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Simulating the temperature and precipitation signal in an Alpine ice core

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Abstract

Accumulation and δ^{18}O data from Alpine ice cores provide information on past temperature and precipitation. However, their correlation with seasonal or annual mean temperature and precipitation at nearby sites is often low. Based on an example we argue that, to some extent, this is due to the irregular sampling of the atmosphere by the ice core (i.e. ice cores only record precipitation events and not dry periods) and the possible incongruity between annual layers and calendar year due to dating uncertainty. Using daily meteorological data from nearby stations and reanalyses we replicate the ice core from the Grenzgletscher (Switzerland, 4200 m a.s.l.) on a sample-by-sample basis. Over the last 15 yr of the ice core record, accumulation and δ^{18}O variations can be well reproduced on a sub-seasonal scale. This allows a wiggle-matching approach for defining quasi-annual layers. For this period, correlations between measured and replicated quasi-annual δ^{18}O values approach 0.8. Further back in time, the quality of the agreement deteriorates rapidly. Nevertheless, we find significant correlations for accumulation and precipitation over the entire length of the record (1938–1993), which is not the case when comparing ice core δ^{18}O with annual mean temperature. A Monte Carlo resampling approach of long meteorological time series is used to further explore the relation, in a replicated ice core, between δ^{18}O and annual mean temperature. Results show that meteorologically very different years can lead to quasi-identical values for δ^{18}O. This poses limitations to the use of δ^{18}O from Alpine ice cores for temperature reconstructions in regions with a variable seasonality in precipitation.

1 Introduction

Alpine ice cores have been used as climate proxies to infer environmental conditions in the past, including temperature and precipitation. Precipitation is reflected in the net accumulation rate, and temperature in the δ^{18}O isotopic composition. However, the direct calibration of these proxy variables with observed seasonal or annual mean temperature and precipitation is difficult and correlations are sometimes low. For instance, for the case of the Grenzgletscher in Switzerland (4200 m a.s.l., see Fig. 1), a high-accumulation site with presumably good data quality (Eichler et al., 2000, 2001), the correlation between $\delta^{18}O$ in the ice core and annual mean temperature from nearby meteorological stations is low, while there is a significant correlation between accumulation and precipitation. In another ice core from the Swiss Alps (Fiescherhorn glacier), the correlation between $\delta^{18}O$ and annual mean temperature as well as between accumulation and precipitation is reasonably high (Mariani et al., 2012).

There are many possible causes why $\delta^{18}O$ might not correlate well with annual mean temperature. For instance, temperature and precipitation may exhibit very local signals that are not captured by nearby sites, particularly in the complex alpine setting. Even if local precipitation was available, local accumulation does not record local precipitation as there may be a substantial re-distribution of snow (wind drift, erosion). Also, $\delta^{18}O$ does not record local air temperature, but depends on the origin and history of the water vapour in the air mass including possibly multiple condensation cycles (e.g. Pfahl and Wernli, 2008). Postdepositional processes (e.g. diffusion, surface melting, lateral percolation, sublimation and desublimation, etc.) lead to a smoothing and dislocation of the signal within the ice core (Eichler et al., 2001) or to changes in the isotopic signature. Ice flow may change the structure of the record. The snow sampled in deeper layer of the ice core might have fallen further up on the glacier under different conditions (upstream effects). Finally, ice cores record climatic conditions only during precipitation events, which may not be characteristic for the average conditions over a year or so. The $\delta^{18}O$ signal thus represents a precipitation-weighted temperature signal (Werner et al., 2000; Läpple et al., 2011).

The direct comparison (e.g. correlation, regression) of accumulation or $\delta^{18}O$ in ice cores with precipitation and seasonal or annual mean temperature works only if all of the above processes can be assumed stationary. However, this assumption may be problematic, specifically in the climatically complex environment of the Alps or mountain systems in general. For instance, a seasonal shift in precipitation from winter to summer

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between the medieval period and the Little Ice Age might produce lower δ^{18}O values in medieval times than during the Little Ice Age even if temperatures were higher in both seasons.

In this paper we consider one of the problems mentioned, namely that of the irregular sampling of weather events by the ice core. We address this by replicating the sampling in daily meteorological data using a very simple forward model. We further study the problem of the definition of annual layers in comparisons between meteorological data and proxies. Finally, a Monte Carlo resampling approach of long meteorological records is used to investigate uncertainties in the relation between ice-core proxies and mean climate due to the fact that ice cores only represent precipitation events.

The paper is organised as follows. Section 2 gives details about the ice core and meteorological data used in this paper. Section 3 describes the forward modelling approach. Results are presented and discussed in Sect. 4, including analyses with the Monte Carlo resampling approach. Conclusions are drawn in Sect. 5.

2 Data

2.1 Ice core data

We use data from an ice core drilled at the upper Grenzgletscher (45°55′ N, 7°52′ E), at an elevation of 4200 m a.s.l. (see Fig. 1). The Grenzgletscher is situated in the Monte Rosa Massif and is a high accumulation site. The core studied here was collected in October 1994 and reached down to 125 m (Eichler et al., 2000, 2001). The time period covered by the ice core is 1937–1994, with a mean annual accumulation rate of 2.7 m water equivalent (w.eq.). The density of each ice core section of about 50 cm length was used to calculate the w.eq. depth in order to correct for compaction of the firn part of the core. Sampling resolution was 5 cm for analyses of δ^{18}O, corresponding to about 70 and 20 measurements per year for the periods 1984–1993 and 1938–1947, respectively. Between 1953 and 1987, only every other sample was analysed with respect to

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$\delta^{18}O$. The core indicated perturbations in the period 1985–89, strongly affecting the chemical composition but leaving the $\delta^{18}O$ mostly undisturbed. Eichler et al. (2001) concluded that these perturbations were most likely due to lateral percolation of melt water.

In addition to $\delta^{18}O$, concentrations of major ions were also determined. Although they are not directly analysed in this paper, they were sometimes used for supporting the identification of seasons. In general, annual layers were then defined as layers between the coldest (lowest) $\delta^{18}O$ sample of a winter season and the coldest $\delta^{18}O$ sample of the next year's winter season (referred to as "cold point year" in the following). Annual accumulation rates were calculated from the obtained annual thicknesses accounting for thinning of annual layers with depth by using a simple ice flow model (Nye, 1963), for details see Eichler et al. (2000).

2.2 Meteorological data

Local meteorological data are used from three main sources: station data, ERA-Interim reanalysis (Dee et al., 2011), and the Twentieth Century Reanalysis (Compo et al., 2011).

The station data is from the Gr. St. Bernhard, ca. 50 km to the west of the ice core site, at an altitude of 2450 m a.s.l. (see Fig. 1). The station is at a saddle (a pass) on the main alpine crest and thus influenced both from the north and the south. The station was erected in 1817; sub-daily data reach back to 1819. However, the data have not yet been fully homogenised. A visual inspection revealed a large, likely unrealistic trend in precipitation up to the 1930s. For the period after 1938, when ice core data is available, no clear inhomogeneity was detected. However, precipitation at Gr. St. Bernhard is measured near a south-facing wall, which is expected to affect the measurements due to shielding effects.

As an alternative to the station data, we further included reanalyses data. On the one hand we used ERA-Interim data from 1979 to the present (Dee et al., 2011). This data

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set represents the latest generation reanalyses. On the other hand, for going back further, we also used the ensemble mean of the Twentieth Century Reanalysis, version 2 (20CR, Compo et al., 2011) which goes back to 1871. 20CR is a global 3-dimensional atmospheric reanalysis dataset at 6-hourly temporal resolution reaching back to 1871 (Compo et al., 2011). It provides a 56-member ensemble of analyses based on an assimilation of surface and sea level pressure observations, i.e. the distribution of atmospheric mass. Assimilation was performed using an Ensemble Kalman Filter technique, with first guess fields generated by a 2008 experimental version of the US National Center for Environmental Prediction Global Forecast System atmosphere/land model (NCEP/GFS). Model boundary conditions were derived from monthly mean sea surface temperature and sea ice distributions (see Compo et al., 2011, for details).

We extracted meteorological data from the closest grid point (with a spatial resolution of $1.5^\circ \times 1.5^\circ$ and $2^\circ \times 2^\circ$ for ERA-Interim and 20CR, respectively) to the Grenzgletscher (see Fig. 1). The time interval of the atmospheric data was 6 h while precipitation in both data sets was available at steps of 3 h from 12 hourly forecasts.

We compared the three data sets on the level of daily averages (precipitation was summed from 06:00 UTC to 06:00 UTC). From the reanalysis data sets we used temperature at 600 hPa (which is close to the altitude of Grenzgletscher). For the remainder of the paper, only analyses based on these daily data are shown. Comparisons were performed on absolute values (i.e. no mean annual cycle was subtracted), for the years 1980–2008. The agreement for temperature is very good between all data sets, with Pearson correlations exceeding 0.95. For precipitation (Fig. 2), both reanalysis data sets, but particularly 20CR (ensemble mean), overestimate the number of precipitation days (i.e. days with ≥ 0.1 mm of precipitation). In these 29 yr, 5869 days were reported, while the numbers for ERA-Interim and 20CR are 7501 and 8578, respectively. The total precipitation amounts agree relatively well, i.e. they are within 30 % of each other.

Correlations for precipitation are relatively low when considering individual days. However, after binning observed precipitation into 21 classes and analysing reanalysis precipitation for each class, the agreement improves (Fig. 2; note the logarithmic

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scale used for the x-axis for display purposes). Pearson correlations of 0.96 and 0.92 are found between class mean values from observations and ERA-Interim or from observations and 20CR, respectively. The relation is non-linear as high values are underestimated. This is expected since observations are point values whereas reanalyses represent precipitation over large areas (also, 20CR is an ensemble mean of 56 members, additionally contributing to an underestimation of extremes and an overestimation of precipitation days). Note also that orography is very crudely depicted in 20CR and hence orographic effects are missing (see Stucki et al. (2012), for a discussion of the accuracy of Alpine precipitation in 20CR and of processes leading to heavy precipitation in the Alps, including orography).

In all, the agreement for precipitation is satisfactory, but not excellent. We use all three data sets in this paper.

3 Forward model

To address the signal preservation of climate variables by the ice core we mimic the formation of an ice core from daily meteorological data (i.e. a simple forward model):

$$A_{\mathrm{fwd\_daily}} = c_1 \cdot P_{\mathrm{daily}} \quad (1)$$

$$\delta^{18}O_{\mathrm{fwd\_daily}} = c_2 + c_3 \cdot T_{\mathrm{daily}} \quad (2)$$

where A is accumulation, P is precipitation, T is temperature and the subscript "fwd" stands for forward model. Note that many other effects could also be incorporated into such a model, which however is not the focus of this paper. In the laboratory, samples of 5 cm ice were analysed. They can be described as:

$$A_{\mathrm{fwd\_sample}} = \Sigma(c_1 \cdot P_{\mathrm{daily}}) \quad (3)$$

$$\delta^{18}O_{\mathrm{fwd\_sample}} = c_2 + c_3 \cdot \Sigma(P_{\mathrm{daily}} \cdot T_{\mathrm{daily}})/\Sigma(c_1 \cdot P_{\mathrm{daily}}) \quad (4)$$

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where the sum is defined such that A_{fwd_sample} corresponds to a sample (mostly close to 5 cm, but exact numbers, which may vary from sample to sample, were used). This requires knowledge of c_1, which is assumed constant over time and which is estimated in the next paragraph. Constants c_2 and c_3 describe the relation between temperature and the isotope ratio. Although values would be available from the literature, we did not take c_2 and c_3 into account at all. Only correlations, which are insensitive to the choice of c_2 and c_3, are analysed in this paper. We therefore analyse only $\Sigma(P_{daily} \cdot T_{daily})/\Sigma(c_1 \cdot P_{daily})$, which we call "weighted temperature".

Note that in reality, the relation between A_{fwd} and P is non-linear but depends on the type and amount of precipitation, and it may vary over time. Also, approximating snow accumulation on the glacier with precipitation from a distant measurement site or a reanalysis inevitably carries a large error.

We applied the model for the period autumn 1979 to spring 1994, where the ice core data show more pronounced seasonality than earlier and meteorological data is better (automated rather than manual weather station) and more abundant (ERA-Interim data). We show results based on station data in the following. To determine constant c_1, precise start and end date of the given period must be defined in the real ice core. We proceeded in the following way: we assumed that the last sample in the ice represents 31 March 1994 and searched for the most likely location of 1 September 1979 in the ice core by smoothing $\delta^{18}O_{fwd\_daily}$ and comparing with observed δ^{18}O of that autumn until a good fit was found. Note that the error in c_1 is relatively small (i.e. corresponding to an error of a week or two over a period of 13 yr) and that the effect of mis-specifying c_1 also is small, especially for those analyses where the ice core is re-dated, as described in Sect. 4. In this way c_1 was set to 1.20. Subsequently, 5 cm samples could be defined and A_{fwd_sample} and $\delta^{18}O_{fwd\_sample}$ could be calculated. We call the result "artificial ice core".

4 Results

4.1 Sample-by-sample comparison

A first comparison on a sample-by-sample basis showed that the weighted temperature in the artificial ice core is more variable than δ^{18}O in the real ice core. This is expected as several processes (surface melting and percolation, diffusion) lead to a smoothing of the signal across the sample within a layer of approximately 30 cm (Johnson et al., 2000). We therefore smoothed the weighted temperature in the artificial ice core with a five point triangular filter. Results are shown in Fig. 3. The agreement between this curve and the ice core δ^{18}O obtained in this way is over all very good. The summer peaks are more smoothed out in the real ice core, most likely due to surface melting (see squared boxes), which however does not affect the winter season. In the other seasons it is often possible to identify individual wiggles in both curves (see open circles for examples). In order to quantify the agreement, the two curves need to be brought onto the same depth scale (i.e. dated). Since the agreement is very good in the autumn to spring season, we tried a wiggle-matching approach for dating. The wiggles representing the lowest mid-winter δ^{18}O values in the real ice core were matched in the artificial ice cores samples. There was ambiguity in this process in about 3–4 cases where we consulted neighbouring wiggles. We did not change decisions ex-post (i.e. after the analysis of the results), so the wiggle matching was not used to further optimize correlations. The identified points are marked with filled dots in Fig. 3.

The values of A_{fwd} and the weighted temperature were then calculated for the period between the points (i.e. the sum in Eq. 2 was taken over all samples between two successive cold points). The result is a series of quasi-annual values shown in Fig. 4. Pearson correlations between the artificial and the real ice core are 0.62 for accumulation and 0.80 for weighted temperature ($n = 14$). The latter number would be even higher (0.92) when omitting the oldest, somewhat uncertain year. These high correlations are surprising in view of the considerable horizontal and vertical distance of the weather station and the ice core site and in view of all other uncertainties mentioned.

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It shows that the ice core does indeed record meteorological information, namely the precipitation-weighted average of temperature.

4.2 Interannual resolution

It was not possible to extend the wiggle matching to the entire record as the agreement of sub-seasonal variability deteriorated rapidly before 1980. Therefore, we used the annual mean values as defined in Mariani et al. (2012) and compared these to two different integrations of the forward model (Fig. 5). In one version (termed "calendar year") we simply averaged the artificial ice core over the calendar year (dashed). In the other approach ("cold point year") we used the central date of the 60-day window with the minimum averaged weighted temperature among a 180 day period during the winter half year (solid). This allows minima to occur in November or March, for instance, while mostly they occurred at some point in January. The model was fed with different meteorological data sets. For visualization, they were scaled with a regression model calibrated against ice core δ^{18}O in the 1979–1993 period. Corresponding correlations are listed in Table 1 for the entire period as well as for the subperiod 1979–1993.

During the last period (1979–1993) all comparisons give satisfactory agreement, although not as good as for the wiggle matching approach. For accumulation, correlations approach 0.6 for the direct comparison with annual means and for the calendar year approach, while they are lower for the cold point year. For δ^{18}O (or weighted temperature) there is hardly any difference. Note that n is low so that differences between correlation coefficients are not significant.

For the full period, correlations are lower as was already indicated by the failure of the wiggle matching approach. While for accumulation, correlations are still significant, this is no longer the case for δ^{18}O and annual mean temperature. Both forward models (calendar or cold point year) still give correlations between 0.3 and 0.4, and correlations are relatively stationary when using 21-yr moving window correlations.

It is interesting to compare within the Gr. St. Bernhard station data the annual mean temperature with the precipitation weighted temperature using the calendar year approach (Fig. 6). The correlation between the two series is low ($r = 0.25$ for the entire 1865–2010 period, $r = 0.45$ for the 1934–2010 period), which suggests that the main reason for the low correlations shown in Table 1 is the fact that the ice core does not record temperatures during dry conditions (note that the definition of the year is the same). The precipitation weighted temperature has a higher variance than annual mean temperature.

In the real ice core, additional effects such as dating uncertainties could further contribute to low correlations. The precision of dating was estimated to be ±1 yr for the period 1970–1994 and ±3 yr for 1937–1969 (Eichler et al., 2000). With respect to observations, the low value in 1951 appears as an outlier. However, Eichler et al. (2000) attributed this value to cold, snowy conditions in January and February of that year causing a large number of avalanches (Pfister, 1999). Also, 20CR shows a slightly lower value in that year. It does appear, however, that negative extremes deviate more strongly from the observations than positive ones, suggesting that the extreme conditions at high-alpine sites are not well represented in some of the data sets.

This analysis shows that the further back in time one goes, the more uncertain the information from ice cores is. It also shows, however, that there still is a significant correlation between ice core and temperature but not with annual mean temperature. There is almost no difference between the calendar year and the cold point year. While the former is simpler, the latter is more plausible given the sampling and arguably less affected by non-stationarity problems.

All attempts to develop the forward model further, i.e. to account for variations in lapse rates between the Gr. St. Bernhard and Grenzgletscher (or to interpolate the reanalyses to a fixed altitude) or to account for the main wind direction by sampling reanalysis temperatures 3 h upwind did not improve the results.

4.3 Low-frequency variability

Interannual variability might still be affected by post-depositional processes or dating errors. We therefore also tested correlations based on 5 yr averages (1938–1967,

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1970–1993; the last period was only 3 yr). The correlations improved considerably for the forward model, to around 0.8 (Table 1), while they remained insignificant for the annual mean temperature. This again shows that a temperature signal is contained in the ice core. The definition of the annual average does not matter much as the corresponding error in one year is largely compensated by the error of the next year.

4.4 Analyses of artificial ice core

Reanalyses are available for 140 yr. The artificial ice core can thus be extended far beyond the real ice core. This allows us to study the relation between annual mean temperature and $\delta^{18}O$ within the artificial ice core (Fig. 7 top). We used both the calendar year and the cold point year. For the former, A_{fwd} and annual mean precipitation have a correlation of 1 by definition. The Pearson correlation between $\delta^{18}O_{fwd}$ and annual mean temperature is 0.6, which is statistically significant. Note that the deviation from a correlation of 1 is only due to the difference between the accumulation-weighted average and the true average. Other potential errors such as the definition of the year or uncertainties in meteorological data or ice core data are excluded by construction. For the cold point year the correlation between $\delta^{18}O$ and annual mean temperature drops further to 0.34. This value is similar to those found in the comparison between the real ice core and the artificial ice core. Note that this experiment still assumes perfect data (no uncertainties in meteorological data or ice core data), thus demonstrating that sampling alone is sufficient to account for the low correlations at interannual time scales. In other words, a given combination of $\delta^{18}O$ and accumulation can be achieved in many different ways so that conclusions about mean temperature are difficult.

4.5 Monte Carlo resampling

In order to improve the data coverage and better populate Fig. 7, we applied a simple Monte Carlo sampling approach to (1) the station observations from the years 1994–2010, representing present climate, and (2) 20CR from 1871–2008, representing

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a long record with a large range of climatic conditions. We formed artificial meteorological records of (1) 1000 or (2) 10 000 yr in length by stacking sequences of length $l = 15$ days (representing an upper-limit of the long range memory of atmospheric circulation). These sequences were randomly sampled from all years in the real records (station observations or 20CR, respectively), but the calendar day was allowed to vary somewhat (i.e. we sampled the corresponding calendar day plus a Gaussian random offset with $\mu = 0$ days, $\sigma = 5$ days). Note that more sophisticated weather generators could be used to produce realistic weather, but this simple weather generator serves the purpose of illustrating the uncertainties in signal preservation by the ice core more fully than in Sect. 3.4.

From the artificial meteorological records we proceeded as before using both the calendar and cold point years. Results are shown in Fig. 7 (middle and bottom). In terms of correlation, the results confirm those obtained from 20CR without resampling. For the calendar year approach, correlations between annual mean temperature and precipitation weighted temperature are 0.47 and 0.29 for case (1) and case (2), respectively. For the cold-point year correlations drop to 0.26 and 0.10, respectively. Similar as the artificial ice core from 20CR, the two Monte Carlo simulated ice cores show a slightly smaller variability of annual mean temperature for low weighted temperatures.

4.6 Using Monte Carlo resampling for reconstruction or for quantifying uncertainties

The Monte Carlo technique could potentially be used for climate reconstruction or for quantifying uncertainties in climate reconstructions. For instance, annual mean temperature could be reconstructed from an ice core by searching, for each year in the ice core, the closest analogue (or pool of close analogues) in the artificial ice core according to the combination of δ^{18}O and accumulation (i.e. sampling Fig. 7). For these years one could then analyse the mean and spread of the annual mean temperature (or any other desired statistics).

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For illustrating the approach we used the 10 000-yr artificial records (both cold point and calendar year), left out ten 56-yr periods within the records and then tried to reproduce annual mean temperature for these ten periods using weighted temperature and A_{fwd} from the remaining years. For selecting analogues, we arbitrarily chose tolerances of ±0.4 m for accumulation and ±0.2 ‰ for $\delta^{18}O$. For the evaluation we used the mean of all analogues or the closest analogue (minimum Euclidian distance calculated from standardized weighted temperature and A_{fwd}). Results revealed interannual correlations for annual mean temperature between 0.2 and 0.4. These results represent an upper limit of the correlation that could be achieved with this approach as other sources of errors (data uncertainties, dating) are not addressed. Moreover, the spread within the selected analogues was very large, i.e. meteorologically very different years can give very similar values of $\delta^{18}O$ and accumulation. An application of the reconstruction approach to real ice core data (not shown) produced no correlations at all with observed annual mean temperatures.

5 Conclusions

The goal of this paper was to formulate a simple forward model that replicates the preservation of the atmosphere signals by the ice core (precipitation event by precipitation event) and the processing of the ice core samples. The model shows that the ice core does contain climate information even though there is only a low correlation between annual mean temperature and $\delta^{18}O$. For the specific case of Grenzgletscher, it was shown that a given combination of $\delta^{18}O$ and accumulation can be achieved in many different ways. Hence, accounting for the signal preservation is important. Accumulation is captured much better in the ice core. The model allows further tests and thus serves as tool for understanding the climate signal in ice cores. Most importantly, the model is not affected by the problem of the stationarity of the seasonal cycle (there are stationarity assumptions, but these will be close to the process level).

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Although for the case of Grenzgletscher, the comparisons between forward model and real ice core data revealed difficulties, suitable forward proxy models could in principle be used to assimilate (well-dated) ice core data into climate models in order to obtain climate reconstructions (Bhend et al., 2012). Even simpler, Monte Carlo or other resampling approaches could possibly be used for local climate reconstruction. Even though these approaches may not give better results than traditional regression approaches, they would suffer much less from possible stationarity problems and could provide probabilistic information.

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References

Bhend, J., Franke, J., Folini, D., Wild, M., and Brönnimann, S.: An ensemble-based approach to climate reconstructions, Clim. Past, 8, 963–976, doi:10.5194/cp-8-963-2012, 2012.

Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Matsui, N., Allan, R. J., Yin, X., Gleason, B. E., Vose, R. S., Rutledge, G., Bessemoulin, P., Brönnimann, S., Brunet, M., Crouthamel, R. I., Grant, A. N., Groisman, P. Y., Jones, P. D., Kruk, M., Kruger, A. C., Marshall, G. J., Maugeri, M., Mok, H. Y., Nordli, Ø., Ross, T. F., Trigo, R. M., Wang, X. L., Woodruff, S. D., and Worley, S. J.: The Twentieth Century Reanalysis project, Q. J. Roy. Meteor. Soc., 137, 1–28, 2011.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P.,

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Tavolato, C., Thépaut, J.-N., and Vitart, F.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Q. J. Roy. Meteor. Soc., 137, 553–597, 2011.
Eichler, A., Schwikowski, M., Gäggeler, H. W., Furrer, V., Synal, H.-A., Beer, J., Saurer, M., and Funk, M.: Glaciochemical dating of an ice core from the upper Grenzgletscher (4200 m a.s.l.), J. Glaciol., 46, 507–515, 2000.
Eichler, A., Schwikowski, M., and Gäggeler, H. W.: Meltwater-induced relocation of chemical species in Alpine firn, Tellus B, 53, 192–203, 2001.
Johnsen, S., Clausen, H., Cuffey, K., Hoffmann, G., Schwander, J., and Creyts, T.: Diffusion of stable isotopes in polar firn and ice: the isotope effect in firn diffusion, in: Physics of Ice Core Records, edited by: Hondoh, T., Hokkaido University Press, Sapporo, 121–140, 2000.
Läpple, T., Werner, M., and Lohmann, G.: Synchronicity of Antarctic temperatures and local solar insolation on orbital timescales, Nature, 471, 91–94, 2011.
Mariani, I., Eichler, A., Brönnimann, S., Auchmann, R., Jenk, T. M., Leuenberger, M. C., and Schwikowski, M.: Temperature and precipitation signal in two Alpine ice cores over the period 1961–2001, Clim. Past Discuss., 8, 5867–5891, doi:10.5194/cpd-8-5867-2012, 2012.
Nye, J. F.: Correction factor for accumulation measured by the thickness of the annual layers in an ice sheet, J. Glaciol., 4, 785–788, 1963.
Pfahl, S. and Wernli, H.: Air parcel trajectory analysis of stable isotopes in water vapor in the eastern Mediterranean, J. Geophys. Res., 113, D20104, doi:10.1029/2008JD009839, 2008.
Pfister, C.: Wetternachhersage – 500 Jahre Klimavariationen und Naturkatastrophen, Haupt, Bern, 1999.
Stucki, P., Rickli, R., Brönnimann, S., Martius, O., Wanner, H., Grebner, D., and Luterbacher J.: Weather patterns and hydro-climatological precursors of extreme floods in Switzerland since 1868, Meteorol. Z., accepted, 2012.
Werner, M., Mikolajewicz, U., Heimann, M., and Hoffmann G.: Borehole versus isotope temperatures on Greenland: seasonality does matter, Geophys. Res. Lett., 27, 723–726, 2000.

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Table 1. Pearson correlations between accumulation and $\delta^{18}O$ from the Grenzgletscher ice core with accumulation and $\delta^{18}O$ from the forward model as well as with annual averages of temperature and precipitation. Different data sets are used (OBS = station observations, 20CR = Twentieth Century Reanalysis, INT = ERA-Interim). Also shown are correlations for 5-yr averages (1938–1942, 1943–1947, 1948–1952, 1953–1957, 1958–1962, 1963–1967, 1971–1975, 1976–1980, 1981–1985, 1986–1990, 1991–1993). Coefficients in bold are statistically significant ($p < 0.05$). Note that we did not account for autocorrelation in determining the degrees of freedom.

	Direct comparison Annual average (T or P)			Forward model Cold point year (A_{fwd} or weighted temperature)			Forward model Calendar year (A_{fwd} or weighted temperature)		
1979–1993	OBS	20CR	INT	OBS	20CR	INT	OBS	20CR	INT
Accumulation	**0.62**	**0.54**	**0.61**	0.41	0.41	**0.52**	**0.62**	**0.54**	**0.61**
$\delta^{18}O$	**0.51**	0.43	0.38	0.45	**0.53**	**0.57**	**0.52**	0.48	0.39
1938–1993	OBS	20CR		OBS	20CR		OBS	20CR	
Accumulation	**0.40**	**0.40**		0.26	**0.31**		**0.40**	**0.40**	
$\delta^{18}O$	0.05	0.12		**0.33**	**0.41**		**0.41**	**0.39**	
1938–1993 (5-yr averages)	OBS	20CR		OBS	20CR		OBS	20CR	
$\delta^{18}O$	–0.06	0.17		**0.76**	**0.79**		**0.84**	**0.85**	

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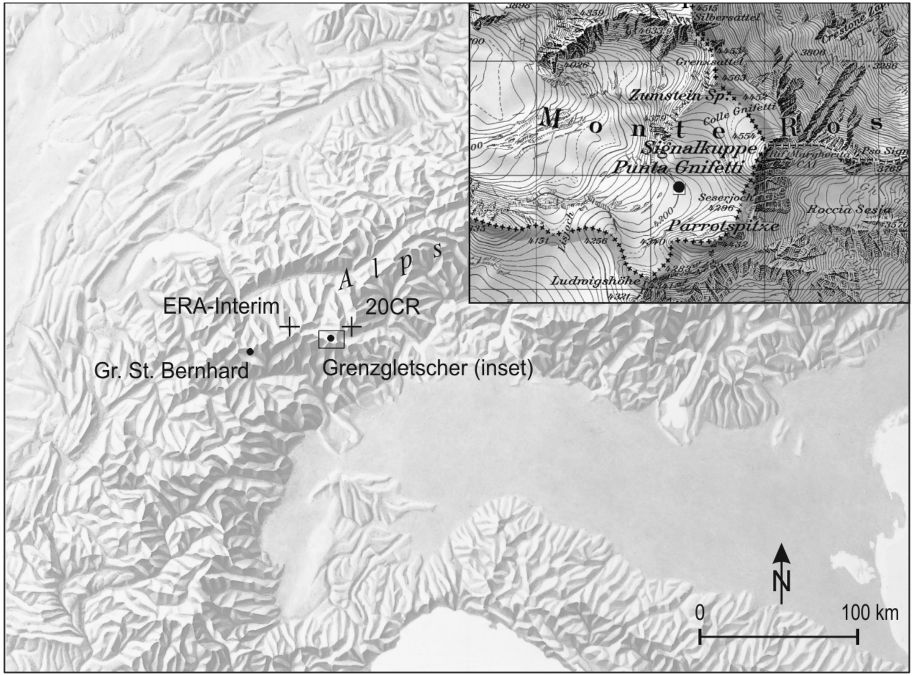

Fig. 1. Map of the study site and the locations of Grenzgletscher and Gr. St. Bernhard. The inset shows the drilling location of the Grenzgletscher ice core. Crosses show the locations of the grid-points from 20CR and ERA-Interim, respectively. Printed with permission of the Schweizerische Konferenz der Kantonalen Erziehungsdirektoren (relief) and swisstopo (inset).

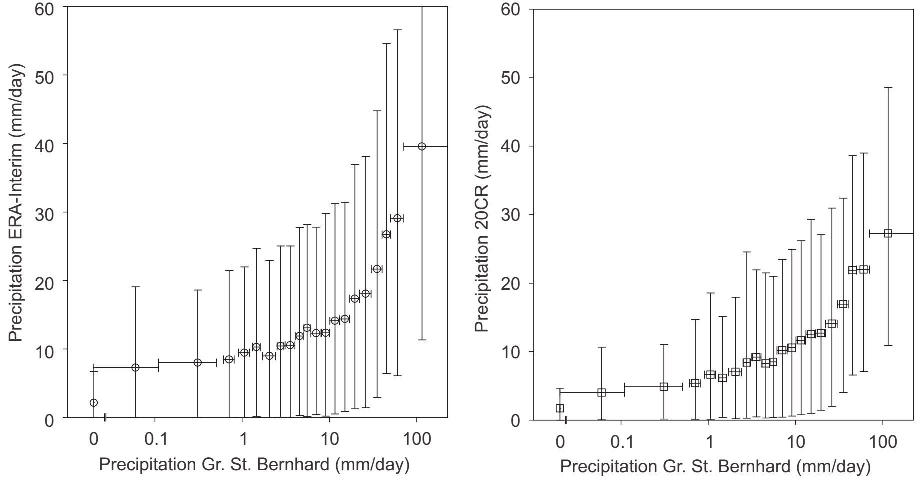

Fig. 2. Comparison of daily precipitation in observations from the Gr. St. Bernhard and from ERA-Interim (left) and 20CR (right) reanalysis data in the period 1980–2008. Observed precipitation was binned (horizontal error bars indicate the bin size). The y-axes give the average precipitation for each bin (error bars give the 10 and 90 percentiles).

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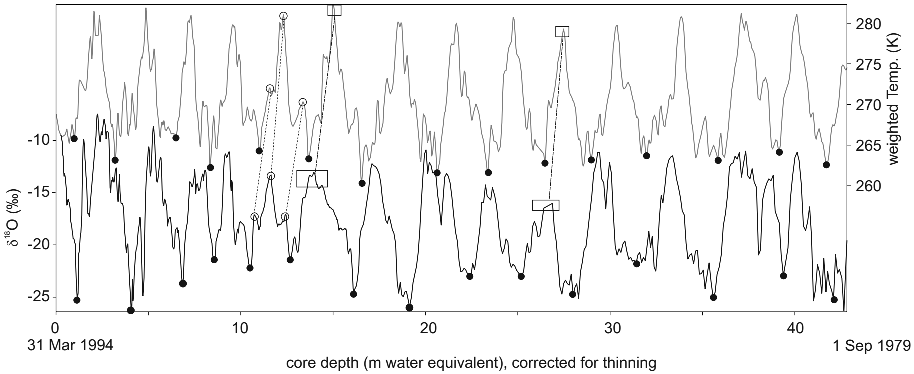

Fig. 3. Sample-by-sample depiction of the ice core δ^{18}O (bottom) as well as the weighted temperature from the forward modelling approach (top, using Gr. St. Bernhard station data). Black dots denote the cross-dating using wiggle matching, open circles show examples of matching sub-seasonal features. Squares show examples for possible melting processes.

Fig. 4. Interannual variability from 1980–1993 in accumulation and $\delta^{18}O$ from the ice core (black solid) and from the forward model (dashed grey line, weighted temperature). The aggregation of samples into annual mean values was done according to the wiggles indicated in Fig. 3.

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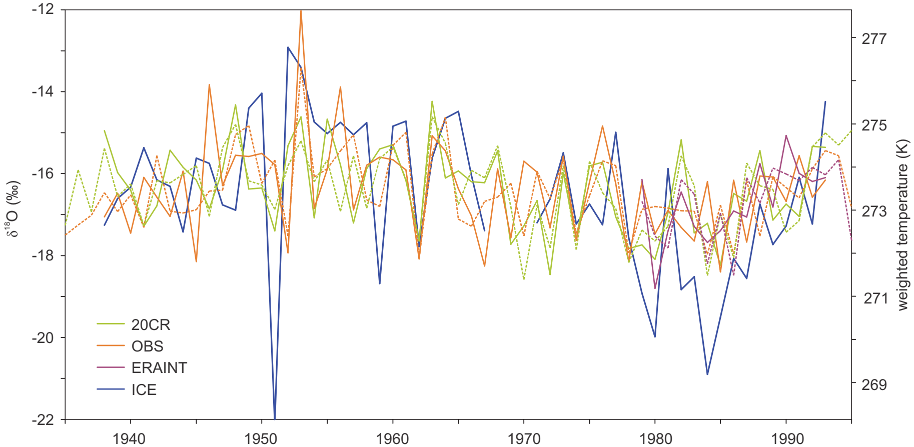

Fig. 5. Interannual variability of δ^{18}O from the ice core and weighted temperature from forward modelling (solid: cold point year, dashed: calendar year) based on different data sets.

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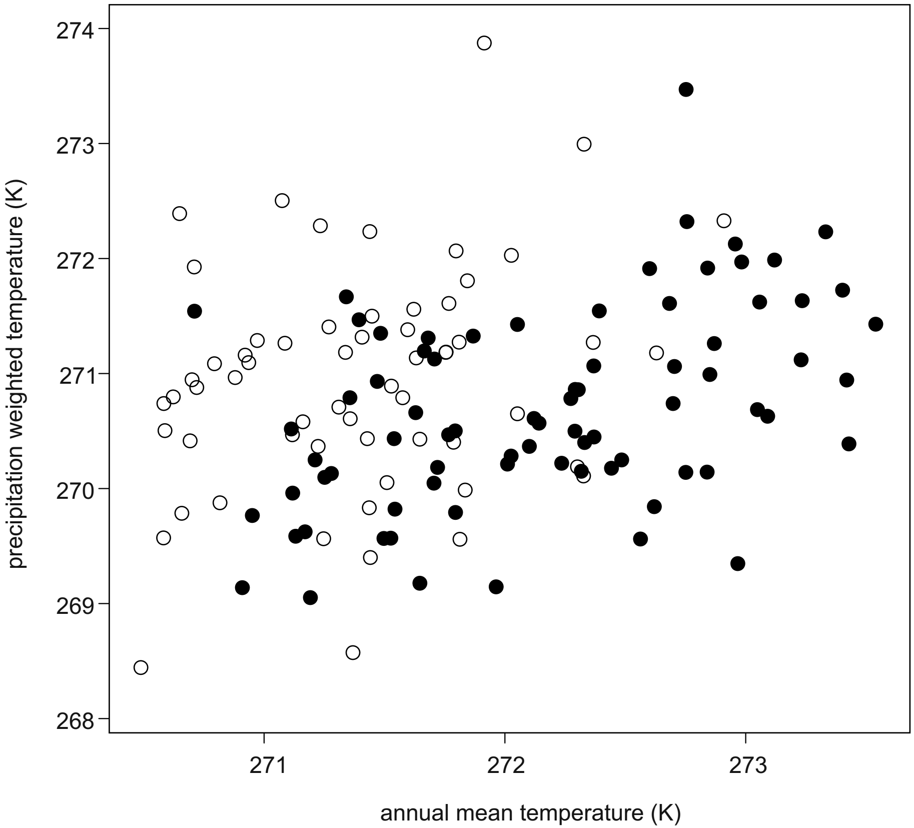

Fig. 6. Comparison of annual mean temperature versus precipitation weighted temperature based on daily data from the Gr. St. Bernhard in the periods 1864–1924 (open circles) and 1934–2010 (filled circles).

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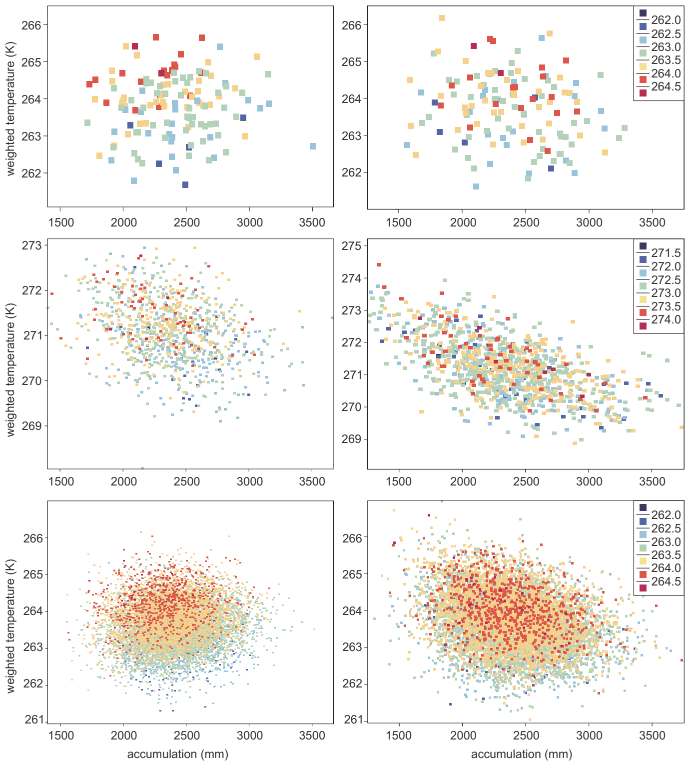

Fig. 7. Annual mean temperature (colour) as a function of A_{fwd} (accumulation) and weighted temperature in the artificial ices cores using the calendar (left) or cold point (right) year. Top: artificial ice core from 20CR. Middle: artificial ice core from a Monte Carlo resampling of the observations from the Gr. St. Bernhard, 1994–2010 (1000 realisations). Bottom: artificial ice core from the Monte Carlo resampling of 20CR, 1871–2008 (10 000 realisations). Note that the temperatures in the top and bottom row represent 600 hPa temperatures but in the middle row it is the Gr. St. Bernhard station temperature.

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