A reconstruction of annual mass balances of Austria's glaciers from 1969 to 1998

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Abstract

We reconstruct annual glacier mass balances for 96% of the Austrian glacier covered area (451 of 470 km²) between 1969 and 1998. The volume change derived from two complete glacier inventories (1969 and 1998) serves as the boundary condition that we aim to reproduce. ERA40 reanalysis data as well as a gridded precipitation dataset (HISTALP) are used to drive a positive degree-day (PDD) model. The results are verified with four independent long-term mass balance series.

We alter the spatial and vertical distribution of the tuning parameters in order to reproduce the measured mean annual surface mass balances of selected glaciers and find a strong correlation between the median elevation of a glacier and the degree-day factor (DDF) at this elevation. The lower a glacier's median elevation, the less ice melt occurs at a given elevation and temperature. We attribute this to the fact that lower altitude glaciers are generally in regions with more winter precipitation, which leads to later exposure of bare ice and a longer period of high albedo snow cover.

A further improvement of the model was achieved by making DDF a function of time as well as space. Our results indicate that over the observation period mean DDFs generally increased which probably reflects the reduction in albedo that results from a sequence of consecutive negative mass balance years.

We finally investigate the major drivers of the observed mass balance evolution and found that anomalies of summer PDD-sums correlate significantly better to the observed mass balance changes than anomalies of annual PDD-sums or precipitation do.

Introduction

Mountain glaciers contribute considerably to observed and predicted sea level rise (e.g. Kaser and others, 2006; Lemke and others, 2007; Meier and others, 2007). In order to estimate this contribution, it is crucial to know glacier mass balances. Mass balance measurements are restricted to few glaciers worldwide, in total around 250 glaciers (Dyurgerov and Meier, 2005), and only about 85 data series last longer than 10 years (Braithwaite, 2002). Most glaciers for which mass balances are measured are chosen for accessibility reasons or by coincidence. However, they might not be representative of the mass balances of all the glaciers in a given catchment or mountain range, and simple extrapolation to other glaciers is known to be unreliable (Fountain and others, 2009).

Different methods have been used to model the total glacier mass balance of mountain ranges. Machguth and others (2009) used GCM-output to run an energy-balance model for all Swiss glaciers, and Schöner and Böhm (2007) applied a statistical approach to model the mass balance of a sample of Austria's glaciers as far back as the glacier maximum of the Little Ice Age. Hock and others (2009) estimate the world's glaciers' total contribution to sea level rise. It has also been shown that reanalysis data can be successfully used to reconstruct the mass balance history of individual glaciers (e.g. Rasmussen and Wenger, 2009; Radić and Hock, 2006).

We reconstruct the annual surface mass balance of 761 Austrian glaciers between 1969 and 1998, which is an important input for run-off modelling on a catchment or larger scale. We show that it is necessary to use temporally and spatially varying DDFs in order to accurately reproduce directly measured volume changes and their variations. Thirdly, we address the generalizability of directly measured mass balances, and finally, we investigate the meteorological factors that control each year's mass balance.

Study Area

The study area is the Austrian part of the eastern Alps (9°50' E - 13°40 E and 46°40' N - 47°35 N) where, in 1998, 910 glaciers covered a total area of 470 km² (Lambrecht and Kuhn, 2007). Fig. 1 shows a map with the glacier extent of 1998 and an ASTER Digital Elevation Model (DEM) of elevations higher than 2000 m in greyscale. The ASTER DEM is used for illustrative purposes only; our analysis was performed with photogrammetrically derived DEMs (see Data). Mass balances have been measured over the entire modeled time span for only four glaciers: Hintereisferner (HEF), Kesselwandferner (KWF), Vernagtferner (VF) and

Stubacher Sonnblickkees (SSK) (Schöner and Böhm, 2007). We use these glaciers (Fig. 1) to validate the model and provide the basic glaciological parameters given in Tab. 1. More information on the distribution of Austria's glaciers and its relationship to climate can be found in Abermann and others (2010).

Data

Glaciological data:

Two glacier inventories serve as glaciological input parameters for this study. Both were produced by aerial photogrammetry including glacier boundaries and DEMs (e.g. Gross, 1987; Lambrecht and Kuhn, 2007). Glacier area changes, which are necessary to compute annual surface mass balances, are approximated by assuming that the initial area (1969) remains constant until the year 1985 and then interpolating linearly to the final glacier area (1998). This pattern of area change does not account for glacier growth in the late 1970s and early 1980s but is similar to the mean glacier area changes of the studied period (Abermann and others, 2009).

Volume change (ΔV) is calculated by subtracting the 1998 DEMs from the 1969 glacier extent. We calculated the total balance B by

$$B = \frac{\Delta V_{1969-1998}}{\rho} \; [kg \; or \; m^3 w.e.] \qquad (1)$$

We assume that the whole volume change has occurred as loss of ice with a density of 900 kgm^{-3}. We are aware of the fact that the resulting B is the upper bound of the actual volume lost as some unknown fraction of the total volume change was lost as snow instead of ice. We discuss this uncertainty below (see Discussion).

Directly measured mass balance data of four glaciers that spans the entire investigation period (Tab. 1) was used to validate the model. Three of the glaciers are situated very close to each other in the Ötztal valley: HEF, KWF (Kuhn and others, 1985; Hoinkes and Lang, 1962; or more recently Fischer and Markl, 2008; Fischer, 2010) and VF (Reinwarth and Escher-Vetter, 1999; Escher-Vetter and others, 2009). SSK (Slupetzky, 1989; Slupetzky, 2003; or e.g. WGMS, 2007) is located in the Hohe Tauern and thus in a somewhat different climate (Abermann and others, 2010).

Meteorological data:

The model takes temperature (T), equivalent-potential temperature (θ_e) and geopotential height (Φ) as meteorological inputs. We use data from the 700 and 850 hPa levels of the ECMWF-ERA40 reanalysis project (Uppala and others, 2005), a dynamically consistent, three-dimensional, gridded dataset with a resolution of 1.25° that combines meteorological and satellite observations with a numerical weather forecast model and covers the period from 1957 to 2002.

The monthly Alps-wide precipitation dataset of the HISTALP-project has a spatial resolution of 10' of arc and includes homogenized weather station data (Efthymiadis and others, 2006). A comparison with rain gauges in high areas showed that the high Alpine precipitation is strongly underestimated, which is only natural, as the dataset was generated with data from valley stations only, (pers. comm. I. Auer) due to well known problems of precipitation measurement at high altitudes (e.g. Frei and Schär, 1998). The general precipitation anomalies tend to have similar values at high and at low altitude stations (Auer and others, 2005). We therefore chose to double the HISTALP-precipitation to generate reasonable precipitations for high Alpine areas. We also introduced a vertical precipitation gradient of 12 mm/100 m/month to a maximum elevation of 3300 m, above which we did not change the precipitation. This vertical gradient is larger than annual gradients given by Kuhn and others (1982). Winter precipitation consists mainly of advective precipitation (unlike summer precipitation, where convection plays an important role); we therefore expect larger vertical gradients for winter precipitation than for annual precipitation. Since accumulation is determined by winter precipitation, the chosen gradient best represented the observed vertical balance profile of selected glaciers. Monthly HISTALP-precipitation values are divided up into the time-steps where precipitation occurred according to ERA40 precipitation data and weighted accordingly. Combining magnitudes from HISTALP with the temporal resolution of ERA40 makes it possible to distinguish liquid from solid precipitation as a function of elevation for each precipitation event.

The Model

We applied a PDD-model as widely used in hydrological modelling (e.g. Hock, 2003; Kuhn, 2003; Hock, 2005; Huss and others, 2008 and references therein) to calculate ablation, with

$$b_{abl}(x,y,z,t) = DDF(x,y,z,t) * T_{>0,day}(x,y,z,t) \ [\text{mm w.e.}] \quad (2)$$

where DDF is used for calibration and $T_{>0,day}$ is the daily mean temperature above 0°C.

Accumulation is estimated by

$$b_{acc}(x, y, z, t) = P(x, y, z, t) * R_{0/1}(x, y, z, t) \ [\text{mm w.e.}] \quad (3)$$

where P is the precipitation and $R_{0/1}$ is a value that indicates whether the precipitation has fallen as snow or rain and can only have the values 0 (rain) or 1 (snow). $R_{0/1}$ is determined following a regression applied to observations using the equivalent potential temperature θ_e (Steinacker, 1983). Liquid precipitation is assumed to not contribute to glacier mass gain. Both ablation and accumulation are computed with a 6 hour timestep. Their sum gives the specific mass balance b.

The spatial and vertical dependence of DDF is a crucial point in the model and needs explanation. We first explain our approach towards the vertical dependence of DDF (dDDF/dz), and then show how we approached dDDF/dx and dDDF/dy.

The results of an energy balance model (SOMARS, for details: Greuell and Konzelmann (1994)) that was applied to two locations on HEF by Schrott (2006) were used to calculate a given season's mean DDF at two elevations. DDF was found to vary vertically by -0.32 mm w.e./(Kd) per 100m of elevation. This 'lapse-rate' of DDFs was extrapolated and used as the vertical dependence of DDF in the model. The vertically changing DDFs are in line with theoretical considerations by Hock (2003). On average over a melt season, the albedo of lower areas is smaller, so, for a given temperature, the energy added to a surface is higher, as more shortwave radiation is absorbed. This is independent of temperature and therefore not reflected in a simplified temperature-index approach.

In addition to the vertically varying DDFs, we introduce a spatial dependence with two dimensions: dDDF/dx and dDDF/dy. These are found by running the model iteratively with dDDF/dz as described above and with the condition that we must obtain the measured B of each glacier as had been previously calculated from the glacier inventories. Each individual glacier thus has its own set of DDFs that best represents the measured B.

The results of the first model run (Run I) for HEF are shown in Fig. 2a. Statistical values of Tab. 2 indicate that a similar quality of results was achieved for the other glaciers where we have cross-validation data (i.e. measured mass balance). Fig. 2a shows that the model approximates the pattern of glacier change. There is a clear temporal dependence of the

differences between measured and modelled balance. Until about 1987, measured balances are more positive than modelled balances, after 1987, this trend is reversed.

We investigated this result further by asking, which annual values do DDFs have to have on average to reproduce the measured mass balance of each year? This is shown in Fig. 3 where mean average DDFs are plotted over time. The average DDFs are calculated as

$$\mathrm{DDF}_{avg} = \frac{\mathrm{B_{ann,meas} - B_{acc,mod}}}{\sum \mathrm{PDD}} \left[\frac{\mathrm{m}}{\mathrm{K*d}}\right]. \quad (4)$$

Fig. 3 shows that there is an increase in DDFs over the observation period for all glaciers for which measured mass balance data exist, that is, at a given temperature, more melt occurs at later points in time. The increasing trend is statistically significant and its magnitude is similar for the four glaciers with complete mass balance data. The absolute values of mean DDFs are largest for VF, followed closely by KWF, significantly lower for HEF and lowest for SSK. For the three glaciers of the Ötztal Alps (HEF, KWF, VF), these differences are likely due to the influence of shortwave radiation, as the south facing VF and southeast facing KWF are expected to receive more short-wave radiation than northeast facing HEF (Tab. 1) and therefore have higher DDFs, a result that is consistent with previous research (e.g. Hock, 2005). SSK provides a valuable comparison as well: it is located in a different climate with significantly more precipitation (Abermann and others, 2010). More precipitation may cause a higher mean albedo and thus lower mean DDFs. We calculated a second order polynomial fit (PF) that best represents the mean of all DDF-increases and found that the overall increase is approximately 1.5 mm $K^{-1}d^{-1}$ over the 29 years observed.

In the second model run (run II), we introduced a DDF time dependence for each glacier in accordance with the findings of Fig. 3. DDF is thus a four-dimensional function of space and time. Fig. 2b shows measured and modelled balances as well as their differences with temporally varying DDFs for HEF. Both the trend and the amounts are better modelled than in the previous run. This is also shown in Tab. 2 in the mean absolute differences (MD_{abs}), mean signed differences (MD), standard deviations (STD) of the differences between measured and modelled balances and the correlation coefficients (R) between measured and modelled balances. With no exception, the second run gave better results; smaller MD_{abs}, MD and STD, and larger R. The MD values, which are for all cases small but largest for KWF (i.e. -0.17 at KWF), suggest that errors largely compensate for each other. The correlation coefficients between measured and modelled balance are highest for HEF (0.85) and lowest

for VF (0.75) and on average 0.81. They are all quite similar, which suggests that the model is applicable to glaciers of different types and that further analysis of the results is likely to be well-founded.

Results

The results of the model run with temporally changing DDFs for all Austrian glaciers for which two DEMs exist (761 out of 900 glaciers or 451 out of 470 km² or comprising 96% of the total glacier area) are shown in Fig. 4, which shows the evolution of modelled cumulative annual b with time for all glaciers (black lines). The wide spread of the curves is due to differences in glacier type and to the individual glacier's deviation from equilibrium. The red curves show the cumulative modelled b of the glaciers with directly measured mass balance, and the total, area-weighted cumulative mean specific mass balance is computed and displayed as a green line. Initially, the glaciers' masses remained constant. Starting in 1975, all glaciers show a period of positive mass balances, with a total gain of about 1.3 m w.e., which corresponds to an ice volume gain of about 1 km³. Since 1980, only a few years (e.g. 1984 or 1989) interrupt the generally negative trend. This temporal sequence is in agreement with the cumulative volume change derived from direct surface mass balance measurements as compiled for example in Abermann and others (2009).

In Fig. 5 we display the set of DDFs that best reproduced the observed glacier mass loss including the glacier’s median elevation (location of the circles) and the mean winter precipitation at the glacier (colours). Each thin line represents the DDF(z) of the run with temporally constant DDFs. For the run with the changing DDFs, each line was altered with time by approximately $1.5*10^3$m (i.e. shifted along the x-axis). There is a clear relationship between the median elevation and the DDF there. The higher the median elevation, the more melt generally occurs at a given temperature and given precipitation. We find two explanations for this apparent paradox convincing. First, glaciers usually exist at low median elevations (below 2700 m a.s.l., colours blue to yellow) because they generally accumulate more mass in the winter, through greater precipitation, more wind drift, more avalanching or some combination of the three. As a result, ice is kept under snow cover for a longer part of the ablation season and thus the albedo is comparatively high. Second, the increasing shortwave radiation with elevation results in higher general DDF values at higher elevations, as suggested by Hock (2003) or Lang and Braun (1990).

Discussion

The dependence of DDF on time is a major challenge when attempting to model future glacier change. As an example, consider the problem faced by a hypothetical modeller in 1975 who sought to model future glacier mass balance through 1998 using mass balance records from Fig. 2 since 1969. He could not have known the future time dependence of DDF, and any reasonable assumption would have resulted in a significant underestimation of ice loss, as is obvious from Fig. 2.

The subject of temporally changing DDFs has been addressed in a recent study by Huss and others (2009) who found a decrease in DDFs of approximately -7% per decade between 1970 and 2008. This seems to contradict the findings of this study but can be explained by the fact that Huss and others (2009) calculated point mass balance, and thus DDFs, at point locations that are all in the accumulation area. The increase in DDFs in our study amounts to about +9% per decade and must be understood as a collective signal for an entire glacier. Since mass balances in recent years have been governed by ablation, it is the ablation area and not the accumulation area that controls recent average DDF change. If we were to combine the findings of the two studies, it could be concluded that DDFs tend to increase over time in accumulation areas (Huss and others, 2009) where surface characteristics have not changed significantly, and decrease over time in ablation areas probably as a consequence of sequential negative balance years and thus albedo decrease. The second process is stronger as shown by the overall signal of Fig. 3. Two recent studies (Fischer, 2010; Oerlemans and others, 2009) support this conclusion, attributing the recent accelerated glacier retreat partly to albedo decrease.

This study has two important simplifications. First, we did not take into account the impact of basal melt. This volume loss is reflected in measured volume changes but not in the modelled surface balance as too little is known about its magnitude to accurately model it. Locally, this may be an important contribution to a glacier's mass loss but on average and compared to the surface mass loss we assume basal melt is negligible.

Our second simplification was the assumption that all volume was lost as ice. Several aerial photographs were examined qualitatively indicating that a fraction of the lost volume was snow. For a study of this scale, however, it was not possible to include a proportion of volume lost as snow to each glacier. Therefore, to estimate the possible impact on our results, we ran the model with the exaggerated assumption that half of the lost volume was snow with a density of 550 kgm^{-3}. The resulting total volume loss amounts then to 0.87 km^3 w.e. less

than that calculated for ice. The pattern of the cumulative mass balance as well as the modifications of DDF as a function of time and space do not change considerably and thus the results would be altered quantitatively, but not qualitatively.

The results and the data presented in this study allow for an estimation of the climatic influences that govern annual glacier mass balances. In Tab. 3 we summarize correlation coefficients between measured balances of the four well-studied glaciers and anomalies of PDD-sums for the whole year, PDD-sums for the summer (JJA), winter precipitation (ONDJFMAM) and summer precipitation, all of which are interpolated to the glacier's gridpoint from the HISTALP dataset. Deviations of winter and summer precipitation correlate only weakly with the measured balance. Annual anomalies of PDD-sums correlate much more strongly to surface mass balance than precipitation anomalies do. The strongest correlation between meteorological data and measured balances is found between summer anomalies of PDD-sums and the measured balance b (between -0.71 and -0.74), which is consistent with the results of Kuhn and others (1999), who examined this for Hintereisferner. All four glaciers have similar correlation values, but SSK shows a significantly higher correlation between summer precipitation anomalies and b than the other glaciers and HEF's balance is more sensitive to winter precipitation than the other glaciers'.

The results presented in Fig. 4 can be taken as a measurement of the generalizability of measured mass balance glaciers to all Austrian glaciers. HEF is much more negative than most and its b is therefore not representative for the overall mass balance of all Austrian glaciers. The specific balance of VF and KWF is close to the average, while SSK's mean specific balance is more positive than average.

Conclusions

We investigated the change over time of mean annual surface mass balance of all Austrian glaciers between 1969 and 1998. With a PDD-model with DDFs that vary in space (3D) we were able to reproduce the balances with correlation coefficients of more 0.8 on average. We found that it is necessary to run such a model with tuning parameters calibrated to each glacier individually and found a relation between the glacier's median elevation, mean winter precipitation and the DDF. We found that the model results were improved by introducing a long term time dependence of DDFs, specifically, a general increase over time. We suggest that this is due to a larger fraction of the glacier surface that exposes bare ice and thus has a lower mean albedo, which is consistent with a sequence of negative balance years and an

increase in equilibrium line altitude. Calibrating a PDD-model with only a few years of measurements and then extrapolating to the past or future seems extremely unreliable without additional knowledge (e.g. DEMs at various points in time). We are extending this study to include a new glacier inventory of 2006 (Abermann and others, 2009) in order to investigate how these parameters have evolved in the very recent past. This model could also be used to reproduce mass balances back to the Little Ice Age glacier maximum, for which information on extent and surface elevation could be reconstructed out of moraines, thus providing a fascinating picture of more than 150 years of glacier history.

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Tables

Table 1: Basic glaciological parameters for the glaciers used for validation of the model: Size, minimal elevation (z_{min}), maximal elevation (z_{max}), median elevation (z_{med}), main aspect of the ablation area, latitude and longitude as given in Lambrecht and Kuhn (2007) or Kuhn and others (2009) for 1998.

	size [km²]	z_{min}[m]	z_{max}[m]	z_{median}[m]	Exposition	lat [°]	lon [°]
HEF	8.4	2400	3710	2990	NE	46°48'	10°46'
KWF	4.2	2690	3500	3140	SE	46°51'	10°48'
VF	8.8	2760	3630	3080	SE	46°53'	10°49'
SSK	1.5	2490	3030	2760	E	47°08'	12°36'

Table 2: Mean absolute difference (MD_{abs}) and the mean signed difference (MD) between annually measured and modelled balances, the correlation coefficient (R^2), and the standard deviation (STD) of the differences for two model runs (Run I: constant DDFs, Run II: temporally changing DDFs following the findings of Fig. 3). MD_{abs}, MD and STD are in m w.e., R^2 is dimensionless.

	Run I				Run II			
	MD_{abs}	MD	R^2	STD	MD_{abs}	MD	R^2	STD
HEF	0.31	-0.03	0.75	0.35	0.22	-0.05	0.85	0.28
KWF	0.33	-0.16	0.70	0.37	0.30	-0.17	0.80	0.35
VF	0.34	0.10	0.60	0.44	0.28	0.08	0.75	0.38
SSK	0.41	0.10	0.72	0.54	0.35	0.07	0.81	0.45

Table 3: Summary of correlation coefficients of the following variables' anomalies against measured balances: winter (october - may) (δP_{winter}) and summer (JJA) precipitation (δP_{summer})as well as annual ($\delta\Sigma PDD_{year}$) and summer ($\delta\Sigma PDD_{summer}$) PDD-sums. Only the last two lines ($\delta\Sigma PDD_{year}$, $\delta\Sigma PDD_{summer}$) are statistically significant at the 99% significance level.

	HEF	VF	KWF	SSK
δP_{winter}	0.36	0.18	0.07	0.12
δP_{summer}	0.11	0.20	0.13	0.39
$\delta\Sigma PDD_{year}$	-0.66	-0.66	-0.59	-0.71
$\delta\Sigma PDD_{summer}$	-0.72	-0.69	-0.74	-0.78

Figures

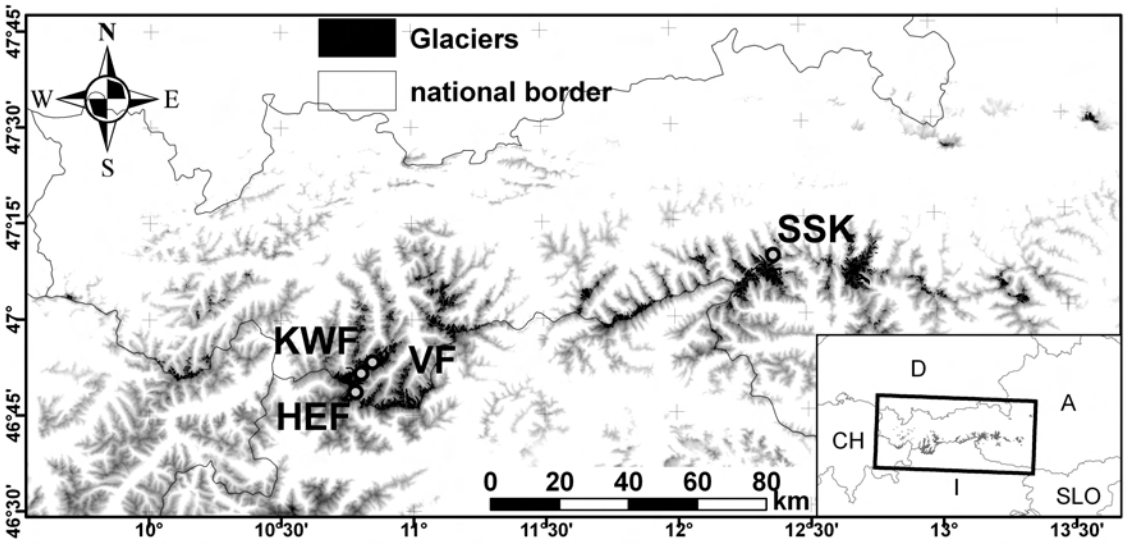

Figure 1: Glacier cover in Austria according to the glacier inventory of 1998 (Lambrecht and Kuhn, 2007). The glaciers HEF, KWF, VF and SSK are marked and an ASTER DEM in the background displaying elevations higher than 2000 m in a grey-scale.

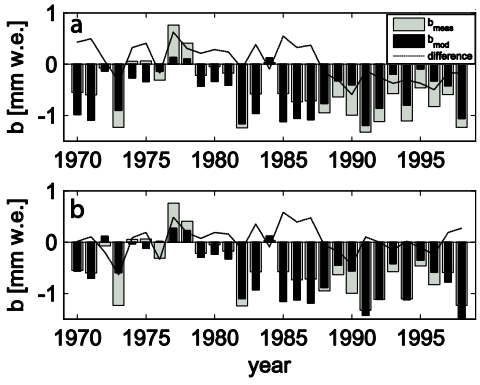

Figure 2: Measured and modelled mean specific surface mass balance b at HEF for two different model runs. Fig. 2a is calculated with constant DDFs over time, in Fig 2b, a temporally rising DDF-value is introduced based on findings of Fig.3.

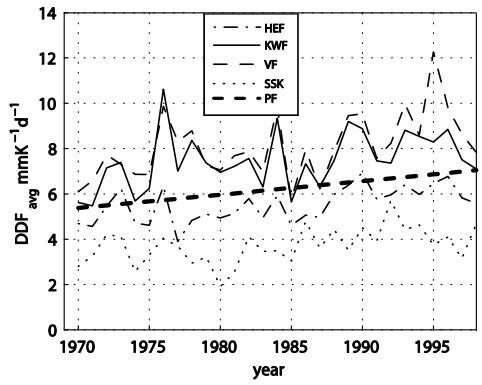

Figure 3: Mean area and elevation weighed DDF that reproduces best the measured annual surface mass balance of HEF, KWF, VF and SSK as calculated according to eq. 4. PF is the polynomial second order fit that is calculated in order to represent the mean of the glacier's individual values.

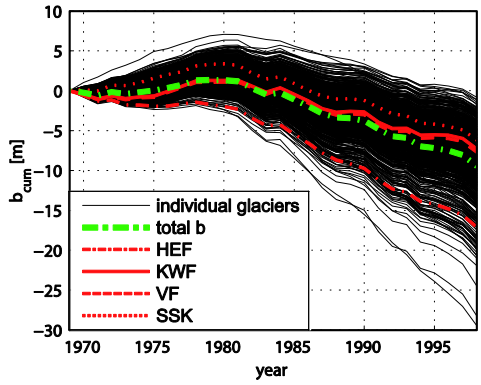

Figure 4: Cumulative mean specific surface mass balance of all Austrian glaciers for which volume change data exist (black lines). The red lines show modelled balances of the glaciers where direct mass balance measurements exist. The blue line refers to the right ordinate and shows the cumulative volume change of all Austrian glaciers.

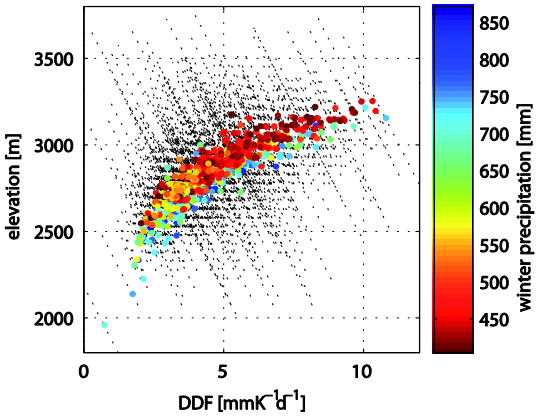

Figure 5: DDF as a function of elevation for each glacier (thin dashed lines). The colour of the dots show the mean winter precipitation at the glacier's coordinate according to HISTALP (October – May, colour scale), their location the DDF at the glacier's median elevation (left scale).