Short-Term Surface Velocity Changes During Summer in the Lower Part of the Ablation Area Using Differential GPS Survey, Storglaciären, Sweden

Korttidsvariationer i isflöde under sommaren i det nedre ablationsområdet på Storglaciären undersökta med differentiell GPS

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Abstract

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The aim of this project was to study the relation between glacier hydrology and its surface motion on short time scale. Four differential GPS stations were installed in the lower ablation area of Storglaciären in Sweden for one week in August 2012. The position data over the period were then compared with the environment information including temperature, precipitation, known hydrology and topography.

The instantaneous velocity results show 9 acceleration events in correlation to temperature and precipitation. The increase of the meltwater inputs drive increases of the motion supposedly through water pressures and basal sliding.

Strain determination using the stations geometry showed that the lower part of the survey area had an extensive behavior when the upper part was showing compressive properties. A deformation event occurring the 14th of August shows an elongation deformation along the centerline from the front of the glacier resulting in a lateral compression on the upper part due to shear stress closer to the margin.

It was proposed that the force driving the elongation is due to the increase of water pressure on the front of the glacier where the internal hydrological system pass from a complex multi-branched system to a channelized output.

Keywords: DGPS, short-term ice velocity, infinitesimal strain, Storglaciären, ablation area

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Populärvetenskaplig sammanfattning

Korttidsvariationer i isflöde under sommaren i det nedre ablationsområdet på Storglaciären undersökta med differentiell GPS

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Syftet med detta projekt var att studera sambandet mellan en glaciärs hydrologi och isrörelse under korta tidsperioder (minuter till timmar). I augusti 2012 installerades fyra differentiella GPS-stationer under en veckas tid i nedre ablationsområdet på Storglaciären i Sverige.Positionsdata under perioden jämfördes sedan med miljöinformation inklusive temperatur, nederbörd, avrinning från glaciären och topografi.

De uppskattade hastighetsresultaten visar på 9 olika accelerationshändelser som relaterar till tempe-ratur och nederbörd. En ökad införsel av smålvatten driver upp vattentrycket vid glaciärens botten som minskar friktionsmotståndet och glaciären får ökad basal glidning.

Isdeformationsberäkningar mellan DGPS-stationerna visar att den nedre delen av undersök-ningsområdet hade extensionell deformation i isrörelseriktningen medan den övre delen visade kompression vinkelrätt mot denna riktning. Deformationshändelsen den 14 augusti visar det motsatta med extensionell deformation längs mittlinjen från fronten av glaciären vilket resulterar i en lateral kompression i den övre delen av det undersökta området kanske orsakade av skjuvspänning vid marginalen.

Det föreslås att utsträckningen av glaciären under dessa händelser är på grund av en ökning av vattentrycket i det område där det interna subglaciala hydrologiska systemet ändras från en complex multigrenade system högre upp i ablationsområdet till ett kanaliserat system vid fronten.

Nyckelord: DGPS, korttidsvariationer i isflöde, deformation, Storglaciären, ablationsområde

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1 Introduction

Glaciers are seen as sensitive indicators of climate change as they are highly impacted by temperature and precipitations fluctuations (Figure 1). Since the alarm was raised for the international community at The United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro in 1992, ice sheets in Antarctic and Greenland have been showing important loses of mass and almost all the glacier in the world have continued to shrink (IPCC, 2014). The projection scenarios of the Intergovernmental Panel on Climate Change (IPCC) for the late 21st century predicts in many region an impact on the hydrological systems due to change of precipitation or melting of snow and ice, affecting the water resources quantity and quality.

Figure 1. Widespread impacts attributed to climate change (IPCC, 2014)

A glacier system gains ice via accumulation processes (snowfall, blown snow, avalanches from slopes…) and loses ice via ablation processes (melting, evaporation, sublimation, scouring by wind…). The result of those gain and loses is the mass balance, also known as Surface Mass Balance (SMB). For most glaciers, it is possible to identify a zone of accumulation and zone of ablation, both separated by an equilibrium line also known as equilibrium line altitude (ELA).
Snow transforms to ice as the snowflakes tend to round up and breaks down. The volume of pores filled with air reduces and the bulk density increases. If we take as reference the density of pure liquid water, which is 1000 kg.m\(^{-3}\), freshly fallen snow has a density between 50 and 200 kg.m\(^{-3}\). Pure ice density is 917 kg.m\(^{-3}\) and the one of glacier varies between 830 and 910 kg.m\(^{-3}\). The metamorphic mechanisms and the time needed to transform ice depend on climate. Melting and refreezing processes tend to greatly accelerate the transformation. Firn is an intermediate state of snow that has begun transformation. It is compacted snow has recrystallized. Its density is generally between 400 and 830 kg.m\(^{-3}\). The transition to ice occurs when interconnected pores sealed off and the density continues to increase as the air bubbles get compressed.

On most land-terminating glaciers, the dominant process of ablation is melting. It occurs when snow or ice exceeds the pressure-melting point via for example a net surplus of energy at the glacier surface or heat generation during stresses. This limit between freezing and melting is also influenced by the ice composition such as the presence of impurities. It plays an important role in the regulation of the glacier motion and meltwater is a fundamental component of the glacier system.

A state of dynamic equilibrium would be the result of a sustained balance between the inputs and outputs of the glacier system. A sustained negative balance would result in the glacier retreat when a sustained positive balance would respectively indicate an advance of the glacier. Climate drives the long-term balance. However, various factors can influence the system into surprising behavior a priori unrelated to climate.

If we have today a good global understanding of the processes behind glacier movement, especially on the long term, many questions remain about the forces controlling flow rates in details.

This work presents the variation of short-term ice velocity in the lower part of the ablation area during summer and its relation with meteorological parameters, hydrology and the known subglacial topography. The four DGPSs stations were installed in a diamond shape in order to observe the horizontal and lateral change of velocity. Vertical velocity was measured but it is supposed to be affected by seasonal scale rather than significant daily variation (Hooke, Calla, Holmlund, Nilsson, & Stroeven, 1989).

1.1 The glacier motion

The glacier flow transports the snow and ice that enter the system in the accumulation area to the ablation area were they exit the system. The motion can be qualify has strain as it occurs in response to applied forces, called stresses. A definition of the stress component that will be use later in this report is proposed in Figure 2. Strain can be divided in two types depending if it is recoverable elastic strain or irrecoverable permanent strain. The two fundamental deformations are pure shear and simple shear.

Pure shear involves flattening or stretching under normal stress (Figure 2e) when simple shear involves shear stress (Figure 2d) and the imaged transformation of a rectangle into a parallelogram.
Pure shear is expected on the flow centerline of a glacier when simple shear occurs mostly near the beds or lateral margins.

![Diagram of stress components](image)

**Figure 2.** Definition of stress components, modified from Twiss and Moores, 1992 in (Benn & Evans, 2010)

Processes of sliding at the bed and deformations of ice cause the flow. The close balance and the spatial variations between the driving forces and the resisting forces control the rates and patterns of the motion.

The motion occurs by strain within the ice, strain within the bed or by sliding at their interface. The driving stress, $\tau_d$, is mainly defined as the basal shear stress. It is the downslope component of gravitational acceleration due to the weight of ice:

$$\tau_d = \rho_i g H \tan \alpha$$  \hspace{1cm} (1)

where $\rho_i$ is the ice density, $g$ the gravitational acceleration (9.81 m s$^{-2}$), $H$ the ice thickness measured vertically and $\alpha$ the ice surface slope.
The resistive stresses are the friction forces at the glacier boundaries. The basal drag and lateral drag nearly balance the force exerted by the ice. Accelerations can be ignored, and the flow is driven by gradients.

If the driving force of the glacier is due to its own weight, several interacting factors such as temperature, ice composition, bed roughness and water pressure control the dynamic.

1.2 Glacier hydrology

The dynamic of glaciers is intimately influenced by their hydrological system. The water change phase, shape the glacier and modify the sensitive balance between driving and resisting forces. A relationship diagram of the production, storage and transportation of water in the glacier system and its environment is proposed in Figure 3.

![Figure 3. Water sources and routing in glacierized catchments (Benn & Evans, 2010)](image-url)
The drainage can be divided in subsystems regarding if the water moves over glacier surfaces (supraglacially), through the ice (englacially) or at the bed (subglacially). The Figure 4 illustrates the drainage systems. Those subsystems are interconnected and associated with storage.

Figure 4: Temperate glacier hydrological model (Irvine- Fynn, Hodson, Moorman, Vatne, & Hubbard, 2011)

The factors that influence the route are the gradients in hydraulic potential driving the water flow and the resistance. For any point on the glacier, the hydraulic potential or head, \( \phi \), can be defined as the potential energy of water (elevation head), meaning its weight and vertical elevation, combined with the weight of ice above this point (pressure head).

\[
\phi = \text{elevation head} + \text{pressure head} \tag{2}
\]

\[
\phi = \rho_w g z + P_w \tag{3}
\]

where \( \rho_w \) is the water density, \( g \) the gravitational acceleration, \( z \) the elevation and \( P_w \) the pressure head. Gravity is the driving force at the surface or where the drainage system is connected to the surface atmospheric pressure (pressure head is zero). Within the ice, contours of equal hydraulic potential can be defined, also known as hydraulic equipotential lines (Figure 4). The water follows pressure gradients within the ice and within the drainage system, perpendicularly to these contours. Because of the pressure head, water-filled subglacial channels are not limited by bed slope and can travel across topography even uphill. The resistance is the energy required to overcome viscosity and depends on the properties of both the water (temperature, composition…) and the flow path (ice, bedrock, dimensions and
roughness of the channel, tortuosity, pores connectedness…). In porous media like ice, the resistance is measured by permeability, $\kappa$, which depends only on material properties or hydraulic conductivity, $K$, which also includes fluids properties.

The permeability of the glacier for water depends if it concerns intact ice or snow (primary permeability) or if it is associated with fractures and other passageways (secondary permeability). It governs the resistance to flow of the englacial system. The subglacial drainage depends on the permeability along the bed and cavitation processes that will be explained later.

Snow and firm are porous and permeable, meaning that the water will easily drain into and through them. However ice with the increasing of density get almost impermeable, meaning that unless there is specific pathways (second permeability), the water will drain on the surface. Pathways are in constant evolution due to the fact that ice can change phase and deform. Conduits open, close, enlarge and contract via a sensitive exchange of energy between the solid and the liquid form of water. Change of freezing and melting occurs with variation of temperature and pressure following the phase diagram of water (Benn & Evans, 2010).

Moulins are vertical channels, connecting the surface to the englacial and subglacial drainage. They are often associated with crevasses. The formation of moulins necessitates that the incision rates, favoured by areas of high stream discharge and surface slope, exceed surface melt rates on the surrounding ice. The melting intensity on the surface is directly connected to atmospheric related variations (temperature, precipitations, radiation…). The supraglacial streams supply the subglacial system where storage and flow mechanisms can trigger acceleration of the basal motion (Benn & Evans, 2010).

In some cases, it is suggested that englacial conduits result of abandonment of older moulins or supraglacial streams after the formation of new ones and their supply is cut-off (Figure 5). This process is called cut-and-closure channel formation (Gulley, Benn, Müller, & Luckmans, 2009).

![Figure 5](image)

**Figure 5.** Schematic of the mechanisms of “cut and closure” channels (Irvine-Fynn, Hodson, Moorman, Vatne, & Hubbard, 2011)
The subglacial drainage systems have been simplified into two categories: distributed systems and channelized systems. A distributed system is, as its name point, diffused in large portion of the bed where the flow gets more tortuous and is therefore less efficient (more resistance). A channelized system is composed of small conduits (cavities) in which water flows rapidly and often indicates a well-connected network.

Cavitation is the process of cavities formation via subglacial drainage and control the degree of coupling at the ice–bed interface. When water fills cavities, the properties of this interface determine the bed resistance and sliding velocities. At a small scale, cavitation reduces bed roughness when bumps are submerged, decreasing the resistance force. The water pressure can create a down glacier traction, which is known as the “hydraulic jack” mechanism (driving force). Finally, with the fact that the coupling ice-bed is reduced at the interface, the stress distribution is modified and is concentrate on the remaining contact ice-bed. This local stress concentration increases the efficiency of refreezing and intensifies ice deformation, which in both case increases sliding rate.

Discharge from glaciers system into proglacial drainage is mainly driven by the diurnal temperature cycle and precipitations. Daily peaks lags behind the time of maximum melting depending on the drainage length and configuration.

1.3 Polythermal glaciers

Because of their different behavior in glacier mechanics, glaciologists distinguish two main types of ice depending of its pressure-melting point. Temperate ice corresponds to ice at the melting point and “cold ice” corresponds to ice below the melting point. This differentiation is used as a classification for glacier depending of their thermal structure composition.

Three glaciers groups have been defined. Temperate glaciers are only composed of temperate ice, cold glaciers are only composed of ice below the pressure-melting point and polythermal glaciers are composed of both.

Polythermal glaciers are the most geographically widespread. They have a large range variation of possible configurations, whose some are illustrated in Figure 6. They are often subdivided into predominantly cold (Figure 6 a–c) and predominantly warm glaciers (Figure 6 d–f). Their drainage system is more diverse in compare to the two other types of glacier but offer comparison affinities. Predominantly warm polythermal glaciers with only a thin cold surface layer in their ablation zone have similar drainage system to temperate glacier.
Figure 6. Schematic view of some possible polythermal structures (Pettersson, 2004). The gray color indicates temperate ice and the white color indicates the cold surface layer.

1.4 Storglaciären

Storglaciären is a small polythermal (predominantly warm) and non-surging-type glacier, flowing in the valley of Tarfala. It is located above the Arctic Circle in the most northern part of Sweden on the eastern side of the Kebnekaise massif (Figure 7). Ice flows dynamic phenomena described on Storglaciären are applicable to other larger glaciers but with the advantage that the size of Storglaciären makes research a bit easier for spatial and temporal coverage (Jansson, 1996). Measurements of mass balance started in 1946 and in the 50s some buildings were built in the valley. Tarfala Research Station, located next to Storglaciären is a modern facility receiving students and researcher on a regular basis.
As a valley glacier, Storglaciären is situated in a deep bedrock valley with ice-free slopes surrounding the glacier surface, which contribute in the accumulation process through avalanches (Figure 8).

Radio-Echo Sounding studies (Björnsson, 1981) have revealed that the bed topography of Storglaciären is characterized by a transverse ridge, called riegel, in the lower ablation area. In details there is actually an overdeepening just after the equilibrium line and the riegel is divided into an upper and a lower overdeepning (Figure 9).
Figure 9. Topography of Storglaciären. A: Map of the bed topography in the lower part of Storglaciären (Björnsson, 1981). B: Mean annual longitudinal strain-rate along a longitudinal cross-section of the glacier (Hooke, Calla, Holmlund, Nilsson, & Stroeven, 1989).

The erosion process of the glacier and the integration of debris in the systems participate in the dynamic. Rock debris falling on the surface (Figure 10) increases the melting locally and can be entrained supraglacially when buried by snow or ingested in crevasses. Supraglacial debris structures are present origins from an incorporation and elevation of subglacial sediment by shearing (thrusting) in correlation with a strong longitudinal compression (Jansson, Näslund, Pettersson, Rickardsson-Näslund, & Holmlund, 2000; Moore, Iverson, Uno, Dettinger, Brugger, & Jansson, 2013).
On a long term, Storglaciären dynamics seem to follow the major changes in climate with advance during Little Ice Age and recession after (Etienne, Glasser, & Hambrey, 2003). On short-term scale (the seasons and daily basis), water pressure variations create accelerations and decelerations of ice flow (Jansson, 1996). For Storglaciären, and other similar glacier, it is believe that the thermal regime has less influence on ice flow trajectories than the hydrology and the subglacial topography (Moore, Iverson, Brugger, Cohen, Hooyer, & Jansson, 2011).

The processes behind the increases in water pressure seem to be the creation of down-forces in cavities and the separation of ice from the bed both leading to an increase of the sliding speed (Hooke, Calla, Holmlund, Nilsson, & Stroeven, 1989).

Storglaciären internal drainage system leads to different part of the main proglacial streams, Nordjåkk, Centerjåkk and Sydjåkk. Nordjåkk presents clear water that has not been in contact with the glacier bed. It has for source the melting at the ice surface (supraglacial system) and the slow drainage of the accumulation area (englacial system) (Figure 11) (Leb. Hooke, B. Miller, & Kohler, 1988). Centerjåkk is a branch that diverted from Sydjåkk and merge with Nordjåkk before reaching Tarfalajåkk, the main stream of the valley. Sydjåkk and Centerjåkk are characterized by high sediment content from the glacier bed (subglacial system). It is mainly surface water that run down into moulins and crevasses in the upper ablation area near the riegel and travel subglacially to the front (Hock & Leb. Hooke, 1993; Jansson, 1996). The drainage is probably interrupted by local short-term storage reservoirs (Jansson, Hock, & Schneider, 2003). During higher flow (as a strong rainfall or a warm day), the blockages can break opening new paths and increasing the water pressure (Holmlund & Hooke, 1983).
Hooke and others have measured seasonal variation of velocity using stakes and geodimeter (Hooke, Brzozowski, & Bronge, 1983; Hooke, Calla, Holmlund, Nilsson, & Stroeven, 1989). The distance measurements made in summer 1989 by Hanson and Hooke in the north cirque of Storglaciären showed diurnal variation in correlation with temperature. Finite element models suggested a strong influence of the water input rather than the longitudinal coupling with lower parts (Hanson & Hooke, 1994). Hanson et al. have measured the daily velocity (sub-hourly scale time resolution) and water-pressure variation for 4 summers (1991-1994) down-glacier from the riegel (Hanson, Hooke, & Grace, 1998). They used Automatic Distance Measurement (ADM). An infrared laser range finder controlled by a pocket-sized computer was positioned on a stationary rock and measured distance with stakes on the glacier. They found good correlation and homogeneous response for large event but small variation were qualified as “enigmatic” as the reaction of the velocity can happen before the increase of water-pressure is expected. They supposed an influence of the upper part of the glacier due to a relaxation extensional strain across the riegel.

Differential GPS measurements were performed on Storglaciären as part of the EU Glaciology Lab (EU Snow and Ice Practical Training Courses) held at Tarfala Research Station showing good agreement with previous observations (Schneeberger, Short, & Landl, 2000; Haresign, 2000). Between April and June 2009, two DGPS stations were installed in the upper and lower part of the ablation area logging data every second (Psaros, 2012). Entering the melt season, it appears that the velocity was responding directly to the external changes in temperature and precipitation. Delays would be explained by the evolution of hydrological system during spring.
2 Methods

2.1 DGPS method

The Global Positioning System (GPS) is a U.S.-owned utility providing positioning, navigation and timing, also abbreviated as PNT, services. The U.S. Department of Defence (DoD) designed and built the system in the early 1970s, initially as a military system to fulfill military needs and was later made available to civilians. This system consists of three segments: the space segment, the control segment, and the user segment. The U.S. Air Force develops, operates and maintains today the space segment and the control segment. The user segment includes military and civilian users.

The space segment reached full initial operational capability to ensure continuous worldwide coverage in 1993. It consists of a constellation of 24 satellites arranged so that four satellites are placed in each of six orbital planes at an altitude of approximately 20,200 km also known as medium Earth orbit. Each satellite circles the Earth twice a day and transmit in continue their current time and position. With this geometry and considering an elevation angle of 10°, four to ten GPS satellites should be visible anytime, anywhere in the world, four satellites being the minimum required for PNT services (El-Rabbany, 2002). In 2011, an expansion of the GPS constellation known as the "Expandable 24" configuration introduced three extra satellites. The 27 satellites constellation improved coverage in most parts of the world.

The control segment is composed of five monitoring stations (Figure 12). The GPS concept is based on time. Satellites carry atomic clocks synchronized to the ones of the control segment. The ground stations determine the broadcasted positions, called ephemerides, and the satellite time. Any drift from the time maintained on the station is corrected daily and the ephemerides and clock adjustments are transmitted back to the satellite.

![Figure 12. GPS control sites (El-Rabbany, 2002)](image)
Updated signals are transmitted to GPS receivers of the user segment. GPS receivers have clocks as well but less stable. The exact position and time deviation must be computed from multiple satellites. A minimum of four is needed, three for position coordinates and one for clock deviation.

Differential Global Positioning System (DGPS) method compares the data between two receivers: One measuring on the field (rover) and one precise fixed point with known coordinates (base receiver). The precise coordinates of the base define an error correction that can be applied to the distance between each satellite and receiver. This difference is then used during post-processing to refine the rover measurement with an accuracy that can today increase from meters to centimeters. DGPS methods offer nowadays enough precision to conduct studies on short-term ice velocity.

2.2 DGPS error sources

Systematic errors associated to DGPS technology are the same than GPS. They can be divided in 4 categories regarding their origin illustrated in Figure 13.

Figure 13. GPS errors and biases (El-Rabbany, 2002). Figure adapted by author.

① Errors originating at the satellites include ephemeris (modeled trajectory versus real position) and clock error (clock accuracy). Selective availability (SA) has been strikethrough in the figure as it is nowadays irrelevant. SA was an intentional degradation of the public GPS accuracy by the US DoD for national security reasons and was terminated in 2000. When precision is required, “satellites errors” tends to be reduced during post-processing of the measured data. Precise ephemeris data are available to download for users with some delay. The satellite clock, monitored by the control segment, tend to have much better accuracy than the GPS receivers clocks.
Errors originating at the receivers include clock errors, multipath error, noise and antenna phase center variations. Unless exception, receivers use crystal clocks in compare to the much more expensive satellites atomic clocks. Accuracy is partially improved through differencing between the satellites available. Multipath error result of the different paths the GPS signal can take before to reach the receiver (reflection) and they depend of the environment surrounding the antenna (Figure 14).

![Figure 14. Geometry of multipath effects (Xu, 2007)](image)

Noise errors are inherent to the quality of the electronic composing the receiver. The instrument must be tested and calibrated. This process is often automatic (self-test of the instrument). The antenna phase center is the point where the GPS signal is received and converted. An error results if the antenna phase center does not perfectly coincide with the physical center of the antenna. But the error is generally small and neglected (El-Rabbany, 2002).

Errors originating at the signal propagation include delays resulting from the passage in the atmosphere in correlation with the incidence angle of the signal. Two layers are considered, the ionosphere and troposphere. GPS signal travel at the speed of light in the vacuum of space and is bended as it enters the ionosphere proportionally with the total electron content (TEC) encountered. The TEC of the ionosphere vary in time (time of the day, seasons…), space (latitude) and is influenced by the solar activity. As it has a high correlation over short distances, DGPS observations remove the major part of the error for this layer via combinations of dual frequency measurements.

The troposphere is a non-dispersive media with respect to GPS signal. As the delay is non-frequency dependent, it can’t be removed as for the ionosphere via combination of dual frequency measurements. The troposphere delay depends on temperature, pressure, and humidity. The signal will be affected by refractivity in air that can be divided into hydrostatic (dry gases) and a wet (water vapour) component. The dry atmosphere (N\textsubscript{2}, O\textsubscript{2}, Ar…), main constituent of the troposphere, is stable and can be easily modeled using the laws of the ideal gases. The wet component is more unpredictable and difficult to model.

Errors originating from the geometry are representative of the quality of the satellites availability for a receiver. The more they are and the more spread out they are seen in the sky by the receiver, the more accurate will be the measurements. If two satellites are close to each other, the uncertainty area is larger (Figure 15).
The geometry effect is given by the dilution of precision (DOP). It is the ratio of position error to the range error (the lower, the more accurate is the geometry). DOP can be evaluated under different components (Figure 16). The value gives a quality rating of the measurements from poor to ideal.

![Dilution of precision components](image)

**Figure 16.** Dilution of precision components

### 2.3 Equipment and fieldwork

The fieldwork carried out between the 9th and 17th of August 2012. The equipment consist of four roving receivers R7 GNSS on the glacier and one base receiver R7 GNSS located permanently in the main office of Tarfala Research Station. The sampling frequency is 1 Hz. A Trimble R7 GNSS receiver can
deliver a submeter-accuracy by itself (Trimble, 2015). Post processing increases the accuracy in the range of ±10 mm +1 ppm root-mean square (RMS) accuracy in the x and y direction and ±20 mm +1 ppm RMS in the z direction (Trimble, 2007).

The stake grid employed for the mass balance measurements of the glacier was used as a reference for the position of the four stations on the glacier (Figure 17). On the lower part of the ablation area, the station 1 is located at the stake 7C, the station 2 at the stake 6S and the station 3 at the stake 6N. The station 4 was positioned near the stake 5C.

![Figure 17: Stake round on Storglaciären and location of the stations](image)

The receivers are equipped with Zephyr Geodetic 2 antenna fixed on a stake around 1.20 m above the ice (Figure 18). The stake was positioned with a steam-driven ice drill (Figure 19) (Heucke, 1999). 12V lead acid (gel cell) batteries were used for the stations on the glacier and changed.
The coordinate system used is SWEREF99 TM (SWEdish REference Frame 1999, Transverse Mercator) and meters as unit. Northing coordinates are measured northward from the Equator and Easting coordinates are measured from the central meridian, increasing eastwards (Lantmäteriet, 2015).

2.4 Weather and Hydrology

Tarfala manage of an automatic meteorological station since 1987 based on a Campbell Scientific CR-10 datalogger (Stockholm University, 2012). The instruments measure temperature, wind, radiation, precipitation and ventilated temperature and humidity. Precipitation data were collected from this station. The Swedish Meteorological and Hydrological Institute (SMHI) installed an official meteorological station in 1995 for the 50th anniversary of the Stockholm University research activities in the Tarfala valley.
During the period of survey, a temporary weather station was installed on Storglaciären accumulation with similar equipment (Figure 20). The temperature data used in this report come from the temporary station. SMHI statistics are used to get an overview of seasons for the limitation of the survey.

![Figure 20](image)

**Figure 20.** Location and photography of the temporary weather station (Matthews, 2013)

Tarfala Research Station is equipped with two gauging hydrological stations (Figure 21). The Rännan station collects the water from Storglaciären, isfallglaciären and tarfala sjön when Lillsjön is located “upstream” from Storglaciären. Rännan, is the main station and is operated throughout the year, whereas Lillsjön is only operated during summer (July-mid-September) (Stockholm University, 2012).

![Figure 21](image)

**Figure 21.** Map of the Tarfala Valley hydrological monitoring sites lillsjön and Rännan (Stockholm University, 2012)

The survey was done in parallel with a hydrological study in the area (Ekblom Johansson, 2013). Their discharge data on Nordjåkk, Sydjåkk and Centerjåkk were collected for this work in order to get
a more detailed overview of the hydrological system at the moment. Discharge volumes were estimated manually using uranine dye injections and a handheld fluorometer (AquaFluor) and then with pressure transducers which together with the breakthrough curves from the discharge dye tracing experiments delivered a continuous discharge estimation via stage-discharge curves (Ekblom Johansson, 2013).

2.5 Post processing

The coordinates measurements from the four rover receivers and the base stations have been processed via Trimble Business Center software v2.20. The elevation mask was set on 10 degrees and the acceptance of horizontal precision to 50,0 mm ± 1.0 ppm. The geodetic coordinates on GRS80 have been converter to Cartesian coordinates in SWEREF99 TM projection and exported into text file to be handle in MATLAB.

Outlier removal was achieved with a threshold of ± 0,02 m and a running mean method. Data gaps inferior to 5 min were interpolated and a low-pass filtering with a window of 1 hour (3600 Hz) was applied on the continuous segments to reduce noise.

2.6 Cumulative distance

Cumulative distance analysis is useful to see how far the stations have moved and how they behave between one another. If we refer to E-W as \( x \) and N-S as \( y \), the distance, \( a \), between two consecutive measurements can be expressed:

\[
a = \sqrt{\Delta x^2 + \Delta y^2}
\]

(4)

Where \( \Delta x \) and \( \Delta y \) are respectively the longitude and latitude difference between the 2 measurements.

The cumulative distance \( d_N \) is the sum of the distances \( a \) between \( N \) consecutive measurements:

\[
d_N = \sum_{k=1}^{N} a_k
\]

(5)

The linear start to end distance “\( d_{linear} \)” is the length of the line that separates the first and the last measurement over the period of survey.

\[
d_{linear} = \sqrt{(x_{end} - x_{start})^2 + (y_{end} - y_{start})^2}
\]

(6)

2.7 Average velocity

For the period of active measurements, \( t_{Active Measurments} \), the average velocity, \( V_{Average} \), of each station for the full-cumulated distance, \( d_{N{\text{max}}} \), can be expressed:

\[
V_{Average} = \frac{d_{N{\text{max}}}}{t_{Active Measurments}}
\]

(7)
It can be compared with the linear start to end average velocity, $V_{Average\_linear}$ expressed for the full period of survey, $t_{survey}$:

$$V_{Average\_linear} = \frac{d\_linear}{t_{survey}} \quad (8)$$

### 2.8 Surface velocity and flow direction

The flow vector of the glacier registered by the station is characterized by its magnitude and direction. The instantaneous glacier surface velocity, $V$, between two consecutive measurements, $t$ and $t_+1$, can be obtained from longitude and latitude velocity components respectively $u$ and $v$ (Figure 22).

**Figure 22.** Two-dimensional motion schematic

The longitude and latitude velocity components are expressed respectively:

$$u(t) = \frac{dx(t)}{dt} \quad (9)$$

$$v(t) = \frac{dy(t)}{dt} \quad (10)$$

The magnitude of the velocity vector is:

$$V = |V| = \sqrt{u^2 + v^2} \quad (11)$$

The flow direction can be expressed as:

$$\theta = 90 - \tan^{-1} \left( \frac{u}{v} \right) \quad (12)$$
2.9 Surface strain

The horizontal strain can be estimated in a triangular area between three non-colinear GPS stations. The survey was divided in two triangles: ABC pointing to station 1 for the upper part of the survey and DCB pointing to station 4 for the lower part (Figure 23). The changes in distances between GPS stations in our time interval are very small in compare to the actual distance between them. The strain measured is infinitesimal and the difference between the displacement gradient within two measures is not significant.

![Figure 23. Triangles definition for strain determination](image)

For each triangle, the East-West instantaneous velocity, $u$, and the North-South instantaneous velocity, $v$, of the three stations can be formulated as a deformation and translation of the triangle from the initial location of the stations (Figure 24). Considering a unit circle located at the centroid of the triangle at the initial state, its deformation results in an ellipse, the 2 dimensional strain ellipse. The direction of the major axis inform on the direction of the deformation. A decreasing of the area of the ellipse in comparison to the initial circle would indicate a compression state of deformation when an increase of the area would indicates an extension state of deformation.
Figure 24. Strain ellipse between three non-collinear GPS stations.

The following equation will demonstrate the reasoning for the triangle ABC that is identical for triangle DCB. The elements of the deformation gradient tensor \((e_{xx}, e_{xy}, e_{yx}, e_{yy})\) and the coordinates of the translation vector \((t_x, t_y)\) are the unknown parameters of a relationship in matrix form.

\[
D = GM
\]  

(13)

where:

- \(D\) = Data matrix with instantaneous velocity \(u\) and \(v\)
- \(G\) = Coefficient matrix containing 0, 1 and initial location in \(x\) and \(y\) relating the matrix \(D\) and the matrix \(M\).
- \(M\) = Model matrix of unknowns containing deformation gradient tensors and the coordinates of the translation vector

\[
\begin{bmatrix}
A_u \\
A_v \\
B_u \\
B_v \\
c_u \\
c_v
\end{bmatrix} =
\begin{bmatrix}
1 & 0 & A_x & A_y & 0 & 0 \\
0 & 1 & 0 & 0 & A_x & A_y \\
1 & 0 & B_x & B_y & 0 & 0 \\
0 & 1 & 0 & 0 & B_x & B_y \\
1 & 0 & c_x & c_y & 0 & 0 \\
0 & 1 & 0 & 0 & c_x & c_y
\end{bmatrix}
\begin{bmatrix}
t_x \\
t_y \\
e_{xx} \\
e_{xy} \\
e_{yx} \\
e_{yy}
\end{bmatrix}
\]  

(14)

Once we have solved the model matrix \(M\) between two measurements, the displacement gradient tensor may be separated into the symmetric infinitesimal strain tensor, \(\varepsilon_{ij}\), and the antisymmetric rotation tensor, \(\Omega_{ij}\).
\[
\epsilon_{ij} = \begin{pmatrix}
\frac{e_{xx}}{2} & \frac{(e_{xy} + e_{yx})}{2} \\
\frac{(e_{xy} + e_{yx})}{2} & \frac{e_{yy}}{2}
\end{pmatrix}
\]

(15)

\[
\Omega_{ij} = \begin{pmatrix}
0 & \frac{(e_{xy} - e_{yx})}{2} \\
\frac{(e_{xy} - e_{yx})}{2} & 0
\end{pmatrix}
\]

(16)

From the strain tensor, \(\epsilon_{ij}\), can be defined the unit vectors that coincide with the principal axes of the strain tensor, the eigenvectors. The eigenvalues gives the magnitude of the principal strain.

### 2.10 Cross correlation

Cross correlation is useful to analyse delay between two vectors, \(X\) and \(Y\), comparing correlation change at different time offset. Highest correlation at a positive offset indicates that \(X\) is in the lead when negative value means that it is \(Y\). For \(N\) samples and \(m\) unit of time, the cross correlation \(R\) between the vectors can be expressed:

\[
R_{XY}(m) = \begin{cases}
\sum_{n=0}^{N-m-1} X_n Y_{n+m}^*, & m \geq 0, \\
R_{XY}^*(-m), & m < 0,
\end{cases}
\]

(17)

where the asterisk denotes complex conjugation.

### 3 Results

#### 3.1 Weather and hydrology

According to the Swedish Meteorological and Hydrological Institute (SMHI, 2014) the beginning of the melt season 2012 was significantly cold (Figure 25). 2011 was globally a warm and humid year in the north with significantly higher temperature and precipitation than the normal. After a relatively normal winter, Mars has been a very warm month beginning the melt of the snow earlier than usual in Norrland region. However cold air and precipitations arriving at the end of Mars and April didn’t results in a significant change for the snowpack in the Kebnekaise area. May and June were colder than the normal. Many places in Norrland registered the coldest June month since 1995-1996.
The period of measurements corresponds to the highest temperature in August (Figure 26). Hydrological studies in the area at the time of field work shows that many moulins were just opening in early August, together with an increase of the supraglacial water flow (Ekblom Johansson, 2013).
The data collected from Tarfala Research Station are presented in Figure 27. One precipitation event of 13.7mm occurred the 15th of August followed by 2 mm the 16th. The stations where then retrieved before the rain on the 17th. The temperatures varied between 3.4°C and 10.2°C and the daily average increased between the 10th and 14th from 4.6°C to 8.8°C.

Automatic discharge results are available for Nordjäkk during the whole period of survey. Unfortunately the automatic discharge has been set up late for Sydjäkk and Centerjäkk and the few manual measurements aren’t representative of the daily variation of the flow. Nordjäkk have a daily periodicity variation that follows the temperature and peaks directly respond to the precipitation event. Field observation shows an increase of water flow and sediment load in Sydjäkk stream during the fieldwork (Ekblom Johansson, 2013). Centerjäkk shows higher discharge values than Sydjäkk.

**Figure 27.** Precipitation, temperature and discharge measurements (manual estimation and continuous discharge estimation via stage-discharge curves) during the period of survey.
Diurnal temperature variation cycles are in correlation with the discharge variation of Nordjåkk. However, they become less visible when the temperature gets warmer after the 13th of August. Peaks of discharge for Nordjåkk follow precipitations.

**3.2 Data post processing**

Position data presented in the results are a variation of position from the start of the measurements (origin) instead of coordinates. The system is right handed. The longitude (x-axis) is a vector pointing towards the east and the latitude (y-axis) is a vector pointing towards the north. As a reminder of the direction of the vector, x-direction and y-direction will be referred respectively W-E and S-N in this report.

The Figure 28 shows the raw data, the data after outlier removal and the data after the low pass filtering which are the one used for the analysis.

![Example of data post processing for station 1 W-E direction](image)

**Figure 28.** Example of data outlier removal and low pass filtering for the station 1 E-W position

**3.3 Horizontal position variation**

The data of the horizontal position variation presented in Figure 29 show several gaps due to the batteries that drained before replacement. As a consequence, considering a survey period from the 9th of August 12:00 to the 17th of August 09:00 and a logging frequency of 1 second, the percentages of data collected are:

- Station 1 = 78%
- Station 2 = 94%
- Station 3 = 82%
- Station 4 = 65%
Several “offset” in the data can be observed and identified as errors. In those situations the stations “jump” between positions and the movements registered can be against the general flow of the glacier. This abnormal behaviour is clear on the horizontal plot of the stations raw data position in Figure 30. The plot is a view from above of the stations on the glacier, showing their cardinal displacement in function of the time represented here in a scatter gradient from cold to warm colours. The red line is an average of the movements via a running mean with a span of 6 hours.

The Station 1 east movement change all of a sudden to west between the 14th and 15th of August. A similar behaviour is observed for station 2 that change from southeast direction to southwest between the 13th and 14th of August. At the same period, the station 3 changes from northeast to southeast direction. A south shift from east is observed for station 4 between the 11th and 12th of August.
Figure 30. Horizontal position variation
3.4 Distance travelled and average velocity

The results of the cumulative distance over the period of survey are presented in Figure 31. They were calculated from the low pass filtered data position of each station.

![Figure 31. Cumulative distances over the period of survey](image)

Looking only at the overlapping measurement of all the stations during the period of the survey, the cumulative distance allows comparing the reactivity of the stations (Figure 32).

![Figure 32. Cumulative distances of the station for overlapping measurements](image)

The total distance travelled during active measurements \( N = N_{\text{max}} \) can be compared with the linear start to end distance, \( d_{\text{linear}} \), of each station (Table 1).
The results reveal that station 4 have travelled between 10 and 17% more during measurements than the other stations. However in term of final position, station 4 have travelled half the distance of station 1 and 2 when station 3 has almost not moved.

Table 2 presents the average velocity results of each station for the full-cumulated distance, only the overlapping measurements and the full period of survey considering the station moving linearly from the first measure to the last.

The results shows high velocities value in comparison to the average of the month expected between 20 and 25 meters per year near the centerline (Hooke, Brzozowski, & Bronge, 1983; Hooke, Calla, Holmlund, Nilsson, & Stroeven, 1989). Considering only the last position and a linear movement,
the velocities are half the averages for station 1 and 2, one-fourth for station 4 and ten times lower for station 3.

3.5 Surface velocity and flow direction

The velocities results for each station are presented in Figure 33 together with the metadata. A low pass filtering, plotted as a red line, has been calculated with a window of 6 hours.

![Figure 33](image)

Figure 33. Horizontal velocities and metadata. The green numbers are the events chosen for analysis.

Nine events (see Figure 33) associated with an increase of velocity have been chosen because of their similitudes or differences between the stations. They are listed in Table 3.
Table 3. Identified velocities events during the period of survey

<table>
<thead>
<tr>
<th>Event number</th>
<th>Information availability (Stations)</th>
<th>Time</th>
<th>Event description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ALL</td>
<td>10th of August Midday</td>
<td>peak</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.4 m per day)</td>
</tr>
<tr>
<td>2</td>
<td>ALL</td>
<td>10th of August Evening</td>
<td>Major peak</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(&gt; 0.5 m per day)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Very marked for</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>station 2 and 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(&gt; 0.7 m per day)</td>
</tr>
<tr>
<td>3</td>
<td>1 and 2</td>
<td>11th of August Evening</td>
<td>Major peak</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(&gt; 0.7 m per day)</td>
</tr>
<tr>
<td>4</td>
<td>ALL</td>
<td>12th of August late</td>
<td>peak</td>
</tr>
<tr>
<td></td>
<td></td>
<td>evening</td>
<td>(0.4 m per day)</td>
</tr>
<tr>
<td>5</td>
<td>2, 3 and 4</td>
<td>13th of August Midday</td>
<td>Peak</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.4 m per day)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Very marked for</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>station 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(&gt; 0.6 m per day)</td>
</tr>
<tr>
<td>6</td>
<td>ALL</td>
<td>13th of August Evening</td>
<td>Peak</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.5 m per day)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Very marked for</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>station 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(&gt; 0.8 m per day)</td>
</tr>
<tr>
<td>7</td>
<td>ALL</td>
<td>14th of August Midday</td>
<td>Peak</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.5 m per day)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Very marked for</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>station 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(&gt; 0.7 m per day)</td>
</tr>
<tr>
<td>8</td>
<td>ALL</td>
<td>15th of August Midday</td>
<td>Major double peak</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(&gt; 0.9 m per day)</td>
</tr>
<tr>
<td>9</td>
<td>ALL</td>
<td>16th of August Midday</td>
<td>Major peak</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(&gt; 0.7 m per day)</td>
</tr>
</tbody>
</table>

The statistical results are presented in Figure 34. The flow is turn towards the east for all the station but can vary from northeast to south direction.
3.6 Surface Strain

The strain area results for the triangle ABC and DCB are presented in Figure 35. A low pass filtering, plotted as a red line, has been calculated with a window of 3 hours.
Negative value refers to a decrease of the area of the ellipse in comparison to the initial circle associated to compression state of deformation when positive value refers to an increase of the area associated to an extension state of deformation. Comparing statistically overlapping measurement of the 2 triangles, the triangle ABC has 50,6% of negative values and the triangle DCB 41,7%. It indicates that during the survey, the lower triangle has been more into an extension state than for the upper triangle.

The Azimuth of the major axis has been evaluated in each triangle for the entire period in order to estimate the main orientation of the deformation (Figure 36). It is observed that in triangle ABC, the orientation is mainly North-South and perpendicular to the glacier flow (compressive behaviour) when on triangle DCB the orientation is mainly West-East in direction of the valley (extensive behaviour).

![Figure 36. Major Axis azimuth distribution during the survey period in each triangle](image)

4 Discussion

4.1 Errors and biases

Looking at the possible origin of the noise and biases observed in the results, all the errors presented in Chapter 2.2 are existent but, for the most, significantly reduce by the instruments themselves and through post-processing.

1. Errors originating at the satellites should have been improved with the precise ephemeris and the DGPS combination of dual frequency measurements. There effects are neglected.

2. Errors originating at the receivers concern most likely multipath error due to the fact that Storglaciären is a valley glacier. The high surrounding mountains reflecting the signal can lead to a poor triangulation. However the Trimble® R7 GNSS System and the Trimble Zephyr™ 2 antenna should in theory reduce those errors (Trimble, 2007) (Trimble, 2015).
Errors originating at the signal propagation should be low for the ionosphere and DGPS technique (combination of dual frequency measurements) but the air humidity could have play a role regarding troposphere delay.

Errors originating from the geometry is probably the most problematic biases source for Storglaciären. The valley reduce the visibility dome for the satellites which moreover become available in a much more narrow area of the sky decreasing accuracy (Figure 15). A higher elevation mask angle in the parameters of the post processing software should have improve accuracy by removing satellites that were most likely not directly visible by the receivers without reflection of the signal.

Over a period of several hours, it seems clear that the position errors are larger to the targeted 1 cm accuracy and that jumps and “upstream” motion are not representative of the real glacier behavior during the period of survey.

The cumulative distance (Table 1), as being averaged over short time steps, may have larger uncertainty levels due to spurious effects of each sample (1Hz). The linear method or “linear start to end distance” is in consequence more reliable to estimate the motion during the period of the survey. The average velocities calculated with the linear method (Table 2) are in the order of magnitude expected in comparison to other author’s results for similar time intervals (Hanson, Hooke, & Grace, 1998; Psaros, 2012).

Despite the errors, it is likely that short time variability of ice velocity exists and the variation results can be interpreted.

4.2 Short-term velocities variations

Velocities events listed in Table 3 seem to follow approximately the peaks of diurnal cycle of temperature and precipitations events (Figure 37). These results agree with the literature (Hooke, Brzozowski, & Bronge, 1983; Hooke, Calla, Holmlund, Nilsson, & Stroeven, 1989; Hanson, Hooke, & Grace, 1998; Jansson, 1996; Psaros, 2012). Temperature and precipitation modify the water input of the englacial and subglacial hydrological system in a short time. Increase of water pressure creates peaks of velocity in the flow of the glacier. This pressure reactivity means that the englacial and subglacial drainage systems are most probably underdeveloped due to the cold melt season. It enhances processes as cavitation during the events with high water input that decrease bed resistance and exert the downglacier traction via hydraulic jacking.
The horizontal position variation (Figure 30) and the linear start to end average velocity results (Table 2) indicate that the motion of station 1 and 2 is faster towards the valley. Station 3 is almost stagnant with a strong deflection towards the centreline. It could be explained by the fact that it is located near the margin above a bedrock depression (Hooke, Calla, Holmlund, Nilsson, & Stroeven, 1989).

The cross correlation between the motion of stations gives information on their relative reactivity and eventual delay between the stations. The results (Figure 38) present strong correlation value with lags inferior to 3 min or even instantaneous between station 1 and 4 (Figure 39) along the centreline. The stations react globally as a unit at this scale of the glacier.
However between the 13th and 15th of August when the diurnal cycle of temperature is less marked, the station 4 variations rise above the others significantly with a peak around noon the 14th of August, synchronic with a discharge peak of Nordjåkk. This reactivity, showed by cumulative distance in Figure 40, is also coexistent with deformations as shown by the strain rates peaks (Figure 35).
4.3 Deformation behaviour

The general upper triangle ABC compressive behaviour opposed to the lower triangle DCB extensive behaviour are representative of the drag effect of the glacier front and the resulting lateral compression.

As an example, the event of the 14th of August places the lower triangle DCB into a peak of extensive deformation towards the valley (Figure 41). The discharge results of Nordjåkk suggest an increase of the melt and probably increase of the water pressure. The time of this event is approximately at 14:15 and it is interesting to see that the triangle ABC has a positive peak value synonym of compression 4 hours after.
It can be suggested that the 14th of August, an acceleration event occurred just after noon on the front of the glacier. It could originate from an increased water pressure due to the previous days significant increase of temperature and the higher meltwater flux. This acceleration results into an extension from the centreline and creates a lateral compression that peaks around 18:10 for the triangle ABC.

The riegel is divides two overdeepnings. They alter the subglacial system and force the subglacial water to travel upwards. It is assumed that the water is rather transported in englacial conduits with low velocity. In the beginning of the melt season the system is braided with small conduits that slowly widen and join allowing the water travel even faster to the pro-glacial streams (Hock & Leb. Hooke, 1993). A significant increase of water pressure on the front of the glacier when the system straighten (Figure 42) could explain the event observed the 14th defined by an east elongation along the centreline. This deformation creates shear stress on the margin resulting in the lateral compression observed.

Figure 41. Longitudinal strain comparison between the 2 triangles

![Strain comparison with low pass filtering](image)
Conclusion

Differential Global Positioning System (DGPS) measurements with high temporal resolution was used to determine the horizontal short-term velocity variations of Storglaciären lower ablation area during one week of August 2012.

The results show that an increase of the meltwater inputs through the effect of temperature and precipitation result in an increase of the motion supposedly driven by water pressures and basal sliding.

Strain determination showed that the lower part of the survey area had an extensive behavior when the upper part was showing compressive aspects. An extension occurred along the centerline, originating down glacier towards the valley, and was resulting in a lateral compression of the upper area due to shear stress closer to the margin. It was proposed that the extension is driven by water pressure concentrated on the front of the glacier where the internal hydrological system becomes channelized.

Complementary information on the subglacial drainage and the overburden pressure should be considered for future studies related to short-term ice velocity variation.

This study demonstrates the practical simplicity of DGPS methods in the role of short-term ice velocity variation determination. As recommendation for future projects using DGPS technics for this...
purpose, it is proposed to secure the energy input aspect of the instruments for continuous measurements and the use of a tripod solution for the antenna fixation in order to assure high stability.

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I am grateful to my supervisor Rickard Pettersson for this project opportunity and my introduction to glaciology fieldwork. I appreciate your friendly attitude from the beginning and the time you took to discuss the method and the results of this work. You have been of great support and I learned a lot from you.

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Finally I would like to thank Adrian and Nico for your tips during the writing of the thesis and Katarina for your continuous encouragement and support.
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