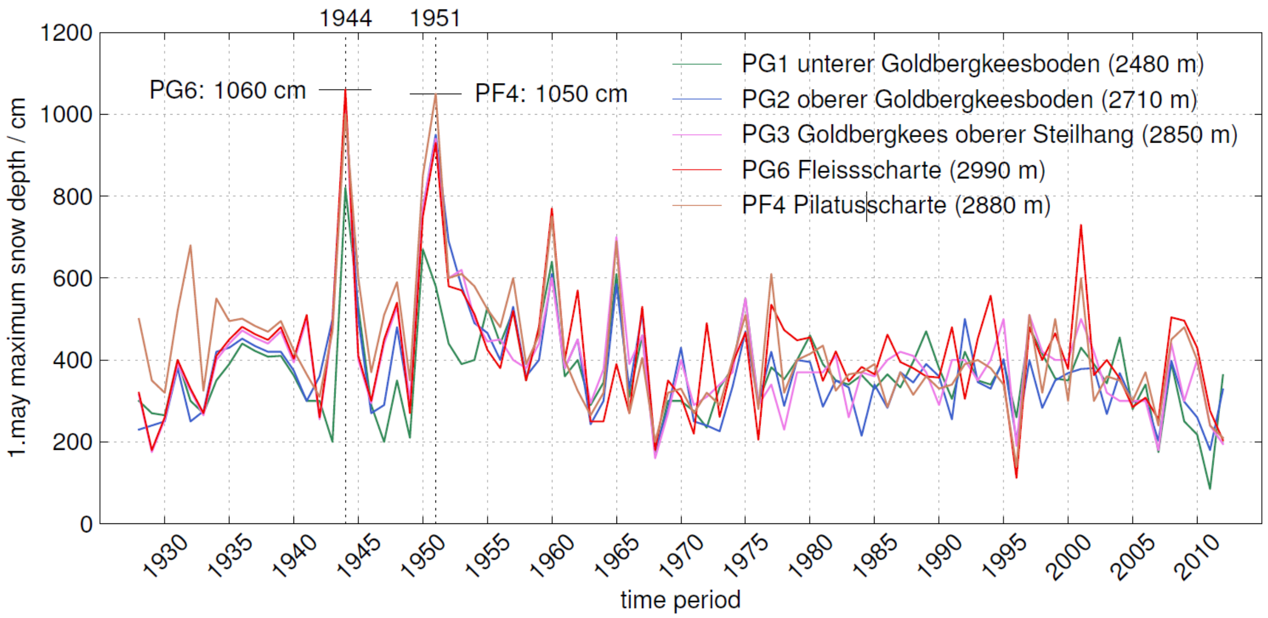


Figure 28: Snow depth at 1 May (maximum snow depth) for all stakes in the Sonnblick area back to 1928

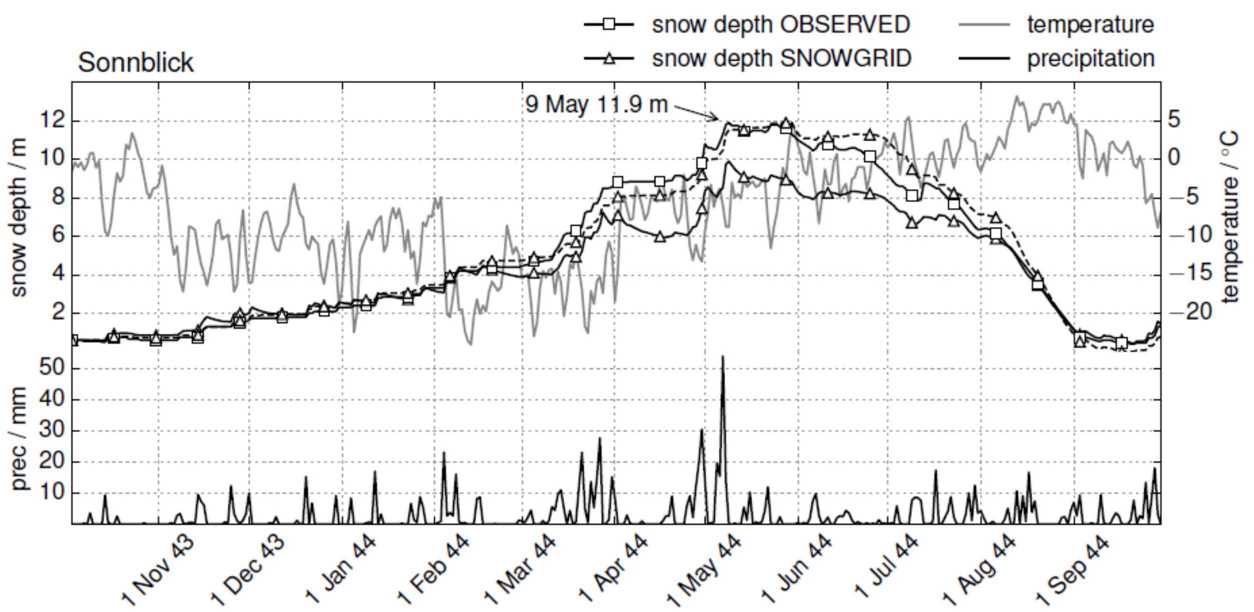


Figure 29: Snow depth at Sonnblick for the winter season 1943/44 for both observed snow depth and simulated snow depth

The effect of the Alpine main divide on the spatial snow precipitation distribution is shown by means of the Sonnblick network of totalizers and gauges. Figure 30 clearly shows the effect of the main divide with significantly less precipitation on the southern side compared to the norther side for same elevations. Whereas the difference is only small at valley floors (ca. 100mm comparing Bad Gastein with Döllach), the difference is increasing to ca. 500mm for elevations around 2500m. Therefore, this precipitation effect is highly relevant for the snow accumulation at glaciers in the Hohe Tauern region.

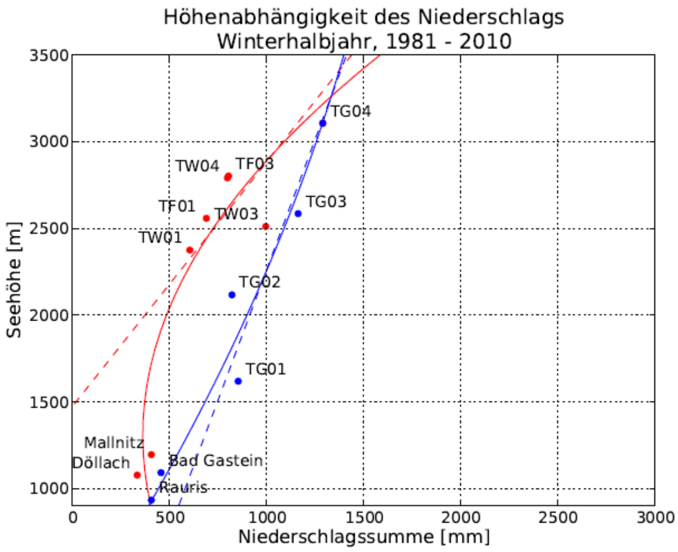


Figure 30: Elevation dependency of snow precipitation for winter season (mean values for 1981-2010) in the Sonnblick region north (blue) and south (red) of the Alpine main divivde

WP7: Dissemination
This WP is described under item 8.

5 Schlussfolgerungen und Empfehlungen

Conclusions homogenisation

Within the scope of the project the suitability of the homogenization of climate snow data records was investigated. The homogenization process applied consisted of the method of PRODIGE (Caussinus and Mestre, 2004) for the detection of multiple inhomogeneities and INTERP (Vincent et al. 2002) for the calculation of correction factors on a seasonal scale. The required reference series have to be homogenous and highly correlated. Detected breaks have been verified against the available metadata.

The snow depth time series are characterized by large spatiotemporal variability. As a matter of fact, artificial shifts are may thus be hidden beneath the snow depth variation yielding less detectable breaks. A careful consideration of the results presented here indicates that low snow depths and the abrupt increase of the number of available reference time series can yield suspicious breaks. Furthermore, negligibly small corrections were found in inhomogeneous snow depth time series of low-elevation sites.

The findings emphasize that the homogenization impact depends on the snow indices investigated, the size of the seasonal correction factor, the length of the corrected period and the temporal scale. For example, the comparison of snow indices at different temporal scales showed a weak impact on the seasonal mean of the snow depth. In this context, the impact remained the same when considering different winter seasons. No significant impact was found on the seasonal snow cover duration.

It is quite clear though that further studies are needed to improve the capability of the break detection algorithm to identify artificial shifts in snow time series. In addition, the findings does leave the question open as to what degree the size of the seasonal correction factors is suitable to correct the inhomogeneous daily base time series. Nevertheless, even in view of these uncertainties, it is evident that the homogenization process yields valuable information.

Conclusions spatiotemporal trends snow in Austria and in the Swiss-Austrian domain

The number of long-term series of snow depth is significantly greater than that for depth of fresh snow in Austria. Applying regionalization methods for Austrian snow series result in 3-4 clusters describing the Austrian snow climate well. The results of Snowpat show very clear, that a simple correlation between increasing air temperatures and decreasing snow precipitation and snow cover has not been observed. In particular, spatiotemporal patterns of snow in Austria are significantly impacted by elevation dependent patterns (high correlation to air temperature at low elevation regions and significant correlation to precipitation changes at high elevation sites. Additionally, the interaction between the orography of the Alps and snow precipitation originating processes results in spatial heterogeneity of trends within Austria. In particular, almost unchanged or slightly increasing snow amounts over the last 50 years in the northeastern part Austria are a clear result of this complexity in precipitation processes.

Additionally, it is obvious from SNOWPAT results that it is important to describe temporal snow cover changes with respect to underlying snow accumulation and snow ablation, which are forced by different atmospheric processes. Whereas snow accumulation (reflected by observations of depth of fresh snow) are quite complex in mountainous terrain, as for precipitation (dependent on weather patterns and associated complex atmospheric processes), snow ablation processes (in particular snowmelt) are more directly linked to air temperature and thus simpler to understand. Thus, inter-annual variability of Alpine snow is quite high and, consequently, changes of Alpine snow are often hard to understand by stakeholders and the public if seen in the context of general climate change. These facts explain why public media and stakeholders (e.g. skiing resorts and special interest groups of winter tourism) discuss temporal changes of Alpine snow climate often quite controversially. However, impact of climate change on Alpine snow is obvious and clear from SNOWPAT results, but need to be carefully explained to stakeholders and the public. The SNOWPAT handbook "Schnee in Österreich", showing relevant snow trends for all SNOWPAT stations and their underlying mechanisms, could serve as a useful base in this case.

Rather probably, observed warmer and drier winter seasons in the Alpine region at the end of the 1980s and in the 1990s are related to the changed distribution of the upper-level wind field over the Northern Atlantic region. Hereby, the location, strengthening and stationary of troughs and ridges (blocking patterns) play an important role for atmospheric winter time conditions over the Alpine area. Evidently, the orientation of mountain ranges subject to the direction of passing atmospheric circulation patterns (lee versus windward slopes) influence the variability of winter precipitation. Besides that, mountain effects on precipitation, such a orographic enhancement of precipitation, can also attribute to the spatial variations.

A clear decrease of cold-wet (CW) weather-modes south of the Alpine Ridge can be linked to consecutive extreme positive winter time NAO Phases in the 1990s and in the early years of the 21st century. During these episodes, the frequency of Mediterranean cyclones declined. Since regions south of the Alpine Ridge receives most of the winter precipitation from Genoa cyclones, one can expect that observed low snow depths reflect the shift of CW-modes to lower values. Analysis of the relationship of the changes of depth of fresh snow with changed weather patterns and atmospheric pressure patterns supports these results. The particularly striking high positive NAO index phases in the 1970s, especially in the late 1980s, and in the 1990s point to a tightening of the west wind drift during these period.

The various regions within Austria receive fresh snow during passages of frontal systems which cross the Alps at different wind directions. Obviously, during the period 1989-2005 fresh snow has decreased especially in the sectors of south to west, partly also northwest. In comparison, snow-causing weather events from the north have increased during the same period. It can be concluded, that regions which receive snow from several sectors (southwest to north) are less affected by changes in the frequency and intensity of certain weather conditions, as, for example, regions south of the Alps, which preferably receive winter precipitation from the south (southwest weather patterns) almost exclusively. The observed negative trends in the snow series south of the Alps can thus be explained in part by the decrease in the frequency and the weakening of southwest weather patterns (Mediterranean cyclones) in the period 1989-2005. In addition, however, the observed increase in temperature decreases the ratio of solid precipitate on total precipitation. Our investigation further revealed that from approximately 2005 onwards, the frequency of southwest-weather patterns has increased again.

From SNOWPAT "lessons learned" and final project results, we recommend the following for possible follow-up studies:

1) Homogenization of climate time series, in particular for daily data, is still not sufficiently solved by today's methods. Clearly, further methodical developments are needed, as time series analysis of climate data, without previous homogenization, could results in wrong interpretation of changes and trends as well as wrong interpretation of model validations, too.

2) Snow is a rather complex phenomenon, whose effects on climate change is sometimes hard to understand, in particular for stakeholders and the public. However, because of its high economic impact for Alpine countries like Austria, high attention should be paid for stakeholder-relevant presentation and processing of the actual status of snow research (snow climatology). Additionally, deriving socio-economical snow indices/characteristics could be a proper method for better engaging stakeholders/practitioners.

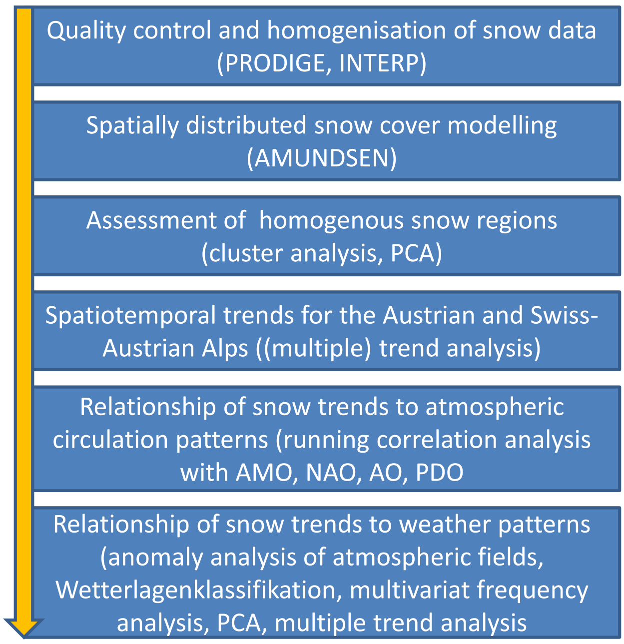
3) Further studies should put much weight on the investigation of snow weather patterns and small scale atmospheric processes in mountainous terrain, as these effects are highly relevant to understand snow precipitation in the Alps.

4) Only by considering 3) future scenarios (e.g. from climate model runs) of snow precipitation and snow cover are useful and provide added value for stakeholders and practitioners.

B) Projektdetails

6 Methodik

The approach applied for SNOWOAT is described by the following diagram:



Homogenization method

The applied homogenization process consisted of the method PRODIGE (Caussinus and Mestre, 2004) for the detection of multiple inhomogeneities in the time series investigated and INTERP (Vincent et al. 2002) for the calculation of corrections, respectively. Both applications are part of the integrated software package HOMOP (Nemec et al., 2013). The snow pack is most sensitive to different atmospheric states, location and elevation. In areas of complex mountainous terrain, e.g., alpine regions, it is expected that the measured daily snow depth has a high variability. In order to overcome high frequency fluctuations on a small timescale, the breakpoint detection and the computation of correction factors are based on seasonal data, respectively.

Break detection

The application of the method PRODIGE (Caussinus and Mestre, 2004) for the detection of an unknown number of breakpoints requires reference stations that are highly correlated with the tested candidate series. Therefore, the correlation coefficient threshold was selected to be $r>0.7$ on a daily scale. In order to obtain reference stations that experienced similar climatic conditions to those of the candidate station, additional distance criteria had been used.

Only reference stations within a horizontal radius of 100 km and a maximum vertical distance of 300 m were considered. The mean number of used reference stations was about 12, though not all of them were available during the whole measuring period of the candidate station.

The detection of breakpoints in the daily snow depth data records is performed in terms of changes in seasonal (DJF and NDJFM) snow depth sums. Thus, accumulated seasonal snow depth series of the candidate time series and the highly correlated reference time series are calculated. Since seasonal variations in the snow depth are expected to be dominated by a multiplicative component, the ratio of the constructed candidate time series to each reference time series is tested for inhomogeneities. Ratio time series covering less than 5 years or having more than 1000 missing data lines on a daily scale are rejected. In addition, the approach is based on a penalized log-likelihood criterion (Mestre et al., 2011) in order to overcome the increased likelihood of detection with an increased number of breakpoints (overfitting). The criteria of Caussinus and Lyazrhi (1997), Jong et al. (2003) and Lebarbier (2005) are used in the detection process.

A break signal for each of the criteria is obtained if more than half of the reference stations detected the break. Only those breaks were considered further on, for which more than one criteria had a signal in both seasons. Additionally, if necessary the break was adjusted using metadata.

Impact of low snow depths and abruptly increased number of reference time series on homogenization

A caveat regarding to PRODIGE needs to be mentioned. The detailed investigation of the detected breaks revealed, that PRODIGE also identified natural shifts in the snow depth time series. It turned out, that winter seasons with on average low snow depths (beginning of the 1970s, end of the 1980s, beginning of the 1990s, see also Marty, 2008) yielded so-called suspicious breaks that cannot be linked to changes in the observational environment (Figure 31). Obviously, the detection algorithm is more sensitive to changes at low snow depths. Furthermore, the abrupt increase of available reference time series resulted in suspicious breaks as well (Figure 32).

The knowledge of these possible suspicious breaks is a matter of great importance to prevent the misleading correction of time series, which are already representing the "true" variation of the snow depth. Thus, one could expect that the identification of suspicious breaks can be a hard challenge, especially if no additional meta-information is available.

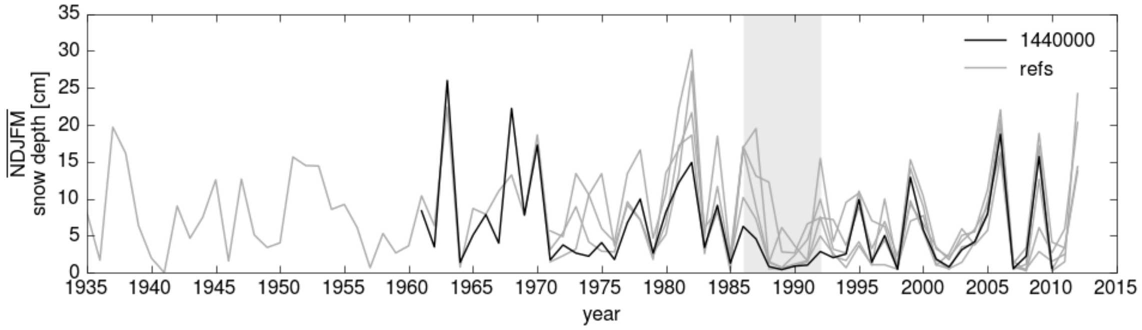


Figure 31: Seasonal (NDJFM) mean snow depths [cm] of a candidate time series (black) and high correlated reference time series (grey). The grey rectangle indicates a time period of low snow depths. Within that time period suspicious breaks were detected.

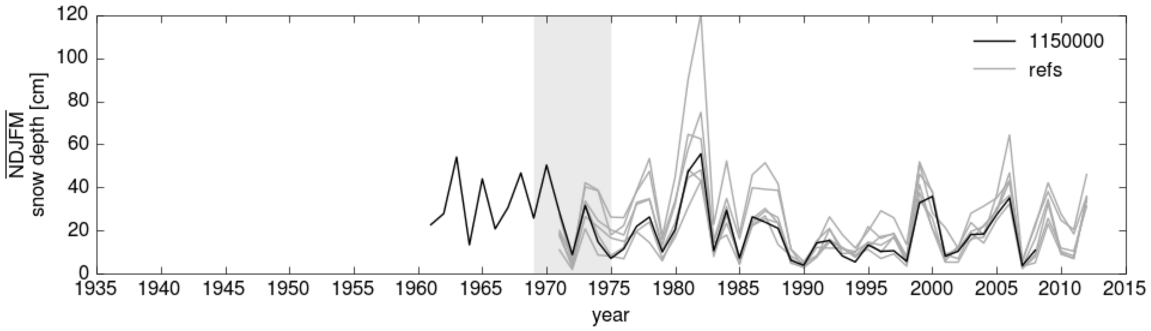


Figure 31: Seasonal (NDJFM) snow depths [cm] of a candidate time series (black) and high correlated reference time series (grey). The grey rectangle indicates the starting point (around 1972) of reference time series.

Correction factor

Once breakpoints were detected, a modified version of the INTERP method (Vincent et al. 2002) was applied to correct inhomogeneities in the daily snow depth data records. The computation of correction factors is based on a seasonal (NDJFM) scale and resulting adjustments are neither smoothed nor interpolated on a daily basis. Since ground-based snow depth measurements are characterized by high spatial and temporal variability due to a lot of different influences, i.e., temperature, wind, radiation, that cannot be taken into account by the correction factor a simple approach was chosen, for which a reasonable improvement of the time series can be expected. A seasonal adjustment was calculated and applied on the daily data. The equation for the calculation of the seasonal adjustment has the form:

$$\text{correction factor} = \frac{\text{median}\left\{\frac{C_a}{R_a}\right\}}{\text{median}\left\{\frac{C_b}{R_b}\right\}},$$

where indices a and b represent the time period after and before the detected inhomogeneity and C (R) is the accumulated seasonal (NDJFM) snow depth of the candidate (reference) time series. The final step involves the multiplication of the inhomogeneous daily scale sub-period before the breakpoint by the seasonal correction factor.

Snow cover modelling

The spatially distributed snow model AMUNDSEN (Strasser, 2008; Hanzer et al. 2016) was applied for the snow modelling tasks in SNOWPAT. AMUNDSEN has been designed as a process-based model for the application in high mountain regions, requiring hourly to three-hourly meteorological input data to calculate the snow surface energy balance. For the application in SNOWPAT, it had to be redesigned in order to enable operation with daily time steps as well as solely using temperature and precipitation as meteorological forcing data. The model runs were performed on a digital elevation model (DEM) with a resolution of 1 km x 1 km.

In each model time step, first a meteorological pre-processor in AMUNDSEN is used to spatially interpolate the point information from the station locations to the model domain. Topographic corrections are carried out either by deriving linear regressions of the meteorological observations with altitude in combination with interpolated residuals, or by applying prescribed monthly lapse rates. Due to the comparatively sparse station coverage, the latter was chosen in the project. After interpolation, precipitation phase is determined. As this was originally performed using wet-bulb temperature, a new method determining precipitation phase on air temperature alone was implemented. Two temperature thresholds describe the temperature range in which mixed precipitation occurs (with linear interpolation of the rain/snow fraction in between), while below and above these thresholds precipitation is assumed to be 100 % snow and rain, respectively. To account for the undercatch of (especially) solid precipitation measured by precipitation gauges, several correction methods were implemented and evaluated in the project: i) adjustment by a prescribed snow correction factor applied on the station time series (i.e., prior to interpolation), ii) adjustment by a prescribed snow correction factor on the interpolated snowfall fields, and iii) adjustment by station-dependent snow correction factors derived from hourly measurements using a common snowfall correction method taking into account temperature and wind speed (Goodison et al. 1998).

For converting simulated snow water equivalent (SWE) to snow depth, two snow layers are distinguished, new snow and old snow. The density of freshly fallen snow is calculated as a function of air temperature, while snow compaction is calculated separately for each layer, with a phase of rapid compaction for newer snow followed by a phase of slower densification which is mainly influenced by the snow load. New snow is converted to old snow when reaching a certain threshold density (Hanzer et al. 2016). Snow albedo is parameterized using an aging curve approach taking snow age and air temperature into account.

Since the meteorological input data in terms of parameters and resolution do not allow a physically based simulation of the snow surface energy balance, a temperature index approach was implemented in AMUNDSEN. Snowmelt is thereby calculated as a function of air temperature as well as snow albedo and potential clear-sky incoming solar radiation. The threshold temperature for snowmelt as well as the temperature and albedo coefficients are calibrated parameters. A recently implemented submodule in AMUNDSEN allows to consider cold content and liquid water content of the snowpack, hence snowmelt is not immediately removed from the snowpack but is retained up to a certain amount and can possibly refreeze again (Hanzer et al. 2016).

Test of significance of trends

In order to investigate the question to what degree the corrected snow depth time series are significantly different from the original time series, bootstrap-samples are evaluated in terms of the difference between the means.

Pattern analysis with Principle Component Analysis (PCA)

In order to identify regions, which experienced similar winter time conditions during the base period 1962 to 2010, patterns that explain the highest proportion of the observed variance are considered. An adequate approach that fulfills the requirement for assessing the spatiotemporal variability is the investigation of the snow depth by the method of principal component analysis (PCA), also called Empirical Orthogonal Function (EOF) analysis (Preisendorfer and Mobley, 1988, Bretherton et al., 1992, Rajagopalan and Cook, 2000). The objective of PCA is to decompose multivariate time series into a set of uncorrelated and orthogonal components (modes). Furthermore, PCA is indifferent to possible temporal autocorrelation in the time records.

In this study the PCA was performed by singular value decomposition (SVD) of the standardized snow data anomalies which is closely related to the mathematical formulation of the eigenvalue decomposition of the data covariance matrix (Mathematical Tools for Physicists, Wallace et al., 1991, Lay David, Linear algebra 2000). By convention, the calculated components are ordered by the corresponding singular values from largest to smallest. The obtained EOFs characterize the spatial variability (spatial dimension), whereas the so-called expansion coefficient time series (PCs) represent the projections of the standardized snow anomalies on the corresponding EOFs and characterize the time-varying variability (sampling dimension).

Since, the structure of neighboring components is not necessarily distinguishable from each other due to sampling errors (Preisendorfer et al., 1981, Overland and Preisendorfer, 1982, North et al., 1982), the so-called North's rule of thumb was used, to choose the number of components to be retained. Thus, only the first three EOFs which account for 68 % of the total variance were considered (Table 7). In addition, it can also be concluded from the visual inspection of the scree plot (Figure 32), that the remaining components associated with small variances can be dropped due to intermixing effects on the structures obtained and as well as noise in the data.

Table 7: Variance explained and cumulative sum of variance explained of the first five EOF components.

	EOF1	EOF2	EOF3	EOF4	EOF5
explained variance	0.49	0.13	0.06	0.04	0.03
cumulative sum	0.49	0.62	0.68	0.72	0.75

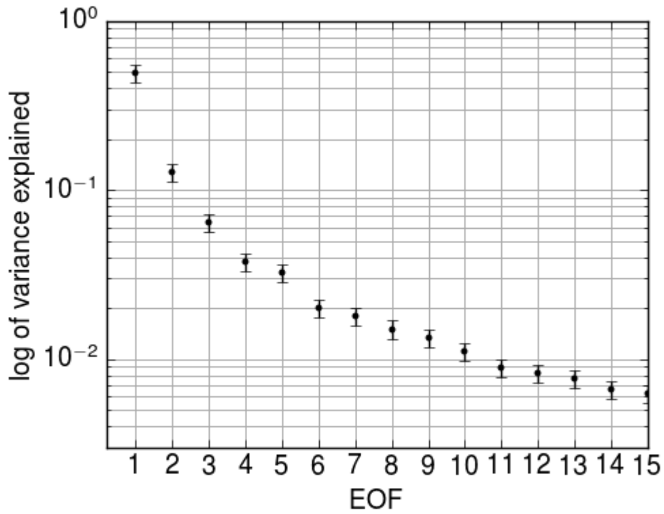


Figure 32: Logarithm of the variance explained as a function of the number of components. The first 25 components are shown. The error bars are based on North's rule of thumb and indicate the uncertainty due to limited sampling.

WLK circulation type classification

In order to investigate the relationship between snow indices and large-scale atmospheric circulation in more detail, a circulation type classification based on the so-called WetterLagenKlassifikation (WLK) was performed. The WLK-classification uses the daily zonal and meridional wind components at 700 hPa (Dittmann et al., 1995; Philipp et al., 2010) as indicators for identifying prominent circulation patterns. The classification technique yields eight main weather types divided by 45-degree wind sectors (N, NE, E, SE, S, SW, W and NW) and one unclassified type (UNC). The latter represents gradient weak large-scale weather currents. Hereby, N represents the wind sector from 337.5 to 22.5 degree, NE the wind sector from 22.5 to 67.5 degree and so on. The classification was done using daily NCAR/NCEP reanalysis data (Kalnay et al., 1996) during the period 1948-2010. The global model integrations were made with a horizontal resolution of T62 (210 km) and with 28 model levels (17 pressure levels) in the vertical. Finally, a particular type of classification is assigned to each day of the time period.

Figure 33 shows averaged maps of the 700 hPa geopotential height for 9 weather types obtained. The maps are derived by averaging the geopotential height of all days with the same type of classification during 1948-2010. Through the construction of the weather types which is based on a rather low-resolution global model, the derived nine weather types mainly represent large-scale information. However, dynamically evolving weather patterns are a combination of various scales often dominated by small scale processes. As a consequence, fine scale circulation features are not captured. Nevertheless, primarily in view of large scale patterns, the obtained weather types provide information which is in line with theoretical considerations.

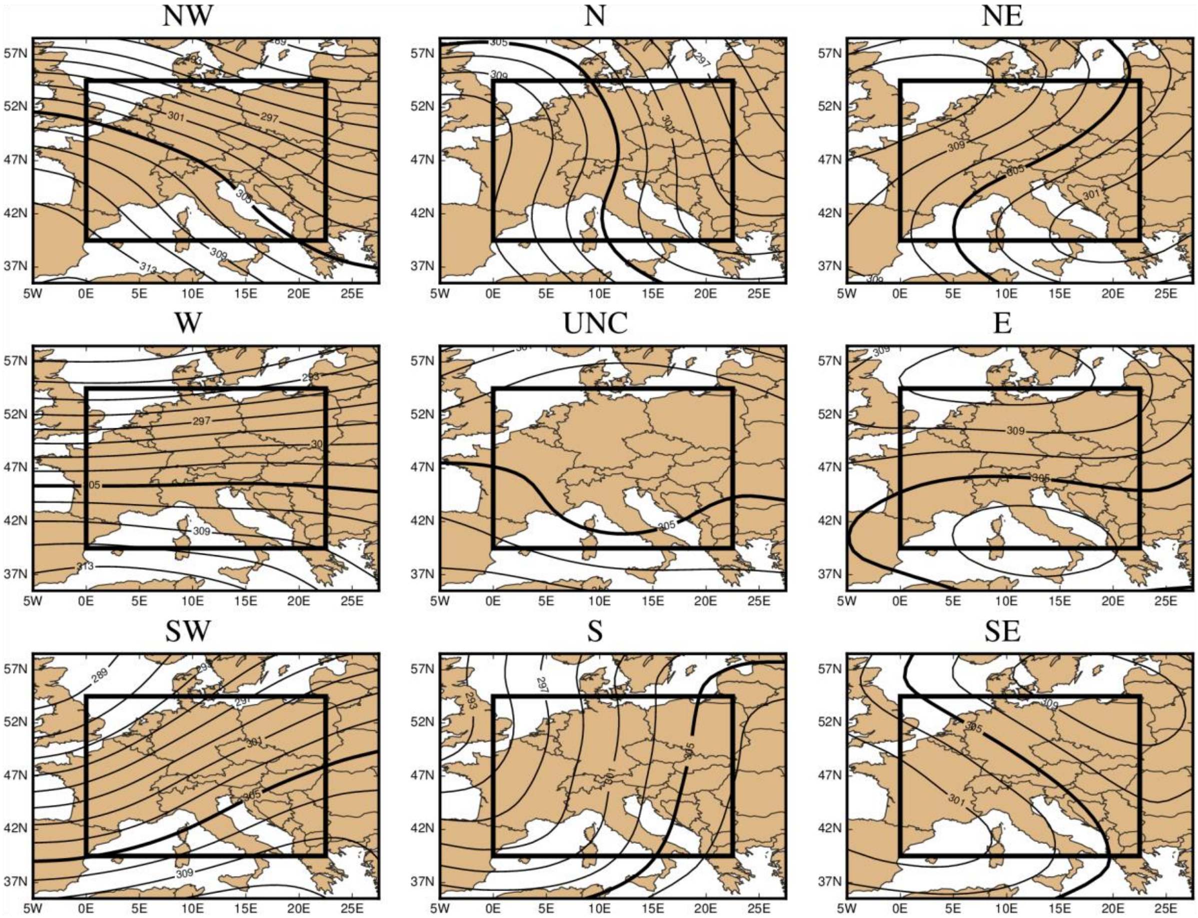
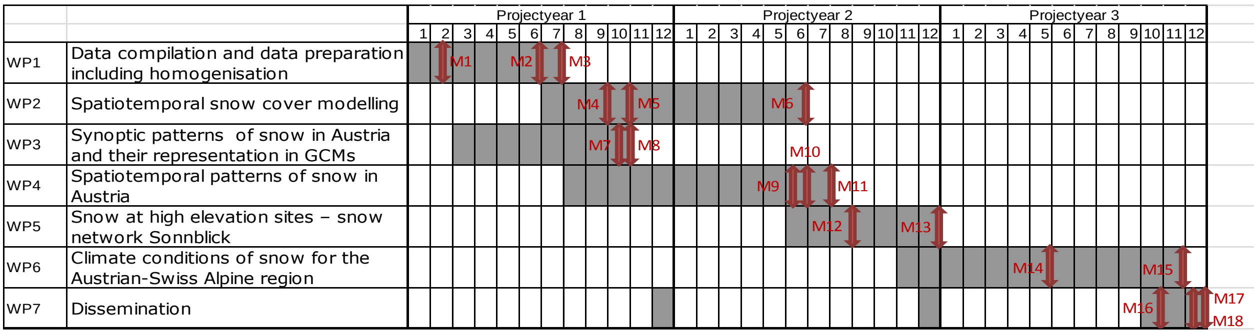


Figure 33: Average maps of geopotential height (10 m) at 700 hPa for 9 (8 wind sectors and 1 unclassified type) synoptic weather types obtained from the WetterLagenKlassifikation (WLK) using NCAR/NCEP reanalysis data for 1948-2010. The black rectangle indicates the target area (0E-22.5E, 40N-55N) for which the classification was performed. The highlighted contour line indicates the 700 hPa contour at 305 dam.

7 Arbeits- und Zeitplan



8 Publikationen und Disseminierungsaktivitäten

Poster presentations:

- Schöner W., Jurkovic A., Reisenhofer S., Koch R., Strasser U., Marke T., Marty C.: Langzeittrends des Schnees in Österreich – Erste Ergebnisse des Projektes SNOWPAT, Klimatag 2013 (Auszeichnung mit 1. Posterpreis)
- Koch R., Chimani B., and W. Schöner: Experiences in homogenization of Austrian snow depth observations, Poster presented at EGU2014, Vienna (Austria)
- Koch R. and W. Schöner: Spatiotemporal analysis of snow trends in Austria, Poster presented at EGU2015, Vienna (Austria)
- Marke T., Hanzer F., Strasser T., Siegmann M., Schöner W. and R. Koch: Spatiotemporal changes in the Austrian snow cover 1948-2009. Poster presented at IUGG 2015, Prag (Czech Republic)
- Schöner W. and R. Koch: Spatiotemporal analysis of snow trends in the Austrian Alps and their relationship to weather patterns. Poster presented at AGU2015, San Francisco (USA)
- Marke T., Hanzer F. and U. Strasser: Past and future of the Austrian snow cover. Poster presented at Alpine Glaciology Meeting 2016, Munich (Germany)

Oral presentations:

- Koch R., Tilg A.M., Schöner W., Chimani B., Marty C., Marke T. and U. Strasser: Räumliche und zeitliche Analysen von –Schneezeitreihen in Österreich. Klimatag 2015, Wien
- Koch R. und W. Schöner: Trendanalyse von Schneezeitreihen in Österreich. MeteorologInnentag 2015, Wien

Publications:

- Koch R.: Spuren im Schnee. ZAMG Newsletter Frühling/Sommer 2013
- Leidinger D. (2013): Analyse der zeitlichen und räumlichen Variabilität des Niederschlags im Gebiet des Hohen Sonnblicks. Diplomarbeit Universität Wien, Institut für Meteorologie und Geophysik, 79 Seiten
- Koch R., Chimani B., and W. Schöner(2014): Experiences in homogenization of Austrian snow depth observations, Geophysical Research Abstracts, Vol16, EGU2014-11665, 2014
- Koch R. and W. Schöner (2015): Spatiotemporal analysis of snow trends in Austria. Geophysical Research Abstracts, Vol17, EGU2015-10274, 2015
- Koch R., Schöner W., Olefs M., Niedermoser B. (2015): Extreme Schneehöhen am Sonnblick. 110-112 Jahresbericht des Sonnblick Vereines, 2012-2014, 20-22
- Marcolini G., Koch R., Chimani B., Schoener W., Bellin A., Disse M., and G. Chiogna (2016). Homogenization of snow depth data: an intercomparison study: Paper to be submitted to Theoretical and Applied Climatology, 15 pages
- Schöner W. (2016): Niederschlag im Hochgebirge. in W. Schöner (Ed): Promet Heft „Hochgebirgsmeteorologie und Glaziologie“ (accepted)

Publications in preparation:

- Koch R., Matulla C., Tilg A.M., Marty C., Schöner W. (2016): Spatiotemporal patterns of winter snow cover in the Austrian-Swiss Alps
- Koch R., Tilg A.M., Marty C., Schöner W. (2016): The relationship of Alpine winter snow fall to large scale weather patterns.
- Tilg A. M., Marty C., Koch R. and W. Schöner (2016): Are there geographical gradients with regard to the climate sensitivity of the Alpine snow cover?

Media presentations:

- Der Standard: Historischer Einbruch der Schneedecke, Forschung Spezial, Mi 21.1.2015, Seite 9

- Klimawandelanpassung.at: SNOWPAT: (kein) Schnee von gestern – die bestmögliche Zeitreihe, 4. Mai 2016

Workshops:
- Workshop on Homogenization of Snow Observations, 12. – 13. January 2015, Davos, Switzerland

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References:

Abegg B., Agrawala C., Crick F., A. de Montfalcon. (2006): Climate change impacts and the adaptation in winter tourism. In: Agrawala A. (Ed): Climate change in the European Alps. OECD Publications, Paris, pp. 25-60.

Auer I, Jurkovic A, Orlik A, Böhm R, Korus E, Sulis A, Marchetti A, Manenti C, Dolinar M, Nadbath M, Vertacnik G, Vicar Z, Pavcic B, Geier G, Rossi G, Leichtfried A, , Schellander H, Gabl K, Zardi D, (2008): High quality climate data for the assessment of Alpine climate, its variability and change on regional scale - Collection and analysis of historical climatological data and metadata. Endbericht FORALPS WP5: Meteo – Hydrological Forecast and Observations for improved Water Resource Management in the Alps. WP 5 Data Set. http://www.zamg.ac.at/forschung/klimatologie/klimawandel/foralps/. Veröfftl. Projektbericht

Auer I, Jurkovic A, Böhm R, Schöner W, Lipa W. (2008): Endbericht StartClim2007A. Erweiterung und Vervollständigung des StartClim Datensatzes für das Element tägliche Schneehöhe. Aktualisierung des existierenden StartClim Datensatzes (Lufttemperatur, Niederschlag und Dampfdruck) bis 2007 04. In StartClim 2007. Auswirkungen des Klimawandels auf Österreich: Fallbeispiele. Veröffentlichter Projektbericht auf CD-ROM.

Auer I, Böhm R, Jurkovic A, Lipa W, Orlik A, Potzmann R, Schöner W, Ungersböck M, Matulla C, Briffa K, Jones PD, Efthymiadis D, Brunetti M, Nanni T, Maugeri M, Mercalli L, Mestre O, Moisselin J-M, Begert M, Müller-Westermeier G, Kveton V, Bochnicek O, Stastny P, Lapin M, Szalai S, Szentimrey T, Cegnar T, Dolinar M, Gajic-Capka M, Zaninovic K, Majstorovic Z, Nieplova E, (2007). HISTALP – Historical instrumental climatological surface time series of the greater Alpine region 1760-2003. International Journal of Climatology 27: 17-46

Barnett T.P., Adam J.C. and D.P. Lettenmaier. (2005): Potential impacts of a warming climate on water availability in snow-dominated regions. Nature Vol. 438/17, 303-309, doi:10.1038/nature04141.

Beniston, M., (1997): Variations of snow depth and duration in the Swiss Alps over the last 50 years: Links to changes in Large-scale climatic forcings, Climatic Change, 36, 281-300,

Beniston M. (2000): Environmental change in mountains and uplands. London, UK, and Oxford University Press, New York, USA: Arnold Publishers, 172 pp.

Beniston, M., Keller, F., Goyette, S. (2002): Snow pack in the Swiss Alps under changing climatic conditions: an empirical approach for climate impacts studies. Theor. Appl. Climatol. 74, 19-31, doi 10.1007/s00704-002-0709-1

Beniston M., F. Keller and S. Goyette. (2003a): Snow pack in the Swiss Alps under changing climatic conditions: an empirical approach for climate impact studies. Theor. Appl. Climatol. 74, 19-31, DOI 10.1007/s00704-002-0709-1.

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

Beniston, M., Uhlmann, B., Goyettea, S., Lopez-Moreno, J.I. (2011): Will snow-abundant winters still exist in Swiss Alps in an enhanced greenhouse climate? Int. J. Climatol., 31, pp. 1257-1263.

Beniston, M., (2012): Is snow in the Alps receding or disappearing?, WIREs Clim Change 2012. doi: 10.1002/wcc.179

Blöschl, G., A. Viglione, R. Merz., J. Parajka, J. Salinas und W. Schöner (2011) Auswirkungen des Klimawandels auf Hochwasser und Niederwasser. Österreichische Wasser- und Abfallwirtschaft, 63, (1-2), 21- 30.

Böhm R. and H. Mohnl. (1987): Statistische Analysen der Schneehöhen im Gebiet des Hohen Sonnblicks. Zeitschrift für Gletscherkunde und Glazialgeologie, Vol 23, 47-63.

Buzzi, A. and Tibaldi, S. (1978): Cyclogenesis in the lee of the Alps: A case study. Quart. J. R. Met. Soc., 104, pp. 271-287.

Caussinus, H. and F. Lyazrhi (1997). Choosing a linear model with a random number of change-points and outliners. Ann. Inst. Statist. Math. 49, No. 4, 761-775.

Caussinus, H. and O. Mestre (2004). Detection and correction of arthificial shifts in climate series. Appl. Statist. 53, 405--425.

Dittmann, E., Barth, S., Lang, J., Müller-Westermeier, G., (1995): Objektive Wetterlagenklassifikation (Objective weather type classification). Ber. Dt. Wetterd. 197, Offenbach a. M., Germany.

Durand Y., Giraud G., Laternser M., Etchevers P., Mérindol L., and Lesaffre B., (2009). Reanalysis of 47 Years of Climate in the French Alps (1958–2005): Climatology and Trends for Snow Cover. J. Appl. Meteor. Climatol., 48, 2487–2512. doi: http://dx.doi.org/10.1175/2009JAMC1810.1

Efthymiadis, D., P.D. Jones, K.R. Briffa, I. Auer, R.Böhm, W. Schoener, C, Frei, and J. Schmidli, (2006): Construction of a 10-min-gridded precipitation data set for the Greater Alpine Region for 1800-2003. J. Geophys. Res., 110, D01105, doi:10.1029/2005JD006120 D01105

Fliri, F., 1992a: Der Schnee in Nord- und Osttirol 1895 – 1991 – Ein Graphik-Atlas, Band 1, Universitätsverlag Wagner, Innsbruck

Fliri, F., 1992b: Der Schnee in Nord- und Osttirol 1895 – 1991 – Ein Graphik-Atlas, Band 2, Universitätsverlag Wagner, Innsbruck

Gocic M., Trajkovic S., 2013: Analysis of changes in meteorological variables using Mann-Kendall and Sen's slope estimator statistical tests in Serbia. Global and Planetary Change, 100, 172–182

Hamed, K. H., 2008: Trend detection in hydrologic data: The Mann Kendall trend test under the scaling hypothesis. J. Hydrol., 349, 350–363.

Hantel, M., Ehrendorfer, M. and A. Haslinger, 2000: Climate Sensitivity of Snow Cover Duration in Austria, Int. J. Climatol., 20, 615-640, doi: 10.1002/(SICI)1097-0088(200005)20:6<615::AID-JOC489>3.0.CO;2-0

Hilmer, M. and Jung, T. (2000): Evidence for a recent change in the link between the North Atlantic Oscillation and Arctic sea ice export. Geophys. Res. Lett., 27, pp. 989-992.

Hurrell, J.W. (1995): Decadal Trends in the North Atlantic Oscillation: Regional Temperatures and Precipitation. Sience, Vol.269, No. 5224, pp. 676-679.

Hurrell, J.W. (1996): Influence of variations in extratropical wintertime teleconnections on Northern Hemisphere temperature. Geophysical Research Letters, Vol. 23, No6, pp. 655-668.

Hurrell, J.W. (2015): The Climate Data Guide: Hurrell North Atlantic Oscillation (NAO) Index (PC-based). Available at URL: https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-pc-based

IPCC. (2007): Climate Change. The IPCC Third Assessment Report. Volumes I (Scinece), II (Impacts and Adaptation), III (Mitigation Strategies). Cambridge, New York. Cambridge University Press.

Jonas T., Marty C., Magnusson J.(2009): Estimating the snow water equivalent from snow depth measurements in the Swiss Alps; Journal of Hydrology, 378, 161-167, doi:10.1016/j.jhydrol.2009.09.021

Jong, K., E. Marchiori, A. van der Vaart, B. Ylstra, M. Weiss, and G. Meijer (2003). Chromo-somal breakpoint detection in human cancer. In EvoWorkshops'03: Proceedings of the 2003, international conference on Applications of evolutionary computing, Berlin, Heidelberg, pp. 54-65. Springer-Verlag.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. C. Mo, C. Ropelewski, J. Wang, A. Leetmaa, R. Reynolds, R. Jenne, and D. Joseph, (1996): The NCEP/NCAR 40-Year Reanalysis Project". Bull. Amer. Meteor. Soc., 77, 437–471.

Keller F., Goyette S. and M. Beniston (2005): Sensitivity analysis of snow cover to climate change scenarios and their impact on plant habitats in Alpine terrain. Climatic Change 72, 299-319.

Kendall, M. G., (1975). Rank Correlation Methods. 4th ed., Charles Griffin, London, 202 pp.

Laternser, M. and M. Schneebeli, (2003). Long-Term Snow Climate Trends of the Swiss-Alps (1931-99), Int. J. Climatol., 23, 733-750

Lauscher A. and F. Lauscher. 1973. Der Aufbau und Abbau der Schneedecke auf dem Sonnblick im Wechselspiel der Wetterlagen. 68.-69. Jahresbericht des Sonnblick Vereins für die Jahre 1970-1971, 3-30.

Lebarbier, E. (2005). Detecting multiple change-points in the mean of gaussian process by model selection. Signal Process. 85 (4), 717-736.

Mann, H. B., (1945). Nonparametric test against trend. Econometrica, 13, 245–259.

Marty, C. and Meister, R., (2012). Long-term snow and weather observations at Weissfluhjoch and its relation to other high-altitude observatories in the Alps. Theoretical and Applied Climatology: 1-11. doi:10.1007/s00704-012-0584-3.

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

Marty, C. and Blanchet, J., (2011): Long-term changes in annual maximum snow depth and snowfall in Switzerland based on extreme value statistics, Climatic Change, doi:10.1007/s10584-011-0159-9.

Mestre, O., Gruber, C., Prieur, C., Caussinus, H., and S Jourdain, (2011): SPLIDHOM: A Method for Homogenization of Daily Temperature Observations. J. Appl. Meteor. Climatol., 50, 2343-2358.

Mohnl H.,(1994): Die Schwankungen der Neuschneehöhe und Schneedeckendauer in Österreich (Periode 1895-1992). 90.-91.Jahresbericht des Sonnblick-Vereins für die Jahre 1992-1993, 5-47.

Moran-Tejeda, E., Herrera, J., Lopez-Moreno, J.I., Revuelto, J., Lehmann, A., Beniston, M. (2013): Evolution and frequency (1970-2007) of combined temperature-precipitation modes in the Spanish mountains and sensitivity of snow cover. Reg. Environ. Change 13, pp. 873-885.

Nemec J., Gruber C., Chimani B., Auer I. (2013): Trends in extreme temperature indices in Austria based on a new homogenised dataset of daily minimum and maximum temperature series. International Journal of Climatology 33/6, 1538-1550, doi:10.1002/joc.3532

Philipp, A., Bartholy, J., Beck, Ch., Erpicum, M., Esteban, P., Fettweis, X., Huth, Radan, James, F., Jourdain, S., Kreienkamp, F., Krennert, T., Lykoudis, S., Michalides, S. C., Pianko-Kluczynska, K., Post, P., Álvarez, D. R., Schiemann, R., Spekat, A., Tymvios, F. S.(2010): Cost733cat-A database of weather and circulation type classifications. Phys. Chem. Earth 35, pp. 360-373.

Pinto J.G., Brücher T., Fink A.H. and A. Krüger. 2007. Extraordinary snow accumulations over parts of central Europe during the winter of 2005/06 and weather-related hazards. Weather Vol. 62/1, 16-21.

Riviere, G. (2011): A dynamical interpretation of the poleward shift of the jet streams in global warming scenarios. Journal of the Atmospheric Sciences, 68, pp. 1253-1272.

Scherrer, S.C.m Appenzeller, C., Laternser M. (2004): Trends in Swiss Alpine snow days: the role of local- and large-scale climate variability. Climate Research 32(3), 187-199.

Scherrer S.C. and Appenzeller C. (2006): Swiss Alpine snow pack variability: major patterns and links to local climate and large-scale flow. Climate Research 32(3), 187-199.

Scherrer S.C., Croci-Maspoli M., Schwierz C., Appenzeller C. 2006. Two-dimensional indices of atmospheric blocking and their statistical relationship with winter climate patterns in the Euro-Atlantic region. Int. J. Climatol. 26, no2, 233-249.

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

Schöner W, Auer I, Böhm R, Thaler S. 2003. Qualitätskontrolle und statistische Eigenschaften ausgewählter Klimaparameter auf Tageswertsbasis im Hinblick auf Extremwertanalysen. Endbericht Projekt 1 im Rahmen von StartClim Startprojekt Klimaschutz: Erste Analysen extremer Wetterereignisse und ihrer Auswirkungen in Österreich. 1-39 (publizierter Projektbericht)

Schöner, W., I. Auer, and R. Böhm, 2009: Long term trend of snow depth at Sonnblick (Austrian Alps) and its relation to climate change. Hydrol. Process., 23, 1052-1063, doi: 10.1002/hyp.7209

Sen, P. K., 1968: Estimates of the regression coefficient based on kendall's tau. J.Am. Stat. Assoc., 63, 1379–1389.

Serquet, G., Marty, C., Rebetez, M., Dulex, J.P., 2011: Seasonal trends and temperature dependence of the snowfall/precipitation day ratio in Switzerland, Geophysical Research Letters, 38, L07703, doi:10.1029/2011GL046976.

Serquet, G., Marty, C., Rebetez, M.,2013: Monthly trends and the corresponding altitudinal shift in the snowfall/precipitation day ratio, Theoretical and Applied Climatology, doi: 10.1007/s00704-013-0847-7.

Sevruk, B., (1986): Correction of precipitation measurements: Swiss experience. Correction of Precipitation Measurements, Zürcher Geogr. Schriften 23, 187-196.

Steger, C., Kotlarski, S., Jonas, T., C. Schär (2013): Alpine snow cover in a changing climate: a regional climate model perspective. Clim Dyn (2013) 41: 735. doi:10.1007/s00382-012-1545-3

Strasser, U., Corripio, J., Brock, B., Pellicciotti, F., Burlando, P. and Funk, M. (2004): Spatial and Temporal Variability of Meteorological Variables at Haut Glacier d'Arolla (Switzerland) During the Ablation Season 2001: Measurements and Simulations, J. Geophys. Res., Vol. 109, D03103, doi:10.1029/2003JD003973.

Strasser, U. (2008): Die Modellierung der Gebirgsschneedecke im Nationalpark Berchtesgaden. Modelling of the mountain snow cover in the Berchtesgaden National Park, Berchtesgaden National Park research report, Nr. 55, Berchtesgaden.

Steinhauser F. (1974): Die Schneeverhältnisse Österreichs und ihre ökonomische Bedeutung . 70.–71. Jahresbericht des Sonnblick-Vereines für die Jahre 1972–1973, Volume 1972/73, Jahresberichte des Sonnblick-Vereines pp 3-42

Szczypta C., Gascoin S., Houet T., Hagolle O., Dejoux J. F., Vigneau C., Fanise Pascal. Impact of climate and land cover changes on snow cover in a small Pyrenean catchment. Journal of Hydrology, 2015, 521, p. 84-99. ISSN 0022-1694

Tabari, H., Marofi, S., Aeini, A., Hosseinzadeh Talaee, P., Mohammadi, K., 2011: Trend analysis of reference evapotranspiration in the western half of Iran. Agricultural and Forest Meteorology, 151 (2), 128-136

Theil, H., 1950: A rank-invariant method of linear and polynomial regression analysis.I/ II/ III. Proc. Kon. Ned. Akad. V. Wetensch., 53, 386–392/ 521–525/1397–1412.

Vincent, L. A., X. Zhang, B. R. Bonsal, and W. D. Hogg (2002): Homogenization of daily temperatures over Canada. J. Clim., 15, 1322-1334.

Wielke, L.-M., Haimberger L. and M. Hantel, 2004: Snow cover duration in Switzerland compared to Austria. Meteorologische Zeitschrift, 13, 13-17.

Yue, S., P. Pilon, B. Phinney, and G. Cavadias, 2002: The influence of autocorrelation on the ability to detect trend in hydrological series. Hydrol. Process., 16, 1807–1829.