Water balance in the Storglaciären catchment, Northern Sweden, summer 2005

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Abstract. The water balance of Storglaciären and its catchment was calculated during the 2005 melt season, using daily values of glacier melt based on downscaled weekly measurements as well as measured daily precipitation and runoff. Water input to the glacier exceeded discharge until late August, resulting in positive water balance. A major rainstorm on August 26 caused major changes in the internal drainage system of the glacier and resulted in a large and quick release of stored water within one day (~0.8×10^{6} m^{3}). A gradual decrease in storage occurred after this event, caused by low melt rates and snowfall, indicating a release of water from basal drainage systems and firn storage. I have also made a comparison with a study on the water balance in 1984. Although the general trend of a change from positive to negative storage throughout the season is similar, the season of positive storage in 2005 was significant longer. There are two possible explanations. (1) Different weather conditions dominated during the different melt seasons. Weather data from 1984 were compared to observations from 2005, showing that substantial snow melt started earlier in 1984 due to relatively higher temperatures and differences in intensity and timing of major rainfall events. Snow and ice melt as well as rainfall are believed to influence the formation of an efficient subglacial and englacial channel network of the glacier. This, in turn, will affect the water storage in the glacier. (2) An increase in internal deformation during the last two decades could delay the formation of an efficient drainage network. Water may therefore be stored longer in the glacier. The latter is speculative since it cannot be supported by observations.

Introduction

Glaciers represent valuable natural reservoirs of water exerting a strong control on drainage characteristics of alpine catchments. Large volumes of precipitation are stored in the winter and subsequently released by summer melting. This produces a pronounced seasonality in discharge, with a very high ratio of summer discharge to the annual discharge (Lang, 1987; Jansson et al., 2003). Glaciers are thought to delay runoff by preventing precipitation to run off directly. Such storage occurs on sub-seasonal and sub-daily basis and involves both factors associated with snow accumulation and melt on the glacier and water storing capacity of the glacier. Water can be stored in surface snow and firn, crevasses, surface pools, englacial pockets, subglacial cavities, the en- and subglacial drainage network, and in basal sediments (Jansson et al., 2003). Glacier cover also affects the inter-annual variability of runoff with a lowest variability at moderate percentages of glacier cover (roughly 40%) and increases as glacier cover both decreases and increases (Fountain and Tangborn, 1985; Röthlisberger and Lang, 1987; Braithwaite and Olesen, 1988; Chen and Ohmura, 1990b). Previous water balance studies have revealed significant internal water storage through the year. The timing of storage and release varies between studies. Östling and Hooke (1986) showed that the storage of water in Storglaciären, Northern Sweden, occurred during May-June and net loss occurred in late July and September (figure 1). The net storage was positive, indicating that release during winter is needed to balance storage occurring during summer, originated from basal water systems and from firn storage.

In this study, the transient water balance was calculated for both the Storglaciären-catchment (4.55 km^{2}) as well as the glacier only (3.21 km^{2}) in the period July 1 until September 15, covering the major part of the ablation season of 2005. The major inputs for calculating the water balance were cumulative rainfall and melt on the glacier, which were both measured weekly or bi-weekly. In order to obtain daily values, as will be

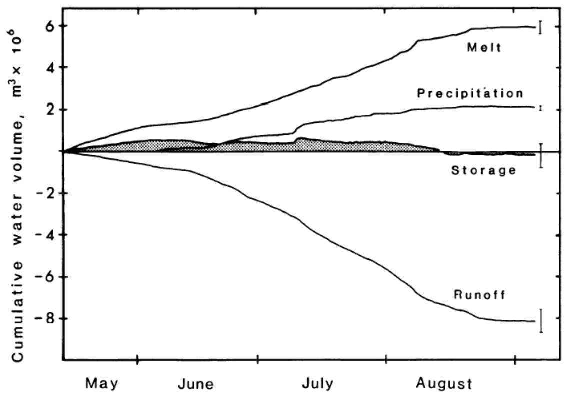

Figure 1. Cumulative curves showing the water balance components (inputs and losses) from Storglaciären, 1984 (from Östling and Hooke, 1986).

discussed below, a downscaling had to be done. This, however, created an uncertainty. Snow melt on the valley sides, melting by geothermal heat, dissipation of strain energy and condensation were assumed to be negligible. The major output was runoff, whereas evaporation (and sublimation), groundwater flow and soil storage were assumed to be of minor importance and were therefore not taken into account (Östling and Hooke, 1986). Bedrock in this area is a relatively impermeable amphibolite, and the layer of till is comparatively thin (Brand et al, 1987; Iverson et al, 1994; Iverson et al., 1995), so neglecting the contribution of ground water and soil storage to the water balance should not introduce significant errors. The daily runoff from Storglaciären was calculated using data from the two hydrological stations in the Tarfala Valley (figure 2). Limitations in this study will be discussed and a comparison will be done with a similar study in 1984.

Area characteristics

Storglaciären (67°55’N, 18°35’E) is a small polythermal valley glacier located on the eastern side of Kebnekaise massif in Lappland, Northern Sweden (figures 2–4). The glacier is 3.2 km long from its head at ~1730 m a.s.l. to the terminus at ~1120 m a.s.l. and has a total surface area of 3.2 km^2 (1969 map). The average and maximum thickness are 95 m and 250 m, respectively. The glacier is frozen to the bed near its margins (Holmlund et al, 1996). The main general characteristics of the glacier can be found in Schytt (1959, 1966, 1968). The Storglaciären drainage basin is typical high alpine with a total area of 4.55 km^2 and an altitude ranging from 1040 to 2040 m a.s.l. (figure 3). It comprises 22% of the entire Tarfala drainage basin which has a total area of 20.6 km^2 with a total glacier cover of 6.18 km^2.

The borders are well defined by surrounding steep ridges and escarpments (Östling and Hooke, 1986; Bronge, 1996; Schneider and Bronge, 1996). Storglaciären is drained by several streams which coalesce into Tarfalajåkk about 400 m downstream of the terminus. The river is gauged at the hydrological station ‘Rännan’ about 800 m downstream of the terminus of the Storglaciären (Schytt, 1973; Bronge, 1989).

The internal drainage system of the glacier was first studied by Stenborg (1965, 1969, 1971). He was able to divide the glacier surface into discrete drainage areas, each draining a specific part of the glacier surface and each connected to a specific part of the system of proglacial streams. The firn area is drained mostly through the northern proglacial stream, Nordjokk, whereas the main part of the ablation area is drained into the southern branch, Sydjokk (figure 5). The ablation area can also be divided into two parts, separated by a zone of moulins and crevasses located over an overdeepening in the bed topography. The area upglacier from this zone drains into the moulins and then to Sydjokk. The downglacier part of the ablation area drains mainly supraglacially into both rivers.

Temperature

The mean temperature for Storglaciären was calculated by subdividing the glacier into 20 m elevation intervals (figure 5). For every interval, the mean daily temperature was calculated using the temperature data measured at Tarfala Research Station and using a constant lapse rate of –0.55 K/100 m rise in elevation. The proportion of the area of each elevation interval compared to the total area of the glacier were multiplied by the mean daily temperature of the corresponding

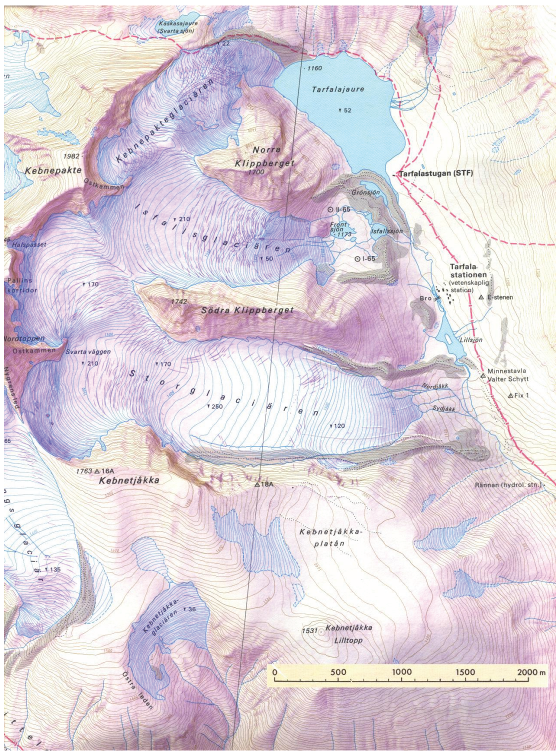

Figure 2. The Tarfala drainage basin and the hydrological stations Rännan and Lake Lillsjön outlet. From Holmlund and Schytt (1994).

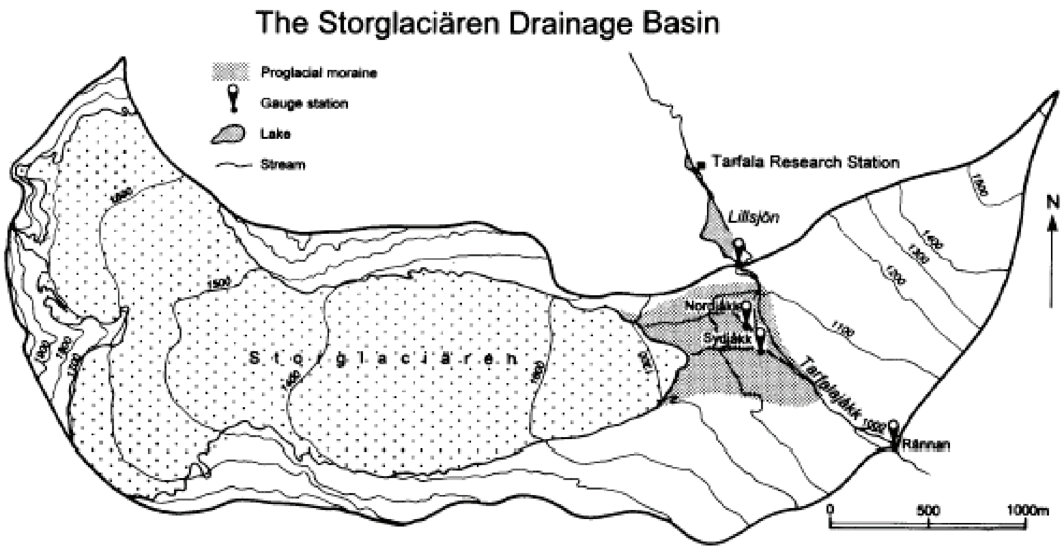

Figure 3. The Storglaciären catchment. From Schneider and Bronge (1996).

elevation interval and summed to obtain an average temperature value for the entire glacier (figure 6).

The 2005 melt season started on June 7, characterized by the onset of substantial periods of melting temperatures (T>0°C). From late June, temperatures rose to values over 10°C. A second relatively warm period occurred in mid-July with the highest mean daily temperature of 11.8°C (July 19). In the following period, temperatures fluctuated between 2.6 and 7.4°C. A relatively cold period occurred in the period July 29 until August 3 with the lowest mean daily temperature of 0.6°C (July 31). A gradual warming followed with temperatures rising close to 10°C (August 10). After a period of frequent temperature fluctuations between 1.9°C and 7.3°C, the winter season started on September 8 with mean daily temperatures below 0°C.

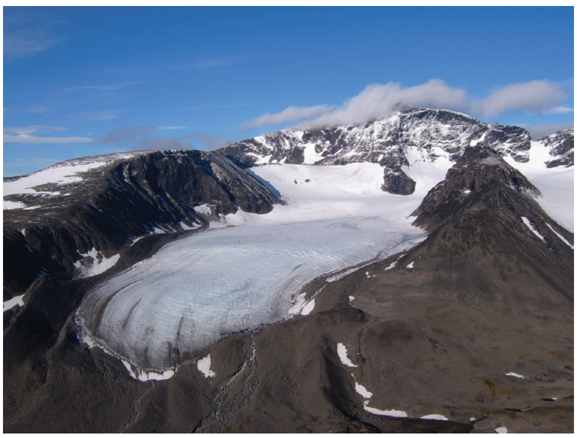

Figure 4. Storglaciären and its watershed, showing proglacial streams draining the glacier. Note Nordjokk on the right side of the glacier terminus and Sydjokk flowing from the central part of the terminus. The overdeepening in the bed topography is reflected by the zone of lateral crevasses. (Photo by Y. Snoek on 28 August, 2005).

Precipitation on Storglaciären

Rainfall was measured with the use of 6 SMHI rain gauges distributed over the glacier at stakes 5C, 10C, 15C, 20C, 24C and 29C (figure 5, above). The volume of water contained in the rain gauges were measured several times during the summer of 2005 (table 1).

Two different methods were applied in order to interpolate the rainfall measurements for the entire glacier: *kriging* (GSLIB Library, 1997) and the *precipitation gradient* method. The latter involves a calculation using the gradient of the rainfall measurements with altitude. The glacier surface was subdivided in elevation intervals of 20 m and a value for each of these intervals was calculated, ending in a total average rainfall value for the entire glacier. To estimate the fraction of the daily rainfall in stead of the total rainfall in between the measurements (as shown in table 1), the measurements from tipping bucket at Tarfala Research station was used. It was assumed that for a give time period, the fraction of the total rainfall for that time period that fell each day was the same. A third approximation of the precipitation on Storglaciären was obtained using the assumption of 10% more precipitation for every 100 m increase in altitude to the daily rainfall measurements in Tarfala. In addition, a correction was made for the mean daily temperature on the glacier. First, the glacier surface was subdivided in elevation intervals of 20 m. Second, the mean daily temperatures were calculated for each 20 m elevation interval, using the assumption of a lapse rate of -0.55K/100 m rise in altitude, as discussed above. Third, it was assumed that rainfall only occurred when the mean daily temperature was higher than 0°C. Hence, the daily rainfall could be calculated for each elevation interval. Finally, the daily rainfall values were multiplied with the proportions of the areas of the different intervals compared to the total area of the glacier. The total sum yielded the mean daily rainfall values for the entire glacier.

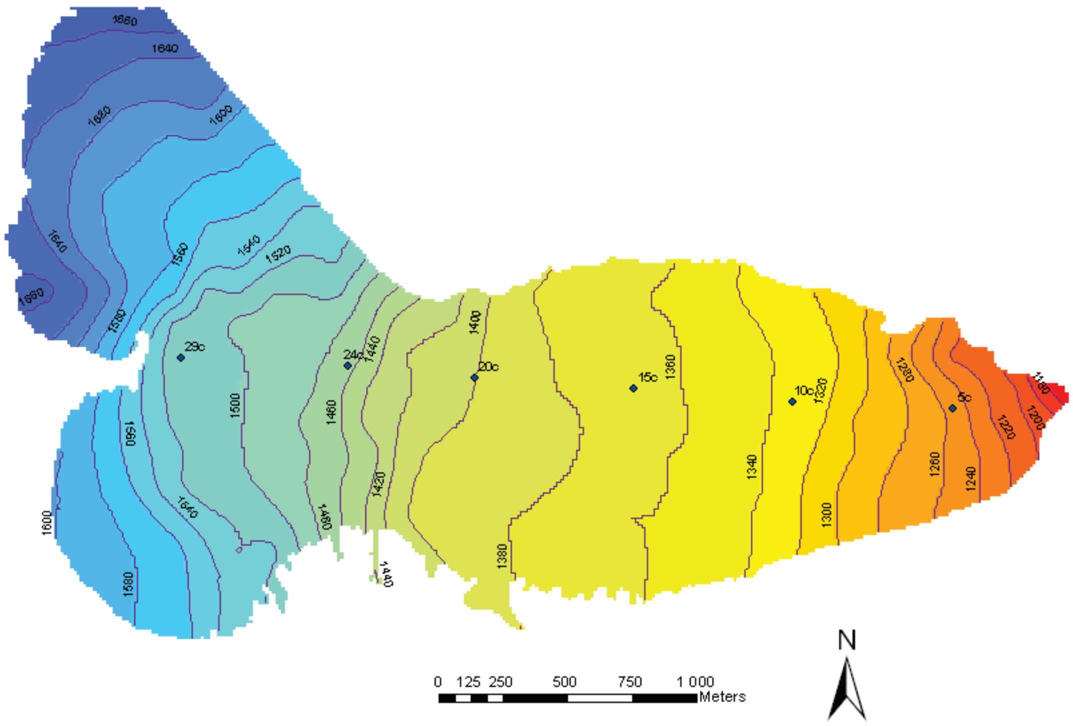

Figure 5. Elevation intervals and rain gauges on Storglaciären.

The cumulative precipitation for the three different methods was calculated for the period July 1 until September 15 (figure 7). Studies of rainfall distribution in the Tarfala valley (Sterner and Sundblad, 1976) suggest that several corrections should be applied to the measured rainfall values. Losses during handling are estimated to be ~2 mm each time the gauges are emptied. Evaporation ranges from 0.07 to 1.26 mm/d. An average value of 0.8 mm/d was assumed. Losses due to wind may be up to 15%, depending on the location of the meter. The correction for the non-vertical orientation of the gauges on the irregular and melting ice surface is difficult to estimate. These latter two factors were assumed to result in a combined loss of 10% (Östling and Hooke, 1986). Hence, 10% extra rainfall was added to the rainfall values of the *kriging*

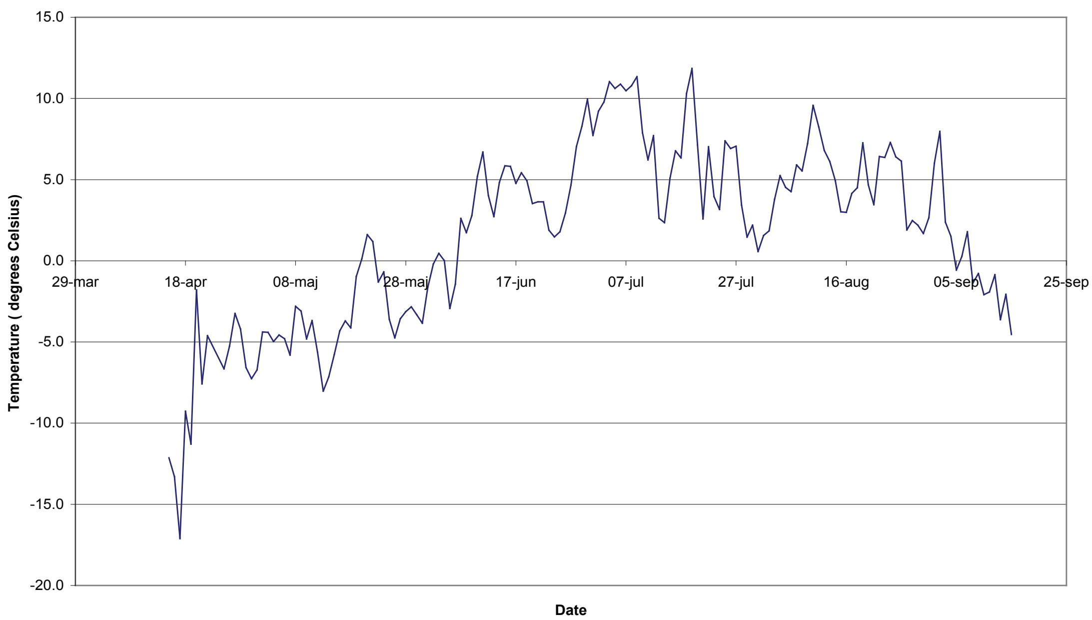

Figure 6. Mean daily temperature, Storglaciären spring and summer 2005.

Table 1. Rainfall measurements at the different rain gauges

Rain gauge	Elevation (m)	13 Jul. (mm)	19-07 (mm)	02-08 (mm)	16-08 (mm)	26-08 (mm)	29-08 (mm)	Total (mm)
5c	1247	18.5	24.4	41.0	—	62.0	108.8	254.7
10c	1321	24.5	43.9	52.5	45.3	68.8	89.0	324.0
15c	1372	12.7	63.0	51.7	45.2	-	149.0	321.6
20c	1413	-	154.5	38.0	62.5	-	175.4	430.4
24c	1472	-	180.9	85.0 *	71.9	-	-	252.8
29c	1505	-	297.2	*snow*	65.1	-	-	362.3

* partly ice in the rain gauge

and the *precipitation gradient* methods. Since the last measurements on the rain gauges were done on August 29 and a full record (until September 15) was required, an extrapolation had to be done with the precipitation data measured at Tarfala Research Station, using the *P+10%* method.

Two points merit further discussion. First, it should be mentioned that the specific mean precipitation was calculated using only the surface area of the glacier, and not the entire area of Storglaciären catchment. It was assumed that the steep cliffs around Storglaciären yielded negligible contributions from rainfall compared to the open and relatively flat surface area of the glacier. The area on the Eastern side of the Tarfala Valley, however, which is also part of the Storglaciären-catchment, should be taken into account. Since a Digital Elevation Model was not available, the total volume of rainfall in the Storglaciären-catchment, was calculated both for the area of Storglaciären (3.21 km^2) as well as the entire Storglaciären catchment (4.55 km^2), assuming that the specific mean precipitation measured at Storglaciären is representative for the entire Storglaciären catchment. Second, the precipitation measured at the rain gauges is likely to be underestimated in stormy conditions when the so-called *horizontal precipitation* is not captured in the rain gauges.

The pattern of the cumulative rainfall was similar for the *kriging* and the *rainfall gradient* methods, although the *rainfall gradient* had higher values. The *P+10%* method had a distinct pattern in the first part of the summer with significant lower values. The glacier apparently experienced higher rainfall amounts than Tarfala, in spite of the applied correction (*P+10%*). However, the rainfall values became more similar to the other two methods from mid-August and on. The amount of rainfall during the largest rainfall event (August 26) calculated by the three methods differed significantly, *e.g.* 50.8, 73.3 and 88.7 mm. for the *kriging*, *rainfall gradient* and *P+10%* methods. These differences confirm the underestimation of the total rainfall amounts captured in the rain gauges, as discussed above.

The general uncertainty in the calculations for the three methods was calculated by the mean standard deviation of the daily precipitation values of the three

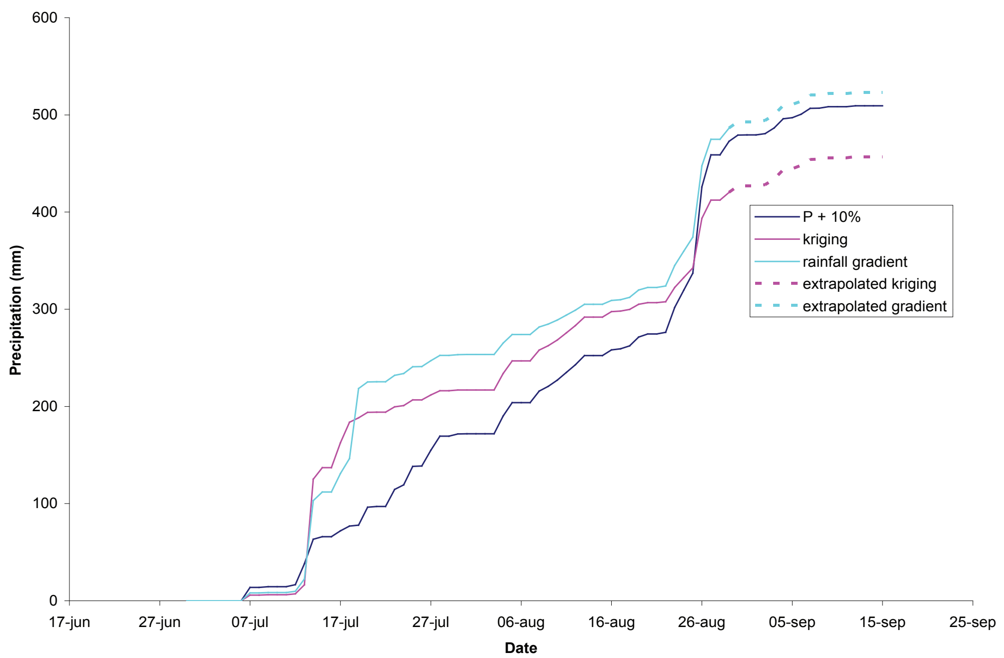

Figure 7. Cumulative rainfall on Storglaciären, using three different interpolation methods.

different methods, which yielded 50 mm. The total amounts of rainfall for the *kriging*, *rainfall gradient* and *P+10%* methods were respectively 456.9±50 mm., 523.0±50 mm. and 509.5±50 mm.

Melting on the glacier, Degree-day Factor

Ablation measurements were done weekly or bi-weekly at approximately 78 stakes distributed over the glacier surface, mainly in the ablation area by determining the height of the stake top over thesurface, snow, superimposed ice, firn or ice. Hence, the transient snow or ice melt throughout the entire melt season could be monitored. This was converted to a net loss of water from the snow pack or ice surface, using the mean densities of snow and ice. Further information about the summer mass balance of Storglaciären in 2005 is given by Snoek (2005, *in press.*).

A simple mass balance model, the Degree-Day Factor (DDF) (*e.g.* Hock, 2003) was applied to estimate the transient daily summer mass balance, using mean daily temperature data collected at Tarfala Research Station and the net loss of water from the snow pack or ice surface, the *ablation* (Snoek, 2005 *in press.*). Measured daily air temperatures in the period April 18 to September 15 were extrapolated to the elevation of every stake with accuracies of 50 m elevation intervals, using a constant lapse rate of -0.55 K/100 m rise in elevation. The mean daily temperatures above 0°C were summed for every elevation interval in order to calculate to total amount of positive degree days. The Degree-Day factor was calculated for each stake for every ablation measurement using:

$$DDF = \frac{M}{\Sigma T^{+}} \qquad \text{(equation 1)}$$

where DDF is the degree-day factor ($mmK^{-1}d^{-1}$), M is the melt (m w.e.), and T^{+} is the positive air temperature.

Two interpolation methods, *kriging* and *ablation gradient*, were applied to interpolate the degree-day factors (DDF) for the entire glacier. The latter method was derived using the relation between DDF and elevation. The glacier surface was subdivided in elevation intervals of 20 m and a DDF value was calculated for every elevation interval. An average DDF value for the entire glacier was obtained using the relative area of every elevation interval with respect to the total glacier surface area. Thereafter, the amount of Positive Degree days (ΣT^{+}) was calculated for the entire glacier by dividing the transient mass balance by the transient DDF (table 2). In addition, the amount of Positive Degree days was calculated at Tarfala Research Station using the measured temperature data.

A linear regression was established between the measured transient summer mass balance, b_s, and the total positive degree-days during the ablation season using the two different interpolation methods (figure 8). In addition, a linear regression was established between the measured transient summer mass balance, b_s, using both *kriging* and *ablation gradient* methods and the total positive degree-days at Tarfala Research Station (figure 9). The temperature was integrated between April 18 (t_1) and September 15 (t_2):

$$b_s = \sum_{t_1}^{t_2} aT \qquad \begin{matrix} \{a_{ij} = 1, t_{ij} > 0\} \\ \{a_{ij} = 0, t_{ij} < 0\} \end{matrix} \qquad \text{(equation 2)}$$

The highest correlations were obtained by the *gradient* method for both calculations of the DDF and the summer mass balance. It should be remarked that the correlation between the transient summer mass balance and the Positive Degree days at Tarfala Research Station was, surprisingly, higher than using the Positive Degree days for the glacier itself and was therefore used in the further analysis.

The positive degree days at Tarfala Research Station were calculated for every day since April 18 throughout the entire melt season. The transient daily summer mass balance could therefore be calculated, using the relations as discussed above. These results were compared with the observed transient summer mass balance (figure 10). The summer mass balance was negative until June 30 and July 3 for both the *kriging* and the *gradient* method. These negative values are unrealistic since mean temperatures above 0°C occurred already in mid-May, indicating melt on the glacier. It was therefore assumed that linear melt occurred between the start of the melt season (mid-May) until the first

Table 2. DDF, b_s and Positive Degree days

Date	DDF (kriging)	b_s (kriging)	Positive Degree days (kriging)	DDF (gradient)	b_s (gradient)	Positive Degree days (gradient)	Positive Degree days at Tarfala
11-07	1.4	0.3	255.5	1.3	0.3	207.5	301.4
19-07	2.3	0.7	286.7	2.4	0.6	252.5	345.7
02-08	2.7	1.0	352.8	2.8	0.9	331.4	437.1
16-08	2.8	1.2	436.9	2.8	1.2	424.8	539.2
29-08	3.1	1.6	510.6	3.8	1.7	449.4	626.6
14-09	3.1	1.7	533.7	3.1	1.6	520.9	672.8

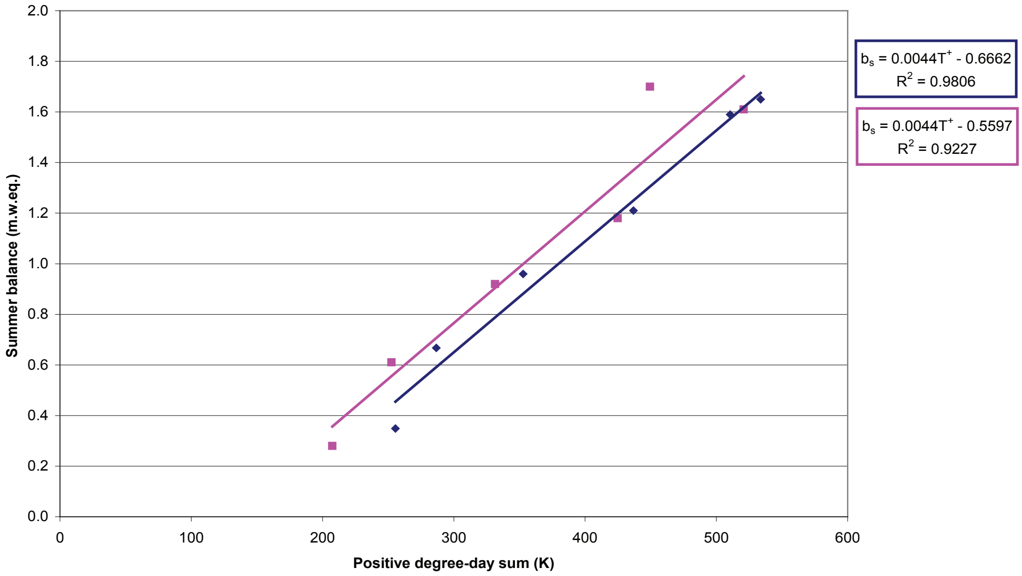

Figure 8. Correlation between transient summer mass balance and the extrapolated. Positive degree-day using kriging (blue) and the ablation gradient (pink).

ablation measurements (July 11) according to the Positive Degree days in this period (figure 10). Finally, the total melt volume (m^3) was calculated by multiplying the modified transient daily summer mass values (m w.e.) with the total surface area of the glacier (3.21 km^2). The final values are shown in table 3. Given the high correlation coefficients and the high similarities of the modeled and the calculated mass balance values, a total uncertainty, caused by errors in measurements, interpolations and models, of 10% was assumed versus an error of 5% for the observed values.

Melt of snow on valley sides

Östling and Hooke (1986) calculated the snow melt on the valley sides around Storglaciären with an uncertainty of 25% in the period June 15 until August 2 using aerial photographs. Unfortunately, no measurements have been done on the extent of snow patches on the valley sides draining to the glacier during the ablation season of 2005. Melt rates on the valley sides are expected to be higher than those on the glacier because air moving over low-albedo bedrock and talus slopes and thence over the snow patches will be warmed by the former. In addition, the snow patches are commonly much steeper than the glacier surface in the corresponding altitude interval, so the surface area for energy exchange is larger on the valley sides (Östling and Hooke, 1986). However, in this study snow melt

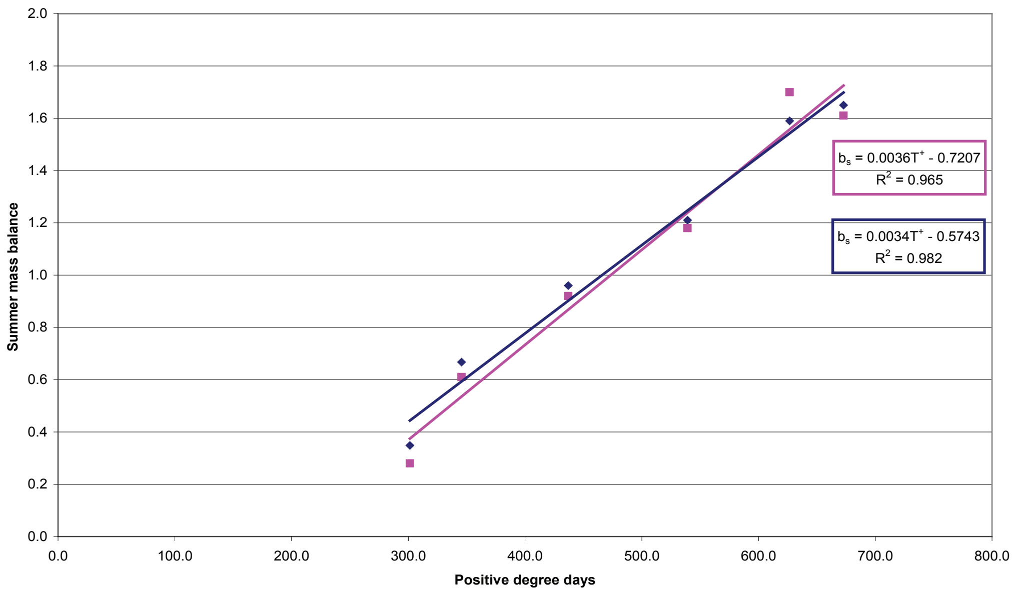

Figure 9.Correlation between transient summer mass balance and the Positive degree-day using. kriging (blue) and the ablation gradient (pink) at Tarfala Research Station.

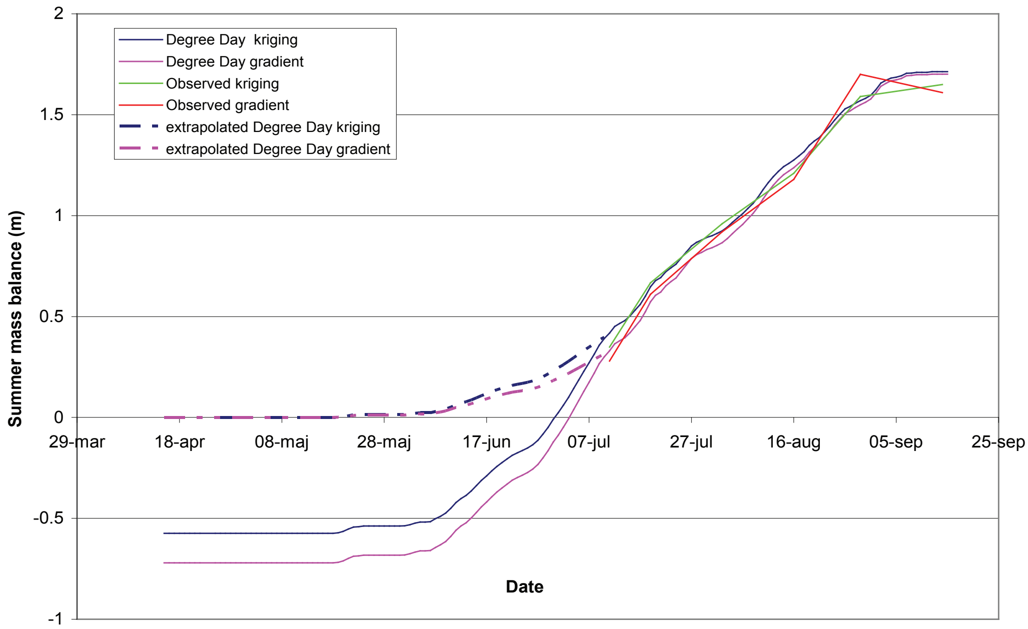

Figure 10. Transient modeled and observed summer mass balance .

on the valley sides was assumed to be negligible in the period July 1 until September 15. Snow remaining on the sides that has melted during the course of this study is thus included in the storage term of eq. (X).

Runoff

The discharge from Storglaciären was determined by subtracting the continuous discharge curve from the hydrological station Rännan by the records from the Lillsjön outlet (henceforth called Lillsjön only), and not, unfortunately, by using the hydrological stations of Nordjokk and Sydjokk. The latter two hydrological stations were inactive during the summer of 2005, although these stations, located directly below the terminus of Storglaciären, could measure the direct runoff from Storglaciären (3.21 km^2). The resulting runoff by subtracting Rännan by Lillsjön consists of runoff from the Storglaciären-catchment (4.55 km^2) which consist of a significant area of non-glacierized (1.34 km^2).

The uncertainty of the calculated runoff from Storglaciären is caused by several factors. First, there are uncertainties in the rating curves of both Lillsjön and Rännan. The rating curves were not extrapolated to high discharge values. No calibration measurements have not been made when discharges were higher than 4.0 and 17.0 m^3/s for respectively Lillsjön and Rännan, respectively. However, these high discharge values are rare in general, and occurred in 2005 only during the large rainfall event late August. Second, it was assumed that the runoff in the Storglaciären-catchment was predominately caused by Storglaciären with a negligible contribution from the non-glacierized areas. However, this assumption is expected to be invalid during large rainfall events, *e.g.* August 26. To overcome these uncertainties, a range of ±10% was calculated for the discharge values.

The hydraulic head was measured at both stations Rännan and Lillsjön every two minutes. This could be converted to a continuous discharge record using the rating curves for both stations (Snoek, 2005 *in press.*). The mean hourly discharge (figure 11) and the cumulative discharge were calculated from July 1 until September 15 by summing the daily discharges. The total discharge during the survey period was 7.50(±0.75)×10^6 m^3/s. The most noticeable features

Table 3. Final modeled and observed summer mass balance values

Period	b_s DDF kriging		b_s DDF gradient		b_s Observed kriging		b_s Observed gradient	
	(m w.e.)	*(10^6 m^3)*	*(m w.e.)*	*(10^6 m^3)*	*(m w.e.)*	*(10^6 m^3)*	*(m w.e.)*	*(10^6 m^3)*
15-04 – 14-09	1.71±0.17	5.50± 0.55	1.70± 0.17	5.46± 0.55	1.65± 0.08	5.30± 0.27	1.61± 0.08	5.17± 0.26
01-07 – 15-09	1.48±0.15	4.75± 0.47	1.52± 0.15	4.88± 0.49	-	-	-	-

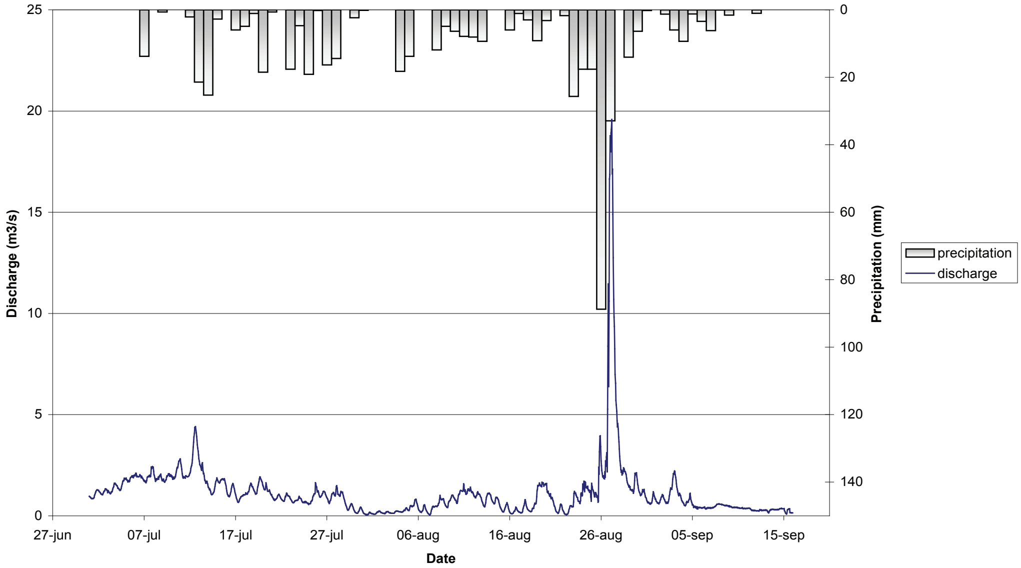

Figure 11. Mean hourly discharge from Storglaciären.

of the discharge curve merit some comments. The first period was characterized by rising discharge values due to high temperatures and therefore high melt-rates. The subsequent lower discharge values were caused by lower temperatures. Small rainfall events caused minor discharge peaks. The low discharge values followed during the cold and stable period in late July-early August. After a period of instable weather with many small rainfall events and corresponding peaks in discharge, a major rainfall event caused very high discharge values (up to 20 m^3/s) on August 26 and 27 (figure 12). The winter recession occurred after September 4, with very low discharge values. However, figure 4 shows that discharge from Storglaciären was very low already two days after the major precipitation event.

Other inputs and losses

Evaporation (including sublimation) and condensation on the glacier surface were assumed to be negligible

Figure 12. High discharge in Nordjokk as it emerges from the terminus of Storglaciären on 26 August 2005 (Photo by Y. Snoek).

(Östling and Hooke, 1986). Studies in humid areas such as the Rocky Mountains (Martinelli, 1960) or Abisko in northern Sweden (Nyberg, 1965) show that evaporation and condensation often nearly balance each other. It should be noted that over time periods of a few days, condensation and evaporation may not be equal (Lang, 1980). Under normal summer conditions, evaporation would dominate during the early part of the melt season and condensation during warm periods later in the season (Östling and Hooke, 1986). This could lead to modest errors in short-term water balances. In the non-glazierized area, evaporation, soil storage and groundwater flow should be taken into account. Although these processes were not studied and numbers are unknown, some qualitative remarks should be done. Evaporation will lower the inputs (rainfall and melt), although the rates are low in high-alpine areas (Verbunt *et al.*, 2003). Soil storage and groundwater flow in the non-glazierized area will delay the runoff. These terms, however, are also considered of minor significance with view of overall water resources in high mountainous catchments (Verbunt *et al.*, 2003). Two other sources of water losses from the glacier are ice melt by geothermal heat and melt by dissipation of strain energy. Both processes could however result in negligible additions of melt water (Östling and Hooke, 1986). Refreezing of melt water and rain in cold firn was assumed to occur only in the early part of the melt season and was therefore excluded in this analysis.

Water balance

Cumulative curves of the inputs to and losses for both Storglaciären only (3.21 km^2) and the Storglaciären-catchment (4.55 km^2) were calculated during the survey period from June 30 to September 15 (table 4 and figure 13). Because precipitation and melt were calculated by different methods (as discussed above), the calculated results were averaged. The storage was calculated as the difference between inputs (melt and precipitation) and losses (runoff), using the equation:

$$\Delta S = (P + M) - Q \qquad \text{(equation 3)}$$

Table 4 Water balance components 1 July-15 September

	Specific m^3/m^2	Total 10^6 m^3
Melt	1.50±0.15	4.81±0.48
Precipitation	0.49±0.05	2.23±0.21 1.57±0.15[a]
Runoff	1.65±0.17 2.34±0.23[a]	7.50±0.75
Storage	0.34±0.37 -0.35±0.43[a]	-0.46±1.44 -1.11±1.38[a]

[a] values were calculated using the surface area of the glacier only (3.21 km^2) instead of the area of the Storglaciären-catchment (4.55 km^2)

where ΔS is the change in storage, P is the precipitation, M is the melt, and Q is the runoff.

Since the arbitrary zero cumulative water balance was defined on June 30, relative curves of all water balance components (melt, precipitation, runoff and storage) were created. As a consequence, an analysis of general trends and relative changes in water storage could only be performed.

Both storage calculations (Storglaciären proper and Storglaciären catchment) show the same pattern. The most remarkable difference, however, is a higher positive storage for the Storglaciären-catchment. The higher storage amounts in the Storglaciären-catchment were caused by higher total precipitation amounts, but several processes in the non-glacierized area as evaporation, soil storage and groundwater flow were neglected in this study since their amounts were considered of minor significance compared to the overall water resources. All these terms, however, represent water loss and the storage of the Storglaciären-catchment input was therefore likely overestimated. Although the runoff was caused by drainage from the glacier (3.21 km^2) as well as from non-glacierized areas (1.34 km^2), I assumed that the runoff from non-glacierized areas was negligible. However, glacial runoff was likely overestimated during rainfall events, because we can expect that the non-glacierized areas also contributed to the total runoff following rainfall events. The true runoff from Storglaciären should therefore have been lower, resulting in a higher storage. The true glacial storage is thus expected to be in between both calculated storage terms from the Storglaciären-catchment and the Storglaciären-glacier.

In mid-July, the storage was negative for both calculations, shown by the negative slope of the storage curves. It is expected that melting of snow on the valley sides due to warm temperatures with high melt rates contributed to a significant increase of the runoff. Since the snowmelt on the valley sides was excluded in this analysis, the melt values used were likely providing an underestimation of the true values, resulting in negative storage. In addition, the melt on the glacier had to be extrapolated since no ablation measurements were available before July 11. The positive slope of both storage curves from July 13 was caused by relative large rainfall amounts (51.6 mm.) in the period July 13–15 and an associated relatively low increase in runoff. This can be explained by the storage of rainfall in firn, which is generally considered as a major factor causing runoff delay (Jansson *et al.*, 2003) and subglacial storage in cavities and channels beneath the glacier (Iken *et al.*, 1996). Whereas a net release of water in mid-summer was expected due to decreasing snow storage (snow melt throughout the season) and a more efficient internal drainage system of the glacier (Östling and Hooke, 1986; Hock and Hooke, 1993; Seaberg *et al.*, 1988), the storage remained positive with an increasing positive slope

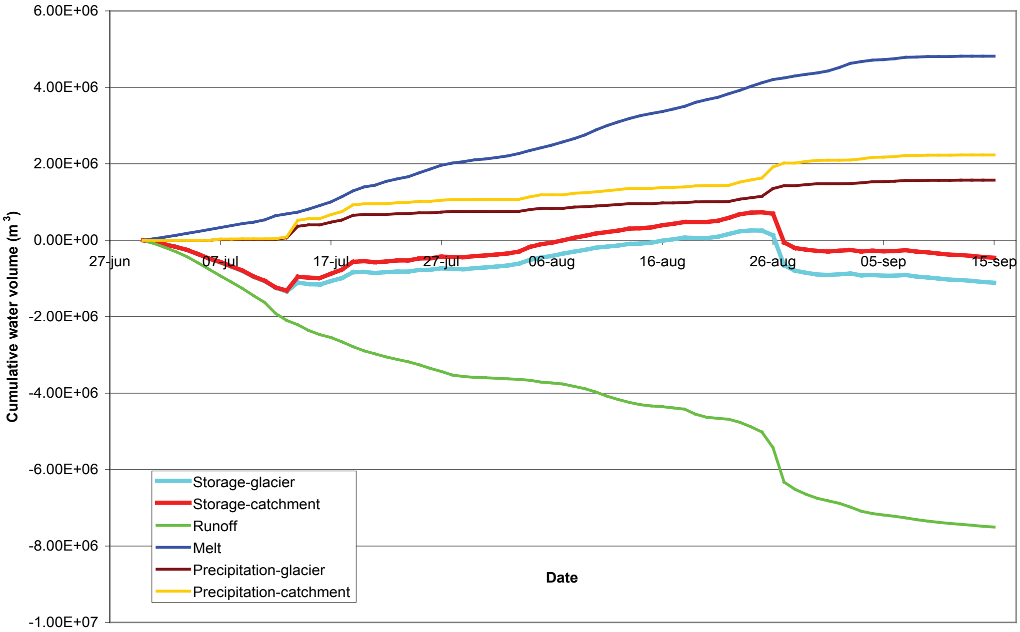

Figure 13. Cumulative curves showing inputs to and losses from Storglaciären (3.21 km2) and Storglaciären catchment (4.55 km2) during the survey period. Storage is the cumulative difference between input and loss.

of the storage curves in August. Since the snowline retreated as the ablation season progressed, the storage must be caused by internal storage in subglacial and englacial cavities, crevasses and channels. The large rainfall event on August 26 caused major changes in the storage curves. Keep in mind that the total amount of rainfall during this rainstorm is likely to be underestimated due to horizontal rainfall which was not captured in the rain gauges. The relative large increase in runoff (0.9×10^6 m^3), however, can not be explained by the precipitation (and the melt) alone (0.1×10^6 m^3). It is therefore expected that this rainfall event caused significant changes in the internal drainage system of the glacier by either rearranging the channel network or by simply enlarging the conduits. About 50% of the stored water was released within one day when considering the Storglaciären-catchment compared to almost 80% for Storglaciären only, equal to ~0.8×10^6 m^3. A similar rearranging of the channel network or enlarging of the conduits after a major rainstorm was also observed in 1992 (Jansson, 1996). Following this sudden release, a gradual decreasing slope continued until the end of the survey period. Cold temperatures caused the glacier melt to stop and the precipitation was in the form of snowfall. The release of water under these winter conditions was likely originated from basal water systems and from firn storage (Östling and Hooke, 1986; Jansson, 1996; Verbunt *et al., 2003*).

Discussion and Conclusions

Water is stored in the major part of the melt season in firn, subglacial and englacial cavities and crevasses. The maximum amount of storage varied between 1.2 and 1.6×10^6 m^3 and occurred in late August (compared to July 1). A release of the stored water (~0.8×10^6 m^3) occurred within one day after a major rainfall event in late August. It is likely that this volume is overestimated caused by an underestimation of the measured precipitation in the rain gauges. A gradual release of stored followed this small outburst flood under winter conditions with very low melt rates and precipitation occurring in the form of snowfall.

A different pattern of the seasonal storage behavior was found compared to a similar study in 1984 (Östling and Hooke, 1986). They found a net storage during May-June and net loss in late July and September. The volume of maximum storage was in good agreement with the maximum volume of subglacial activities found in the study from Hooke *et al.* (1983a). They found that subglacial cavities begin to open in mid-July and reach a maximum of ~0.5×10^6 m^3 in early to mid-August. This volume is however lower than the estimate of the maximum volume of water storage found in this study. Since the ice velocities have been increased during the last two decades (Jansson, 2005, *pers. comm.*), changes in internal drainage characteristics are expected. In general, glacial channel conduits and cavities experience both pressures from melt water as well as pressure from the ice flow (Östling and Hooke, 1986). It is speculated that increasing flow rates will decelerate the channel and cavity growth throughout the melt season, resulting in a slower efficient drainage system development. Water will therefore probably be stored longer in the glacier.

Differences in the internal drainage system characteristics of Storglaciären were studied when considering the water balance components in detail for both 1984 and 2005. It should be remarked that the final storage calculations in 2005 were performed in the period July 1 until September 15, whereas the study in 1984 covered the period May until September. The summer of 2005 had a higher mean summer temperature (6.7°C *at Tarfala Research Station*) than the summer of 1984 (5.2°C *at Tarfala Research Station*) although 1984 was characterized by profound melting conditions (T>10°C *at Tarfala Research Station*) in late-May; these high temperatures did not occur before mid-July in 2005. Precipitation amounts (rainfall) were significant higher in 2005, 513.9 mm in 2005 (May until mid-September) versus 413.2 mm in 1984. The summer mass balance was slightly lower in 2005 (1.65 m w.e.) than in 1984 (1.73 m w.e.). Runoff values in the period mid-June until mid-September were significant higher in 2005 with a total value of 8.8×10^{6} m^{3} versus 7.0×10^{6} m^{3} in 1984. The runoff amounts started to decrease from mid-August in 1984, whereas 2005 was characterized by a significant increase in runoff in late-August. It is likely that weather conditions (mainly temperature and precipitation) have a significant impact on the internal drainage system of a glacier. As discussed above, the melt season of 1984 started relatively early (mid-May). In addition, the first part of the summer was characterized by relative higher rainfall amounts compared 2005. Three major rainfall events occurred in the period late-June until mid-July 1984 (P>25 mm. *at Tarfala Research Station*). A relative dry and cold late-summer followed. The melt season of 2005 started later (begin June) and was relative drier during the first part of the summer. The second part of the summer 2005 was significant wetter with a major rainstorm on August 26 (P = 67 mm. at Tarfala Research Station). Warm and wet weather conditions in the first part of the melt season (as in 1984) will enhance the water supply (meltwater and rain) to the subglacial and englacial drainage system. This, in turn, will stimulate the development of an efficient subglacial and englacial channel network, reducing the water storage in the glacier. In contrast, relative dry and cold weather conditions in the first part of the summer will reduce the speed of the channel network development resulting in a longer period of storage. However, the very wet conditions in the late summer accompanied by relative little firn coverage on the glacier caused significant amounts of water to enter the subglacial and englacial drainage system and a subsequent quick development of an efficient drainage system.

Further research is required in order to understand the processes involved in glacial storage and the intra-annual and inter-annual variations of these processes.

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