Technical Report

TR-09-13

# Spatial and temporal variations in glacier hydrology on Storglaciären, Sweden

Peter Jansson, Department of Physical Geography and Quaternary Geology, Stockholm University

Jens-Ove Näslund, Svensk Kärnbränslehantering AB

June 2009

**Svensk Kärnbränslehantering AB**
Swedish Nuclear Fuel
and Waste Management Co

Box 250, SE-101 24 Stockholm
Phone +46 8 459 84 00

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# 1 Introduction

The aim of the current research project was to provide a framework of real conditions within which to interpret theory and extrapolate likely conditions beneath a future ice sheet over Fennoscandia. The purpose of this report is to summarize the experimental work on glacier hydrology and basal hydraulic conditions performed on Storglaciären, northern Sweden, during the years 1990–2006.

Surface fed subglacial hydrological systems are extremely dynamic because the input rates of rain and temperature-controlled surface melt fluctuate, and the geometry of flow paths is constantly changing due to ice deformation which tends to open and close the flow paths. The hydrological system of a glacier is quite unusual because since liquid water flows through conduits made of its solid phase (ice). Understanding the expected dynamic range of a glacier's hydrological system is best studied by *in situ* measurements. The processes studied on Storglaciären can be expected to apply to ice sheet scale, albeit on different spatial scales. Since Storglaciären is a polythermal glacier /e.g. Fowler and Larson 1978/ with a large fraction of ice below freezing and at the melting point and with a surface-fed hydrological system of conduits and tunnels, results apply to the lower elevation regions where the surface is composed of ice (ablation zone) rather than composed of snow (accumulation zone) found at higher elevations of the glaciers and ice sheets, Therefore, our results apply to the ablation zone of the past Fennoscandian Ice Sheet.

In this report we discuss the measurements made to assess the subglacial conditions that provide a potential analogue for conditions under the Fennoscandian Ice Sheet. For this purpose field work was performed on from 2003 to 2006 yielding subglacial water pressure measurements. We have included a large quantity of unpublished data from Storglaciären from different research projects conducted since 1990. Together these data provide a picture of the temporal and spatial water pressure conditions in and under Storglaciären. This report is the first comprehensive analysis of these subglacial water pressure records.

# 2 Glacier hydrology and hydraulics

A glacier's hydrological system is complex and numerous studies have attempted to describe the features of the system and to model and its components /e.g. Hooke 1989, Hubbard and Nienow 1997, Fountain and Walder 1998, Hooke 2005/. /Fountain and Walder 1998/ and /Jansson et al. 2007/ summaries the state of theoretical knowledge on glacier hydrology and we will not elaborate these topics further in this report. Instead, we focus on the empirical results and insights gained from field studies at Storglaciären.

Basal water pressure variations under glaciers and ice sheets affect many aspects of the glacier environment. The dynamics of glaciers is directly affected by water pressure because of the dependence of the glacier sliding speed upon basal water pressure /*e.g*. Iken and Bindschadler 1986, Jansson 1995/. Indeed, similar relationships have now invoked to explain seasonal variations in speed of the Greenland ice sheet /e.g. Zwally et al. 2002/. Subglacial hydrology also affects groundwater /e.g. Boulton et al. 1995, Boulton and Caban 1995/. The subglacial pressures are higher than atmospheric which forces water into the ground more efficiently than subaerial surface water. In addition, the subglacial water pressure gradients follow the surface gradient of the ice sheet with some distortion from underlying surface topography /*e.g*. Shreve 1972, Piotrowski 1997, Bremer et al. 2002, Hoaglund et al. 2004, Bauder et al. 2006/, and hence water flow can be directed in different directions to that inferred from the surface gradient of the ice sheet.

# 3 Field site

Storglaciären (Figure 3-1 and 3-2) is a 3.1 km$^2$ valley glacier in northern Sweden (67º55’N, 18º35’E; 1,139–1,700 m.a.s.l.) and is one of the best studied glaciers in the world /*e.g*. Jansson 1996, Holmlund and Jansson 1999, Holmlund et al. 2005/. This glacier has a long history of study dating from 1946 when a mass balance monitoring program was initiated /Schytt 1959/. This program now constitutes the world’s longest continuous measurement of glacier mass balance /*e.g*. Østrem and Brugman 1991, Kaser et al. 2003/ and is of fundamental importance to climate research, such as the /IPCC 2001, Lemke 2007/ and the /ACIA 2004/ reports.

The subglacial topography of the glacier is well known /Björnsson 1981, Herzfeld et al. 1993/ with a maximum depth of about 250 m. This allows accurate modeling of both ice flow dynamics /*e.g*. Hanson 1995, Albrecht et al. 2000/ and hydrology /Kohler 1992, 1995, Schneider 2001/.

The wide variety of glaciological research performed on the glacier, including studies of glacier mass balance, hydrology and dynamics, which have yielded a wealth of background information that allow design and execution of advanced studies of different aspects of the glacier system. Earlier studies focussed on the role of the hydrological system on the dynamics of the glacier /*e.g*. Jansson and Hooke 1989, Hooke et al. 1989, Jansson 1995, 1997, Hooke et al. 1997/. Among the noteworthy findings are the first identification of a spring speed-up in response to the onset of melting /Jansson and Hooke 1989/; the seasonal, sub-seasonal and diurnal variations in ice surface velocity in response to variations in water pressure /Hooke et al. 1989, Jansson 1995, Hanson and Hooke 1994, Hooke et al. 1997/; and finally the coupling mechanisms between the glacier and its bed /Iverson et al. 1994, 1995, Hooke et al. 1997/.

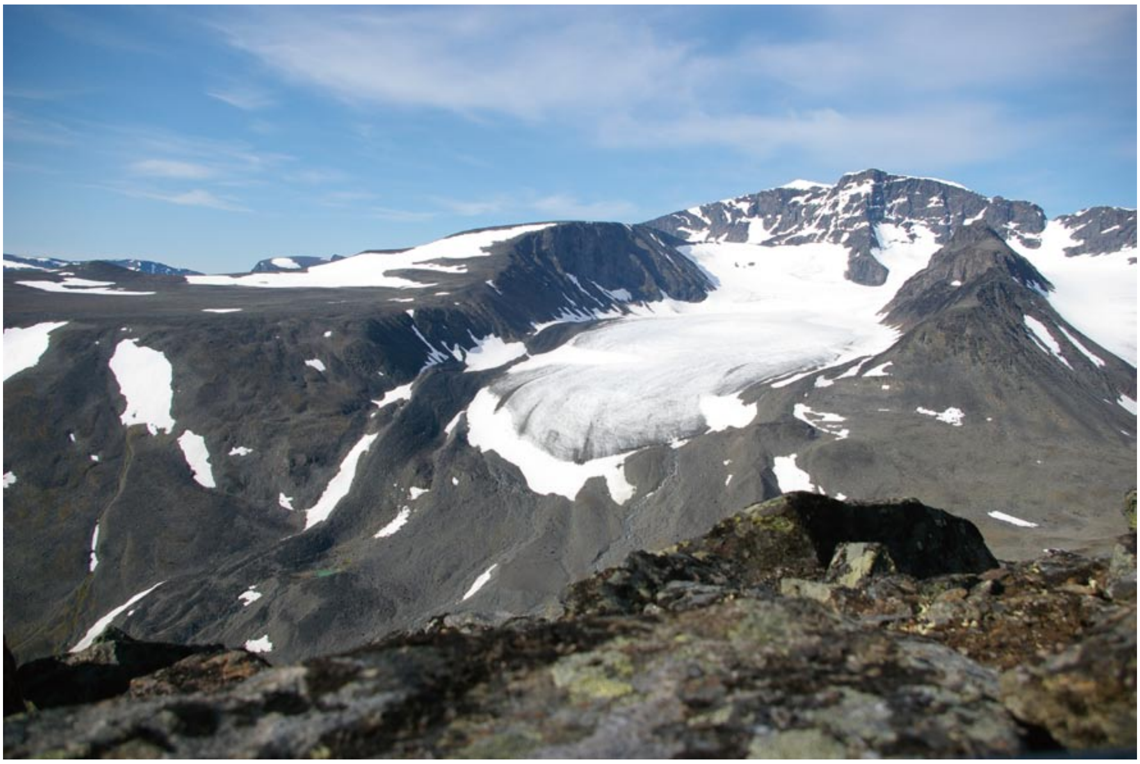

***Figure 3-1.*** *Storglaciären in the Tarfala valley, northern Sweden 18 August, 2008 at 09:00 in the morning. The snow clad peak in the background is the Kebnekaise south peak, the highest peak in Sweden (2,105 m.a.s.l. in Aug. 2006) and capped by a glacier. Photo Peter Jansson ©.*

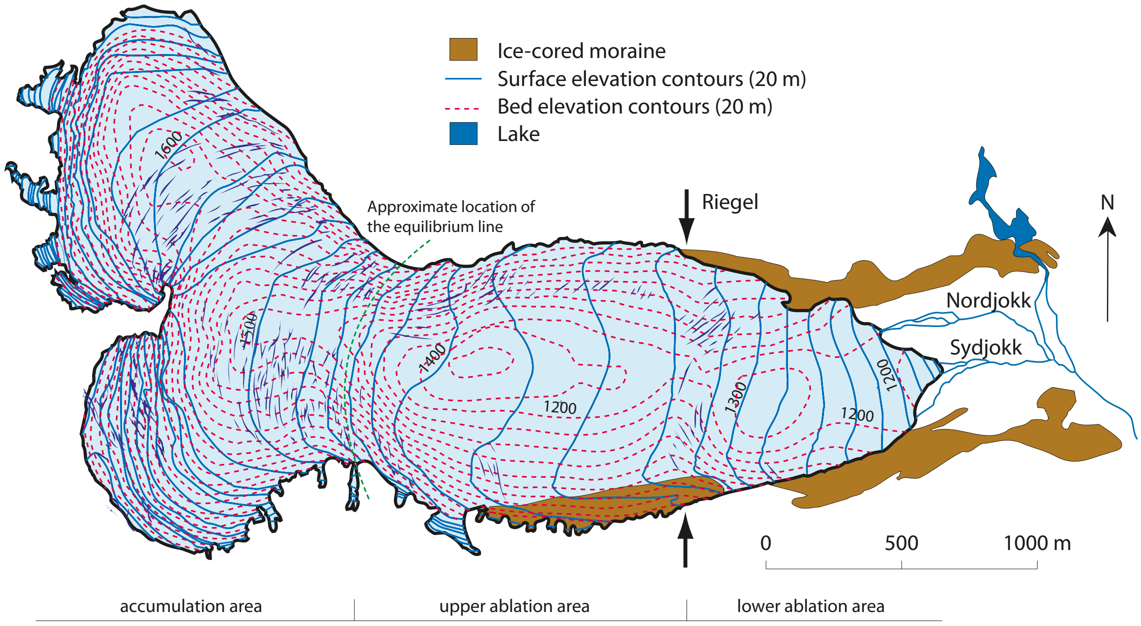


***Figure 3-2.*** *Map of Storglaciären showing both surface (solid contours) and bed topography (dashed contours). Note the overdeepenings as indicated by closed bed elevation contours and the location of the bedrock riegel downstream from the main overdeepened basin.*

Storglaciären has a perennial cold (< 0ºC) surface permafrost layer encompassing much of the ablation zone and a small fraction of the accumulation zone /Holmlund and Eriksson 1989, Pettersson et al. 2003, 2004, in press/. The cold surface layer has an average thickness of 30 m with a thickness range from about 20 to 50 m. Water penetrates this cold layer through crevasse fields just up-glacier from the equilibrium line and in the lower part of the ablation zone /Fig 3-2; e.g. Stenborg 1969/. Water emerges in two streams, Nordjokk and Sydjokk. These have been shown by /Stenborg 1969/ to drain different parts of the glacier. Nordjokk largely drains water from the accumulation area whereas Sydjokk largely drains surface melt generated in the ablation area that enters the glacier in moulins forming over the riegel area. Nordjokk flows past the ablation area along the bed fn the northern margin of the glacier. Sydjokk water flows below the lowermost part of the ablation area (down-stream of the riegel). A large over-deepened section exists in the bed topography down-glacier of the equilibrium line. Due to the overdeepend basin, the glacier has both an extensive englacial and subglacial drainage system The diversity in drainage systems represented in Storglaciären is one of the features of this glacier that make it an ideal test site.

# 4 Local conditions in Storglaciären from previous studies

The internal drainage system of the glacier was first studied by /Stenborg 1965, 1969, 1973/. He showed (1965) that there was water drained from the glacier throughout the winter season indicating a storage of free water in the glacier He also showed that the glacier surface could be divided into discrete drainage areas /Stenborg 1969, 1973/, each draining a specific part of the glacier surface and each connected to a specific part of the system of proglacial streams exiting from Storglaciären, a result confirmed by /Kohler 1992, Hock and Hooke 1993/.

Most of 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 3-2). The ablation area can also be divided into two parts, separated by a zone of moulins located over subglacial bedrock ridge. Upglacier from this zone the ablation area drains into the moulins and routed to Sydjokk. Downglacier, the ablation area drains mainly supraglacially into both streams. /Stenborg 1973/ correctly postulated the existence of a subglacial ridge based on his interpretation of the tracer studies.

/Nilsson and Sundblad 1975/ modeled the run-off from the glacier using linear reservoir theory and showed that surface melt is not routed directly to the proglacial streams.

An investigation of moulins showed that water backed up in the moulins /Holmlund and Hooke 1983/. /Holmlund 1988a/ applied the model of /Shreve 1972/ to infer subglacial drainage paths underneath Storglaciären. He also map the surface expression of relict moulins to a depth of 40 m below the initial surface /Holmlund 1988b/. A large number of tracer studies were performed during the years 1984 to 1989 /Zimmerer 1987, Hooke et al. 1988, Seaberg et al. 1988, Hooke 1991, Kohler 1992, Hock and Hooke 1993/, during which most of our current understanding of the geometry and behaviour of the subglacial drainage system was established. The tracer studies have been augmented by borehole video investigations /Pohjola 1994, Hooke and Pohjola 1994/, indicating the presence of englacial conduits in the over-deepened basin of the glacier.

Cumulatively, these hydrological studies show there is a difference in the drainage through the lower and upper parts of the ablation area, as divided by the zone of moulins over the riegel. The upper part seems to drain slowly and englacially with most of its water originating in the firn area /Hooke et al. 1988, Hooke and Pohjola 1994/. /Hooke et al. 1988/ found that water drained englacially from thermally drilled boreholes that connected with the bed. Tracers poured into a borehole in the centre of the main overdeepening appeared at the terminus over a 1–3 day period The same study also showed that water flowed from the bed into the hole. The water pressure at this location is generally high, > 75% of the ice overburden pressure (B94-4 in Figures 4-1; refer also to Fig 5-9), but diurnal oscillations in water pressure are small /e.g. Jansson 1995/. The pressure record in Figure 4-1 exhibits diurnal variations that are much larger than previously recorded in this area of the glacier. However, the borehole was located in a crevassed area (c.f. Fig 3-2 and 4-1) and may thus be influenced by melt water influx into the crevasses reaching the borehole. The water exiting the glacier from this area is found mainly in Nordjokk, which has relatively little suspended sediment. This implies that most of the water is not in contact with the glacier bed but drains englacially.

/Fountain et al. 2005ab/ investigated the englacial hydrology of the overdeepened basin in order to test the hypothesis proposed by /Röthlisberger 1972/ and /Fountain and Walder 1998/ regarding the development and characteristics of englacial drainage through overdeepened troughs in the glacier bed. Fountain et al. found that there is an active englacial drainage system in the overdeepening (upper ablation area in Figure 3-2) and that it is made up of linked englacial crevasses. This hydrological system has never been observed prior to this study although englacial crevasses have been observed earlier without making a connection to a drainage system.

The entire drainage network in the lower part of the glacier (downstream of the riegel) seems to be poorly developed at the start of the melting season with a large number of smaller conduits that connect in a braided pattern /Hock and Hooke 1993/. As the season progresses the drainage system develops into one consisting of a few large conduits. Because of this, the transfer time of water pulses becomes shorter as the season progresses. At the end of the season the conduit system

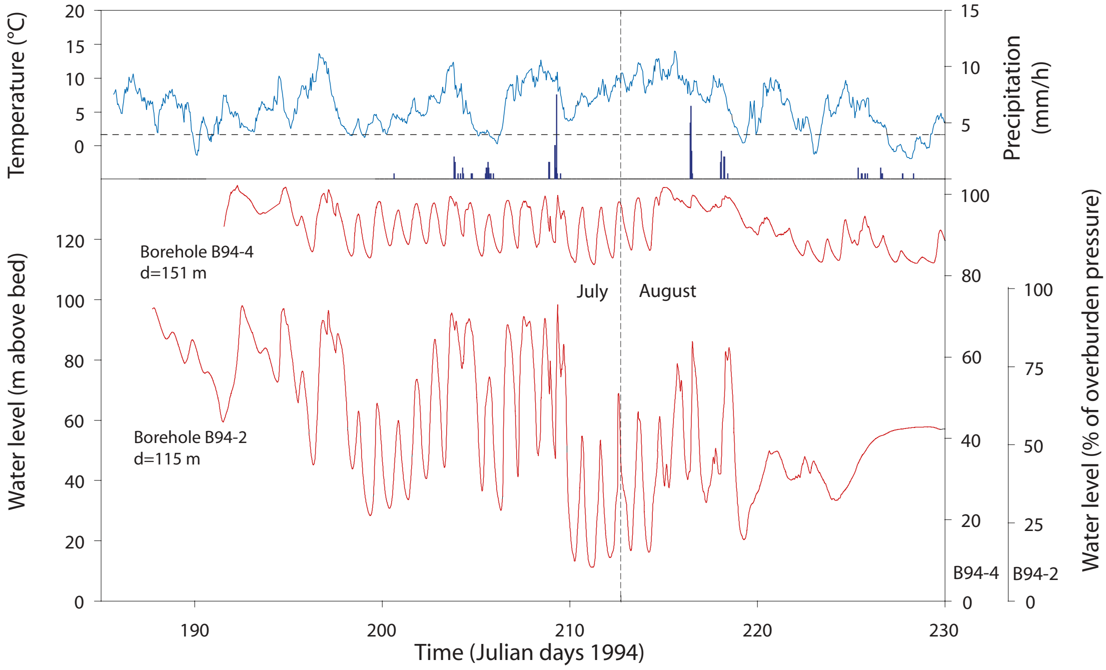


***Figure 4-1.*** *Water pressure records from boreholes B94-2 and B94-4 (see Figure 5-9 for locations). Air temperature recorded on site on the glacier is shown as the solid line in the upper panel (sale to the left). Precipitation recorded at nearby Tarfala Research Station is shown as bars in the upper panel (scale to the right) /from Jansson 1996/.*

probably is similar to that of the root system of a tree /Hock and Hooke 1993, fig 6 p. 543/. Based on hydraulic properties of the system, the subglacial tunnels are envisioned to be low and wide which causes them to close rapidly when water pressure is low /Hooke et al. 1990/. This water exits the glacier mainly in Sydjokk that usually is very turbid, inferring good contact with the bed through the entrainment of basal sediments. During summer the water pressure exhibits large amplitude diurnal fluctuations, with highs near or even above the ice overburden pressure and lows near atmospheric pressure (B94-2 in Figure 4-1). During winter the water pressure gradually starts to build up as conduits close from plastic deformation. The water thus drains through the moulins to the bed and remains subglacial to the terminus. The surface water of the lower part of the ablation area drains directly into the proglacial streams by way of surface run-off /Kohler 1992/.

The drainage system on Storglaciären is thus divided into two significantly different parts (Figure 4-2). In the lower part of the ablation area, downstream of the riegel, water pressures vary from close to atmospheric pressure to around overburden pressure and respond with a clear diurnal signal from water input in moulins at the riegel. In the upper part of the ablation area, water pressures are generally high, to within 20% of over-burden pressure showing lower amplitude variations, sometimes in response to diurnal variations in input but sometimes also forced by other factors such as reorganization of the drainage system. The riegel thus imposes a distinct break in the continuity of the system.

The firn area has not been investigated to the same extent as the ablation area. A tracer poured into a crevasse appeared at the terminus over a 35 day period, 25% of the dye was never recovered /Hooke et al. 1988/. A similar test done in a moulin on the southern side of the glacier, well above the equilibrium line, did not yield any dye in Sydjokk. Most of the dye seems to have passed through the glacier slowly and emerged in Nordjokk. /Schneider 1994/ showed that diurnal fluctuations in the water table do occur in crevasses and water pockets at his investigation location, but the fluctuations are small. The water level in the firn aquifer exhibits only longer-term fluctuations that correlate with rainfall events and possibly longer-term temperature variations. The coupling between the firn aquifer and the rest of the drainage system is poorly known.

/Schneider 2001/ used /Shreve's 1972/ formulation of the equipotential field in glaciers and applied it to Storglaciären. A basic assumption in Shreve's theory is that the local water pressure in conduits is in equilibrium with the local ice pressure everywhere in the ice mass. This is not true for a real

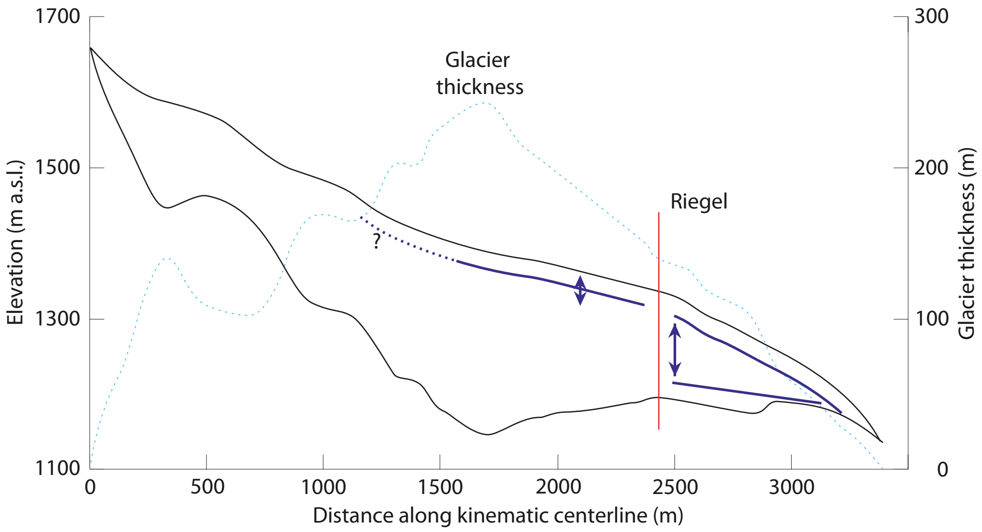


***Figure 4-2.*** *Schematic drawing summarizing expected variability and general water levels in the hydrological system along the inferred kinematic centreline of Storglaciären. The figure also shows the surface and bed topography and the ice thickness.*

glacier, where water pressures vary, but still serves to provide a first order picture of expected flow directions. By applying this equation to the geometry of Storglaciären, Schneider calculated the potential field shown in Figure 4-3. An analysis of Shreve's equation shows that the equipotential planes slope at an angle corresponding to $-11\alpha$, where $\alpha$ is the local surface slope of the glacier. Figure 4-3b shows this relationship well. The equipotential field therefore forces water flow from the surface towards the bed, in a direction perpendicular to the equipotential planes. Water will thus be forced towards the bed. Since glaciers are typically significantly longer than their thickness, surface water will inevitably reach the bed. It is important to remember that Shreve's model does not include crevasses, or low pressure conduits that can be found on real glaciers. If low pressure conduits are present, the pressure field will be distorted and water flow redirected accordingly. Once water flow is at the base of the glacier it will follow flow paths determined by the gradient in the potential field at the base of the glacier (Figure 4-3a).

The calculated water potential field beneath Storglaciären provides means for understanding the effect of pressurized water flow in a glacier: water injected at A in the figure will flow along the path outlined by the solid line (Figure 4-3a). The deepest part of the valley, and therefore, the routing of water under atmospheric conditions, is given by the dashed line. As can be seen, the two paths diverge and the end result is that water under glaciated conditions will not emerge at the deepest point in the valley. In the case of Storglaciären the difference between pressurized and atmospheric conditions is not large, a translation of about 100 m after some 3 km of flow distance. However, Storglaciären is a valley glacier and as such it is completely controlled by the valley geometry.

Water being forced to flow uphill poses a special problem /e.g. Röthlisberger and Lang 1987/. Water in and under glaciers will be at or very near the melting point. Water entering the glacier will be able to equilibrate with the temperate ice by heat exchange with the surrounding ice, causing melting. Water will also be heated from friction and viscous dissipation of heat. The change in potential energy as it is moving lower into the glacier of course accelerates the water and yields the frictional heat components. Similarly, when water is forced uphill, the gain in potential energy must be acquired somewhere. Since no excess energy is available, the only possible source of energy would be the heat released by freezing ice. Thus, a tunnel on an uphill slope would tend to freeze up, or, put differently, it is unlikely that tunnels will exist on uphill slopes unless certain conditions are met. Supercooling /e.g. Lawson et al. 1998/, however, may reduce the freezing rate and provide a means for water to flow uphill.

/Röthlisberger and Lang 1987/ investigated the conditions under which uphill flow would be severely hampered by freezing and concluded that ratios of 1.3 to 2.0 of surface to bed slope, depending on air saturation in the water, are critical. These values can be used to investigate the locations where subglacial flow beneath Storglaciären is subject to such critical conditions. /Schneider 2001/ has made

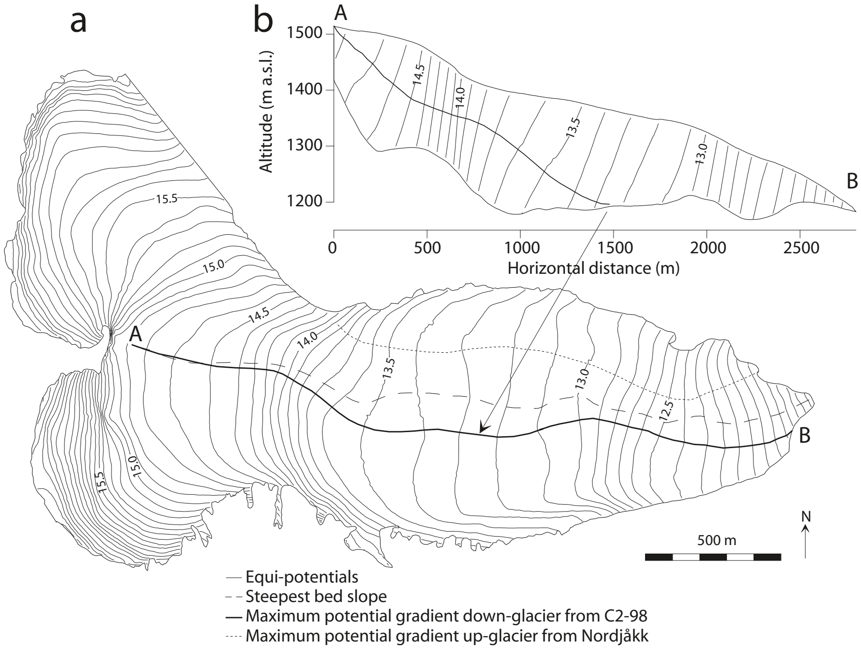


***Figure 4-3.*** *The equipotential field in Storglaciären. (a) Basal equipotential lines indicating the direction of water flow at the base of the glacier (perpendicular to equipotential lines). Water injected at A will follow the thick solid line and emerge from the glacier at B. The dashed line shows the water routing under atmospheric conditions (along the deepest part of the valley). The dotted line shows where the drainage emerging from the northern proglacial stream originates. (b) A cross-sectional view of Storglaciären with the equipotential field showing the routing of water through the ice mass from the surface injection point A. The point at which water from point A theoretically reaches the bed is clearly seen, indicating transport along the glacier bed is likely /from Schneider 2001/.*

such calculations (Figure 4-4) and showed that conditions favourable for freezing occur in patches in the larger over-deepening of Storglaciären. Conditions are not, however, favourable across the entire upslope area of the over-deepening but occur in laterally extensive bands that impose possible restrictions on possible routing of water. Based on this, we can conclude that water flow may be severely restricted as it flows through the main over-deepened trough in the bed topography.

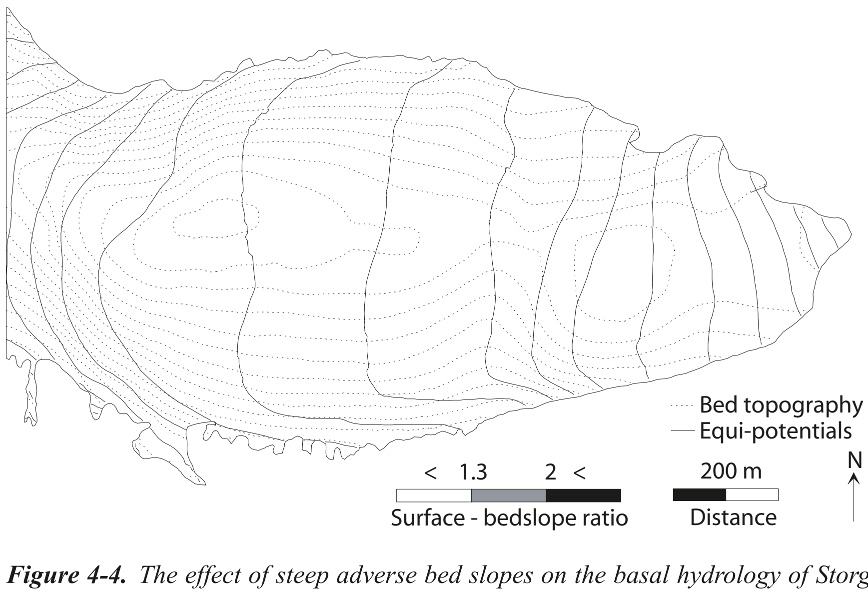


***Figure 4-4.*** *The effect of steep adverse bed slopes on the basal hydrology of Storglaciären. Areas of critical bed-surface slope ratios (1.3–2.0; /Röthlisberger and Lang 1987/) are shown by gray shading and illustrate areas where conduits are not likely to be maintained /from Schneider 2001/.*

# 5 Methods

## 5.1 Boreholes

Boreholes reaching the glacier bed through the entire ice column were drilled using the Stockholm University hot-water drill. The drill used on Storglaciären (Figure 5-1) was designed by /Hedberg and Strand 1998/ and is based on a KEW Contractor diesel-driven hot water high pressure cleaner. Water is pumped from a glacier surface stream and through the system at high pressure by a Speck Triplex Kolbenpumpe P30/30–180 driven by a Briggs and Stratton I/C model 133252 (5 HP/3600 rpm) four stroke engine (Figure 5-2). Water enters the KEW Contractor diesel burner (Figure 5-3) and is heated to 60–80ºC. The heater is coupled to an electronic unit that monitors water flow and temperature and automatically adjusts burner efficiency to maintain even water temperature In case of sudden drop in working pressure or burner flame, the unit automatically is turned off. . The hot water is routed through SPECMA 350 hydraulic hoses that were selected for their insulation properties and low weight. The hot water is ejected through a 2 m long rigid stainless steel drill stem with a sharply conical drill tip attached (Figure 5-4). The shape of the drill tip follows recommendations of G.K.C. Clarke (pers. comm. 1997) and experimental testing.

While drilling, it is important to maintain a vertical direction. This is aided by (1) having the 2 m long drill stem to prevent the nozzle from tilting in the borehole and by (2) using a drill rig (Figure 5-5). The drilling is performed by manually lowering the hose into the hole and making sure the drill tip is not in contact with the borehole bottom, since such incidents may cause the drill stem to tilt in the borehole and hence result in a non-vertical hole. For water pressure measurements, the borehole does not need to be vertical since the pressure from the water column will be the same regardless of the borehole geometry. However, it is advantageous to maintain a vertical drilling direction to reduce the likelihood that the pressure transducer may get hung up in the borehole during lowering.


***Figure 5-1.** The Stockholm University hot water drill in operation on Storglaciären. Photo Peter Jansson ©.*

***Figure 5-2.*** *The Stockholm University hot water drill, burner and operation electronic unit assembly. Photo Peter Jansson ©.*

***Figure 5-3.*** *The Speck high pressure piston pump used to drive water through the hot water drill system. Photo Peter Jansson ©.*

***Figure 5-4.*** *The hot water drill 2 m drill-stem and nozzle under full pressure. Photo Peter Jansson ©.*

***Figure 5-5.*** *The hot water drill drill-rig in operation. Use of the rig enables better control of the drilling process to e.g. prevent non-vertical boreholes. Photo Peter Jansson ©.*

## 5.2 Water pressure measurements

Water pressure measurements were made with Geokon 4500 vibrating wire transducers (www.geokon.com) connected to Campbell CR10X automatic data loggers (www.campbellsci.co.uk). The Geokon vibrating wire transducers are based on the principle of a self-vibration frequency of strings. The sensor (Figure 5-6) is built up of taught string housed in a hermetically sealed and evacuated space in which it is anchored at one end to a fixed wire grip and anchored at the other end to a pressure sensitive flexible metal membrane. As the sensor experiences a change in pressure, the membrane will flex, tightening or loosening the tension of the wire. A coil excited with an alternating current signal with set frequency spectrum, the wire vibrates. Depending on the wire tension and hence the pressure, the resulting vibration will occur at a certain frequency, which can be empirically coupled to a given pressure. By simply counting the number of pulses or oscillations of the wire at its self-vibrating frequency over a given time period, the sensed pressure can be calculated.

Since metals typically are temperature sensitive in terms of thermal expansion, the vibrating wire sensors also have a built in thermistor to record the sensor temperature. With this temperature, it is possible compensate for temperature effects; however, for our investigations on Storglaciären, we set the temperature to 0ºC since we can assume the melt water is at or very near its melting point. It is possible that the basal water beneath Storglaciären is a few tenths of a degree lower than zero but such small temperature effects do not influence the recorded water pressure by more than 100 Pa (0.01 m of water).

On Storglaciären, Campbell Scientific CR10X data loggers have been used to monitor the pressure gauges. The CR10X has a built in function for measuring vibrating wire sensors. This instruction takes a user provided lower and upper frequency and subjects the sensor to a gradually changing alternating current voltage between these frequencies. Once the excitation of the sensor has been made, the logger records the time it takes to count 500 cycles of the now self-vibrating wire vibrations. This number is then converted by factory calibration information to a water pressure. An example of a typical logger program for water pressure measurements is given in Appendix 1.

The employment of a sensor is made by lowering the sensor into a borehole. Since the depth of the borehole is roughly known (to the nearest meter) by the length of drill hose used during drilling, the sensor can be lowered until reaching the expected depth. Once near the expected borehole depth, the sensor is lowered carefully until the tug or the sensor weight ceases in the hand-fed cable, which indicates it has reached the bottom of the borehole. The sensor is gently lifted and lowered until it is certain that the sensor is hanging only a few cm over the bed. It is important to have the sensor as close to the bed as possible without actually resting on the bed because (1) if the borehole closes by ice creep, the sensor will maintain better contact with the basal system if it is near the bed, and (2) if the sensor is *on* the bed it may be pulled beneath the ice and the cable severed by the sliding motion of the ice. Once resting at the bed the water pressure is recorded together with the borehole depth so that the measured pressure can be related to the ice thickness. We assume that the sensors remain in a position negligibly different from the true base of the ice, at least in the sense of the sensor measurement accuracy of 0.1% of full range.

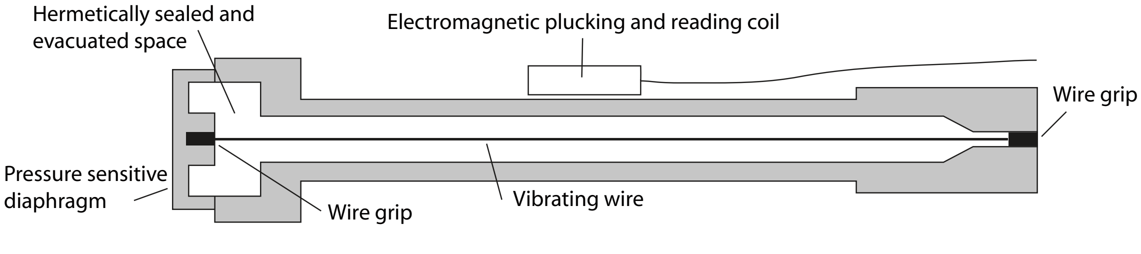


***Figure 5-6.*** *Schematic cross-section of a vibrating wire sensor. See text for more details.*

Because of the cold surface layer on Storglaciären /Pettersson et al. 2003, 2004, 2007/ boreholes tend to freeze shut near the ice surface within a few days of drilling. The time required for the borehole to freeze up depends on several parameters such as the local sub-freezing temperature in the cold surface layer, the rate of input of running water into the borehole and the borehole diameter. The fact that all of our boreholes freeze closed, is a positive effect since it closes the connection between the subglacial drainage and the atmosphere. Once closed the measured water pressures correctly reflect the subglacial pressures. There is, however, no indication that a borehole open to the atmosphere and lacking surface input of water would affect the measured pressures of pressure signal.

## 5.3 Meteorological measurements

Meteorological parameters of air temperature and precipitation are used in this report as a proxy for water input into the glacier and, hence, show the potential for times of high subglacial water pressure assuming good connections between the surface and the bed are provisioned by crevasses and moulins. Comparing recorded water pressure signals and a proxy input signal provides a means for interpreting the state of the system. In this sense, the hydrological system is similar to a black box into which we put the meteorological parameters and from which we receive the system response in terms of a water pressure signal. In order to correctly assess the effects of the meteorological time-series, it is necessary to understand their strengths and weaknesses.

Meteorological measurements are made by the Tarfala Research Station as part of the station monitoring program. A meteorological station is located at the research station at 1,135 m.a.s.l. The station consists of a Campbell scientific data logger logging, on an hourly basis, air temperature incoming radiation, wind speed and direction, air humidity, and precipitation. The sensors have varied slightly through the years but have essentially remained the same since the electronic station was set up in 1987 /Grudd and Schneider 1986/

Several issues regarding the meteorological data need to be addressed.

1. The difference in location between the Tarfala Research Station meteorological station (a point) and the glacier (a ~3 km$^2$ surface).
2. The difference in altitude between the meteorological station (1,135 m.a.s.l.) and the glacier (1,130–1,700 m.a.s.l.).
3. The difference between temperature records measured with different sensors (primarily the difference between ventilated and unventilated temperature sensors).
4. The problem of recording precipitation in mountain environments.

All meteorological data comes from the Tarfala Research Station meteorological station located in the Tarfala Valley, roughly 1 km away from Storglaciären. The station is good for assessing long-term trends on the glacier rather than short term (daily) patterns because of the difference in environment between the station and the glacier (e.g. the station is experiencing clear skies while parts of the glacier may be in either shade from nearby mountains).

The Tarfala Research Station meteorological station is located at an elevation lower than the entire glacier. Because of the reduction in temperature with elevation, the adiabatic lapse rate, temperature is lowered by between 0.6–1ºC/100 m elevation change. The average elevation for Storglaciären is ~1,400 m.a.s.l. which translates in up to 3ºC lower temperature on the glacier than at Tarfala. In reality, this translates into a melt gradient. The melt signal will thus be similar across the glacier but the magnitude of melt varies across the glacier and decreases with altitude. This is most critically illustrated when air temperatures are TRS are positive but close to zero: decreasing temperatures with elevation will ensure much of the glacier's elevation range will experience sub-zero temperatures and, therefore, no melting. In summary, the record shown from the meteorological station is indicative of the melt on the glacier but caution is needed when considering temperatures below, say 5ºC.

Throughout this study, unventilated temperature sensors have been used by Tarfala Research Station. Such sensors typically over-estimate temperature on sunny, low wind speed days (e.g. ref SMHI). Since winds are very common in the Tarfala valley and on the glacier, such errors are probably not very critical. A comparison between one ventilated and two unventilated sensors indicate deviations of up to 4ºC (Figure 5-7). These differences, however, seem most common during sunny spring days. Deviations in summer are between 2ºC and 3ºC.

Figure 5-8 shows the ventilated temperatures as a function of the unventilated temperature. Again the deviations are clearly visible, indicating that the unventilated Young screen sensor in particular yields higher temperature than the ambient air temperature recorded by the ventilated sensors. These deviations may introduce errors when calculating melt from meteorological data but it is evident that the deviations are smaller than the larger scale variability in air temperature. This indicates that the temperature curves from the station are indicative of the relative amount of melt occurring on the glacier.

Precipitation measurements are notoriously uncertain. Under normal conditions, a rain gauge underestimates precipitation by as much as 10%. This is under conditions where strong winds usually do not affect the gauge and where the gauge also has a wind protector which is designed to operate under at most moderate wind speeds. The Tarfala valley has the Swedish wind speed record (81.6 m/s) and is a very windy place. Since vegetation is lacking, winds also strongly affects the precipitation gauge. Although we are unclear about the wind induced error of the gauge, we are confident that it accurately reflects the timing and the intensity of precipitation events but not the absolute magnitude.

## 5.4 Experimental setup

The purpose of this field study was to (1) establish the temporal and spatial variations in subglacial water pressure and (2) establish water pressure behaviour in the proximity of a subglacial channel.

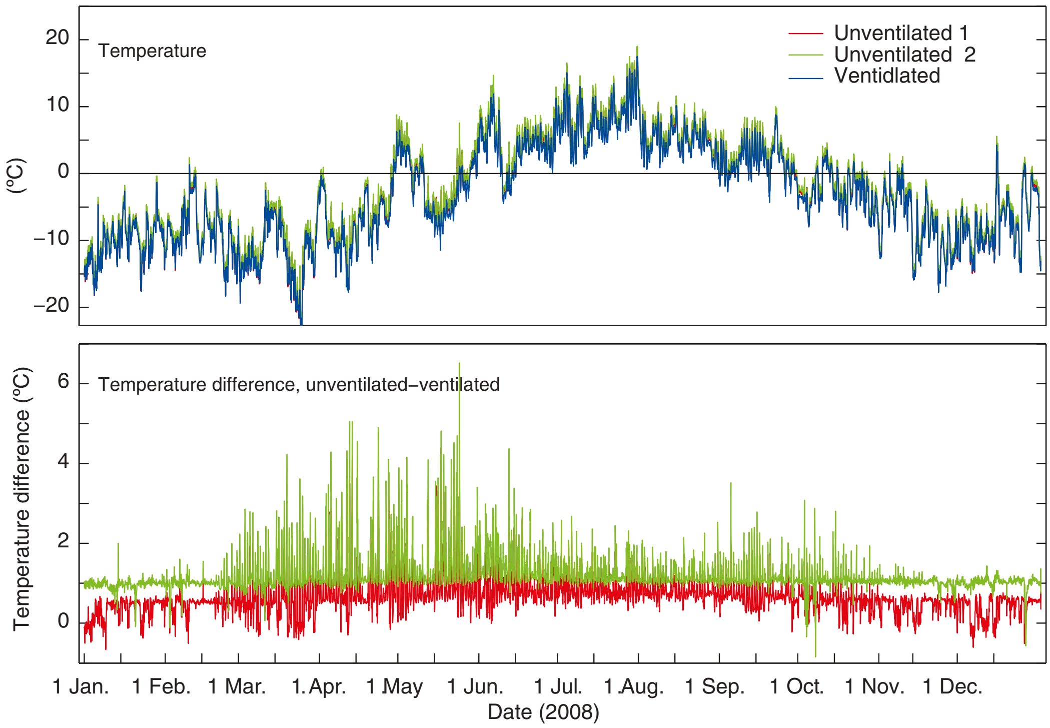


***Figure 5-7.*** *(Upper panel) Temperature records from one ventilated (blue solid line) and two unventilated (red, Stevenson screen, and green, Young radiation shield, solid lines, red line largely obscured by unventilated sensor record) temperature gages at the Tarfala Research Station meteorological station. (Lower panel) Temperature difference between unventilated and ventilated sensors (line color indicates which of the unventilated sensors in the upper panel is differenced with the unventilated sensor). Offset indicates differences (errors) in calibration between sensors.*

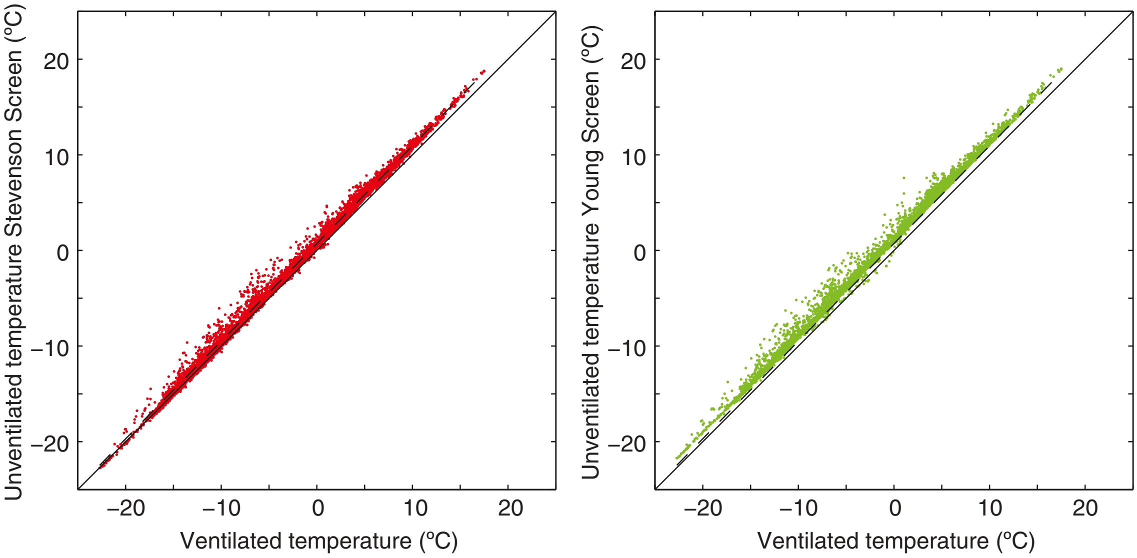


***Figure 5-8.*** *Unventilated temperature as a function of ventilated temperature. Black solid line shows line of slope 1 indicating perfect correlation. The dashed line shows a least squares fit to the temperature data. Note that both sensors deviate from the slope = 1, especially at higher temperatures.*

To establish how water pressures vary in both time and space, a low density network of instrumented boreholes were established on Storglaciären between 1990 and 2006 (see Figure 5-9). The basic goal was to achieve a reasonable spatial coverage of the ablation area. The resulting, seemingly random, network of boreholes is the result of several complicating factors, such as surface crevasses, benefits of using the logistics of other projects and snow conditions which vary between years as well as general field conditions during the field campaigns. Cold weather hampers drilling by terminating melt water for drilling. Once the surface has frozen or been covered by fresh snow, it may take weeks before suitable melting conditions occur. Hence the network of boreholes is sparse; however, boreholes cover the important hydrologically different parts of the glacier including on borehole sensor (XE3778 in Figure 5-9) in a very deep (for Storglaciären) bore hole.

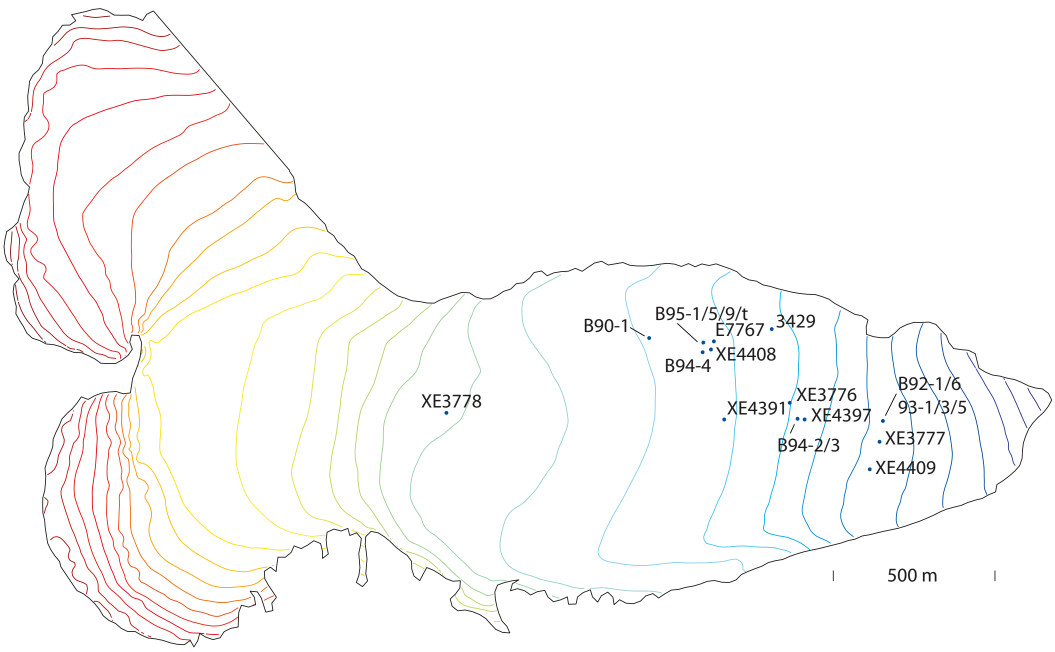


***Figure 5-9.*** *Locations for water pressure measurements on Storglaciären between 1990 and 2006. 20 m contour intervals given for reference.*

To establish the water pressure characteristics around a subglacial channel, a series of boreholes was established in a pattern oriented perpendicular to the general direction of ice slope. The basic assumption is that water flow will occur mostly in the direction of the surface slope which is generally the case on Storglaciären (c.f. Figure 3-2 and 3-3). Hence a series of closely spaced boreholes is more likely to encounter a basal conduit than would any other sampling configuration. Since the exact location of basal channels is *a priori* unknown, the drilling strategy still relied on educated guessing of possible locations. Based on experience from earlier drilling and theoretical considerations, it seemed likely that conduits would emerge from the lowermost point of the bedrock threshold (riegel in Figure 3-2) and flow toward the southern margin to emerge at the Sydjokk southern proglacial stream. This narrowed the possible locations for experiments to a zone downstream of the riegel and towards the southern side of the glacier. Still, exact positioning of drilling locations was a combination of qualified guess work and possible locations to land the drill equipment in relatively flat areas on the ice surface.

## 5.5 Earlier work on water pressure

A large quantity of water pressure measurements have been recorded at Storglaciären as part of a number of different, independent research projects. Small portions of this data has been published /Jansson and Hooke 1989, Hooke et al. 1990, 1997, Hooke 1991, Iverson et al. 1992, 1994, 1995, 1999, Pohjola 1993, Hanson and Hooke 1994, Hooke and Pohjola 1994, Jansson 1995, 1996, Cutler 1998, Fischer et al. 1998, Hanson et al. 1998, Fountain et al. 2005ab/. Measurements are available from 1990 and 1991–2002 (when the current project was initiated). The techniques for drilling observation holes have been the same as discussed in Section 5.1. Measurements have also been made using the same type of data logging equipment and largely using the same type of sensor, except in 1990 when the transducer was home made based on a car oil-pressure gauge cast in an epoxy resin cover to prevent leaks and, therefore, sensor failure commonly occurred under high pressure. These latter sensor types were made to operate under atmospheric pressure with the pressure gauge exposed to high pressure through a threaded pipe that was intended to be screwed into for instance a car engine; they were cheap but turned out to have limited life span which hampered the continuity of the measurements. The calibration of sensors showed that they had about meter or 10 kPa resolution, were nonlinear in response to pressure changes, and suffered from hystheresis effects when pressure was rising and falling. In 1992 a sensor similar in construction to the car oil pressure gauge was used. This gauge had much higher precision, a linear response and no hystheresis effects. However, they too were prone to failure because of water entering the gauge. This limited the data obtained by these sensors. From 1994 Geokon pressure transducers were used in all measurements yielding long continuous pressure records. These transducers do not suffer from hystheresis effects, at least not within the resolution of the sensor (0.1% of full range).

# 6 Results and interpretation

## 6.1 Borehole water pressure variations between 2002 and 2006

Drilling for pressure characteristics around channels was performed during three seasons, 2002–2004. In each season, one or two profiles were drilled with a total of around 25 boreholes. During the first year, 2002, 12 boreholes were drilled. Only four of these (XE4391, XE4397 XE4408, XE4409) connected to the basal system (see Figure 5-9). This low success rate was surprising since previous experience told us drilling led us to expect few problems. Surprisingly, drilling was significantly slower in the lower part of the borehole and was slowed to very low drilling speeds in the last 5–10 m before progress was completely halted. It was virtually impossible to detect drilling had ceased because of the low drill speeds at the bottom of the borehole. It is possible that drilling ceased one to a few meters above the bed. A likely cause would be rock and sediment frozen into the bottom of the glacier. As these fragments are liberated they accumulate in the bore hole, they minimize the turbulence of the hot water jet and insulate the ice greatly, reducing the drill rate. One of the successful boreholes was inspected by borehole video. It was evident that as much as the lower 30 m of the glacier ice contained small amounts of debris. We concluded that the accumulated effect of 30 m of melt-out debris may have been sufficient to prevent the drill from penetrating to the bed.

As mentioned, the cold surface layer of Storglaciären causes the boreholes to freeze closed in 3–5 days. Consequently, boreholes that do not drain were accessible for borehole video inspections only for that short period of time. Unfortunately, the fine sediment was suspended in boreholes occluding observations and precluding borehole logging. We therefore acquired little information about the quantity of sediment in the bottom of the unsuccessful boreholes or of the sediment structures in the ice. The sediment problems with the drilling equipment prevented us from establishing our network of boreholes to monitor pressures near a subglacial conduit. Hence, we will concentrate on the spatial and temporal variations in water pressure on the glacier.

Figure 6-1 shows an overview of pressure measurements made between 2002 and 2006 as part of this project, from the successful boreholes shown in Figure 5-9. The different pressure records vary widely in length due to differences natural circumstances that severed the connection between the surface of the glacier and the sensors at the base of the ice. Our experience is that the life span of a sensor is determined by the general stress field at the location of the sensor. If the glacier experiences vertical extensional strain, as is the case over much of the ablation area since the glacier is decelerating and horizontal strains are compressional, then cables are subjected to tension and are likely to break. Other factors also beyond our control, such as how the cable freezes into the ice or the sensor being buried or crushed by rocks at the base of the glacier can possibly also affect the life span of a sensor. Because of logistical reasons re-drilling and insertion of new sensors once older ones fail was not feasible.

Discontinuities within the water pressure records (see Figure 6-1) are typically the result of battery failure during winter. Because the loggers are operating unsupervised for up to 6 months during winter, and subject to low temperatures (often between –15 and –20ºC) and sometimes buried by snow, battery life can be affected. Solar panels are also of limited use during the winter darkness at the latitude of Storglaciären. During many winter seasons, batteries can be exchanged securing data retrieval but breaks inevitably occur.

Broadly speaking, the data retrieved from the glacier within this project (Figures 6-1 to 6-6) can be divided into two main types. Data from the summer melt season showing significant variability, and data from the winter season showing few often slow but sometimes rapid pressure changes. The actual water pressure varies depending on the location of the borehole. Absolute pressures cannot be compared directly between holes but have to be viewed in the light of the local ice thickness. The water pressure in all records obtained is relatively high and varying around this high value; only in one case (Figure 6-6) does the pressure vary between overburden pressure and low values equivalent to only 10–20% of the ice overburden.

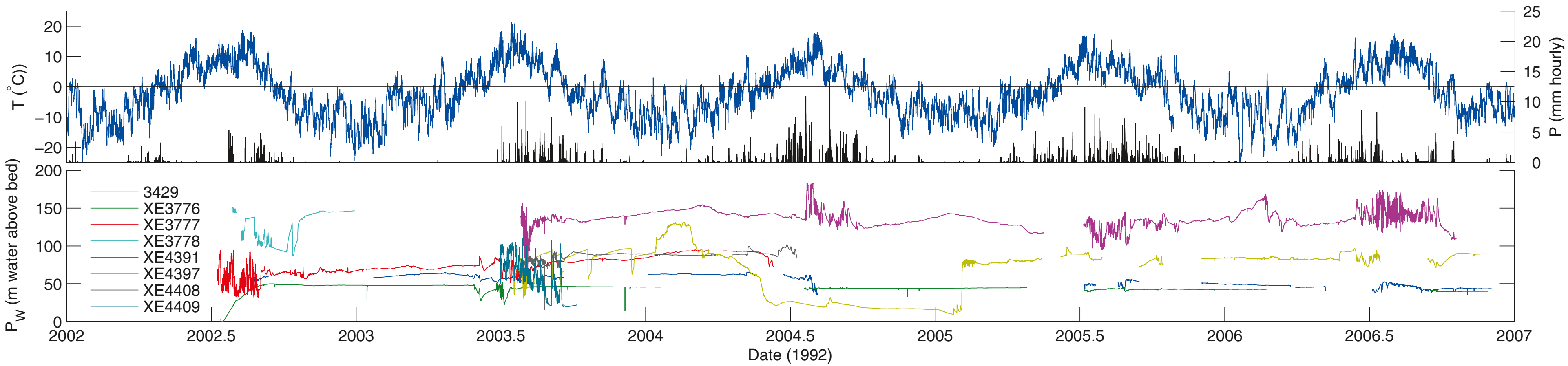


***Figure 6-1.*** *5 years of water pressure measurements from 2002 to 2006 on Storglaciären. Air temperature (top blue curve, scale to the left) and precipitation (bars scale to the right) from measurements at Tarfala Research Station. This figure shows the extent of the different records and the characteristics of each sensor. Note the difference between the winter (low variability) and summer (high variability) periods. Details of annual records are discussed in the text and in conjunction with Figures 6-2 to 6-6, for which graph layout is identical to here.*

### 6.1.1 Pressure records from 2002

In 2002 four instrumented boreholes were established, XE3776, XE3777, XE3778, and 3429 (Figure 5-9). Borehole XE3777 shows a distinct diurnal water level fluctuation lasting until around 1 September. Although brief periods with sub-freezing temperatures occur around this date, the cessation of diurnal variations may coincide with the onset of lower but not necessarily freezing temperatures across much of the glacier.

Borehole XE3776 contains a transducer that became jammed in what is inferred to be an englacial crevasse. Hence if the crevasse is not connected to the subglacial drainage system, the transducer is recording the pressure in the englacial system. The water level shown by this record first increases slowly and then remains steady with no significant variations. It implies either that no direct connection exist with the surface, hence the absence of fluctuations caused by variations in water input, or, that the transducer was sitting in what can be thought of as an overflowing pool where the water level remains that same regardless of the input rate since outflow rates would vary similarly and that water level changes would be on the order of centimeters.

Borehole XE3778 is located in the upper part of the overdeepening, just below the approximate equilibrium line on the glacier (Figure 5-9). The pressure transducer is recording water level above the sensor because the depth of the sensor relative to the borehole length was not recorded; it is likely that a significant offset should be applied in order to obtain the true basal water level. If the maximum water levels recorded are near overburden pressure, this offset may be +20–25 m. The cold surface layer is very thin in this part of the glacier and the area 300 m and more upstream of the borehole is heavily crevassed. The water level shows diurnal fluctuations but with interruptions by periods of no change. Some of the diurnal fluctuations are synchronous to fluctuations at XE3777, others are not. At the end of the summer there are large fluctuations in water level which are unrelated to any input variations; these must be reflective of internal arrangements of the drainage system. The connection with the sensor at XE3778 was lost during the winter of 2002/2003.

The record from borehole 3,429 is very short and shows only small fluctuations. This transducer is located near the edge of the glacier where the cold surface layer intersects the bed; the glacier is thus frozen to its base on the glacier margin-side of the borehole. The water level fluctuations reflect the same longer-term trends as recorded by XE3777 and therefore seems like a filtered version of the XE3777 record. This may be a good example of a part of the drainage system which is not directly connected with the conduit system.

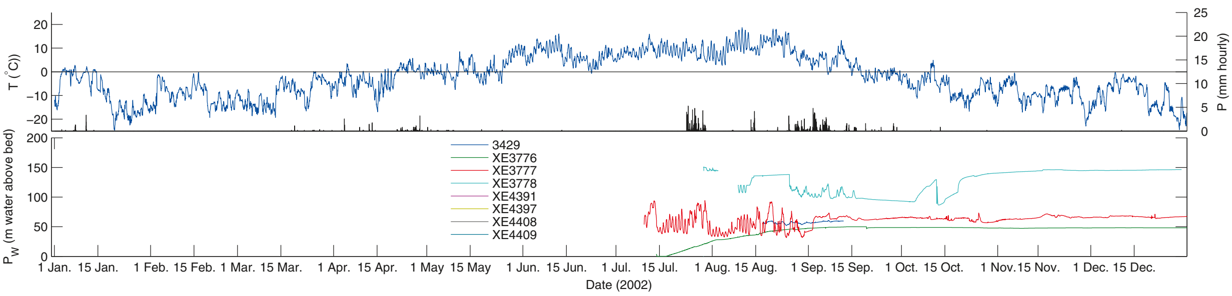


***Figure 6-2.*** *Water pressure records from 2002. Graph details described in the caption of figure 6-1.*

### 6.1.2 Pressure records from 2003

The pressure records from 2003 (Figure 6-3) show a clear seasonal pattern of very low amplitude variations during winter and high amplitude (diurnal) variations during summer. The sensors 3429, XE3776, and XE3777 all show relatively steady water levels during the winter of 2002/2003. They all also react to the first major warm up that occurs in early June (Figure 6-3). This may imply that some surface melt water reaches the subglacial drainage system. Note that the reaction is slightly different in each sensor but that a common peak occurs on June 4–5, albeit weak at 3429. Thereafter, diurnal behavior starts in late June in all three sensor records, perhaps with a shift of s few days, however, because of the weak signal it is difficult to assess when the diurnal signal starts.

Borehole XE3776 shows its only variability during its four year operation during late May to mid-July, 2003, indicating that it was in connection with the conduit drainage system during this period but was either isolated from any basal system or was measuring a part of the basal system that was completely disconnected during the remaining part of the record both before and after the connected period. Whether or not this means the sensor lost contact with the basal system is unclear.

During summer 2003 the new sensors XE4391, XE4397, XE4408, and XE4409 were deployed. In all cases a diurnal signal is recorded but with varying amplitude. The record from XE4409 shows strong peaks particularly in response to precipitation events, whereas the other records show smaller responses or an absence of diurnal signals during such events, the latter indicating that the precipitation event overprints the melt signal. After the last peak around 15 September, the water level remains low and in early October the connection to the sensor was lost.

Borehole XE4391 shows strong variations during its first approximately ten days of operation. The general water level seems to drop during this time. After that the pressure slowly rises with a superimposed diurnal signal until it reaches a fairly stable level which is maintained during the following winter.

The record from XE4408 shows small amplitude variations superimposed on longer wavelength variations during the entire summer. The water level generally remains the same during both the summer and following winter at this sensor.

The record from XE4397 shows a peculiar response. During parts of the summer the sensor records diurnal variations similar to what is recorded by other sensors. The diurnal pattern is interrupted by periods of quasi-stable or very slowly changing water pressure. After 4 August the pressure rises slowly until 15 August when it rises abruptly by about 50 m. The rise is characterized by a near instantaneous rise which when reaching higher pressures is slowed until a small linear rate of increase is established. During the following winter the water level remains stable but with periods of rapid lowering, at first slowly but then quickly rising pressure to a level lower than before the event. Between events, the water level slowly rises to about the same peak levels. This may indicate that a change occurs in the drainage system once a threshold pressure has been reached. The initial rapid recuperation during an event may be due to that large pressure gradients may build up as a result of the sudden lowering of the local water level.

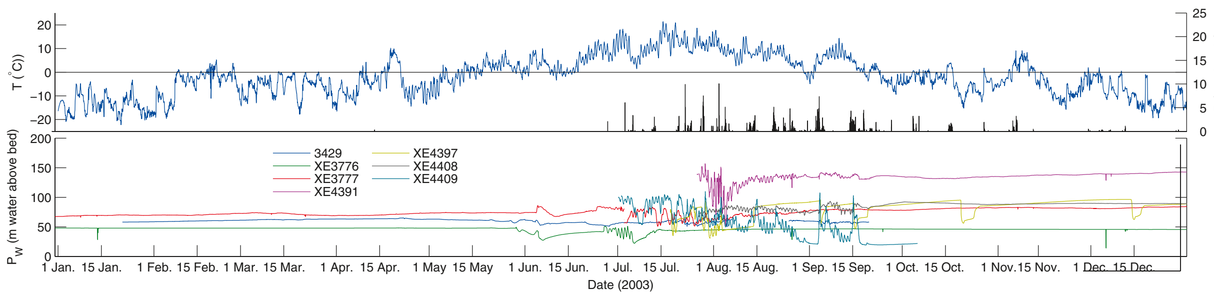


***Figure 6-3.*** *Water pressure records from 2003. Graph details described in the caption of figure 6-1.*

### 6.1.3 Pressure records from 2004

During the winter of 2003/2004 (Figure 6-4) water pressure records remain stable with the notable exception of that from XE4397. Borehole XE4397 shows some large amplitude and wavelength variations during January and February 2004 and in late April and May the water level drops to very low values where they remain for the rest of the year. There is a small response in water pressure on 20 August to the major rainstorm that occurred that day. This was an extraordinary rainstorm that caused flooding at many places in the northernmost part of Sweden. This influx of rainwater was apparently enough to affect the subglacial system also at this sensor.

Borehole XE3776 shows little fluctuation except for a period in late July and early August when a very faint diurnal pattern can be distinguished. There is also a small peak just when the major rainstorm occurs indicating that some connection exists or that the glacier reacts to the water input in such a way as to affect the local pressure.

Borehole XE4408 shows some small fluctuations coinciding with the onset of melting as indicated by the rising temperature above 0ºC. The fluctuations appear to correlate to both temperature variations and with precipitation events. Borehole 3429 also shows weak diurnal oscillation which increase towards the end of July, also coinciding with a lowering of the general water level. This may indicate that 3429 becomes better connected to a fast drainage system during this time.

Borehole XE3777 shows a stable water level until the early part of June when levels drop, shows some low frequency variations and the sensor connection is finally severed.

### 6.1.4 Pressure records from 2005

For 2005, the pressure records largely continue to show similar patterns as before: high frequency variability during the melt season and small or negligible variability during winter. The main exception is the record from borehole XE4397 that goes through a dramatic increase in pressure in early February 2005. This is followed by very high frequency low amplitude variations for about 20 days after which the water level remains stable until the beginning of the melt season. The record from borehole XE4397 is broken by long periods of lost data but indications would suggest likelihood for pressure continues to vary with low amplitude and long wavelength. There are indications of diurnal signals during summer and around mid-October during a late fall warm spell.

The record from borehole 3429 and to a lesser extent XE3778 also shows very faint traces of diurnal oscillations. The general water levels remain very stable in time in both records. XE4391 shows very slow but relatively large fluctuations during the 2004/2005 winter, with a slow rise during fall and slow fall during spring, the peak level being reached approximately in mid-January. The summer season at this sensor's location is characterized by diurnal variations superimposed on longer-term changes in general water level. Small fluctuations continue into late fall in response to late melt periods. By early November, the water level remains stable for the remainder of the year.

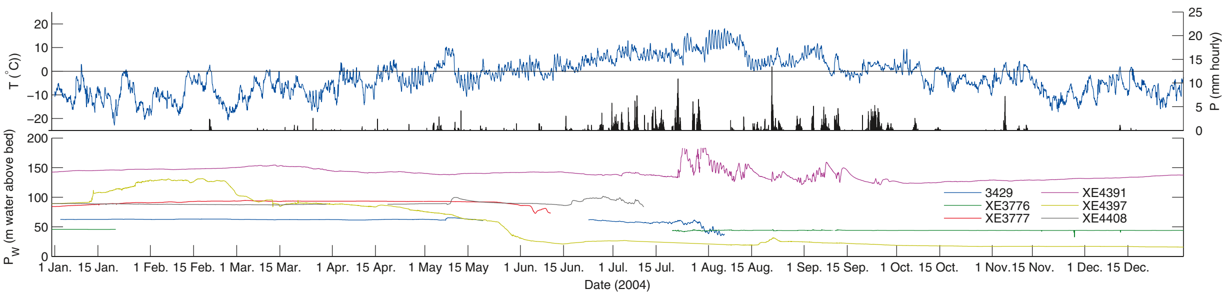


***Figure 6-4.*** *Water pressure records from 2004. Graph details described in the caption of figure 6-1.*

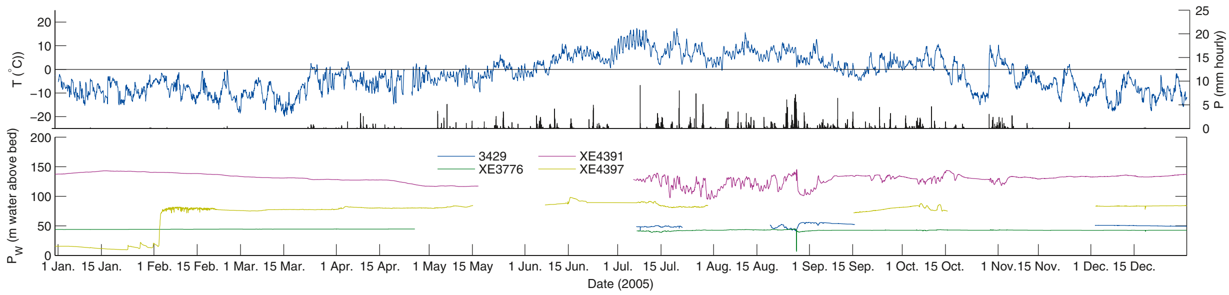


***Figure 6-5.*** *Water pressure records from 2005. Graph details described in the caption of figure 6-1.*

### 6.1.5 Pressure records from 2006

The water pressure records for 2006 (Figure 6-6) broadly follow the patterns described for 2005. Boreholes 3429, XE3776, and XE4397 shows very small diurnal variations during summer whereas XE4391 shows relatively large fluctuations. The records from boreholes 3429 and XE3776 have stable winter values whereas XE4397 and more so XE4391 shows lager fluctuations during winter.

## 6.2 Water pressure variations from previous studies, 1990–2002

### 6.2.1 Borehole water pressure records from 1990, 1992 and 1993

The locations of boreholes drilled in 1990, 1992, and 1993 are shown in Figure 5-9.The record from 1990 (borehole B90-1; Figure 6-7) shows low frequency variations with water pressures within 20% of ice over burden pressure (solid line in the figure). There is a weak overprinting of a diurnal signal in this record but it is not significant. Note that the pressure exceeds the inferred ice overburden pressure in short periods around approximately 19 July and 4 August.

In 1992, water pressure records exist from four boreholes, B92-1, B92-3, B92-5 and B92-11. Of these only B92-1 and B92-3 yielded reasonable results (Figure 6-8). The pressure record from B92-1 shows a distinct diurnal pattern varying between 10–15 m to 100 m. B92-3 shows much less variation, the pressure remains around 100 m but shows variations during a period centred on 10 July where the response may be synchronous with that in B92-1. The response in B92-3 seems to occur only when pressures in B92-1 is very high. Because of the intermittent records, the correlation of pressure variations to meteorological parameters is difficult if not precluded entirely.

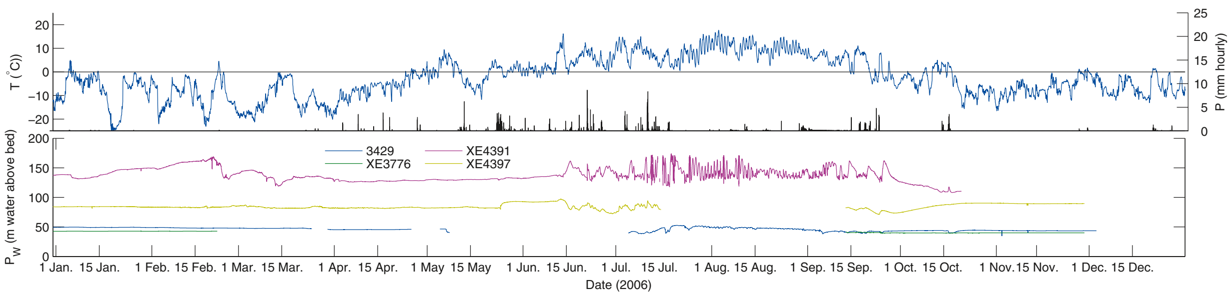


***Figure 6-6.*** *Water pressure records from 2006. Graph details described in the caption of figure 6-1.*

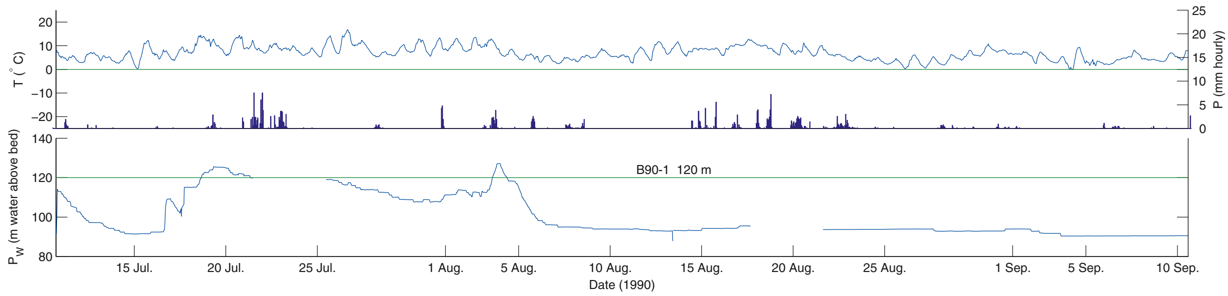


***Figure 6-7.*** *Water pressure records from borehole B90-1 in 1990. Glacier overburden pressure given by the solid horizontal line in the water pressure graph.*

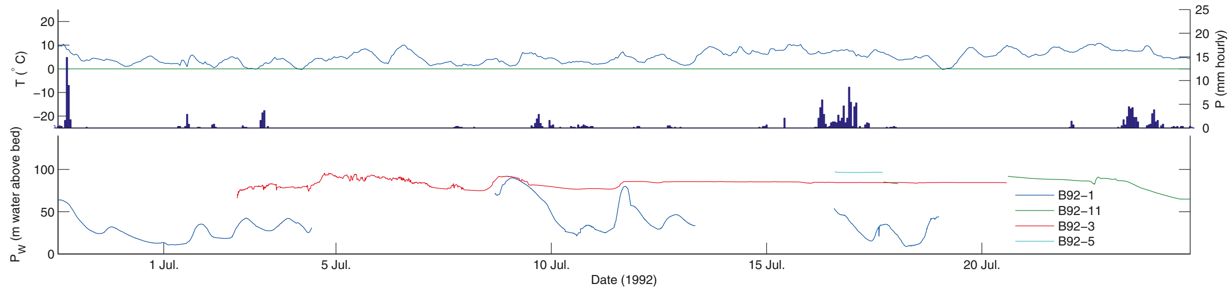


***Figure 6-8.*** *Water pressure records from boreholes B92-1, B92-3, B92-5, and B92-11 in 1992. Air temperature (curve, scale to the left) and precipitation (bars scale to the right) from measurements at Tarfala Research station.*

The pressure records from boreholes B93-1, B93-3, and B93-5 in Figure 6-9 show clear diurnal patterns for most of the span of the record (summer season only). It is also evident that all three boreholes react simultaneously to the diurnal variations, however, there are periods when this is not the case. On July 16–17 pressures in borehole 93-1 and 93-5 deviate significantly from each other although the general pressure excursions have similar signs. On 21–22 July the pressure variations in borehole B93-1 cease to be diurnal, the pressure slowly rises thereafter with an abrupt increase on 20 August. The noisy behaviour of pressure transducer B93-5 from approximately July23 to the end of its life is likely due to sensor failure. The record from B93-3 shows a clear correlation with the precipitation record with high water pressure peaks during high precipitation events.

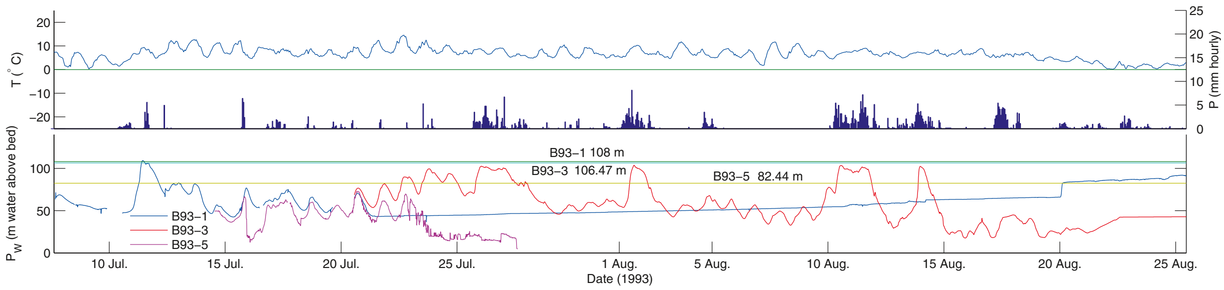


***Figure 6-9 (previous page).*** *Water pressure records from B93-1, B93-3, and B93-5 in 1993. Glacier overburden pressure is given by the solid horizontal lines in the water pressure graph. Air temperature (curve, scale to the left) and precipitation (bars scale to the right) from measurements at Tarfala Research station.*

### 6.2.2 Borehole water pressure records lasting from 1994 to 1996

The pressure records from boreholes 94-2, 94-3, 94-4, and B94-12 (Figure 6-10) show two distinctly different regimes, similar to what was described for the pressure recordings from 1990, 1992, 1993 and 2002–2006. Fluctuations are large with a distinct diurnal fluctuation during summer. In winter fluctuations are more erratic but may involve very large and rapid fluctuations. The boreholes monitored between 1994 and 1996 are located in two different regimes on the glacier. B94-2 and 3 are located in the lower ablation area (Figure 3-2) where water pressures are known to vary with high diurnal amplitude whereas B94-4 is located upstream from the riegel (Figure 3-2) where water pressures are known to remain high through out the season /*e.g.* Hooke 1991, Jansson 1996/. Furthermore boreholes B94-2 and 3 are located only 15 m apart.

#### *Pressure records from 1994*

In 1994, boreholes B94-2 and B94-3 (Figure 6-11; boreholes were separated by approx. 10 m on a N-S axis) show strong diurnal signals with an amplitude of more than 60 m, which is roughly 30–40% of the local ice thickness, and peaks reaching local overburden pressure. Note that the variations are identical, without phase shifts or differences in amplitude, hence the holes are coupled. The connectivity between the bore holes progressively deteriora

B94-12 shows a similar diurnal pattern but will not be discussed further since it only covers a period of three days. B94-4 shows very high water level, at or slightly in excess of the overburden pressure. The pressure record shows distinct diurnal variability but with relatively small amplitude, c. 10–15 m. Unlike the record from B-94-2 and B94-3, the diurnal signal continues through to the end of August. This coincides with low air temperatures and possibly the termination of surface melting. The pressure records from September and on to the end of 1994 shows a few but in the case of boreholes B94-2 and B94-3, large amplitude variations. The pressure record at B94-4 is very stable during winter.

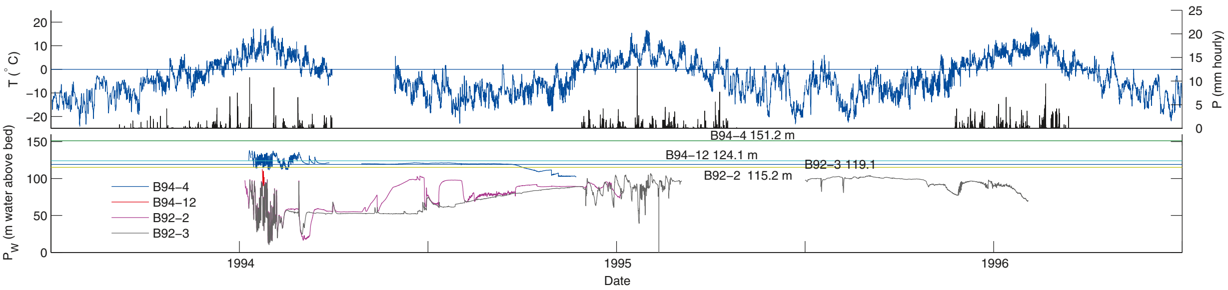


***Figure 6-10.*** *Water pressure (in meter water column above the glacier bed) records from 1994 to 1996 in boreholes B94-2, B94-3, B94-4, and B94-12. Glacier overburden pressure is given by the solid horizontal lines in the water pressure graph. Air temperature (curve, scale to the left) and precipitation (bars scale to the right) from measurements at Tarfala Research station.*

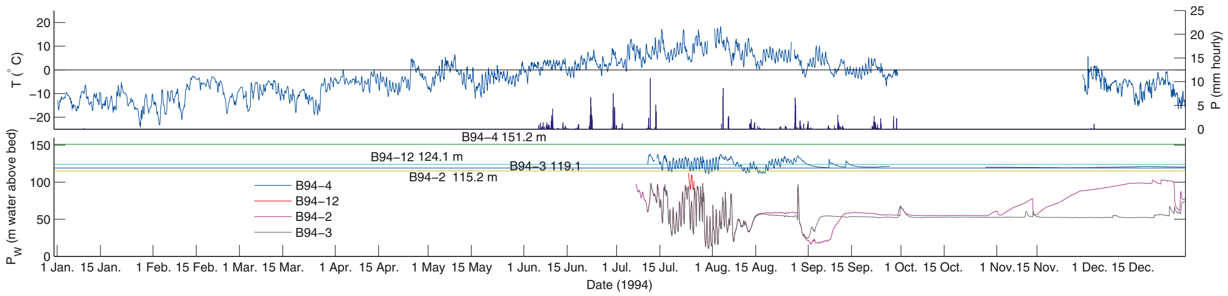


***Figure 6-11.*** *Water pressure (in meter water column above the glacier bed) records from 1994 in boreholes B94-2, B94-3, B94-4, and B94-12. Glacier overburden pressure is given by the solid horizontal lines in the water pressure graph. Air temperature (curve, scale to the left) and precipitation (bars scale to the right) from measurements at Tarfala Research station.*

#### Pressure records from 1995

In 1995, the sensor in borehole B94-4 ceases to operate in late May; prior to this, the recorded pressure remained high and stable from Jan but with a slightly declining trend in April and a few sudden drops in pressure in late April, early May. The record from B94-2 and 3 show similar general trends during winter except that B94-2 is subject to significant pressure increases lasting 15–20 days in both January and late March-early April. There are also high frequency, low amplitude variability in the pressure recorded between the two excursions that cannot be seen in B94-3. This means that the general water level affecting both sensors was the same but that B94-2 was subjected to additions of water. Since the sensors are only separated by 15 m it is interesting to see such large differences in pressures (30–40 m of water) being maintained over almost a month. The B94-2 sensor shows a slow sinusoidal oscillation during June and ceases to function around 4 July. This oscillation fits nicely as a low frequency response to the more rapidly varying pressure during the same time period at B94-3. Hence, again, the general water level at these boreholes remains the same but the details differ. B94-3 shows relatively strong variations that in part can be interpreted as diurnal from June 1 to late August. It is obvious that the strong relationship between the temperature and precipitation forcing seen during 2004 is not present during 2005. In fact, it is difficult to see from where these variations originate.

#### Pressure records from 1996

In 1996, the water pressure recorded by B92-3 remains relatively constant, when compared to 1994 and 1995, throughout both the winter and summer. Diurnal signals are not distinguishable during summer. Instead there are a series of events of different character. During January and February two similar drops in pressure occur, lasting only 1–2 days each. During May the pressure drops but starts rising again by the very end of May. This rise is characterized by very rapid fluctuations. Once the pressure is back to near April values the signal becomes stable again and it is not until mid June that high frequency, low amplitude fluctuations commence. The sensor in B94-3 ceases operation in early August, preceded by a slight but characteristic drop in pressure, as see for X.

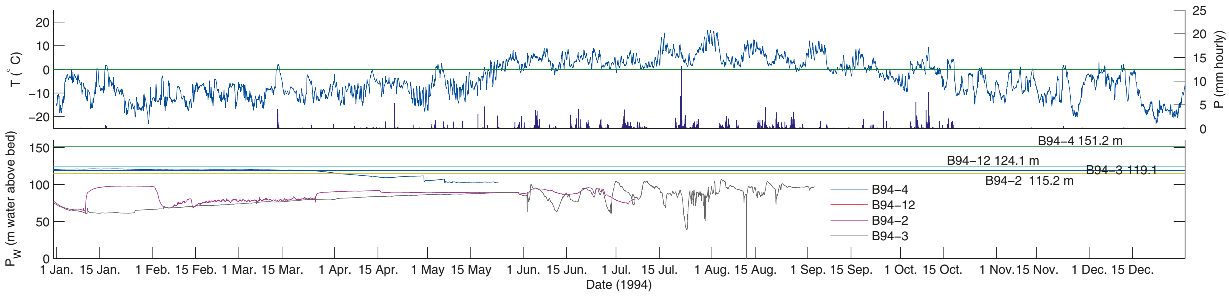


***Figure 6-12.*** *Water pressure (in meter water column above the glacier bed) records from 1995 in boreholes B94-2, B94-3, and B94-12. Glacier overburden pressure is given by the solid horizontal lines in the water pressure graph. Air temperature (curve, scale to the left) and precipitation (bars scale to the right) from measurements at Tarfala Research station.*

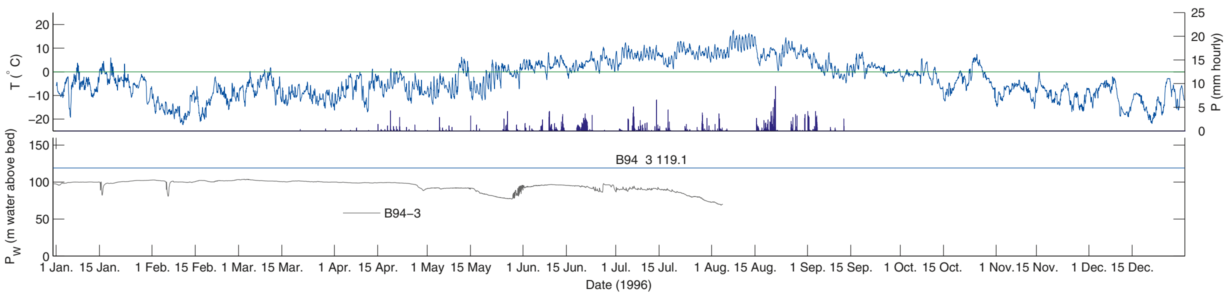


***Figure 6-13.*** *Water pressure (in meter water column above the glacier bed) records from 1996 in boreholes B94-3. Glacier overburden pressure is given by the solid horizontal lines in the water pressure graph. Air temperature (curve, scale to the left) and precipitation (bars scale to the right) from measurements at Tarfala Research station.*

## 6.3 Borehole water pressure records lasting from 1995 to 2003

In 1995 a project concerning deformation of till beneath the glacier required numerous boreholes to be drilled and instrumented. Boreholes B95-1, B95-5, B95-9, all located within a 25 m radius, were instrumented with pressure transducers, and a fourth transducer, named B95-t was inserted into the till beneath the glacier in the same borehole as B95-5 to measure water pressure in the basal till (see Figure 5-9). These transducers hence show the variability within a relatively small area and in the case of B95-5 and B95-t also the difference between sensors separated by < 1 m. Interestingly, transducer B95-t survived the longest and stopped operating almost 8 years after insertion despite occassional discontinuities due to battery failure (Figure 6-14).

In the till deformation boreholes, transducers were inserted in rapid succession during the first half of June 1995 (Figure 6-15). Once all transducers were in place, their records show a strong inter-correlation. The boreholes were also likely directly connected to each other from the drilling operation, producing some 19 boreholes within an approximately 25 m radius.

The first transducer to experience poor coupling relative to the others is B95-t around 10 September, shortly after the onset of freezing conditions at the glacier surface. Around September 15, B95-9 also shows some deviations but only for about two days. It is not until later September that all sensors start to show diverging pressure signals. A peak in pressure in mid-October associated with positive air temperatures and therefore likely liquid precipitation momentarily causes the sensors to record similar pressures, once the event decays signals begin to diverge again. For the remainder of the year the water levels remain different in the boreholes. There are even some high frequency fluctuations in B95-1 that is not visible in the other sensor records. The implication of this is that the boreholes are interconnected from the time of their formation in June until early September when input rates decrease to zero. Although the pressure is not lowered significantly, it is likely that creep closure keeps up with the lower input rates so that the pressure remains relatively high. Closure of the drainage system in conjunction with decreased flow rates is then responsible for the likely isolation of the individual boreholes.

During the pressure peak in mid-October the connections are momentarily re-established but probably only by the pressure decreasing the ice pressure on the bed, enabling water to move more freely. It is worth noting that B95-t is the first sensor to show a different pressure signal. Since B95-t and B95-5 were inserted in the same borehole, B95-t in the till bed of the glacier, the signal recorded by B95-t indicates that it begins to record a pressure that is atypical for the boreholes and their interconnected system. One possibility is that it is recording pressure beneath the ice some distance from the borehole in which it was inserted since the till sensor was left with some slack cable during insertion to prevent it from being pulled up from the till as the bore hole slid away from the original point of insertion. Indeed, from the time when the B95-t signal deviates from the other sensors to the point when the final pressure variation occurs, and therefore no longer enables us to see effects clearly, the sensor picks up similar variations but with much lower amplitude. It also shows a significantly smoothed response to the peaks with longer return limbs. In, short, B95-t records the pressure away from the connected system to which the boreholes belong or alternatively records the pressure in the till which may be governed by till deformation processes.

### 6.3.1 Pressure records from 1996

During 1996, water pressures in B95-1, B95-5, B95-9, and B95-t (Figure 6-16) show little fluctuation. There is a weak tendency for water levels to rise during late winter and spring and to decrease during late fall and early winter with a clear change in trend in the early part of August. During the melt season, high frequency variations can be seen in all sensor signals. Unfortunately, the correlation with meteorological forcing is poor. It is likely that the higher frequency variability is the result from effects from the glacier sliding over the bed causing changes in the water flow pathways or perhaps more correctly, water flow field at the base of the glacier. During late August the signals in boreholes B95-9 and B95-t start to follow each other and the sensors record similar pressure perturbations for the remainder of the year, although they start to deviate in recorded water level towards the end of the year. The other two sensors (B95-1 and B95-5) show independent water level signals.

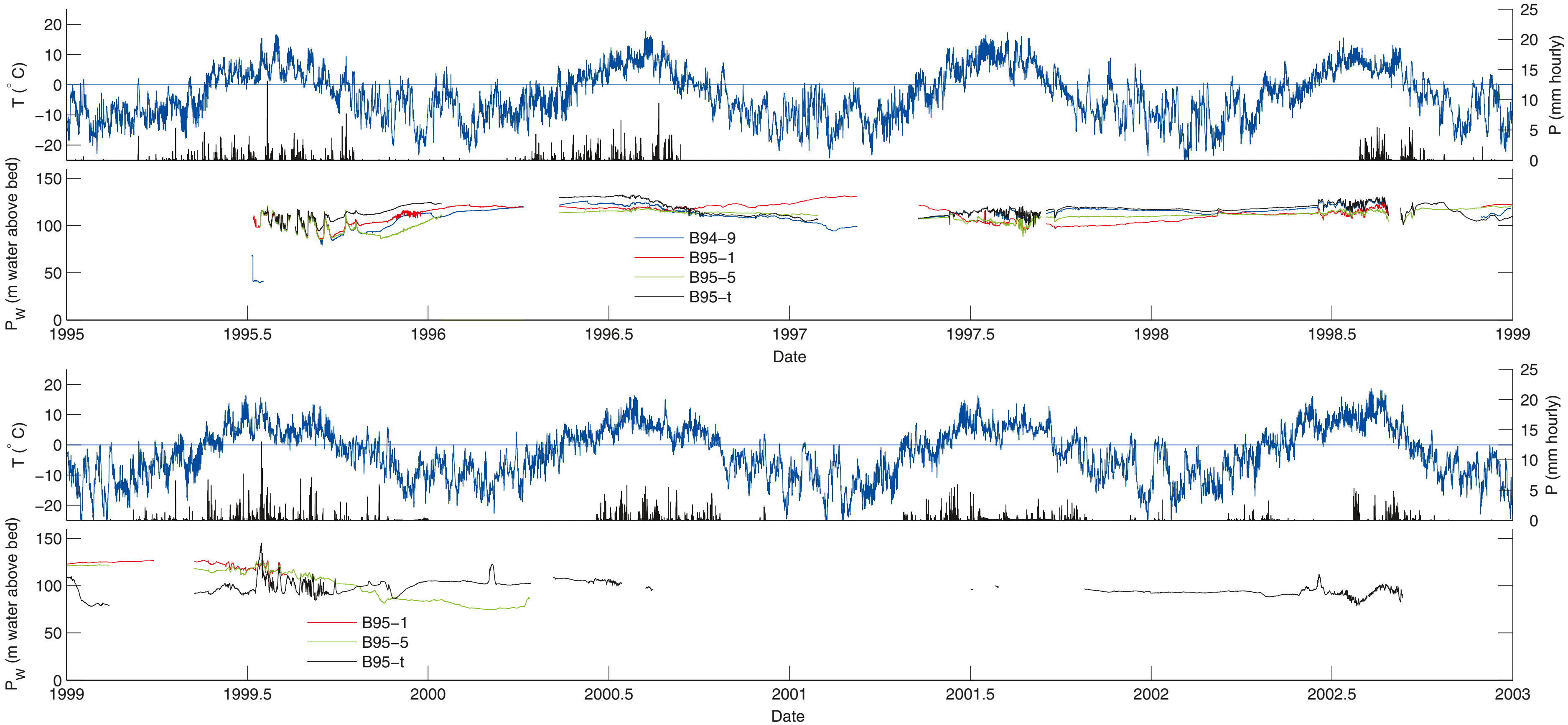


*__Figure 6-14.__ Water pressure (in meter water column above the glacier bed) records from 1995 to 2002 in boreholes B95-1, B95-5, B95-9, and B95-t (sensor emplaced in basal till beneath the glacier). Air temperature (curve, scale to the left) and precipitation (bars scale to the right) from measurements at Tarfala Research Station.*

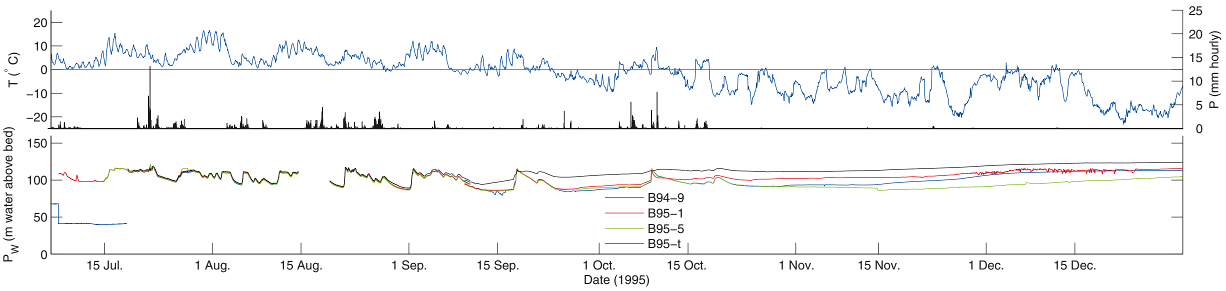


***Figure 6-15.*** *Water pressure (in meter water column above the glacier bed) records from 1995 in boreholes B95-1, B95-5, B95-9, and B95-t (sensor emplaced in basal till beneath the glacier). Air temperature (curve, scale to the left) and precipitation (bars scale to the right) from measurements at Tarfala Research station.*

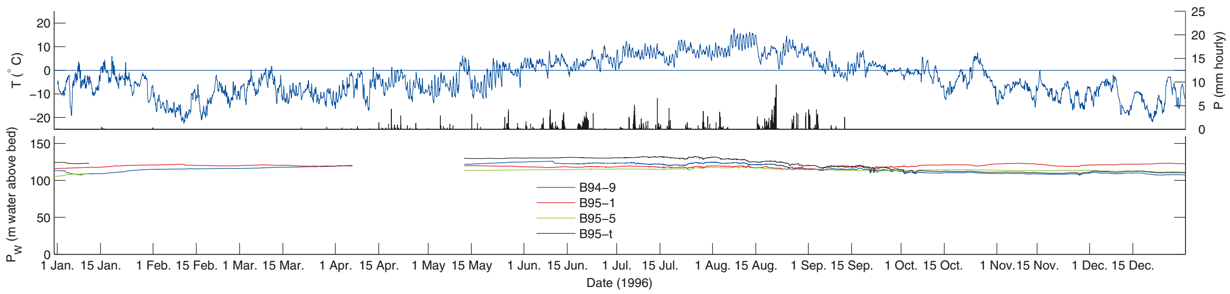


***Figure 6-16.*** *Water pressure (in meter water column above the glacier bed) records from 1996 in boreholes B95-1, B95-5, B95-9, and B95-t (sensor emplaced in basal till beneath the glacier). Air temperature (curve, scale to the left) and precipitation (bars scale to the right) from measurements at Tarfala Research station.*

### 6.3.2 Pressure records from 1997

In 1997, the water pressure records (Figure 6-17) follow the same general behavior as during 1996, *i.e.* showing high frequency fluctuations during summer. The amplitude of fluctuations during 1997 are larger than those during 1996, they are even larger later in the summer than earlier. It is difficult to see a clear explanation to this behavior. The pressure records from B95-9 and B95-t show identical records, both in terms of pressure level and variability throughout the year, with the possible exception of a period in mid-winter but a lack of data prevents us from making further-reaching inferences. It is furthermore possible that B95-5 also is coupled to the B95-9/B95-t system for a period during spring until mid-June. Around mid-June, the B95-5 record switches from following the B95-9/B95-t record to following the B95-1 record. However, B95-1 and B95-5 do not seem to be perfectly coupled since the water levels differ over time, but the variability is similar in both records. A brief warm spell in late September seems to affect all pressure records in the same way by a sudden lowering of water level. This can be interpreted as that the system undergoes similar changes as was described for the 1995 late fall events.

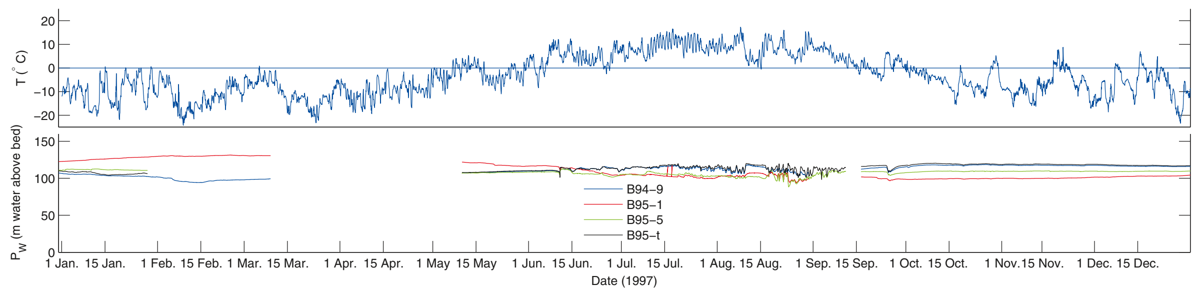


***Figure 6-17.*** *Water pressure (in meter water column above the glacier bed) records from 1997 in boreholes B95-1, B95-5, B95-9, and B95-t (sensor emplaced in basal till beneath the glacier). Air temperature (curve, scale to the left) and precipitation (bars scale to the right) from measurements at Tarfala Research station.*

### 6.3.3 Pressure records from 1998

During the winter of 1997/1998 (Figure 6-18) pressure change very little with B95-1 showing a slight increase during mid-winter. As with earlier years the pressure undergoes high frequency variability during the melt season with an amplitude similar to what was recorded during 1997 (Figure 6-17). During the second half of August, water levels seem to drop. During the following fall and early winter, water levels undergo low frequency variations with much higher amplitude than recorded since the summer 1995.The B95-9 and B95-t signals follow each other as during previous years but start to deviate at the end of the year. B95-1 and B95-5 also show some degree of coupling reflected by similar pressure variations through out the year. B94-9 ceases to function during the early winter 1998.

### 6.3.4 Pressure records from 1999

The pressures recorded during 1999 (Figure 6-19) differ from those recorded in previous year in that the variability increases and also the general water levels decrease over the year. The B95-1 and B95-5 records continue to largely follow each other until B94-1 ceases operation in mid-August. There is more high frequency variability during summer compared to previous years. B95-t experiences large variations starting with a general drop in water level in early January. This is a permanent change which is slowly accomplished also in the other borehole records but over the length of the entire year so that all roughly match at the end of the year. The record from B95-t during the melt season shows very large amplitude variations, similar to those recorded during 1995 when the system of boreholes was deemed interconnected and also connected to some external system. The pressure variations correlate with variations in temperature and precipitation events and hence reflect input rate variations. However, diurnal behavior is only weakly represented in the record as fluctuations superimposed on larger water level fluctuations. This may reflect that the basal system, naturally, is fed by surface water but that the signal reaching B95-t mostly reflects input variations on time scales longer than days. The records from B95-1 and B95-5 also shows similar low frequency variability but with much smaller amplitude. In September the variability seen in B95-t is barely distinguishable in B95-5. This indicates that the variations are too small to penetrate through to B95-5 from the better connected B95-t. Note that these sensors were originally inserted in the same borehole. During the fall and winter both remaining borehole sensors record large scale fluctuations that do not seem to have any connection with each other.

### 6.3.5 Pressure records from 2000

The water pressure record from 2000 (Figure 6-20) shows few fluctuations with one notable exception, a large pressure increase at B95-t in early March. Since the variation occurs during winter it is not caused by sudden input of surface water. It is rather the result of internal reorganization from glacier flow or by emptying of some internal storage location. B95-5 ceases operation in mid April and B95-t shows little fluctuation during the entire record. Unlike in 1999, the variability shown by B95-t during the melt season is small in amplitude, roughly similar to that recorded in 1996. Because of significant loss of data during the last half of the year, not much more can be added about the conditions for this year.

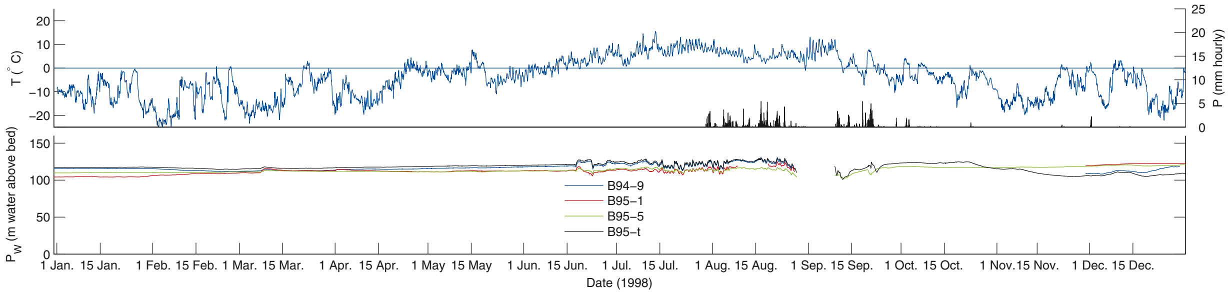


***Figure 6-18.*** *Water pressure (in meter water column above the glacier bed) records from 1998 in boreholes B95-1, B95-5, B95-9, and B95-t (sensor emplaced in basal till beneath the glacier). Air temperature (curve, scale to the left) and precipitation (bars scale to the right) from measurements at Tarfala Research station.*

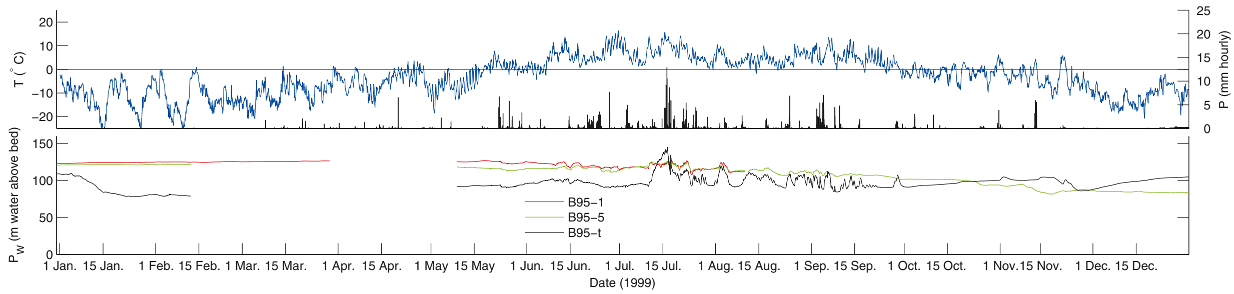


*__Figure 6-19.__ Water pressure (in meter water column above the glacier bed) records from 1999 in boreholes B95-1, B95-5, and B95-t (sensor emplaced in basal till beneath the glacier). Air temperature (curve, scale to the left) and precipitation (bars scale to the right) from measurements at Tarfala Research station.*

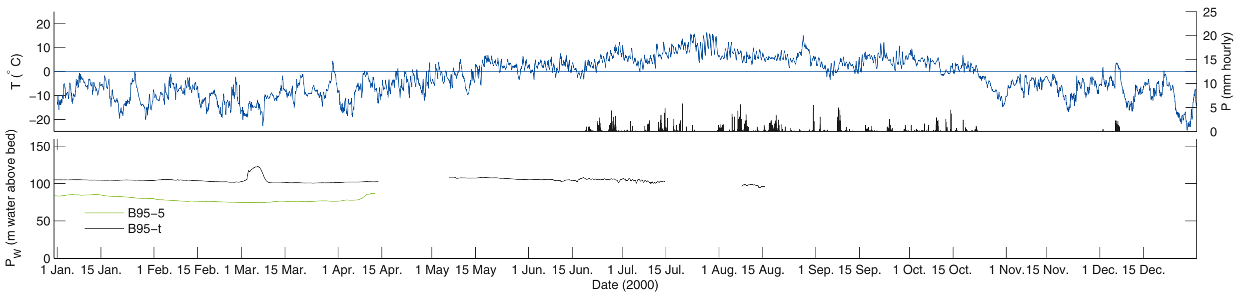


*__Figure 6-20.__ Water pressure (in meter water column above the glacier bed) records from 2000 in boreholes B95-5, and B95-t (sensor emplaced in basal till beneath the glacier). Air temperature (curve, scale to the left) and precipitation (bars scale to the right) from measurements at Tarfala Research station.*

### 6.3.6 Pressure records from 2001

The pressure record from B95-t in 2001 (Figure 6-21) does not provide much information because of the short duration of retrieved records, mostly caused by a malfunctioning data logger. We will therefore not discuss this record further.

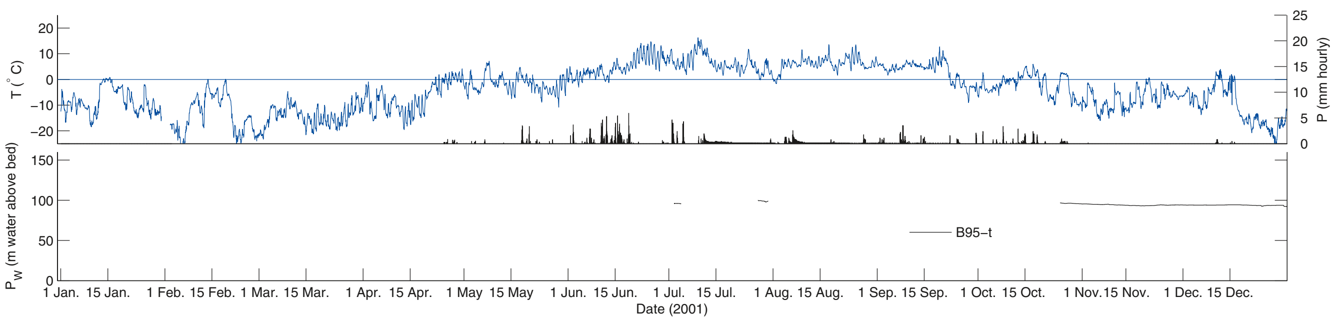


*__Figure 6-21.__ Water pressure (in meter water column above the glacier bed) records from 2001 in borehole B95-t (sensor emplaced in basal till beneath the glacier). Air temperature (curve, scale to the left) and precipitation (bars scale to the right) from measurements at Tarfala Research station.*

### 6.3.7 Pressure records from 2002

The pressure record from 2002 constitutes the last year of operation of sensor B95-t (Figure 6-22). The winter 2001/2002 shows a very steady water level. As melt conditions start on the glacier in late May to early June, small amplitude, diurnal water level fluctuations commence. A larger peak in water pressure occurs around 20–22 June for reasons unclear because no precipitation record exists for this part of the melt season. During the remaining summer the general water level fluctuates. Superimposed is the small diurnal signal which does not seem to be significantly affected by precipitation. Some larger variations seem to start at the end of the record, perhaps in response to precipitation.

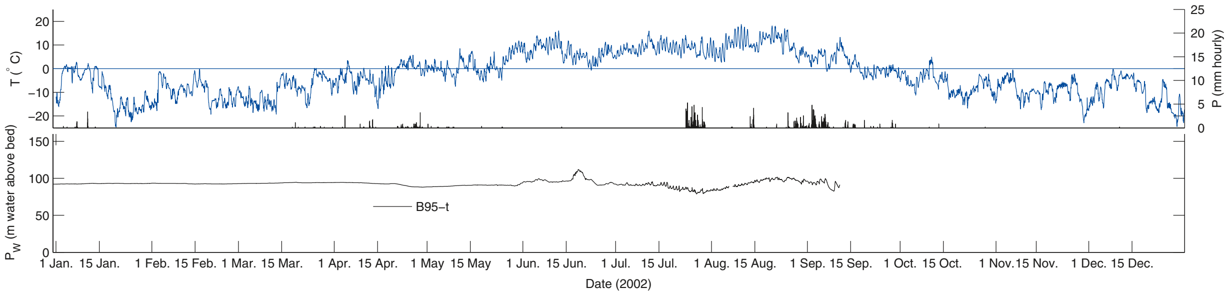


***Figure 6-22.*** *Water pressure (in meter water column above the glacier bed) records from 2002 in borehole B95-t (sensor emplaced in basal till beneath the glacier). Air temperature (curve, scale to the left) and precipitation (bars scale to the right) from measurements at Tarfala Research station.*

# 7 Discussion

The water pressure records can be classified into two categories based on the annual response, a quiet winter regime dominated by low frequency variations and occasional high amplitude variations, typically of short duration, and a summer regime with both high frequency and high amplitude variations. This difference is the result of the difference in water supply to the basal system between summer and winter.

In summer, melt water is generated at the surface through melting and by rain fall. Melt rates are strongly correlated to air temperature /*e.g*. Collins 1934, Hock 1999/ and variations in runoff from melt varies diurnally and is superimposed on longer-term variations controlled by the advection of air masses over the region. Therefore, summer water pressure variations are strongly correlated to the meteorological conditions (e.g. Figure 6-9).

In winter, sub-freezing temperatures terminate surface melt and precipitation falls as snow. Little variability in water pressure occurs and as can be seen in the records, water pressures remain quite high even during winter (e.g. Figure 6-11). The winter regime records are, however, not devoid of variations (e.g. Figure 6-10, winter of 1998/99). In autumn, subglacial conduits are adapted to the high water discharge of the summer regime. Once the input decreases at the onset of autumn, water pressures drop and the conduits start to close by creep continuing until the water pressure in the conduit balances the ice pressure. Smaller conduits require high water pressure gradients to drive the existing flux of water through the system. Hence, the creep closure of the conduits produces a rise in water pressure during the fall and early winter and melt-enlargement caused by the high flow of water causes lower water pressures in summer /Röthlisberger 1972/.

As can be seen in the winter records (e.g. Figure 6-12), constant high water pressures are not necessarily maintained during the entire winter. There are instances of very rapid changes followed by a relaxation towards seemingly long-term quasi-constant levels for each site. These transient perturbations from the background levels are likely the result of sudden reorganization of flow structures at the bed or abrupt drainages from or to englacial or subglacial pools of water. The glacier slides over its bed all year round, conduits in the glacier become deformed and cut-off, opening of new links or the complete re-routing of water can easily take place. Because we infer the winter hydrologic system to be much more closed than the summer system, reorganizations of water flow would produce larger effects in winter.

In glaciers, the general concept of the basal water system is one in which a fast and a slow system exists in parallel /e.g. Fountain and Walder 1998/. The fast system can be exemplified by a conduit system in which water is routed along distinct pathways /*e.g*. Röthlisberger 1972/. The slow system is best thought of as a flow regime with multiple pathways along the ice bed interface /*e.g*. Shreve 1972, Weertman 1972/; in the case of a basal sediment layer, perhaps as groundwater flow through such an aquifer. The slow system can also be a low gradient, distinct pathway system such as that envisioned by /Kamb 1987/ for the basal network and as low gradient linked fractures as inferred by /Fountain et al. 2005ab/ for the englacial system. This has important consequences.

The conduit system is fed from the surface and its dimensions determined by the water flux originating at the surface. The pressure in this system is determined by a combination of the current meltwater flux, the flux history and through the competition between creep closure of conduit walls and the conduit enlargement by melt from viscous dissipation of heat. The fast system reacts quickly to increases in water influx and slowly to decreases in flux. The slow system maintains a more steady pressure and is not strongly influenced by the rapid influx changes from the surface. It is not clear what determines the water pressure in this system. One possibility is that its pressure reflects some average condition in the conduit system, *i.e*. that pressure variations occurring in the conduit affect a zone around the conduit but are attenuated to a level that is determined by the longer-term conditions in the conduit. This has been suggested by several studies /e.g. Weertman 1972, Nye 1976, Walder 1982, Weertman and Birchfieldd 1983, Lappegard 2006/. In this case it would be longer-term trends in water pressure on, for instance, weekly to multi-weekly time scales that determine the pressure in the slow system.

Not much is known about the relative importance or the relative areas affected by these two drainage systems. There are, however, a few observations that can provide some indications. Water pressure variations are known to directly influence the measured glacier velocity, this is thought to be coupled to the basal sliding speed /*e.g*. Iken and Bindschadler 1986, Jansson 1995, Hooke et al. 1997/. Thus changes in the narrow conduits are enough to accelerate the entire ice mass. If conduits were few and far between, or perhaps equivalently, if the portion of the bed occupied by conduits was very small relative to the area covered by the slow system, the effect from the conduits and zones near them must be very strong as suggested by /Hubbard et al. 1998/ to explain velocity patterns on Haut Glacier d'Arolla. We do not observe such localized accelerations on Storglaciären. Hence, it seems as if the network of conduits must either be dense or that there are large zones along the conduits in which the water pressure fluctuations are transmitted and influence the ice. Alternatively, the generally high water pressure in the slow system provides a good basis for sliding but that the low pressure conditions in and around the conduits act so as to reduce the sliding, hence only allowing sliding during high water pressure events.

The experience from our borehole pressure sensor measurements shows that a borehole will be strongly coupled to a fast drainage system during the summer when the borehole is drilled /e.g. Smart 1996/. Because of small dimensions of the boreholes and conduits, it is highly unlikely that boreholes intersect basal conduits. Therefore, we infer that boreholes reach the bed either in regions of slow systems because they are spatially distributed widely or in transition areas between the two systems. Based on the large number of boreholes, monitored and unmonitored, that have reached the bed and have connected to the drainage system, as indicated by a drop in water level and observable rapid, typically diurnal, variations in water level, we can conclude that boreholes may create connections to the fast system regardless to its proximity to the system. Since a borehole is always filled to the top during drilling, excess water from the drilling overflowing onto the glacier surface, the initial pressure head when intersecting the bed is higher (by a factor ~1.1) than that of the local ice thickness. Hence, if the over-pressurized pulse of water connected with the slow system, the slow system is locally overwhelmed and may lift the glacier so as to create an efficient connection between the borehole and the fast system. In reality, water continues to be added to the partly drained borehole because water flow to the drill cannot be stopped instantaneously after connection is made. This aids to enlarge the new connecting conduit. It seems as if such a connection is not easily closed during the course of the summer season despite glacier sliding which amounts to a few meters in the summer months at Storglaciären /Hooke et al. 1992, Pohjola 1993/.

In borehole sensors that have survived one winter, the pressure records during the subsequent summer markedly differ from those of the previous (e.g. Figure 6-14). We should point out that it is unclear how long the physical borehole persists in the ice. Since it is at least partially filled with water it may remain open for significant periods of time. However, it is likely that the sensor eventually is coupled to the basal system while not located in a borehole *per se*. This indicates that the connection between the borehole sensor and the fast system has been severed. Our interpretation is that the sensor now is measuring the local characteristics of the system rather than that of a distant fast system to which it was originally connected. If this is true, it is only during this phase of the borehole pressure measurement that we can deduce anything about the distribution of the different systems and the proximity to conduits.

The distribution of drainage system pathways beneath a glacier remains a critical unknown to investigate. Our research shows that boreholes often connect when reaching the bed during drilling. In some cases where drilling could not proceed, perhaps 0.5 m above the bed, may provide a connection after a few days, indicating that the mechanism suggested by /Weertman 1973/ is in operation. We have no unambiguous evidence that any of the boreholes directly hit a subglacial pathway. During the mid 1980s one bore hole drilled on top of the riegel seemed to be directly connecting into a conduit. This was evident for hearing sounds of rushing water from the bore hole and water levels almost at zero, indicating possible open channel flow. This bore hole was never monitored by a pressure transducer so no further direct conclusions can be drawn from the experience. This experience shows that it is rare to drill directly into the fast system but common to connect near the system.

The investigations performed on Storglaciären are intended to provide insight into what can be expected beneath and immediately downstream of a portion of an ice sheet where surface input can occur. Our understanding of ice sheet hydrology has long been ignored. It seems very little of  ommon knowledge about glacier hydrology has entered the discussion /*e.g*. Boulton et al. 2007ab/. Only recently has the situation changed /*e.g*. Zwally et al. 2002, Alley et al. 2005, Das et al. 2008/. The picture that now emerges is that a cold or polythermal ice sheet with a surface melt ablation area may have the capability to route water to the bed tens if not hundreds of km from the glacier terminus. This means we also need to apply the knowledge obtained from valley glaciers to the ice sheet scale. The ice sheet hydrological system is complicated by the fact that the basal thermal regime sets the boundaries for where subglacial hydrology can occur. Since large areas of an ice sheet might experience basal melting but at the same time no surface melt due to low surface temperatures, subglacial water can be generated and routed from subglacial areas upstream from the uppermost surface input points (feeding surface generated water into the system). How this entire system reacts to the seasonal and shorter input variations is far from certain, at least not when considering seasonal and shorter time scales. The wide spread drainage of large supraglacial lakes /*e.g*. Das et al. 2008/ is common feature of ice sheets providing singular local short but very high pressure events. Considering the patchwork of drainage basins identified over a portion of the Greenland Ice Sheet by /Thomsen et al. 1986, 1989ab, 1993/, it is possible to see the ablation area being affected simultaneously by input changes, despite the large distances involved. Hence, the ablation area of an ice sheet such as that of south-western Greenland experiences water influx variations on both diurnal and seasonal time scales similar to that of valley glaciers in e.g. the sub-arctic. Thus, the hydrological characteristics identified on valley glaciers should be applicable on the ice sheet scale.

# 8 Concluding remarks

Long term measurements of water pressure on Storglaciären reveals that borehole measurements of water pressure record variations relating to input variations during their first melt season of operation. The inference is that boreholes connect to active drainage pathways and remain connected for as long as the system remains active. During the winter following drilling, long-term changes occur, occasionally interrupted by sudden and apparently violent changes. These rapid changes probably occur in a system with very small volume so that even small rapid changes of system storage yield large and rapid fluctuations in water pressure. In only a few cases do water pressure sensors seem to remain connected to the main drainage system during a second melt season. This indicates that the artificial connections created during drilling have been severed during the intervening winter. Connections may have been severed by closure of the drainage conduits ice or by rearrangements created from glacier sliding over the bed. The second season is typically characterized by an increase in fluctuation but generally a lack of diurnal variations. This indicates that the sensor is picking up longer-term variations in water pressure but without the diurnal signal so strongly overprinting the signal during the first year. Although we cannot infer distances from the boreholes to the conduits from the present study, diurnal pressure variations probably do not reach far outside the channel. This conclusion is mainly based on the fact that boreholes easily connect to the basal system when drilled but are easily disconnected during the winter following their creation. If true, it poses an important question regarding how water pressure affects ice velocity. Our inference implies that most of the bed is not experiencing diurnal signals and that only a narrow zone of unknown sizae is directly affected by such variations. Yet, the glacier responds with diurnal velocity variations. In light of developments in ice sheet hydrology, these processes and characteristics of valley glacier hydrology should be applicable to the ice sheet scale. This implies that large short-term (diurnal to weekly) to seasonal variations will affect the base of ice sheets as has been shown /Zwally et al. 2002/.

# 9 Acknowledgements

Thanks are due to Jason Amundsen who helped with the drilling operation during the 2002 field season. Rachel Brown provided much assistance during the 2004 campaign. Tarfala Research Station and personnel are also gratefully acknowledged for helping with the logistics of flying the drill up to and down from the glacier each summer and helping out with different aspects of the work. Tarfala Research Station superintendent Henrik Törnberg's mechanical understanding helped in preparing and maintaining the drill. We are also indebted to Andrew Fountain cost sharing in terms of fuel and drill logistics between our projects. Careful comments by Andrew Fountain and Tristam Irvine-Fynn helped improve the report.

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# Appendix 1

Below is an example of an archetypal data logger program run on the Campbell Scientific CR10X to monitor water pressure with a Geokon 4500 vibrating wire pressure sensor.

```
;{CR10X}
*Table 1 Program
; Measure every 600 seconds (10 minute interval)
 01: 600.0000 Execution Interval (seconds)

; Measure battery voltage
1: Batt Voltage (P10)
 1: 15 Loc [ _________ ]

; Set high res mode
2: Resolution (P78)
 1: 1 High Resolution

; Measure vibrating wire pressure transducer
3: Vibrating Wire (SE) (P28)
 1: 1 Reps
 2: 1 SE Channel
 3: 1 Excite all reps w/Exchan 1
 4: 25 Starting Freq. (100 Hz units)
 5: 31 End Freq. (100 Hz units)
 6: 500 No. of Cycles
 7: 0 Rep Delay (0.01 sec units)
 8: 1 Loc [ _________ ]
 9: -47.824 Mult
10: 436.69 Offset

;Make output every 10 minute (or whatever the sampling interval is
4: Do (P86)
 1: 10 Set Output Flag High (Flag 0)

; Record Year, day, hor/minute
5: Real Time (P77)
 1: 1110 Year,Day,Hour/Minute (midnight = 0000)

; Sample the water pressure
6: Sample (P70)
 1: 1 Reps
 2: 1 Loc [ _________ ]

; Sample the battery voltage
7: Sample (P70)
 1: 1 Reps
 2: 15 Loc [ _________ ]

End Program
```

ISSN 1404-0344
CM Gruppen AB, Bromma, 2009