# Dynamics of the Northeast Greenland Ice Stream: the role of geothermal heat and subglacial hydrology

Silje Smith-Johnsen

Thesis for the degree of Philosophiae Doctor (PhD)
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# Abstract


Ice streams are rivers of fast flowing ice, crucial for the mass balance of ice sheets. The Greenland Ice Sheet shows a complex flow pattern, where a few major ice streams drain most of the ice sheet, contributing to sea level rise. It is therefore crucial to capture ice streams in ice flow models when predicting the future response of the Greenland Ice Sheet to a warmer climate.

The Northeast Greenland Ice Stream (NEGIS) drains 12% of the ice sheet, and holds 1.1 m of sea level equivalent. It displays a unique velocity pattern with fast flow initiated close to the ice divide. This is further inland than any other ice stream in Greenland.

Geothermal heat flux, the natural heat from the Earth, is thought to be the trigger of the ice stream. A local high geothermal heat flux at the head of the Northeast Greenland Ice Stream generates basal water which lubricates the ice-bed interface and induces fast flow. Models of geothermal heat flux display a large range for Greenland, and their coarse resolution is unable to capture local anomalies, as the one suggested at the onset of the Northeast Greenland Ice Stream.

Previous studies investigated how geothermal heat flux influences ice dynamics, and did not find a significant impact. However, these studies focused on the direct thermal effect on ice softness, and did not include the indirect effect of water pressure. I hypothesize that, excluding the combined effect of geothermal heat flux and subglacial hydrology, accounts for the fact that the observed velocity of the Northeast Greenland Ice Stream is poorly represented in ice sheet models.

This thesis investigates how geothermal heat flux influences the subglacial hydrology and the dynamics of ice streams. The goal is to understand the processes at the bed of the Northeast Greenland Ice Stream, and to improve its representation in an ice sheet model. The model used is the Ice Sheet System Model (ISSM), a state of the art fully coupled thermomechanical ice flow model. Here, for the first time, a sophisticated subglacial hydrology model is coupled to ice dynamics in ISSM.

The simulations show that the choice of geothermal heat flux largely controls whether the bed of the Northeast Greenland is frozen or thawed. This sets the basal melt rates and controls the subglacial hydrology. As a consequence, the effect of geothermal heat flux on ice flow is increased tenfold when including the coupling between subglacial hydrology and ice dynamics.

In summary, local geothermal heat flux anomalies can induce fast flow. For the Northeast Greenland Ice Stream, subglacial hydrology accounts for a substantial part of the observed velocity pattern. By introducing an exceptionally high and locally contained geothermal heat flux anomaly, the ice flow model successfully reproduces the velocity pattern of the Northeast Greenland Ice Stream.

# List of Papers

1. Smith-Johnsen, S, de Fleurian, B., Nisancioglu, K. H., *The role of subglacial hydrology in ice streams with elevated geothermal heat flux*, Journal of Glaciology, in review, 2019.
2. Smith-Johnsen, S, Schlegel, N., de Fleurian, B., Nisancioglu, K. H., *Sensitivity of the Northeast Greenland Ice Stream to Geothermal Heat*, Journal of Geophysical Research: Earth Surface, in review, 2019.
3. Smith-Johnsen, S, de Fleurian, B., Schlegel, N., Seroussi, H., Nisancioglu, K. H., *Exceptionally High Geothermal Heat Flux Needed to Sustain the Northeast Greenland Ice Stream*, The Cryosphere, manuscript prepared for submission 2019.

# Contents

# Chapter 1

# Scientific Background and Motivation

Ice sheets and glaciers are of great scientific and societal interest; when ice masses shrink the sea-level rises. The majority of the planets population is concentrated along coastlines, and changes in sea level will have, and already have had, grave implications for local communities. Ice sheets gain mass by accumulating snow, and lose mass by melting at the surface or by discharging ice directly into the ocean. The latter is referred to as the dynamics component of mass loss. The state of ice sheets depends on the balance between mass gain and mass loss. With a negative mass balance over many years, the ice thins, the ice margins retreat and inevitably, the sea level rises.

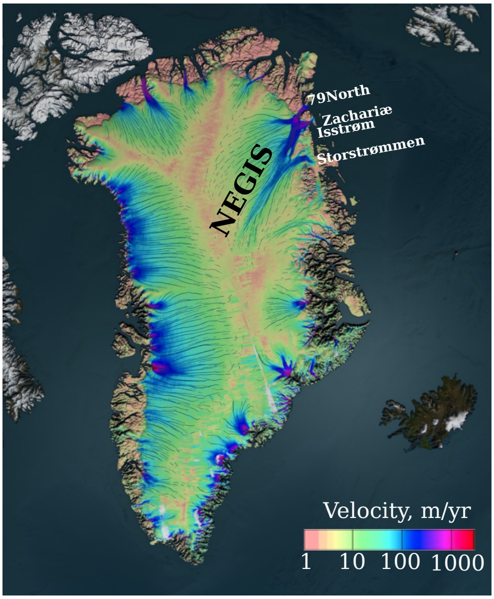


Figure 1.1: Observed surface velocity of the Greenland Ice Sheet (Rignot and Mouginot, 2012), including the Northeast Greenland Ice Stream (NEGIS). NEGIS displays fast flow further inland than any other ice stream on Greenland; with high velocities close to the ice divide. The ice stream flows from a point, and widens downstream where it terminates in three outlets.

Today, we observe a global retreat and reduction of ice masses, and it has been thought that present day sea level rise is mostly caused by the disappearing mountain glaciers. However, new observational methods (GRACE, IceSAT and Operation Ice Bridge) have greatly improved the monitoring of the major ice sheets, revealing an increasing contribution to sea level rise from Antarctica and Greenland (1.26 mm/yr) relative to mountain glaciers (0.65 mm/yr) (Reager et al., 2016). This change originates in the rapid dynamic response of the ice sheet to ocean and atmospheric warming, causing ice shelf collapse and abrupt outlet glacier acceleration (Hock et al., 2017).

The Greenland Ice Sheet (GrIS) holds more than 7 m of sea level equivalent (Morlighem et al., 2017), and its contribution to sea level rise has accelerated over the last decades (Talpe et al., 2017). The dynamic mass loss of the GrIS is driven by a complex surface velocity pattern (Figure 1.1, Rignot and Mouginot (2012)). An important component of the ice sheets are the large arteries draining the interior: the ice streams. Ice streams are rivers of ice, flowing faster than the surrounding areas of the ice sheet, and critical for the mass balance of the ice sheets. Dynamic mass loss constitute half of the present sea level rise contribution from the Greenland Ice Sheet, the other half coming from surface melting (Van Den Broeke et al., 2016). Understanding and simulating the dynamic behaviour of the Greenland Ice Sheet is therefore crucial to correctly predict its future sea level contribution.

The fourth assessment report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) did not include ice dynamics in their sea level predictions, and it was concluded to be one of the largest sources of uncertainty. Major progress was made in ice sheet model development the following years, but AR5 (IPCC, 2013) still did not fully account for the rapid dynamic changes observed in Greenland. Process studies and model development are needed to understand the boundaries between the ice and the atmosphere, ocean and bed (Hock et al., 2017). Straneo et al. (2013) recognized that the most important processes needed to be improved in ice sheet models to better capture future sea level rise are ice ocean interactions, glacier dynamics, calving, fjord circulation and glacial hydrology. It is therefore of great interest for the scientific community to understand how the marine terminating ice streams behave, and how they respond to a warming climate.

This dissertation focusses on the Northeast Greenland Ice Stream (NEGIS, Figure 1.1), draining a substantial part of the GrIS. One of the outlets (Zachariæ Isstrøm) of NEGIS recently lost its floating ice tongue and accelerated over the last decade, causing an increase in ice discharge to the ocean (Mouginot et al., 2015). The onset of the ice stream is exceptionally far inland, draining the centre of the ice sheet and therefore a potential weakness, making the Northeast Greenland sector vulnerable for future warming.

## 1.1 Ice Stream Dynamics

Ice streams are dynamic features known to switch on and off, to migrate and change flow direction (Cofaigh et al., 2010; Stokes and Clark, 2001; van der Veen et al., 2007). They are found in both the Antarctic and the Greenland Ice Sheet (summarized by Bennett (2003)), and recognised in the geomorphology of paleo ice sheets like the Fennoscandian and the Laurentide Ice Sheet (Stokes and Clark, 2001). The location of ice streams have several controls (Winsborrow et al., 2010); bed topography, bed geology, subglacial hydrology and geothermal heat flux (the natural heat from the Earth). The two latter controls are of special importance for the Northeast Greenland Ice Stream. To understand the impact of subglacial hydrology and geothermal heat on ice streams, a general background on temperature and dynamics of ice is presented in this section, and summarized in Figure 1.2.

The observed surface velocity of ice sheets and glaciers are a sum of two main components: internal deformation and basal slip due to sliding or deformation of sediments (Figure 1.2). For ice streams basal slip is important, and internal deformation only dominates the areas of the ice sheet outside the main outlets. Ice flows, due to gravity, toward lower altitudes in the direction of the steepest surface gradient (Cuffey and Paterson, 2010). This is called driving stress. The flow speed of glaciers is a balance between the driving stresses and resisting stresses. We assume no inertia and acceleration, and the sum of stresses must be equal to zero:

$$\tau_d = \tau_b + \tau_L + \tau_w \tag{1.1}$$

where $\tau_d$ is the driving stress, $\tau_b$ basal drag, $\tau_L$ is the longitudinal stress (that can be either positive or negative), and $\tau_w$ is the lateral or wall drag along the sides of the ice stream. The right side of the equation shows the resistive stresses, and will vary with velocities. Ice streams display small driving stresses, relative to for example mountain glaciers, but low resistance at the bed allows for high velocities.

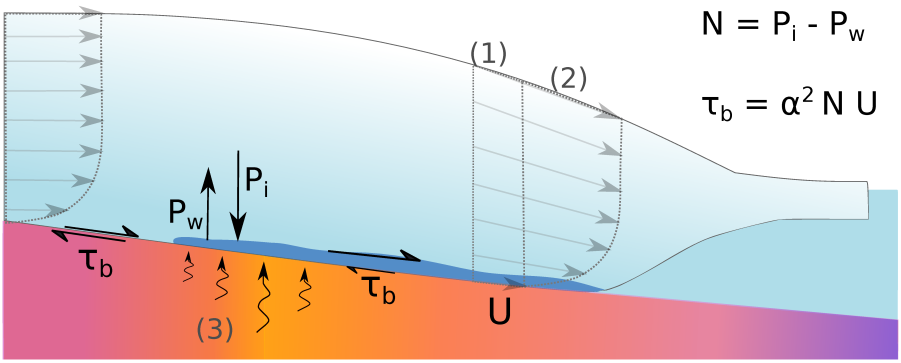


Figure 1.2: Conceptual figure showing interactions between geothermal heat flux (3), basal melt, subglacial hydrology and ice dynamics of a marine terminating glacier. Effective Pressure (N) is defined as the difference between ice overburden pressure ($P_i$) and water pressure ($P_w$). Basal drag ($\tau$) is a function of the friction coefficient ($\alpha$), effective pressure and basal velocity (U). (1) shows the sliding component and (2) shows the internal deformation component of the ice velocity.

### 1.1.1 Internal Deformation and Influence of Temperature

Glacier ice can be considered an incompressible fluid with high viscosity. Ice is deformable, and the deformation due to applied stress is referred to as strain. Glacier ice is non-Newtonian, so the strain response to stress is non-linear (Cuffey and Paterson, 2010). Ice flow is described by Glen's Flow law (Glen, 1955):

$$\dot{\varepsilon} = A\tau^n \tag{1.2}$$

where $\dot{\varepsilon}$ is the strain rate, $A$ the creep factor, $n$ is Glen's flow law exponent and $\tau$ is the shear stress. $A$ is dependent on temperature and fabric. The warmer the ice, the softer it gets and the faster it may flow. For this reason, it is important to know the thermal state of the ice sheet.

Temperature at the surface of ice sheets is controlled by the climate, and the temperature at the base is controlled by frictional heating and geothermal heat flux. The interior of the ice is heated by deformation and the refreezing of melt water. Heat is then transferred through ice by conduction and advection (Cuffey and Paterson, 2010). Temperature profiles from deep boreholes in Greenland often show an isothermal upper part with a temperature increase towards the bed. Accumulation brings cold ice down from the surface, ablation brings warm ice up towards the surface, and in this way the vertical temperature profile is altered. If there was no accumulation or ablation, the gradient of the entire temperature profile would be the same as the geothermal heat flux divided by the thermal conductivity of ice. The temperature of the ice advected down, varies in time as the surface temperature changes due to climate variability. Therefore, the observed temperature profiles in bore holes are a consequence of surface temperature changes over the past millennia, and the ice sheet is never in equilibrium with the present day surface climate.

If the basal temperature remains below the pressure melting point, the ice is frozen to its bed, and flow occurs only as a results of internal deformation. The temperature gradient at the bed is then equal to the geothermal gradient. This relationship is used to estimate the geothermal heat flux based on temperature profiles measured in deep bore holes on the ice sheets. However, the geothermal heat flux is not constant in space, and as ice moves over new terrain, the temperature gradient at the base may not represent the local geothermal heat flux. On the other hand, if the basal ice reaches pressure melting point, the ice will melt and water is produced. In this case, the temperature gradient will be lower than the geothermal heat flux. Water lubricates the bed and allows the ice to slide; an important process in ice streams. As ice slides over the bedrock, frictional heat is produced at the base of the ice. In this case, the temperature gradient in the ice will be higher than that expected due to the geothermal heat flux alone.

### 1.1.2 Basal Slip and Influence of Subglacial Hydrology

The fast flow of ice streams is largely governed by processes at the bed (Bennett, 2003). Up to 90% of the velocity observed at the surface is due to basal sliding (Van Der Wel et al., 2013). Despite its importance, basal sliding remains a major challenge in ice flow modelling (Hock et al., 2017).

Lliboutry (1968) observed that glaciers sped up with increased water input, and suggested that variations in velocity could be related to the subglacial drainage system. Water at the bed of glaciers can come from surface melt, reaching the base through moulins and crevasses, or it can come from basal melt. Water availability at the bed thus fluctuates on seasonal and diurnal scales, and there are numerous examples of observations of ice velocity responding to changes in water input (Bartholomew et al., 2010; Hoffman et al., 2011; Van De Wal et al., 2008; Zwally et al., 2002). Surface lakes may drain catastrophically and reach the bed of the ice, causing an acceleration of the ice motion (Stevens et al., 2015).

How exactly does water at the bed increase basal sliding and enhance ice velocity? Effective pressure ($N$) is defined as the difference between overburden ice pressure ($P_i$) and basal water pressure ($P_w$)(Figure 1.2). With an increase of water at the glacier bed, the water pressure increases and effective pressure is reduced. As effective pressure decreases, larger cavities in the ice may open, in particular on the lee side of bedrock bumps. As a consequence, the ice-bed contact area is reduced, leading to a speed up of the ice (Iken, 1981). This is only the case for ice masses situated on a hard bed, but many ice streams have soft, deformable beds consisting of glacial till (Christianson et al., 2014). Basal melt may fill the layer of till. As the till become saturated, effective pressure decreases. The shear strength of the till layer is weakened, allowing the ice stream to slide as it deforms the till. This has been shown to be case for the Whillans Ice Stream in Antarctica (Cuffey and Paterson, 2010). Effective pressure controls ice velocity by reducing basal drag for both soft and hard bedded ice streams, and is therefore key to understanding ice stream dynamics.

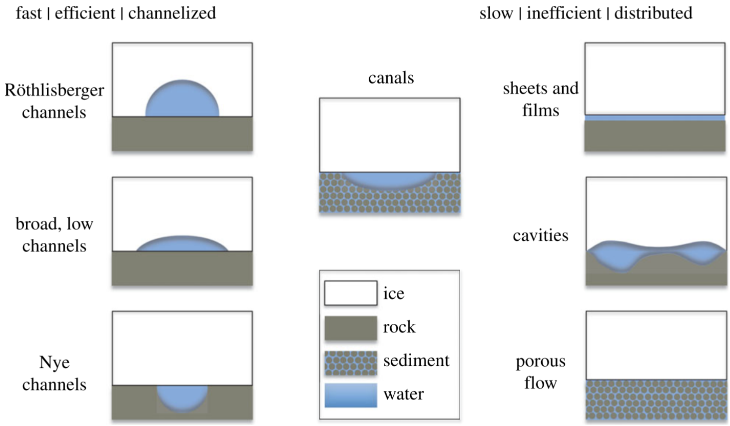


Figure 1.3: Examples of inefficient (left) and efficient(right) subglacial hydrology drainage systems. Figure from Flowers (2015)

It may seem simple: more water, lower effective pressure, and higher velocity. However, many examples of the exact opposite have been observed (Bartholomew et al., 2012; Nienow et al., 2017; Sundal et al., 2011; Tedstone et al., 2015) and the relationship is more complex. To understand why, we need to explore the geometry of the subglacial drainage system. There are two types of drainage systems at the bed of glaciers: inefficient and efficient drainage systems (as summarize by Flowers (2015)). The inefficient system is also referred to as a distributed system. This occurs when the water input is low, during for example winter time, when surface melt is minimal. This type of drainage system evacuates water slowly, inefficiently, and with a resulting low effective pressure (Figure 1.3). Examples of inefficient drainage systems are sheets of water, linked cavities and porous flow within a sediment layer at the base of the ice. A glacier with an inefficient drainage system responds, with increased velocity as water input increases.

When water availability is higher, the hydrological system evolves, and the glacier may develop an efficient drainage system, also knowns as a channelized system (Figure 1.3). Conduits open and evacuate water quickly under low water pressure, hence higher effective pressure. Examples of efficient drainage systems are channels cut into the sediment or bedrock beneath the ice (Nye-channels) or channels cut into the ice itself (Röthlisberger-channels). This means that effective pressure stays low during the winter when the drainage system is inefficient. As the melt season start, water reaches the bed and the effective pressure further decreases, and the glacier accelerates. At some threshold, the glacier develops an efficient drainage system, conduits open, water is efficiently evacuated and effective pressure increases. This results in a slowdown of the glacier, despite having a high water input. Studies have shown that despite increased melt, the ice motion is not enhanced on annual time scales. This may be explained by the development of channels to accompany the increase in water volume into the system. This raises the question of whether ice masses will accelerate as a result of a warming climate or not.

To predict the future response of ice sheets to global warming, subglacial hydrology must be taken into account in ice sheet models. Early subglacial hydrology models used theory from groundwater models, and computed hypothetical water pathways using the hydro potential (Shreve, 1972). Present day models can compute effective pressure, simulate both efficient and inefficient systems, they are 2 dimensional, coupled to ice flow models and may evolve through time (as summarized by Flowers (2015)). It is widely accepted that basal slip of glaciers depends on effective pressure (Stearns and van der Veen, 2018). Thus, it is included in friction laws; the empirical relationship linking shear stress, basal velocity and basal conditions in ice sheet models (Figure 1.2).

However, the most sophisticated subglacial hydrology models demand very small time-steps and high resolution. At present, this is not feasible for longer simulations of continental scale ice sheets. In addition, many of the parameters required to constrain the subglacial hydrology in the models are highly uncertain. Unfortunately, the knowledge needed in order to move forward in the field of subglacial hydrology is challenged by the difficulty in obtaining reliable observations from this highly inaccessible environment.

## 1.2 Basal conditions of the Greenland Ice Sheet

The Greenland Ice Sheet shows a complex flow pattern with fast flowing ice streams (Figure 1.1, Rignot and Mouginot, 2012). The three major outlets; Jakobshavn Isbræ, Helheim and Kangerdlugssuaq Gletscher, together drain approximately 40 % of the entire ice sheet (Rignot and Kanagaratnam, 2006). The flow of these outlets are thought to be topographically controlled, where large drainage basins are funnelled into narrow fjords inducing fast flow. In recent years, the ice sheet modelling community have gained a good overview of the basal topography of the Greenland ice sheet (Morlighem et al., 2017). For this reason, ice sheet models are now able to represent a large part of the observed complex flow pattern (Aschwanden et al., 2016). However, not all ice streams have a clearly defined topographic trough. For example the Northeast Greenland Ice Stream is not initiated by a visible topographic feature. Instead, thermal and hydrological conditions at the base are thought to be more important.

Observations of the subglacial drainage system underneath the Greenland Ice Sheet are mostly from borehole measurements in the land-terminating glaciers on the west coast (e.g. Stevens et al., 2015; Van De Wal et al., 2015). The beds of fast-flowing marine terminating outlets are even more inaccessible due to crevasses, and hence observations are scarce. Therefore, it is unclear if the knowledge gained from observations of hydrology under land terminating glaciers also applies to marine-terminating ice streams. However, we do know there is a clear link between the spatial distribution of basal water and the basal temperatures of the Greenland Ice sheet (Jordan et al., 2018).

As with hydrology, direct measurements of thermal conditions beneath the Greenland Ice Sheet are limited. Deep ice core drilling sites give vertical temperature gradients, but are point measurements only and do not provide information on spatial variations. Furthermore, ice cores are drilled at sites where the bed is cold, in order to preserve the annual layers, and hence not helpful for investigating basal conditions in fast flowing regions. As a consequence, one must use alternative methods to produce spatial maps of temperature of the ice sheet base.

Macgregor et al. (2016) did a thorough synthesis on the thermal state of Greenland bed using four independent methods: 3D thermomechancial ice flow modelling; basal motion inferred from radiostratigraphy; surface velocity; and surface texture. The authors concluded that most of the bed at the ice divide is frozen, apart from around NorthGRIP, and thus consistent with the deep ice core sites. The margins of the ice sheet are mainly thawed, particularly in the southern part of the ice sheet. Where the bed is thawed, it can be assumed that water is available. Jordan et al. (2018) used radio-echo sounding data and predicted where basal water could exist under the Greenland ice sheet. The authors then compared the water with the frozen-thawed likelihood map of Macgregor et al. (2016), and found an overall good match. However, more than 1/3 of the base still remains uncertain in the map by Macgregor et al. (2016). One possible explanation could be the highly uncertain geothermal heat flux distribution under the ice sheet.

### 1.2.1 Geothermal heat flux

Geothermal heat flux (GHF) is the natural heat from the Earth, and influences the lower part of the temperature profile in ice sheets. GHF thus impacts the basal thermal state and hence control the basal melt rates. The formation of a temperate basal layer influences ice dynamics by determining the extent of deformation (Figure 1.2, (2)). The basal melt rates influence subglacial hydrology and hence how and where ice sheets flows (Figure 1.2, (1)) (Cuffey and Paterson, 2010; Larour et al., 2012b; Pittard et al., 2016; Pollard et al., 2005).

GHF can be directly retrieved from the thermal gradient in bore holes, as long as the ice sheet is below pressure melting point. When the ice sheet is at the pressure melting point, a more extensive analysis is needed to estimate the GHF, accounting for frictional heat and other heat sources within the ice sheet. However, bore hole measurements only give point estimates, and modelling is needed to retrieve the spatial variations for GHF.

There are several different geophysical approaches to model GHF in Greenland:

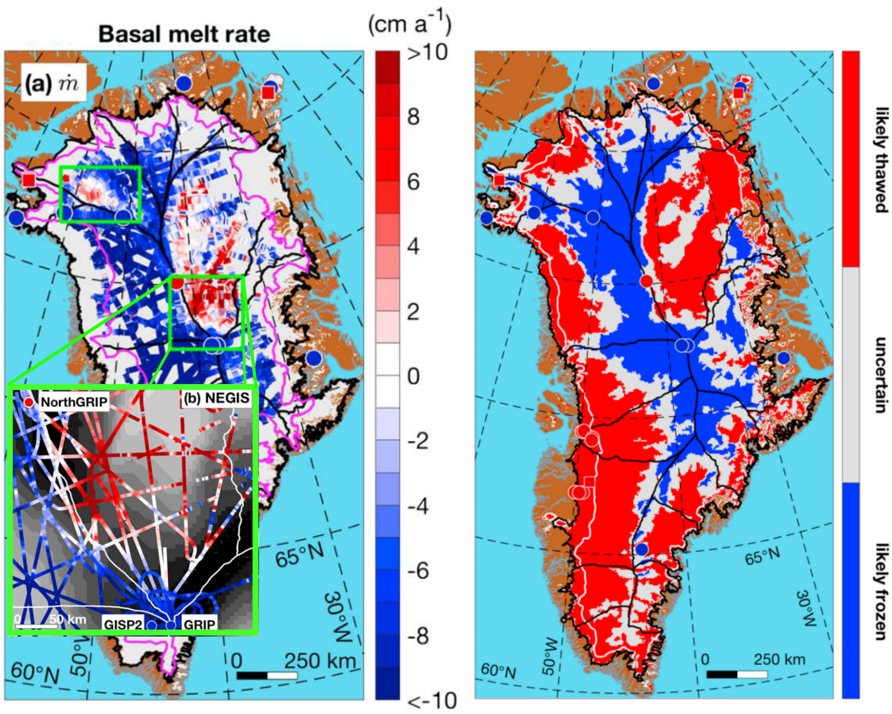


Figure 1.4: Basal conditions of the Greenland Ice Sheet from Macgregor et al. (2016). The left figure shows basal melt rates inferred from radiostratigraphy, where the green box shows a close up of the high basal melt rates at the onset of NEGIS. The right figure shows the likelihood of a thawed or frozen bed, based on multiple ice sheet models.

using tectonic age and structure of bedrock (Pollack et al., 1993), magnetic field observations (Fox Maule et al., 2009) or seismic tomography (Shapiro and Ritzwoller, 2004). GHF models can be further refined by using ice sheet modelling, and constrained by the deep drill site estimates and measurements (Greve, 2019; Rogozhina et al., 2016). Rogozhina et al. (2012) applied three GHF maps (Fox Maule et al., 2009; Pollack et al., 1993; Shapiro and Ritzwoller, 2004) to a Greenland simulation in the SICOPOLIS ice flow model (SImulation COde for POLythermal Ice Sheets; www.sicopolis.net), and found that none of the maps matched the observed bore hole measurements of basal temperature. Jordan et al. (2018) compared basal melt rates from airborne radio-echo sounding to geothermal maps, and found the best agreement with the GHF map by Martos et al. (2018). Unfortunately, the various GHF model results show a wide range of values, indicating large uncertainties in both spatial pattern and magnitude of GHF in Greenland (Rogozhina et al., 2012).

Greenland is considered a stable craton, with an average crustal thickness of 40 km (Martos et al., 2018). It mainly constitutes of precambrian provinces, and with old crustal age it is expected to have low GHF (Dawes, 1976). However, many studies point toward heterogeneities in GHF under the central Greenland, with anomalous high values (Greve, 2019; Martos et al., 2018; Rogozhina et al., 2016). High values may

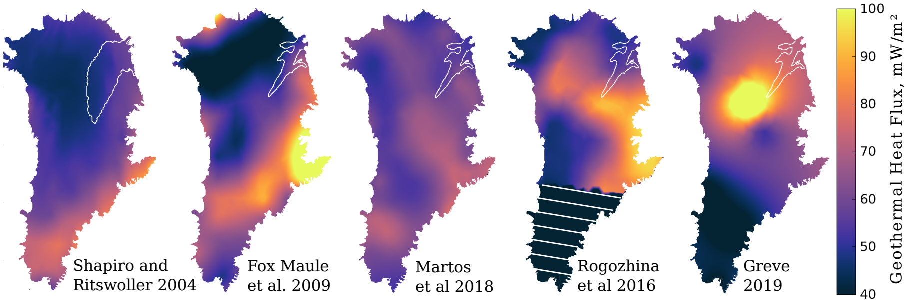


Figure 1.5: Five geothermal heat flux datasets for Greenland (Paper II). The white contour in the map by Shapiro and Ritzwoller (2004) shows the model domain, and in the remaining maps the white contour outlines the 50 m/yr ice surface velocity for the Northeast Greenland Ice Stream. Straight white lines in the map by Rogozhina et al. (2016) indicate an area with no model data.

arise from the passage of Greenland over the Iceland mantle plume from 30 to 90 million years ago (Braun et al., 2007). The exact hotspot track is strongly debated, and many different tracks have been proposed (summarized by Martos et al. (2018), see Figure 1.6).

The hotspot may have thinned the lithosphere and left behind molten rock, enhancing geothermal heat flux (Figure 1.5). In addition, a weakened lithosphere allows for easier penetration of dikes as pressure loading varies during ice age cycles (Alley et al., 2019; Stevens et al., 2016). Dike formation may transport the molten rock toward the surface leading to local high GHF anomalies. Hydrothermal fluid system are found outside the east coast of Greenland (Rysgaard et al. (2018) and references therein) and may also exist underneath the ice sheet. This would cause local anomalies in heat transport to the base of the ice sheet. Intraplate volcanism has also been discovered in SE Greenland (Uenzelmann-Neben et al., 2012), and may exist beneath the ice sheet as well.

Large uncertainties in GHF have motivated previous studies to investigate the influence of GHF on ice sheet dynamics. An increase in GHF raises ice temperature and the ice becomes softer and hence increases internal flow, particularly close to the base. However, the influence on ice dynamics is shown to be limited on short scale; Larour et al. (2012b) showed that an increase of 50 $mW/m^2$ only lead to a 1% change in the mass flux through Pine Island Glacier in Antarctica. GHF errors are found to have a small impact on ice flow, relative to uncertainties in surface mass balance and thickness (Larour et al., 2012b; Schlegel et al., 2015). Elevated GHF values may induce basal water production, and decrease basal drag. This effect is not included in the previous studies, as they focuses on the GHF impact on ice rheology and not sliding.

To include this effect, Pittard et al. (2016) used a simple hydrology model to investigate the influence of locally elevated GHF on ice dynamics in Antarctica. Similarly to previous studies they found a small impact in fast flowing areas, as frictional heat is the dominant heat source in these regions. However, on longer time scales GHF is important for ice sheet geometry and also shown to initiate ice streaming (Bell, 2008).

A GHF anomaly is thought to trigger the onset of the Northeast Greenland Ice

Stream (Alley et al., 2019; Fahnestock et al., 2001; Joughin et al., 2001; Macgregor et al., 2016), explaining the observed high velocities starting from the ice divide.

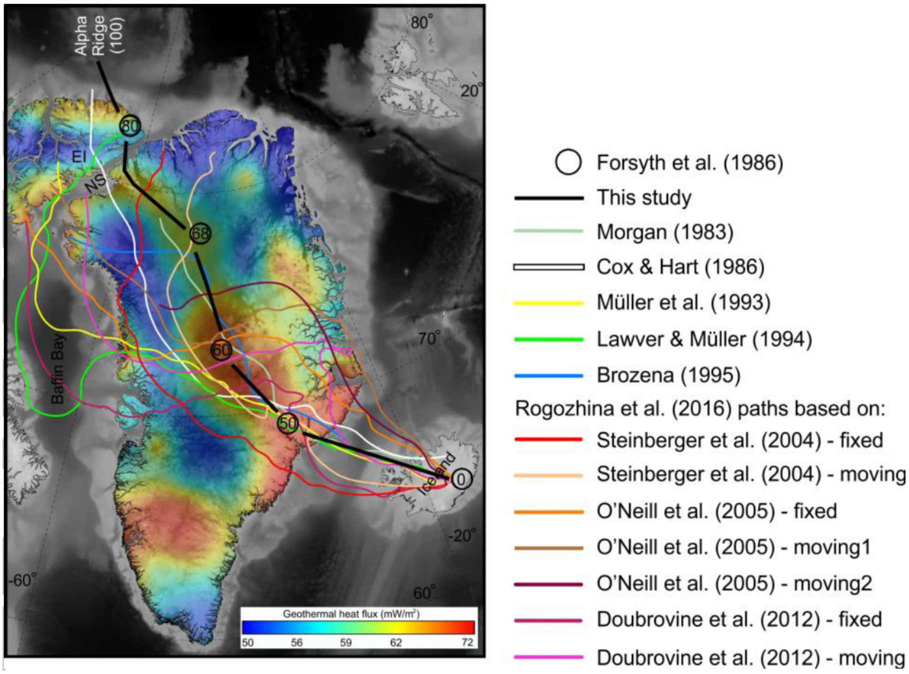


Figure 1.6: Geothermal heat flux map from Martos et al. (2018), with main Iceland Hotspot tracks proposed by various studies. EI: Ellesmere Island; NS: Nares Strait. Figure taken from Martos et al. (2018)

### 1.2.2 The Northeast Greenland Ice Stream

The Northeast Greenland Ice Stream is 700 km long, drains 12% percent of the Greenland ice sheet area, and holds a potential of 1.1 m sea level equivalent (Mouginot et al., 2015). The ice stream acts as an important link between the interior of the ice sheet and its margin, and is thus crucial to capture in models to predict future sea level contributions from Greenland. NEGIS is exceptional by displaying high velocities further inland than any other outlet in Greenland (Figure 1.1). Velocities increase quickly from the ice divide, reaching 20 m/yr less than 150 km divide, and flow up to 2 km/yr across the grounding line. NEGIS is also distinctive by starting from a point and widening downstream, compared to most other ice streams that show opposite.

The ice stream has clear, sharp shear margins upstream, which is possible to observe in the surface topography (Keisling et al., 2014). These sharp boundaries are present, despite the fact that NEGIS does not have a clear defined bed topography trough (Morlighem et al., 2017). The bed consists of a thick layer of dillitant till, and velocities are suggested to be controlled by water routing instead of topography

(Christianson et al., 2014). In contrast, the downstream part of NEGIS is topographically constrained and terminates in three outlets: Zachariæ Isstrøm, 79North glacier and Storstrømmen (Keisling et al., 2014).

Zachariæ Isstrøm has accelerated recently with tripled surface velocities from 2000 to 2012 (Mouginot et al., 2015). The calving front retreated, and the floating tongue was lost in 2014. The grounding line is retreating fast, with a rate of 800 m/yr (Mouginot et al., 2015). 79North glacier has not experienced the same dramatic changes. Its 70 km long floating tongue is still intact; pinned at the front and confined within narrow fjord walls (Khan et al., 2014). After a quarter of a century with stable conditions, NEGIS is now showing a dynamic thinning, due to warming and loss of sea ice (Khan et al., 2014). Karlsson and Dahl-Jensen (2015) showed how changes in surface slopes upstream may alter the subglacial water routing system, which may lead to velocity changes at the terminus. Zachariæ Isstrøm is predicted to retreat another 30 km within the next century, before stabilizing due to bed topography (Choi et al., 2017). The predicted retreat will contribute 16.2 mm of sea level rise (Choi et al., 2017).

The large potential sea level contribution makes the representation of NEGIS in ice sheet models crucial. Most models use inversion of basal friction to reproduce NEGIS in ice flow models (Choi et al., 2017; Karlsson and Dahl-Jensen, 2015; Larour et al., 2012b; Schlegel et al., 2015; Seroussi et al., 2013). Inversion is a powerful tool to represent present day conditions, without having information about basal conditions. The basal friction is kept constant in time, and all information are often masked under one parameter. Any error in the ice sheet model from parameters choices, representation of physical processes, mesh resolution, or errors in observation data sets are transferred to and masked by the constant basal friction coefficient. Basal friction may not be constant in time, as more water may reach the bed and enhance basal sliding as a results of warmer climate. Inversion is therefore not ideal for future simulations, where basal conditions are changing.

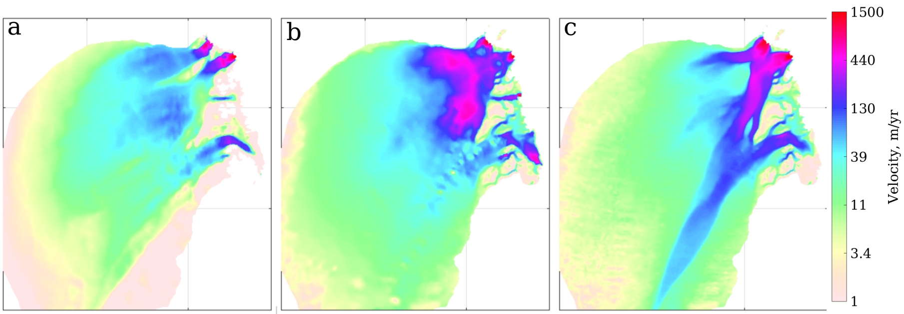


Figure 1.7: State-of-the-art simulated surface velocity of the Northeast Greenland Ice Stream, without inverting for basal friction. (a) shows the velocity from Aschwanden et al. (2016) using the Parallel Ice Sheet Model (PISM). (b) shows velocity results from Beyer et al. (2018) using a subglacial hydrology model and ISSM. (c) shows the observed velocity by Rignot and Mouginot 2012. Figure modified from Beyer et al. (2018).

Goelzer et al. (2018) showed in the initMIP-Greenland intercomparison that models without inversion, do not capture the characteristic upstream velocity of NEGIS. Previous research have tried to represent NEGIS in ice flow models without inversion (Aschwanden et al., 2016; Beyer et al., 2018). The downstream area is captured rather well, with high velocities and well defined shear margins for the outlet glaciers. However, high velocities far inland are still missing (Figure 1.7). Why is NEGIS poorly represented in ice sheet models without inversion?

As previously mentioned, the onset of NEGIS is thought to be triggered by a GHF anomaly giving high basal melt production at the head of the ice stream. Local GHF anomalies, like the one at the head of NEGIS, are not represented in GHF models, and hence not included in the GHF maps commonly used as boundary conditions in ice sheet models. In addition, subglacial hydrology; the most important link between GHF and ice dynamics, is often not included in ice sheet models. Subglacial hydrology models demand small time steps and fine resolution, and hence are computationally heavy to run and couple to ice dynamics. The lack of enhanced geothermal heat flux and the missing link between subglacial hydrology and ice dynamics in ice sheet models may explain why the velocity of NEGIS is poorly represented.

# Chapter 2

# Objectives

To narrow down the uncertainties in sea level predictions, controls on ice stream dynamics and their representation in numerical ice sheet models must be improved. The Northeast Greenland Ice Stream (NEGIS) is a highly dynamics feature, crucial for the mass balance of the Greenland Ice Sheet. Inverting for basal conditions by matching observed surface velocities is currently the only way to fully represent NEGIS in ice sheet models. However, inversion is not ideal for future simulations as basal conditions and other uncertainties in the model are masked under one friction coefficient, which can only be computed at the time where velocity observations are available.

High geothermal heat flux (GHF) values at the onset of the NEGIS are hypothesised to explain the high velocities, reaching exceptionally far inland in Greenland. GHF is unfortunately highly uncertain, and GHF models do not capture local anomalies. Additionally, subglacial hydrology models are commonly not included in ice sheet models to account for the reduced friction as GHF (and melt water production) is enhanced. Lack of locally high GHF values at the head of NEGIS, and the ability to model its impact on ice dynamic through a higher water pressure, may explain why the complex flow pattern of NEGIS is poorly represented in ice sheet models, particularly the high velocities close to the ice divide.

The overall aim of this dissertation is to understand the links and interactions between the basal conditions of ice streams and their ice dynamics, with particular focus on geothermal heat flux and subglacial hydrology of NEGIS.

The main research questions for this thesis are:

- What are the relative importance of the frictional and rheological component on ice dynamics, when geothermal heat flux is enhanced.
- What is the influence of subglacial hydrology when modelling ice streams with elevated geothermal heat flux?
- How sensitive is the ice discharge of NEGIS to errors in the geothermal heat flux?
- How can we improve the representation of NEGIS in ice sheet models for better predictions of future sea level rise?

# Chapter 3

# Methods

The general approach for this thesis is as follows; in Paper I we start with a simple and idealized ice stream, to find the influence of hydrology when geothermal heat flux is locally enhanced. Then we set up a realistic simulation of the Northeast Greenland Ice Stream model for Paper II, and investigate the sensitivity of the system to geothermal heat flux by using Uncertainty Quantification. In the final paper, we combine what we learned from Paper I and Paper II, and introduce a locally enhanced geothermal heat flux anomaly to reproduce the observed complex velocity pattern of NEGIS.

## 3.1 Ice Sheet System Model, ISSM

For all the papers, we use the Ice Sheet System Model (Larour et al., 2012a), hereafter ISSM; a state of the art numerical model that solves governing equations describing glacier physics. ISSM is a finite element model using a adaptive mesh. In the next section, key components relevant for this dissertation are described, and thus also the reasons for choosing ISSM for the simulations.

Mass is conserved in ISSM, and thickness evolves with time through the continuity equation. The temperature of the ice is solved relying on the enthalpy solution after Aschwanden et al. (2012). We prescribe the surface temperature, which remains fixed through time, despite a surface lowering or increase. At the base of the ice we prescribe the geothermal heat flux as either uniform, from published maps or computed by a mantle plume model (Seroussi et al., 2017). Ice is a non-Newtonian fluid and the rheology, the ice softness, is dependent on temperature. As temperature varies between time steps, so does rheology, linking temperature to ice flow.

To compute the ice velocity, we use different approximations to the Stokes equations to speed up the computation and save resources. Higher Order (HO) is a 3D approximation to the Stokes equations (Pattyn, 2003), that assumes horizontal derivatives of the vertical velocity can be ignored. HO neglects bridging effects but includes extensional and compressional forces, and lateral drag. The L1L2 approximation (Hindmarsh, 2004) is a 3D hybrid scheme between Shallow ice approximation (SIA) and Shallow Shelf Approximation (SSA). SSA is 2D, vertically integrated, approximation that make the same simplifications as HO and in addition no vertical shearing. The entire ice column have the same velocity so it works well where we have plug flow, like fast flowing ice streams and shelves, where extensional and compressional forces dominate. SIA is the simplest 2D approximation, calculating horizontal velocities only based on surface slope i.e. ice creep/internal deformation. SIA neglects compressional and extensional forces, as well as lateral drag. As a consequence, the in driving stress is balanced only by basal drag (Equation 1.1). This works well in slow moving areas far away from side wall drag, for example in the interior of an ice sheet.

At the base we use a friction law relating basal drag to velocity and a spatially varying, constant in time friction coefficient, $\alpha$ (Figure 1.2). The friction coefficient is inverted for by matching observed surface velocity to modelled velocity. The friction law is also linearly dependent on effective pressure; the difference between the weight of the ice and the water pressure at the base. The water at the base comes from the thermal model as a result of basal melting. This is the only water source into the two-layered subglacial hydrology model that computes water heads, and translate this to effective pressure in the friction law.

In addition, uncertainty quantification (UQ) tools embedded into ISSM are used (Larour et al., 2012b). This allows for launching multiple simulations in parallel, where some input parameters are perturbed, and the statistics of a chosen diagnostic output can be tracked.

**Paper I**: *The role of subglacial hydrology in ice streams with elevated geothermal heat flux*
In this paper we couple the thermomechanical ice flow (L1L2) to a subglacial hydrology model, for the first time in ISSM. We use an idealized ice stream geometry from the MISMIP+ project (Asay-Davis et al., 2016). We perform experiments where we insert a mantle plume with high GHF at the head of the ice stream, with increasing degree of water influence on ice dynamics. With this approach we can disentangle the effect the geothermal heat flux has on rheology, basal friction and more complex feedbacks arising with changing geometry.

**Paper II**: *Sensitivity of the Northeast Greenland Ice Stream to Geothermal Heat*
In the second paper we set up a present day NEGIS model, and investigate the sensitivity of ice mass transport through the ice stream to variations in geothermal heat flux. We use Uncertainty Quantification to keep track of all 900 simulations, where GHF is perturbed between maximum and minimum values based on published GHF maps. Similar to Paper I, we aim to disentangle the influence GHF has on dynamic changes associated with rheology and those associated with basal drag. In this paper we use the L1L2 ice flow approximation, and the subglacial hydrology is kept constant through time, to save computational resources.

**Paper III**: *Exceptionally High Geothermal Heat Flux Needed to Sustain the Northeast Greenland Ice Stream*
Finally, we aim to tackle the problem of representing NEGIS in ice sheet models, without inverting for basal drag. We use the same model as in Paper II, but the friction coefficient is dependent on bed topography, instead of being inverted for from the observed surface velocity. We also experiment with altering the geothermal heat flux by inserting a mantle plume of size and magnitude as proposed by previous work. In this final paper we use the HO approximation, as we now only need to run a few simulations.

# Chapter 4

# Summary of Papers

**Paper I**: *The role of subglacial hydrology in ice streams with elevated geothermal heat flux*

Geothermal heat flux (GHF) is an important boundary condition for ice sheet models. Unfortunately, GHF maps display a large range of values and patterns, and are of coarse resolution. GHF anomalies are shown to exist in Antarctica and Greenland, and are thought to control the initiation of ice streams. Previous studies conclude that GHF does not have a large impact on ice dynamics, particularly in high velocity regions where frictional heat is dominating. However, these mostly focus on the impact on ice rheology. Here we study the influence of a GHF anomaly on ice dynamics, and the novel part is to include a friction law with subglacial hydrology. To understand how important hydrology is in the ice sheet model, we perform three tests with increasing degree of hydrology-ice dynamics interactions. We find that the impact of a GHF anomaly has little effect on ice dynamics when hydrology is excluded. On the other hand, velocity increases 50 percent when we include hydrology in the friction law. Coupling hydrology and ice dynamics, to account for geometric changes in the ice stream, gives rise to negative effects as the ice stream compensates for the new velocities by thinning and thus cooling. Our findings imply that previous studies without effective pressure in the friction law may have largely underestimated the influence of GHF on ice dynamics, and overestimated the thermal influence.

**Paper II**: *Sensitivity of the Northeast Greenland Ice Stream to Geothermal Heat*

Geothermal heat flux (GHF) under the Greenland ice sheet is highly uncertain, and a range of maps with a large spread have been suggested. How does this GHF uncertainty impact ice flux trough the most dynamic region in Greenland; the Northeast Greenland Ice stream (NEGIS)? Previous uncertainty quantification (UQ) studies only looked at the influence on ice softness. Here we include the GHF impact on sliding, by utilizing a subglacial hydrology model, and we use a larger range of GHF maps in our UQ. We find that GHF largely controls whether the ice reaches pressure melting point, or remains frozen to its bed. This further dictates the size of the hydrology area and the efficiency of the hydrology system. Subglacial hydrology can explain a large portion of the spatial pattern of NEGIS velocity. Errors in GHF cause an ice flux uncertainty of 2.10 Gt/yr for the main outlets of NEGIS, but this number is highly dependent on ill constrained hydrology parameters. These findings suggest that the GHF controls the subglacial hydrology system under NEGIS, potentially influencing the ice stream response to future climate warming.

**Paper III**: *Exceptionally High Geothermal Heat Flux Needed to Sustain the Northeast Greenland Ice Stream*

The Northeast Greenland Ice Stream (NEGIS) shows a velocity pattern with high velocities starting from a point close to the ice divide, and widens symmetrically downstream toward the sea. NEGIS is only represented in ice sheet models by inverting for basal friction using observed surface velocity. All unknown bed properties and other errors in the ice flow model are thus hidden in a friction coefficient, and assumed to be constant in time. This assumption is not valid for future projections in a warmer climate , where more water is assumed to be transported to the bed and influences friction. The ice stream is suggested to be triggered by geothermal heat flux (GHF) and shown to have high melt rates at its head, explaining why the ice stream starts further inland than any other outlet of Greenland. We reproduce NEGIS in an ice sheet model by imposing a locally high GHF with an interactive subglacial hydrology model. To reproduce high upstream velocities a high GHF value of 970 $mW/m^2$ is needed, in agreement with previous proposed values.

## 4.1 Main Conclusions

The main conclusions of the thesis are the following:

- Geothermal heat flux models for Greenland show a large spread, and for the Northeastern sector the magnitude of the heat flux varies by up to 150% between the minimum and the maximum. The maximum geothermal heat flux causes a larger portion of the ice sheet base to reach the pressure melting point, relative to the minimum. This enhances basal melt rates and influences the subglacial hydrology system. With a warmer base, effective pressure is lowered and the efficient drainage system reaches further inland (Paper I,II and III).

- Higher geothermal heat flux below an ice sheet causes basal water pressure to increase. A reduction in basal friction follows, causing a speed-up and thinning of the ice stream. The difference between the minimum and maximum geothermal heat flux proposed for the Northeast Greenland Ice Stream, causes a 10 percent ice mass flux uncertainty. When subglacial hydrology is not accounted for, and only the influence on ice rheology is regarded, the effect is decreased by a factor of ten (Paper I and II).

- Subglacial hydrology can explain a substantial part of the complex velocity pattern observed for the Northeast Greenland Ice Stream. The downstream area is controlled by bed topography and oceanic forcing, whilst basal thermal and hydrological conditions control the upper area of the ice stream. By including subglacial hydrology in the inversion for basal friction, we mask out less unknown information in the temporally constant friction coefficient (Paper II and III).

- We show that a locally enhanced geothermal heat flux initiates fast flow. Frictional heat from observed velocities, combined with published geothermal heat flux maps, only provide sufficient basal water to sustain the downstream area of the Northeast Greenland Ice Stream, and not the observed high velocity upstream. By including an exceptionally high geothermal heat flux anomaly of 970 $mW/m^2$ close to the ice divide, we successfully reproduce the observed ice stream, for the first time without inverting for basal friction (Paper I and III).

# Chapter 5

# Future Perspectives

This thesis focuses on improving the understanding of basal processes and how they influence ice stream dynamics, with particular focus on geothermal heat flux and the onset of the Northeast Greenland Ice Stream.

In Paper I we hypothesise and confirm that ice dynamics are more sensitive to geothermal heat flux when subglacial hydrology is taken into account. This implies that previous sensitivity studies underestimated the importance of geothermal heat flux. We investigate this further in Paper II, and find that ice flux uncertainty of the Northeast Greenland Ice Stream due to GHF errors is 10 times higher when hydrology is included. The Northeast Greenland Ice Stream is used as case study, but the findings should apply to other ice streams in Greenland and Antarctica. Antarctica in particular, should be investigated further, where low accumulation rates, and thus small vertical velocities, causes geothermal heat flux to influence a larger part of the vertical temperature profile. There is also widespread volcanism. In summary, the results call for better constraints on geothermal heat flux maps for use as boundary conditions in ice sheet models.

One way to limit GHF errors is to obtain direct measurements from new deep drilling sites, such as the currently ongoing deep drilling at NEGIS (EastGRIP). This is the first ice core drilled into an ice stream in Greenland, and will provide valuable information about the dynamics and basal conditions of NEGIS. EastGRIP will give an additional crucial point measurement of geothermal heat flux. However, it will not give information on the spatial GHF pattern. For this we need models. Unfortunately, the existing GHF models do not produce consistent spatial patterns or magnitudes (Rogozhina et al., 2012). New methods such as the thermal isostasy method (Artemieva, 2019), machine learning (Rezvanbehbahani et al., 2017), or the use of magnetotelluric data (Magnetotelluric Analysis for Greenland and Postglacial Isostatic Evolution, MAGPIE) may produce better GHF maps, and possibly help explain the discrepancy between previous GHF models.

Estimates of GHF from geophysical data (Fahnestock et al., 2001; Macgregor et al., 2016) and ice sheet models (Greve, 2019) are inconsistent and poorly correlated with GHF models. This is possibly due to the inability of models to capture local anomalies. In Paper I and III we show how crucial local GHF anomalies can be for ice flow, which underlines the importance of improving GHF maps. van der Veen et al. (2007) showed how topographic effects may enhance the GHF by 100 % under outlet glaciers in Greenland with deeps troughs. Future studies should investigate this topographic effect by using subglacial topography and intensify the background GHF in valleys and attenuate it on ridges. Greve (2019), modified the GHF map by Pollack et al. (1993) in five deep ice core locations, by matching the measured temperature from bore holes to the simulated temperature in an ice sheet model. Zhu et al. (2016) inverted for GHF by matching surface velocities in an ice sheet model. The inverse problem becomes challenging, as the GHF is a boundary condition impacting the velocity, and is only tested on synthetic observations and idealized geometries with cold based ice. In Paper III we found that the modelled basal melt rates match the melt rates from Macgregor et al. (2016) when a GHF anomaly was introduced. Future studies may capture GHF anomalies using data assimilation to retrieve GHF by matching modelled basal melt rates to the gridded basal melt rates dataset by Macgregor et al. (2016) covering most of Greenland.

We find that subglacial hydrology can explain a substantial part of the velocity pattern of the Northeast Greenland Ice Stream (Paper II and III). This is without tuning and testing the highly uncertain parameter space of the hydrology model. Future studies should investigate the sensitivity of the results to changes in the hydrology parameters. Unfortunately, the parameters of the subglacial hydrology model are difficult, or even impossible to observe directly, thus the parameter space is largely unconstrained. This underlines the importance of constraining subglacial hydrology model parameters, and further sensitivity tests should be prioritized.

The knowledge about subglacial hydrology in Greenland is mostly from land terminating glaciers on the west coast (e.g. Stevens et al., 2015; Van De Wal et al., 2015). We need to know if this data also applies to fast flowing marine terminating ice streams like NEGIS. Marine terminating glaciers flow faster, which may induce higher basal meting from frictional heat. Despite this, Schoof (2010) suggested fast flow to suppress an extensive efficient drainage system to evolve, as the fast flow may cause higher creep closing rates of the channels. To investigate this we need more direct or indirect observations (e.g. Gimbert et al., 2016; Schroeder et al., 2015), but this may be difficult due to inaccessible and hazardous crevassed regions and hard to obtain spatial information. Future studies should investigate how we can develop new remote sensing techniques to observe subglacial hydrology (e.g. Gimbert et al., 2016; Schroeder et al., 2015). Another approach may be to constrain the conditions influencing the subglacial hydrology system, like till extent and thickness, thermal state of the ice, including melt rates and bed roughness. By capturing these spatial patterns, it may be possible to use data assimilation to gain information on the subglacial hydrology, including its spatial extent and whether the system is inefficient or efficient.

The friction law is the crucial link coupling the subglacial hydrology to the ice dynamics in ice sheet models. Finding a universal friction law was recognized as the biggest problem in glaciology by Weertman et al. (1979), and the problem still remains unresolved today. In this thesis, a simple friction law is used, where the friction is linearly dependent on effective pressure. However, various sliding relations exist, with higher complexity, particularly close the grounding line where ice goes from grounded to floating (e.g. Gagliardini et al., 2007; Schoof, 2005). It would be interesting to investigate if our findings still apply when using other sliding laws. For example, in the friction law used in the MISMIP+ experiments (Asay-Davis et al., 2016; Tsai et al., 2015), effective pressure is included only where the coulomb criterion is met, a few km upstream of the grounding line. This would give negligible influence of basal melt rate changes in the slow upstream regions in the simulations of Paper I and III.

In this thesis a subglacial hydrology model was one-way coupled to ice dynamics. This is the first time this is done in the Ice Sheet System Model. Paper I shows that a model with a temporally constant subglacial hydrology overestimates the dynamic response of the ice stream to a GHF anomaly, relative to a model where the subglacial hydrology interacts with geometry and thermal changes. However, in Paper II and III we model NEGIS with a constant effective pressure only, which may lead to an overestimation of the velocity response to the GHF, indicating that even higher GHF values are needed to initiate NEGIS. Findings from Paper I suggest that if we are to use ice flow models to constrain GHF maps (Greve, 2019), we need fully coupled ice flow and subglacial hydrology models. In Paper III we found that the downstream area of NEGIS is self-sustained with melting from frictional heat, given today's observed velocity. However, to determine if the downstream velocity pattern is triggered by the GHF anomaly, we need a model with thermomechanical ice flow fully coupled to subglacial hydrology, and initialize it without using present day velocity. Future studies should improve the coupling between hydrology and ice dynamics in regional ice sheet models. Here, the challenge will be the very different time steps and resolution between ice flow and hydrology models.

We successfully represent an improved NEGIS velocity pattern in an ice sheet model, without bundling the unknown parameters at the bed in a constant friction coefficient. To achieve this we used an effective pressure dependant friction law, allowing us to treat the impact of water and bed roughness on the sliding of the ice stream, separately. With this initialization we allow the ice dynamics to evolve with a change in water supply to the bed, which is of importance for simulations aiming to model the response of ice flow to a future warming scenario. The only water input to our hydrology model was basal melting. However, observations show that an increase in water input from surface melt influences ice dynamics (Bartholomew et al., 2010; Hoffman et al., 2011; Van De Wal et al., 2008; Zwally et al., 2002). Again, most observations of these connections are from land terminating ice, and further investigations are required to assess how fast flowing ice streams respond to an increase in surface melt and input of water at the base.

In Paper I and II we found that the efficient drainage system was more evolved and covering a larger area when the GHF was enhanced. An efficient drainage system may be more robust against climate warming, as the increased water supply to the bed is efficiently evacuated away. It would be interesting to investigate whether a system with high GHF is less responsive to a warmer climate and increase in water supply, than a system with lower GHF and less developed efficient drainage. Further, to investigate how ice streams responds to climate change, ice sheet models should include surface mass balance models with supraglacial and englacial hydrology models connected to subglacial hydrology, and in turn be fully coupled to ice dynamics. Additionally, this would allow us to estimate subglacial water discharge into the fjords, shown to have an important control on the submarine melting of calving fronts and floating ice tongues in Greenland (Xu et al., 2013).

The fifth assessment report of the Intergovernmental Panel on Climate Change (2013) recognizes the rapid dynamic behaviour of outlet glaciers as one of the largest sources of uncertainty in future mass loss projections for the Greenland Ice Sheet. In order to estimate Greenland's contribution to sea level rise, it is urgent to limit this uncertainty. This thesis investigates basal processes and their influence on ice dynamics. However, to predict the response of ice streams to climate, other key processes demand attention. In addition to subglacial hydrology, processes at the shear margins of ice streams, ice-atmosphere and ice-ocean interactions must be better represented in ice sheet models. To constrain the uncertainty and improve representation of these key processes, more observations are crucial. By incorporating all processes governing the flow of ice streams in models, the community can simulate how the Greenland Ice Sheet responds to a climatic warming, and ultimately provide better predictions of future sea level rise for the large population of people living in coastal areas.

# Chapter 6

# Scientific Results

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# Errata for
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**Silje Smith-Johnsen**

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UNIVERSITY OF BERGEN
Faculty of Mathematics and Natural Sciences

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