Water balance of the Vernagtferner high alpine basin based on long-term measurements and modelling

Heidi Escher-Vetter, Ludwig N. Braun, Matthias Siebers and Markus Weber
Commission for Glaciology, Bavarian Academy of Sciences and Humanities, Munich
www.glaziologie.de

Abstract

Long-term monitoring of the Vernagtferner (approx. 9 km²) annual glacier mass balance since 1964, along with measurements of precipitation and other climatological variables and discharge since 1974 at the gauging station “Pegelstation Vernagtbach”, are the basis of the data analysis presented here. In this Austrian high alpine basin with an area of 11.4 km² extending from 2640 m to a maximum elevation of 3630 m the mean annual precipitation amounts to about 1560 mm (20 % of which falls as rain and 80 % as snow), evaporation is estimated at 170 mm, mean discharge amounts to 1800 mm, a value that can only be maintained by a mean negative glacier mass balance of -400 mm with respect to the total basin area over the 29 years of record. While the Vernagtferner winter balances have remained more or less stable at a value of 1000 mm over the past 40 years, the summer balances show an obvious trend from values of -1000 mm in balanced years when measurements began, towards strongly negative values in the 1990s, culminating in the year 2002/03 with a record summer balance of -3000 mm, and a record basin runoff of 3300 mm. Using daily mean air temperature and daily precipitation sums as input, a conceptual runoff model can simulate daily discharge (R² about 0.90) and glacier mass balance (R² about 0.78) satisfactorily, suggesting a fraction of 30% of precipitation falling as rain and 70 % as snow. The highly transient runoff conditions necessitate the continuation of the monitoring efforts on a long-term basis, so that models predicting possible trends in water yield from high alpine basins under conditions of climate change can be validated.

Introduction

Comprehensive long-term observations over decades are needed in order to detect evidence of climate change during the past and in the future. Due to the “long memory” of the processes involved, it is necessary to provide information over a period long enough to explain the current evolution of glaciers as a reaction to climate variation. For this reason it is important that data series are continuous and homogeneous, requirements which are not easy to fulfil. For the determination of the water balance components, for example, the challenge lies in the reliable evaluation of the areal precipitation, estimation of evaporation, direct measurement of glacier mass balance and the continuous recording of the glacier runoff.

Figure 1: Pegelstation Vernagtbach situated at 2640 m a.s.l. with the climate station on the left. (Photo taken September 30, 2003).

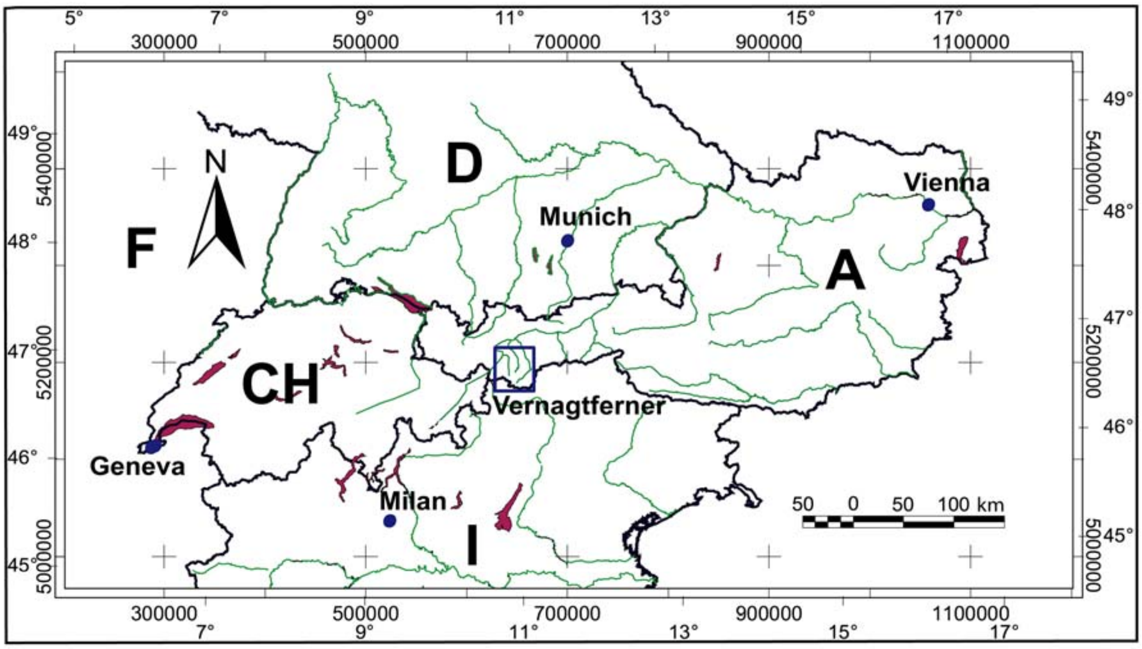

Figure 2: Location of the Vernagtferner basin in the Alps.

For the last parameter mentioned, the “Pegelstation Vernagtbach” (**Figure 1**) provides the means to obtain an accurate, long-term record of the total discharge of the Vernagtferner. This hydro-meteorological station is situated at 2640 m a.s.l. about 1.5 km downstream from the glacier terminus of the Vernagtferner in the Oetztal Alps (Austria). In **Figure 2**, the position of the catchment in the Alps is indicated with a rectangle on the map showing the major neighbouring states of this alpine region. For the Vernagtferner basin catchment (**Figure 3**) hydro-meteorological data have been recorded since 1974 as part of the glacier monitoring programme of the Bavarian Academy of Sciences and Humanities. The data set comprises meteorological parameters i.e. radiation, air temperature, humidity, pressure and wind velocity, while runoff and precipitation are the major hydrological ones. Even earlier, direct measurements of annual glacier mass balances were initiated in 1964, resulting in a data set spanning four decades of total glacier mass balance. Thus, the three quantitatively most important terms of water balance have been available since 1973/74. Initial results were already published for the period 1973/74 to 1984/85 by Moser et al. (1986). The analysis presented here was obtained with rather similar methods and extended to the period 1973/74 to 2002/03.

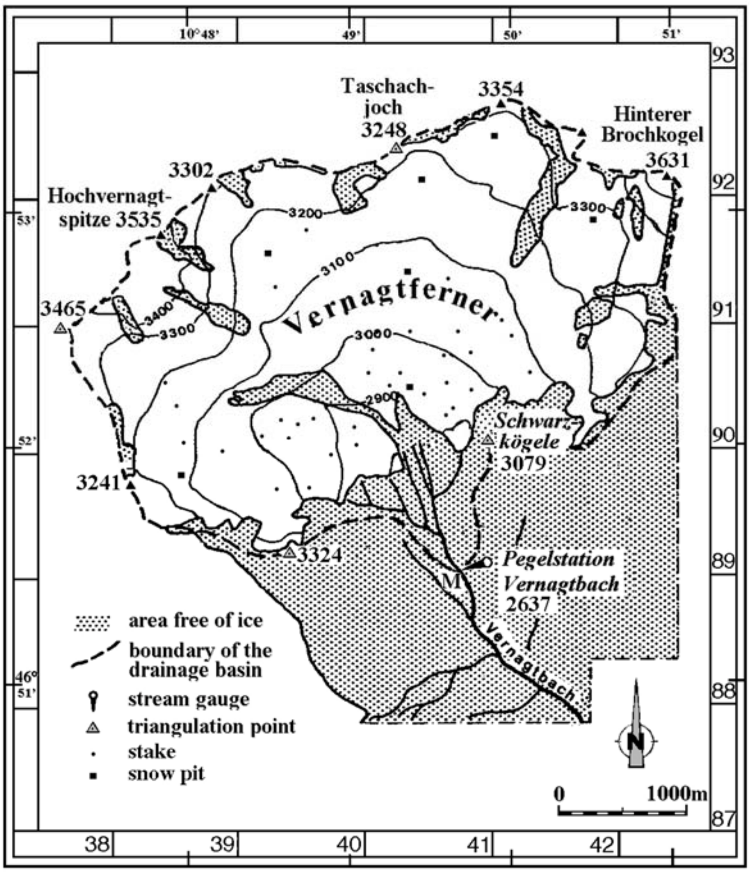

Figure 3: The Vernagtferner basin with position of recording sites and location of ablation stakes and snow pits. Basin area is 11.4 km².

For presentation of the data and discussion of the results, the “fixed-date” system for the glaciological year is applied as an averaging period, i.e., the time span from October 1 to September 30. The spatial analysis is performed for the whole basin of the Pegelstation Vernagtbach; thus the glacier-free area of the catchment has to be considered separately for determining the individual components. Due to shrinkage of the glacier, this part of the basin increased from 17% in 1964/65 to 25% in 2002/03.

Precipitation

In a high alpine, strongly glaciated catchment such as the Vernagtferner, the type of precipitation plays a major role in the determination of its amount and spatial distribution. Whereas the winter precipitation falls entirely in solid form in the Vernagtferner basin, the proportions of snow and rain vary considerably during summer. Therefore, the areal precipitation is determined separately for winter and summer seasons.

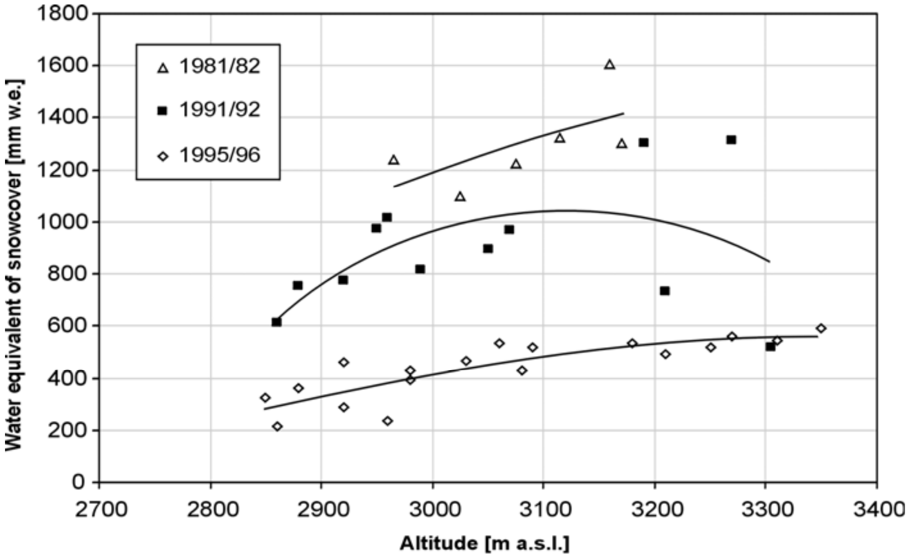

Figure 4: Altitudinal distribution of the snow-pack at the end of the accumulation period on Vernagtferner in three selected years (30 April 1982, 12 May 1992, 28 April 1996).

During the winter, all precipitation is conserved in the snow cover over the basin, minor evaporation losses can be neglected. Thus the determination of the water equivalent of the snow cover at the end of April delivers the seasonal integral of precipitation. On the glacier, the spatial distribution is analyzed with the aid of a large number of snow depth measurements and several snow pits (c.f. **Figure 3**), where the density of the snow-pack is determined. Then the altitudinal distribution of the water equivalent of the snow cover is interpolated with a quadratic function and integrated over altitudinal belts of 50 meters. **Figure 4** displays the altitudinal distribution for selected years. The maximum amount of winter precipitation lies typically in the middle part of the glacier, but in some years a nearly linear increase with altitude is observed. In the proglacial areas the variability of the snowpack is greatly increased, and for the sake of simplicity a value of 60% of the water equivalent from the lowest altitudinal interval is assumed, based on sporadic snow depth measurements and the extension of the precipitation records from the Pegelstation Vernagtbach.

During summer, no distinction is made between precipitation on the forefield and the glacier area but, as already mentioned, snow and rain is differentiated. This is based mainly on the air temperature records at the Pegelstation Vernagtbach and photographs of the glacier surface, which are taken daily around noon. A threshold of + 2°C as daily average at this lowest point of the basin is used to separate snow and rain, and if the photographs still show a snow-covered glacier at noon, the previous precipitation event is categorized as snowfall. For rain, the daily sums as recorded at the Pegelstation are increased by 20% to allow for measurement errors. No altitudinal gradient is applied afterwards, as these precipitation events are caused mainly by convective processes. In the case of snowfall, the correction factors for measurement errors given in the literature can be as high as a factor of 3 (Fuchs et al., 2001), mainly due to wind influences. As monthly means of wind velocities vary typically between 2.5 m/s and 3.5 m/s in the Vernagtferner basin, an increase of 100% is uniformly applied to the recorded amounts. **Figure 5** shows the time series of precipitation for winter, summer and the whole year. The uncorrected values as recorded at the gauging station are also included. Typically, precipitation is higher in the seven winter months than in the five summer months. Only for the years 1976/77, 1986/87, 1996/97 and 1998/99 the corrected summer values were slightly higher than or equal to the winter amounts. Neither winter nor summer values show a significant trend, but the winter amounts for the years 1974/75 to 1985/86 are distinctly higher than those for the period 1986/87 to 2002/03.

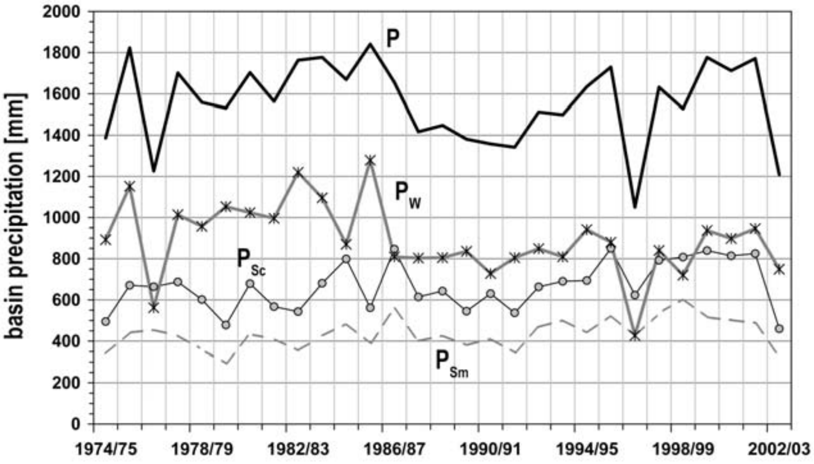

Figure 5: Winter P_w (October – April), Summer P_s (May – September) and annual precipitation P in the Vernagtferner basin for the period 1973/74 to 2002/03. P_{sm} refers to measured values at the gauging station, P_{sc} are the corrected ones (see text).

Glacier Mass Balance

Table 1: Mass balance values of the Vernagtferner for the period 1964/65 to 2002/03. No winter accumulation data are available for the year 1972/73.

Hydrological year	Winter balance	Summer balance	Annual balance
	mm w.e.	mm w.e.	mm w.e.
1964/65			751
1965/66	1570	-938	632
1966/67	1292	-1209	83
1967/68	677	-376	301
1968/69	616	-923	-307
1969/70	916	-1140	-224
1970/71	761	-1185	-424
1971/72	878	-741	137
1972/73			-455
1973/74	851	-621	230
1974/75	1131	-960	171
1975/76	613	-563	50
1976/77	1190	-838	352
1977/78	985	-697	288
1978/79	993	-949	44
1979/80	868	-728	140
1980/81	936	-991	-55
1901/82	1313	-2158	-845
1982/83	1081	-1618	-537
1983/84	870	-850	20
1984/85	1410	-1522	-112
1985/86	870	-1678	-808
1986/87	988	-1278	-290
1987/88	899	-1396	-497
1988/89	949	-1261	-312
1989/90	855	-1423	-568
1990/91	912	-1991	-1079
1991/92	947	-1805	-858
1992/93	895	-1367	-472
1993/94	1031	-2059	-1028
1994/95	979	-1377	-398
1995/96	486	-899	-413
1996/97	928	-1415	-487
1997/98	807	-1810	-1003
1998/99	1116	-1224	-108
1999/00	1079	-1366	-287
2000/01	1139	-1363	-224
2001/02	1013	-1279	-266
2002/03	986	-3119	-2133

The annual mass balance of the Vernagtferner has been determined using the direct glaciological method since 1964/65. Reinwarth and Escher-Vetter (1999) presented the total balance values for three sections of the glacier up to 1996/97, the actual discussion concentrates on the separation of winter and summer balance. The winter balance evaluation was already discussed within the context of winter precipitation (c.f. **Figure 4**). Melting during summer is assessed with the aid of ablation stakes (locations, see **Figure 3**), where the difference in height of the ice surface between 1 October of the previous year and 30 September indicates the ablation at the stake location. These data are collected at the end of each balance year and interpolated by an experienced glaciologist, keeping in mind the typical accumulation and ablation patterns and surface topography. The areal distribution of the total mass balance is then determined for the same altitudinal intervals as that of the winter accumulation. In addition, the independent evaluation of winter and annual balance allows the calculation of the summer balance as the difference between the two values (see **Table 1**). This separation facilitates the investigation of the causes for the present glacier development. The records as given in **Figure 6** indicate that the glacier shrinkage over the last decades does not primarily result from decreasing accumulation during winter but from summer balances which show a clear trend from -1000 mm w.e. in the 1960s and 1970s to some –2000 mm w.e. in the 1980s and 1990s, culminating in more than -3000 mm w.e. in 2002/03. The total balance for this year amounted to –2130 mm w.e., while in the lowest part of the glacier the ice lost 5.8 m in depth.

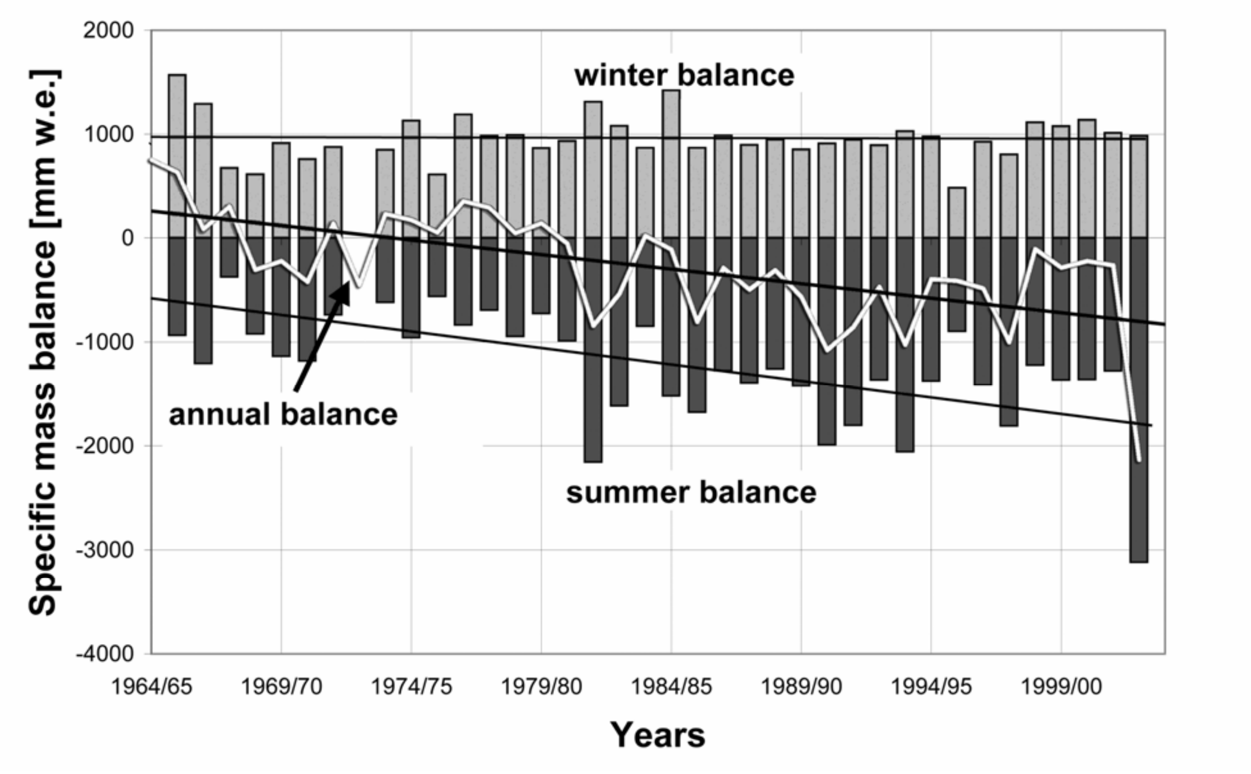

Figure 6: Winter, summer and annual mass balance of the Vernagtferner for the period 1964/65 to 2002/03. No winter data are available for the year 1972/73. The trend lines indicate the evolution of the individual terms. Glacier area varies between 9.6 km² in 1969 and 8.5 km² in 2002.

Runoff

As the Pegelstation Vernagtbach is positioned on a solid rock barrier, the recorded discharge comprises all the water drainage from the glacier. Several independent measuring and recording devices enable a near to uninterrupted discharge series on an hourly basis since 1974. The diurnal variations of discharge have increased over these thirty years due to strong glacier mass losses since 1980 and the thinning of the firn areas. In October 1995 and July 2000 the measurement channel of the gauging station had to be rebuilt to adapt the flow capacity to increased diurnal flood peaks. These structural adaptations were essential in order to protect the gauging station against flood damage (Reinwarth and Braun, 1998), in particular when strong melt was combined with intense rainfall. This was the case, for example, in the summers of 1987 and 1994, where the measurement channel was unable to capture total discharge. The estimated peak discharge was approximately 20 m³/s, whereas the highest recorded hourly value from melt water alone amounted to 15 m³/s on August 5, 2003. These values are contrasted by winter runoff data with only some 10 l/s, which is typical for the glacial runoff regime. On the whole, the annual sums of discharge have approximately doubled within the thirty years of the station's operation (see **Figure 7**). Whereas no hourly average surpassed the amount of 10 m³/s until 1992 (Escher-Vetter and Reinwarth, 1994), this limit was surpassed during 135 hours on 37 days in the summer of 2003. The annual amount of discharge volume of this exceptional year was 22% higher (3300 mm w.e.) than in the year 1993/94 (2600 mm w.e.), which until then was the year with the highest annual discharge.

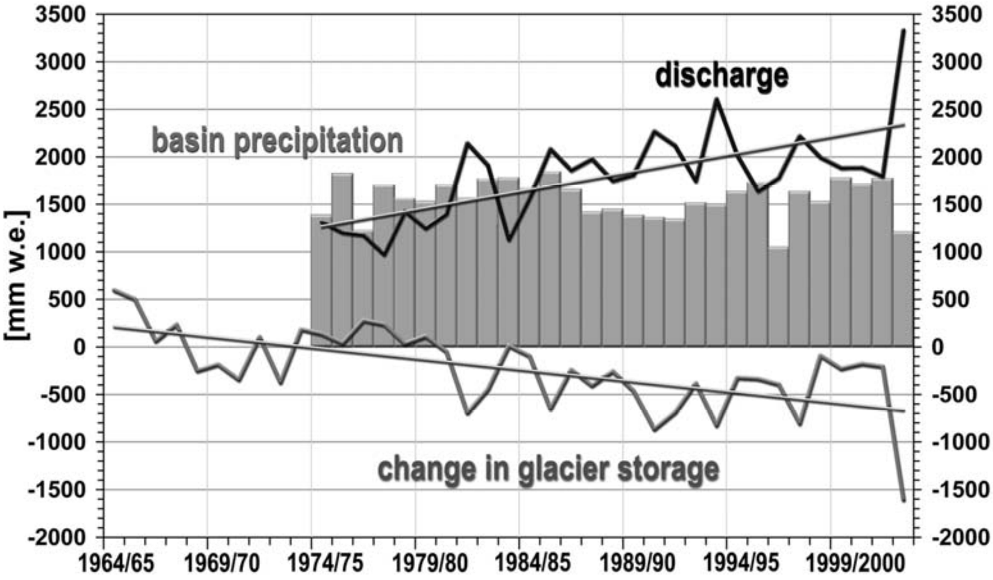

Figure 7: Selected terms of the water balance of the Vernagtferner drainage basin as based on direct measurements.

Evaporation

The remaining water balance term – evaporation, poses the greatest difficulties for continuous regional evaluation. At the gauging station, where records of air temperature, air humidity, radiation and wind velocity are available, the local evaporation rate can be calculated by using the energy balance method. For the glacier surface, the nearly all-year constant surface temperature of 0 °C partly facilitates the flux calculations. Therefore the latent heat flux was determined with this method for the summers of the years 1978 to 1985 during the special research programme “Runoff in and from glaciers” (Moser et al., 1986). The average over those 8 summers amounted to 157 mm with a range of 124 to 186 mm. Investigations on other glaciers resulted in evaporation values between 114 mm/a and 221 mm/a (Braun et al., 1994). For this study, a constant value of 170 mm/a is set for the evaporation losses. This value is slightly higher than the one determined with the energy balance method for the glacier surface itself, as it takes into account the higher surface temperatures on the non-glaciated parts of the catchment. Within two extensive field studies in the framework of the HyMEX-programme, turbulent fluxes were investigated directly on the glacier surface with eddy correlation and gradient methods (Weber, 2004). These results show that the associated mass and energy fluxes are rather small though very crucial for determining the glacier surface albedo and thus have a rather important impact on the radiation balance.

Modelling water balance components in glacierized basins

In the past decade numerous contributions have been put forth in literature dealing with the modelling of the water balance components in high mountain basins, where the melting of snow and ice plays an important role in runoff production. The calculation of melt is done either by a “pure” energy balance approach (Escher-Vetter, 2000; Klok and Oerlemans, 2003, among many others) or a temperature index method in a hybrid form including potential solar radiation as suggested by Hock (1998, 1999), which for example, allow the calculation of the diurnal variation in melt water production and the spatial distribution of glacier mass balance. The performance of the Hock hybrid temperature index method has been demonstrated recently by Strasser et al. (2004) at individual points on the Arolla Glacier, Switzerland, and by Verbunt et al. (2003) in the calculation of discharge in three Swiss high alpine basins of different levels of glaciation (Massa, Rhone and Dischma basins). This latter contribution discusses the altitudinal distribution of the terms snowmelt, ice melt, precipitation, evapotranspiration and total runoff for these three basins, and figures are given for basin precipitation, evapotranspiration, storage change (attributed to glacier mass balance), glacier runoff and total runoff for the period 1981 to

2000. Very good modelling efficiencies were achieved for runoff in all cases (R^2 of 0.92, 0.91 and 0.87 for the Massa, Rhone and Dischma basins, respectively).

The question is whether this good runoff modelling performance is achieved by adequate reproduction of all involved physical processes, or rather by error compensation of the individual model components. It is possible to clarify this is by comparing intermediate modelling results, such as calculated glacier mass balance, with direct measurements carried out in the Vernagtferner basin. In this study, the HBV/ETH runoff model was applied to calculate runoff as a response to accumulation and ablation processes. A detailed description of the original version is given in Bergström (1992), and the extensions for the special application in glacierized basins are described in Braun and Renner (1993) and Braun et al. (2000). The calibration of model parameters was based on measured discharge and glacier mass balance.

It was decided to use the “classical” temperature index (degree-day) approach using mean daily air temperature data in the calculation of snow and ice melt as an integral value over one day, and over individual elevation belts and exposition classes as follows:

$$\text{Melt} = \text{CMF}\ (\text{Tair} - \text{T0}) \qquad (1)$$

where

Melt is the daily melt rate (mm/d) of snow,

CMF [mm/d K] is the melt factor varying in a sinusoidal form between Cmin on 21 Dec. (minimum value) and Cmax on 21 June (maximal value), thus representing the varying length of daytime and therefore duration of melt,

Tair is the daily mean air temperature [°C] measured at 2 m above ground,

T0 stands for the transition air temperature between snowfall and rainfall as well as a general air temperature correction factor, e.g. due to adiabatic warming within catabatic flows.

To account for the enhanced melt rate over ice surfaces due to increased absorbed solar radiation, the multiplicative factor Rmult (>1.0) is applied to equation (1). The second multiplicative factor Rexp covers the influence of slope aspect on melt (> 1.0 for south-facing slope and 1/Rexp for north-facing slopes).

The optimal parameter values were determined by a trial-and-error procedure, using both discharge and glacier mass balance data. This multiple-response calibration and validation procedure is widely used in conceptual modelling to attain confidence in runoff generation processes (Uhlenbrook and Leibundgut, 2002). In the case of the Vernagtferner simulations CMF varies between Cmin = 0 and Cmax = 3.8, T0 was found to be - 0.5, Rmult = 1.4 and Rexp = 1.7.

An air temperature gradient of –0.0065 K/m was found reasonable, corresponding to the vertical gradient in the free atmosphere. The optimal correction factor for precipitation amounts was found to be 1.6 during rainfall (RCF) and 2.05 during snowfall (SCF). No additional elevational dependency of precipitation was assumed for the elevation range between the climate station and the glacier.

The model does not attempt to localize the spatial distribution of melt water production but to produce a reliable integral basin value of discharge, precipitation, changes in snow and ice storage, and evaporation. The original temperature index method has been shown to have a sound physical basis (Kuhn, 1984; Ohmura, 2001), and Weber (2004) was able to demonstrate that the method works especially well in the case where temperature data are collected at a station downvalley from the glacier. Here, there is a marked difference between air temperature over snow and glacier surfaces and the non-glaciated, snow-free areas as a result of the energy sink at the snow and ice surface due to melt.

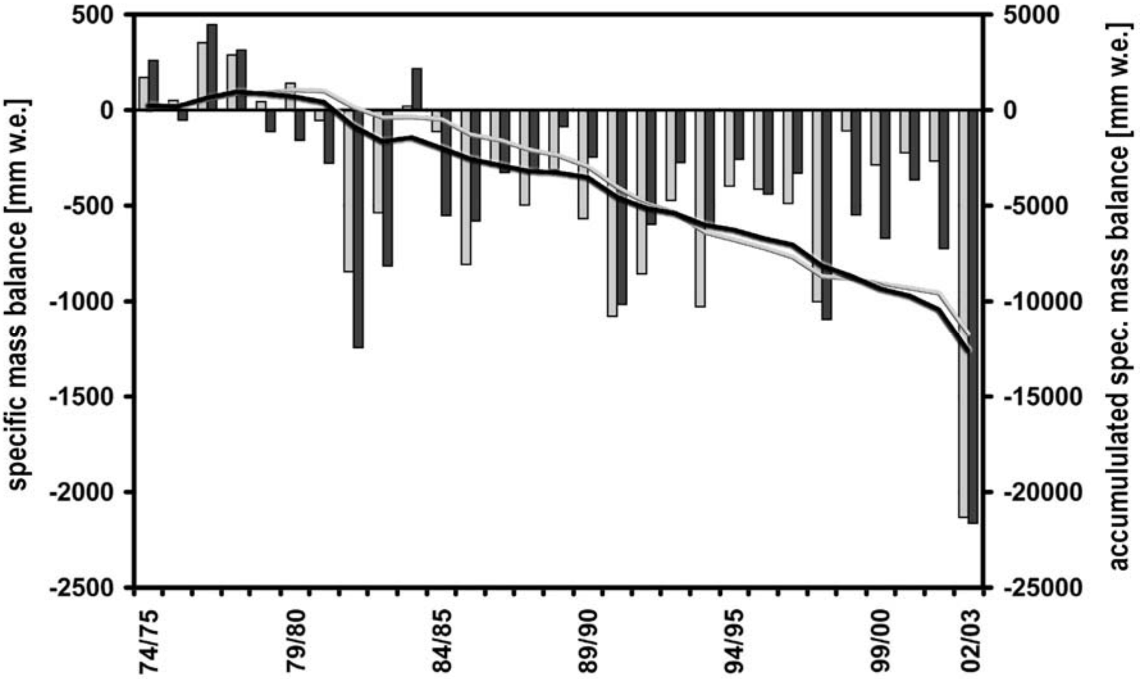

Figure 8: Measured (black) and modelled (gray) glacier mass balances of the Vernagtferner for the period 1964/65 to 2002/03. In addition to the annual values, the cumulative balances are also included.

In **Figure 8** modelled annual glacier mass balance values are compared with measured ones, along with the corresponding accumulated curves. Over the 29 years of record, 78 % of the variation in glacier mass balance is accounted for by the model, and the model yields a mean annual mass balance of –434 mm w.e., which is less than 10 % below the measured one (-400 mm w.e., also refer to **Table 2**). The standard deviations of modelled and measured values are practically identical (514 mm and 500 mm, respectively). It is worth mentioning that measured and modelled glacier mass loss of the exceptional year 2002/03 agree nearly perfectly, demonstrating that accumulation and ablation processes are both well represented in the model. In respect to mean annual discharge, the model underestimates the measured value by about 5% (**Table 2**). The mean Nash-Sutcliffe efficiency criterion (R^2-values) amounts to 0.87 for the calibration period (1974-1980) and 0.90 for the validation period (1980-2003) on the basis of daily runoff values. Modelled basin evaporation yields a mean value of 179 mm, which compares well to the assumed constant value of 170 mm for the "measured" values of the water balance terms.

Water balance – comparison of measured and modelled results

In **Figure 7**, all the terms of water balance – with the sole exception of evaporation – are presented for the last three decades. Basin precipitation is the only component showing no significant trend over this period, whereas the change in glacier storage leads to continuously rising discharge amounts. In this Figure, all the terms are based on measurements and extrapolations using the methods described. In **Table 2**, the overall averages of these records are given in the first line. For individual years the deviations are larger, but on the whole the results show that it is possible, at least in this small catchment, to evaluate all terms of the water balance on the basis of measurements with reasonable assumptions for the correction and spatial distribution of the measured quantities.

Table 2: Mean values (in mm w.e.) of water balance terms for the Vernagtferner basin (A = 11.4 km²) between 1974/75 and 2002/03 based on direct measurements (discharge and glacier mass balance), corrected measurements (basin precipitation) and model results from the conceptual runoff model HBV3-ETH9 (the residual in this case is the snow storage term). AP_{sol} represents the solid precipitation in winter and summer, AP_{liq} the liquid proportion in summer.

Method	Basin precipitation			Evaporation	Glacier mass balance	Discharge	Residual
	AP_{sol}	AP_{liq}	Sum				
Measurements or derived from measurements	1246	312	1558	170	-400	1800	-12
Runoff odelling	1061	459	1520	179	-434	1712	+ 63

Summary

The long-term monitoring programme of the Commission for Glaciology of the Bavarian Academy of Sciences and Humanities has produced a comprehensive database which assists the study of global warming impact on the hydrology of high alpine environments. The strong trend towards more negative summer mass balances makes it necessary to continue this monitoring and modelling effort in order to assess the consequences of glacier mass changes on runoff yield and flood potential (Braun and Weber, 2003). Complementary process-orientated studies such as those presented by Weber (2004) are necessary to gain further insight into the climate-glacier relationship.

Acknowledgements

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References

Bergström, S. (1992): The HBV model – its structure and its applications. *SMHI* RH No.4, April 1999.

Braun, L.N. and Renner, C. (1993): Application of a conceptual runoff model in different physiographic regions of Switzerland. *Hydrological Sciences Journal*, 37 (3), pp. 217 - 231.

Braun, L.N., Aellen, M., Funk, M., Hock, R., Rohrer, M.B., Steinegger, U., Kappenberger, G., Müller-Lemans, H. (1994): Measurement and simulation of high alpine water balance components in the Linth-Limmern head watershed (North-Eastern Switzerland). *Zeitschr. f. Gletscherkd. und Glazialgeol.*, Bd. 30, 161-185.

Braun, L.N., Weber, M. and Schulz, M. (2000): Consequences of climate change for runoff from Alpine regions. *Annals of Glaciology,* Vol. 31, pp. 19-25.

Braun, L.N. and Weber, M. (2003): Auswirkungen von Global Change auf Wasserspende und Hochwasserdisposition vergletscherter Gebiete. *Tagungsband „Tag der Hydrologie 2003: Klima – Wasser – Flussgebietsmanagement im Lichte der Flut“,* Institut für Hydrologie, Universität Freiburg i. Br., 20. & 21. März 2003. Forum für Hydrologie und Wasserbewirtschaftung, Heft 04.03, H.-B. Kleeberg (Hrsg.), Univ. der Bundeswehr, München, S. 95-103.

Escher-Vetter, H. (2000): Modelling meltwater production with a distributed energy balance method and runoff using a linear reservoir approach – results from Vernagtferner, Oetztal Alps, for the ablation seasons 1992 to 1995. *Zeitschr. f. Gletscherkd. und Glazialgeol.*, Bd. 36, 119-150.

Escher-Vetter, H., and Reinwarth, O. (1994): Two decades of runoff measurements (1974 to 1993) at the Pegelstation Vernagtbach/Oetztal Alps. *Zeitschr. f. Gletscherkd. und Glazialgeol.*, Bd. 30, 53-98.

Fuchs, T., Rapp, J., Rubel, F., and Rudolf, B. (2001): Correction of synoptic precipitation observations due to systematic measuring errors with special regard to precipitation phases. *Physics and Chemistry of the Earth series C (Solar, Terrestrial and Planetary Science)* 26 (9), 689-693.

Hock, R. (1998): Modelling of Glacier Melt and Discharge. *Züricher Geographische Schriften*, ETH Zürich, Heft 70, 126 p.

Hock, R. (1999): A distributed temperature-index ice- and snowmelt model including potential direct solar radiation. *Journal of Glaciology,* 45 (149), pp. 101-111.

Klok, E.J. and Oerlemans, J. (2002): Model study of the spatial distribution of the energy and mass balance of Morteratschgletscher, Switzerland. *Journal of Glaciology*, 48 (163), pp. 505 – 518.

Kuhn, M. (1984): Physikalische Grundlagen des Energie- und Massenhaushaltes der Schneedecke. *Mitteilungen Dtsch. Verband f. Wasserwirtschaft und Kulturbau*, 7, pp. 5 - 56.

Moser, H., Escher-Vetter, H., Oerter, H., Reinwarth, O. and Zunke, D. (1986): Abfluss in und von Gletschern. *GSF-Bericht* 41/86, Gesellschaft für Strahlen- und Umweltforschung mbH, München, 408 p.

Ohmura, A. (2001): Physical basis for the temperature-based melt-index method. *Journal of Applied Meteorology*, 40, pp. 743 - 761.

Reinwarth, O. and Braun, L.N. (1998): Structural adaptation of a high-alpine gauging station (Vernagtbach, Oetztal Alps / Austria) to greatly enhanced glacial discharge. *Proceedings of the International Conference on Ecohydrology of High Mountain Areas*, Kathmandu, Nepal, 24-28 March 1996, edited by S.R. Chalise et al., ICIMOD, Kathmandu, pp. 199-205.

Reinwarth, O. and Escher-Vetter, H. (1999): Mass balance of Vernagtferner, Austria, from 1964/65 to 1996/97: results for three sections and the entire glacier. *Geografiska Annaler*, 81A (4), pp. 743-751.

Strasser, U., Corripio, J., Pellicciotti, F., Burlando, P., Broock, B. and Funk, M. (2004): Spatial and temporal variability of meteorological variables at Haut Glacier d'Arolla (Switzerland) during the ablation season 2001: measurements and simulations. *Journal of Geophys. Res.*, Vol. 109, D03103, 18 p.

Uhlenbrook, S. and Leibundgut, Ch. (2002): Process-oriented catchment modelling and multiple-response validation. *Hydrological Processes*, 16, 2, pp. 423-440.

Verbunt, M., Gurtz, J., Jasper, K., Lang, H., Warmerdam, P. and Zappa, M. (2003): The hydrological role of snow and glaciers in alpine river basins and their distributed modeling. *Journal of Hydrology*, 282, pp. 36 – 55.

Weber, M. (2005): Mikrometeorologische Prozesse bei der Ablation eines Alpengletschers. Dissertation, Institut für Meteorologie und Geophysik der Universität Innsbruck, 311 S.