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Discussions

Spatial distribution of stable water isotopes in alpine snow cover

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Abstract

The aim of this study was to analyze and predict the mean stable water isotopic composition of the snow cover at specific geographic locations and altitudes. In addition, the dependence of the isotopic composition of the entire snow cover on altitude was analyzed. Snow in four Swiss catchments was sampled at the end of the accumulation period in April 2010 and a second time in Mai 2010 and analyzed for stable isotope composition of ^{2}H and ^{18}O. The sampling was conducted at both south-facing and north-facing slopes at elevation differences of 100 m for a total altitude difference of approximately 1000 m. The observed variability of isotopic composition of the snow cover was analyzed with stepwise multiple linear regression models. The analysis indicated that there is only a limited altitude effect on the isotopic composition when considering all samples. This is due to the high variability of the isotopic composition of the precipitation during the winter months and, in particular in the case of south-facing slopes, an enrichment of heavy isotopes due to intermittent melting processes. This enrichment effect could clearly be observed in the samples which were taken later in the year. A small altitudinal gradient of the isotopic composition could only be observed at some north-facing slopes. However, the dependence of snow depth and the day of the year were significant predictor variables in all models. This study indicates the necessity to further study the variability of water isotopes in the snow cover to increase prediction for isotopic composition of snowmelt and hence increase model performance of residence time models in alpine areas and to better understand the accumulation processes and the sources of water in the snow cover of high mountains.

1 Introduction

Since more than 40 yr the stable water isotopes ^{18}O and ^{2}H have been used to determine hydrological pathways and processes in catchment hydrology (McDonnell, 2003). Due to their conservative nature in the water cycle, the relative simple sampling and

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nowadays cheaper and faster measurement technique, they have become a dominant role as tracers to determine the mean residence time of water in a catchment (Vitvar and McDonnell, 2007). One of the first studies that used stable isotopes of water to determine snowmelt runoff was from Dincer et al. (1970) and were followed by several of other studies (e.g. Rodhe, 1981; Wels et al., 1991; Unnikrishna et al., 2002; Laudon et al., 2002). But modeling the isotopic composition of snowmelt water and the resulting isotopic composition of surface and groundwater is complicated due to different isotope fractionations during formation, accumulation, and ablation of snow and phase changes during snowmelt (Cooper, 1998). Especially isotope fractionation processes during the ablation period are still poorly understood (Unnikrishna et al., 2002).

In contrast to liquid precipitation, which undergoes isotopic exchange with atmospheric humidity while falling, snow maintains the isotopic content that was formed while condensation in the clouds (Gat, 1996). When snow accumulates on the ground it preserves the isotopic signature from every single snowfall, only disturbed by mass transport through wind drift and avalanches. During precipitation-free periods the snow is removed layer by layer through sublimation. Unlike the evaporation from the surface of a water body in which the remaining water accumulates steadily in heavy isotopes, one would expect that no isotopic change occur in the remaining snow cover due to complete sublimation of individual snow crystals. In practice, however, an enrichment of heavy isotopes in the upper snow layers takes place, which happens due to diffusion of water vapor in the pores of the snow pack and also due to partial melting which causes evaporation and percolation of melt water in the remaining snow (Gat, 1996; Stichler et al., 2001).

The altitude effect of stable water isotopes in precipitation is a well-known effect since the benchmark paper of Dansgaard (1964). Moser and Stichler (1970, 1971) showed that the altitude effect of precipitation by orographic uplift of air masses and the related decrease in the condensation temperature leads to a depletion of heavy isotopes with altitude and can also be observed in fresh snow. In their work they sampled fresh snow in the Eastern and Western European Alps and found an average elevation gradient

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about −3 ‰ per 100 m altitude for δ^2H, with variations between −2 to −10 ‰ per 100 m. Other authors such as Renaud (1969) in Greenland, Gonfiantini (1970) at the Kilimanjaro or Friedman and Smith (1970) in the Sierra Nevada also observed a depletion of heavy isotopes with altitude in fresh snow. These authors examined a depletion of δ^{18}O between −0.25 to −1.25 ‰ per 100 m. Niewodniczanski et al. (1981) presented a comprehensive study on the altitudinal gradient of the ^{18}O isotope in mountains regions of the world. In the South American Andes, the Central Asian Hindu Kush and Himalaya as on Mount Kenya and Mount Kilimanjaro in Africa they took fresh snow samples 5 to 10 cm below the snow surface. They found an elevation gradient for δ^{18}O between −0.6 and −1.0 ‰ per 100 m. However, the samples are subject to a wide variation with small-scale inverse gradient and are thus only partly attributable to a linear elevation gradient. Niewodniczanski et al. (1981) attributed the variation to the conditions during and after deposition of snow, such as wind drift and fractionation by melting processes, and to topography and climatic conditions of the sampled areas. Moran et al. (2007) collected fresh snow samples in the Canadian Rocky Mountains during two periods of snow accumulation and examined the δ^{18}O isotope content. They determined elevation gradients ranging from −0.3 to +1.8 ‰ per 100 m and the data collected is subject to a wide variation. It can thus be concluded that an elevation gradient of the isotopic content in fresh snow is only partially observable or very weak. A non-existing elevation gradient can be explained by the fact that air masses in which snow is formed expert no small-scale orographic uplift and secondly that the source and the trajectory of air masses is essential to the average isotopic content, as well as to the development of a gradient (Moran et al., 2007).

In contrast to the altitudinal gradient in fresh snow samples, the behavior of the isotopic content of an entire snow pack is even more complex (Moser and Stichler, 1974). Especially in temperate climates, the snow pack is altered by sublimation, evaporation, metamorphism of snow crystals, percolating melt water, and isotopic enriched precipitation (Judy et al., 1970; Ambach et al., 1972; Arnason et al., 1972; Martinec et al., 1977; Raben and Theakstone, 1994; Aizen et al., 1996; Stichler et al., 2001; Sinclair

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and Marshall, 2008; Sokratov and Golubev, 2009). These processes can superimpose the isotopic altitude effect of fresh snow and lead to inverse gradients, as observed for example by Moser and Stichler (1970) at the Kitzsteinhorn in Austria. Other authors (Raben and Theakstone, 1994; Gurney and Lawrence, 2004; Königer et al., 2008) observed no significant relation between the isotopic signature of the entire snow pack and elevation. However the total elevation range in these studies was only between 230 m and 650 m. Mast et al. (1995) took snow samples of the entire snow pack in an alpine basin in the Rocky Mountains, USA, and could neither detect any relations of the $\delta^{18}O$ value with altitude nor with snow depth or snow water equivalent. To conclude, the origin of the different air masses is crucial for the isotopic content of the entire snow cover, as the isotopic content of the different snow layers is preserved stratigraphically. Furthermore, the conditions during deposition of snow, and the atmospheric influences after deposition, which depend heavily on the topography of the sampled area, are possible key factors influencing the isotopic content.

To better understand the different factors such as altitude, aspect, slope and snow depth influencing the stable isotope composition of the entire snow pack, we sampled stable water isotopes in snow at eight different slopes in Switzerland covering an altitude difference of approximately 1000 m per slope. To gain a better understanding of isotopic processes during the ablation period, every slope was sampled at the end of the accumulation period and a second time one month later during the ablation period. Therefore the main hypothesis of this study was that a variety of factors in addition to altitude influence the variation of stable water isotopes in snow in space and time.

2 Methods

2.1 Sites and sampling design

Snow was sampled in four Swiss catchments covering a wide range of climatic influences of the alpine region, altitudinal differences of more than 1000 m, included only

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a low proportion of glaciated area, and having accessible north-facing and south-facing slopes. The geographical location of these catchments is illustrated in Fig. 1. Three of the watersheds are located in the Eastern Alps close to the boarder to Austria and Italy. The north-facing one is the Taschinasbach, the south-facing one the Laschadura, and the one in between the Dischma catchment. The Engstligen catchment is located in the Western Alps or more precisely in the Bernese Alps. In all four catchments snow samples were taken from a north-facing and a south-facing slope with altitude differences between the sample points of 100 m while covering a total altitude difference of approximately 1000 m (Fig. 2). Every sample location is presented with its associated elevation and aspect in Fig. 2 highlighting the total altitude difference between 1200 m and 3000 m and the focus on southern and northern aspects with a natural variability of the locations within the slopes. Additionally, GPS coordinates, slope inclination, aspect, and snow depth were measured at each sampling point. The first samples in the four catchments were taken at the end of the accumulation period in April 2010, and the second samples were taken in May 2010 approximately 30 days later. All sampling points were in the open and not influenced directly by vegetation cover.

All samples were collected with an aluminum probe, which consists of three 1 m long pipes with a diameter of 6 cm that can be plugged together and assured by a screw. For all of the samples, the maximum length of the aluminum probe of 3 m was exceeded only at one point, where it had to be inserted an additional 20 cm. To record the mean isotopic content of the entire snow pack, the aluminum probe was pushed to the ground at each point, which was checked by looking for soil or vegetation pieces at the bottom of the probe. The samples were collected according to the principles for collecting snow samples as described in Clark and Fritz (1997). The sampled snow was packed into airtight plastic bags and poured into bottles after it had melted. Thereby the snow was not melted actively; instead it could rather thaw slowly during transport and storage at room temperature. This process took, depending on the size and density of the snow sample 5 to 15 h. Since the melting process took place in a hermetically sealed plastic bag, an isotopic change of the samples was excluded.

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Isotope analyses were conducted at the laboratory of the Chair of Hydrology in Freiburg. For this purpose a Wavelength-scanned Cavity Ring Down Spectrometer from Picarro was used. All isotope concentrations are expressed as δ-values in per mil notation (‰) relative to the Vienna standard mean ocean water (VSMOW). The standard error of the isotope analyzer is < 0.2 ‰ for δ^{18}O and < 1 ‰ for δ^{2}H. Hence one can infer that the relative standard error for δ^{18}O is approximately twice than of δ^{2}H assuming a relation based on the meteoric water line.

2.2 Statistical analysis

Stepwise multiple linear regression (MLR) analysis was carried out for every single catchment and also for all samples taken. At first δ^{18}O and δ^{2}H were chosen separately as response variables, however, it turned out that the same explanatory variables were selected. For this reason, the fact that the behavior of both isotopes in the hydrological cycle is nearly the same as long as evaporation is not a dominating process, and the smaller relative standard error of δ^{2}H, we focus on the characteristics of ^{2}H.

To determine the most meaningful MLR all variables were first checked for multicollinearity, which was based on the variance inflation factor (VIF) whose value should not exceed 10 (Helsel and Hirsch, 2002). None of the used variables exceeded a value of 5. In order to obtain the most significant MLR equation, the selection of variables for each model was conducted by stepwise backward elimination according to the adjusted R^2 (Stahel, 2007). This procedure was performed with the statistical software "R" (http://www.r-project.org/index.html), like all other statistical analysis in this study. To select statistically relevant predictor variables an automatically implied stepwise backward elimination according to the Akaike information criterion (AIC) was performed. After having chosen the most significant variables, every computed equation was checked for normal distribution, Cook's distance, outliers with leverage, and homoskedasticity.

The mean isotopic content of the entire snowpack at a point is influenced by many factors. Since the isotopic content of individual precipitation events was not available it was attempted to specify the input by the altitude effect and thus the altitude of each

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sampling point was included as a predictor variable. During deposition of solid precipitation as snow, wind drift plays a major role. To describe this factor, the snow depth measured at the point is used as a further variable. Snow depth is not only influenced by wind drift, but also includes ablation processes. Since this parameter turned out not to be significant for the isotopic content of the sample points, a linear regression between altitude and snow depth was performed for each catchment and sampling date and the deviation of every point from the regression line was calculated. This deviation (Δ_{snow}) was used as the second predictor variable. After snow is deposited, the fractionation processes affecting the isotopic content of snow cover is mainly controlled by evaporation, percolation, and diffusion. These factors depend primarily on exposure. This factor may partly be described by snow depth as on locations with high solar radiation snow depth definitely will be less. Other factors that can exhibit the influence of solar radiation are slope, aspect, and vertical convexity (C_{vert}). These three predictor variables were computed from a 25 m digital elevation model (DEM). Aspect was transformed with the cosine function and is therefore dimensionless resulting in a value of 0 for north and 1 for south-facing points. Values for the vertical convexity are given in 1/100 of the z-unit (m), while positive values indicate concavity and negative values convexity. To express enrichment of heavy isotopes during the ablation period the day of the year (DOY) of sampling was included as well. Finally, longitude and latitude were derived from the GPS measurements.

3 Results

3.1 Altitude influences on the variation of stable isotopes in snow

An altitude effect in the entire snow pack is often superimposed by relocation of snow through wind drift and avalanches and also through an enrichment of heavy isotopes in upper layers of the snow pack that mostly depends on exposure to the sun. In the present work a significant ($R^2 > 0.5$) altitude effect was determined for two of

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15 sampling days (Fig. 3). These were first samplings in north-facing slopes of the Taschinasbach- and the Dischma-catchment with gradients of δ^2H −2.6 ‰/100 m and −0.7 ‰/100 m for δ^2H. The second ascents gradients were about −1.6 ‰/100 m and −1.4 ‰/100 m, respectively, but with a lower R^2.

A depletion of heavy isotopes with altitude could be observed at the first ascent in the north-facing slope of the Engstligen catchment with a gradient of −0.7 ‰/100 m (R^2 = 0.2), at the first ascent in the south-facing slope of the Dischma catchment with a gradient of −0.9 ‰/100 m (R^2 = 0.3), and at the second ascents in the south-facing slopes of the Taschinasbach and the Dischma catchment with a gradient of −1.6 ‰/100 m and −6.2 ‰/100 m. The last two gradients are derived from five, respectively three samples. For all other sampling dates and locations a positive gradient was observed, which ranged from 0.2 ‰/100 m to 3.1 ‰/100 m. Especially in the Laschadura catchment all gradients represent a slight enrichment of heavy isotopes with altitude. Since a significant depletion of heavy isotopes with altitude could only be observed on few north-facing slopes and were less pronounced after one month of ablation, altitude does not seem to influences snow isotope composition signifcantly.

When analyzing the differences between first and second ascents a distinct enrichment of heavy isotopes was observed. This enrichment ranged at individual sample points from 3 ‰ to 35 ‰ δ^2H and in average for the catchments between 10 ‰ and 20 ‰ δ^2H. Only in the Engstligen catchment some sample points show a depletion of heavy isotopes from the first to the second sampling date. Since snow was disappearing relative fast on the south-facing slopes, only a few points could be compared and moreover the samples of the second ascents were partly taken from a new snow cover than from the seasonal snow.

3.2 Other influences on the variation of stable isotopes in snow

For a first screening of the predictor variables the correlation coefficient in each catchment between the predictors and the response variable δ^2H was calculated and is shown in Table 1. As already shown, altitude has only a limited explanatory power

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on δ^2H. Significant correlations ($p < 0.1$) were found for the Laschadura catchment in which an inverse altitudinal gradient was detected. In the other three catchments the deviation of snow depth Δ_{snow} is significantly correlated. The most significant variable in all catchments is the day of the year that explains the enrichment of heavy isotopes over the ablation period. Except for the Engstlingen catchment, the variables slope, aspect and vertical convexity have only a small effect on the variation of δ^2H.

The stepwise multiple regression analysis with backward elimination supports the results from the individual linear regression analysis and altitude, Δ_{snow}, and DOY show a significant influence on δ^2H (Table 2). At the Engstligen catchment aspect and vertical convexity (C_{vert}) were additional predictor variables in the model and at Laschadura catchment slope and C_{vert} were selected as an additional predictors. The adjusted R^2 for the MLR and the level of significance is also illustrated in Table 2.

To demonstrate the influence of one predictor variable on the response variable in dependence of the other variables in the model, a partial residual plot with every selected variable of the MLR is presented in Fig. 4. Apparently the significance of the variable altitude is more visible in the MLR than in the linear regression in Table 1, especially in the Taschinabach and the Dischma catchment. The Dischma catchment shows the highest altitude gradient of all catchments. Furthermore the inverse altitudinal gradient in the Laschadura catchment can be seen. In the Taschinabach the variable Δ_{snow} has a smaller effect in contrast to the other three catchments. A distinct influence in all catchments is demonstrated by DOY. The variable vertical convexity represents a significant effect only in the Engstligen and the Laschadura catchment and the other two variables aspect and slope play a distinctive role in one of these catchments.

For the MLR including data from all catchments and all sampling dates the predictors latitude and longitude were additionally included and mainly longitude turned out to be significant (Fig. 5 and Table 2). Most significantly were the variables Δ_{snow} and DOY. The variables altitude, aspect, vertical convexity and latitude had a minor influence. The regression equitation for all samples had an adjusted R^2 of 0.55 with a level of significance $p = 2.2 \times 10^{-16}$.

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4 Discussion

The altitude effect of δ^2H of fresh snow in the Alps was examined by Moser and Stichler (1970) and they found an elevation gradient of −3 ‰/100 m and deviations between −2 and −10 ‰/100 m. Every single snowfall has its own isotopic signature and accumulates stratigraphically providing a weighted average signature of the entire snow pack with slight changes due to melting processes (Raben and Theakstone, 1994). In the final accumulation and melting season these processes, caused by solar radiation and temperature variations, can substantially alter the isotopic content of snow and therefore lead to differing and even inverse altitudinal gradients in entire snow pack (Moser and Stichler, 1974). In this research a significant altitudinal gradient for entire snow cover was only observed in the first sampling dates of some north-facing slopes ranging between −2.6 and −0.7 ‰/100 m. At the respectively second sampling date the gradients were less pronounced. In addition, the altitudinal gradients at the south-facing slopes ranged from −6.2 ‰/100 m to 2.6 ‰/100 m δ^2H with a wide variability of the individual samples. These results confirm in particular the influence of melting processes on the mean isotopic content of snow cover for the south-facing slopes. For further interpretation of the altitudinal gradients only the results from the north-facing slopes will be discussed. Recent studies (e.g. Moran et al., 2007) pointed out that an altitudinal effect in fresh snow strongly depends on the type of weather system and that Raleigh distillation can lead to inverse altitudinal gradients in leeward slopes. This is maybe the case in the Laschadura catchment, which is located east of the upper Inn Valley (Engadin) and where all altitudinal gradients show an enrichment of heavy isotopes with altitude.

The effect of higher condensation levels, as for example discussed by Siegenthaler and Oeschger (1980), inducing isotopic depleted precipitation can be seen in the Dischma catchment. The snow cover is in average isotopically more depleted than in the other catchments and furthermore the altitudinal gradient is less distinctive than in the nearby Taschinasbach, which is located at the same longitude but 50 km more north at

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the edge of the Alps. In the Engstligen catchment, which is located in the Bernese Alps, all altitudinal gradients were not significant. The north-facing slope of this catchment is a steep avalanche prone slope popular for ski touring. These factors may lead to transport of snow and disturb the altitudinal gradient. This finding was supported by a third sampling date where samples also show a widespread isotopic signature.

To sum up a significant altitudinal gradient exists only in some north-facing slopes during the end of the accumulation period. For all south-facing slopes and for north-facing slopes during the melting season the potential altitudinal gradients are disturbed by melting processes. These processes influence the isotopic content of entire snow cover in dependence of the exposure to the sun and can be seen in the magnitude of enrichment on heavy isotopes between first and second ascent. This result is similar to findings of Gustafson et al. (2010), which detected significant spatial variations of Deuterium and ^{18}O in snow pack but not in precipitation.

The goal of the stepwise multiple regression was to discover correlations and interactions between isotopic signature of snow cover at a point scale in dependence of altitude and other predictors. In general, the deviation of snow depth Δ_{snow} explains more of the observed variability than altitude. This variable represents the measured snow depth relative to the expected snow depth based on altitude and explains on one side transport of snow through wind drift and avalanches and on the other side influences of melting processes resulting in decreasing snow depth. The most significant variable is DOY, which explains the enrichment of heavy isotopes in snow cover through melting processes during the ablation period. This enrichment between the first and the second sampling dates varied from 3 to 35 ‰ at the individual points and from 10 to 20 ‰ at catchment scale.

The results from the MLR show that only between 50 and 61 % of the observed variation of stable isotopes of water in the entire snow pack can be explained by the selected predictors. The influence of some predictors are relative stable among the catchments, in particular DOY and Δ_{snow}. At the Laschadura and the Engstligen catchment the result is improved slightly by the additional predictors vertical convexity, slope and aspect.

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The MLR applied to all catchments show that longitude is the most significant variable followed by DOY, latitude and Δ_{snow}. The variables altitude, slope and vertical convexity have a smaller effect. The strong influence of longitude can be attributed to the continental effect, which defines the depletion of heavy isotopes in precipitation during the trajectories of air masses about the continents (Dansgaard, 1964). Including latitude in regression equitation was an attempt to specify the spatial contribution of the isotopic content at the catchments beside the mentioned continental effect. Table 1 shows that latitude has only a limited influence when used it as single predictor, but in Fig. 5 it is demonstrated that it has a more pronouced influence when used in the MLR. Samples for this research were taken over a period of 63 days and despite the wide spatial contribution of the catchments the enrichment of heavy isotopes during ablation, presented by the variable DOY, is the most significant predictor in the correlation and the second most important predictor in the multiple regression. In addition Δ_{snow}, like at catchment-scale, has a distinctive influence on the isotopic content of snow cover.

In summary the predictor variables altitude, aspect, slope and vertical convexity can hardly explain the variation of stable isotopes in alpine snow cover. This is due to the high variability of the isotopic composition of the precipitation during the winter months, which are all preserved in the snow cover and influenced by enrichment of heavy isotopes due to melting processes. Instead the snow depth relative to the expected snow depth based on elevation, which can be measured easily, and the day of the year have significant effects in predicting stable isotopes of water at the catchment scale. For implementation in catchment hydrology these results may allow to measure mean isotopic content of the snow pack at two points in a catchment during time and predicting the spatial distribution of the isotopic content in the snow cover based on snow depth. Using the information over time at the two sampling points the enrichment specific for this season can be calculated by the day of the year.

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5 Conclusions

To better understand the different factors such as altitude, aspect, slope and other factors influencing the stable isotope composition of the entire snow pack, we sampled stable water isotopes in the snowpack at the end of the accumulation and during the ablation period at eight different slopes in four catchments in Switzerland covering an altitude difference of approximately 1000 m per slope. We could proof the hypothesis that additional factors like the deviation of snow depth from the expected value due to altitude and the day of the year influence the variation of stable water isotopes in snow in space and time. These variables may serve as additional important predictors to altitude to predict the spatial and temporal variability of stable water isotopes in the entire snow pack. However, we need more research to understand the isotopic development of the snow pack in time and space and its affect on the isotope content of melt water during the ablation period to increase model performance of residence time models in alpine areas and to better understand the accumulation processes and the sources of water in the snow cover of high mountains.

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Table 1. Correlation coefficients (R^2) for different predictor variables and the response variable δ^2H. Italic values are statistically significant correlations ($p < 0.1$).

Predictor variables	Engstligen	Taschinasbach	Dischma	Laschadura	All samples
Altitude	0.07	0.01	0.00	*0.15*	0.00
Δ_{snow}	*0.18*	*0.14*	*0.15*	0.00	0.04
Slope	*0.10*	0.05	0.01	0.02	0.00
Aspect	*0.10*	0.06	0.03	*0.10*	0.05
C_{vert}	*0.22*	0.00	0.02	0.01	0.02
DOY	*0.42*	*0.56*	*0.35*	*0.38*	*0.17*
Latitude	–	–	–	–	0.01
Longitude	–	–	–	–	*0.14*

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Table 2. Adjusted R^2 for computed regression equations, level of significance (p value) and values of β-coefficients (ns = predictor variable not selected, na = variable not applicable).

Variables	Engstligen	Taschinasbach	Dischma	Laschadura	All samples
Altitude	−0.0065	−0.0059	−0.0093	0.0223	−0.0026
Δ_{snow}	−6.66	−3.86	−7.34	−7.34	−5.63
Slope	ns	ns	ns	−1.12	ns
Aspect	4.8	ns	ns	ns	2.25
C_{vert}	6.39	ns	ns	5.24	1.11
DOY	0.348	0.377	0.386	0.48	0.40
Latitude	na	na	na	na	38.5
Longitude	na	na	na	na	−11.4
Intercept	−149.1	−152.9	−165.5	−220.9	−1863
R^2_a	0.5	0.61	0.54	0.51	0.55
p	2.6×10^{-05}	6.4×10^{-07}	2.0×10^{-05}	3.1×10^{-03}	2.2×10^{-16}

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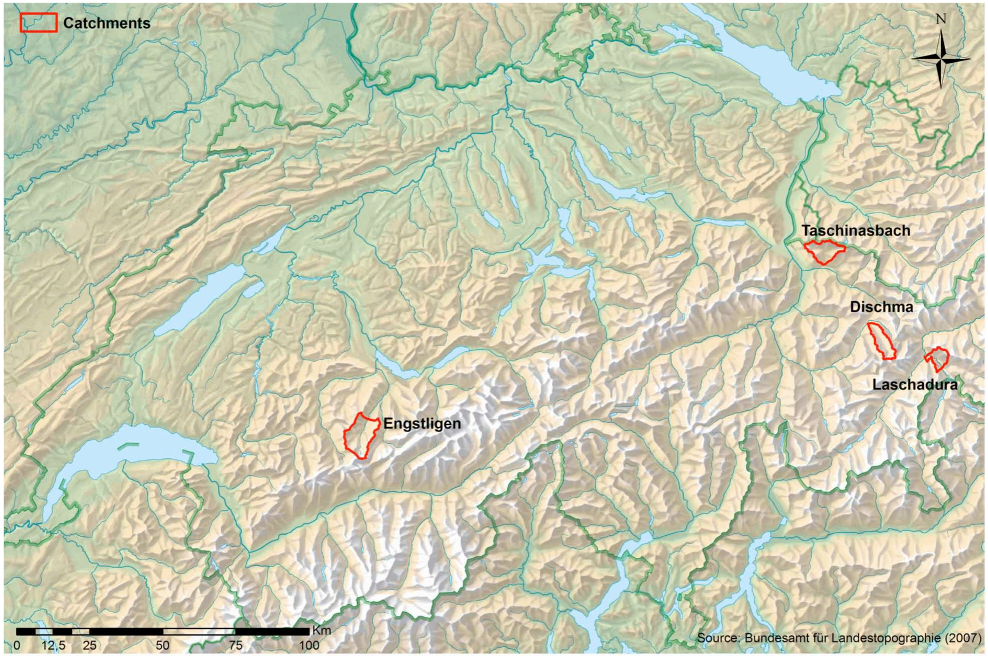

Fig. 1. Location of the four catchments in the Swiss Alps.

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Spatial distribution of stable water isotopes

N. Dietermann and M. Weiler

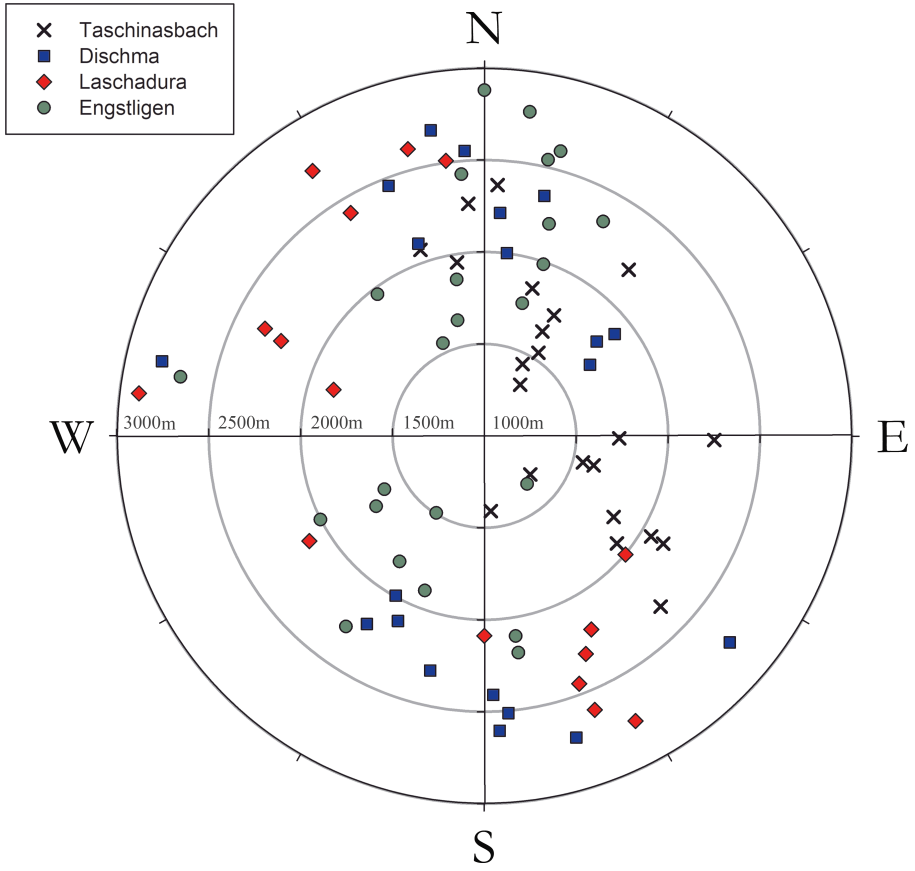

Fig. 2. Elevation and aspect of every sampled point of each catchment.

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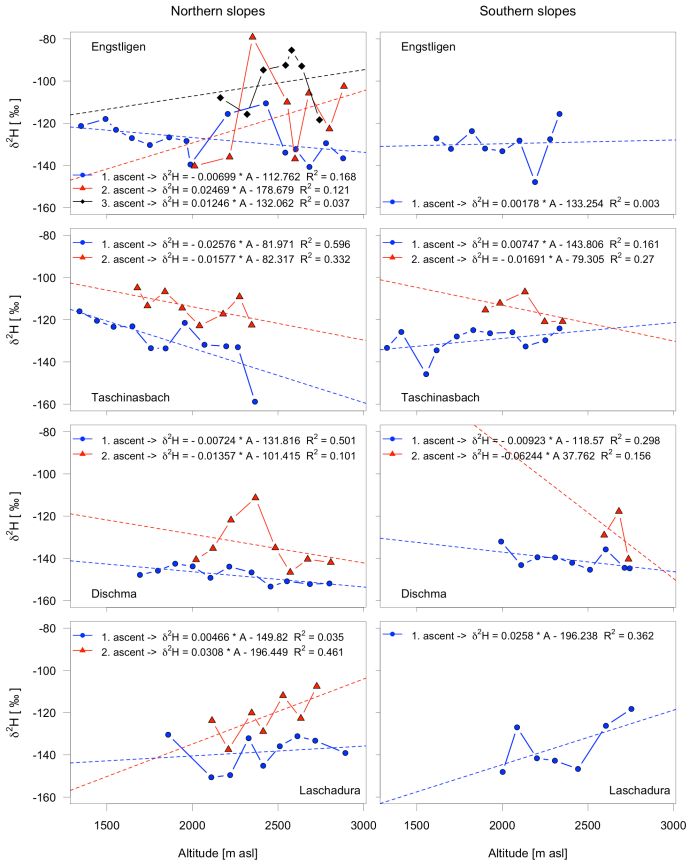

Fig. 3. Mean isotopic content of δ^2H in snow cover at every sample point and associated altitudinal gradient for every sampling time (ascent).

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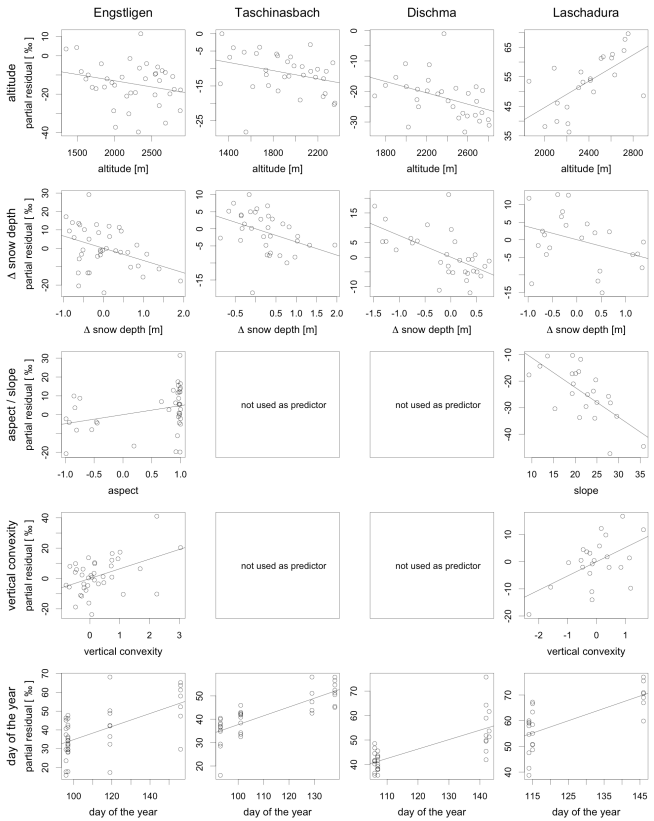

Fig. 4. Partial residuals of each predictor for the four watersheds selected by the stepwise MLR.

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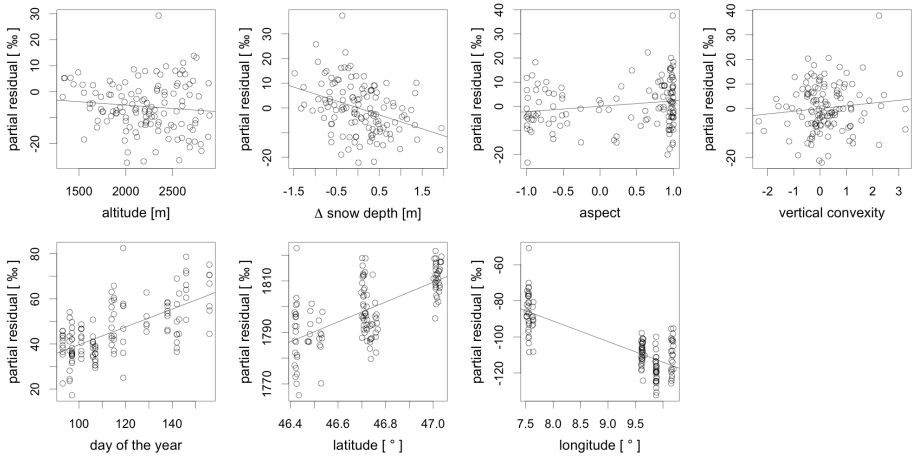

Fig. 5. Partial residuals of each predictor in the regression equitation for all samples.

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