Seasonal Velocities on Nordenskiöldbreen, Svalbard

Säsongvariationer i isflöde på Nordenskiölbreen, Svalbard

Lena Elisa Ehwald
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Abstract

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Global warming leads to increased precipitation in the Arctic, as warmer air can carry more moisture. The consequence is that many arctic glaciers get steeper slopes over time as increased melt at their lower part causes thinning and increased solid precipitation in their upper regions leads to thickening of the glacier. Ice flow of glaciers is strongly controlled by the surface slope, where steeper slopes leads to increased ice flow. An altered flow regime of the glaciers can lead to unpredicted contributions to sea-level changes as more glacier ice is delivered to lower regions and eventually to the sea through calving of melt-runoff. Long-term measurements of ice-flow velocities are therefore crucial to receive a better understanding of how glaciers respond to climate changes in a temporal and spatial scale.

This study investigates ice flow velocities measured over a period of 10 years between 2006 and 2015 on Nordenskiöldbreen, Svalbard. The poly-thermal outlet glacier is centrally located on Spitsbergen; the main island of the Svalbard archipelago (74°N, 10°E / 81°N, 35°E). Ice-flow velocities are measured continuously using stand-alone single-frequency GPS receivers attached to 8 metal stakes along the central flow line of Nordenskiöldbreen. The Institute for Marine and Atmospheric research in Utrecht, the Netherlands (IMAU) has developed such GPS units to measure ice-flow velocities at low costs and all year-round. Ice flow velocities at the central-flow line of Nordenskiöldbreen for the period 2006-2016 are estimated to be between 40 and 60 m a⁻¹. Results show that maximum ice flow velocities can reach up to 80 m a⁻¹ and occur mainly in the beginning of July. The highest annual averaged velocity of 53.88 m a⁻¹ was measured during summer 2014. Averaged ice-flow velocities show an increasing trend of about 1.78 m a⁻¹ during summer seasons. Results are further compared with mass balance observations and temperature records to analyze how glacier systems respond to climate changes.

Keywords: Ice-flow velocity, Nordenskiöldbreen, climate change, mass balance, dynamical behavior of glaciers, Svalbard

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De uppskattade hasiltesresultaten visar att Nordenskiöldbreen rör sig med en medelhastighet av 45-53 meter per år. Isrörelse kan nå upp till 80 meter per år och är främst förekommande under juli månad när temperaturen är hög. Detta producerar då mer smältvatten vilket driver upp vattentrycket vid glaciärens botten och leder till basal glidning.

Nyckelord: Glaciär, Svalbard, Nordenskiöldbreen, isflöde, massbalans, klimatuppvärmning

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List of Figures and Tables

Figure 4.1 Temperature recorded at Svalbard Airport 1901-2016 ..................................................10
Figure 4.2 Map of GPS Stations on Nordenskiöldbreen .................................................................11
Figure 5.1 Ice flow velocities on Nordenskiöldbreen 2006-2009 ......................................................12
Figure 5.2 Ice flow velocities and surface height changes of Nordenskiöldbreen 2006-2009 .....14
Figure 6.1 Visualization of how GPS works ....................................................................................15
Table 6.1 Characteristics of different GPS stations ......................................................................18
Figure 6.2 GPS receiver .................................................................................................................18
Figure 7.1 Movement of reference station ....................................................................................21
Figure 7.2 Scatter plot of reference station ....................................................................................22
Figure 7.3 Comparison between DGPS and GPS ....................................................................23
Figure 7.4 Observed ice-flow velocities .......................................................................................24
Figure 7.5 Ice flow-velocities in different elevations .................................................................26
Figure 7.6 Ice flow velocities compared with temperature ........................................................27
Figure 7.7 Summer ice-flow velocities .........................................................................................28
Figure 7.8 Summer ice-flow velocities compared with temperature ........................................29
Figure 7.9 Summer ice-flow velocities compared with mass balance ......................................30
Figure 7.10 Winter ice-flow velocities .........................................................................................31
Figure 7.11 Winter ice-flow velocities compared with temperature ........................................33
Figure 7.12 Winter ice-flow velocities compared with mass balance ..........................................33
Figure 7.13 Surface topography ..................................................................................................34
Figure 7.14 Comparison between Temperature, Velocity and Surface Topography ..................35
Figure 8.1 GPR Profile beneath Station S7-S11 ..........................................................................37
Figure 8.2 Comparison between summer temperature and mass balance ................................39
Figure 8.3 Comparison between winter temperature and mass balance .................................40
# Table of Contents

1 Introduction .........................................................................................................................................1

2 Aim........................................................................................................................................................3

3 Background..........................................................................................................................................4

  3.1 Glacier Motion ...........................................................................................................................4

  3.2 Glacier Hydrology ......................................................................................................................6

  3.3 Thermal Regime of Glaciers ......................................................................................................8

4 Study Site .............................................................................................................................................9

  4.1 Svalbard ......................................................................................................................................9

  4.2 Nordenskiöldbreen ...................................................................................................................10

5 Previous Research .............................................................................................................................12

  5.1 Velocity Observations on Nordenskiöldbreen ..........................................................................12

  5.2 Velocity Observations on other Svalbard Glaciers ..................................................................13

  5.3 Mass Balance Observations on Nordenskiöldbreen .................................................................13

6 Methodology .......................................................................................................................................15

  6.1 Global Positioning System (GPS) ............................................................................................15

     6.1.1 Error Sources .........................................................................................................15

  6.2 Differential Global Positioning System (DGPS) ......................................................................16

  6.3 Data ..........................................................................................................................................17

  6.4 Data Processing ........................................................................................................................19

7 Results ................................................................................................................................................21

  7.1 Reference Station .....................................................................................................................21

  7.2 Comparison between GPS and DGPS ......................................................................................23

  7.3 Flow Velocity Observations .....................................................................................................24

  7.4 Surface Topography .................................................................................................................34

  7.5 Comparison of Temperature, Velocity and Surface Topography ............................................35

8 Discussion ...........................................................................................................................................36

9 Conclusion ..........................................................................................................................................42

Acknowledgements ...............................................................................................................................44

References .............................................................................................................................................45

Appendix A Observed ice-flow velocities.........................................................................................48

Appendix B Observed ice-flow velocities .........................................................................................49

Appendix C Observed ice-flow velocities .........................................................................................50

Appendix D Mass Balance Observations ..........................................................................................51
1 Introduction

The Svalbard archipelago is located in the Arctic region between 74° and 81° north latitude. Today, 60% of the island is covered by ice (Hagen, 1993). Averaged over the past 40 years, Svalbard lost, about 9.71±0.55 km³ of ice mass every year (Nuth et al., 2010). Metrological observations at Svalbard Airport recorded a temperature increase of about 2.6°C per decade over the last 100 years (Førland et al., 2011; Nordli et al., 2014). The consequence of warmer air temperatures in the arctic region is that glaciers produce more meltwater at the glacier surface. Most of the meltwater which is produced at the glacier surface is transported towards the glacier base. Enhanced meltwater supply towards the glacier bed reduces the strength of basal shear stresses which in turn allows the glacier body to flow faster.

Arctic glaciers get steeper slopes over time as increased melt at their lower part causes thinning and increased solid precipitation in their upper regions leads to thickening of the glacier (Van Pelt et al., 2012). Glacier motion is strongly controlled by the surface slope of the glacier and steeper slopes lead to increased ice flow velocities (Benn & Evans, 2010).

The combination of enhanced meltwater supply towards the glacier bed and steepening of the glacier surface leads to higher ice-flow velocities of the glacier body over time. An altered flow regime of the glaciers can lead to unpredicted contributions to sea-level changes as more glacier ice is delivered to lower regions and eventually to the sea through calving of melt-runoff. Long-term measurements of ice-flow velocities are therefore crucial to receive a better understanding of how glaciers respond to climate changes in a temporal and spatial scale. The knowledge of how glacier systems respond to changes in climate helps to estimate their contribution to global sea level rise.

This project will use ice-flow velocities that are measured continuously over the past 10 years using stand-alone single-frequency GPS receivers attached to 13 metal stakes along the center line of Nordenskiöldbreen between 300 m to 1200 m above sea level. Nordenskiöldbreen is a marine terminating glacier and a major outlet glacier from the largest ice field on Svalbard. The Institute for Marine and Atmospheric research in Utrecht, the Netherlands (IMAU) has developed such GPS units to measure ice-flow velocities at low costs and all year-round.

To ensure that the accuracy of ice-flow measurements is accurate enough for the purpose of the thesis, I will first of all compare calculated ice-flow velocities from the GPS receivers operating on Nordenskiöldbreen with carrier phase DGPS measurements. Carrier phase DGPS is using a higher frequency compared to GPS and has therefore a much higher accuracy. Carrier phase DGPS measurements were examined for each of the 13 GPS stakes once a year.

In my thesis I will give a broad overview of observed ice-flow velocities on Nordenskiöldbreen over the past ten years. I will moreover compare velocities measured in different elevations of the glacier and try to find explanations why stations in different elevations show different velocity variations. My main focus will be the investigation of seasonal velocities of Nordenskiöldbreen.
Seasonal velocities are further set into comparison with mass balance observations and temperature records from Svalbard Airport. This comparison might help to explain trends in ice-flow velocities on Nordenskiöldbreen and to understand the relation between seasonal velocities and climate variables.

Since 1997 has Uppsala University, Department of Earth Sciences conducted field measurements on Nordenskiöldbreen to measure mass balance, ice flow and environmental changes. Measurements of surface elevation on the glacier show that the glacier has steepened considerably over the past 10 years, which indicate that a speed-up of the glacier could be possible. Thus, evaluating the recorded ice velocities with the measurements of the surface elevation and mass balance can give an idea of future behavior of the glacier in a warming climate.
2 Aim

Aim I

The first aim of my master thesis is to analyze seasonal trends in ice-flow velocities measured over the past 10 years (since 2006) on Nordenskiöldbreen, Svalbard. Understanding the dynamical behavior of Nordenskiöldbreen show us how glaciers react to environmental changes and helps us to make predictions for the future.

Aim II

My second aim is to investigate the relation between seasonal velocities, glacier mass balance, surface topography and temperature. Investigating how those parameters are related to each other helps us to find explanations why we see these trends in ice-flow velocities.

It is suggested that enhanced precipitation in the Arctic region leads to changes in mass balance. Mass gain is dominating in higher elevations while mass loss is dominating in lower elevations of the glacier. This mass displacement leads to steepening of the glacier surface. Ice flow velocities are strongly correlated to the surface slope of the glacier as steeper slopes lead to higher flow velocities.

Another explanation which could explain enhanced ice-flow is that higher air temperatures lead to a higher energy flux at the glacier surface which results into enhanced meltwater production. The meltwater which is produced at the glacier surface is then transported towards the glacier bed and enhances basal lubrication. Increased basal lubrication results into higher ice-flow velocities. The surface slope of the glacier as steeper slopes lead to higher flow velocities.
3 Background

3.1 Glacier Motion

Before we discuss glacier motion, we need to clarify the terms stress and strain: Stress is defined as force per unit area and a measure of how strong a material is pushed or pulled. Stress may be distinguished into normal stress and shear stress. Normal stress is acting within a right angle to a surface while shear stress is acting parallel to a surface. Stresses result in strain, which is a measure of change in size and shape of materials. The strain rate describes how fast a material is deforming over time (Benn & Evans, 2010). Glen’s flow law (Glen, 1995, eq.1) is a way of expressing the relationship between strain rate and shear stress for ice:

\[ \varepsilon = A \tau^n \]  

(eq.1)

where \( A \) and \( n \) are constants, is the effective strain rate and the effective shear stress (Benn & Evans, 2010). Glaciers flow downslope because gravitational stresses act on the glacier body. Glaciers with steeper slopes experience often higher velocities than those with flatter mass balance gradients (Clarke, 1987).

Glacier motion is depending on the strengths of basal shear stresses occurring at the glacier bed. The strength of basal shear stresses is controlled by ice thickness (\( h \)), ice density (\( \rho_i \)), gravity (\( g \)) and slope of bedrock and glacier surface (\( \alpha \)) (Benn & Evans, 2010).

\[ \tau_d = \rho_i gh \sin \alpha \]  

(eq.2)

The distribution of basal shear stresses is influenced by occurring hydrological and thermal conditions at the glacier bed (Clarke, 2005). The glacier terminus plays also an important role for calving glaciers since these glaciers are tidal influenced by water pushing against the glacier front holding it back (Benn & Evans, 2010). Ice speed tends to increase from the top of the glacier towards the equilibrium line altitude and to decrease from there towards the glacier front. A steepening of the glacier surface can be emerged by an unbalanced mass balance gradient where mass gain is dominant in the accumulation zone and mass loss in the ablation zone. The ice flow from upper to lower elevations cannot compensate the mass displacement within the glacier body (Clarke, 1987).
Glacier motion is driven by gravity and occurs from three different processes:

**Process 1: Internal Deformation or so called creep.** Internal deformation of glacier bodies occurs when ice deforms and moves downslope due to stress (pressure) differences within the glacier body (Benn & Evans, 2010). Internal deformation is driven by gravity and mass balance of the glacier. Changes in mass balance affect the relation of orientation between applied stresses and ice crystal planes which is important for the ability of ice to deform. The orientation of ice crystals is a result of processes which change the texture and form of ice crystals. The texture of ice is thermodynamically related and affected by impurities within the ice crystals. Such impurities can consist of soluble, particulate and gas-phase impurities. The first two types of impurities are generated by atmospheric depositions. The latter type of impurities is referring to bubbles containing liquid water or atmospheric gases. The form of ice grains is changing with time by grain growth and ice crystal recrystallization (Cuffey & Paterson, 2010).

**Process 2: Soft Bed Deformation.** Soft bed deformation occurs for glaciers overlying soft deformable sediments. When basal shear stress is greater than yield strength of the underlying bed, deformation takes place (Benn & Evans, 2010).

**Process 3: Basal Sliding.** Basal sliding occurs most effective where meltwater is available. Meltwater acts as a basal lubricant and reduces frictional stresses at the glacier bed which allows the glacier to flow. The amount of water at the glacier bed is varying on seasonal scale and is controlled by melting of the glacier base and meltwater supply from the glacier surface. Melting of the glacier base is controlled by the pressure melting point of ice as well as heat generated by frictional forces or ground heat fluxes (Benn & Evans, 2010).
3.2 Glacier Hydrology

Glacier hydrology is the study of water movement through glacier bodies. The amount of water travelling through glaciers is strongly depending on the energy budget of the glacier. When air temperatures are high during summer seasons, the amount of water within a glacier body increases as ice starts to melt and rainfall events occur more often. The amount of water flowing through a glacier is thus varying on seasonal scale and is depending on the regional climate (Ben & Evans, 2010; Cuffey & Paterson, 2010).

Water can enter the glacial system by melt at the glacier surface and rainfall and is then first of all transported over the glacier surface before it runs-off, refreezes or enters into the glacier body. The ice surface of glaciers is covered by channels generated by water streams.

These incisions are centimeters to meters deep and occur especially in middle to lower elevations of the glacier where surface slopes are steep. At some locations at the ice surface supraglacial water penetrates deeper into the glacier body and generates moulins. Moulins are vertical shafts and are just as long open as water is passing through. On glaciers with gentle slopes water can accumulate and form meltwater lakes. Meltwater can also be stored on the glacier surface where firn is present. The firn layer becomes saturated with water and forms a ‘swamp zone’ (Cuffey & Paterson, 2010).

When scientists talk about hydrological processes that occur at the glacier surface, they summarize them as supraglacial drainage system. Glacial hydrological systems such as supraglacial-, englacial- and subglacial-systems are named after their occurrence within the glacier body. The supraglacial system is one of three in literature defined hydrological systems of glaciers. Englacial systems include all hydrological processes occurring inside the glacier body while subglacial systems describe hydrological processes at the glacier bed (Benn & Evans, 2010).

A temperate glacier body is potholed with several pipelines transporting meltwater originating from melt processes or entered previously from supraglacial waters. The englacial water-transport takes places via moulins and conduit systems. Conduit drainage systems consist of numerous interweaved channels interrupted by chambers. In such chambers, water can remain trapped for some time until it starts flowing again. How long water remains in the glacier system is difficult to trace back since some pipelines transport water directly outside of the glacier into proglacial lakes while others transport water through complex channel networks (Benn & Evans, 2010).
The third hydrologic system has probably the biggest implication on glacier motion. The subglacial system is located beneath the glacier. The amount and distribution of basal meltwater influences the strengths of occurring stresses at the glacier bed. Basal meltwater originates mostly from meltwater which is transported from the supraglacial or englacial drainage system towards the glacier base. However, meltwater can also originate from other sources such as geothermal heating, frictional heating, pressure melting from the weight of the ice mass above or from the supraglacial and englacial system. Subglacial systems can be described as either distributed or channelized. A distributed subglacial system can reduce resistive stresses and enhances glacier motion as water pressure rises. Such systems at the glaciers bed transports water at relatively low pressure. A distributed subglacial system can occur as thin water film. Thin water films occur where temperate ice is overlying hard rock or ice and transport mainly water produced by basal melting. Meltwater production is locally enhanced by regelation at the up-glacier side of bumps where ice-bed contact pressures are high. High pressures at the up-glacier side of obstacles reduce the pressure-melting point of the ice and lead to enhanced melting while refreezing takes place on the down-glacier side of the obstacle. In context, high flow velocities are expected to occur on the up-glacier sides of obstacles while lower velocities are expected to occur on the down-glacier side of obstacles. Another form of distributed system is the linked cavity system. Linked cavity systems consist of interconnected cavities incised into the bedrock and connected by orifices. Distributed water transportation between ice and sediment include braided canal networks. Water transportation through drainage systems consist of a network of channels incised into the ice or into the bedrock (Benn & Evans, 2010; Fountain & Walder, 1998). Water flowing in temperate glaciers is following hydraulic potentials and is flowing from higher to lower elevations and pressures. The hydraulic potential is depending on elevation \((z)\), pressure \((P_w)\) gravity \((g)\) and water density \((\rho_w)\) (eq.1; Benn & Evans, 2010).

\[
\phi_h = P_w + \rho_w g z
\]  

(eq.3)
3.3 Thermal Regime of Glaciers

The thermal regime of a glacier describes the temperature distribution within glacier bodies. How temperature is distributed in glacier bodies is depending on several exogenic and endogenic factors. The heat distribution on the glacier surface for example is depending on climatic factors such as solar Radiation latent heat fluxes. Heat transported by precipitation has a rather small effect on the thermal regime of glaciers.

The temperature of glacier surfaces is variating on seasonal scale as solar radiation variates throughout the year. During summer seasons the heat flux at the glacier surface is high due to enhanced solar radiation. High solar radiation at the glacier surface is thus resulting in higher melt rates at the glacier surface. The fluctuation of temperature is highest at the glacier surface and decreases with ice depth. Temperature is transported from the surface into deeper parts of the glacier. This heat transport in depths is time lagged due to diffusion. Temperature distribution within glacier bodies is further controlled by ice deformation, firn compaction and heat released by refreezing of subsurface waters. Heat distribution at glacier beds is thereby controlled by strain heating, geothermal heat flux and frictional heating. Heat is distributed within glaciers through conduction and advection and is depending on water content, pressure and ice properties (Cuffey & Paterson, 2010; Benn & Evans, 2010).

Glaciers are often characterized after their thermal structures and are classified in three groups: temperate glaciers, cold glaciers and poly-thermal glaciers. Temperate glaciers first of all consist of temperate ice at the pressure melting point. These types of glaciers are extremely sensitive to climate variations and are located for example in tropical mountainous regions, New Zealand, Norway or southern Iceland. Cold glaciers in contrast respectively are consisting of cold ice below the pressure melting point.

Cold glaciers are mainly in extreme cold environments like Antarctica. Poly-thermal glaciers constitute however a mixed type of cold glaciers and temperate glaciers and consist of both cold ice and temperate ice. Poly-thermal glaciers are typically formed under climate conditions with cold winters with low precipitation and low melt rates during summer. These climate conditions occur for example on Svalbard. The thermal structure of poly-thermal glaciers shows a wide range depending on climate conditions (Benn & Evans, 2010).
4 Study Site

4.1 Svalbard

The Svalbard archipelago is located 650 km north of Norway in the Arctic Ocean between 74N°, 10°E and 81N°, 35°E. The archipelago consists of several smaller islands with the main and largest island Spitsbergen. Today, the most populated town of Svalbard is Longyearbyen with about 2000 inhabitants. Longyearbyen is located at the head of Adventdalen south of middle Isfjorden. Once a coal miner town, Longyearbyen is nowadays mostly populated by researchers and tourist agencies. During winter time, Svalbard is fully covered by snow. During summer months on the other hand the snow coverage is about 40 per cent less (Harald, 1997). In total, the ice caps and glaciers on Svalbard extend over an area of around 36 600 km (Hagen, 1993). The estimated total ice volume of Svalbard is 7000 m³, contributing yearly 0.01 mm to global sea level rise (as an average value calculated over the past 30 years by Hagen et al., 2003). The climate over the Svalbard archipelago is driven by two oceanic currents: The West Spitsbergen Current, as a remnant of the Gulf Stream, is transporting warm water northwards along the west coast of Svalbard. The East Spitsbergen Current by contrast is transporting cold water and sea ice from the North along the east coast of Svalbard. Temperatures on Svalbard are mild, considering its location. Average summer air temperatures reach up to 5°C while average winter temperatures drop to -12°C. However, weather on Svalbard is changing fast and daily temperatures show high variations with maximum winter temperatures from to -50°C and maximum summer temperatures of +22°C (Harald, 1997).

The annual precipitation of Svalbard is relatively frequent with about 10 m per year in the east and 300-400 mm along the west coast (Harald, 1997). It is suggested that precipitation in the Svalbard region increased by 15% between 1966 and 2003 (ACIA, 2005). Referring to Førland et al., 2003 annual precipitation during 1981-2010 in Ny-Ålesund is 10% higher compared to 1961-1990. Until 2100, changes in precipitation patterns are expected with an increase of 40% in the northeast of the island (Førland et al., 2011). The implications of increasing temperatures and changed precipitation patterns of the Svalbard archipelago are reflected in ice loss. Svalbard’s glaciers show an overall ice mass reduction of -0.36±0.02 m a⁻¹ for the past 40 years, which corresponds to a sea level rise of 0.026 mm per year (Moholdt et al., 2010; Nuth et al., 2010). The modelled surface mass balance of Svalbard for the period 1979-2013 is -1.6 Gt a⁻¹ (Lang et al., 2015).

Average annual temperatures measured at four different stations in Svalbard have increased by up to 2.6°C per decade for the latest 100 years (Nordli et al., 2014, Figure 4.1). During 1935-2011 temperatures show an even higher increase of 2.7-4.0 °C per decade. Especially winter temperatures show a high increase by 4.8-6.5 °C per decade. The largest increase in temperatures is in spring with st up to 3.9°C per decade (Førland et al., 2011; Nordli et al., 2014). Climate projections for the 21 century indicate an increase in annual temperature in arctic regions of up to 7 °C for the A2 emission
scenario (IPCC, 2007). It is further suggested that the number of days with high temperatures will increase by 25 days between 2021 and 2050 with a greater trend in the northeast of Svalbard (Førland et al., 2011; Førland et al., 2003).

4.1 Nordenskiöldbreen

Nordenskiöldbreen is located close to Pyramiden on the Svalbard archipelago (78.6°N, 17.1°E) (Figure 4.12). The polythermal glacier is connected to the Lomonosovfonna ice cap. The Lomonosovfonna ice cap is one of the highest located ice fields in central Spitsbergen at 1250 m a.s.l. (Isaksson et al., 2001). Nordenskiöldbreen extends over an area of 242 km² (Hagen et al., 2003).

The glacier flows around the two rock formations Terrierfjellet and De Geer fietlet towards Adolfbukta, a tributary fjell to Billefjorden (Plassen et al., 2004). The equilibrium line altitude is located in approximately 719 m a.s.l.. The polythermal glacier is characterized by temperate snow/firn in the accumulation zone and cold ice in the ablation zone (Van Pelt et al., 2012). Nordenskiöldbreen retreated with a mean average retreat rate of 35 m a since the end of the Little Ice Age. The total glacier shrank since then by 5.3% (132400 m²a⁻¹) in area (Rachelwicz et al., 2007).

Figure 4.1. Temperature in °C from 1901-2016 recorded at Svalbard Airport, Data is downloaded from the database eKlima of the Norwegian Meteorological Institute.
Figure 4.2. Map of Nordenskiöldbreen, Svalbard. Red Points show the location of the GPS receivers on the glacier surface. The blue line signalizes the main flow line of Nordenskiöldbreen. The big red cross on the overview map is showing the location of Nordenskiöldbreen, the small red cross is showing the location of Longyearbyen on the Svalbard archipelago. The map was created with ArcGIS and is adapted from toposvalbard.npolar.no.
5 Previous Research

5.1 Velocity Observations on Nordenskiöldbreen

Den Ouden et al. (2010) observed ice flow velocities on Nordenskiöldbreen for the period 2006-2009 using nine stand-alone single-frequency GPS receivers. The study is applying the same methodology as used in this study but is investigating flow velocities on a shorter time scale. Annual average ice flow velocities measured by Den Ouden et al. (2010) for the period 2006-2009 vary between 40-55 m a\(^{-1}\) on the central flow line. Maximum flow velocities were suggested to be about 60-90 m a\(^{-1}\). Highest ice flow velocities were occurring mainly in the beginning of July as cause of enhanced meltwater production. A time lag between stations in different elevations was not observed. According to Den Ouden et al. (2010) summer ice velocities are correlated with air temperatures and melt rates while winter velocities are rather unrelated. The unrelated variability of winter velocities is explained by lunar and oceanic tidal effects which were observed previously on other glaciers on Svalbard and Greenland. The hypothesis that lunar and oceanic tidal effects could be the reason for the variations in winter velocities is not yet validated (Den Ouden et al., 2010).

Figure 5.1. Ice flow velocities of Nordenskiöldbreen 2006-2009 by Den Ouden et al. (2010)
5.2 Velocity Observations on other Svalbard Glaciers

The Austfonna ice cap is about 200 km northeast of Nordenskiöldbreen. Flow velocities were measured between 2008 and 2010 and compared to temperature records. The study examined by Dunse et al., (2012) applied the same technique to measure ice flow velocities as used in this study. The aim of this study was to investigate the relationship between surface melt and ice flow dynamics. The measured flow velocities showed speed-ups occurring especially during the summer melt season. It is proposed that this summer speed ups are a cause of enhanced surface meltwater production which is percolation into the subglacial system. A prominent summer speed up was recorded in 2008 and is assumed to be mainly driven by basal lubrication. Annual mean velocities during May 2008 and May 2009 are estimated to be between 120 to 400 m a⁻¹. It was also observed that the mean summer velocity in 2009 were up to 23% faster than those in 2008. The increase in velocity of summer 2009 is proposed to be closely linked to positive diurnal air temperatures corresponding with enhanced surface meltwater input into the englacial/subglacial drainage system (Dunse et al., 2012, Dunse et al., 2011). Observations have shown that the Austfonna ice cap experienced a surge over the period April 2012 to May 2013. The surge of the ice cap was triggered by a hydro-thermodynamic feedback mechanism which leads to enhanced basal lubrication (Dunse et al., 2015).

Flow velocity measurements using GPS stakes have also been applied on Hansbreen (Vieli et al., 2004). The tidewater glacier Hansbreen is located in southern Spitsbergen about 185 km south of Nordenskiöldbreen. The study was examined during summer 1999 with a temporal resolution of 3-4 hours, depending on satellite availability. Short term velocity observations showed speed-ups with duration of about one to two days. These speed-ups were interpreted as result of changes on basal motion and not by internal deformation. The speed-ups are closely linked to high water input due to rainfall events or enhanced surface melting (Vieli et al., 2004). Results have proven further that ice-flow on Hansbreen is controlled by seasonal changes in meltwater input (Pälli et al., 2003).

Likewise the first two studies, speed ups on Kronebreen and Kongsbreen are thought to be closely linked to available meltwater and rainfall within the hydrological system of the glacier. Basal water pressure enhances basal lubrication and triggers speed ups of up to 1168 m a⁻¹ on Kronebreen in summer 2013 and 985.5 m a⁻¹ on Kongsbreen in late autumn 2012 (Schellenberger et al., 2015). It was further observed that maximum velocities occurred mainly in July on Kronebreen (Kääb et al., 2005).

5.3 Mass Balance Observations on Nordenskiöldbreen

Net mass balance describes the change in glacier volume over a specific period of time. The mass budget of a glacier is controlled by precipitation, runoff and sublimation/riming. Mass balance can be measured using ablation stakes drilled into the ice. The change in volume is then calculated by measuring the distance between glacier surface and the tip of the ablation stake. Indirect methods according mass balance imply hydrological methods, geodetic methods or gravimetric methods. The
net mass balance of a glacier is often divided into summer and winter mass balance to investigate seasonal trends. A negative mass balance value refers to mass loss whereas a positive mass balance value refers to mass gain. Often, mass loss dominates in the ablation zone in lower elevations of the glacier. Mass gain in contrary is characteristic for the accumulation area in higher elevations of the glacier. The equilibrium line altitude (ELA) defines the transition zone between accumulation and ablation area. The mass budget of a glacier is significant for understanding how climate change influences glacier volume over time (Benn & Evans, 2010).

Measurements of mass balance on Nordenskiöldbreen were examined since 1997 by Uppsala University, Department of Earth Sciences. Studies indicate that mass balance within the accumulation area of Nordenskiöldbreen is mainly dominated by mass gain. Snow accumulation in the upper parts of the glacier is thought to increase towards the end of the 20th century (Pälli et al., 2002; Pohjola et al., 2002). Enhanced mass gain in the accumulation area above 720 m a.s.l is a cause of changes in precipitation patterns and refreezing of subsurface waters. It was shown that 25% of all melt- and rainwater refreezes. Refreezing of subsurface meltwater stored below the glacier surface contributes with 0.27 w.e. a\(^{-1}\) to net mass balance (Van Pelt et al., 2012). Net mass balance within the accumulation area for the period 1969-1986 was estimated to be 0.75 m a\(^{-1}\) (Hagen et al., 2005).

Mass balance in the ablation zone on the other hand is dominated by mass loss due to high melt rates between early May and early June in lower elevations of the glacier (Van Pelt et al., 2012; van Pelt et al., 2014).

Modulations for the period 1989-2010 suggest likewise a negative net mass balance of -0.39 m w.e. a\(^{-1}\) with variations between 0.17 and -0.95 m w.e.a\(^{-1}\). Variations in net mass balance are explained by yearly changes meteorological parameters (Van Pelt et al., 2012).

Temperature and velocity observations during summer months on Nordenskiöldbreen show a positive correlation. Variations in temperature occur on average 3 days earlier than variations in velocity. Same correlation is described between melt rates and velocity whereas peaks in velocity occur 4 days later than peaks in velocity (Den Ouden et al., 2010; Figure 5.3).
6 Methodology

6.1 Global Positioning System (GPS)

The global positioning system (GPS) is a space based navigation system developed by the U.S. Department of Defense for accurate navigation. The navigation system provides information about location and time and is commonly used for glaciological applications. GPS was originally developed for military purposes during the 1970s. Since 1995, GPS is operating with full capability and is available to civilians. The navigation system consists of a space segment, user segment and control segment (Figure 6.1, A). The space segment contains 24 satellites or more. The satellites are placed on six orbital planes. The orbits of the GPS satellites are operating on nearly circular orbits with an inclination of 55°. The constellation of the 24 satellite, also called the initial operational capability (IOC), is organized in that sense, that four to ten satellites are available independently on time and location. The user segment includes commercial and scientific users of GPS receivers. Such GPS receivers consist of an antenna, receiver and clock to receive and transmit information from/to the space segment. The third element of the navigation system is the control segment. The purpose of the control segment is to ensure the proper operation of the GPS system. The control segment is composed of a worldwide network of tracking stations making corrections for the GPS system (El-Rabbany, 2002; King et al., 2002; King 2004).

The basic idea behind GPS is to measure the distance between GPS receiver and satellite. Satellite forward a radio signals towards GPS receivers which contain a C/A code with information about at what time the information has been sent. Out of the travel time, the GPS receiver can calculate the distance to the satellite by using the velocity of the signal. However, calculating the distance between GPS receiver and one satellite gives us just an imaginary sphere where the GPS receiver is located. To determine the exact point location of a GPS device, three more measurements are necessary for the triangulation between the distance (Figure 6.1.B) (Hurn, 1989).

6.1.1 Error Sources

GPS measurements are affected by errors originating from different sources (Hurn, 1989; Hurn, 1993):

- **Satellite errors** – Satellites are equipped with atomic clocks which work with very high accuracy. However, even these clocks may generate inaccuracies. Other errors generated by satellites include ephemeris or orbital errors.
- **Atmospheric delays** – The speed of light is only constant in vacuum. When light travels through our atmosphere it becomes deflected by electrically charged particles in the ionosphere and water molecules in the troposphere.
- Multipath errors - Multipath errors are generated by deflection from surrounding objects of the GPS signal traveling towards the GPS receiver. Buildings, trees or even the ground reflect the signal and induce noises.
- Receiver errors – Also clocks in receivers can be inaccurate and generate errors. Other errors arise from internal noise from for example mathematical errors.
- Geometric dilution of Precision – The accuracy of the satellite signal is depending on the angle of the satellite in relation to the GPS receiver on earth. A narrow angle between satellite and GPS receiver generates higher inaccuracies than a wider angle.

Figure 6.1. Visualization of how GPS systems work. A) Three main components of GPS system. B) Triangulation of three satellite orbits to estimate the exact location of the GPS receiver. (adapted from El-Rabbany, 2002)
6.1.2 Differential Global Positioning System (DGPS)

GPS is one of the most accurate navigation systems of the world. However, for some scientific purposes GPS measurements are not accurate enough. One way to increase the accuracy of GPS is to apply a differential global positioning system (DGPS). The concept of DGPS is to eliminate inaccuracies of GPS measurements. To do so, DGPS uses two receivers instead of one. One of the receivers is thereby located at a known locating while the other receiver is moving. The concept of DGPS is to calculate the difference between coordinates of the receiver at the known location and the receiver at the moving position. The difference between these two receivers is used as the correction factor and can be applied to all other receivers (Hurn, 1993).

6.2 Data

The data gathered in this study is collected by GPS stakes located on Nordenskiöldbreen (Figure 6.2). The data is collected over a period of 10 years between 2006 and 2016. The GPS stakes are provided with single-frequency receivers using the L1 signal. The GPS devices consist of 3.5 v lithium batteries supplying 15 Amp hours per year. The batteries are able to run for one a year without maintenance. The advantage of this approach is the relatively low finical and time expenses for collecting the data. The stand-alone single-frequency GPS receivers were developed by the institute for Marine and Atmospheric research in Utrecht, the Netherlands (IMAU).

The GPS receiver’s records information about temporal and spatial parameters as well as temperature and elevation. The system is initialized every 24 hours to store the data collected within this time period. The GPS receivers measure every hour. During one measurement the device switches on for three minutes.

In total, 13 GPS receivers are operating on Nordenskiöldbreen between 2006 and 2016 (Table 6.1). Eight 8 of the GPS stakes were installed in April 2006 followed by four additional stations in March 2007 and March 2009. The GPS stations are mainly located along the main flow line of the glacier at different elevations. Station 1 and 2 however, are located on side of the main flow line of Nordenskiöldbreen because the lower part of the glacier is heavily crevassed. Station 5A is operating together with a sonic ranger and is measuring supplementary surface elevation. Since Station 5A broke the station became de-installed in April 2009. The sonic ranger was moved to station S6. For comparison, a reference station is installed on a fixed position on the nunatak of Terrierfjellet. The reference station is necessary to remove temporal errors of the GPS system using differential correction. The removal of errors by the reference station is a very complex task.
Table 6.1. Overview of characteristics of different GPS stations on Nordenskiöldbreen, Svalbard

<table>
<thead>
<tr>
<th>Station</th>
<th>Elevation (m a.s.l.)</th>
<th>n</th>
<th>Active Time</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS</td>
<td>±520</td>
<td>79225</td>
<td>April 2006-April 2015</td>
<td>Terrierfjellet</td>
</tr>
<tr>
<td>S1</td>
<td>±150</td>
<td>26226</td>
<td>March 2006-March 2009</td>
<td>Side</td>
</tr>
<tr>
<td>S2</td>
<td>±230</td>
<td>26203</td>
<td>April 2006-March 2009</td>
<td>Side</td>
</tr>
<tr>
<td>S3</td>
<td>±310</td>
<td>35600</td>
<td>March 2007-April 2011</td>
<td>Main flow line</td>
</tr>
<tr>
<td>S4</td>
<td>±350</td>
<td>34798</td>
<td>March 2006-March 2010</td>
<td>Main flow line</td>
</tr>
<tr>
<td>S5</td>
<td>±456</td>
<td>52996</td>
<td>March 2009-April 2015</td>
<td>Main flow line</td>
</tr>
<tr>
<td>S5A</td>
<td>±435</td>
<td>26265</td>
<td>March 2006-March 2009</td>
<td>Sonic Ranger, side</td>
</tr>
<tr>
<td>S6</td>
<td>±529</td>
<td>79201</td>
<td>March 2006-April 2015</td>
<td>Main flow line, sonic ranger</td>
</tr>
<tr>
<td>S7</td>
<td>±620</td>
<td>79133</td>
<td>April 2006-April 2015</td>
<td>Main flow line</td>
</tr>
<tr>
<td>S8</td>
<td>±667</td>
<td>79204</td>
<td>April 2008-April 2015</td>
<td>Main flow line</td>
</tr>
<tr>
<td>S9</td>
<td>±822</td>
<td>61534</td>
<td>March 2009-April 2015</td>
<td>Main flow line</td>
</tr>
<tr>
<td>S10</td>
<td>±1053</td>
<td>52962</td>
<td>March 2009-April 2015</td>
<td>Main flow line</td>
</tr>
<tr>
<td>S11</td>
<td>±1147</td>
<td>52965</td>
<td>March 2009-April 2015</td>
<td>Main flow line</td>
</tr>
</tbody>
</table>

Figure 6.2. The data was collected by GPS receivers attached to metal stakes. The metal stakes are drilled into the glacier surface. (by Den Ouden et al., 2010)
6.2.1 Accuracy of the GPS system

Calculating ice flow velocities requires a very high accuracy of the data. Minor errors in the data can result in deviations in flow velocities and lead to wrong interpretations. This study uses GPS receivers to calculate ice flow velocities of Nordenskiöldbreen. GPS is one of the most accurate navigation systems in the world. However, measuring positions with GPS is accompanied by noise in the GPS system. Such noises in the data can be corrected by applying carrier phase DGPS measurements. Carrier phase DGPS measurements were taken for each of the 13 GPS stakes on Nordenskiöldbreen one a year. The comparison between the average position of GPS stakes and carrier phase GPS measurements is presented in chapter 7.2.

6.3 Data Processing

6.3.1 Preparation of raw Data

The processing of the dataset used in this study is accomplished by using Matlab R2015a. The aim of data processing is to calculate ice-flow velocities out of GPS coordinates over a period of 10 years. Measuring locations with GPS systems over such a long time goes along with data which contains errors and wrong values. Therefore it is necessary to process the data to guarantee a reasonable result in the end and to avoid wrong interpretations of the ice flow velocities.

However, before the processing of the data can be examined some preparatory steps need to be done. The raw dataset which is stored in a text document needs to be separated into columns to make it readable for Matlab. The next preparatory step is to convert geodetic coordinates (GRS80) to Cartesian WGS84 coordinates with the zone 33X. Also the date of the coordinates is converted to a Matlab readable format. Now the raw dataset is readable for Matlab and ready for processing.

6.3.2 Data Processing

The processing of the data starts with removal of obvious wrong values in the dataset. Obvious wrong values are for example data which contains no reasonable values such as -999 degrees as temperature record. Such unreasonable values are generated by technical problems of the GPS receiver itself. Technical problems in arctic environments are not uncommon as harsh weather conditions can for example lead to damages of the receiver or simply bury GPS receivers under a snow cover. However, unreasonable values are simply to identify and easy to remove by using a filter which identifies error values and sets them to ‘no data values’ for these measurements.
The second step in data processing is to apply a differential correction by the base station. The base station is working as a reference station for the other stations located on the glacier. Motion measured by the reference station can be interpreted as noise in the GPS system since it is known that this station is located at a fixed position on the nunatak of Terrierfjellet. This noise from the reference station is subtracted from the positions of the other stations operating on the glacier.

In some cases, GPS stakes need to be re-drilled as they melt out when the spring season starts. The replacement of GPS stakes creates large velocity jumps in the dataset. However, those jumps in velocity can be easily identified and the gaps with missing data are then set to ‘no data values’ for these measurements.

6.3.3 Removal of Outliers

The removal of outliers in the dataset is examined by a running average window. The chosen window size applied in this study is 240 as it turned out that this window size removes the right amount of outliers. The running average window calculates the mean of all data points within the window frame. All data points which are located one standard deviation below and above the mean are then removed from the dataset.

6.3.4 Filtering and Calculation of ice-flow velocities

Now the dataset contains data with realistic values which are ready for the calculation of the actual velocity. To do so, the specific distance (d) between two coordinates for each x- and y- direction is calculated using following formula:

$$d_x = \frac{\Delta x}{\Delta t}, \quad d_{xy} = \frac{\Delta x y}{\Delta t}$$

The velocity in x-direction and y-direction is further calculated using the following formula with t = time:

$$\bar{v}_x(t) = \frac{d_x}{\Delta t}, \quad \bar{v}_y(t) = \frac{d_y}{\Delta t}$$

The next step is to remove outliers on each of the velocity components to smooth the dataset. The last step is to combine the two velocity components to calculate the summed speed v(t). This is done by taking the square root of the sum of the squared velocity in x direction and the squared velocity in y-direction as following:

$$\bar{v}(t) = \sqrt{\bar{v}_x^2 + \bar{v}_y^2}$$

Finally the velocity is calculated and the data is ready to be averaged over a monthly period.
7 Results

7.1 Reference Station

The reference station BS is located on the nunatak of Terrierfjellet and is operating since April 2006. Since the reference station is located on a fixed position, it shall here theoretically have a velocity of 0 m a⁻¹. However, the reference station recorded annual averaged velocities in combined direction for the period 2006-2016 of 0.02±0.01 m d⁻¹ for filtered velocity and 0.05±0.02 m d⁻¹ for unfiltered velocity. The aim of the filter process of the data was to reduce the standard deviation of the velocity. The standard deviation was reduced by 48% comparing both standard deviations for filtered and unfiltered data.

These recorded velocity values of the reference station are generated by noise in the GPS system. Daily velocity variations measured by the reference station are interpreted as noise and are subtracted from the other stations operating on Nordenskiöldbreen.

Table 7.1. Movement of the reference station in combined direction in m/day. Grey points show the unfiltered data, green points the filtered data.
Figure 7.2 presents the movement of the reference station in East-West and North-South direction in m d\(^{-1}\) for both filtered (in green) and unfiltered data (in grey). Results of the unfiltered data show that the reference station is moving on average 5.49 m d in longitude direction and -2.8 m d in latitude direction. The uncertainties for the unfiltered data are 0.04 m d in both directions. Results of the filtered data show that the reference station is moving on average 4.76 m d in longitude direction and -2.72 m d in latitude direction. The uncertainties for the filtered data are 0.02 m d and 0.01 m d respectively. The standard deviation of the velocities in latitude and longitude direction was reduced through the filtering process by 35% comparing filtered and unfiltered data.

Table 7.2. Scatter plot with movement of the reference station in East-West and North-South direction in m/day. Grey points show the unfiltered data, green points the filtered data. The swinging out of the green line shows an remaining outlier occurring in 2014.
7.2 Comparison between GPS and DGPS

Comparing the measurements with carrier phase DGPS measurements is one way to ensure that the data which is used in a study is accurate enough to calculate ice flow velocities. Figure 7.3 presents the comparison between yearly DGPS and annual averaged GPS measurements on Nordenskiöldbreen. The comparison between those two measurement techniques is supposed to ensure that the GPS system operating on the glacier surface of Nordenskiöldbreen is operating with a high accuracy.

The result of the comparison shows that the difference between DGPS and GPS data is on average about 2.5%, but not higher than 5.2%. The average difference between DGPS measurements and GPS measurements is about 0.52 m a⁻¹. The year with the highest uncertainties was 2012 with an average difference in velocity of 1.99 m a⁻¹.

Figure 7.3. Comparison between averaged carrier phase DGPS and annual averaged GPS measurements on Nordenskiöldbreen for each year 2008 – 2015. Carrier Phase DGPS measurements were examined once a year at each GPS station on Nordenskiöldbreen. GPS measurements were collected every hour all year around. The red line shows the calculated median. The error bars show the distribution range of the data.
7.3 Ice-Flow Velocity Observations

This chapter is subdivided into three sections presenting first the results for the entire measurement period (chapter 7.3.1), then for the summer season (chapter 7.3.2) and finally for winter season (chapter 7.3.3). Observed ice flow velocities are also compared in each section to temperature records from Svalbard Airport and mass balance observations of Nordenskiöldbreen to explain the seasonal trend in ice flow velocities.

7.3.1 Entire measurement period

Monthly averaged ice-flow velocities measured at the main flow line of Nordenskiöldbreen for the period 2006-2016 show a median velocity of 47.8 m a\(^{-1}\) (Figure 7.4). Maximum velocities reach up to 80 m a\(^{-1}\) while minimum velocities are below 30 m a\(^{-1}\). The average velocity measured at the main flow line is 48.89±8.18 m a\(^{-1}\) for the whole period of 10 years. Stations located along the mean flow line show a high stationary periodicity over one year. These periodicities are seasonal related as maximum velocities occur mainly in the beginning of July. The highest average velocity was measured over the period 2015-2016 with 52.3±6.34 m a\(^{-1}\). However, it needs to be mentioned that the period 2015-2016 just includes the months January to April. The second highest average velocity was measured over the period 2014-2015 with 51.04±6.52 m a\(^{-1}\). Lowest average velocities on the other hand were measured in the beginning of the experiment over the period 2006-2008 with an average value of 45.52±5.68 m a\(^{-1}\).

![Figure 7.4. Monthly averaged ice-flow velocities measured at the main flow line of Nordenskiöldbreen over the period 2006-2016. The different colored lines show the observed ice flow velocities at station S3-S9](image-url)
7.3.1.1 Flow Velocities in different Elevations

Figure 7.5 shows annual velocities variations in meters per year for each of the 12 stations operating on Nordenskiöldbreen for the period between April 2006 and April 2015. Time series analysis shows no significant lag between the timing of peak velocities between different stations. Maximum velocities occur at the mean flow line in all elevations at the same time. The stations S4-S7 are located on the main flow line and show a strong linear correlation with a correlation coefficient of 0.70 within a confidence interval of 95%.

Station S1 and S2 are located on side streams of Nordenskiöldbreen and show in comparison to other stations relatively low ice speeds with 0.11 m a\(^{-1}\). Station S5A was buried under snow and is due to technical issues no longer operating on the glacier since spring 2009. Station S7 shows compared to other stations high velocities of up to 80 m a. Station S7 shows furthermore a higher amount of peaks in ice-flow velocity during the year compared to neighboring stations. The reason for this phenomenon is enhanced basal lubrication beneath the station and is further discussed in the previous chapter 7.3.1.1.

Station S11 and S10 show relatively low ice speeds compared to other stations. The ice speeds measured at station S10 are on average under 24 m a\(^{-1}\). Averaged ice speeds measured at station S11 are even lower with maximal 11 m a\(^{-1}\). The low ice speeds are probably due to their high location on the glacier of over 1000 m a.s.l.

To summarize, annual velocities at all stations show a seasonal periodicity with maximum velocities occurring in the beginning of July. High velocities are observed close to the glacier front at station S3 due to high water pressure. High velocities are also observed close to the equilibrium line altitude at station S9 where surface slopes are steep. Stations above an elevation of 1000 m a.s.l show relatively low ice speeds compared to other stations operating in lower elevations.
Figure 7.5. Annual velocity observations in meters per year in different elevations recorded at 12 GPS receivers located in Nordenskiöldbreen for the period 2006-2015. White boxes are interpreted as no data. Blue colors show low velocities of fewer than 30 m per year while red colors signalize high velocities of up to 80 meters per year. The elevation of the different stations is listed in table 1. Stations with lower numbers are in lower elevations than stations with higher numbers.
7.3.1.2 Flow Velocities compared with Temperature

Temperatures recorded at Svalbard Airport are averaged over a monthly period between 2006 and 2016. Observed temperatures are on average -2.9°C with maximum temperatures reaching up to 8.1°C and minimum temperatures of -15.9 °C. Maximum temperatures are mainly observed during July while minimum temperatures are mainly observed during February.

Figure 7.6 illustrates that maximum ice-flow velocities of Nordenskiöldbreen occur at the same time as maximum temperatures. The maxima occur mainly in July. It is also seen that minimum temperatures occur at the same time as minimum ice-flow velocities. The minima occur mainly in February.

**Figure 7.6.** Monthly averaged temperatures recorded at Svalbard Airport (black line) are downloaded from the database eKlimat of the Norwegian Meteorological Institute. Monthly averaged ice-flow velocities of Nordenskiöldbreen are illustrated as orange line. The comparison shows that maxima occur at the same time.
7.3.2 Summer Season

Maximum velocities on Nordenskiöldbreen occur mainly in the beginning of July. Figure 7.7 summarizes ice-flow velocities observed during July months for the period 2006-2014. Results show that velocities range between 39.42 m a⁻¹ and 53.88 m a⁻¹. The calculated average velocity for summer seasons over the entire measurement period is estimated to be 47.80±5.37 m a⁻¹. Velocities measured during July show an increasing trend between July 2007 and July 2010. Between July 2010 and July 2012 velocities decrease from 52 m a⁻¹ to 48 m a⁻¹. After 2012, ice flow velocities start to increase again from 48 m a⁻¹ in July 2012 to 53 m a⁻¹ in 2014. Overall, ice flow velocities observed in July show a significant positive trend with an increase rate of 1.78 m a⁻¹ per year with a r-squared value of 0.82 within a confidence interval of 95% (confidence bounds: 1.035; 2.519).

![Figure 7.7](image-url)  
*Figure 7.7. Ice-flow velocities along the main flow line on Nordenskiöldbreen in m/year observed in July for each year between 2006 and 2014 (orange line)*
7.3.2.1 Summer velocities compared with Temperature

Temperatures at Svalbard Airport are varying during July from 6.2°C to 7.1 °C. The mean temperature during July is $7.1\pm0.55$ °C (calculated for the years between 2006 and 2014).

Figure 7.8 presents recorded temperatures measured during July for each year between 2006 and 2014 (black line). It is expected that high temperatures lead to enhanced melting at the glacier surface. The meltwater is transported towards the glacier bed. Enhanced meltwater supply towards the glacier bed has a positive effect on ice flow velocities since basal lubrication reduces frictional forces between glacier body and glacier bedrock.

The graph shows that the r-square value of 0.53 is significant within a confidence interval of 95%. This results means that temperatures and velocities during summer seasons show low correlation. However, the graph shows that high temperatures occur at the same time as high velocities (compare summer 2009, 2011, 2013 and 2014) or the other way around that low temperatures occur at the same time as low velocities (compare summer 2008 and 2012).

![Figure 7.8](image_url)

**Figure 7.8.** Ice-flow velocities observed in July for each year between 2006 and 2014 (orange line) compared with observed Temperatures during July (black line).
7.3.2.2 Summer velocities compared with Summer Mass Balance

It is expected that high summer ablation occurs at the same time as high ice-flow velocities (figure 7.9) as enhanced melt has a positive effect on ice flow.

However, summer flow velocities compared with summer mass balance observations show both a parallel linear increase from summer 2007 towards summer 2010. Ice flow velocities and mass balance increase parallel by 25% from summer 2007 until summer 2010. After summer 2010 mass balance and velocity show an anti-correlation with transposed high and low peaks. After summer 2010, summer mass balance observations show high peaks every second summer (2010, 2012 and 2014). Velocities during July and summer mass balance are significant low positive correlated to each other with a correlation coefficient of 0.58 within a confidence interval of 95%. Ice flow velocities on the other hand show peaks during summer 2011 and 2014. The highest summer mass balance was recorded for summer 2014 with -0.43 m w.e.. The average summer mass balance over the entire measurement period is -0.73 m w.e..

Figure 7.9. Ice-flow velocities on Nordenskiöldbreen in m/year observed in July for each year between 2006 and 2014 (orange line) compared to observed summer mass balance (black line) on Nordenskiöldbreen.
7.3.3 Winter season

Winter velocities on Nordenskiöldbreen are highest during February months. Figure 7.10 summarizes those observed velocities during February for each year between 2006 and 2014. Velocity observations for February show quite continuous values with no major variations between February 2008 and February 2013. Velocities during this time vary between 40.31 m a\(^{-1}\) and 41.73 m a\(^{-1}\). Velocities measured during the first two years in February 2006 and February 2007 show relatively low values of about 29 m a\(^{-1}\). The highest observed winter velocity of 48.36 m a\(^{-1}\) was measured during the February 2014.

The average over the entire measurement period is estimated to be 39.22 ±5.98 m a\(^{-1}\). Overall, winter velocities show a significant positive trend with an increase rate of 1.76 m a\(^{-1}\) per year for 95% of the data with confidence bounds between 0.608 m a and 2.917 m a\(^{-1}\). The r-square value is estimated to be 0.65 within a confidence interval of 95%.

![Figure 7.10. Ice-flow velocities on Nordenskiöldbreen in m/year observed in February for each year between 2006 and 2014 (orange line)](image-url)
7.3.3.1 Winter velocities compared with Temperature

Temperatures recorded at Svalbard Airport during February are ranging between -13.9°C and -1.7°C over the period 2006-2014. The average temperature is -9.36±3.74°C.

Figure 7.11 shows the observed temperature recorded at Svalbard Airport for each year during February between 2006 and 2014 compared with ice flow velocities observed on Nordenskiöldbreen during February. The r-square value of 0.07 between temperature and observed ice-flow velocity confirms that there is no correlation between those two parameters. The graph shows that temperature has no direct effect on ice flow velocities.

![Figure 7.11. Ice-flow velocities on Nordenskiöldbreen in m/year observed in February for each year between 2006 and 2014 (orange line) compared to observed winter temperature (black line) at Svalbard Airport.](image)
7.3.3.2 Winter velocities compared with Mass Balance

The annual average mass balance for the entire glacier during winter on Nordenskiöldbreen is estimated to be 0.24 m.w.e. in the ablation area and 0.72 m.w.e. in the accumulation area. The average value for winter mass balance of the entire glacier is 0.48 m.w.e.. Winter mass balance on Nordenskiöldbreen is relative constant with values between 0.42 m.w.e. and 0.45 m.w.e.. One exception is winter 2012 were a maximum mass balance of 0.67 m.w.e. was observed.

The comparison between winter mass balance and winter velocities of Nordenskiöldbreen shows that also winter velocity observations show a maximum during winter 2012 with 40.31 m a\(^{-1}\) (Figure 7.12). Time series analysis of winter velocities compared to winter mass balance show a correlation of 0.12 with no significant probability. Hence, a correlation between winter velocity and winter mass balance is not given.

Figure 7.12. Ice-flow velocities on Nordenskiöldbreen in m/year observed in February for each year between 2006 and 2014 (orange line) compared to observed winter temperature (black line) at Svalbard Airport.
7.4 Surface Topography

The equilibrium line altitude (ELA) of Nordenskiöldbreen is located in an elevation of about 660 m which lies approximately between station S7 and S8 (Hagen et al., 2005). Hence, mass balance observations from stations S1-S6 are identified as mass balance within the ablation zone. Mass balance observations from stations S7-S11 are identified as mass balance within the accumulation zone.

The data suggests (figure 7.13) that mass loss in the ablation area is due to high summer ablation. The mass balance in the ablation area is decreasing by -0.89 m w.e. per year over the period 2007-2014.

The accumulation area on the other hand is dominated by mass gain during winter seasons. Mass loss is not high in the accumulation area during summer seasons. The mass balance in the accumulation zone is increasing by 0.41 m w.e. per year over the period 2007-2014.

Figure 7.13. Annual averaged mass balance (in m w.e.) observations on Nordenskiöldbreen over the period 2007-2014. The ELA at station S7 divides the glacier surface in ablation and accumulation area. Net mass balance (blue line), Winter mass balance (green line), summer mass balance (orange line).
7.5 Comparison of Velocity, Temperature and Surface Topography

Temperature records from the metrological station at Svalbard Airport were downloaded from the database eKlima of the Norwegian Meteorological Institute which is in about 60 km air-line distance to Nordenskiöldbreen. Monthly averaged temperatures for 2006-2016 show a mean value of -2.89 ±6.68°C. Maximum values were measured during August 2015 with 8.1 °C. The lowermost measured temperature occurred during April 2009 with a value of -15.9°C.

Since ice speeds are varying on seasonal scale it is self-evident that these variations might be correlated to temperature. Thus, figure 7.14 compares annual averaged temperatures compared with ice-flow velocities and changes in surface height for the period of 2007-2014. The comparison shows that temperature and ice-flow velocities are significant depended on each other with an r-square value of 0.66 within a confidence level of 95%. The Pearson correlation coefficient is 0.81 with a probability of 95% confirms the relationship between those two parameters.

It is seen that temperature and changes in surface height show a high peak during 2012 and a low peak during winter 2008. Temperature and changes in surface height not significant correlated with a R-value of 0.28.

![Figure 7.14. Annual averaged velocities (orange) compared with changes in surface height (red line) and annual averaged temperature records from Svalbard Airport (blue line) over the period 2007-2014.](image-url)
8 Discussion

8.1 Reference Station

Ice flow velocities recorded by the reference station are on average calculated to be 5.63±3.97 m a⁻¹ for filtered velocities and 18.06±8.20 m a⁻¹ for unfiltered velocities. The filtering of the raw dataset reduced the standard deviation by 48%. Velocities recorded by the reference station are interpreted as noise and is subtracted from the velocity measured by the other stations operating on Nordenskiöldbreen.

8.2 Comparison between Carrier Phase DGPS measurements and GPS

The comparison between carrier phase DGPS and GPS measurements illustrates the accuracy of the data which is used in this study. The difference between DGPS and GPS measurements is not higher than 5.2%. The results of comparison between carrier phase GDPS and GPS observations show that the measurements are in agreement. The average difference between the location of carrier phase DGPS and GPS of 2.5% supports that the GPS system works with a high accuracy. High accurate GPS data is a requirement to calculate accurate ice-flow velocities and allow correct interpretations of the data.

8.3 Observed ice-flow velocities

8.3.1 Entire measurement period

Annual flow velocities measured on Nordenskiöldbreen over the last 10 years show velocity variations within a range of 40-53 m a⁻¹. The study by Den Ouden et al. (2010) calculated that flow velocities on Nordenskiöldbreen are between 40-55 m a⁻¹ over the period 2006-2009. Ice-flow velocities calculated in this study are hence within the same range than reported in previous studies. As observed in this thesis, the study from den Ouden et al., 2010 showed that maximum ice flow velocities have maximum speeds in the beginning of July due to an increase of meltwater supply towards the glacier bed. Comparison presented that ice speeds calculated in this study are on average 12% higher than ice speeds calculated by den Ouden et al., 2010 for the period 2006-2009. The reason why ice speeds in this study are higher than ice speeds in the study from den Ouden et al., 2010 is that the studies applied different methods to process the data and calculate the ice speed.

Time series analysis indicated that maximum flow velocities show no time lag for stations in different elevations. This observation is evidence for a high correlation between the stations and shows further that the stations operating on Nordenskiöldbreen are working with high temporal and spatial accuracy.
The good correlation between the GPS stations (especially station S4 and S5) is due to their relatively close location to each other within a distance of below ±13 km.

The comparison of velocity variations in different elevations shows that high velocities occur close to the glacier front at station S3 where high water pressure is present. High velocities occur also close to the ELA at station S9 where surface slopes are steep. It is conspicuous that flow-velocities measured at Station S10 and S11 show relatively low ice-speeds of fewer than 30 m a\(^{-1}\). It is suggested that those low velocities are generated by the low surface slope of the glacier and due to the fact that the glacier is cold based in higher elevations.

Overall, the results show that velocity variations show similar amplitudes over time as maximum velocities occur at the same time at each station. However, the average velocity differs from each station. The reason for the deviation in average velocity is that the stations are located in different elevations where surface slopes are steeper/flatter.

Figure 8.1 shows a GPR profile between station S7 and S10. It shows that the bedrock beneath station S10 is smoother compared to the bedrock beneath station S9. Bedrock with rough surface generates regelation mechanisms which may lead to enhanced basal lubrication. Enhanced basal lubrication might be a reason for an increase in ice-flow velocities beneath station S9.

However, it should also be noted that the glacier is cold based in higher elevations and basal lubrication is not the driving factor for glacier motion. This could also be a reason why station S10 shows low ice flow velocities.

Figure 8.1. Ground Penetrating Profile examined between station S7 and S10 on Nordenskiöld-breen. The grey area illustrates the underlying bedrock beneath the glacier body. The blue line signalizes the glacier surface.
The comparison between observed ice-flow velocities and temperature records from Svalbard airport in figure 7.6 shows that maximum velocities occur at the same time as maximum temperatures. This correlation between those parameters suggests that ice-flow velocities on Nordenskiöldbreen are controlled by maximum temperatures in July. High temperatures enhance the meltwater production at the glacier surface. Meltwater can be transported towards the glacier bed and enhance basal lubrication which has a positive effect on ice flow. This theory is further explained in the next chapter which analysis ice flow-velocities measured during summer season.

8.3.2 Summer Season

Ice flow Velocities measured on Nordenskiöldbreen show a clear seasonal periodicity with maximum velocities occurring in the beginning of July. The same observation was made on Nordenskiöldbreen by den Ouden et al. (2010) and on other Svalbard glaciers like Kronebreen (Kääb et al., 2005).

The reason for the occurrence of maximum velocities in the beginning of July is suggested to be a result of high meltwater supply towards the glacier bed during spring time. From previous studies it is known that ice flow velocities are strongly correlated to meltwater production (Vieli et al., 2004; Pälli et al., 2003; Dunse et al., 2012; Schellenberger et al., 2015). Enhanced meltwater production leads to higher basal lubrication since more meltwater is transported within the drainage system of the glacier. The amount of meltwater entering the subglacial system of the glacier determines the strengths of frictional forces between glacier bed and bedrock. If meltwater production is high, water pressure in the subglacial system increases which in reverse enhances the basal lubrication. High basal lubrication results in enhanced ice-flow velocities.

The results of this study showed further that ice flow velocities during summer months have an increasing trend of 1.78 m a\(^{-1}\) over the past 10 years. The increase of summer flow velocities is suggested to be caused by increased meltwater supply towards the glacier bed which also has been observed in previous studies (Vieli et al., 2004; Pälli et al., 2003; Dunse et al., 2012; Schellenberger et al., 2015 and chapter 7.3.2). The comparison between summer mass balance observations on Nordenskiöldbreen and summer velocities for the period 2007-2014 in chapter 7.3.2 shows that summers with high ablation occur mainly at the same time as summers with high temperatures and ice-flow velocities (figure 8.2).

Based on the observations made in this study, it is suggested that summer ice-flow velocities occur in the beginning of July due to enhanced basal lubrication. Warm air temperatures during July enhance meltwater production at the glacier surface. Meltwater is then transported towards the glacier bed and reduce frictional forces between glacier body and bedrock.

Another reason why ice-flow velocities are highest during July is that summer ablation is high in lower elevations of the glacier. High melt in lower elevations of the glacier could lead to an increased elevation gradient. As described in chapter 3 by equation 2, steeper surface slopes of the glacier lead to increased ice-flow velocities.
Figure 8.2. Summer mass balance on Nordenskiöldbreen (blue line) over the period 2007-2014 in comparison to temperatures measured in July at Svalbard Airport for each year between 2007 and 2014 (orange line). The comparison shows that years with high temperatures occur at the same time as years with high summer ablation (low mass balance).
8.3.3 Winter Season

Winter velocities on Nordenskiöldbreen are highest during February when temperatures are lowest. Winter velocity observations on Nordenskiöldbreen show an increasing trend over the last 10 years. The increase rate is estimated to be 1.78 m a\(^{-1}\) per year. Generally, winter velocities seem to be continuous without high variations from year to year. The reason for enhanced ice-flow during February is not obviously shown in the comparison winter velocities, winter temperature and winter mass balance.

However, the reason why ice flow velocities are enhanced during February is suggested to be caused by steepening of the glacier surface. The accumulation zone is gaining mass during winter due to enhanced precipitation and refreezing of subsurface waters (according to Van Pelt et al., 2010). The ablation zone on Nordenskiöldbreen is dominated by high summer ablation. The mass balance is unbalanced and cannot be compensated by ice flow.

The comparison between temperature and mass balance in figure 8.3 shows that winters with high temperatures occur at the same time as winters with mass accumulation. This is due to the fact, that warmer air can carry more moisture (can be seen especially during winter 2011, 2012 and 2013).

![Figure 8.3. Winter mass balance on Nordenskiöldbreen (blue line) over the period 2007-2014 in comparison to temperatures measured in February at Svalbard Airport for each year between 2007 and 2014 (orange line). The comparison shows that years with low temperatures occur at the same time as years with high mass balance.](image-url)
8.4 Surface Topography

Mass balance observations of Nordenskiöldbreen over the period 2007-2014 show the mass balance gradient on Nordenskiöldbreen is unbalanced as mass gain is enhanced in the accumulation area. Ice flow cannot compensate the mass displacement within the glacier body. The mass gain is a result of enhanced precipitation during winter and refreezing of subsurface waters in the accumulation zone (Van Pelt et al., 2010).

The ablation area is dominated by mass loss due to high summer ablation. The refreezing of subsurface waters in the ablation zone during winter is not possible since meltwater is (different than in the accumulation area) not stored in firn layers. Meltwater produced during summer reasons is running off right away.

This result would, seen over a longer period than 10 years, lead to thickening in the accumulation zone and thinning in the ablation zone. This process results then in steepening of the glacier surface. A steepening of the glacier surface may be reason for an increase in winter velocity as basal shear stresses are enhanced by a steepening of the glacier surface.

The study from Van Pelt et al. (2012) shows similar results for 1989-2010 as presented in this study. In this study it is suggested that precipitation dominates the net mass balance in the accumulation zone. Refreezing of melt- and rainwater contributes with 69% to mass balance since 25% of subsurface waters refreeze below the surface (Van Pelt et al., 2012). The mass budget in the ablation area is dominated by melt. Refreezing is here less dominant since the snow in the ablation area is melting entirely during the melting season. The study from Van Pelt et al. (2012) suggests that the glacier surface is steepening over time and is therefore in agreement with mass balance observations presented in this study.

8.5 Comparison of Velocity, Temperature and Surface Topography

Statistical analysis showed that temperature and velocity are stronger correlated (r-squared=0.66) while velocity and changes in surface topography are less correlated (r-squared=0.28). However, the results indicate that years with high velocities show high temperatures and high changes in surface elevations.

This result gives an idea of how velocities are related to changes in temperature and surface topography. Figure 7.13 shows that temperature and the topography of the glacier surface might have an effect on glacier motion.
The investigation of seasonal trends in ice-flow velocities on Nordenskiöldbreen over the past 10 years indicated further that ice-flow velocities are highest during February. To find an explanation for this trend, the study compared ice flow-velocities observed during February with temperatures recorded at Svalbard Airport during February. Results show that there is no obvious relation between
those parameters which indicates winter ice flow velocities are not directly controlled by temperature variations during winter (chapter 7.3.3). However, it is suggested that temperatures during winter seasons have an effect on the amount of precipitation. The comparison between mass accumulation and temperatures (figure 8.3) has shown that mass accumulation is higher during winters with milder temperatures. Warmer air is able to carry more moisture than cold air, which in consequence indicates that warmer temperatures are associated with enhanced precipitation. This study suggests that winter ice-flow velocities are enhanced in February due to steepening of the glacier surface. Mass balance observation of Nordenskiöldbreen over the period 2007-2014 illustrated that the mass balance of Nordenskiöldbreen is unbalanced and cannot be compensated by ice flow. Lower elevations are dominated by enhanced summer ablation due to increasing air temperatures. Higher elevations are dominates by mass accumulation due to enhanced precipitation and refreezing of subsurface waters during winter seasons. This processes lead to a steepening of the glacier surface over time. As described in chapter 3, basal shear stresses are controlled by the surface slope of the glacier as steeper slopes lead to enhanced ice-flow. Ice-flow velocities on Nordenskiöldbreen are hence controlled by the steepening of the glacier surface which is suggested to be the main driving factor for enhanced ice-flow velocities during winter seasons (chapter 7.4 and chapter 8.3.3).

Comparison between annual variations in velocity, temperature and surface topography of Nordenskiöldbreen showed that ice flow velocities are stronger correlated to changes in temperature than to changes in surface topography. However, figure 7.14 gives just an idea of the relation between ice flow-velocities, surface topography and temperatures and should not display a scientific declaration. To ensure that the statements suggested in this thesis are proven, long-term measurements of both ice-flow velocities and mass balance observations are indispensable (chapter 7.5).

Overall, it seems like ice-flow velocities at the main flow line of Nordenskiöldbreen increased over the past 10 years by up to 1.78 m a⁻¹ (compare with Figure B1 in Appendix B). It is suggested, that ice-flow velocities on Nordenskiöldbreen will continue to increase in the future. The reason for this suggestion is based on chapter 3, where it is mentioned that temperatures and precipitation are expected to increase over the coming years (IPCC, 2007 and chapter 3).

This study has clearly shown that glacier motion is related to changes in climate parameters such as temperature and precipitation. The dynamical behaviors of glacier bodies provide information about how climate change influences our ecosystems. Further research will be required to preserve sustainable research of glaciers on the Svalbard archipelago. Data collection of mass balance and flow velocity over long-time periods is important to understand the effect of climate change on glaciers. The knowledge about how climate change effects our environment is indispensable for preserve a sustainable future for following generations.
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I also want to thank all people I studied with! I really enjoyed studying at Uppsala University with you guys and I will remember it with joy!

Finally I would like to thank my family and closest friends for your endless encouragement and support. Without you I would not be where I am today. Thank you <3
References


Appendix A: Observed ice-flow Velocities on Nordenskiöldbreen

Figure A1. Monthly averaged velocities (in m/year) at all stations operating on Nordenskiöldbreen over the period 2006-2016.
Appendix B: Observed ice-flow Velocities on Nordenskiöldbreen

Figure B1. Annual averaged ice-flow velocities of station S3-S9 along the main flow line on Nordenskiöldbreen over the period 2006-2016.


### Table C1: Annual averaged ice flow velocities of Nordenskiöldbreen for each year between 2006 and 2016

<table>
<thead>
<tr>
<th>Period</th>
<th>Average V (m/year)</th>
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</thead>
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<tr>
<td>2006-2007</td>
<td>45.59±6.08</td>
</tr>
<tr>
<td>2007-2008</td>
<td>45.45±5.28</td>
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<tr>
<td>2008-2009</td>
<td>45.59±6.08</td>
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<td>2009-2010</td>
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<td>2013-2014</td>
<td>45.45±5.28</td>
</tr>
<tr>
<td>2014-2015</td>
<td>45.59±6.08</td>
</tr>
<tr>
<td>2015-2016</td>
<td>45.45±5.28</td>
</tr>
<tr>
<td>Total</td>
<td>48.89±8.18</td>
</tr>
</tbody>
</table>

### Table C2: Annual averaged ice flow velocities for each station on Nordenskiöldbreen for each year between 2006 and 2016

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<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
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<td>7.7±4.6</td>
<td>8.4±5.8</td>
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<tr>
<td>S2</td>
<td>53.1±41.5</td>
<td>42.5±32.4</td>
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<td>S3</td>
<td>56.9±41.3</td>
<td>49.6±36.2</td>
<td>35.0±23.4</td>
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<td>5.6±3.5</td>
<td>4.9±3.5</td>
<td>5.6±3.5</td>
</tr>
<tr>
<td>S5</td>
<td>6.0±4.1</td>
<td>5.2±3.9</td>
<td>5.6±3.5</td>
</tr>
<tr>
<td>S6</td>
<td>5.6±3.5</td>
<td>5.0±3.5</td>
<td>5.6±3.5</td>
</tr>
<tr>
<td>S7</td>
<td>5.6±3.5</td>
<td>5.0±3.5</td>
<td>5.6±3.5</td>
</tr>
<tr>
<td>S8</td>
<td>5.6±3.5</td>
<td>5.0±3.5</td>
<td>5.6±3.5</td>
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<tr>
<td>S9</td>
<td>45.5±6.5</td>
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<tr>
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<tr>
<td>S11</td>
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<td>45.5±6.5</td>
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Appendix C: Observed ice-flow Velocities on Nordenskiöldbreen
Appendix D: Mass Balance

Figure D1. Cumulative Mass Balance in the Ablation Area for summer (orange), winter (green) and over the entire period (blue) between 2007 and 2014.

Figure D2. Cumulative Mass Balance in the Accumulation Area for summer (orange), winter (green) and over the entire period (blue) between 2007 and 2014.