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Temperature and precipitation signal in two Alpine ice cores over the period 1961–2001

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Abstract

Water stable isotope ratios and net snow accumulation in ice cores are usually interpreted as temperature and precipitation proxies. However, only in a few cases a direct calibration with instrumental data has been attempted. In this study we took advantage of the dense network of observations in the European Alpine region to rigorously test the relationship of the proxy data from two highly-resolved ice cores with local temperature and precipitation, respectively, on an annual basis. We focused on the time period 1961–2001 with the highest amount and quality of meteorological data and the minimal uncertainty in ice core dating (±1 yr). The two ice cores come from Fiescherhorn glacier (Northern Alps, 3900 m a.s.l.) and Grenzgletscher (Southern Alps, 4200 m a.s.l.). Due to the orographic barrier, the two flanks of the Alpine chain are affected by distinct patterns of precipitation. Therefore, the different location of the two ice cores offers the unique opportunity to test whether the precipitation proxy reflects this very local condition. We obtained a significant spatial correlation between annual δ^{18}O and regional temperature at Fiescherhorn. Due to the pronounced intraseasonal to interannual variability of precipitation at Grenzgletscher, significant results were only found when weighting the temperature with precipitation. For this site, disentangling the temperature from the precipitation signal was thus not possible. Significant spatial correlations between net accumulation and precipitation were found for both sites but required the record from the Fiescherhorn glacier to be shifted by −1 yr (within the dating uncertainty). The study underlines that even for well-resolved ice core records, interpretation of proxies on an annual or even sub-annual basis remains critical. This is due to both, dating issues and the fact that the signal preservation intrinsically depends on precipitation.

1 Introduction

The stable isotopes ratios in meteoric water ($^{18}O/^{16}O$, and, similarly, $^{2}H/^{1}H$, not discussed in this paper) are widely used as temperature proxies (Craig, 1961; Dansgaard, 1964). Commonly these ratios are reported in the delta notation ($\delta^{18}O$ and $\delta^{2}H$ or δD) with δ denoting the deviation from an international reference standard (usually being VSMOW, Vienna Standard Mean Ocean Water) in per mil (‰). Several natural archives offer the opportunity to reconstruct the past temperature from these proxies, e.g. ice cores from polar regions (Jouzel et al., 2007), mountain and temperate zones (Eichler et al., 2009), sea and lake sediments, tree rings (Bradley, 1999), and stalagmites (Genty et al., 2003). Since 1961, the Global Network of Isotopes in Precipitation (GNIP) stations have been collecting meteoric waters and measuring $\delta^{18}O$ worldwide (http://www-naweb.iaea.org/napc/ih/IHS_resources_gnip.html).

The interpretation of the $\delta^{18}O$ (or δD) signal, however, may not be straightforward. The primary microphysical processes affecting this proxy within the water cycle (equilibrium and kinetic fractionations) are known and can be quantified (Dansgaard, 1964; Jouzel and Merlivat, 1984; Ciais and Jouzel, 1994; Gat, 1996; Araguás-Araguás et al., 2000). However, additional effects might modify the $\delta^{18}O$ before, during, and after the deposition of snow. Seasonality in precipitation, for example, may bias the annual $\delta^{18}O$ in contrast to the ideal case of a constant signal deposition throughout the year (Persson et al., 2011). Processes related to the precipitation event such as moisture recycling, sub-cloud evaporation (Froehlich et al., 2008), and amount effect (Lee and Fung, 2008) may induce additional fractionation. For ice cores, post-depositional effects such as melting (Moran et al., 2011) or diffusion (e.g. Johnsen, 1977; Johnsen et al., 2000) are known to modify the signal. For the Alpine region, the relation between altitude and change of the isotopic value has been quantified (Siegenthaler and Oeschger, 1980). However, the understanding of the $\delta^{18}O$ signal is further complicated by the interplay of different moisture sources contributing to the total annual precipitation of a specific site as shown by investigations of air mass back-trajectories (Sodemann and Zubler, 2009). Moreover, the Alpine chain acts as an orographic barrier, dividing the region in the Northern Alps, dominated by North Atlantic air masses in winter and by land evaporation in summer, and the Southern Alps, with a higher intraseasonal precipitation variability and a generally stronger contribution from the Mediterranean region (Frei and Schär, 1998; Eichler et al., 2004; Sodemann and Zubler, 2009).

In a region dominated by such high temporal and spatial variability of the moisture sources, the interpretation of an ice core derived net snow accumulation rate as a proxy for regional precipitation might be limited, because precipitation at high altitudes can be a very local phenomenon. Nevertheless, some accumulation reconstructions from the polar ice sheets are available (Alley et al., 1993; Appenzeller et al., 1998), and similar studies were conducted for mountain glaciers (Henderson et al., 2006; Schwerzmann et al., 2006). In most of the cases, an accurate description of the ice flow in the glacier by means of physical models is necessary to account for thinning effects, but not always feasible. Moreover, post-depositional phenomena, like snow removal by winds or partial melting in summer, may reduce the actual layer thickness with consequent loss of information.

In this study we investigate annual records of δ^{18}O and net accumulation from two high-resolution ice cores from the Northern and the Southern Alps (Fig. 1), in order to understand whether the temperature and precipitation signals are captured at these sites. The Alpine region offers the unique opportunity to conduct a detailed study, thanks to the dense network of observation stations present in this area. We focus on the most recent decades (1961–2001), where amount and quality of the available instrumental data is highest and the dating uncertainty in the ice cores is minimal. Section 2 describes the datasets. The analysis of δ^{18}O/temperature and accumulation/precipitation relationship is discussed in Sect. 3, conclusions and implications are presented in Sect. 4.

2 Data

2.1 Ice core sites

Ice core drilling at the Fiescherhorn glacier, Northern Alps (46° 33′ 3.2″ N, 8° 04′ 0.4″ E, 3900 m a.s.l., FH in Fig. 1) was conducted in December 2002 down to the bedrock at a depth of 151 m (Jenk, 2006). The glacier is located in a region dominated by North Atlantic air masses, with moisture mostly transported by westerlies in winter and contributions from land evaporation in summer (Sodemann and Zubler, 2009). The intraseasonal variability and the amount of precipitation are generally lower than in the Southern Alps (Frei and Schär, 1998; Eichler et al., 2004; Sodemann and Zubler, 2009). The ice core from Grenzgletscher in the Southern Alps (Monte Rosa massif, 45° 55′ 28″ N, 7° 52′ 3″ E, 4200 m a.s.l., GG in Fig. 1) was extracted in October 1994, reaching the depth of 125 m (Eichler et al., 2000). This region is more affected by the Mediterranean, especially in spring and fall, and by convective precipitation in summer (Sodemann and Zubler, 2009). In winter the predominant sources of precipitation are the frontal systems associated with the polar front, carrying moisture by the westerlies from the North Atlantic (Eichler et al., 2004; Sodemann and Zubler, 2009). A detailed description of the analytical procedures is given in Eichler et al. (2000, 2001) and Jenk (2006).

2.1.1 δ^{18}O

The Fiescherhorn core covers the time period of ∼ 1680–2002 AD, and the Grenzgletscher core the period of ∼ 1937–1994 AD, with a gap in the data between 1968 and 1970, due to a failure in the cooling system of the cold room and consequent melting of the corresponding ice core sections. Nevertheless, a good dating of this ice core could be established (Eichler et al., 2000). The Fiescherhorn record contains ∼ 15–25 data points per year in the upper part discussed here (see Sect. 2.2), Grenzgletscher ∼ 20–90 points per year (raw data shown in Fig. 2). The analytical uncertainty of δ^{18}O in the

Fiescherhorn core was < 0.05 ‰ (Jenk, 2006) and in the Grenzgletscher core < 0.5 ‰ (Eichler et al., 2000). Fiescherhorn and Grenzgletscher annual δ^{18}O (Figs. 3 and 4, top, respectively) was obtained according to the dating procedure (see Sect. 2.2), averaging all the values belonging to the same year. δ^{18}O in the Fiescherhorn and the Grenzgletscher ice cores spans the typical summer-to-winter values between −10 ‰ and −25 ‰, expected for the respective altitude (Fig. 2, Siegenthaler and Oeschger, 1980; Sigl, 2009). This suggests that there is no particular seasonality in the signal deposition and no strong erosion of snow by wind. The latter process was observed in an ice core from Colle Gnifetti, the glacier saddle 300 m upstream of the Grenzgletscher site. There, most of the winter snow is eroded, resulting in annual δ^{18}O biased toward summer values (Sigl, 2009).

2.1.2 Accumulation

The past net accumulation was obtained following the approach given by (Henderson et al., 2006), using Eq. (1):

$$\lambda_R = (\lambda_E/\lambda_M)\lambda_0 \qquad (1)$$

where λ_R is the reconstructed net accumulation, λ_E the annual thickness of ice estimated from the dating procedure, λ_M the annual thickness estimated from ice thinning model and λ_0 is the estimated surface accumulation rate. These factors were obtained with the following procedure.

First, the depth-age chronology was established using multiple parameters including:

- annual layer counting of the seasonally varying signals, like δ^{18}O (see Fig. 2) and concentration of NH_4^+, whose maxima correspond to summer and minima to winter (Schwikowski et al., 1999),
- horizons indicated by spikes in the records of chemical species which correspond to well documented events: e.g. the Ca^{2+} maximum in 1977 as a tracer

for a prominent dust fall (Jenk, 2006) and ^{3}H with a peak in 1963 from thermonuclear bomb tests (Eichler et al., 2000),

- nuclear dating using ^{210}Pb (Eichler et al., 2000).

Due to the presence of stratigraphic markers and good preserved δ^{18}O seasonality, the resulting dating uncertainty for the period considered in this study is ±1 yr for both ice cores. The annual layer thickness λ_E was obtained from the depth differences between the age markers of subsequent years. In order to correct for the changing density in the firn, results in meters total depth were normalized to meters water equivalent (m w.e.) by multiplying the depth of the sample with the respective density which was derived from measurements performed for the top 100 m of the Fiescherhorn core and for the whole (125 m) Grenzgletscher core.

In order to reconstruct the net accumulation at the surface it is necessary to account for the ice thinning with depth (Cuffey and Paterson, 2010). The correction factor λ_M in Eq. (1) is the layer thickness estimated using an age-depth model to include this effect. Here we used the ice flow model proposed by Nye (1963), which assumes a constant thinning with depth. This assumption is generally valid for the upper two thirds of the glacier thickness of the vast ice sheets (Hammer et al., 1978), but could still be applied in the case of Fiescherhorn and Grenzgletscher ice cores, because we deal with the uppermost ~60 and ~70 m w.e. of a total of 124 and 170 (estimated) m w.e., respectively.

This model was used in two previous studies involving Fiescherhorn and Grenzgletscher. For Fiescherhorn, it was compared to a more sophisticated accumulation reconstruction, derived from the measurement of the vertical velocity of the ice (Schwerzmann et al., 2006). Here, we do not apply the latter reconstruction, because the dating of the Fiescherhorn ice core has been revised, and is based now on an extended data set after analyses of the stable isotopes and concentrations of major ions were completed. In Grenzgletscher, the Nye model was applied as an additional and independent dating technique (Eichler et al., 2000).

In order to obtain λ_{M}, we first used the reverse Nye function to fit the data (Dansgaard and Johnsen, 1969), using Eq. (2):

$$t = t_0 - H/\lambda_0 \ln\left(\frac{H-z}{H}\right) \tag{2}$$

where t is the year, t_0 the drilling date (2002.92 for Fiescherhorn, 1994.67 for Grenzgletscher), H the glacier thickness (124 m w.e. for Fiescherhorn, 170 m w.e. for Grenzgletscher), z the height above the bed in m w.e. and λ_0 the surface accumulation rate in m w.e. yr^{-1}, obtained by averaging the upper layer thicknesses for which thinning can be neglected (1.7 m w.e. yr^{-1} for Fiescherhorn, by averaging the layers from 1990 to 2002 (Jenk, 2006), 2.7 m w.e. yr^{-1} for Grenzgletscher (Eichler et al., 2000)). From the fit we obtained a reduced $\chi^2 = 0.93$ over the upper ∼ 70 m w.e. in Fiescherhorn, corresponding to the period 1950–2002, and a reduced $\chi^2 = 0.67$ for Grenzgletscher over the period 1938–1994. We retrieved the modeled depth corresponding to the calendar year and formed, in analogy with λ_{E}, the modeled layer thickness λ_{M}. The final accumulation reconstruction for Fiescherhorn and Grenzgletscher is shown in Figs. 3 and 4 (bottom), respectively.

2.2 Weather data

To account for the high elevation of our study sites, δ^{18}O was compared to high altitude temperatures and the monthly 700 hPa (∼ 3500 m a.s.l.) temperature from the Twentieth Century Reanalysis Dataset (Compo et al., 2011). We selected a region from 40° N to 60° N and from 15° W to 25° E, with a spatial resolution 2° × 2°. For precipitation, because of its sporadic nature in space and time, we used higher resolution data (nominally 2.2 km × 2.2 km) provided by Meteoswiss. This monthly, gridded dataset covers the area of Switzerland and starts in 1961. Further evaluations were conducted with the HISTALP gridded data at a resolution of 5′ × 5′ (Auer et al., 2007; Chimani et al., 2011), available at http://www.zamg.ac.at/histalp. Weather stations nearby the ice core sites, whose data were provided by Meteoswiss, were used as well. The resulting period of overlap among the different datasets is 1961–1993 for Grenzgletscher (with a gap between 1968 and 1970), and 1961–2001 for Fiescherhorn.

3 Results and discussion

3.1 δ^{18}O and temperature

The capability of δ^{18}O to capture the regional temperature is investigated performing spatial correlation analysis between the ice core values and the gridded instrumental data. To account for the dating uncertainty, we analyzed the correlations at lags of −1, 0, +1 yr, i.e. allowing the absolute dating to be offset by one year which is within the dating uncertainty. The analysis was performed with the KNMI Climate Explorer tool (http://climexp.knmi.nl). Figure 5a–c shows the spatial correlation between Fiescherhorn annual δ^{18}O and the Twentieth Century Reanalysis temperature at 700 hPa at lag −1, 0, +1 yr, respectively. Ice core δ^{18}O significantly correlates with the regional temperature only with lag = 0 (Fig. 5b). Similar results were obtained at different levels (surface, 850 hPa, not shown). In the case of Grenzgletscher, no significant result (Fig. 6a–c) was found for neither of the lags. Over the Southern Alps, precipitation shows high intraseasonal to interannual variability (Eichler et al., 2004; Sodemann and Zubler, 2009). This non uniform snow deposition throughout the seasons results in a temperature proxy signal biased toward the season with highest precipitation. Therefore, we need to account for the precipitation variability in the case of Grenzgletscher δ^{18}O. In Eq. (3) we define the precipitation weighted temperature:

$$T_{\text{ann}} = \frac{\sum_{i=1}^{12} P_i T_i}{P_{\text{ann}}} \tag{3}$$

where T_{ann} is the annual precipitation weighted temperature, P_i the monthly amount of precipitation used to weight the monthly Twentieth Century Reanalysis temperature at 700 hPa T_i, P_{ann} the annual amount of precipitation. In order to mimic the temperature signal recorded only during precipitation events over the Grenzgletscher region, we investigated datasets from the Grand Saint Bernard weather station (2472 m a.s.l., 45° 52′ N, 7° 10′ E), located 50 km west of the site (correlation between precipitation and Grenzgletscher accumulation $\rho = 0.47$, $p < 0.05$), and the nearest point to the glacier extracted from the HISTALP dataset (4174 m a.s.l., 45° 55′ 1.2″ N, 7° 49′ 59.88″ $\rho = 0.36$, $p < 0.10$). This gridded data offers the opportunity to select only the solid part of precipitation (Chimani et al., 2011). We excluded the Meteoswiss data because no correlation was found in the proximity of Grenzgletscher region (Sect. 3.2, Fig. 6e).

A significant correlation between the precipitation-weighted temperature and δ^{18}O was obtained for most of Europe (Fig. 7, weights: Grand Saint Bernard precipitation). Weaker positive correlations were found when weighting the temperature with the precipitation extracted from the HISTALP grid point (not shown). We conclude that at the Grenzgletscher site it is not possible to disentangle the temperature signal from precipitation. The most significant result was found weighting the temperature with the precipitation data from the Grand Saint Bernard weather station instead of using the gridded data. This may be due to the evaluation process involved in the production of the gridded datasets, which smoothes part of the variability describing the precipitation over this region. This result is in apparent contrast with the good correlation between monthly δ^{18}O and unweighted Grand Saint Bernard temperature over the period 1980–1994 reported in Eichler et al. (2001). This can be explained by the fact that in the uppermost part of the ice core the number of samples per year is higher, and the subseasonal features can likely be captured in the δ^{18}O record.

3.2 Net accumulation and precipitation

The relation between net accumulation and precipitation was investigated using the higher resolution Meteoswiss gridded data (Figs. 5d–f, 6d–f). Figure 5e shows that there is no correlation between Fiescherhorn annual net accumulation and precipitation with lag = 0, in contrast with what was found between δ^{18}O and temperature. Interestingly, significant correlations were observed at lag = −1, with both gridded precipitation and weather station data in regions from southwest to northeast of the ice core site, which is the expected pattern for the Northern Alpine region (Fig. 5d, Table 1). A lag of one year is explainable with the dating uncertainty of ±1 yr. However, for that case no correlation with temperature was seen (Fig. 5a, c). We suggest that the presence of different trends in the δ^{18}O and accumulation records together with a more uncertain dating of the earlier time periods could explain this finding. We split the two series in two parts, 1961–1977 and 1978–2001, according to the well documented Saharan dust horizon of 1977. δ^{18}O data show no significant trend in the earlier part (Fig. 3, top), but an increasing trend in the most recent period (significant at a 5 % level according to the Mann Kendall test), where the dating is more accurate. This explains the good correlation between δ^{18}O and temperature at lag 0. Conversely, the accumulation record shows no trend in the most recent period (Fig. 3, bottom), but an increasing trend in the lower part, where the dating uncertainty increases, explaining the overall correlation with the precipitation data at lag = −1.

A further reason may be the uncertainty introduced by the depth-year attribution procedure. The annual layer counting assigns the beginning of the year to the stable isotope minimum. In presence of prolonged stable isotope minima, the attribution of the year introduces an unavoidable uncertainty (e.g. year 1995 in Fiescherhorn, Fig. 2, top, where the minimum extends for ~ 40 cm w.e.). Moreover, this minimum is associated with the coldest temperature, which may not fall in January. When inspecting the coldest month at the high-alpine weather station Jungfraujoch (46° 33′ N, 7° 59′ E, 3580 m a.s.l., correlation with annual δ^{18}O over the period 1961–2001 is $\rho < 0.45$, $p < 0.005$), only 6 km west of the Fiescherhorn, we found that over the period 1961–2001 the coldest temperature was in February in 44 % of the winters, the remaining in January, December and March. The year assignment may then be shifted enough to affect significantly the year/depth attribution in contrast to the annual δ^{18}O, which is the average of many values, and anyway intrinsically smoothed by diffusion. To test this hypothesis we built a new gridded dataset, where the annual sum of Meteoswiss gridded precipitation was taken according to the coldest month at the Jungfraujoch, and we repeated the spatial correlation with the Fiescherhorn accumulation. However, we did not find any correlation with this field (not shown). This indicates that such shifts in the depth-year assignment do not affect significantly the dating uncertainty of the Fiescherhorn ice core.

For Grenzgletscher, despite the high accumulation rate at the site (2.7 m w.e. yr^{-1}), and the considerable intraseasonal to interannual variability of precipitation, a good correlation with the instrumental data was observed only for lag = 0 (Fig. 6e), with the most significant results ($0.4 < \rho < 0.8$) found over Ticino, Southern Alps, and Northwestern Switzerland. The spatial pattern is consistent with the expected one over the region. No uniform correlations were obtained nearby the Grenzgletscher region. This may be explained by the sparseness of the weather stations, especially at such high altitude, resulting in less accurate precipitation reconstruction in the gridded data. Nevertheless, a significant correlation was found with precipitation at the Grand Saint Bernard station, as discussed before. The lagged correlations (Fig. 6d, f) do not give any significant result, confirming that the dating of the Grenzgletscher core was correct.

4 Conclusions and implications

δ^{18}O (or δD) and annual net snow accumulation in ice cores are usually interpreted as temperature and precipitation proxies, respectively. In this study we tested the validity of this assumption investigating two highly-resolved Alpine ice cores on an annual basis, where the dating uncertainty of the proxies in the uppermost part is minimal (±1 yr over the period 1961–2001). We took advantage of comprehensive instrumental datasets over the European region and performed spatial correlations allowing for the dating to be shifted by ±1 yr. The two ice cores from Fiescherhorn and Grenzgletscher come from distinct regions of the Alps, where the orographic barrier usually divides the precipitation patterns in Northern and Southern Alpine. Therefore with this study we could also test whether the two ice cores reflect this very local condition.

A significant spatial correlation between annual δ^{18}O and temperature over the period 1961–2001 was observed at Fiescherhorn, whereas at Grenzgletscher this was only the case for the precipitation weighted temperature. The latter site has a high accumulation rate (2.7 m w.e. yr^{-1}), and the seasonal variability in precipitation in the Southern Alps is usually pronounced, making it impossible to disentangle the temperature signal from the precipitation.

Regarding net accumulation, significant ($p < 0.05$) spatial correlations with local precipitation were observed for both sites. For Fiescherhorn glacier significant results with precipitation in the southwestern to northeastern part of Switzerland were found if allowing the absolute dating to be offset by one year (lag $= -1$), where the correlation was determined by the presence of a stronger trend in earlier part of the data with increased dating uncertainty. For Grenzgletscher we obtained, despite the high intraseasonal to interannual precipitation variability, the highest Spearman correlations over the Southern and Northwestern Alps. The resulting spatial patterns likely reflect the different precipitation features at both sites, with the Alps acting as orographic barrier. These findings have important general implications for temperature and precipitation reconstruction from high-alpine ice cores.

1. Seasonality in precipitation may bias the δ^{18}O signal so that only a precipitation weighted temperature can be obtained, which is not useful for any paleoclimate reconstruction. In cases when the seasonality is regular, seasonal (e.g. summer) temperatures can be reconstructed (not discussed in this paper).

2. The correlation with the instrumental data might be enhanced by the presence of trends. If they occur in the earlier periods, where dating uncertainty is increased, this should be taken into account, by introducing a corresponding offset.

3. Even for high-resolution ice core records with a pronounced seasonal signal, the dating uncertainty is rarely below ±1 yr and cannot be neglected.

4. The dating uncertainty, and, in the case of Fiescherhorn, the decoupling of temperature from the precipitation proxy, cannot be overcome but its influence can be minimized by averaging or smoothing the annual data, on the cost of losing the information on high frequency variations, but still allowing for longer term reconstructions.

The study underlines that even for well-resolved ice core records, interpretation of proxies on an annual or even sub-annual basis remains critical.

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Table 1. Rank correlation of annual accumulation (lag = −1) at Fiescherhorn with annual precipitation at nearby stations, over the period 1961–2001. Values of correlation coefficients statistically significant at the 5 % level are italic.

1961–2001 Station	Coordinates Latitude	 Longitude	Altitude (m a.s.l.)	Lag = −1 Spearman's ρ
Engelberg	46° 49′ N	8° 25′ E	1035	0.28
Grimsel Hospiz	46° 34′ N	8° 20′ E	1980	*0.32*
Grindelwald	46° 38′ N	8° 02′ E	1158	0.17
Guttannen	46° 39′ N	8° 17′ E	1055	*0.38*
Interlaken	46° 40′ N	7° 52′ E	577	*0.42*
Kleine Scheidegg	46° 35′ N	7° 58′ E	2061	0.20
Lauterbrunnen	46° 36′ N	7° 54′ E	818	0.27
Leukerbad	46° 23′ N	7° 38′ E	1390	*0.45*
Meiringen	46° 44′ N	8° 10′ E	588	*0.42*
Mürren	46° 33′ N	7° 53′ E	1638	0.30

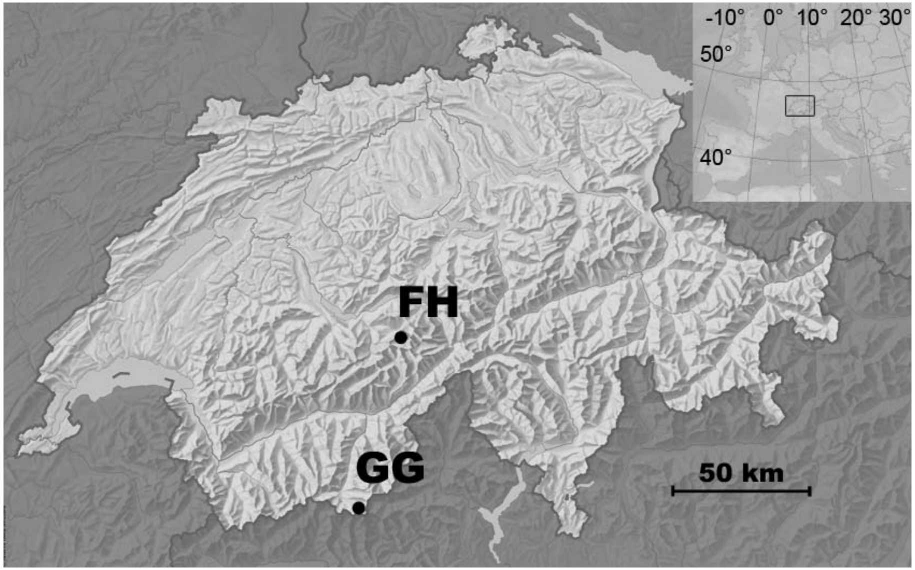

Fig. 1. Topographic map of Switzerland showing the location of the two ice core drilling sites, Fiescherhorn (FH), and Grenzgletscher (GG) (source: Atlas of Switzerland, http://www.atlasderschweiz.ch/). The insert gives the location of Switzerland in Europe.

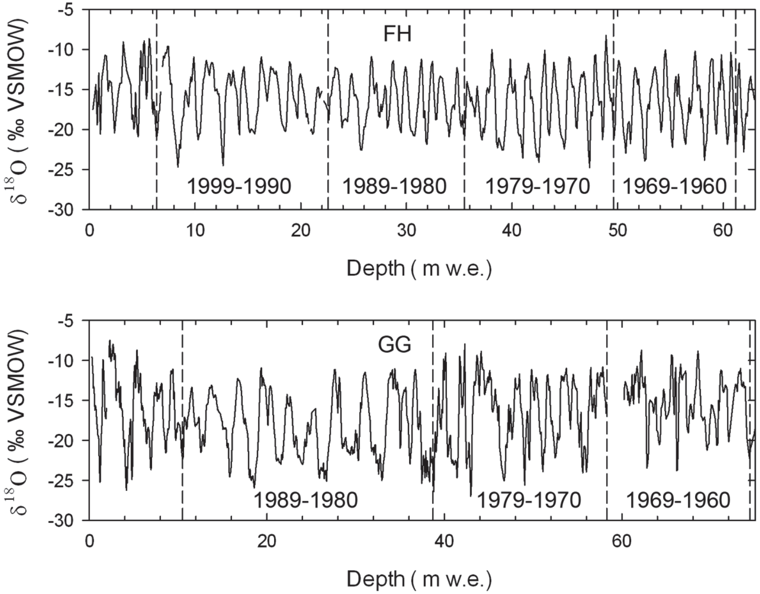

Fig. 2. δ^{18}O raw data from Fiescherhorn (FH, top, first 60 m w.e. corresponding to the period 1961–2001), and Grenzgletscher (GG, bottom, first 70 m w.e., corresponding to the period 1961–1993, with a gap in the period 1968–1970).

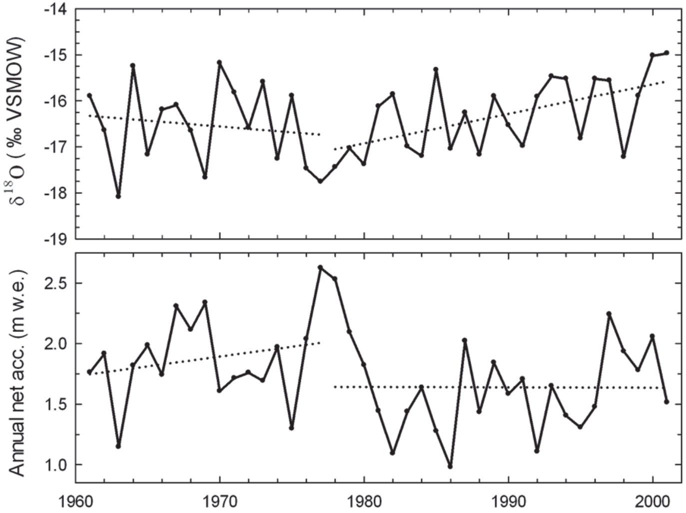

Fig. 3. Fiescherhorn annual values of δ^{18}O (top), and past annual net accumulation (bottom). Mean values over the period 1961–2001 are −16.40 ‰ and 1.7 m w.e., respectively, the last one coinciding with the estimated surface accumulation rate λ_0 described in Sect. 2.1.2. Trends for the two different subperiods are highlighted with dotted lines: Trend in δ^{18}O over 1961–1977 (−0.03 ‰ yr^{-1}), and 1978–2001 (0.06 ‰ yr^{-1}). Trend in accumulation over the period 1961–1977 (0.01 m w.e. yr^{-1}), and 1978–2001 (−0.0003 m w.e. yr^{-1}).

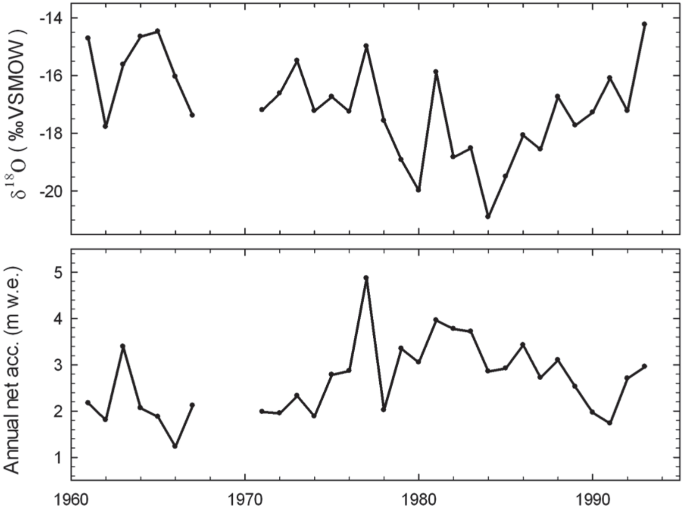

Fig. 4. Grenzgletscher annual values of δ^{18}O (top), and past annual net accumulation (bottom). Mean values over the period 1961–1993 are −17.07 ‰ and 2.7 m w.e., respectively, the last one coinciding with the estimated surface accumulation rate λ_0 described in Sect. 2.1.2.

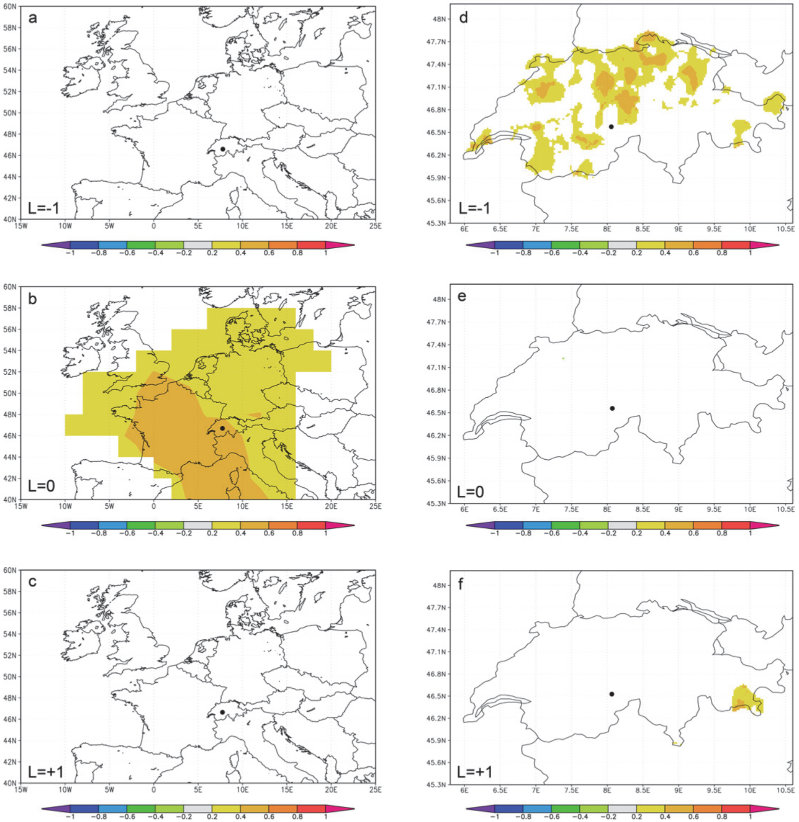

Fig. 5. Spatial rank correlation map of annual Fiescherhorn δ^{18}O with the Twentieth Century Reanalysis temperature at 700 hPa (left) and of annual accumulation with the Meteoswiss annual precipitation (right) over the period 1961–2001. In order to take the dating uncertainty into account, the absolute dating was allowed to be offset by 1 yr (lag −1/0/+1). **(a, d)**: Lag = −1, **(b, e)**: lag = 0, **(c, f)**: lag = +1 yr. Areas with correlation coefficients statistically significant at the 5 % level are shaded.

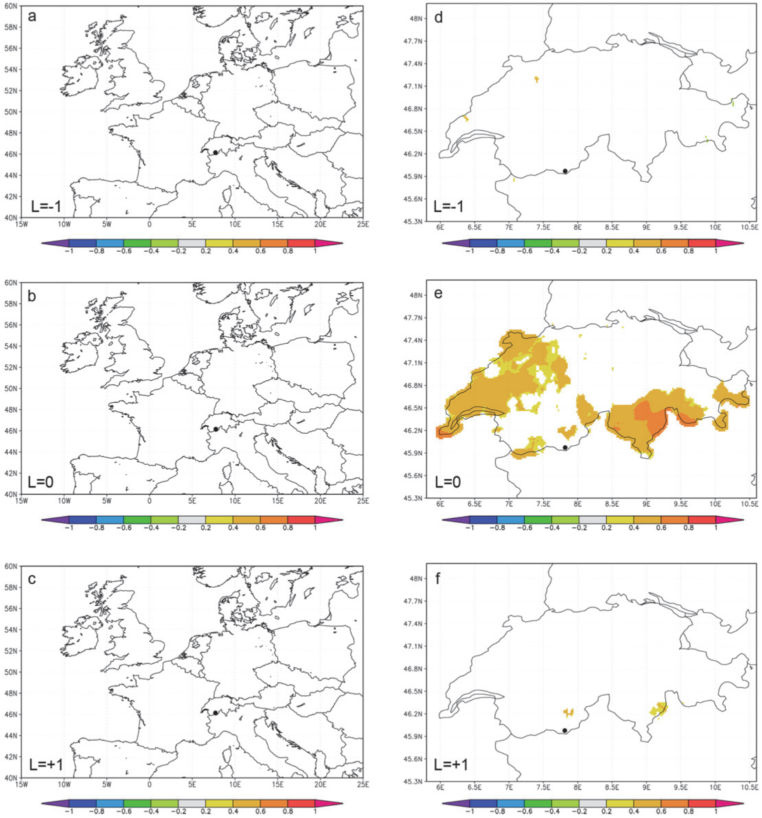

Fig. 6. Spatial rank correlation map of annual Grenzgletscher δ^{18}O with the Twentieth Century Reanalysis temperature at 700 hPa (left) and of annual accumulation with the Meteoswiss annual precipitation (right), over the period 1961–1993. In order to take the dating uncertainty into account, the absolute dating was allowed to be offset by 1 yr (lag −1/0/+1). **(a, d)**: Lag = −1, **(b, e)**: lag = 0, **(c, f)**: lag = +1 yr. Areas with correlation coefficients statistically significant at the 5 % level are shaded.

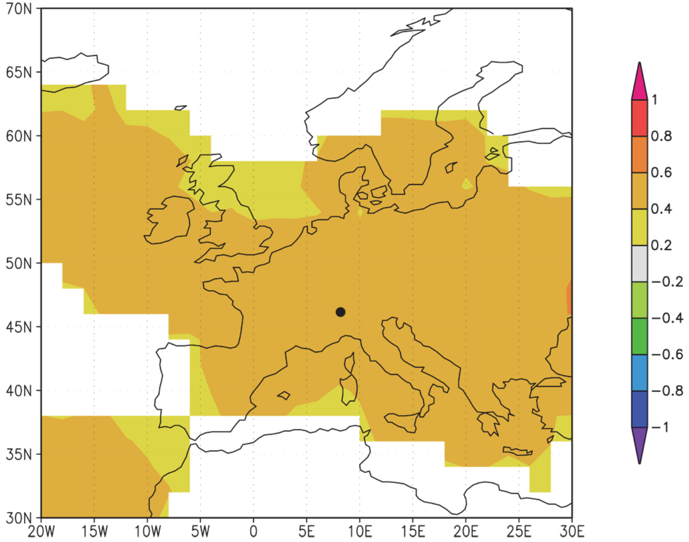

Fig. 7. Spatial rank correlation map of annual Grenzgletscher δ^{18}O with the precipitation-weighted Twentieth Century Reanalysis temperature at 700 hPa (1961–1993). Grand Saint Bernard precipitation was used to weight the temperature. Areas with correlation coefficients statistically significant at the 5 % level are shaded.