A statistical mass-balance model for reconstruction of LIA ice mass for glaciers in the European Alps

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ABSTRACT. Stepwise linear regression models were calibrated against the measured mass balance of glaciers in the Austrian Alps for the prediction of specific annual net balance and summer balance from climatological and topographical input data. For estimation of winter mass balance, a simple ratio between the amount of winter precipitation and the measured winter balance was used. A ratio with a mean value of 2.0 and a standard deviation of 0.44 was derived from the sample of measured winter balances. Climate input data were taken from the HISTALP database which offers a homogenized data source that is outstanding in terms of its spatial and temporal coverage. Data from the Austrian glacier inventory were used as topographical input data. From the group of possible predictors summer air temperature, winter precipitation, summer snow precipitation and continentality (as defined from seasonal temperature variation) were selected as climatological driving forces in addition to lowest glacier elevation and area-weighted mean glacier elevation as topographical driving forces. Summer temperature explains 60% of the variance of summer mass balance and 39% of the variance of annual mass balance. Additional factors increase the explained variance by 22% for summer and 31% for annual net balance. The calibrated mass-balance model was used to reconstruct the mass balance of Hintereisferner and Vernagtferner back to 1800. Whereas the model performs well for Hintereisferner, it fails for some sub-periods for Vernagtferner due to the complicated flow dynamics of the glacier.

INTRODUCTION

The mass balances of glaciers directly reflect climate on both local and larger spatial scales. Many factors contribute to local climate and consequently to the mass balance of an individual glacier. Some of them are of a very local nature. Such local variable driving factors can result in adjacent glaciers with remarkably different glacier behaviour (not only length changes but also mass balance), as in the well-known example of Hintereisferner and Kesselwandferner in the Alps (Kuhn and others, 1985). A model which describes the mass balance of a glacier in general is therefore difficult to derive. Nevertheless the large efforts for such a model are balanced by the added value to climate research. Beside the interpretation of glacier-geomorphologic features in terms of climate (if combined with an ice-flow model) and resulting paleoclimate reconstructions, a climate–mass-balance model can be used for physical plausibility studies of paleo-climate data. Finally, the mass balance of a glacier, which results from the interaction of various climate elements, is also a highly sensitive measure of climate change.

Many studies have investigated the relationship between climate and glacier behaviour in the Alps and elsewhere. For example, Oerlemans and others (1998) and Reichert and others (2001) used a combined mass-balance and ice-flow model to estimate changes of glacier length and validated the model against observed glacier length records. In turn, Oerlemans (2005) used measured glacier length records worldwide and a simplified version of a combined mass-balance and ice-flow model to reconstruct annual global temperatures back to 1600 and compared it to other temperature proxy reconstructions. Besides physically based models, different types of statistical models have been used for investigation of climate–glacier relationships (see the

review by Reynaud and Dobrovolski, 1998). This group of models includes degree-day approaches (e.g. Hoinkes and Steinacker, 1975; Braithwaite, 1981; Laumann and Reeh, 1993), simpler linear regression methods using monthly/seasonal/annual data of air temperature and precipitation (e.g. Kuhn and others, 1997) as well as neural network approaches (e.g. Steiner and others, 2005). Another promising approach consists in distributed (e.g. geographical information system (GIS)-based) mass-balance modelling for entire mountain chains (e.g. Machguth and others 2006). Although models based on physical laws should be the first choice for modelling the mass balances of glaciers, this group of models is limited if applied to long-term reconstructions. One major limitation for the application of physically based models comes from the lack of multiple meteorological input data, which is quite often overcome by parameterization (and consequently non-physical laws).

The European Alps represent a unique example in terms of climate information of the past from both direct (e.g. instrumental measurements) and indirect (proxy data) sources. Systematic instrumental measurements are available back to about 1750. They therefore cover the final part of the Little Ice Age (LIA) period, which is known to be systematically cooler by about 2°C compared to present-day climate. Moreover, in contrast to other regions elsewhere, three-dimensional evaluations of the lower troposphere of the Alps are possible from long-term instrumental series, using both lowland and high-elevation stations back to the early 19th century (Auer and others, 1998; Böhm and others, 1998). Applying long-term instrumental data, however, without any data processing is not useful. Many investigators showed that the potential of instrumental climate data can only be exploited if the data are subject to careful homogenization and quality control (e.g. Auer and others, 2006).
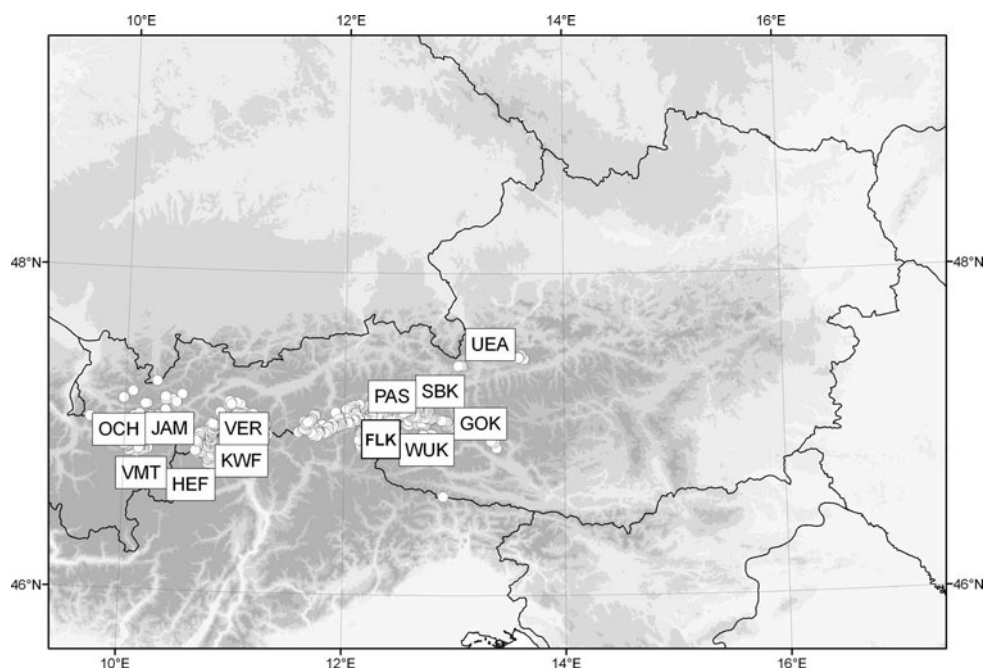
Fig. 1. Distribution of glaciers in Austria (white dots) and sample of glaciers with mass-balance measurements (UEA: Übergossene Alm; WUK: Wurtenkees; GOK: Goldbergkees; FLK: Kleinfleißkees; SBK: Stubacher Sonnblickkees; PAS: Pasterze; VER: Vernagtferner; HEF: Hintereisferner; KWF: Kesselwandferner; JAM: Jamtalferner; VMT: Vermuntferner; OCH: Ochsentaler Ferner).

Within the framework of the European Commission project ALP-IMP (www.zamg.ac.at/alp-imp), homogenization was applied on instrumental data of air temperature, precipitation and air pressure, respectively, from a dense network of climate stations covering the Greater Alpine Region (GAR; 43–49° N, 4–19° E). The primary step of data homogenization was followed by a secondary step of interpolation of the irregularly distributed time series from climate stations to gridded data series. The whole procedure of homogenization and interpolation to the final HISTALP database is described by Auer and others (2006). The spatial density of long-term climate station series only allowed the interpolation for climate anomalies and not for absolute values, because anomaly fields are much smoother compared to absolute value fields. Given that users of climate data are primarily interested in absolute values and not in climate anomalies, the gridded anomaly fields of precipitation were merged with the high-resolution gridded precipitation climatology of the Alps (cf. Frei and Schär, 1998). The resulting absolute fields of precipitation are part of the HISTALP database (for details see Efthymiadis and others 2006).

The primary goal of this study was to calibrate a statistical mass-balance model for a sample of Austrian glaciers. The HISTALP database enables it, for the first time, to drive such a model with homogeneous climate input data for the entire region of the Alps. In addition to climate, glacier topography is known as another important driving source of glacier mass balance. We therefore used data from the Austrian glacier inventory in 1969 (Patzelt, 1980) as an additional forcing of our model. Finally, the calibrated model is used to reconstruct a long-term series of glacier mass balances (summer, winter and annual) for a large sample of Alpine glaciers. Emphasis is put on the reconstruction of long-term mass changes of glaciers and not on precise modelling of individual annual mass balances.

CLIMATE DATA PRE-PROCESSING AND STATISTICAL MASS-BALANCE MODELLING

We developed a statistical mass-balance model which estimates glacier mass balance from major driving factors in the literature (e.g. Oerlemans and Hoogendoorn, 1989). The model therefore predicts mass balance from both climate data and glacier topography data. Winter accumulation and summer ablation are the dominant processes defining annual net balance of a glacier. Obviously, winter accumulation is strongly determined by winter precipitation. We argue that liquid precipitation during the winter period will refreeze within the snow cover and will consequently contribute to winter accumulation. Redistribution of snow by wind erosion/accumulation and avalanche activity, however, will significantly bias the relationship between winter precipitation and winter accumulation. Summer ablation is highly correlated to summer temperature because melting of snow and ice is the predominate process of ablation. The physical basis of the high correlation between summer air temperature and the energy balance during the melt season was discussed in detail by, for example, Braithwaite (1981) and Ohmura (2001).

Besides winter precipitation and summer air temperature, other factors affect the mass balance of glaciers in a significant way. The following factors are considered in our model:

Summer albedo of glacier surface which is captured by its relationship to the amount of snow precipitation during summer;

Continentality, which determines the sensitivity of the relationship between climate and glacier mass balance (Oerlemans, 2001). A simple estimation of continentality can be made from the difference between air temperature in July and January ($T_{Jul} - T_{Jan}$) as well as the annual

Table 1. Mass-balance measurements in the Austrian Alps

Glacier	Mountain region	Begin	End	Winter balance	Method	Institution
Stubacher Sonnblickkees	Hohe Tauern	1964		No	Direct (STR)	Institut für Geographie und Angewandte Geoinformatik, Universität Salzburg
Pasterze	Hohe Tauern	1980		No	Direct (FXD)	Tauernkraft, Zentralanstalt für Meteorologie und Geodynamik
Wurtenkees	Hohe Tauern	1983		Yes	Direct (FXD)	Zentralanstalt für Meteorologie und Geodynamik
Goldbergkees	Hohe Tauern	1987		Yes	Direct (FXD)	Zentralanstalt für Meteorologie und Geodynamik
Kleinfleißkees	Hohe Tauern	1999		Yes	Direct (FXD)	Zentralanstalt für Meteorologie und Geodynamik
Jamtalferner	Silvretta	1989		Yes	Direct (FXD)	Institut für Meteorologie und Geophysik, Universität Innsbruck
Vermuntferner	Silvretta	1991	1999	Yes	Direct (FXD)	Institut für Meteorologie und Geophysik, Universität Innsbruck
Ochsentaler Ferner	Silvretta	1991	1999	Yes	Direct (FXD)	Institut für Meteorologie und Geophysik, Universität Innsbruck
Hintereisferner	Ötztaler Alpen	1953		No	Direct (FXD)	Institut für Meteorologie und Geophysik, Universität Innsbruck
Kesselwandferner	Ötztaler Alpen	1953		No	Direct (FXD)	Institut für Meteorologie und Geophysik, Universität Innsbruck
Vernagtferner	Ötztaler Alpen	1965		Yes	Direct (FXD)	Kommission für Glaziologie, Bayerische Akademie der Wissenschaften
Übergossene Alm	Hochkönig	1965	1977	Yes	Direct (FXD)	Institut für Geographie und Angewandte Geoinformatik, Universität Salzburg

precipitation amount. The incorporation of continentality in the model is further motivated by the work of Schöner and others (2000).

Topographic characteristics of a glacier (lowest elevation, mean elevation, highest elevation, glacier area, maximum length, exposition) which significantly affect melt during summer as well as glacier dynamics. Moreover, altitudinal changes of the glacier snout and changes of the area-weighted mean elevation of the glacier alter the amount of precipitation to be captured as well as the energy balance during the melt season.

Glacier-topography input data used in this study were taken from the Austrian glacier inventory of 1969 (Patzelt, 1980). For this inventory, characteristics of all Austrian glaciers were derived from interpretation of aerial photographs (they were not only derived for 1969 but also for 1920 and 1850 from interpretation of moraines).

Other important data sources for calibration of the statistical mass-balance model are high-quality measurements of glacier mass balance. Schöner and others (2000) gave an overview of mass-balance measurements in Austria. Here we also deal with measurements of winter mass balance, which are quite sparse and much shorter in series length. The most detailed measurements are available from Wurtenkees (since 1983), a small glacier in the Hohe Tauern region. Longer time series are published from Vernagtferner (back to 1966) (Escher-Vetter and others, 2005), which were estimated from a less dense measurement network compared to Wurtenkees.

The geographical distribution of measurement sites is shown in Figure 1, and some metadata are listed in Table 1. It is obvious from Table 1 that many glaciers are only measured during the period of strong glacier retreat during the 1980s and 1990s. Very few glaciers were measured during the positive mass-balance years of the 1960s and 1970s. Consequently, calibration of any statistical mass-balance model of the Austrian Alps is likely to be biased to negative mass balances. Such model characteristics have to be taken into account if the model is used for long-term mass-balance reconstructions.

Summer air temperature is known to be the dominant predictor of summer melt (e.g. Ohmura, 2001). HISTALP, however, only provides anomaly fields of air temperature. As discussed earlier, Efthymiadis (2005) merged the HISTALP anomaly fields of precipitation with the high-resolution climatology of Frei and Schär (1998) to derive long-term fields of absolute precipitation. We use a similar approach to reconstruct absolute values of Alpine air-temperature fields from HISTALP anomaly fields:

$$T(t, x, y, z) = T_c(x, y, z) + T_a(t, x, y, z)$$

with T the absolute air temperature, T_c the 1961–90 climatology of air temperature, T_a the anomaly of air temperature from 1961–90 mean temperature, t time (monthly values), x, y geographical coordinates and z elevation.

Such an approach implies several important assumptions. Most importantly, it assumes that the climatology is a conservative quantity. Moreover, as we merged low-elevation anomaly fields with the climatology field to fully exploit the series length of instrumental data, the temperature model assumes identical temporal air-temperature trends for low-elevation (<1500 m a.s.l.) and high-elevation regions of the Alps. Based on the assumptions above, the mass-balance model now benefits from a long series of input data, enabling mass-balance reconstructions of Alpine glaciers back to 1800.

Because of our interest in the glaciated area of the Alps, we restricted air-temperature modelling to the altitude range higher than 1500 m a.s.l. For this purpose, quality-checked
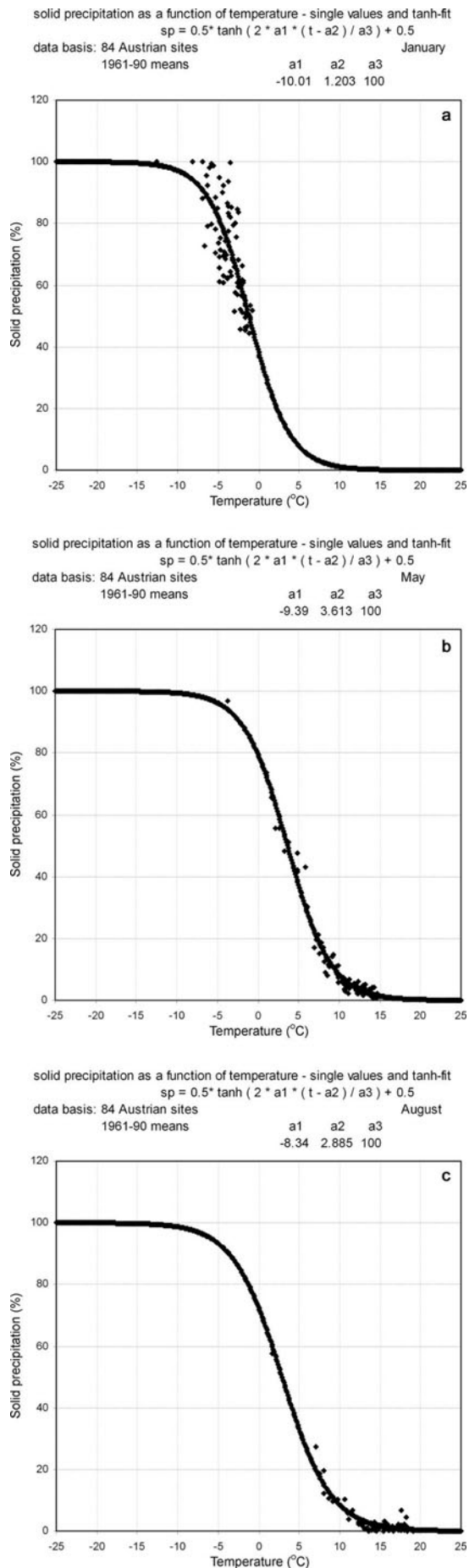
solid precipitation as a function of temperature - single values and tanh-fit
sp = 0.5* tanh (2 * a1 * (t - a2) / a3) + 0.5
data basis: 84 Austrian sites   January
1961-90 means   a1   a2   a3
                                      -10.01 1.203 100

solid precipitation as a function of temperature - single values and tanh-fit
sp = 0.5* tanh (2 * a1 * (t - a2) / a3) + 0.5
data basis: 84 Austrian sites   May
1961-90 means   a1   a2   a3
                                      -9.39   3.613 100

solid precipitation as a function of temperature - single values and tanh-fit
sp = 0.5* tanh (2 * a1 * (t - a2) / a3) + 0.5
data basis: 84 Austrian sites   August
1961-90 means   a1   a2   a3
                                      -8.34   2.885 100

Fig. 2. Curves of tanh fit between monthly air temperature and the fraction of solid precipitation in comparison to the measurements for January, May and August.

climate means (1961–90) of monthly air temperature were used from a climate station network of about 60 stations. A stepwise multiple linear regression method was fitted to predict monthly air temperature from elevation, longitude and latitude. Table 2 summarizes the results of this method. It can be seen from Table 2 that explained variances of individual months are quite high, in the range 87–98%.

In our model, the effect of summer snow albedo on mass balance is parameterized by the amount of summer snowfall. Such data are not available from HISTALP or any other data source covering the entire region of the Alps back to the 18th/19th century. We therefore used a statistical relationship between air temperature and the fraction of solid precipitation to compute monthly values of solid precipitation from air temperature and total precipitation. This statistical relationship is based on physical laws which include not only air temperature but also humidity and air pressure, for example. Hantel and others (2000) used a similar approach to model the number of days with snow cover from air-temperature data. Based on a dataset of 84 climate stations in Austria, a least-squares hyperbolic tangent fit was applied to predict monthly values of fraction of solid precipitation from monthly air temperatures:

$$\mathrm{FS}(t, x, y, z) = 0.5 \tanh\left[\frac{2a_1(t)(T(t, x, y, z) - a_2(t))}{a_3(t)}\right] + 0.5$$

with FS the fraction of solid precipitation and a_1, a_2, a_3 fitted monthly parameters.

The measurements from 84 climate stations and the fitted curve for the 3 month example are shown in Figure 2. It appears from Figure 2 that the model works well during summer but performs more weakly during December/January at cold sites (high-elevation sites). From these results we can expect accurate estimations of summer snow precipitation amounts from air temperature and total precipitation.

The mass-balance model can be driven by both climate and topographic input data, assumed to be highly related to glacier mass balance. These are: summer air temperature (May–September), winter precipitation (October–April), summer snow precipitation (May–September), annual total precipitation, continentality ($T_{\mathrm{Jul}} - T_{\mathrm{Jan}}$), lowest elevation of glacier, area-weighted mean glacier elevation, highest elevation of glacier, glacier area and greatest length of glacier. It is obvious from the quantities listed above that some driving factors of glacier mass balance are still not included (e.g. solar radiation, wind speed and wind direction). Such data are not available from instrumental series (at least not in proper data quality and at sufficient spatial resolution). Though solar radiation, as the primary energy source, is not included in the model, it is, however, parameterized to some degree by its correlation to air temperature.

In this study, mass-balance modelling is treated in two different ways. In model 1 we split the annual net balance into the components winter balance and summer balance. From this step we expect stronger statistical relationships between mass-balance and climate input data. For model 2 we directly relate annual net balance to the climate and topography of glacier sites. Finally, we introduced strengthening/weakening mechanisms in both models. We used a stepwise multiple linear regression procedure which only introduces predictors with a statistically significant contribution to the model. As an important restriction, such models only allow us to model linear relationships between

Table 2. Results of the stepwise linear regression model of air temperature predicted from altitude, latitude and longitude for altitude >1500 m (derived from a set of 60 Alpine climate stations for 1961–90 mean values). rmse: root-mean-square error

Month	Const.	Alt.	Lat.	Long.	R^2	rmse
Jan.	6.7	−0.0055		−0.134	0.91	0.75
Feb.	7.8	−0.0058		−0.181	0.91	0.78
Mar.	41.8	−0.0063	−0.705		0.94	0.71
Apr.	55.9	−0.0068	−0.919		0.96	0.62
May	63.7	−0.0066	−1.028	0.116	0.96	0.61
June	85.0	−0.0068	−1.409	0.144	0.96	0.62
July	81.1	−0.0068	−1.239		0.97	0.53
Aug.	72.7	−0.0064	−1.102	0.095	0.98	0.46
Sept.	38.0	−0.0061	−0.401		0.98	0.45
Oct.	0.3	−0.0056	0.326		0.94	0.61
Nov.	9.4	−0.0055			0.93	0.64
Dec.	6.4	−0.0054			0.87	0.91

Fig. 3. Ratio of winter mass balance to winter precipitation from measured winter mass balances of seven Austrian glaciers plotted against winter precipitation (winter precipitation as derived from HISTALP 1/6° gridpoint series).

predictand and predictors. Therefore, non-linear relationships either have to be treated in advance (e.g. the non-linearity between air temperature and fraction of solid precipitation) or cannot be captured by the model. Finally, it is important to point out that statistical models only find statistical relationships and not physical relationships (which are quite often confused in the literature).

Winter mass balance

Winter mass balance is strongly related to winter precipitation and to redistribution processes by wind and avalanches. To gain a better insight into the relationship between winter mass balance and winter precipitation, we analyzed data from all measured glaciers in Austria and compared them to the respective gridpoint winter precipitation taken from the HISTALP database. Several studies (e.g. Frei and Schär, 1998) have shown that Alpine monthly precipitation depends on altitude. We therefore adjusted the HISTALP 1/6° precipitation to the mean elevation of glaciers by using altitudinal gradients of precipitation taken from the high-resolution precipitation climatology of Schwarb and others (2001).

The ratios between adjusted winter precipitation and winter mass balances of all measured glaciers and all available years are shown in Figure 3. A surprisingly stable ratio was found, with a mean of 2.0 and standard deviation of 0.44. The ratio coincides with computed linear regression between annual net balance b of Hintereisferner and winter precipitation N_{wi} as well as summer temperature T_{su} from a nearby climate station, with $b = 4060 - 600T_{su} + 2.0N_{wi}$ (Kuhn and others, 1997). It has, however, to be taken into account that the sample of measured glaciers (7) is quite low in comparison to the total number of glaciers in Austria (925) and that the subset of measurements is short (maximum 40 years) compared to the length of time since LIA maximum extent in 1850.

Summer mass balance

After treatment of winter mass balance we used a stepwise multiple linear regression method to compute summer mass balance from the sample of climate and topographical predictors listed previously. Application of such an approach to one glacier would result in very high explained variance
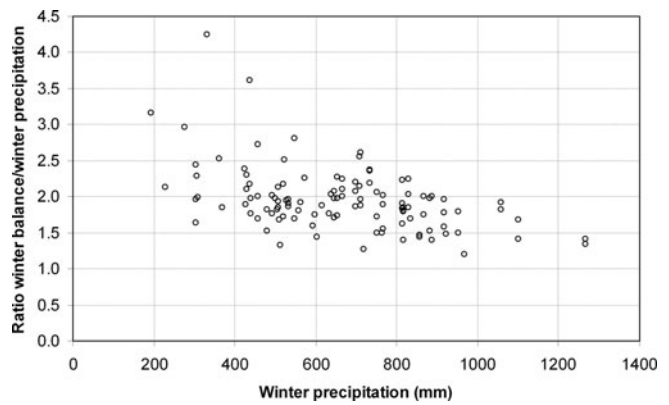
by the model. In this study, however, we want to explain summer mass balance in general for an arbitrary glacier by one model. From there we included all measured summer mass balances of all glaciers into one dataset and then applied stepwise multiple linear regression. Under the assumption of a sufficiently large (representative) sample from the population of all Austrian glaciers, this model should explain summer mass balance of an arbitrary glacier selected from the population of all Austrian glaciers. This comment already introduces possible shortcomings of the model, as the sample of measured glaciers with summer mass balance is biased towards a certain range of glacier types, namely the group of small-sized glaciers. Consequently we increased the sample size by computed summer mass balances which were derived by:

$$b_s = b - 2P_{win}$$

with b_s specific summer balance, b annual net balance and P_{win} winter precipitation.

Applying this method, summer mass balance was computed for Hintereisferner, Kesselwandferner and Pasterze, which introduces two large valley glaciers to the sample. The procedure resulted in a final sample size of 232 measurements. Results of regression computation are shown in Table 3 and Figure 4. Explained variance of the model is high (83%). Summer air temperature is the dominant predictor of the model (59%), whereas additional predictors account for 24%. Standard deviation of the modelled data is smaller (620 mm) compared to measurements (682 mm), resulting in a significant underestimation of maxima and overestimation of minima. Model bias is only 2 mm w.e. Application of the linear regression model to individual glaciers results in explained variances between 58% (Pasterze) and 91% (Goldbergkees). For Pasterze the inhomogeneous dataset of mass-balance measurements could be the reason for lower performance of the mass-balance model.

A simple sensitivity experiment was used to estimate the robustness of the calibrated regression model. Regression equations were fitted for different subsamples of measurements excluding individual glaciers from the sample. Some of these subsamples showed significant differences for the stepwise multiple linear regressions. From this finding we
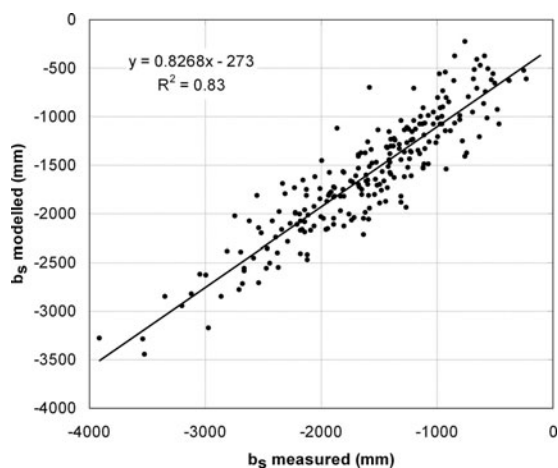
Fig. 4. Modelled vs measured summer mass balance from ten Austrian glaciers (the model used for prediction of summer mass balance is a stepwise linear regression).

Fig. 5. Modelled vs measured summer mass balance from ten Austrian glaciers. MOD1: computed by stepwise linear regression calibrated by annual mass-balance data; MOD2: computed as the sum of b_w (Fig. 3) and modelled summer mass balance (Fig. 4).

suggest that the sample of measurements is still too small and does not represent the population of Austrian glaciers sufficiently.

Annual net balance

Annual net balance was modelled by a twofold approach. First, the annual net balance was computed as the sum of modelled winter balance and summer balance. Second, stepwise multiple linear regression was applied for annual net balance using the same selection of climate and topographical predictors as for summer balance. On the one hand, computation of regression directly from annual net balance benefits from a much larger sample size of measurements. On the other hand, computation of regression directly from annual net balance could result in less sharp statistical relationships.

For reasons of comparison we estimated stepwise linear regression of annual net balance for the same sample of measured glaciers as for summer balance. As expected, the explained variance of the model of annual net balance is lower (70%) compared to the model of summer mass balance (83%). Summer temperature explains 39% of variance, and additional predictors account for a further 31%. Clearly, climate predictors as well as topographical predictors contribute significantly to the model.

We now compared annual mass balances computed from winter balances and summer balances (MOD1) with annual mass balances computed directly from climate and topographical data (MOD2) (Fig. 5). The explained variance of
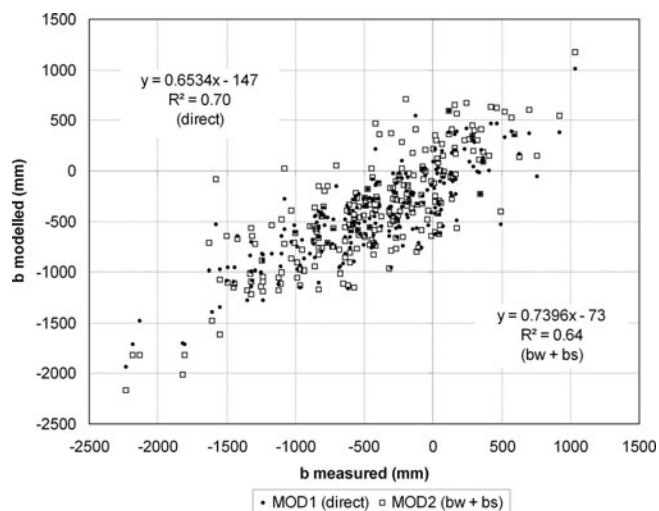
MOD1 is lower (53%) compared to MOD2. Computation of winter balance from winter precipitation appears to be too simple and shifts the good performance of the summer balance model to a systematic bias of MOD2 of 35 mm. Accumulated mass-balance values of MOD2 are therefore shifted towards too positive mass balances. The standard deviation of measurements (587 mm) is, however, captured much better by MOD2 (536 mm) compared to MOD1 (456 mm). Compared to other studies of mass-balance modelling of glaciers from climate data, our model does not perform better. A major result of this study, however, is that the model derived is applicable to a much larger sample of glaciers.

Two examples of time series comparing modelled mass balances with measurements are shown in Figure 6, namely for Hintereisferner and Kesselwandferner within the period 1952–2003, respectively. These two glaciers are a well-known example of adjacent glaciers with different mass-balance behaviour (Kuhn and others, 1985). For both glaciers, the mass balances are modelled well ($R^2 = 75\%$ for Hintereisferner and 66% for Kesselwandferner). Cumulative mass balances are about –26 m w.e. (Hintereisferner) and –1 m w.e. (Kesselwandferner) from the model and –24 m (Hintereisferner) and –3 m (Kesselwandferner) from the measurements. This result confirms the selection of parameters for topographic characterization of glaciers.

Table 3. Results of the stepwise linear regression model for summer balance, b_s, and annual net balance, b, calibrated from mass-balance measurements of Austrian glaciers. T_{sum}: summer air temperature May–September; E_{min}: minimum elevation of glacier; P_{win}: winter precipitation October–April; E_{mea}: area-weighted mean glacier elevation; P_{Ssum}: summer snow precipitation May–September; C: continentality $T_{Jul} - T_{Jan}$; R^2: explained variance; rmse: root-mean-square error

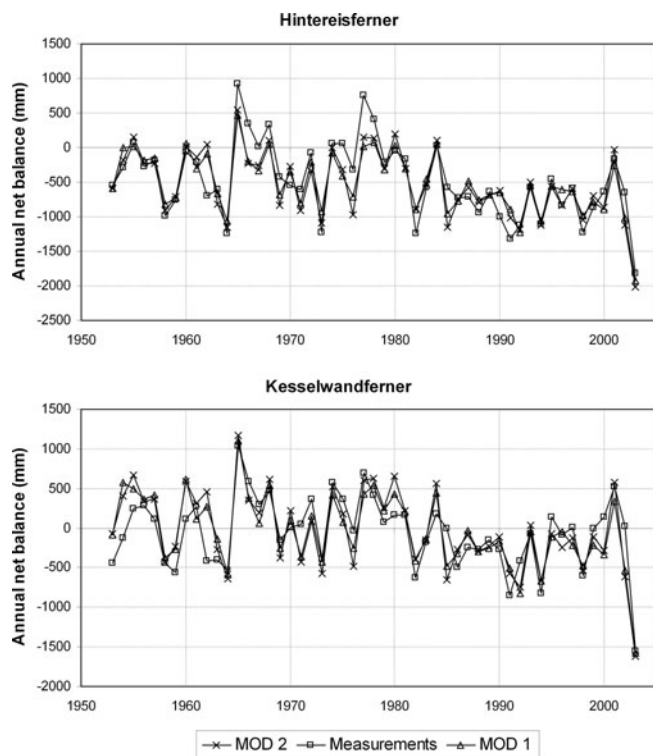|	Regression equation	R^2	rmse
			mm
b_s	$3140 - 450.48 T_{sum} - 3.01 E_{min} + 1.51 E_{mea} + 1.52 P_{Ssum} - 33.98 C$	0.83	287
b	$2779 - 376.45 T_{sum} - 2.82 E_{min} + 1.03 P_{win} + 1.50 E_{mea} + 1.88 P_{Ssum} - 30.64 C$	0.70	322

Fig. 6. Time series of measured and modelled annual net balance of Hintereisferner and Kesselwandferner. MOD 1: direct modelling approach; MOD 2: $b_w + b_s$.

Fig. 7. Validation of modelled mass balance (MOD 1 and MOD 2) against mass balances determined by geodetic method (GEO) and direct measurements (MEA) for Vernagtferner and Hintereisferner.

RECONSTRUCTION OF GLACIER MASS BALANCE AND MODEL VALIDATION

The calibrated mass-balance model is now used for reconstruction of mass balance back to 1800 for two glaciers in the Austrian Alps, Hintereisferner and Vernagtferner. These glaciers were selected because of their long data series of direct measurement of mass balance and because of the available long-term series of estimated changes of glacier height from interpretation of maps and aerial photographs. To fully exploit the potential of the climate and glacier topographical data, we implemented strengthening/weakening procedures in the model by adjusting air temperature and the fraction of solid precipitation due to changes in the minimum elevation of the glaciers. Real altitudinal changes of the glacier snout are not known, so we used simple linear interpolation of measured minimum elevations from the Austrian glacier inventory (1850, 1920 and 1969). It is obvious that such a simple interpolation can differ remarkably from real geometry (e.g. if a glacier moves over a steeper rock formation within a short period and approaches a flat part of a valley). Such differences between our simplified profile and real geometry can significantly alter the summer mass-balance term. For altitudinal adjustment of air temperature we used a constant vertical lapse rate of 0.006 K m^{-1}.

Figure 7 compares the modelled mass balances of Vernagtferner and Hintereisferner with both the measured mass balances and the computed changes in the height of the glacier surface from interpretation of maps (geodetic method of mass-balance estimation). For such a comparison, mass-balance estimations by the geodetic method imply some uncertainty, with error bars that are quite seldom dealt with. For both glaciers, the model underestimates the
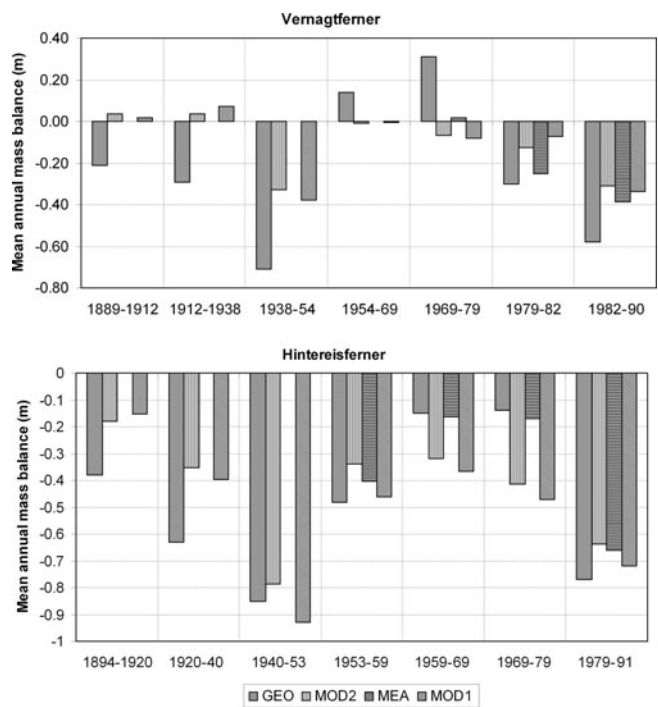
variance in mass balances. The model performs very well, however, for estimation of the total amount of mass change of Hintereisferner since 1894, which is –49 m from interpretation of maps and –50 m from the model. These values indicate an average of about –0.45 m a^{-1}, which is comparable with values derived for the Northern Hemisphere from cumulative length changes and a continuity approach (Hoelzle and others, 2003) and with Alpine mass-balance reconstructions far back in time (Haeberli and Holzhauser, 2003).

A striking feature of the model is that it shows a continuous mass loss since 1800 without any significant period of positive mass balances around 1820 and 1850 (which are known as common signals of Alpine glacier advance). This finding coincides with the model results of Greuell (1992) who showed that Hintereisferner retreated almost continuously since 1650. For Vernagtferner, the mass-balance model significantly underestimates cumulative mass balance since 1889 by 16 m (–8 m instead of –24 m from interpretation of maps). The low performance of the model for Vernagtferner probably results from the complicated bed topography and ice-flow dynamics of Vernagtferner. A rapid surge-like advance of Vernagtferner around 1900 is known from the literature (Hoinkes, 1969). Similar to Hintereisferner, model results of Vernagtferner show a period of almost continuous mass loss between 1800 and 1875 (with only a very short period of positive mass balances around 1820).

If HISTALP Alpine air temperatures are compared to the reconstructed Alpine air temperatures of Oerlemans (2005), a striking discrepancy can be seen before about 1870: reconstructed air temperatures are much too low compared to the instrumental measurements. The reconstruction of Oerlemans (2005) is supported in a way by reconstructed glacier mass balances from our study which would need

lower air temperatures to be shifted towards expected positive mass balances between 1800 and 1850. This finding requires more detailed evaluation by additional modelled glacier mass balances back to 1800.

CONCLUSIONS

A stepwise multiple linear regression model was used to estimate the annual mass balance of Alpine glaciers from a set of climate and topographical predictors. The model uses a homogenized dataset of climate input data (HISTALP) and the dataset of the Austrian glacier inventory in 1969 as input. It was calibrated with measured data of summer mass balance and annual mass balance. This is the first time that such a model has been derived from high-quality climate data of sufficient spatial coverage and of outstanding series length.

Results of stepwise fitting of a regression equation show that the model incorporates both climate and topographical predictors. Summer air temperature accounts for 60% of variance of summer mass balance and 39% of annual net balance, respectively. Further predictors incorporated by the model were the amount of summer snow precipitation, the amount of winter precipitation, the difference between July and January air temperature (continentality), the minimum elevation of the glacier and the maximum elevation of the glacier. These predictors increase the explained variance by 22% for summer mass balance and 31% for annual mass balance. The selection of predictors included in the model reflects the reasonable physical meaning for both climate and topographical factors.

Investigation of the ratio between winter precipitation and measured winter mass balance shows a surprisingly stable value of about 2.0. Applying this ratio for computation of winter mass balance from winter precipitation, however, introduces some noise in the final model results of annual net balance (sum of winter and summer balance).

The model uses temperature and precipitation gridpoint series data computed from anomaly fields of low-elevation sites (<1500 m a.s.l.), which implies that trends in air temperature and precipitation are identical for low-elevation and high-elevation sites. Though this assumption is motivated by instrumental measurements from high- and low-elevation sites back to about 1860, it requires critical evaluation, especially for the period before 1850. Although some strengthening/weakening effect was introduced into the model by adjusting air temperature by the respective shifts of the minimum elevation of the glaciers, and by adjusting resulting changes in the fraction of solid precipitation, the model still does not cover a variety of other adjustments and amplifying processes. For example, changes in precipitation resulting from temporal changes in mean elevation of the glacier are quite hard to handle, as vertical precipitation gradients are unstable in space.

Reconstructed mass balances from two Austrian glaciers show almost continuous mass loss between 1800 and 1850. Although the strength of this finding is restricted by the uncertainty of the mass-balance model, it shows a suspicious discrepancy between measured Alpine glacier behaviour and the mass balances modelled from climate data. Such systematic bias is also indicated by Alpine air temperatures reconstructed from glacier length by Oerlemans (2005), which are too cold compared to the HISTALP instrumental measurements.

In contrast to other glacier mass-balance models, the model in this study can be applied to an increased sample of Alpine glaciers. The extent to which the model can be fitted to all glaciers of the Alps needs further investigation. Validation of the model against mass changes determined by the geodetic method shows that some glaciers (e.g. the Vernagtferner, with complicated ice-flow dynamics) are not well captured for individual sub-periods.

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