

Closing the Balances of Ice, Water and Sediment Fluxes Through the Terminus of Gepatschferner

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Abstract

The terminus of Gepatschferner (46°52' N, 10°46' E) was subject to detailed glaciological investigations in the joint project PROSA. Both direct and geodetic methods were applied. Specifically, ice surface lowering measured at ablation stakes determined mass loss at the glacier surface, ice surface velocity was measured directly at the same stakes with differential GPS, and geodetic radar and vibroseismic soundings came into operation to investigate ice thickness and thickness of subglacial sediments. Multiple high-resolution airborne laser scanning (ALS) surveys document total volume changes. In contrast to a differentiated examination of the balances of ice water and sediments, the combination of these balances was an appropriate approach for investigating glacier mass exchanges and identifying dominant processes within the glacial system.

The calculation or estimate of the fluxes of ice, water and sediments entering the narrow terminus at an elevation of 2875 m and leaving it at the glacier snout at 2200 m was based on glacier motion, surface and basal melt rates and on the lateral mass transport to the glacier from rock face and moraine bedrock erosion recorded from repeated terrestrial laser scans. In the course of the investigations on Gepatschferner, multiple rockfall events and the rapid evacuation of subglacial sediments were observed. The highest mass fluxes within the glacial system of Gepatschferner were associated with these extreme or episodic events, which exceeded the normal annual processes by multiple orders of magnitude. The relevant geophysical processes in this study period were thus not representative of long-term averages, if these ever existed. They did, however, display an interesting spectrum of naturally occurring situations. In that period, the mean velocity through the cross section at 2875 m was 22.5 m per year. Below that profile, the ice loss at the terminus corresponds to a mean surface lowering of 3.61 m per year between 2012 and 2015.

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Keywords

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Sediment flux

List of variables and indices

Variables

a	Ablation
A	Area
B	Glacier width
C	Cross section
E	Evaporation
h	Elevation
H	Thickness
M	Mass flux
P	Precipitation
Q	Volume flux
R	Run-off
S	Storage
t	Time
u	Velocity
V	Volume
ρ	Density

Indices

b	Basal
bed	Bedload
d	Deformation
i	Ice
lat	Lateral
r	Bedrock
s	Surface
sed	Sediment
sus	Suspension
top	From the area above 2875 m to the terminus
w	Water

close the respective balances of ice, water and sediments. Estimating the magnitudes of each term of the balancing approach helps to separate dominant processes from less important ones and their contribution to the ongoing change of proglacial systems under conditions of rapid deglaciation (Heckmann et al. 2012). This chapter is based on the idea of conceptualizing a connection between the budgets of ice, water and sediment and their seasonal variation within a glacial system on the basis of state-of-the-art measurements.

Surface and total mass balance measurements at several glaciers in the Alps and their production of meltwater have been investigated for a long time (e.g. Hoinkes 1970; Thibert et al. 2008; WGMS 2012; Fischer et al. 2013) as well as the fluvial sediment transport and the transport of suspended solids in the glacial stream (e.g. Gurnell and Clark 1987; Hofer 1987; Warburton 1990; Chaps. 12 and 13). Likewise, measurements of glacier surface velocity have a long history (Span et al. 1997; Span and Kuhn 2003) and provide important information about glacier dynamics (Van der Veen 2013). Geophysical methods offer a wide range of possibilities for investigating glaciological issues such as physical properties of ice or the internal structures of glaciers, ice thickness distribution and bedrock topography or subglacial sediments (Hauck and Kneisel 2008). The potential of Airborne Laser Scanning (ALS) data for glaciological questions has been demonstrated in several publications (e.g. Abermann et al. 2010; Bollmann et al. 2011; Helfricht et al. 2012) and can be taken as one of the most important databases for direct and indirect investigations. Carrivick et al. (2015) show that combining multiple methods yields insights into glacier evolution.

Gepatschferner, located in the Kaunertal in the Ötztal Alps (46°52' N, 10°46' E), is the second biggest glacier of the Eastern Alps (Patzelt 1980; Groß 1987; Lambrecht and Kuhn 2007; Kuhn et al. 2012) and extended over 16.4 km² in 2006, 15.6 km² in 2012 (Fischer et al. 2015) and 15.3 km² in 2015. It was subject to a wealth of measurements in past decades. Length changes of the glacier terminus have been measured since

5.1 Introduction

Changes in glacier mass can be quantified with geodetic, hydrological and direct glaciological measurements (Hoinkes 1970; Cuffey and Paterson 2010). A combination of such measurements and investigations (Hubbard and Glasser 2005) is the basis for an approach to

1856 (e.g. Fritzsche 1898; Fischer 2016). Seismic investigations were carried out between 1953 and 1958 (Förtsch et al. 1955) and were continued in 1960 and 1961 (Giese 1963); ice thickness measurements with ground penetrating radar were conducted in 1996 (Span et al. 2005). Changes in length, area and volume between 1850 and 2006 were calculated by Hartl (2010). Since 2012, the glacier is part of a catchment where detailed investigations of geomorphodynamics have been carried out (Heckmann et al. 2012; Chap. 1). The glaciological measurements in this study are mainly confined to the terminus, defined as the glacier below 2875 m, except calculations of area, elevation and volume changes from ALS data, which are calculated for all glacier areas. Detailed investigations on the terminus of the glacier focus on surface melt, surface velocities, ice thickness and the thickness of subglacial sediments.

With a synopsis of these measurements at the terminus of Gepatschferner, an approach to close the balances of ice, water and sediments is given in the first part of this chapter. That means, we need to know how much ice is flowing into the glacier terminus at 2875 m surface elevation, what is the balance of accumulation and of ice melt at the terminus below, how much water enters the terminus from above and what is the run-off from the glacier, how much sediment reaches the terminus from above and from the lateral slopes and how much leaves the glacier as bedload and as suspension in the river. In the second part, we attempt an estimate of the magnitudes of the turnover volumes.

5.2 Methods

High-resolution airborne laser scans (Abermann et al. 2010) are fundamental databases to arrive at distributed surface elevation changes and to georeference measurements of ablation, glacier motion, ice thickness and thickness of subglacial sediments. In this study, ALS data from 04.07.2012 and 22.08.2015 are used; they set the time frame of the balances. The digital elevation models (DEMs) were aggregated as mean values

form the ALS point clouds on a raster size of 1×1 m. Gaps were closed by a stepwise resampling using a bilinear interpolation. The DEMs, which are the basis of the calculations, aim at a vertical accuracy of ± 0.2 m for each DEM and ± 0.4 m for the DEM of difference (DoD) (Bollmann et al. 2011), which is in the same order as the basal change rates. An additional DEM is available from orthophotographs from 18.07.2014. Differential Global Positioning System (DGPS) measurements and direct stake readings were carried out on the glacier terminus at 15 stake positions (Fig. 5.1). Five of the stakes are located at a cross section in the root zone of the terminus at an elevation of 2875 m. Additionally, vibroseismic measurements (Eisen et al. 2010) were carried out at the terminus of Gepatschferner in 2012, 2013 and 2014 to investigate the thickness of subglacial sediment layers. A DEM of the glacier bed is provided by Span et al. (2005). It was produced by interpolating between ground penetrating radar (GPR) measurements.

The mean hydrological balance was calculated with a semi-distributed, conceptual model (Kuhn and Batlogg 1998, 1999; Kuhn 2000, 2003; Kuhn et al. 2016) for the period 2006/07–2014/15, based on the geodetic total glacier mass balance and measured values of temperature and precipitation. The model provides monthly values of basin precipitation, snow cover, glacier mass balance and run-off, separated into melt-water and rain for 100 m elevation bands partly verified by the basin run-off measured at Gepatschalm gauging station, situated at 1900 m.

Bedload transport and the transport of suspended solids are measured directly in the proglacial river at the glacier snout (Fig. 5.2; see details in Chap. 13). The lateral mass flux from adjacent hillslopes to the glacier surface was calculated from ALS and terrestrial laser scanning (TLS) data (Fig. 5.2; see details in Chaps. 9, 11).

5.2.1 Ice and Water Fluxes

Several factors contribute to elevation changes of the glacier surface over time (dh_s/dt) at a specific

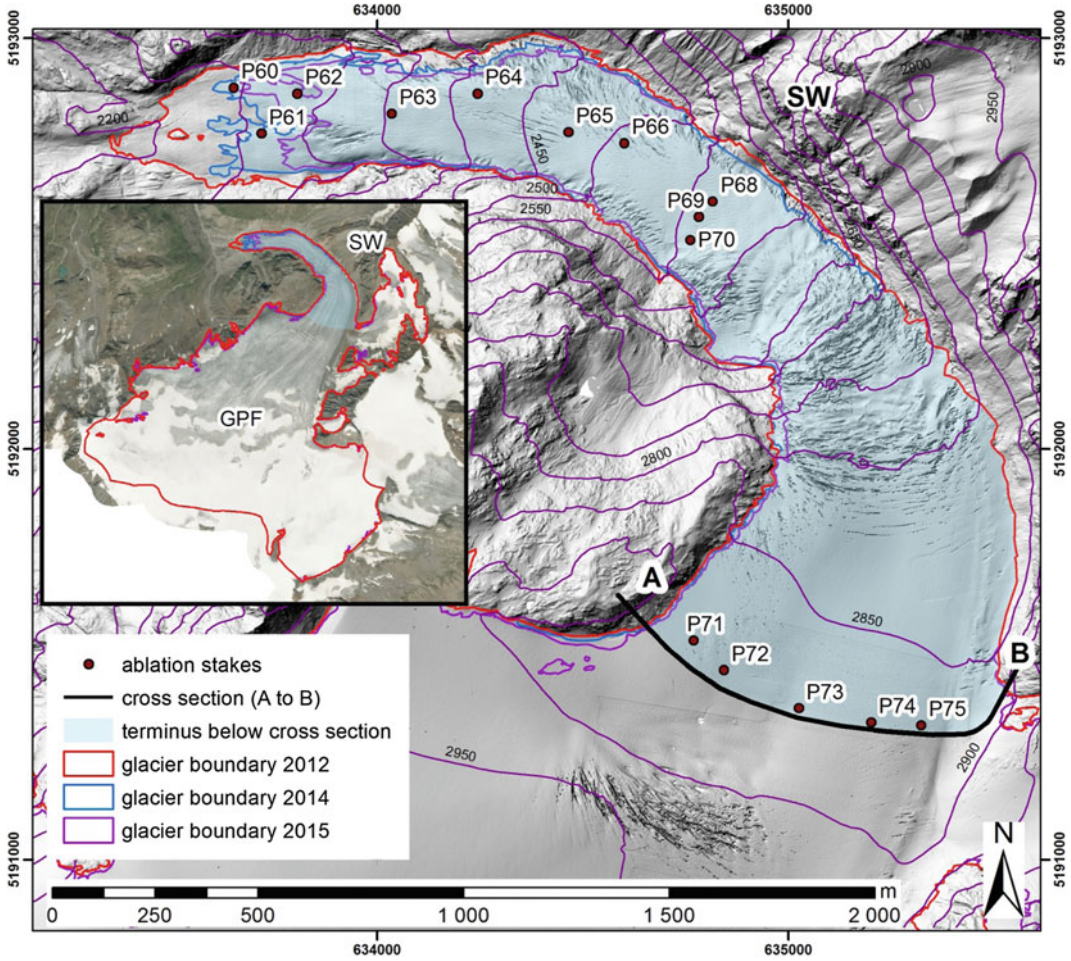


Fig. 5.1 Position of ablation stakes at the terminus of Gepatschferner 2014 and glacier boundaries 2012, 2014 and 2015 as well as the cross section at the root zone of the terminus between point A and B. Hill shade dated July

2012. Inset: the entire Gepatschferner (GPF) on orthophotograph (data source Land Tirol—data.tirol.gv.at). SW: Schwarze Wand

point, including the ablation on the surface ($a_s < 0$), basal melt ($a_b < 0$), thickness changes of the subglacial sediment layer (dH_{sed}/dt) and bedrock (dh_r/dt) erosion, advection of ice thickness ($u * dH_i/dx$), convergence or divergence of ice ($H_i * du/dx$). Englacial and subglacial water is seasonally stored, mostly in the matrix of sediments and ice, and has negligible changes from year to year (Jansson et al. 2003).

At any point (x, y) on the glacier surface

$$\frac{\partial H_i}{\partial t} = (a_s + a_b) - \frac{\partial Q_i}{B \partial x} \quad (5.1)$$

$$\frac{\partial Q_i}{B \partial x} = \frac{\partial}{\partial x} (\bar{u} * H_i) = H_i \frac{\partial \bar{u}}{\partial x} + \bar{u} \frac{\partial H_i}{\partial x} \quad (5.2)$$

The flux of ice to the terminus (Q_i) through a cross section (C) at a mean glacier width (B) and

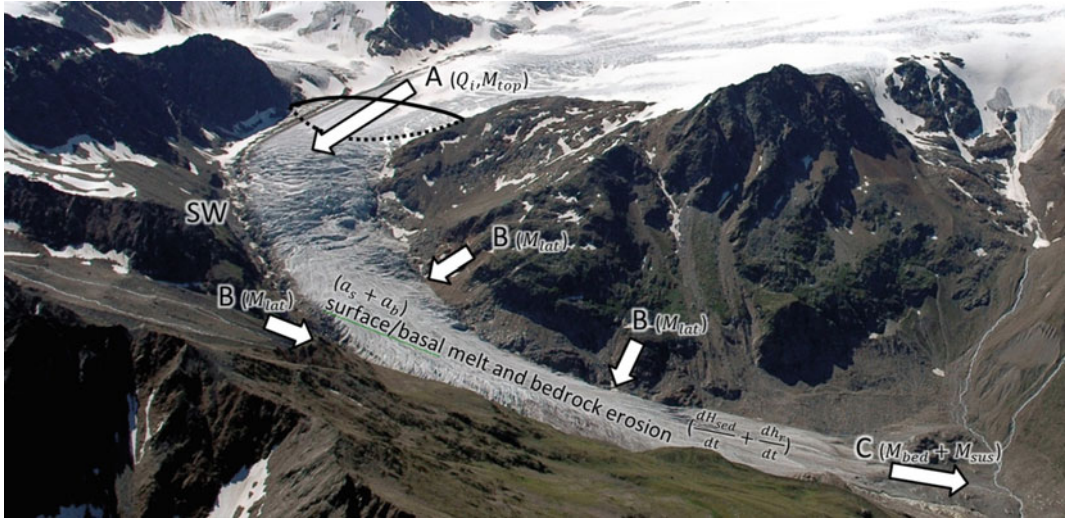


Fig. 5.2 Photograph of the terminus of Gepatschferner. A: transport of ice and sediments through the cross section to the terminus (Eqs. 5.3, 5.4 and 5.11); B: lateral mass transport on to the terminus from rock slopes and

moraines (Eq. 5.11); C: bedload transport and transport of suspended solids within the glacial stream (Eq. 5.11); SW: Schwarze Wand

the mean ice thickness (H_i) at the root zone of the terminus depends on the velocity of ice (\bar{u}), which is the sum of the mean deformation velocity (\bar{u}_d) and the mean velocity of basal sliding (\bar{u}_b).

$$Q_i = B * H_i(\bar{u}_d + \bar{u}_b) \quad (5.3)$$

$$Q_i = C * \bar{u} \quad (5.4)$$

The volume of ice (V_i) stored in the terminus in relation to the area (A) each year is

$$V_i = Q_i + (a_s + a_b) * A \quad (5.5)$$

from the glaciological method, equivalent to

$$V_i = \frac{\partial H_i}{\partial t} * A \quad (5.6)$$

from the geodetic method. This means that the amount of subglacial melt (a_b) can be inferred in metres of ice per year as

$$a_b = \frac{\partial H_i}{\partial t} - \frac{Q_i}{A} - a_s \quad (5.7)$$

where H_i , a_s and a_b are means over the entire terminus, and

$$\frac{\partial H_i}{\partial t} = \frac{\partial h_s}{\partial t} - \frac{\partial H_{sed}}{\partial t} \quad (5.8)$$

where h_s is determined from ALS and H_{sed} from seismic soundings.

The densification of snow or firn can be neglected at the terminus, except for a minor volume change due to closing crevasses, and also because the cross section is located within the ablation zone; thus, the density of ice (ρ_i) is kept constant, giving a straightforward way of converting volume to mass fluxes. The conventional glaciological mass balance measurements refer indeed to the weighed mass of snow where accumulation is concerned. All other measurements, i.e. ablation, changes of surface elevation, ice flow velocity and sediment thickness, are measured in terms of metres. This is why we prefer to express the balance terms of thickness ($H[m]$), volume ($V[m^3]$), volume fluxes per year ($Q[m^3/a]$) and volume flux densities per year ($[m^3/m^2a]$, which is equivalent to mean

velocities horizontally or to accumulation or ablation vertically, in metres per year). Only in those cases where several components (ice, water, sediments) are involved do we refer to mass fluxes per year ($[kg/a]$ or water equivalent (w.e.) per year $[m\ w.e./a]$).

Mass losses at the terminus can be calculated from the absolute values of surface and subglacial ablation ($a_s + a_b$) over the terminus area (A). The ‘remaining’ ice of the specified area corresponds to the storage of ice ($S[m\ w.e.]$).

$$S = Q_i \frac{\rho_i}{\rho_w} + (a_s + a_b) \frac{\rho_i}{\rho_w} * A \quad (5.9)$$

The storage of water (S) in the form of glacier ice (Jansson et al. 2003) is the connection to the hydrological balance of precipitation (P), run-off (R) and evaporation (E).

$$S = P - R - E \quad (5.10)$$

5.2.2 Sediment Fluxes

The mass flux of the bedload transport (M_{bed}) and the transport of suspended solids within the glacial stream to the snout of the glacier (M_{sus}) equals the thickness changes of the subglacial sediments ($(\partial H_{sed}/\partial t)\rho_{sed}$) of the terminus area (A), the flux of sediments from the firn area to the terminus (M_{top}) and the lateral input to the glacier from landslides and rockfalls of the surrounding slopes (M_{lat}). Neglecting bedrock erosion, the thickness change is a result of the divergence in the sediment transport. Assuming a stationary case, the terms of mass fluxes are balanced by thickness changes of the subglacial sediments (s. Table 5.1).

$$M_{bed} + M_{sus} = M_{top} + M_{lat} - \frac{\partial H_{sed}}{\partial t} \rho_{sed} * A \quad (5.11)$$

5.2.3 Balancing Approach

The absolute elevation of the glacier surface above sea-level (h_s) depends on the elevation of

the bedrock topography (h_r), the thickness of ice (H_i), the thickness of subglacial sediments (H_{sed}) and of liquid water (H_w) and changes in time. In this case, bedrock erosion is neglected, so the bedrock topography does not change. Likewise, annual changes of englacial and subglacial water are neglected.

$$h_s = h_r + H_{sed} + H_i + H_w \quad (5.12)$$

$$\frac{\partial h_s}{\partial t} = \frac{\partial H_{sed}}{\partial t} + \frac{\partial H_i}{\partial t} \quad (5.13)$$

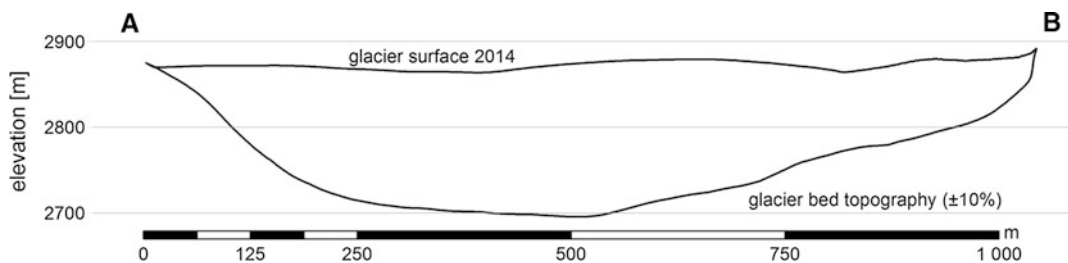
Of the terms in Eqs. 5.12 and 5.13, h_s is determined from ALS data, h_r from GPR data, H_{sed} from seismic data, H_i follows from Eq. 5.12 if H_w is neglected, because englacial water does not change the surface elevation and subglacial water is mostly contained within the sediment matrix.

5.3 Estimating Magnitudes of the Fluxes

At a cross section at the root zone of the terminus, at an elevation of 2875 m, the mean ice thickness is about 100 m and the maximum ice thickness 150 m. The cross-sectional area (C) between the bed topography and the ice surface represented in the DEM 2014 is 125,547 m² (Fig. 5.3). Between 2012 and 2015, the cross-sectional area varied by only 2–3% to the sectional area of 2014. Maximum ice surface velocities were found at the central stakes ‘P73’ and ‘P74’ (Fig. 5.1) of the cross-profile at the centre flow line of the glacier, with 35 m per year as a mean value between 2012 and 2015. The mass flux of ice to the terminus (Eq. 5.3) is thus calculated from the cross-sectional area of 2014 and the maximum velocity at the central stake. The mean velocity through the section is taken as approximately 64% of the maximum ice surface velocity (Span and Kuhn 2003). So the mean annual velocity through the section is 22.5 m per year, or 67.6 m for the period (04.07.2012–22.08.2015), which leads to a total volume gain of the terminus of 8,489,060 m³, or 6.20 m/m² during the period, calculated for the 1.369 km² area of the terminus in 2014. For the investigated

Table 5.1 Measured, calculated and estimated quantities within the PROSA catchment with respect to the balancing approach to the terminus of Gepatschferner

Measured quantities		
Glacier area of Gepatschferner 2015	15.281 ± 0.23	km ²
Terminus area 2014 (<2875 m)	1.369 ± 0.03	km ²
Cross-sectional area (2875 m), bedrock to surface 2012	0.128 ± 0.01	km ²
Cross-sectional area (2875 m), bedrock to surface 2015	0.122 ± 0.01	km ²
Mean ice thickness cross section	100 ± 10	m
Max. ice thickness at cross section	150 ± 15	m
Max. velocity on cross-sectional surface	35 ± 0.2	m/a
Max. thickness of subglacial sediment layers (Stocker-Waldhuber et al. 2017)	20 ± 5	m
Min. surface melt rate at the terminus	-1.14 ± 0.10	m/a
Max. surface melt rate at the terminus	-8.72 ± 0.10	m/a
Calculated and estimated quantities (04.07.2012–22.08.2016)		
Mean velocity through the cross section per year	22.5	m/a
Ice volume flux to the terminus	8.489	10 ⁶ m ³
Mean specific ice mass gain of the terminus	6.20	m
Mean elevation change at the terminus (DoD)	-10.84	m
Mean specific surface mass balance at the terminus	-15.59	m
Subglacial changes at the terminus (basal melt and bedrock erosion)	-1.45	m
Hydrological balance based on Kuhn et al. (2016) (2006/07–2014/15)		
Mean specific annual glacier mass balance	-868	mm w.e.
Mean annual storage of the catchment; negative part of the glaciers	-314	mm w.e.
Mean annual catchment run-off	1,740	mm
Contribution of the glaciers to the total run-off	18	%
Contribution of Gepatschferner terminus to total run-off	6.1	%
Lateral contribution of Schwarze Wand	66,000	t/a
Estimated transport duration at central flow line	10–30	a
Estimated sediment production of Gepatschferner	10 ⁴ –10 ⁶	m ³ /a
Mean erosion Gepatschferner 2012–2015 (assuming: 1 mm, $\rho = 2500 \text{ kg/m}^3$)	38,618	t/a

**Fig. 5.3** Vertical cross section from point A to point B (Fig. 5.1) between the glacier surface 2014 and the interpolated glacier bed topography calculated from ice

thicknesses values determined by ground penetrating radar with an estimated uncertainty of $\pm 10\%$ by Span et al. (2005)

three-year period, the geodetic determination of the change in surface elevation of the terminus out of the DoD is -10.84 m of ice. The direct investigations at the glacier surface by stake readings returned a specific surface balance of the terminus of -15.59 m of ice within three years (04.07.2012–22.08.2015). From Eq. 5.1, the subglacial changes are -1.45 m for this period or about -48 cm per year as the remainder of the DoD, the mass gain due to the specific mass flux of ice to the terminus and the specific surface mass balance. The basal rate of change of -0.48 m per year consists of the basal melt rate and minor contributions of the bedrock erosion.

A comparison of the uncertainty of each term of the ice mass balance of the terminus reveals different orders of magnitude. The uncertainty of the surface mass balance measured with the direct glaciological method (Hoinkes 1970) is assumed to be smaller than 0.1 m of ice per year (Kuhn et al. 1999). The surface velocities measured with DGPS aim at a horizontal precision of a few centimetres (Monteiro et al. 2005) and are in the range of ± 0.2 m per year at the cross section on Gepatschferner. The variation in the maximum surface velocity per year at the cross section during the three years of stake measurements was $\pm 5\%$ and affects the basal change rate by about ± 0.11 m. The uncertainty of GPR measurements and the bedrock topography at the cross section is an order of magnitude higher and can only be estimated. However, we assume that about 10% of the given ice thickness should be a good approximation. In the case of Gepatschferner, a calculation with $\pm 10\%$ of the mean ice thickness within the cross section at the root zone of the terminus leads to a calculated range of the basal change rate at the terminus between -0.28 and -0.69 m per year.

Water storage within an Alpine catchment can be separated into liquid water and ice components. Within a highly glaciated catchment, the dominant storage of liquid water is within snow or firn (Kuhn et al. 2016), but those components are not as significant for total run-off as the volume of ice. For the whole catchment, the storage term of the hydrological balance (Eq. 5.10) equates the ice mass loss of the

glacier. This negative part of the specific glacier mass balance between 2006/07 and 2014/15 amounts to -314 mm w.e. (water equivalent) per m^2 and year or 18% of the total headwater run-off. By calculating the specific contribution of the terminus relative to the whole catchment area, the negative balance of the terminus of Gepatschferner amounts to -107 mm w.e. per year. So the terminus below 2875 m makes a specific contribution of about 6.1% to the total run-off. A model run with higher temperatures ($+2$ °C) and constant glacier area shows a significant increase of 36% in the meltwater production (Kuhn et al. 2007). An assumed reduction of the ice-covered area until 2050 due to higher temperatures still leads to an increase of 27% of the total run-off.

The bedload transport and the transport of suspended solids within the proglacial stream (see details in Chap. 13) represent the mass loss or export from a catchment and thus lead to a mean surface lowering in the order of magnitude of millimetres to centimetres per year (Carrivick et al. 2013). The sediment mass originates from active rock slopes, moraines and from subglacial bedrock erosion. However, only a small part of the surrounding steep slopes and moraines provide a lateral mass transport directly on to the surface of the terminus of Gepatschferner. Most of the material from active rock slopes ($>40^\circ$) is deposited on moraines, and often, the material from moraines is transported underneath the terminus at the peripheral zones (see details in Chap. 11).

On Gepatschferner, the very active rock slope Schwarze Wand is responsible for most of the deposited material on the glacier surface, with approximately $66,000$ tons a year between 2012 and 2015 (see details in Chap. 9). Such active rockfall zones or comparable ‘extreme’ events exceed the average transport processes many times over. On Alpine glaciers, a ‘final’ deposition of solid rocks in the glacier forefield, which were previously deposited on the glacier surface, is delayed by the glacier motion and/or retreat by up to several hundred years (Span et al. 1997). In the case of Gepatschferner, solid rocks from the Schwarze Wand, deposited at the central flow

line of the glacier, will arrive in the forefield of the glacier in approximately 30 years under present conditions of glacier motion and the present extent of the terminus. Given retreat rates of the terminus of about 100 m per year between 2012 and 2015 (Fischer 2016), the transport time to the forefield can be assumed as approx. 10 years. Material from rock faces or moraines deposited on dead ice bodies has not been taken into account, because these regions are dynamically almost decoupled from the terminus itself.

The distribution and thickness of subglacial sediment layers at specific profiles was investigated with vibroseismic soundings on the terminus of Gepatschferner. In one profile at the lowermost part of the glacier, a sediment trap measured maximum thicknesses of 20 ± 5 m. During a heavy precipitation event (Baewert and Morche 2014), the subglacial sediment layers were flushed out rapidly, resulting in an increased deepening process of a surface depression (Stocker-Waldhuber et al. 2017). In contrast to this extreme event, the specific erosion of the glacier should be in the order of magnitude of millimetres up to a few decimetres per year (Hallet et al. 1996). The volume of sediments evacuated during the extreme event mentioned above would be in the same order of magnitude as a specific erosion rate of a few centimetres per year in relation to the area of the terminus. The glacier area further up the terminus (Gepatschferner >2875 m) was not taken into account because the sediment transport from the firn area is unknown. However, the estimated magnitude of the sediment production from bedrock erosion of the whole Gepatschferner is assumed to be in the range of 10^4 – 10^6 m³ per year, with a calculated range of specific erosion rates of about one millimetre to a five centimetres per year (c.f. Chap. 17).

5.4 Conclusions

The balancing approach presented here aims at combining measured quantities and magnitudes only estimated on an annual basis. A regionalized analysis of each parameter should be taken

into account and is as important as the separation of periodic/annual from episodic processes. On Gepatschferner, the glaciological measurements are mainly confined to the terminus or even more specific locations, such as the vibroseismic investigations at the surface depression. On the terminus, we found from geodetic investigations that the mean surface lowering from 04.07.2012 to 22.08.2015 was -10.84 m. In contrast, the directly measured surface ablation of -15.59 m within the same period is largely compensated by the ice mass flux to the terminus, calculated out of surface velocities and ice thickness data, which leads to a gain of 6.20 m. The remainder of this balance suggests a basal change rate of -0.48 m per year. These basal changes consist of subglacial ice melt and the erosion of sediments and the bedrock. However, the three-year time window is a snapshot that may be short compared to the recurrence of extreme events. Thus, an extrapolation of the measured and calculated changes and processes to the whole glacier area remains problematic, as indicated by examples of ‘extreme’ or episodic events, which are multiple orders of magnitude higher than changes within ‘normal’ daily or annual cycles, like the rockfalls on Schwarze Wand or the rapid evacuation of subglacial sediment layers during a heavy precipitation event.

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