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RECONSTRUCTION OF MASS BALANCE AND RUNOFF OF VERNAGTFERNER FROM 1895 TO 1915

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With 9 figures and 2 tables

ABSTRACT

Mass balance and runoff of Vernagtferner were calculated by applying the conceptual runoff model HBV3-ETH9 for the 20 years between 1895 and 1915. Based upon the first accurate map of the glacier of 1889 by Finsterwalder and a photogrammetric survey of 1912 by Gruber, two digital terrain models were derived to determine the geodetic mass balance between 1889 and 1912. Due to the lack of measured runoff data, this mass balance was used to calibrate the model. Daily values of air temperature and precipitation on the glacier level could be derived from the meteorological recordings of two adjacent valley stations and were used to drive the model on a daily time step. The results of the modelling presented here show the development of mass balance and runoff on an annual time step.

REKONSTRUKTION VON MASSENBILANZ UND ABFLUSS DES VERNAGTFERNERS VON 1895 BIS 1915

ZUSAMMENFASSUNG

Die Massenbilanz und der Abfluss im Einzugsgebiet des Vernagtferners wurden mit Hilfe des konzeptionellen Abflussmodells HBV3-ETH9 für den Zeitraum von 1895–1915 rekonstruiert. Auf der Basis der ersten genauen Gletscherkartierung aus dem Jahre 1889 von Finsterwalder sowie eines Schichtlinienplans des Jahres 1912 von Gruber wurden zwei digitale Geländemodelle erstellt und aus diesen die geodätische Massenbilanz abgeleitet. Mangels gemessener Abflusswerte erfolgte die Kalibrierung des Modells über diese Massenbilanz. Tageswerte von Temperatur und Niederschlag auf Gletscherniveau konnten von den meteorologischen Aufzeichnungen zweier benachbarter Talstationen abgeleitet werden und wurden als Treiberdaten auf Tagesschrittbasis für das Abflussmodell verwendet. Die hier dargestellten Ergebnisse der Modellierung zeigen die Entwicklung von Massenbilanz und Abfluss in jährlicher Auflösung.

1. INTRODUCTION

The impact of glaciers on the hydrology of mountainous regions is crucial as the large ice bodies cause wide variations in the runoff conditions due to the storage capacity of precipitation in the form of snow and the melt water yield in warm and dry periods. Because of the strong relationship between climate and glaciers the predicted global warming will certainly also influence the glaciohydrological system and affect the living conditions of the inhabitants living downstream. Parallel to the rise in global mean temperature of 0.7 K, Vernagtferner in the Oetztal Alps has lost two-thirds of its ice mass during the last 150 years. The assessment of future glacial environments requires also a "glance at the past" in order to estimate the reaction of the glacier to modified climatological and meteorological conditions.

Vernagtferner has been under observation since the end of the 16th century due to the potential danger to the valleys downstream posed by glacial lake outburst floods of the glacier-dammed lake, "Rofener Eisstausee" (Richter 1888). The reconstruction of the glacier surface as of 1889 can be derived from the first accurate map of the glacier published by Finsterwalder in 1897. From the photogrammetric survey of the year 1912 by Gruber (unpublished) and other mappings in 1938 by Schatz (unpublished) and 1969 by Brunner and Rentsch (1972), the mass balance of Vernagtferner can be reconstructed using the geodetic method. In 1966 a seismographic survey of the glacier and the bedrock yielded the volume and mass of Vernagtferner (Miller 1972). Since 1965 the glaciological method of mass balance has been applied (Reinwarth and Escher-Vetter 1999), meteorological recordings and runoff measurements exist since 1973.

The topic of this paper is the application of the conceptual runoff model HBV3-ETH9 to the reconstruction of the glaciological and hydrological conditions shortly after the first topographic survey of the glacier, and the addition of another piece of the puzzle of mass balance history of Vernagtferner. The investigation period was limited by the availability of input data. The years around the turn of the 20th century are of special climatological interest as this early instrumental period offers, on the one hand, the first directly-measured records of atmospheric items (air temperature, precipitation) in good spatial and temporal resolution, while on the other hand, the observations show climatic conditions which were, for the most part, unaffected by anthropogenic influence.

2. METHODOLOGY

Figure 1 gives an overview of the methodological approach used in this study. The meteorological input data required by the model consist of daily means of air temperature and daily sums of precipitation, both measured at a station which is representative of the investigated catchment area. In former studies (Braun et al., 2000), data from the meteorological station "Pegelstation Vernagtbach" (2635 m a.s.l., cf. Fig. 2, briefly referred to as "Vernagt") built in 1973 were used. For the examination period of the survey presented here, records from the neighbouring valley stations of Vent (1906 m a.s.l., 6.6 km to the NE) and the monastery of Marienberg (South Tyrol, 1335 m a.s.l., 28 km to the SW) were available.

In a first step, the meteorological conditions at the Vent, Marienberg and Vernagt stations were analysed in a reference period (1974–88) which provided meteorological data for all three stations. The results made it possible to derive the statistical relations between the data sets of the stations which were used in a second step to extrapolate the valley stations' recordings to glacier level. The extrapolation methodology was based on simple linear regressions with the regression equations being calculated for every month separately, as this method provided the best adjustment on the seasonally differing weather patterns. The simple linear regression method provided a good agreement between extrapolated and measured daily temperatures at the glacier level with an average R^2-criterion of 0.96. In the case of daily precipitation sums, the explained variances between the meteorological relations were reduced due to the strongly structured high-alpine relief to an average level of 60 %. In addition, precipitation events at Vernagt could only be calculated for days with recorded precipitation in Vent. This produced a lower calculated precipitation on the glacier level than in reality. The differences between the measured and extrapolated daily precipitation sums were within an average range of ± 2 mm – deviations which are still acceptable for the model input data. The simple linear regression method was applied to extrapolate the summer precipitation, whereas winter precipitation was computed by a quotient method, since during the accumulation period, the exact dating of precipitation events for runoff modelling is less crucial than the monthly precipitation sum.

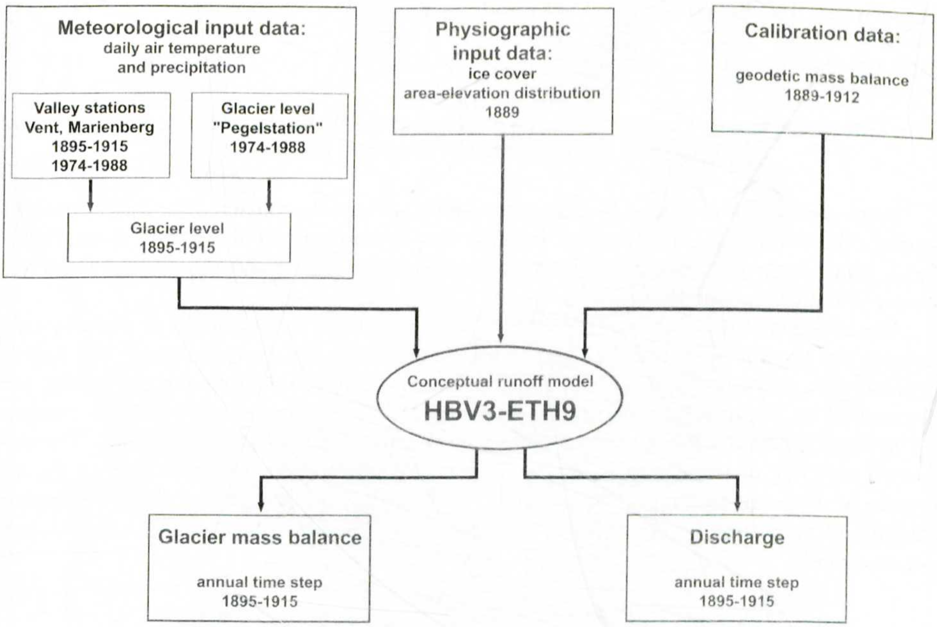

Fig. 1: Overview of the methodological approach for the reconstruction of mass balance and runoff of Vernagtferner 1895–1915

In general the meteorological data of the Vent and Vernagt station were more highly correlated than those of the Marienberg and Vernagt station, mainly due to their shorter geographical distance. Furthermore, because of their location on the south side of the Central Alpine Ridge, the precipitation records of Marienberg already indicate characteristics of a North Mediterranean precipitation regime, with secondary peaks in spring and autumn. Conversely, Vent and Vernagtferner show characteristics of a more continental climate regime of the central alpine environment with a single precipitation peak in July/August. The meteorological characteristics at glacier level were thus calculated mainly from the recordings at Vent, whereas the data from Marienberg were mainly used to fill the gaps in the series of measurements at the Vent station.

The physiographic characteristics of the catchment area required by the model are composed of the area-elevation distribution using elevation bands of 200 m equidistance and three exposure classes (South, North and East-West-Horizontal). These values were derived from the 1889 mapping by creating a digital terrain model and used for the whole modelling time interval. The extent of the catchment basin is controlled by the position of an ice cave at the lower end of the glacier tongue from which the subglacial water emerged (Table 1). This so-called "glacier portal" (Hambrey and Alean 1992) was used as a virtual gauging station (Fig. 2).

Table 1: Selected physiographic characteristics of the investigated catchment basin 1889 compared to the current conditions

Basin characteristics	1889*	1999*
Highest elevation (m a.s.l.)	3633	3633
Elevation band with the most significant area fraction (m a.s.l.)	3000–3200	3000–3200
Lowest elevation	2510	2635
Basin area (km^2)	15.04	11.44
Ice cover (%)	77.1	78.4

* The 1889 catchment area is based on the virtual gauging station at the glacier portal, the 1999 catchment area is based on the "Pegelstation Vernagtbach" gauging station.

In the absence of measured hydrographs, which are usually consulted for the purpose of model calibration, the geodetic mass balance was determined for the period from 1889–1912, based upon the topographic map of Finsterwalder (1897) and the photogrammetric survey of Gruber (unpublished).

The conceptual runoff model HBV3-ETH9 simulates the redistribution of mass by calculating the accumulation and melt for each elevation band and exposure class. The aggregational state of precipitation as well as the distinction between melting and re-freezing are determined by a temperature threshold parameter, and the amount of melt water is computed by the temperature-index method using a seasonally variable day-degree factor. The enhanced melt rate of ice in comparison to snow is also taken into account, as well as the influence of exposure on melting (Braun et al., 2000). All other processes leading to a redistribution of mass from higher to lower elevations (e.g., wind drift, avalanches, ice flow) are not considered.

3. RESULTS AND DISCUSSION

3.1 GEODETICALLY-DERIVED GLACIER MASS BALANCE

Volume and surface change between 1889 and 1912 could be deduced from the digital terrain models' data in a spatial resolution of 5 m (Fig. 3). Assuming a mean density in the top layer (the layer most affected by melting and snow accumulation) of 0.75 g/cm^3 (bare ice area 0.9 g/cm^3, firn area 0.5 g/cm^3), the average specific mass change between the two dates was calculated and used for calibration. The calculated changes in volume shown in Table 2 are confirmed by an analysis by Brunner and Rentsch (1972), whereas Hoinkes (1969) assumed a volume change of $-99 \cdot 106$ m^3.

Table 2: Changes of Vernagtferner between 1889 and 1912

	1889	1912	Difference
Area (km^2)	11.59	11.55	–0.04
Volume (10^6 m^3)	803	744	–59
Mass (10^6 t)	602	558	–44
Specific mass balance (mm w.e.)			–3840

The change of surface and volume between 1889 and 1912 derived by the subtraction of the digital terrain models shows a heterogeneous distribution on the glacier area (Fig. 3).

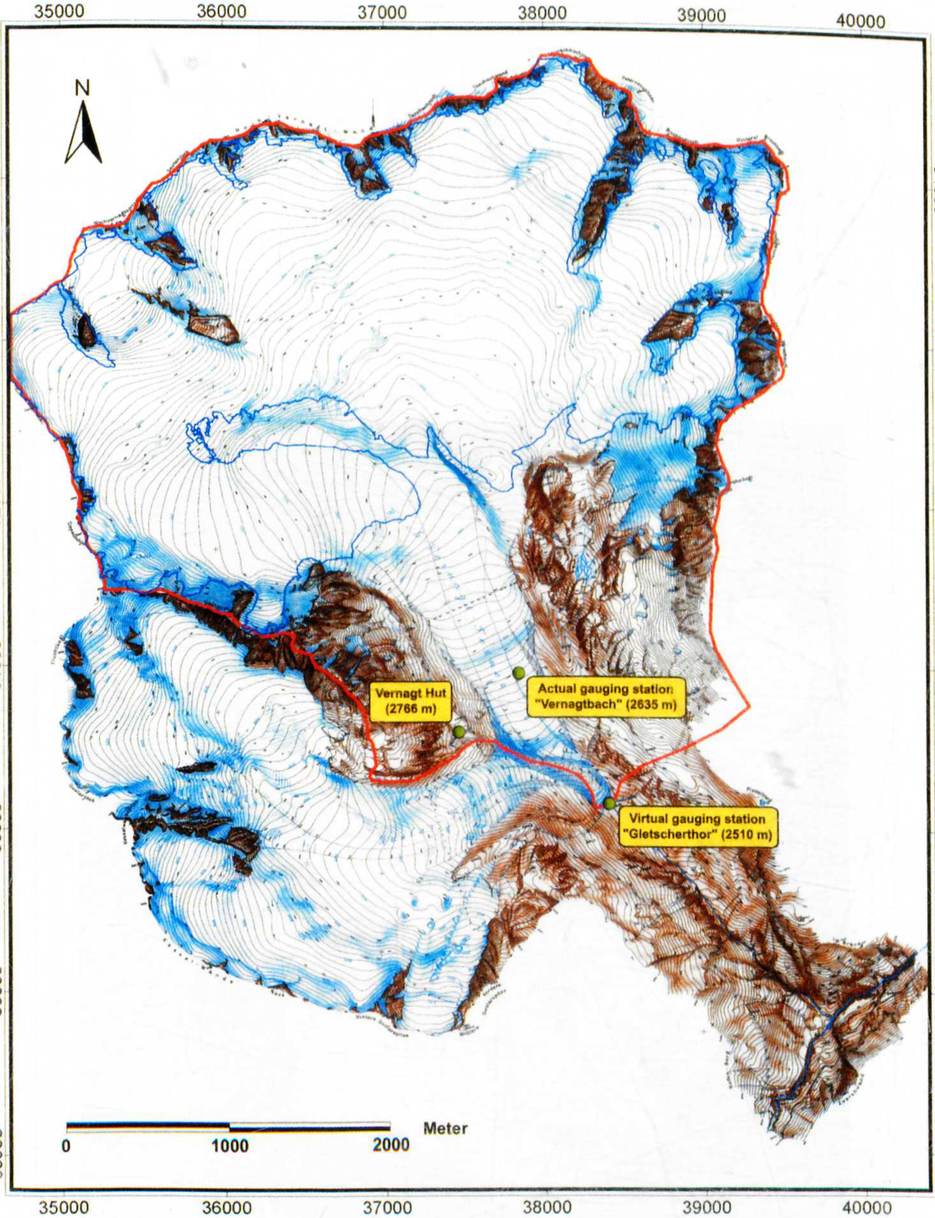

Fig. 2: Vernagtferner in 1889. Modified from the topographic map "Der Vernagt Ferner im Jahre 1889" by Finsterwalder (1897)
The red outline shows the limit of the catchment area based on the virtual gauging station "Gletscherthor", the blue outline marks the present extent of glaciation (1999).

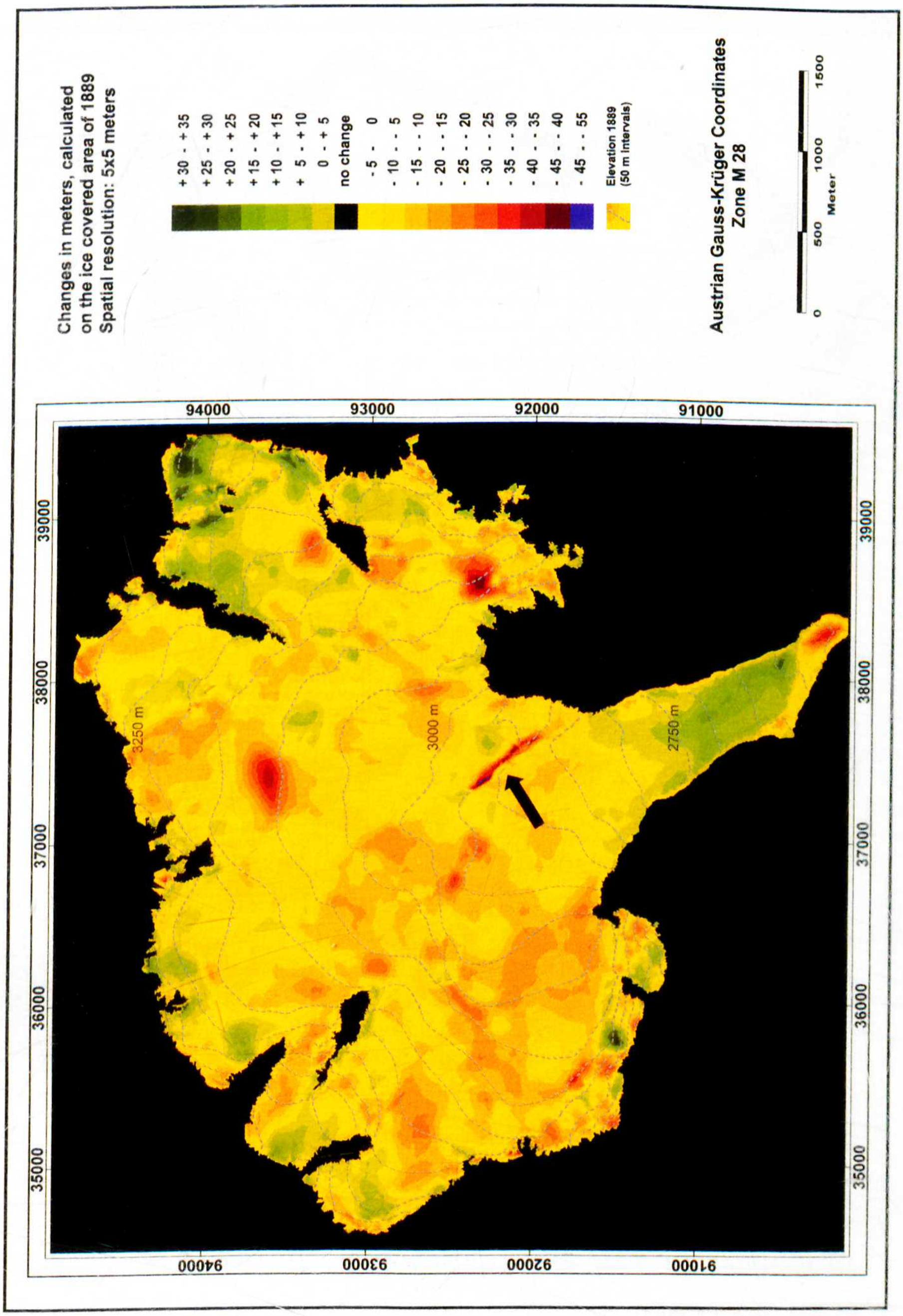

Fig. 3: Change of surface elevation of Vernagtferner between 1889 and 1912, based on the topographic map of Finsterwalder (1897, 1:10.000) and the photogrammetric survey of Gruber (unpublished, 1:10.000)

The increase of mass at the glacier tongue (below 2800 m a.s.l.) is contrasted with a loss in the accumulation area. This observed redistribution of mass was certainly not caused by climatic forcing but by the dynamics of the glacier: between 1898 and 1902 a minor surge took place at Vernagtferner with a maximum velocity of 280 m/year (Finsterwalder and Hess 1926).

Figure 3 also shows some indications of the morphology of the bedrock: zones of high surface lowering (labelled by an arrow) correspond with an underlying rock face. Finsterwalder and Hess (1926) reported on a rupture in the ice flow ("rock window") which appeared right at this place between 1910 and 1912.

3.2 HYDROLOGICALLY-MODELLED GLACIER MASS BALANCE

In comparison with the geodetic method, hydrological modelling offers a higher temporal resolution of the glacier mass balance as it yields annual values. According to the results displayed in Figure 4, three phases of mass balance development can be distinguished at Vernagtferner between 1895 and 1915:

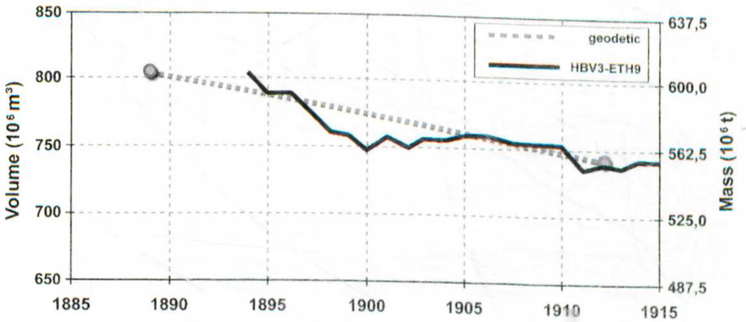

Fig. 4: Cumulative specific mass balance of Vernagtferner simulated by the HBV3-ETH9 model in comparison with the result of the geodetic method. Estimated mean density of the top layer: 0.75 g/cm^3

(I) a period of high losses between 1895 and 1900,
(II) a plateau phase with moderate losses and slight mass increases from 1900 to 1915, which was interrupted by a
(III) singular heavy loss in 1911.

Altogether, 13 of the 19 simulated hydrological years feature negative mass balances with only 6 years of increase. The average annual mass balance is − 195 mm w.e.

The annual mass balances (b) as well as the accumulation area – total area ratio (AAR) show a very good correspondence with the climatic conditions (Fig. 5). Due to the area-elevation distribution of Vernagtferner, the AAR offers a better correlation to the mass balance than the also simulated equilibrium line altitude (ELA) does (Reinwarth and Escher-Vetter 1999). For this reason only the AAR is displayed in Figure 5. The AAR was calculated by the following equation which was derived from a comparison of present-day values of directly measured mass balance with the AAR:

$$AAR = 0.001 \cdot b + 0.68$$

which yields the AAR as a percentage when b has the unit mm w.e.

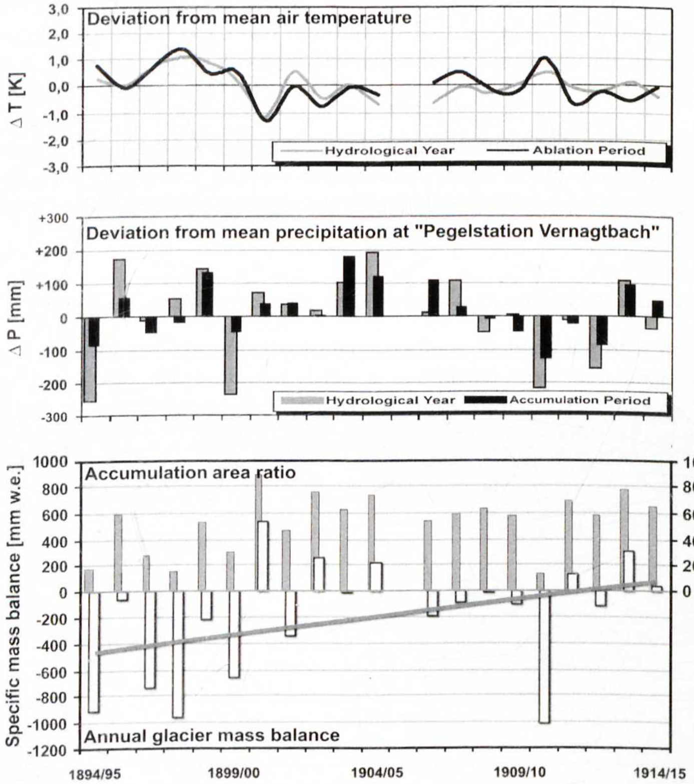

Fig. 5: Simulated annual mass balance and accumulation area ratio of Vernagtferner, set against normalized precipitation sums of the hydrological years and accumulation periods and normalized mean air temperatures of the hydrological years and ablation periods. The normalization is based on the mean air temperature and annual precipitation sum of the investigation period 1895 to 1915. Due to the lack of recorded meteorological input data, no results could be calculated for the hydrological year 1905/06.

The years with negative mass balances before the turn of the century can be attributed to the above-normal air temperature both during the hydrological years (Oct.-Sept.) and the ablation periods (May-Sept.). In these years the AAR takes on values between 16 % and 64 % (average for 1895 to 1915: 57 %) with ELAs between 3200 and 3350 m a.s.l. (average for 1895 to 1915: 3160 m a.s.l.). With the exception of 1896, air temperature during the ablation season is between 0.5 and 1.4 K above the mean of the investigation period (2.4 °C). Precipitation sums from the accumulation period (Oct.-Apr.) show predominantly dry winters. The warmest hydrological year (– 1.0 °C) and ablation period (3.8 °C) for 1897/98 yields a loss of more than 960 mm w.e. with an AAR of 16 %.

The trend reversal towards the plateau phase starts in the hydrological year 1900/01 with a glacier mass gain of 530 mm w.e. This mass balance is accompanied by temperatures of 1.3 K below average during the ablation season and moderate above-average winter precipitation. The plateau phase itself is characterized by predominantly below-normal air temperatures in summer and several wet accumulation periods. The AAR rises to a value of 66 % on average, while the highest value is obtained in 1900/01 with 96 %.

An exception is the hydrological year 1910/11 when the highest loss of glacier mass during the investigation period was simulated by the HBV3-ETH9 model. Although the temperatures of the ablation season 1911 do not reach the peak of 1898, the annual mass balance takes a value of – 1010 mm w.e. The reason for this can be found in the antecedent accumulation period, whose substandard precipitation sum (126 mm below average) provided a very shallow winter snow pack (cf. Fig. 6). This led to an early melt-out and thus intensified the effect of the high summer temperatures. The negative balance year is also reflected by the low ratio of the accumulation area of 13 %. ELA rises in this year up to nearly 3400 m a.s.l. Surveys of other glaciers (Patzelt 1970: glaciers of the Eastern Alps; Schlosser 1997: Hintereisferner) also report this particular deficit year.

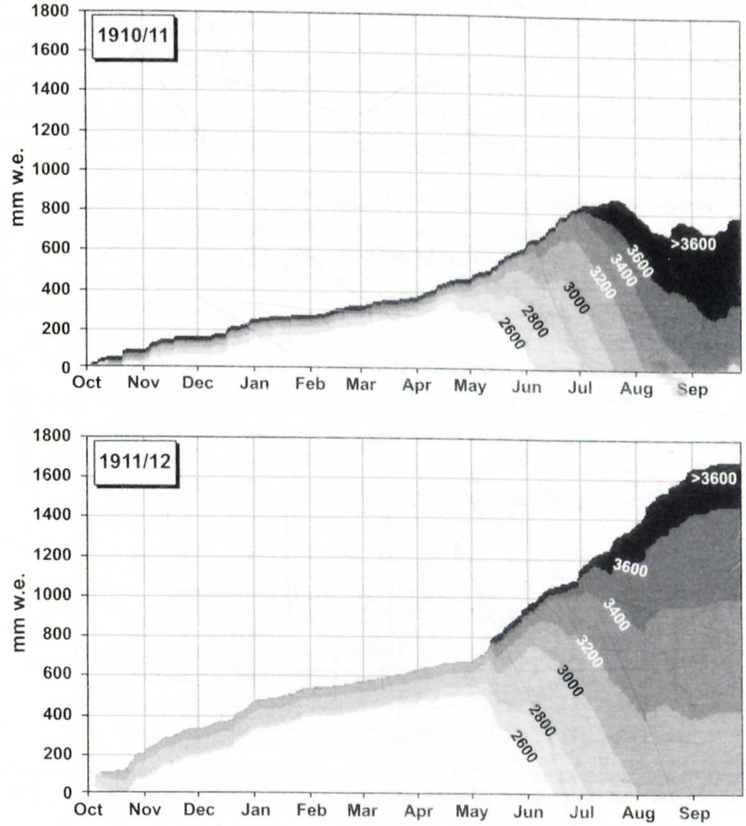

Fig. 6: Development of the snow water equivalent in the elevation bands of the exposure class "East, West and Horizontal" during the hydrological years 1910/11 and 1911/12

As shown in Figure 5, the hydrological year following the maximum loss, i.e. 1911/12, also features below-average annual and winter precipitation. On the other hand, mass balance in this time segment is slightly positive. The example of these two hydrological years displays the main advantage of the HBV3-ETH9 model over climate-glacier-relations approaches with lower temporal resolution as it considers not only seasonal or annual climatic aspects but observed weather data on a daily time scale. The influence of weather on the build-up of the snow pack is simulated as the development of the snow pack water equivalent in a semi-distributed manner for each elevation band and exposure class. Figure 6 shows the comparison of the snow pack formation exemplarily in the exposure class "East, West and Horizontal" during the hydrological years 1910/11 and 1911/12. Particular attention should be focused here to the elevation bands ranging from 3000 to 3200 m and 3200 to 3400 m a.s.l. This elevation span is crucial for the glacier's mass balance as it occupies together more than 57 % of the glacier area. In 1910/11 the snow cover of the 3000 to 3200 band disappears according to the simulation on August 6th, while on September 3rd the basin has become snow-free up to 3400 m a.s.l. In contrast to this, the simulated snow pack in 1911/12 persists in both altitudinal zones during the whole ablation season and even builds up again on August 7th and from August 12th to 18th (cf. Fig. 6). Obviously precipitation events during the summer of 1912 (which was more humid than average) occurred predominantly in the solid phase whereas in the drier summer of 1911 rainfall dominated over snowfall at these elevations. These summer precipitation characteristics affected the respective mass balance as summer snowfall increases the surface albedo of the glacier and thus reduces ice melt.

Figure 7 shows the higher temporal resolution of mass balance yielded by hydrological modelling compared to the geodetic method. For the examination of the history of Vernagtferner, these results bear more information than the long-term steps.

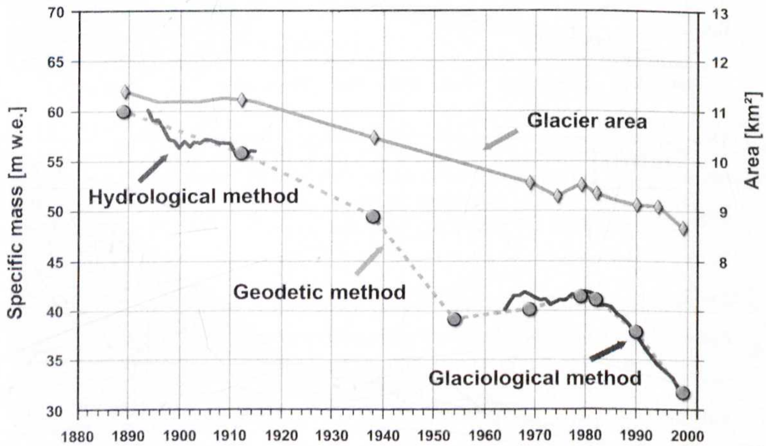

Fig. 7: Changes of area and specific mass of Vernagtferner 1889 to 2000, completed by the results of the hydrological modelling 1895 to 1915. Estimated density of the top layer: 0.75 g/cm^3

The geodetic method of mass balance yields values of more or less randomly chosen dates and offers neither the distinction of the two phases of mass balance development described here, nor the detection of particular years like 1910/11.

Furthermore, the long time span between the cartographic surveys which are used as a basis for the geodetic method cannot help to explain the causes for the surge event between

1898 and 1902 (cf. Chapter 3.1). With the results published in this paper we can assume that the surge was probably not caused by high accumulation rates in the preceding years but rather by internal glacier dynamics. Reconstructions of the regional climate published by Auer et al. (2001) show annual temperatures during the period from 1875 to 1890 which are between 0.2 and 1.8 K lower than the average from 1961 to 1990. Several years in this timeframe show above-average annual precipitation sums. It is during these decades that the accumulation rates which later caused the rapid glacier advance may have occurred.

The surge event itself affected the mass balance of Vernagtferner in the following years as it transported a large amount of ice and firn into lower regions with higher temperatures and thus augmented the rate of ablation in these areas. The result of this mass transportation is manifested in the increase of thickness of the glacier tongue between 1889 and 1912 (cf. Fig. 3). Furthermore it caused a prolongation and a broadening of the glacier tongue and, as a consequence, a re-glacierisation of parts of the glacier forefield which had become ice-free between 1889 and 1897 (Finsterwalder and Hess 1926). For this reason the area-elevation distribution and the expansion of the glacier according to the map of 1889 can be regarded as representative of the whole investigation period up to 1915.

3.3 DISCHARGE

Due to the lack of measured hydrographs, the absolute values of simulated runoff cannot be validated. But as the input for runoff from glaciated catchment basins consists mainly of liquid precipitation and melt water yield, the comparison of these components may allow the detection of changes in the hydrological characteristics of the glacier system (Braun and Weber 2002). Figure 8 shows the decreasing trend of specific annual discharge. Whereas precipitation sums do not show systematic changes apart from interannual fluctuations during the investigation period, the change in glacier storage displays a tendency from strongly negative to positive balance years.

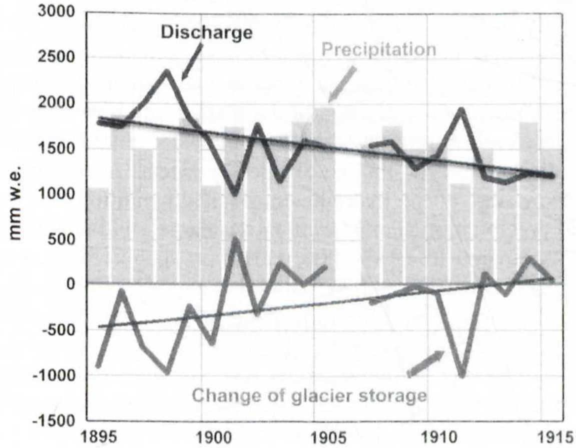

Fig. 8: Specific discharge, areal precipitation and change of glacier storage as simulated by the HBV3-ETH9 model. For 1905/06 c.f. comment on Fig. 5.

The decrease in discharge can thus be attributed to diminishing melt water yield. The major cause for reduced runoff can be attributed to reduced ice melt as a result of an increasing frequency of snowfall events during summer months. Figure 9 shows the percentage of rain and snow in the total areal precipitation sums of the hydrological years. The ratios are calculated by the model using a temperature threshold parameter. This threshold temperature was set during the calibration process to a value of −1.5 °C. Over the course of the investigation period, solid precipitation shows a trend of increase at the expense of liquid precipitation. As already mentioned in Chapter 3.2, summer snowfall events augment the surface albedo and diminish ice melt and thus reduce the glacial discharge yield.

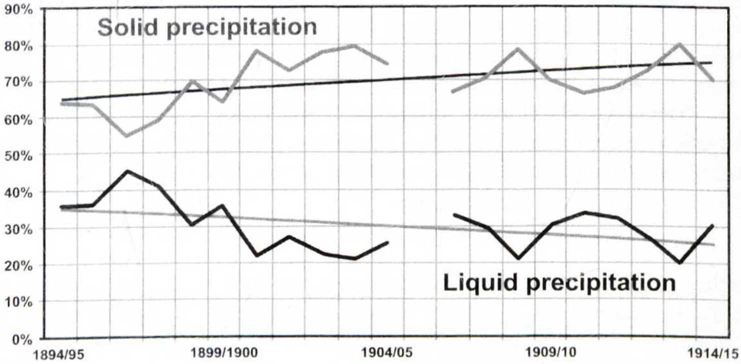

Fig. 9: Percentage of snow and rain in the areal precipitation sums of the hydrological years, complemented by the corresponding linear trends. For 1905/06 c.f. comment on Fig. 5.

The annual amounts of specific runoff during the period from 1895 to 1915 simulated by the model are within the range of 1000 and 2400 mm. These values can be compared due to their specific nature to discharge data from recent years (as shown in Braun and Weber 2002). Sensitivity analyses of the model relating to modified characteristics of the catchment basin (extension, degree of glaciation) have shown that an increase of ice cover (up to the state of 1889) causes an increase in the annual specific discharge yield as the melt water production rises due to the extension of the glacier into lower elevations. The enlargement of the catchment basin (up to the virtual gauging station at the glacier portal of 1889) also augments the discharge, even though to a lesser extent. According to these sensitivity analyses and the knowledge of the hydrometeorological conditions during the investigation period (larger areal precipitation sums), a larger discharge yield should be expected for the period 1895–1915 compared to 1974–2000. However, specific annual runoff values from 1974 to 2000 range between 1000 and 2620 mm and average out on a higher level than during the investigation period around the turn of the 19th to the 20th century. The peaks of mean daily runoff from 1895 to 1915 were also lower in comparison to the present values. The reason for this can be seen in the generally lower temperatures during the investigation period which raised the ratio of solid precipitation, diminished the snowmelt and thus reduced the melt water yield.

4. SUMMARY AND CONCLUSIONS

The approach to the reconstruction of glacier mass balance and runoff in the catchment area of Vernagtferner by conceptual modelling with the HBV3-ETH9 model is generally suitable. The rather modest data input requirements of the model (daily mean air temperature, daily sums of precipitation, degree of glaciation, surface characteristics) allow a larger spectrum of application in periods or regions with a minor supply of input data. This quality compensates the disadvantage of the model caused by its conceptual character (parameterisation of the physical processes of snow and ice melt by a temperature-index method, disregard for the distribution of accumulated snow by wind drift and avalanches). Additionally the calibration of the model by a geodetic mass balance offers new possibilities of model application in areas and times where discharge data is lacking. It can certainly be regarded as an advantage of the model that not only annual or seasonal climate influence (e.g. in Schlosser 1997) is considered, but that actually-observed sequences of weather patterns and their impact on the glacier are taken into account.

As the simulation of mass balance with the HBV3-ETH9 model showed satisfactory results for the period from 1895 to 1912, further investigation attempts will focus on the reconstruction of annual mass balance for the 1915 to 1963 time period using this method, with the aim of completing the record shown in Figure 7. Special attention will be turned to the years from 1938 to 1950 where Vernagtferner showed strongly negative mass balance years and suffered a loss of approximately 20 % of its mass. Meteorological records for this period exist from the Vent and Marienberg valley stations, physiographic characteristics and geodetic mass balances can be derived from the mappings of 1912, 1938, 1952 and 1969.

Provided that an adequate meteorological database and historical maps are available, this procedure could be a supplement or even an alternative to other climate-glacier-interaction-based methodologies (e.g. Steinacker 1979, Kerschner 1996) or dendrochronological approaches (e.g. Nicolussi 1995).

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