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Ice sheet hydrology from observations

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Preface

This report summarizes our understanding of ice sheet hydrology as reported on observations from Antarctica and Greenland. Much of our general understanding of ice sheet hydrological processes are based on work performed on valley glaciers. Since processes do not differ in function but perhaps in magnitude, the understanding gained from smaller glaciers work applies to ice sheets. Hence, this report does not deal with such basic processes. Glacier hydrological investigations on ice sheets have been few but are perhaps accelerating in numbers with the increased focus on both Greenland and Antarctica from the scientific community in the light of effects from climate change. The process oriented studies carried out over the past 50 years or so have not generally been much applied to ice sheets and observations on the morphology of ice sheet and valley glacier hydrological systems have not been connected although most glacier hydrologists would not consider such parallels a stretch of their imagination. Much of the new studies on ice sheet hydrology, thus far, fits in two categories. One concerns verification of well-documented processes but on an ice sheet scale; the other concerns ice sheet specific features. These categories constitute the basis for this report.

Contents

1. Introduction

Studies of ice sheet hydrology are relatively few and a small fraction of studies are older than the 1990s. Most of the early ice sheet research has focused on rapid moving ice streams and other processes; however, with the ongoing climate change (*e.g.* Lemke *et al.*, 2007) more interest is diverted to other parts of the ice sheets. The increased general interest in climate change research and the impact of changes to the Cryosphere has provided both technological advances and a financial basis for a strong focus on studies on ice sheets.

The hydrology of glaciers and ice sheets has important implications for assessing the stability of these ice masses. Much research concerning the coupling between glacier hydrology and glacier dynamics has hitherto focused on smaller glaciers, largely due to logistical and technical reasons; any field work on an ice sheet requires expedition scale logistics and drilling as well as measurement techniques capable of ice thicknesses almost one order of magnitude larger than for the vast majority of smaller glaciers. Hence our general knowledge of the hydrology beneath small glaciers is quite extensive (see the following reviews: Weertman, 1972; Lang, 1987; Röthlisberger and Lang, 1987; Hooke, 1989; Hubbard and Nienow, 1997; Fountain and Walder, 1998; Schneider, 2000; Boulton *et al.*, 2001; Jansson *et al.*, 2003; Hock and Jansson, 2005; Hock *et al.*, 2005). Ice sheets, however, are less well understood. The general glacier hydrological processes (summarized by *e.g.* Jansson *et al.*, 2006) are similar under both glaciers and ice sheets since the driving forces are the same, differing only in magnitude and spatial scale. Bell (2008) reviewed the role of water beneath the ice sheets on their stability and hence their mass balance since the ice sheet dynamics influences fluxes of ice into the oceans. Indications also emerge that temperate basal conditions favoring sliding in the presence of water may be important for the observed waxing and waning of past ice sheets (Bintanja and van de Wal, 2008). Bamber *et al.* (2007) has summarized the developments in our view of ice sheets going from slow behemoths responding on time perspectives of millennia or longer to dynamically active features, capable of reactions on the order of years to decades.

In this review I will summarizes the different types of occurrences of water beneath the current ice sheets and their sources. It is evident that our view of ice sheet basal hydrology is incomplete and that there is need to further improve our understanding of these systems and how they interact. Key factors to improving the situation involve better understanding of the geographical distribution of the cold-temperate boundary beneath the ice sheets as well as the distribution of the geothermal heat fluxes that influence this boundary and the volumes of water produced beneath the ice sheets. It is furthermore necessary to better understand the routing of water from surface to bed in melting zones on ice sheets. These data are not easily gathered and significant efforts must be made to establish better boundary conditions of the base of the ice sheets.

Before embarking on the quest to establish our current understanding of ice sheet hydrology, it is important to pin down the general conditions expected in and around the ice sheet domain that makes a hydrological system exist. Ice sheets do not necessarily have an extensive hydrological system. An ice sheet, furthermore, imposes some unique restrictions on glacier hydrology which is normally not met with valley glacier. The following is a qualitative view of the general conditions expected on ice sheets and follows Figure 1.1.

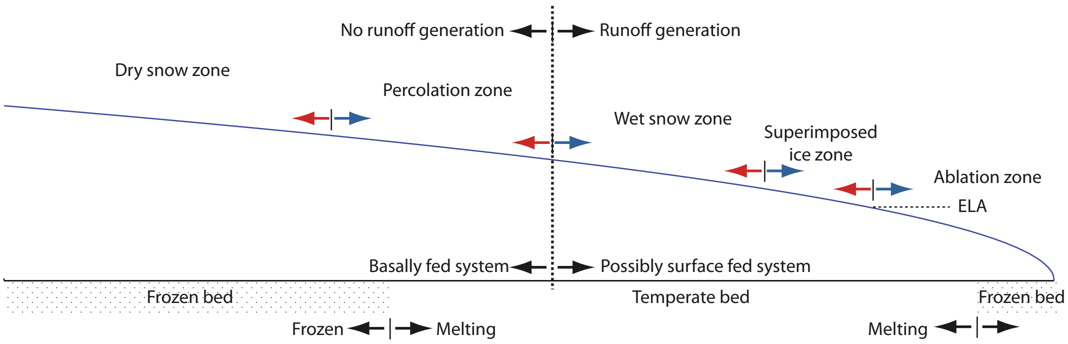

Figure 1.1. Schematic view of the components of the hydrological system of an ice sheet. Note that the ice sheet geometry and the relative extent of the different zones are not to any scale and only intended to show principles. See text for details.

First water must be generated; this can be achieved by either surface melting or rainfall occurring on the upper surface of the ice sheet or by melting basal ice from heat contributed by the local geothermal heat flux. It is possible some water may also be generated internally from heat generated by the deformation processes involved in ice flow, however, this volume is in general probably small (*e.g.* Näslund *et al.*, 2005) compared to other sources. Surface melting and rainfall can only contribute if the the surface temperature is conducive for the occurrence of liquid water. Thus low temperatures currently precludes the majority of the surface of the Antarctic Ice sheet from exhibiting a surface hydrological system; the same is also true for some, apparently dwindling (Steffen *et al.*, 2004), central parts of the Greenland Ice Sheet.

At the upper surface where melt and rain water gathers, ice sheets will exhibit a thermo-hydrological zonation as described by (Benson, 1961; Müller, 1962). The distribution of these zones determine the extent to which surface-fed hydrological processes can occur. At the highest elevations, cold conditions will prevail throughout the year (Dry snow zone; Figure 1.1). At lower elevations, melting will commence leading to a percolation zone. This zone is subjected to melting but not enough to produce runoff; water will refreeze within the snow pack. Once the snow pack becomes temperate, runoff can occur. This is by definition the wet snow zone. Below the wet-snow zone, we find a zone free from snow but still maintaining a positive net balance because of refreezing of water onto the ice surface, this is the superimposed ice zone. The lower boundary of the superimposed ice zone is the equilibrium line of the ice sheet and all zones hitherto described are part of the accumulation area. Below the superimposed ice zone, we find the ablation zone (or area) which will be covered by snow only on a seasonal basis. This zonation is typical for conditions on Greenland and was probably also typical for the former Fennoscandian and Laurentide ice sheet. Note that the boundaries between the zones vary within a year due to the annual cycle in surface energy balance and that the location may also vary from year to year depending on the specific meteorological conditions for that year. In a changing climate the inter-annual variations also exhibit a trend. In figure 1.1 Blue arrows indicate the direction under cooling conditions (cooling climate or fall conditions) and red arrows indicate warming conditions (warming climate or spring conditions). The zonation and its annual variability has in part been described by Steffen *et al.* (*e.g.* 2004). In Antarctica, ablation zones are practically absent and net accumulation occurs over the entire area (*e.g.* Vaughan *et al.*, 1999) due to the cold climate except for areas on the Antarctic Peninsula and locally on the ice sheet in the form of so-called blue ice areas (*e.g.* Bintanja, 1999) and what can be called "accublation" zones (Siegert and Fisher, 2002; Siegert *et al.*, 2003) where mostly sublimation causes the negative net balance of the area. The difference between Greenland and Antarctica with respect to their zonation, means surface input of water is basically absent in Antarctica but available over large areas on the Greenland ice sheet.

The basal conditions beneath an ice sheet is not different from that of valley glaciers. The basal boundary can be either cold (ice frozen to the bed) or temperate (ice free to slide over the bed). The thermal zonation is crucial for knowing where water will will flow at the base of the ice sheet since such flow is impossible where the ice is cold based. The thermal zonation is, at least primarily, not coupled to surface melting conditions. The zonation will change due to climate change since it depends on the convection (vertical ice flow) and diffusion of heat through the ice sheet. Since geothermal heat fluxes are constant (under stable crustal conditions), it is the upper thermal boundary conditions and the dynamics and its effects on flow and geometry of the ice sheet that can change the thermal structure of the ice sheet. Where the basal ice is at the melting point, basal melt is caused by geothermal heat fluxes and from flow-dependent factors such as strain heating and basal friction. Connections between the surface hydrological system and the basal system is only possible where there is surface melting. It is thus possible to have parts of the subglacial system at melting conditions without any input from the surface, whereas other parts will experience both surface and basal melting. Figure 1.1 indicates a simple zonation but in reality zones are complex and there are probably freezing patches within the melting zone due to for example subglacial topography.

The water generation available for feeding an en- and subglacial system is thus limited by several factors, coupled and uncoupled to each other. In the following I will start with the upper surface and follow the routing of water through the ice to the bed and the systems found there. Since the hydrology of ice sheets is difficult to study, I will start by looking at indirect evidence for ice sheet hydrological systems where the systems are not explicitly described but where the effects of water are evident.

2. Indirect observations of the ice sheet hydrological system

There are many studies that implicitly involve a subglacial drainage system and processes therein. Observations of large, and from a glaciological perspective, abrupt changes in ice dynamics without corresponding changes in for example driving stress imply changes in the basal boundary condition. Ongoing thinning of sectors of ice sheets (*e.g.* Wingham *et al.*, 2009) may occur from changes in mass balance or from changes in ice dynamics. In West Antarctica, Shepherd *et al.* (2001) observed a thinning rate of $1.6\ \mathrm{m\,a^{-1}}$. This change could not be explained by mass balance alone and hence a change in the dynamics of the outlet Pine Island Glacier must be invoked. Joughin *et al.* (1996) observed a three-fold increase in velocity over a 7-week period, of the Ryder Glacier, north Greenland, after which the velocities decreased to pre-speed-up values. Drainage of supraglacial lakes into the ice sheet could be responsible for this event. Zwally *et al.* (2002) used GPS measurements at the equilibrium line near Jakobshavn to show that the ice sheet undergoes large annual variations in surface speed. They attributed these variations to the seasonal variations in water influx to a basal water system through moulins and crevasses, since velocity variations were clearly correlated to seasonal melt rates variations. Price *et al.* (2008) used modeling to show that variations in ice velocity, such as observed by Zwally *et al.*, need not be forced locally but can also be the result from longitudinal coupling effects from movement further downstream. The location of Zwally *et al.*'s experiment was located in the vicinity of the Jakobshavns Isbræ which could at least partially explain observations. It is evident that dynamic changes occur on time scales that indicate basal hydrological forcing but also that longitudinal coupling effects are possible. The latter still requires some dynamic change to occur and is not by itself an argument against subglacial hydrology forced dynamic variations.

Satellite data has the advantage of providing spatially extensive flow patterns. Moon and Joughin (2007) used satellite interferometry to investigate the spatial variability in ice front position of 203 Greenland outlet glaciers. Their results indicate that the behavior is closely linked to climate variability, thus implying that dynamic responses are forced by climate and not sustainable unforced processes. Rignot *et al.* (2008) find a robust correlation between the surface mass balance and the ice discharge around the ice sheet perimeter from the period 1958 to 2007. Their balance calculations show that the ice sheet rapidly started losing mass from 1997 after having been in near balance for several decades. The variability in ice discharge explain $60 \pm 20\ \%$. van de Wal *et al.* (2008) have recorded large velocity variation along the K-transect (*e.g.* van de Wal *et al.*, 2005) in the Russell Glacier (a land-terminating outlet) drainage area of east Greenland. They show annual velocity variations varying by up to a factor of 4. The increase in velocity occurs within days of measured melt rate increase. Shepherd *et al.* (2009) used a combination of satellite imagery and continuous dGPS measurements to show how the Russell Glacier catchment of the West Greenland ice sheet undergoes velocity variations on a variety of scales. The satellite data reveal that the ice sheet accelerates on a seasonal basis corresponding to the availability of melt-water. This acceleration is strongest along what is probably a subglacial valley, a likely route for water. Through dGPS measurements they also show that the velocity varies on a diurnal basis, reflecting diurnal variations in melt-water input. There is also physical uplift of the ice during these events. Hence the Greenland ice sheet experiences seasonal dynamic variations in both land and sea-terminating parts.

Ice streams are sensitive flow features and many emanating from the current ice sheets terminate in the sea. Joughin *et al.* (2004) observed changes in the flow speed of the Jakobshavn Isbræ where velocity was seen to decrease in the period 1985–1992 and then accelerate between 1992–2000 with additional acceleration up to 2003. Their study clearly indicates that the ice stream response can be complex and include both periods of deceleration and acceleration. Holland *et al.* (2008) proposed a different cause for the speed-up of Jakobshavns Isbræ. A sudden increase in subsurface ocean temperature occurred in 1997 along the entire west coast of Greenland. Such warm water could have accelerated the basal melting of the ice stream at the grounding line and hence causing the ice stream to become unstable. Whereas this process will be able to affect outlets reaching the sea, it does not help to understand the general increase in velocity observed around the perimeter of the Greenland ice sheet (Rignot and Kanagaratnam, 2006; Joughin *et al.*, 2008a). Joughin *et al.* (2008a) showed that the land-terminating parts of the West Greenland ice sheet underwent seasonal velocity changes. Howat *et al.* (2007) showed that two of Greenland's major outlets, the Helheim and Kangerdlussuaq, underwent a rapid increase in flow in 2004 with a subsequent decrease in 2006 to near the pre-2004 levels. They argue that this response is due to re-equilibrium of the terminus after a calving event. There is thus need to carefully assess the possible dynamic framework of the investigated glaciers investigated to correctly identify potential forcing processes.

Acceleration of ice masses involve rapid changes in stresses which can result in strain-rates sufficient for fracturing the ice, even at depth. Hence seismic events can be indicative for changes in dynamics. Ekström *et al.* (2003), Ekström *et al.* (2006), and Tsai and Ekström (2007) analyzed recorded seismic events from beneath the Greenland ice sheet and concluded that they represent stick-slip events. Such events are indicative of sliding motion of a temperate base glacier. Their events seem to coincide with known outlet glaciers. Joughin *et al.* (2008b) also found that the seismic events coincide with calving events of the Helheim and Kangerdlussuaq tide-water outlet glaciers in Southeast Greenland. Tsai *et al.* (2008) explored the mechanisms for such earthquakes by modeling the processes in the calving outlets and suggest calving as the cause for the events. Stick slip motion has also been detected in the West Antarctic ice streams (Bindschadler *et al.*, 2003a,b; Wiens *et al.*, 2008). In the Antarctic case the stick slip motion is forced by tidal action on the marine based ice streams. Gudmundsson (2006) also observed tidally induced flow speed variations in Rutford ice stream, West Antarctica. Hence, marine-based outlet glaciers and ice streams may provide temporally variable fluxes induced by tidal forcing rather than from surface water influx. The seismic investigations yield good information on the timing and spatial distribution of changes in dynamics at the base of a glacier which can be used to understand the processes involved, the forcing of the processes and how perturbations propagate at the bed.

There is thus ample evidence that ice sheets change in dynamics on time periods from diurnal and up to perhaps millennia. The variations observed on diurnal to annual scales are in perfect harmony with theory and observations on valley glaciers where the coupling to variability in the hydraulic system is evident. Ice sheets seem to also have larger time-scale variability than typically observed on valley glaciers. Good examples are the on-off behavior of the Siple Coast ice streams (*e.g.* Catania, 2004; Catania *et al.*, 2006). This longer periodicity variability is due to processes that occur on scales that cannot be found on valley glaciers and thus cannot produce similar features on the smaller glaciers.

3. Surface melt

Water generated at the glacier surface, and thus available for input to the glacier hydrological system, comes from a combination of melting of ice and snow and from rain. Water input at the surface of an ice sheet can be modeled by applying surface energy models of different complexity.

Direct measurements of melt has occurred within the framework of local projects over time. van de Wal (1996) and Six *et al.* (2001) have summarized some of this data originating from transects. Their data shows a potential 4-year cycle in melt with no clear trend. The melt on ice sheets is of course forced by the surface energy balance. The Greenland ice sheet exhibits a zonation in albedo caused by dust particles (Bøggild, 1997; Bøggild *et al.*, 2010; Wientjes and Oerlemans, 2010) which shows that albedo variations can be larger than expected from normal albedo variation on clean ice.

The Gravity Recovery and Climate Experiment (GRACE) has provided means for establishing mass change signals for regions such as the Greenland ice sheet where mass change due to climate change occur. Chen *et al.* (2006), Luthcke *et al.* (2006), Ramillien *et al.* (2006), and Velicogna and Wahr (2006) used GRACE data to evaluate mass losses from the Greenland ice sheet. Their results provide a strong independent indication that mass losses from the southern part of Greenland ice sheet has increased substantially, thus verifying more local studies from Rignot *et al.* (1997), Howat *et al.* (2005), Rignot and Kanagaratnam (2006), and Luckman *et al.* (2006). Much of the mass losses observed are thus from dynamic response at outlet glaciers. It is unclear if this acceleration is due to increased surface melt or if there are other critical triggering factors. It seems unlikely, however, that simultaneous response over larger lengths of the Greenland ice sheet margin should be caused by local triggering factors. Wouters *et al.* (2008) expands on the previous GRACE investigator's results and provide a refined and extended data record showing continued mass loss from the ice sheet including large losses from the upper parts of the ice sheet, which was not observed in earlier studies. Clearly data such as that retrieved from the GRACE experiment can provide large scale estimates of volume change due to for example melt on a scale that is logistically difficult with a network of automatic weather stations. The methods is thus a very useful complement for verifying ground based measurements. as well as adding large scale spatial estimates.

Melt is largely coupled to temperature (Ohmura, 2001) and hence subject to variations due to for example global warming. Velicogna and Wahr (2006) and Hanna *et al.* (2008) found that the increase in melt on the ice sheet is coupled to northern hemisphere temperatures. Box *et al.* (2008) used a mesoscale model to calculate the mass balance of the Greenland ice sheet. They obtained results indicating that both the accumulation and ablation has increased in an offsetting matter. Melting conditions have, however, increased in duration by about 10 days and up to 40 days in places. Prior to 1990, Hanna *et al.*'s results indicate that the coupling between temperature and melt was less obvious. This indicates that the Greenland ice sheet in essence now is influenced by the northern hemisphere climate rather than perturbing the climate system by its presence, which seems to have been the case before 1990. Melting is also increasing. Chylek *et al.* (2006) have, however, observed that an earlier warming on Greenland (1920–1930) was at least similar to the modern warming (1995–2005) but with 50% higher warming rates. Strong warming is thus something that may be typical for the climate system in the vicinity of Greenland, perhaps due to weakening of the local climatic system of Greenland itself. Through measurements of passive microwave emissions, Abdalati and Steffen (2001); Steffen *et al.* (2004) show how the Greenland ice sheet experiences large spatially variable melt conditions (Figure 3.1). Bougamont *et al.* (2005) have reproduced Steffen *et al.*'s observations by applying a surface mass balance model to the Greenland ice sheet and forcing the model with ERA-40 re-analysis data (Uppala *et al.*, 2005). Their work indicates surface melt can readily be obtained from large scale re-analysis data given model tuning through surface meteorology data from the ice sheet. Lewis and Smith (2009) modelled the hydrological drainage network for Greenland using existing elevation models and a climatological forcing from Polar MM5 (Pennsylvania State University/National Center for Atmospheric Research, PSU/NCAR, mesoscale model) data and automatic weather stations (Box *et al.*, 2004). Their results indicate volumes ranging from very small up to 16 km^2 a^{-1} run off rom these basins. Bhattacharya *et al.* (2009) uses the melt-area time series covering the period 1979–2008 to show that the melt-area abruptly increased in 1995. This change can be successfully coupled to a sign-reversal in the North Atlantic Oscillation. The change is also manifested in higher measured temperatures around the ice sheet. There is thus confidence in that melt can be satisfactorily estimated from data collected from the ice sheet by both ground and space-borne measurements.

The warming climate will raise melt rates. Ridley *et al.* (2005) performed numerical modeling experiments with the Greenland ice sheet under warming scenarios. When subjecting the ice sheet to a $4\times CO_2$ scenario for 3000 years the ice sheet almost completely disappeared. One lesson from this experiment is that when more ground is exposed around the perimeter of the ice sheet, feedbacks from local summer circulation produced from warm ground around the ice sheet can augment the melting.

The surface mass balance is obviously variable and directly coupled to the forcing climate variability. The water produced by melting also seems to affect the dynamics, not only on diurnal and annual time scales but also affecting longer term trends in mass loss of peripheral parts, probably by influencing the dynamics of the ice sheet.

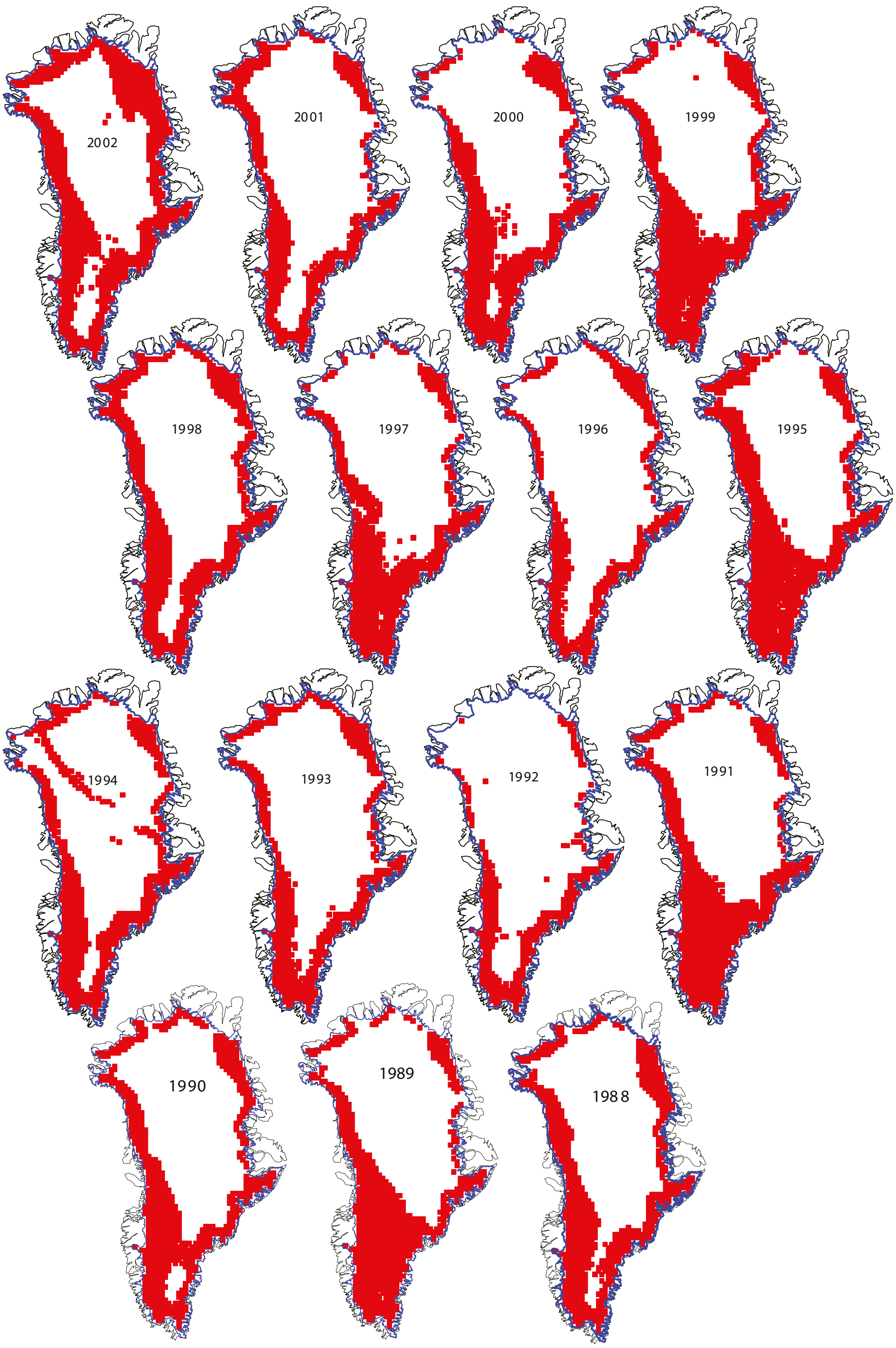

Figure 3.1. Greenland ice sheet melt extent based on passive microwave satellite data for the period 1988–2002 (Abdalati and Steffen, 2001; Steffen *et al.*, 2004). Red areas indicate the extent of melting surface conditions, white areas are (dry) snow surfaces without liquid water content. (figure from Konrad Steffen unpublished data)

4. Supraglacial lakes

Most of the water in a glacier hydrological system is generated at the glacier surface from melting and rainfall. In the case of ice sheets this is also true as long as the ice sheet has a melting zone. This is not generally the case for the Antarctic ice sheet but is the case for Greenland and was for the Fennoscandian and Laurentide ice sheets. Surface water runs off in surface streams that may become significant if their catchments are large enough. Mapping of surface catchments by Thomsen *et al.* (1986, 1989a,b, 1993) (Figure 4.1) indicate that a complex pattern of smaller isolated drainage basins exist. Their mapping also seems to indicate that drainage basins become larger away from the terminus, indicating a relationship between either the thickness or surface slope or both and size of drainage basins. Close to the terminus, ice surface topography of the ice sheet probably is heavily influenced by subglacial topography and hence also affecting the distribution of drainage pathways and drainage patterns. Echelmeyer *et al.* (1991) described lakes in the Jakobshavn Isbræ drainage area and how these are created by ice surface undulations caused by bed topography. The lakes occurred above $\sim$ 600 m a.s.l. and up into the lower accumulation zone at about $\sim$ 1500 m a.s.l.

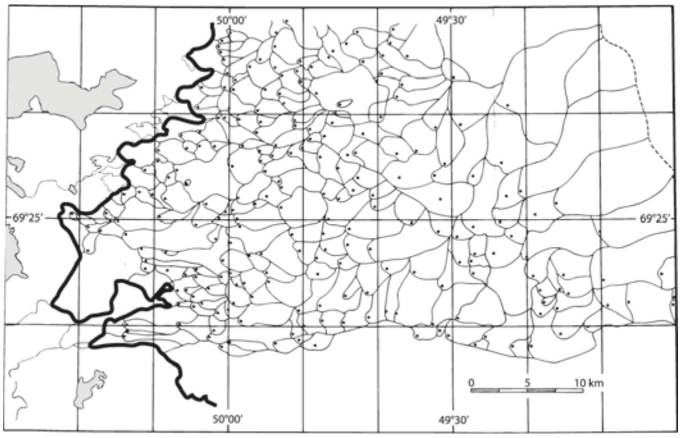

Figure 4.1. Delineation of surface catchments and their sinks (moulins) in the ablation zone of the Greenland ice sheet near Ilulissat, West-Greenland. (after Thomsen *et al.* (1989a))

Many supraglacial lakes (Figure 4.2) appear to be perennial with an annual cycle of growth and decay. Lüthje *et al.* (2006) used a one-dimensional energy balance model to investigate the seasonal evolution of supraglacial lakes on the Greenland ice sheet. Their results indicate enhanced ablation beneath the lakes compared to surrounding areas. Satellite imagery investigations further showed that lake extents were not variable between years. They could conclude that lakes were largely topographically controlled and hence not likely to substantially change in

Figure 4.2. Supraglacial lake (1.8 km^2 with 6.3 km circumference) in the ablation area on Russell glacier, West Greenland. Note the camp of tents near the lower center of the picture. Photo Malin Johansson, July 31, 2010

area over time. Furthermore, Lüthje *et al.* postulate that a warming climate should favor larger lakes to form on the shallower slopes higher up on the ice sheet. Sneed and Hamilton (2007) developed an algorithm for estimating the volume (depth) of supraglacial lakes based on multispectral satellite imagery. By applying the method to a set of images they could obtain volumes for different seasons and times of a single season. Results show volumes changing between 4.35×10^6 m^3 to 2.66×10^7 m^3, area varying between 10.1 km^2 to 48.7 km^2 in their test area (265 km^2). McMillan *et al.* (2007) investigated the seasonal development of supraglacial lakes on the western margin of the Greenland Ice Sheet.The lakes occupied a total area of 75 ± 5 km^2 in early July, 2001, but lost 36 ± 3.5 km^2 over the following 25 days. This indicates that the lakes, although semi-permanent features go through drainage events on a wide scale. Sundal *et al.* (2009) and Johansson *et al.* (2010) improved on McMillan *et al.*'s study by evaluating imagery over larger areas of the eastern Greenland margin. Their results yield the same general result but improve on the total number of lakes. The cause for the variation in size over a season is probably drainage of lakes which either reduce their size or completely empty the lake basins.

The supraglacial lakes constitute striking features on the Greenland Ice Sheet. It is important to remember, however, that lakes are transient reservoirs with both in and outflow of water. If a lake drains it adds the volume of water to an existing throughput of water. The importance of lakes on the general hydrological system of the ice sheet is thus debatable other than for localized effects around drainage points.

5. Transfer of water from the ice sheet surface to the bed

The issue of how water can create pathways from the surface of a glacier or an ice sheet was first investigated by Weertman (1973), who used mechanical principles to show that a water filled crevasse should propagate through a glacier. This theory has never been verified by observations but has been propagated through many textbooks and scientific papers. van der Veen (1998b,a, 2007) developed a fracture mechanics model to show that crack propagation can occur independently of fracture toughness and far-field tensile stresses as long as the crevasse is subjected to inflow of water. Alley *et al.* (2005) developed existing theory for magma intrusions bedrock to existing stress and temperature conditions for the ice water combination found in glaciers and ice sheets. The processes described by Alley *et al.* has yet not been verified but indications from other studies seem to indicate that a mechanism for propagating water from the surface through cold ice to the bed operates. The crucial point for both Weertman's and Alley *et al.*'s work is the continuous recharge of water to the crevasse to keep it over-pressurized. Over pressure exist as long as the crevasse is filled to more than 90% of its depth due to the density difference between glacier ice (~ 900 kg m^{-3}) and water. Having crevasses form across supra-glacial streams or in surface melt ponds is thus an excellent environment for the process to be active. In the ablation area of glaciers, water is generally abound and it is not hard to meet these criteria anywhere. Fountain *et al.* (2005a,b) also observed englacial water-filled crevasses at varying depths in Storglaciären, where they appear to be an intrinsic part of the drainage system. This study changed the notion that englaclal crevasses could not exist under typical conditions found in glaciers. Unfortunately, no theory exists for the englacial formation of crevasses. Harper *et al.* (2010) showed the existence of basal crevasses that can both link the englacial drainage to the basal system but also act as storage basal of water.

Boon and Sharp (2003) observed ponding and drainage events on a polythermal glacier which suggested a crevasse propagation mechanism responsible for establishing a connection through the cold ice. In addition, observations of surface lake drainage events on Greenland revitalized the theories by Weertman (1973); Alley *et al.* (2005) and van der Veen (2007). Das *et al.* (2008) observed the complete drainage of a 5.6 km^2 (0.44 ± 0.01 km^3) supra-glacial lake in $\sim$1.4 hours into an opening crevasse on the Greenland ice sheet. They also observed significant change in the velocity of the ice sheet as well as local uplift during the event. From this Das *et al.* infer that water reached the bed through 980 m of ice and resulting in pressures enough to cause the uplift. Although the actual drainage pathways were not investigated or mapped, water seems at least to have gained access to the bed near the input point. This work shows compelling indications that the process described by Weertman (1973) and Alley *et al.* (2005) is realistic. Krawczynski *et al.* (2009) used a model to calculate the volume of water required to propagate crevasses through the Greenland ice sheet. They found that small lakes of 250–800 m in diameter are sufficient to drive crevasses through 1–1.5 km of ice. Hence the conditions for propagating crevasses through the ice are commonly met.

Catania *et al.* (2008) used common offset radar images to detect drainage pathways between the surface and the bed of the Greenland ice sheet in the vicinity of Jakobshavn. They find that detected connections are more abundant in the ablation zone than near or above the equilibrium line. Furthermore, the drainage features coincide with inferred regions of longitudinal extension, indicating that crevasse formation may play a decisive role for the location of moulins also on the ice sheet. In a subsequent, ground penetrating radar-based study Catania and Neumann (2010) identified that the drainage connections between surface and bed seemed to be associated with areas of significant basal melting. Their conclusion was thus that the drainage features were persistent. This also implies that the drainage system to some extent is persistent in space.

The transfer of water from the surface of an ice sheet such as Greenland, through its cold interior mass of ice, is thus possible. The mechanisms outlined by Weertman (1973); Alley *et al.* (2005) and van der Veen (2007) allows for propagation of water filled surface crevasses to the bed as long as the steady sufficient supply of water is maintained. Since melt water occurs in abundance in the ablation area and wet snow zone during the melt season, conditions are favorable over large areas of the Greenland Ice Sheet marginal zone. The connections obtained through the crevasse propagation mechanism will probably be more or less vertical. It is unclear if they remain so over time.

6. Water generation inside the ice

Englacial melting comes from two sources originating from two different mechanisms. First, melt occurs when water flows through englacial conduits due to the viscous dissipation of heat from friction in the turbulent water and, second, melt can generated by the deformational processes in the ice.

Melt from viscous dissipation of heat occurs where water is flowing in passageways through the ice. This is a very localized form of melt. Röthlisberger (1972) and Hooke (1984) provided theory for the processes involved in maintaining open conduits in ice. The melt rates originating from the water flow is largely a function of the velocity of the water flow. There is also a change in temperature due to the change in potential energy as water is flowing downwards but this change is small under normal turbulent flowing conditions. The melt can thus be substantial but is highly localized. When taking into account the density of input points on the margin of the Greenland ice ce sheet (as exemplified by Thomsen *et al.*'s 1989a study) we can estimate the area over which ablation occurs. If we estimate that an englacial conduit is 5 m in diameter (based on visual observations of surface river size and discharge) and that the ice on average is 1000 m thick in the ablation area, we obtain a surface area of $\sim 15000\ \mathrm{m}^2$. With a density of about 40 conduits in a 10×10 km area (center area of the map in Figure 4.1), and an annual (seasonal) melt rate of, say, $2\ \mathrm{m\,a}^{-1}$, the water produced corresponds to 0.001 m w.e. over the ice sheet surface area. This, admittedly, ball-park estimate is about four orders of magnitude lower than the contribution of water from surface melt and hence a negligible contributor to water flow.

Melt from englacial deformation is produced by heat generated from the deformational processes as ice flows. This contributions depend on strain rates and larger contributions therefore occur near the bed and where the ice moves faster. In the case of fast flowing ice streams, where much movement is by sliding, large strain rates are primarily found in the marginal shear zones of the streams. It is important to realize that englacial melting can only occur once the ice is at the pressure melting point, in temperate ice. Thus, for a cold ice mass with basal melting, the strain heating will only contribute to heating the cold ice. Heating the lowermost section of the ice column, in turn, causes lower temperature gradients in the basal ice. This will affect the basal melt since the lower temperature gradient conducts less heat away from the base and more heat can then be used for basal melting.

To understand the underlying physics of the strain heating, we can consider *simple shear*. The rate of energy dissipated by internal deformation can then be described by

$$\frac{dE}{dt} = \tau_{xz}\dot{\varepsilon}_{xz} \tag{6.1}$$

where τ_{xz} is the basal shear stress (parallel to the bed) and $\dot{\varepsilon}_{xz}$ is the the strain rate parallel to the bed, defined by $\dot{\varepsilon}_{xz} = (\tau_{xz}/B)^n$, where B and n are the constants of Glen's flow law for ice (Glen, 1955). Equation 6.1 can be rewritten as

$$\frac{dE}{dt} = \frac{(\rho g h \sin\alpha)^{n+1}}{B^n} e^{k\theta} \tag{6.2}$$

by using $\tau_{xz} = \rho_I g h \sin\alpha$ and the approximation that the temperature dependence of B can be accommodated by an exponential effect ($e^{k\theta}$ Hooke, 2005). Because of the strong deformation rates, most of the contributed heat is produced near the bed. Budd (1969, table 4.2b, p. 69) shows that only 3% of the heat from internal deformation is produced in the upper half of the ice column. The lower 1/5 contributes 67% and the bottom 10% of the ice contributes over 40% of the heat. Hence much heat is generated near the basal boundary where melting is most likely to occur.

In the case of the Greenland Ice Sheet, the thermal structure is such that the ice column is cold but may reach melting temperatures at the bed where conditions are favorable. We thus do not expect internal melting from deformational heat in the Greenland ice sheet. Deformational heat will, however, affect the temperature gradient near the base and affect the amount of basal melting possible beneath the ice sheet

7. Water generation at the bed

Meltwater generation at the bed is only possible where the basal ice is at the pressure melting point. Since any melting requires a phase change, energy must be supplied to facilitate this change. Possible contributing heat sources are heat from internal deformation of the ice conducted towards the bed, frictional heating from ice sliding over a hard bed or sediments, frictional heating in subglacial deforming sediments, and geothermal heat from radioactive decay in the earth's crust and deeper interior (*e.g.* Näslund *et al.*, 2005). Any heat transfer by conduction in the ice must follow a temperature gradient. The basal ice must therefore reach the pressure melting point at the bed since conduction of heat towards the bed under temperate conditions will not occur due to the negative temperature gradient resulting from the negative slope of the solidus of the ice-water vapor phase -0.09 K Pa^{-1}.

All geothermal heat can be conducted up through the ice if the base of the glacier is either entirely cold (frozen to its bed) or just reaching the melting point at the bed. The basal temperature of a glacier is determined by the general heat equation (considering incompressible ice)

$$\kappa\left(\frac{\partial^2\theta}{\partial x^2}+\frac{\partial^2\theta}{\partial y^2}+\frac{\partial^2\theta}{\partial z^2}\right)-u\frac{\partial\theta}{\partial x}+v\frac{\partial\theta}{\partial y}+w\frac{\partial\theta}{\partial z}+\frac{Q}{\rho C}=0 \tag{7.1}$$

where θ is the temperature, κ is the thermal diffusivity, ρ_I is the density of ice, C is the heat capacity of ice, Q is the change in heat from *e.g.* internal deformation, u, v, and w are the velocity components in the x, y, and z-directions, respectively. Diffusion and convection largely determines the temperature distribution in the ice, however, internal deformation as well as frictional heating at the ice-bed interface contributes as heat sources. The basally produced heat can be considered an addition to the geothermal heat flux. In a glacier with some finite thickness of temperate ice at the bed, heat cannot be conducted away from the bed upwards in the ice column due to the negative slope of the solidus in the Pressure-temperature phase space of water. Energy thus contributed to the bed from friction or geothermal sources can only be used for melting.

The geothermal heat flow has two main components, one originating from the mantle (reduced- or Moho heat flow) and one constituting radiogenic heat produced within the upper part of the Earth's crust (*e.g.* Furlong and Chapman, 1987). Over typical continental cratons, such as the West European craton hosting Fennoscandia, the Moho heat flow show smooth large-scale spatial trends. The Moho heat flow is lowest in the central part of the Baltic Shield (Čermak, 1989). The crustal part of the geothermal heat flow displays much larger spatial variations, down to a regional scale (Näslund *et al.*, 2005). In the upper part of the crust energy produced by the natural radioactive decay of primarily ^{40}K, ^{238}U, and ^{232}Th is absorbed by the bedrock and stored as heat. There is a close correlation between the distribution of heat produced in the crust and regional geological units, with higher heat flow observed in granitic rocks. As example, over Sweden and Finland the total geothermal heat flow observed at the crustal surface varies with a factor of more than 2 on a regional scale Näslund *et al.* (2005). The geothermal heat flow has a strong control on basal temperatures of ice sheets (*e.g.* Waddington, 1987). Typically, for a 3 km thick ice sheet at steady-state, a 20% error in geothermal heat flux generates a 6 K error in basal temperature. This has direct implications on for example numerical ice sheet modeling, if the geothermal heat flow is not realistic in the model setup, ice sheet models will not produce useful patterns on basal melting.

The basal melting beneath an ice sheet can not easily be estimated from the geothermal heat flux, although, in a relative sense, melting will be a function of the flux. Since the basal conditions are determined by all components of Equation 7.1, knowledge of the geothermal heat flux will not suffice, typically numerical modeling of the Equation with known and estimated boundary conditions are required.

Qualitatively, the energy available for melting is determined by the flux of heat conducted away from the base through the overlying ice. At the boundary this reduces to the difference between the geothermal heat flux and the conduction of heat through the ice near the boundary. The melt rate is thus determined by

$$\dot{m} = \frac{\tau_b u_b + G - K\beta_0}{K\rho_I} \tag{7.2}$$

(*e.g.* Tulaczyk *et al.*, 2000; Hooke, 2005), where β_G is the geothermal heat flux, $K\beta_0$ is the heat conducted away from the bed interface upwards in the ice (K is the thermal conductivity of ice and β_0 is the local thermal condition in the ice), $\tau_b u_b$ is the frictional heat production, τ_b is the basal shear stress and u_b is the basal sliding speed, L is the latent heat of fusion, and ρ_I is the density of ice.

The geothermal heat flux varies spatially as discussed above. For the Fennoscandian ice sheet the average value from Näslund *et al.* (2005) of 49 mW m^{-2}, can be considered typical. To provide an order of magnitude estimate of basal melting, we can consider data calculated by (Hooke, 1977) from which we can extract a temperature gradient of 0.015 °C m^{-1}. If we disregard frictional heating from the bed a typical melt rate would be on the order of millimeters to a centimeter per year. Fahnestock *et al.* (2001) show estimated annual melt rates beneath Greenland to on the order of cms, although much higher values reaching 0.15 m are inferred in areas of rapid ice motion, indicating the typical feedback between basal water and glacier sliding. Through a combination of measurements and analytic modelling, Beem *et al.* (2010) provides estimates of basal melting from beneath an active Antarctic ice stream (0.02–0.05 m a^{-1}) and its upstream slow flowing source areas (0.003–0.007 m a^{-1}). Modelling results also yield values from a several millimeter per year to a few centimeter per year (J. Johnson, personal communication, Nov. 10, 2006). Hence, values on the order of cm a^{-1} can be expected and used to estimate the volumes of water produced beneath an ice sheet if the area of melt is considered known.

To roughly estimate the maximum contribution of discharge from basal melt, we can perform a rough calculation using the following assumptions.

1. We consider a straight flow line from an ice divide to the terminus of an ice sheet. We arbitrarily choose a length of several hundred kilometers for typical

ice sheet scale: 300 km (this number should hence be taken for its magnitude, not absolute value).

2. The width of the drainage area would be triangular with an apex at the divide and widening towards the margin, as envisioned by Shoemaker (*e.g.* 1986). We consider the esker spacing a measure of drainage area width at the margin which yields a rough width of 30 km (Geological Survey of Finland, 1984).

3. The entire triangular drainage area experiences a uniform 0.01 m a^{-1} basal melt rate.

Performing the simple calculation yields a discharge of 14 $m^3\ s^{-1}$ or $1.2 \times 10^6\ m^3\ d^{-1}$. This corresponds to normal discharge in a medium size natural stream. The importance of this water, however, is that it is highly pressurized through most of its transport in the basal meltwater film and that it is a constant flow throughout the year.

That basal melting from geothermal heat is important for understanding the stability of ice sheets is gaining more support. (Näslund *et al.*, 2005) provide a first detailed geothermal heat flux distribution of the Fennoscandian ice sheet and show that significant differences occur in response to local variations. The ice sheet average melting and discharge, however, is not severely affected. It should be remembered that the paleo-ice-sheet geothermal heat distributions are more easily obtainable than those for Antarctica and Greenland (Fox Maule *et al.*, 2005). Hence studies introducing large scale variable geothermal heat flux boundaries are emerging (*e.g.* Fahnestock *et al.*, 2001; Pollard *et al.*, 2005; Näslund *et al.*, 2005, in prep).

Observations of basal melt regime beneath ice sheets are also emerging. Dahl-Jensen *et al.* (2003) used NorthGRIP data and an ice flow model to calculate geothermal heat flow along a flow line obtaining variations between 50 and 200 mW m^{-2}. This yields basal melt rates of between 7.5 mm a^{-1} at the drill site and 11 mm a^{-1} further upstream from NorthGRIP. Fahnestock *et al.* (2001) used age-depth relationships from internal layering obtained from airborne radar surveys to calculate basal melt rates in northern Greenland. In one region, melt rates reach and exceed 100 mm a^{-1}, indicating geothermal heat fluxes of up to 970 mW m^{-2}. Such high geothermal heat fluxes indicate the presence of a geological setting not found in the marginal areas of the Greenland ice mass. Oswald and Gogineni (2008) used radar echo intensity to map occurrence of subglacial water beneath the northern part of the Greenland ice sheet. They conclude that significant portions of the bed may be melting. Basal conditions at ice core drilling sites verify their results (*e.g.* Fahnestock *et al.*, 2001; Dahl-Jensen *et al.*, 2003). Oswald and Gogineni's data show that approximately 17% of the total flight line lengths indicated melting conditions. Unfortunately, this does not easily translate into a fraction of the basal area so more investigations are needed. A modelling studies by for example Huybrechts (1995) and Marshall (2005) yielded negative temperatures beneath most of the ice sheet, thus either contradicting the observational data or unable to provide enough spatial resolution to capture smaller scale deviations. By including the inferred basal temperatures from the deep drilling sites into a numerical ice sheet model, Greve (2005) obtained a very different scenario where large parts of the Greenland ice sheet bed was at the pressure melting point. Siegert *et al.* (2005a) have yielded similarly high values for Antarctica. van der Veen *et al.* (2007) also showed how subglacial topography affects geothermal heat fluxes, introducing additional complexity in the basal boundary condition. Their results indicate strong feedbacks between topography and heat fluxes. The reason for this effect is that the isotherms will be more closely stacked beneath deeper troughs than beneath the neighbouring highs causing higher geothermal gradients. This allows more heat to reach the bed in the troughs and hence also allow the ice to reach the melting point. They calculate a 100% increase in heat flux beneath deep troughs such as the Jakobshavns Isbræ. Clearly we do not have good grasp of the geothermal heat fluxes beneath ice sheets and the resulting basal temperature.

Basalt melt contributes significant volumes of water to the basal drainage system. In areas of surface influx of water to the bed during summer, the basally generated volumes are over-printed by the surface influxes. During winter, the entire basal drainage system experiences the basal melt derived fluxes. Basal melt is thus important in that it maintains subglacial flow throughout the season and in all areas where the ice sheet base is at the pressure melting point.

8. Subglacial lakes

Subglacial lakes beneath ice sheets have been known to exist since the discovery of Lake Vostok, east Antarctica, in 1996 (Kapitsa *et al.*, 1996). Numerous large lakes have since been identified to exist beneath the Antarctic ice sheet (Siegert *et al.*, 1996; Siegert, 2005; Siegert *et al.*, 2005a; Smith *et al.*, 2009) by for example satellite based remote sensing methods (Figure 8.1). The lakes leave a footprint in the surface topography of the ice sheet. Because the ice sheet is locally floating in the water of the lakes, the basal shear stress is locally zero which produce a near horizontal ice surface over the lake. It is reasonable to assume that lakes are identifiable by this method as long as they have larger width and length than the local ice thickness since the effect would otherwise be taken up by the ice mass

Lake Vostok is the largest lake found beneath the Antarctic ice sheet and measures 280 km in length and 50–60 km in width and with a maximum depth of in excess of 1000 m, Comparable to Lake Ontario in North America. The subglacial lake alters the basal ice composition through melting-refreezing and other processes (Petit *et al.*, 1998; Duval *et al.*, 1998; Jouzel *et al.*, 1999; Siegert *et al.*, 2000, 2001). Carcione and Gei (2003) showed that the overlying lake ice contains several seismically identifiable layers and that the lake also contains a significant sediment layer on the bottom. Ice flow in the region is very slow. Wendt *et al.* (2005) reports ice flow velocities for the Vostok station of 2.00 m $a^{-1}\pm 0.01$ m a^{-1}. Vertical changes in elevation have been attributed to tidal effects (amounting to a few mm) and atmospheric pressure forcing (of about 40 mm; Wendt *et al.*, 2005). In the case of Lake Vostok hydrothermal activity does not seem to be present for maintaining the water body (Jean-Baptiste *et al.*, 2001). Siegert and Glasser (1997) have shown that it is possible that either strain heating or geothermal heat or both produce excess heat that can melt and maintain water bodies at the base of the ice sheet. Dowdeswell and Siegert (2002) provide a physiographic perspective on the subglacial lakes beneath Antarctica. Their results indicate that the volume of the Antarctic subglacial lakes is (at least) 4000 to 12000 km^3 and that their distribution largely follows the modeled distribution of pressure melting bed conditions (Huybrechts, 1992). Tabacco *et al.* (2006) mapped 14 new lakes in the Vostok-Dome C area of east Antarctica and were able to classify them in three categories, relief lakes (deep, 100 m), basin lakes (large extent), and trench lakes (caused by local faulting), depending on their tectonic setting.

If the subglacial lakes are in thermal equilibrium, water is generated through melting and lost through freezing at equal rates, thus maintaining a constant water volume. If the lake water is generated by for example high anomalies in geothermal heat fluxes and strain heating it is likely that a positive water balance results. Souchez *et al.* (2003) argue that although Lake Vostok water has low salinity, it is enough for thermohaline circulation to occur. Such circulation could then be responsible for creating a melting-refreezing system between melting at the northern shore and frazil ice formation at the southern. Royston-Bishop *et al.* (2005) showed through analysis of particle sizes frozen into the accreted ice that some circulation of water must occur in the lake and that there may have been variable flow velocities in the water body through time. Through analysis of isotope rations, Ekaykin *et al.* (2010) concluded that there should not be significant mixing between glacial meltwater, the main water body of the lake. They found that there likely is a hydrothermal source which mixes with the glacially derived water. Thoma *et al.* (2008) modeled the energy balance of Lake Vostok. The results show that a lake such as Vostok is relatively insensitive to variations in geothermal heat flux, heat flux into the ice sheet, salinity of the lake and small changes in overburden pressure. The processes present in Lake Vostok are hence not clear.

Subglacial lakes have the possibility to grow until thresholds are reached where they can drain. Such inferences have been made from observation of changes in the East Antarctic Ice sheet surface topography (Wingham *et al.*, 2006) and expanded upon by Smith *et al.* (2009). Such re-organization of subglacial water will likely reach the marginal areas through outburst-like phenomena. It is not certain that outbursts will be similar to the spectacular Jökulhlaups from Icelandic ice caps where subglacial lakes formed by extremely high geothermal heat fluxes from volcanoes generate large quantities of water that catastrophically drains through the overlying ice caps (Björnsson, 1998). The effect of large bodies of water at the base of ice sheets can be sudden outburst floods which yield transient extreme pressure and discharge peaks. Smith *et al.* (2009), however, also noted that numerous lakes appear to exchange water with their surroundings in a diffuse way, possibly with systems lubricating ice flow.

The studies of Lake Vostok, and other lakes of similar type, formed a view that subglacial lakes are semi-stable features (*e.g.* Kapitsa *et al.*, 1996; Siegert *et al.*, 2001; Bell *et al.*, 2002, 2006), however, this view has been modified by the realization that some lakes are very dynamic features. By comparing the known location of subglacial lakes with the velocity distribution (Joughin *et al.*, 1999; Bamber *et al.*, 2000) on the Antarctic ice sheet, Siegert and Bamber (2000) were able to show that subglacial lakes seem to be associated with rapid flow features in the ice sheet. Bell *et al.* (2007) identified a region containing four subglacial lakes directly associated with the onset of the Recovery Ice Stream in east Antarctica. Bell *et al.* conclude that the lakes both initiate and maintain the flow of the ice stream.

The role of lakes in ice sheet hydrology remains to be evaluated. The lakes systems described above are fed by basal melting and seem to be semi-stable features in the subglacial system. They provide a large volume source of water for recharging underlying aquifers and are maintained under large ice overburdens resulting in similarly high pressure conditions in the water.

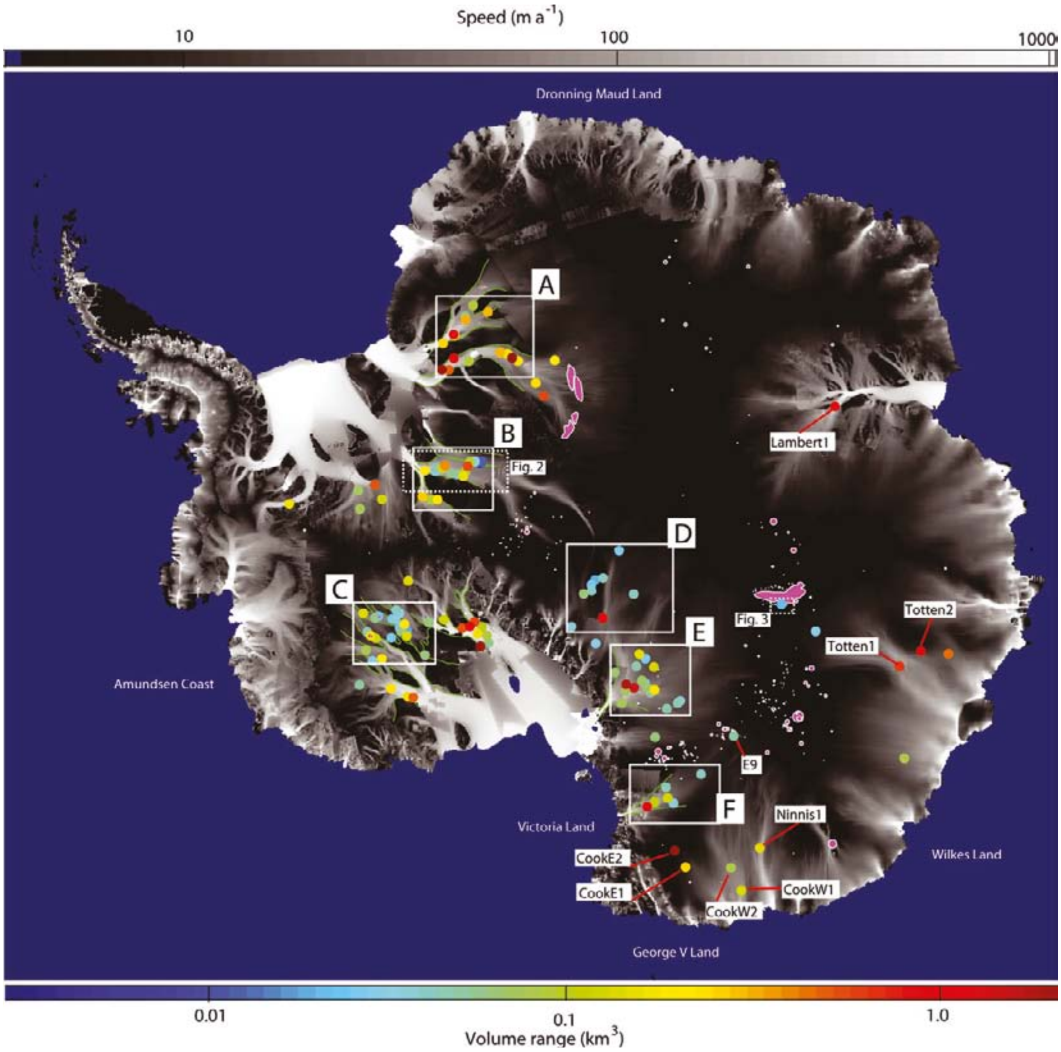

Figure 8.1. Locations of known subglacial lakes beneath the Antarctic ice sheet (from Smith *et al.* (2009)). Magenta areas with white outlines show lakes from studies by Studinger *et al.* (2003), Gray *et al.* (2005), Siegert *et al.* (2005b), Wingham *et al.* (2006), Bell *et al.* (2007), Carter *et al.* (2007) and Popov and Masolov (2007), color circles show lakes found by Smith *et al.* (2009) color coded by their volume. Green lines outline streaming ice for selected areas. The background shading shows the calculated balance velocity distribution (Bamber *et al.*, 2009) combined with satellite derived surface velocities (Joughin *et al.*, 1999, 2006).

9. Ice streams

Ice streams constitute spectacular features of ice sheets draining large volumes of ice from the interior areas of the ice sheets. There is, however, certain debate around the role of ice streams in ice sheets. Fowler and Johnson (1995, 1996); Sayag and Tziperman (2008) and Sayag and Tziperman (2009), for example, argue that ice streams are natural features caused by instability within the ice sheets. These studies are typically based on either mathematical models or numerical ice sheet model experiments. A pivotal point is also the sensitivity of the basal boundary condition to a change in dynamics. Because of the effects of internal heat generation on the basal temperature, ice streaming is associated with feedback mechanisms that directly influence the formation or cessation of basal melting and also sliding conditions.

The typical example of an ice stream, often referred to, are the Siple Coast ice streams (Figure 9.1 which are not obviously determined by large subglacial topography; in many if not most cases, ice streams are bounded by subglacial topography. In the earlier studies of Siple Coast ice streams (Blankenship and Bentley, 1986; Blankenship *et al.*, 1986, 1987, 1989; Alley *et al.*, 1987; Rooney *et al.*, 1987a,b, 1988) it was shown that ice streams were underlain by deforming sediments. Borehole experiments further proved the existence of deforming sediments beneath the ice stream (Kamb, 1991). Anandakrishnan *et al.* (1998) used seismic investigations to show that the faster flowing ice is underlain by thick sediment fills, whereas the surrounding areas are devoid of subglacial sediments. Bell *et al.* (1998) and Behrendt *et al.* (2004) concluded based on aero-geophysical investigations that the subglacial troughs in which the ice stream flow are caused by preferential erosion of less resistant volcanoclastics. Rippin *et al.* (2003) showed that the Bailey/Slessor ice stream in East Antarctica is determined by subglacial troughs. Bamber *et al.* (2006) conclude that subglacial sediments also underlay the east Antarctic ice streams. Hence indications are that the conditions found beneath the West Antarctic ice streams are not unique to that part of Antarctica but can be expected also in other parts.

In addition to the studies cited above that point at the basal sediment and topography, other studies indicate that these ice streams are located in tectonically active areas. Blankenship *et al.* (1993) used airborne measurements to show that the onset area of the Siple Coast ice streams may be concentrated to a subglacial volcano. Obviously this would be a large source for geothermal heat, possibly also waxing and waning in conjunction with eruptions and intervening dormant periods. For some reason, this paper has been largely neglected in discussions regarding the Siple Coast ice streams. Dalziel and Lawyer (2002) provides an overview of the lithospheric setting of the West Antarctic Ice Sheet from which it is easy to see that the area has undergone significant tectonic activity in the geological past. Behrendt *et al.* (1998) performed aeromagnetic surveys over parts of the ice divide of the

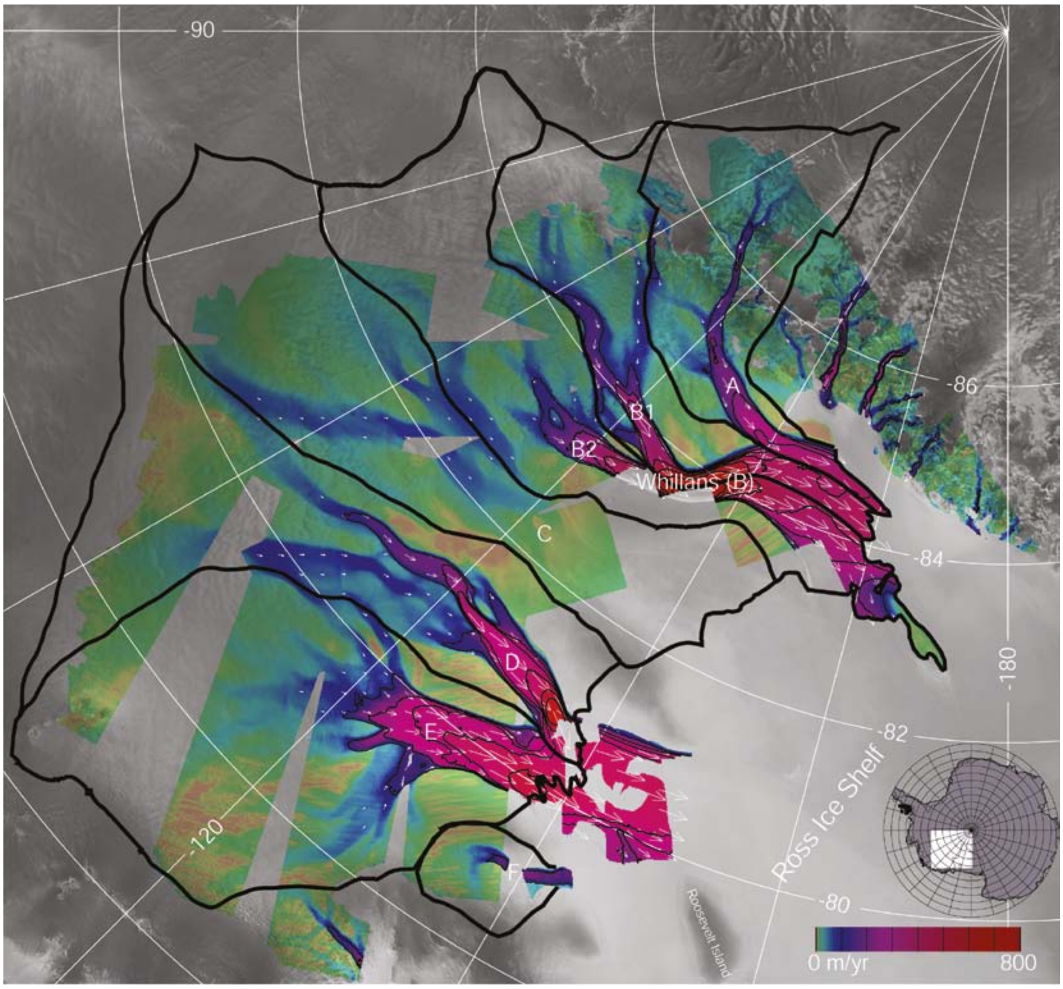

Figure 9.1. The Siple Coast ice streams A through E, West Antarctica (also know by alternative names: A – Mercer; B – Whillans; C – Kamb; D – Bindschadler; E – MacAyeal). The figure shows the streams outlined by the velocity patters and their respective catchments. Note Ice Stream C which is largely in a dormant state. Image from Joughin and Tulaczyk (2002) in public domain by NASA.

West Antarctic ice sheet and found anomalies that could be explained by a large caldera complex. Their study strengthens the findings of Blankenship *et al.* (1993) of high geothermal activity and possibly volcanism beneath the West Antarctic ice sheet. Jones *et al.* (2002) showed that the Evans Ice Stream is located in a zone of rift basins. This involves significant crustal thinning and hence also increased geothermal heat fluxes. This has also been verified by observing satellite magnetic data over Antarctica. Fox Maule *et al.* (2005) used such data to calculate the geothermal heat fluxes beneath Antarctica. Their hot spots coincide with localities indicated by and Blankenship *et al.* (1993); Behrendt *et al.* (1998) and Jones *et al.* (2002) and hence it seems likely that some ice streams are forced by anomalous geothermal heat fluxes. High geothermal heat fluxes have also been inferred to cause faster flowing ice in central Greenland (Fahnestock *et al.*, 2001). In this case age depth relationships determined from internal layering of the ice sheet has been used to infer rates of basal melting, 15–30 times inferred background. They also found a relationship between airborne gravity measurements and basal melt rate which they infer to mean that the abnormal heat fluxes may have volcanic origin. Evidence from non-glaciated areas (Näslund *et al.*, 2005) also indicate that geothermal heat flux vary substantially over shorter distances even in crystalline shield bedrock. Corr and Vaughan (2008) found indirect evidence of volcanic activity influencing the ice flow and stability of the Pine Island area of West Antarctica. Their dating of internal layering of the ice puts the eruption to 207 BC±240 years. This shows that volcanic activity has occurred relatively recently.

These studies indicate that ice streams do not spontaneously form but seem to have clear cause and effect relationship with either topography or geothermal heat fluxes. Now, clearly *absence of evidence is not evidence of absence* so awaiting hard evidence for spontaneous initiation of ice streams, such processes must be considered possible although mechanisms remain purely theoretical.

10. The dynamic subglacial drainage system

Ice streams are thus often intimately connected to the occurrence of subglacial water sources. Since basal water is generated by energy from the geothermal heat flux, which does not vary in time, water production can also be assumed constant in time. This should hold true for time perspectives where the ice sheet configuration does not significantly change, causing for example changes in ice thickness that would affect the basal thermal regime or over periods where volcanic activity is not changing. It is possible, however, that instabilities can be caused by periodic buildup and release of subglacial lakes. The jökulhlaup phenomena of icelandic ice caps is a good example of this (Björnsson, 2002). In the case of Grimsvötn, the lake is formed by high geothermal heat fluxes melting basal ice until the hydraulic dam formed by the overlying ice is broken resulting in catastrophic outbursts. Hence high but stable geothermal heat can produce periodic events if the geometry of the ice-water configuration is favorable. A similar mechanism has also been suggested by Alley *et al.* (2006) for producing periodic outburst floods and accompanying dynamic events. Their mechanism involves growth of ice shelves onto proglacial sills where they freeze on producing a seal. Water is thus trapped in deeper parts upstream of the sill, which with a growing ice sheet can become over-pressurized. If the basal temperature decreases on the sill, the over-pressurized water may escape causing an outburst flood. They suggest this process may have been involved with the so-called *Heinrich events* (*e.g.* Hemming, 2004) seen in marine cores in the north Atlantic and for creation of subglacial lakes such as Lake Vostok. Evatt *et al.* (2006) developed a numerical model to investigate the potential for subglacial lakes. They find that lakes should fill and drain periodically, basically as a function of the filling rate. The calculations allowed Evatt *et al.* to predict possible locations for subglacial lakes beneath the Laurentide ice sheet. Their locations agree with the positions of the paleo-subglacial lakes proposed by Munro-Stasiuk (2003) and Christoffersen *et al.* (2008), however, the larger predicted lakes have not yet been identified.

Examples of dynamic processes have been identified from sudden changes in elevation of parts of the ice sheet. (Gray *et al.*, 2005) used RADARSAT data from the 1997 Antarctic Mapping Mission to interferometrically solve for the 3-dimensional surface ice motion in the interior of the West Antarctic Ice Sheet (WAIS). They showed that an area of ~ 125 km^2 in a tributary of Ice Stream C (Kamb Ice Stream) slumped vertically downwards by up to ~ 50 cm (September 26 to October 18, 1997). Areas in Ice Stream D (Bindschadler Ice Stream) also exhibited comparable upward and downward surface displacements. The uplift and subsidence features corresponded to sites at which the basal water apparently experiences a hydraulic potential well. Thus transient movement of pockets of subglacial water could the most likely cause for the vertical surface displacements. Wingham *et al.* (2006) used surface elevation change observations to map the movement of what they infer being pulses of water moving between known subglacial lakes beneath the east Antarctic ice sheet. They calculate that 1.8 km^3 of water moved 290 km in a 16 month period. Vaughan *et al.* (2007) Identified an 18 km^2 lake, Lake Ellsworth, beneath the West Antarctic ice sheet. This lakes does not seem to have any barrier preventing outflow and Vaughan *et al.* postulate that the lake is likely a reservoir balancing in- and outflow. Gray *et al.* (2005) and Fricker *et al.* (2007), however, showed that even this constant water production can cause very transient behavior. In their study of Whillans Ice Stream (Ice Stream B) they observed large vertical fluctuations over a three year period, 2003–2006, including both monotonic surface uplift and lowering as well as fluctuations over sub-annual time period. They attribute this to movement of water through a subglacial water system. They calculate that a volume of 2.0 km^3 drained from a subglacial lake over the three year period. Simultaneously, similar volumes of water was building up elsewhere. Similarly, Stearns *et al.* (2008) observed a speedup, associated with surface elevation lowering coinciding with two upstream lakes at Byrd Glacier, East Antarctica. A volume corresponding to 1.7 km^2 of water may have been displaced during this inferred drainage event. Fricker and Scambos (2009) also identified patterns of linked drainage systems undergoing different types of events on both Whillans ice stream (B) and the lower parts of ice stream A (Mercer). The interpretations indicate an active and rapidly changing drainage system beneath the ice streams. Sergienko *et al.* (2007) showed that the observed surface elevation changes do not simply reflect their basal counterparts. Estimates of water volumes based on surface elevation changes must thus be conservative. Shoemaker (2003) provide a theoretical mechanism for how subglacial lakes modify subglacial outburst floods through ponding and thereby redistributing the discharge peak to longer term flows. Such phenomena are well known in surface runoff through combined streams and lake systems. Subglacial lakes can thus turn a singular event to a sustained event. Murray *et al.* (2008) identified regions of sliding in presence of what they infer to be a linked cavity system (Kamb, 1987) beneath Rutford Ice Stream. In areas of bed inferred deformation they identify 50 m wide linear features deemed to be canals evacuation water. Although the sources for water in Rutford Ice Stream are not as obvious as for the Siple coast streams, it seems as if ice streams are underlain by complex drainage systems.

The interaction of a channelized subglacial drainage system with the unchannelized parts of its drainage area is of interest because of the water pressure gradients. Boulton *et al.* (2007a,b) investigated the subglacial pressure field around a subglacial stream on Breiðamerkurjökull, Iceland. Their results show that the channel provides a low-pressure sink to which the surrounding unchannelized areas drain. They furthermore postulate that high surface melt water input events can cause locally reversing flows near the input point, provided that the input point is connected to the main drainage through an under-dimensioned channel unable to transmit the incoming flux. This study shows that the subglacial water pressures should be spatially variable with local lows following the channels. Temporal variations are superimposed on these and may cause shorter-term effects where the pressure field may be reversed. The channels thus interact with their surrounding in a complex fashion.

These studies thus indicate that a complex interconnected system of subglacial lakes and drainage pathways can exist beneath ice sheets. Some lakes, such as Lake Vostok may not be part of such drainage systems, but many lakes area active parts of the subglacial drainage system. Many lakes beneath Antarctica are the result of the tectonic setting of the subglacial topography and high geothermal heat fluxes seem to be common in such areas. The geothermal heat flux hot spots mapped by Fox Maule *et al.* (2005) only partially overlaps with known regions of subglacial lakes. It is, however, not necessary to have large heat flux anomalies to produce basal melting.

11. Geological evidence for subglacial drainage

Subglacial drainage beneath ice sheets have been known to exist largely in view of the vast systems of eskers left by the ice sheet (Figure 11.1). Clark and Walder (1994) has discussed the distribution of eskers in terms of a subglacial geology framework. They conclude that a vast system of subglacial tunnels or canals should exist beneath an ice sheet.

Figure 11.1. Esker systems in Scandinavia showing the branching complexity of such systems. (from Boulton *et al.* (2001))

There are several indications that large floods have occurred from ice sheets. In Antarctica, for example Denton and Sugden (2005) and Lewis *et al.* (2006) discuss observable melt water generated features originating from larger extents of the ice sheet. Sawagaki and Hirakawa (1997) observed traces of meltwater in coastal areas of

Antarctica. There are indications that large quantities of water drained through the Laurentide ice sheet during its waning phase (*e.g.* Josenhans and Zevenhuisen, 1990; Barber *et al.*, 1999; Clarke *et al.*, 2003). Some of the observations from Antarctica have been heavily discussed but the evidence is mounting that large floods do occur. Spectacular floods have been inferred from re-interpretation of landforms typically not thought to be associated with floods (*e.g.* Shaw, 2002). This flood hypothesis has not gained general acceptance (*e.g.* Clarke *et al.*, 2005) but cannot be completely disregarded. Hence, large scale, low frequency drainage phenomena are possible in ice sheets. In the case of the Fennoscandian ice sheet all identified large scale drainage phenomena area associated with subaerial lakes dammed by ice at the margin and not subglacial phenomena.

Evidence for subglacial lakes are also emerging from the past ice sheets. Munro-Stasiuk (2003) identified lake sediments in a buried valley in souther Alberta Canada as indicative of a subglacial lake. Munro-Stasiuk also concluded that the valleys may have acted as interconnected systems routing water beneath the Laurentide ice sheet. Munro-Stasiuk *et al.* (2005) have reinterpreted the so-called *P-forms* found on islands in Lake eire, North America as formed by subglacial drainage. Knight (2002) identified two possible subglacial lakes in north-central Ireland. These were located near the local ice center. Christoffersen *et al.* (2008) also infer such a lake from sedimentary sequences found in Great Slave lake, Canada. The lake sediments indicate an active subglacial drainage system contributing sediments to the subglacial lake environment.

Water can also be routed through the ice sheet from ice dammed lakes. Several catastrophic outburst floods have been recognized, some examples are the Glacier lake Missoula (*e.g.* Pardee, 1942) and glacier dammed lakes in the Altai mountains (Herget, 2005) Lajeunesse and St-Onge (2008) provide evidence for subglacial drainage of the Agassiz-Ojibway proglacial lake to the Hudson Bay area beneath the Laurentide ice sheet. The sand wave landforms on the Hudson bay sea floor indicate that water flowed in sheet-like fashion along distinct flow routes.

The number of identified possible subglacial lakes beneath the former ice sheets are few, however, the number is likely to increase since because new ideas emerge from observations beneath the existing ice sheets. What is lacking, however, are clear criteria for how to identify such lakes and the potential subglacial drainage pathways connecting them.

12. Conclusions

The hydrological systems of ice sheets are complex. Our view of the system is split, largely due to the complexity of observing the systems. Our basic knowledge of processes have been obtained from smaller glaciers and although applicable in general to the larger scales of the ice sheets, ice sheets contain features not observable on smaller glaciers due to their size.

The generation of water on the ice sheet surface is well understood and can be satisfactorily modeled. The routing of water from the surface down through the ice is not complicated in terms of process. What has been problematic is the way in which the couplings between surface and bed has been accomplished through a kilometer of cold ice, but with the studies on crack propagation and lake drainage on Greenland we are beginning to understand also this process and we know water can be routed through thick cold ice.

Water generation at the bed is also well understood but the main problem preventing realistic estimates of water generation is lack of detailed information about geothermal heat fluxes and their geographical distribution beneath the ice. Although some average value for geothermal heat flux may suffice, for many purposes it is important that such values are not applied to sub-regions of significantly higher fluxes. Water generated by geothermal heat constitutes a constant supply and will likely maintain a steady system beneath the ice sheet. Such a system may include subglacial lakes as steady features and reconfiguration of the system is tied to time scales on which the ice sheet geometry changes so as to change pressure gradients in the basal system itself.

Large scale re-organization of subglacial drainage systems have been observed beneath ice streams. The stability of an entirely subglacially fed drainage system may hence be perturbed by rapid ice flow. In the case of Antarctic ice streams where such behavior has been observed, the ice streams are underlain by deformable sediments. It is possible that soft beds through their ability to deform and be eroded can yield quasi-stable patterns of drainage pathways that with either erosion of critical sills or filling of temporary basins may reorganize itself periodically on time scales much shorter than the reorganization of the driving stresses for ice flow.

In areas where the surface generated water (melt and rain), the basally generated fluxes dwarf the influx from the surface and hence the drainage system in such areas will be dominated by surface fluxes and variations therein. Since surface fluxes have a strong seasonal variation with no influx during winter, areas experiencing surface influx will also be subject to large seasonal variations in both flux and pressure. In addition, during the melt season, fluxes and also pressures will also vary on diurnal as well as longer time frames in response to variations in air temperature that drives melt and occurrence of precipitation events.

The emerging picture of glacier drainage consists of different types of models applicable to different regimes found beneath an ice sheet (with our without surface influx, ice streams, subglacial lakes). It is not, however, clear how these systems are coupled, or even *if* they are. This makes it inherently difficult to assess what can be expected beneath a given sector of an ice sheet without some detailed understanding of the underlying geology (geothermal fluxes), geomorphology (possible water routing) and ice properties (cold -temperate base and ice thickness).

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References

Abdalati, W. and Steffen, K., 2001 Greenland ice sheet melt extent: 1979–1999, *J. Geophys. Res.* 106 (D24), 33983–33989.

Alley, R.B., Blankenship, D.D., Bentley, C.R., and Rooney, S.T., 1987. Till beneath ice stream B. 3. Till deformation: evidence and implications. *J. Geophys. Res.* 92 (B9), 8921–8929.

Alley, R.B., Dupont, T.K., Parizek, B.R., and Anandakrishnan, S., 2005. Access of surface meltwater to beds of subfreezing glaciers: Preliminary insights. *Ann. Glaciol.* 40, 8–14.

Alley, R.B., Dupont, T.K., Parizek, B.R., Anandakrishnan, S., Lawson, D.E., Larson, G.J., and Evenson, E.B., 2006. Outburst flooding and the initiation of ice-stream surges in response to climate cooling. *Geomorphol.* 75 (1–2), 76–89.

Anandakrishnan, S., Blankenship, D.D., Alley, R.B., and Stoffa, P.L., 1998. Influence of subglacial geology on the position of a West Antarctic ice stream from seismic observations. *Nature.* 394 (6688), 62–65.

Bamber, J.L., Vaughan, D.G., and Joughin, I., 2000. Widespread complex flow in the interior of the Antarctic Ice Sheet. *Science.* 287 (5456), 1248–1250.

Bamber, J.L., Ferraccioli, F., Joughin, I., Shepherd, T., Rippin, D.M., Siegert, M.J., and Vaughan, D.G., 2006. East Antarctic ice stream tributary underlain by major sedimentary basin. *Geology.* 34 (1), 33–36.

Bamber, J.L., Alley, R.B., and Joughin, I., 2007. Rapid response of modern day ice sheets to external forcing. *Earth Planet. Sci. Lett.* 257 (1), 1–13.

Bamber, J.L., Gomez-Dans, J.L., and Griggs, J.A., 2009. A new 1 km digital elevation model of the Antarctic derived from combined satellite radar and laser data – Part 1: data and methods. *The Cryosphere.* 3 (1), 101–111.

Barber, D.C., Dyke, A., Hillaire-Marcel, C., Jennings, A.E., Andrews, J.T., Kerwin, M.W., Bilodeau, G., McNeely, R., Southon, J., Morehead M.D., and Gagnon, J.-M., 1999. Forcing of the cold event of 8,200 years ago by catastrophic drainage of Laurentide lakes. *Nature.* 400 (6742), 344–348.

Beem, L.H., Jezek, K.C., and van der Veen, C.J., 2010. Basal melt beneasth Whillans Ice Stream, West Antarctica. *J. Glaciol.* 56 (198), 647–654.

Behrendt, J.C., Finn, C.A., , Blankenship, D., Bell, R.E. 1998. Aeromagnetic Evidence for a Volcanic Caldera(?) Complex Beneath the Divide of the West Antarctic Ice Sheet. *Geophys. Res. Lett.* 25, 23, 4385–4388.

Behrendt, J.C., Blankenship, D.D., Morse, D.L., Bell, R.E., 2004. Shallow-source aeromagnetic anomalies observed over the West Antarctic Ice Sheet compared with coincident bed topography from radar ice sounding – new evidence for glacial "removal" of subglacially erupted late Cenozoic rift-related volcanic edifices. *Glob. Planet. Change.* 42 (1–4), 177–193.

Bell, R.E., 2008. The role of subglacial water in ice sheet mass balance. *Nature*

Geosci. 1 (5), 297–304.

Bell, R.E., Blankenship, D.D., Finn, C.A., Morse, D.L., Scmbos, T.A., Brozena, J.M., and Hodge, S.M., 1998. Influence of subglacial geology on the onset of a West Antarctic ice stream from aerogeophysical observations. *Nature.* 394 (6688), 58–62.

Bell, R.E., Studinger, M., Tikku, A.A., Clarke, G.K.C., Gutner, M.M., and Meertens, C., 2002. Origin and fate of thLake Vostok water frozen ot the base of the east Antarctic ice sheet. *Nature.* 416 (6878), 307–310.

Bell, R. E., Studinger, M, Fahnestock, M.A. and Shuman, C.A. 2006. Tectonically controlled subglacial lakes on the flanks of the Gamburtsev Subglacial Mountains, East Antarctica. *Geophys. Res. Lett.* 33, L02504, doi:10.1029/2005GL025207.

Bell, R.E., Studinger, M., Shuman, C.A., Fahnestock, M.A., and Joghin, I., 2007. Large subglacial lakes in east Antarctica at the onset of fast flowing ice streams. *Nature.* 445 (7130), 904–807.

Benson, C.S., 1961. Stratigraphic studies in the snow and firn of the Greenland Ice Sheet. *Folia Geographica Danica.* 9, 13–37.

Bhattacharya, I., Jezek, K.C., Wang, L., and Liu, H., 2009. Surface melt area variability of the Greenland ice sheet: 1979–2008. *Geophys. Res. Lett.* 36, L30502, doi:10.1029/2009GL039798.

Bindschadler, R.A., King, M.A., Alley, R.B., Anandakrishnan, S., and Padman, L., 2003. Tidally controlled stick-slip discharge of a West Antarctic Ice Stream. *Science.* 301 (5636), 1087–1089.

Bindschadler, R.A., Vornberger, P.L., King, M.A., and Padman, L., 2003. Tidally driven stick-slip motion in the mouth of Whillans Ice Stream, Antarctica. *Ann. Glaciol.* 36, 263–272.

Bintanja, R., 1999. On the glaciological, meteorological and climatological significance of Antarctic blue ice areas. *Rev. Geophys.* 37, 337–359.

Bintanja, R., and van de Wal, R.S.W., 2008. North American ice-sheet dunamics and the onset of 100,000-year glacial cycles. *Nature.* 454 (7206), 869–872.

Björnsson, H., 1998. Hydrological characteristics of the drainage system beneath a surging glacier. *Nature.* 395 (6704), 771–774.

Björnsson, H., 2002. Subglacial lakes and jökulhlaups in Iceland. *Glob. Planet. Change.* 35 (3–4), 255–271.

Blankenship, D.D., and Bentley, C.R., 1986. Seismic mapping of a till at the base of Ice Stream B. (Abstract) *Eidgenössische Technische Hochschule (ETH) Zürich, Versuchsanstalt für Wasserbau und Hydrologie. Glaziologische Mitteilungen*, 90, 29–30.

Blankenship, D.D., Bentley, C.R., Rooney, S.T., and Alley, R.B., 1986. Seismic measurements reveal a saturated porous layer beneath an active Antarctic ice stream. *Nature.* 322 (6074), 54–57.

Blankenship, D.D., Bentley, C.R., Rooney, S.T., and Alley, R.B., 1987. Till beneath Ice Stream B. a. Properties derived from seismic travel times. *J. Geophys. Res.*, 92 (B9), 8903–8911.

Blankenship, D.D., Rooney, S.T., Alley, R.B., and Bentley, C.R., 1989. Seismic evidence for a thin basal layer at a second location on Ice Stream B. (Abstract) *Ann. Glaciol.* 12, 200.

Blankenship, D.D., Bell, R.E., Hodge, S.M., Brozena, J.M., Behrendt, J.C., and Finn, C.A., 1993. Active volcanism beneath the West Antarctic ice sheet and

implications for ice-sheet stability. *Nature.* 362 (6412), 526–529.
Bøggild, C., 1997. Different melt regimes indicated by surface albedo measurements at the Greenland ice sheet margin: Application of TM image. *EARSeL. Advances in Remote Sensing.* 5, 82–88.
Bøggild, C.E., Brandt, R.E., Brown, K.J., and Warren, S.G., 2010. The ablation zone in northeast Greenland: ice types, albedos and impurities, *J. Glaciol.* 56, 101–113.
Boon S. and Sharp M., 2003. The role of hydrologically-driven ice fracture in drainage system evolution on an Arctic glacier. *Geophys. Res. Lett.* 30 (18), 1916, doi:10.1029/2003GL018034.
Bougamont, M., Bamber, J.J., and Greuell, W., 2005. A surface mass balance model for the Greenland Ice Sheet. *J. Geophys. Res.* 110, F04018, doi:10.1029/2005JF000348.
Boulton, G.S., Caban, P.E., and van Gijssel, K., 1995. Groundwater flow beneath ice sheets. Part I – Large scale patterns. *Quat. Sci. Rev.* 14 (6), 545–562.
Boulton, G.S., Zatsepin, S., and Maillot, B., 2001. *Analysis of groundwater flow beneath ice sheets.* Swedish Nuclear Fuel and Waste Management Co. Technical Report TR-01-06.
Boulton, G.S., Lunn, P., Vidstrand, P., and Zatsepin, S., 2007a. Subglacial drainage by groundwater-channel coupling, and the origin of esker systems: Part 1 – glaciological observations. *Quat. Sci. Rev.* 26, 1067–1090.
Boulton, G.S., Lunn, P., Vidstrand, P., and Zatsepin, S., 2007b. Subglacial drainage by groundwater-channel coupling, and the origin of esker systems: Part 2 – theory and simulations of a modern system. *Quat. Sci. Rev.* 26, 1091–1105.
Box, J.E., Bromwich, D.H., and Bai, L.S., 2004. Greenland ice sheet surface mass balance for 1991–2000: Application of Polar MM5 mesoscale model and in-situ data. *J. Geophys. Res.* 109 (D16105), 1–21.
Box, J.E., Bromwich, D.H., Veenhuis, B.A., Le-Sheng Bai, Stroeve, J.C., Rogers, J.C., Steffen, K., Haran, T., and Sheng-Hung Wang, 2008. Greenland ice sheet surface mass balance variability (1988–2004) from calibrated Polar MM5 output. *J. Clim.* 19, 2783–2800.
Budd, W.F., 1969. The dynamics of ice masses. *ANARE Scientific Reports. Series A (IV) Glaciology. Publ. No.* 108.
Carcione, J.M. and Gei, D., 2003. Seismic modelling study of a subglacial lake. *Geophys. Prospecting.* 51, 501–515.
Carlson, A.E., Jenson, J.W., and Clark, P.U., 2007. Modeling the subglacial hydrology of the James Lobe of the Laurentide ice sheet. *Quat. Sci. Rev.* 26 (9–10), 1384–1397.
Carter, S.P., Blankenship, D.D., Peters, M.F., Young, D.A., Holt, J.W., and Morse, D.L., 2007. Radar-based subglacial lake classification in Antarctica. *Geochem., Geophys., Geosyst.* 8 (3), Q03016, doi:10.1029/2006GC001408.
Catania, G.A., and Neumann, T.A., 2010. Persistent drianage features in the Greenland Ice Sheet. *Geophys. Res. Lett.* 37, L02501, doi:10.1029/2009GL041108.
Catania, G.A., 2004. The dynamic history of Kamb Ice Stream, Antarctica: Controls on streaming behavior and ice stream shutdown. PhD diss. Earth & Space Sciences, University of Washington. 109 p.
Catania, G.A., Scambos, T.A., Conway, T., and Raymond, C.F., 2006. Sequential stagnation of Kamb Ice Stream, West Antarctica. *Geophys. Res. Lett.* 33, L14502,

doi:10.1029/2006GL026430.
Catania, G.A., Neumann, T.A., and Price, S.F., 2008. Characterizing englacial drainage in the ablation zone of the Greenland ice sheet. *J. Glaciol.* 54 (187), 567–578.
Čermák, V., 1989. Crustal heat production and mantle heat flow in Central and Eastern Europe. *Tectonophysics.* 159 (3–4), 192–215.
Chen, J.L., Wilson, C.R., and tapley, B.D., 2006. Satellite gravity measurements confirm accelerated melting of Greenland ice sheet. *Science.* 313 (5795), 1958–1960.
Christoffersen, P., Tulaczyk, S., Wattrus, N.J., Peterson, J., Quintana-Krupinski, N., Clark, C.D., Sjunneskog, C., 2008. Large subglacial lake beneath the Laurentide ice sheet inferred from sedimentary sequences. Geology. 36 (7), 563–566.
Chylek, P., Dubey, M.K., and Lesins, G., 2006. Greenland warming of 1920–1930 and 1995–2005. *Geophys. Res. Lett.* 33, L11707, doi:10.1029/2006GL026510.
Clark, P.U., and Walder, J.S., 1994. Subglacial drainage, eskers, and deforming beds beneath the laurentide and Eurasian ice sheets. *GSA Bull.* 106, 304–314.
Clarke, G.K.C., Leverington, D., Teller, J., and Dyke, A., 2003. Perpectives. Superlakes, megafloods, and abrupt climate change. *Science.* 301 (5635), 922–923.
Clarke, G.K.C., Leverington, D.W., Teller, J.T., Dyke, A.S., and Marshall, S.J., 2005. Fresh arguments against the Shaw megaflood hypothesis. *Quat. Sci. Rev.* 24 (12–13), 1533–1541.
Corr, H.F.J., and Vaughan, D.G., 2008. A recent volcanic eruption beneath the West Antarctic ice sheet. *Nature Geosci.* 1 (1), 1–4.
Dahl-Jensen, D., Gundestrup, N., Gogineni, P., and Miller,H., 2003. Basal melt at NorthGRIP modeled from borehole, ice-core and radio-echo sounder observations. *Ann. Glaciol.* 37, 207–212.
Dalziel, I.W.D., and Lawyer, L.A., 2002. The lithospheric setting of the West Antarctic Ice Sheet. In: *The West Antarctic Ice Sheet: behavior and environment. Antarctic Research Series.* 77, 29–44.
Das, S.B., Joughin, I., Behn, M.D., Howat, I.M., King, M.A., Lizarralde, D., and Bhatia, M.P., 2008. Fracture propagation to the base of the Greenland ice sheet during supraglacial lake drainage. *Science.* 320 (5877), 778–781.
Denton, G.E. and Sugden, D.E., 2005. Meltwater features that suggest Miocene ice-sheet overriding the Transantarctic Mountains in Victoria Land, Antarctica. *Geogr. Ann.* 87A (1), 67–85.
Dowdeswell, J.A., and Siegert, M.J., 2002. The physiography of modern Antarctic subglacial lakes. *Glob. Planet. Change.* 35 (3–4), 221–236.
Duval, P., Lipenkov, V., Barkov, N.I., and de La Chapelle, S., 1998. Recrystallization and fabric development in the Vostok ice core. *Supplement to EOS Transactions Fall 1998 Meeting, AGU.* 79 (45), F152.
Echelmeyer, K., Clarke, T.S., Harrison, W.D., 1991. Surficial glaciology of Jakobshavns Isbræ, West Greenland: Part I: Surface morphology. *J. Glaciol.* 37 (127), 368–382.
Ekström, G., Nettles M., and Abers, G.A., 2003. Glacial earthquakes. *Science.* 302 (5645), 622–624.
Ekström, G., Nettles M., and Tsai, V.C., 2006. Seasonality and increasing frequency of Greenland earthquakes. *Science.* 311, 1756–1758.
Kaykin, A.A:, Lipenkov, V.Y., Petit, J.R., Johnsen, S., Jouzel, J., and Masson-

Delmotte, V., 2010. Insights into hydrological regime of Lake Vostok from differential behaviour of deuterium and oxygen-18 in accreted ice. *J. Geophys. Res.* 115, C05003, doi:10.1029/2009JC005329.

Evatt, G.W., Fowler, A.C., Clark, C.D., and Hulton, N.R.J., 2006. Subglacial floods beneath ice sheets. *Phil. Trans. R. Soc. A.* 364, 1769–1794, doi:10.1098/rsta.2006.1798

Fahnestock, M.,Abdalati, W., Joughin, I., Brozena, J., and Gogineni, P., 2001. High geothermal heat flow, basal melt and the origin of rapid ice flow in central Greenland. *Science.* 294 (5550), 2338–2342.

Fountain A.G., and Walder, J.S., 1998. Water flow through temperate glaciers. *Rev. Geophys.* 36 (3), 299–328.

Fountain, A.G., Jacobel, R.W., Schlichting, R., and Jansson, P., 2005. Fractures as the main pathways of water flow in temperate glaciers. *Nature.* 433 (7026), 618–621.

Fountain, A.G., Schlichting, R., Jansson, P., and Jacobel, R.W., 2005. Observations of englacial flow passages – a fracture dominated system. *Ann. Glaciol.* 40, 25–30.

Fowler, A.C. and Johnson, C. 1995. Hydraulic runaway: a mechanism for thermally regulated surges of ice sheets. *J. Glaciol.* 41, 554–561.

Fowler, A.C. and Johnson, C. 1996. Ice sheet surging and ice stream formation. *Ann. Glaciol.* 23, 68–73.

Fox Maule, C., Purucker, M.E., Olsen, N., and Mosegaard, K., 2005. Heat flux anomalies in Antarctica revealed by satellite magnetic data. *Science.* 309 (5733), 464–467

Fricker, H.A., Scambos, T., Bindschadler, R., and Padman, L., 2007. An active subglacial water system in West Antarctica mapped from space. *Science.* 315 (5818), 1544–1548.

Fricker, H.A. and Scambos, T., 2009. Connected subglacial lake activity on lower Mercer and Whillans Ice Streams, West Antarctica, 2003–2008. *J. Glaciol.* 55 (190), 303–315.

Furlong, K.P., and Chapman, D.S., 1987. Crustal heterogeneities and the thermal structure of the continental crust. *Geophys. Res. Lett.* 14 (3), 314–317.

Glen, J.W., 1955. The creep of polycrystalline ice. *Proc. Roy. Soc. Lond.* A228 (1175), 519–538.

Geological Survey of Finland, 1984. Quaternary deposits of Finland. 1:1000000.

Gray, L., Joughin, I., Tulaczyk, S., Spikes, V.B., Bindschadler, R., and Jezek, K., 2005. Evidence for subglacial water transport in the West Antarctic Ice Sheet through three-dimensional satellite radar interferometry. *Geophys. Res. Lett.* 32, L03501, doi:10.1029/2004GL021387.

Greve, R., 2005. relation of measured basal temperature and the spatial distribution of the geothermal heat flux for the Greenland ice sheet. *Ann. Glaciol.* 42, 424–432.

Gudmundsson, G.H., 2006. Fortnightly variations in the flow velocity of Rutford Ice Stream, West Antarctica. *Nature.* 444 (7122), 1063–1064.

Hanna, E., Huybrechts, P., Steffen, K., Cappelen, J., Huff, R., Shuman, C., Irvine-Fynn, T., Wise, S., and Griffiths, M., 2008. Increased runoff from melt from the Greenland Ice Sheet: A response to global warming. *J. Clim.* 21 (2), 331–341.

Harper, J.T., Bradford, J.H., Humphrey, N.F., and Meierbachtol, T.W., 2010. Vertical extension of teh subglacial system into basal crevasses. *Nature.* 467, 579–582. doi:10.1038/nature09398.

Hemming, S.R., 2004. Heinrich events: massive Plestocene detritus layers of the North Atlantic and their global climate imprint. *Rev. Geophys.* 42 RG1005, doi:10.1029/2003RG000128.

Herget, J., 2005. Reconstruction of Pleistocene ice-dammed lakes in the Altai Mountains, Siberia. *GSA Spec. Paper.* 386, 118 p.

Hock, R., and Jansson, P., 2005. Modelling glacier hydrology. In: *Anderson, M.G., and McDonnell, J., (eds.), Encyclopedia of Hydrological Sciences. John Wiley & Sons, Chichester.* 4, 2647–2655.

Hock, R., Jansson, P., and Braun, L., 2005. Modelling the response of mountain glacier discharge to climate warming. In: *Huber, U.M., Bugmann, H.K.M., and Reasoner, M.A., (Eds.), 2005, Global Change and Mountain Regions (A State of Knowledge Overview), Springer, Dordrecht.* 243–252.

Holland, D.M., Thomas, R.H., de Young, B., Ribergaard, M.H., and Lyberth, B., 2008. Acceleration of Jakobshavn Isbræ triggered by warm subsurface ocean waters. *Nature Geosci.* 1, 659–664.

Hooke, R.LeB., 1977. Basal temperatures in polar ice sheets: a qualitative review. *Quat. Res.* 7, 1–13.

Hooke, R.LeB., 1984. On the role of mechanical energy in maintaining subglacial water conduits at atmospheric pressure. *J. Glaciol.*, 30 (105), 180–187.

Hooke, R.LeB., 1989. Englacial and subglacial hydrology: A qualitative review. *Arct. Alp. Res.* 21 (3), 221–233.

Hooke, R.LeB., 2005. *Principles of glacier mechanics. Second Edition.* Cambridge University Press, Cambridge.

Howat, I., Joughin, I., Tulaczyk, S., and Gogineni, S., 2005. Rapid retreat and acceleration of Helheim Glacier, east Greenland. *Geophys. Res. Lett.* 32, L22502, doi:10.1029/2005GL024737.

Howat, I.M., Joughin, I., and Scambos, T.A., 2007. Rapid changes in ice discharge from Greenland outlet glaciers. *Science.* 315 (5818), 1559–1561.

Hubbard, B. and Nienow, P., 1997. Alpine subglacial hydrology. *Quat. Sci. Rev.* 16 (9), 939–955.

Huybrechts, P., 1992. The Antarctic ice sheet and environmental change: a three dimensional modelling study. *Reports on Polar research (Alfred-Wegener-Institut für Polar und Meeresforschung).* 99, 241 p.

Huybrechts, P., 1995. Basal temperatrue conditions of the Greenland ice sheet during the glacial cycles. *Ann. Glaciol.* 23, 226–236.

Jansson P., Hock, R., and Schneider, T., 2003. The concept of glacier storage: A review. *J. Hydrol.* 282 (1–4): 116–129.

Jansson, P., Näslund, J.–O., and Rodhe, L., 2006. *Ice sheet hydrology – a review.* Swedish Nuclear Fuel and Waste Management Co. Technical Report TR-06-34.

Jean-Baptiste, J., Petit, J.R., Lipenkov, V.Ya., Reynaud, D., and Barkow, N.I., 2001. Helium isotope in deep Vostok ice core (Antarctica): constraints on hydrothermal processes and water exchange in the subglacial lake. *Nature.* 411, 460–462.

Johansson, A.M., Brown, I.A., and Jansson, P., 2010. Multi-temporal, multi-sensor investigations of supra-glacial lakes on the Greenland Ice Sheet. *ESA Special Publication* SP-686.

Jones, P.C., Johnson, A.C., von Frese, R.R.B., and Corr, H., 2002. Detecting rift basins in the Evans Ice Stream region of West Antarctica using airborne gravity

data. *Tectonophysics*. 347 (1–3), 25–41.
Josenhans, H.W., and Zevenhuizen, J., 1990. Dynamics of the Laurentide Ice Sheet in Hudson Bay, Canada. *Marine Geol.* 92 (1–2), 1–26.
Joughin, I. and Tulaczyk, S., 2002. Positive mass balance of the Ross ice streams, West Antarctica. *Science*. 295, 476–480.
Joughin, I., Tulaczyk, S., Fahnestock, M., and Kwok, R., 1996. A mini-surge on the Ryder Glacier, Greenland, observed by satellite radar interferometry. *Science*. 274 (5285), 228–230.
Joughin, I., Gray, L., Bindschadler, R., Price, S., Morse, D., Hulbe, C., Mattar, K., and Werner, C., 1999. Tributaries of the West Antarctic Ice streams revealed by RADARSAT interferometry. *Science*. 286 (5438), 283–286.
Joughin, I., Abdalati, W., and Fahnestock, M., 2004. Large fluctuations in speed on Greenland's Jakobshavn Isbræ glacier. *Nature*. 432, 608–610.
Joughin, I., Bamber, J.L., Scambos, T., Tulaczyk, S., Fahnestock, M., and MacAyeal, D.R., 2006. Integrating satellite observations with modelling: basal shear stress of the Filcher-Ronne ice streams, Antarctica. *Philos. Trans. R. Soc. London, Ser. A*, 364 (1844), 1795–1814.
Joughin, I., Das, S.B., King, M.A., Smith, B.E., Howat, I.M., Moon, T., 2008a. Seasonal speedup along the western flank of the Greenland Ice Sheet. *Science*. 320 (5877), 781–783.
Joughin, I., Howat, I.M., , Alley, R.B., Ekstrom, G., Fahnestock, M., Moon, T., Nettles, M., Truffer, M., and Tsai, V.C., 2008b. Ice-front variation and tidewater behavior on Helheim and Kangerdlussuaq glaciers, Greenland. *J. Geophys. Res.* 113 (F01004), doi:10.1029/2007JF000837.
Jouzel, J., Petit, J.R., Souchez, R., Barkov, N.I., Lipenkov, V.Ya., Raynaud, D., Stievenard, M., Vassiliev, N.I., Verbeke, V., and Vimeux, F., 1999. More than 200 meters of lake ice above subglacial lake Vostok, Antarctica. *Science*. 286 (5447), 2138–2141.
Kamb, B., 1987. Glacier surge mechanism based on linked cavity configuration of the basal water conduit system. *J. Geophys. Res.*, 92 (B9), 9083–9100.
Kamb, B., 1991. Rheological nonlinearity and flow stability in the deforming bed mechanism of ice stream motion. *J. Geophys. Res.* 96 (B10), 16585–16595.
Kapitsa, A.P., Ridley, J.K., Robin, G. de Q., Siegert, M.J., and Zotikov, I.A., 1996. A large deep freshwater lake beneath the ice of central East Antarctica. *Nature*. 381 (6584), 684–686.
Knight, J., 2002. Bedform patterns, subglacial meltwater events, and late Devensian ice sheet dynamics in north-central Ireland. *Glob. Planet. Change*. 35 (3–4), 237–253.
Krawczynski, M.J., Behn, M.D., Das, S.B.. and Joughin, I., 2009. constraints on the lake volume required for hydro-fracture through ice sheets. *Geophys. Res. Lett.* 36, L10501, doi:10.1029/2008GL036765.
Lajeunesse, P., and St-Onge, G., 2008. The subglacial origin of the Lake Agassiz-Ojibway final outburst flood. *Nature Geosci.* 1 (3), 184–188.
Lang, H., 1987. Forecasting meltwater runoff from snow-covered areas and from glacier basins. In: *Kraijenhoff, D.A., Moll, J.R., (eds.), River flow modelling and forecasting. Reidel, Dordrecht.* 99–127.
Lemke, P., J. Ren, R.B. Alley, I. Allison, J. Carrasco, G. Flato, Y. Fujii, G. Kaser, P. Mote, R.H. Thomas and T. Zhang, 2007. Observations: Changes in Snow,

Ice and Frozen Ground. In: *Climate Change 2007 The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA*.

Lewis, A.R., Marchant, D.R., Kowalewski, D.E., Baldwin, S.L., and Webb, L.E., 2006. The age and origin of the labyrinth, western Dry Valleys, Antarctica: evidence for extensive middle Miocene subglacial floods and freshwater discharge to the Southern Ocean. /Geology. 34 (7), 513–516.

Lewis, S.M. and Smith, L.C., 2009. Hydrologic draianage of the Greenland Ice Sheet. *Hydr. Proc.* 22, 2004–2011. doi:10.1002/hyp.7343.

Luckman, A., Murray, T., de Lange, R., and Hanna, E., 2006. Rapid and synchronous ice-dynamic changes in East Greenland. *Geophys. Res. Lett* 33, L03503, doi:10.1029/2005GL025428.

Lüthje, M, Pedersen, L.T., Reeh, N., and Greuell, W., 2006. Modelling the evolution of supraglacial lakes on the West Greenland ice-sheet margin. *J. Glaciol.* 52 (179), 608–618.

Luthcke, S.B., Zwally, H.J., Abdalati, W., Rowlands, D.D., Ray, R.D., Nerem, R.S., Lemoine, F.G., Mccarthy, J.J., and Chinn, D.S., 2006. Recent Greenland ice mass loss by drainage system from satellite gravity observations. *Science*. 314 (5803), 1286–1289.

Marshall, S.J., 2005. Recent advances in understanding ice sheet dynamics. *Earth Planet. Sci. Lett.* 240 (2), 191–204.

McMillan, M., Nienow, P., Shepherd, A., Benham, T., and Sole, A., 2007. Seasonal evolution of supra-glacial lakes on the Greenland Ice Sheet. *Earth Planet. Sci. Lett.* 262 (3–4), 484–492.

Moon, T., and Joughin, I., 2007. Changes in ice front position on Greenland's outlet glaciers from 1992 to 2007. *J. Geophys. Res.* 113, F02022, doi:10.1029/2007JF000927.

Müller, F., 1962. Zonation in the accumulation area of the glaciers of Axel Heiberg Island, N.W.T., Canada. *J. Glaciol.* 4 (33), 302–313.

Munro-Stasiuk, M.J., 2003. Subglacial Lake McGregor, south-central Alberta, Canada. *Sed. Geol.* 160 (4), 325–350.

Munro-Stasiuk, M.J., Fisher, T.G., and Nitsche, C.R., 2005. The origin of the western Lake Erie grooves, Ohio: implications for reconstructing the subglacial hydrology of the Great Lakes sector of the Laurentide ice sheet. *Quat. Sci. Rev.* 24 (22), 2392–2409.

Murray, T., Corr, H., Forieri, A., and Smith, A.M., 2008. Contrasts in hydrology between regions of basal deformation and sliding beneath Rutford Ice Stream, West Antarctica, mapped using radar and seismic data. *Geophys. Res. Lett.* 35, L12504, doi:10.1029/2008GL033681.

Näslund, J.-O., Jansson, P., Fastook, J.L., Johnson, J. and Andersson, L., 2005. Detailed spatially distributed geothermal heat-flow data for modeling of basal temperatures and meltwater production beneath the Fennoscandian ice sheet. *Ann. Glaciol.* 40, 95–101.

Näslund, J.-O., Johnson, J. Pattyn, F., and Jansson, P., in prep. High resolution geothermal heat flux data-implications for ice sheet dynamics. *manuscript in preparation for J. Geophys. Res.*

Ohmura, A., 2001. Physical basis for the temperature-based melt-index method. *J. Appl. Meteor.* 40, 753–761. doi:10.1175/1520-0450(2001)040<0753:PBFTTB>2.0.CO;2

Oswald, G.K.A., and Gogineni, S.P., 2008. Recovery of subglacial water extent from Greenland radar survey data. *J. Glaciol.* 54 (184), 94–106.

Padilla, F., and Villeneuve, J.P., 1992. Modelling and experimental studies of frost heave including solute effects. *Cold Reg. Sci. Technol.* 20 (2), 183–194.

Pardee, J.T., 1942. Unusual currents in glacial Lake Missoula. *GSA Bull.* 53, 1569–1600.

Petit, J.R., Basile, I., Jouzel, J., Barkow, N.I., Lipenkov, V.Ya., Vostretov, R.N., Vasiliev, N.I., and Rado, C., 1998. Preliminary investigations and implications from the 3623 m Vostok deep ice core studies. In: *Lake Vostok Study: Scientific objectives and technological requirements, International Workshop, Arctic and Antarctic Research Institute, St. Petersburg.* 43 p.

Pollard, D., DeConto, R.M., and Nyblade, A.A., 2005. Sensitivity of Cenozoic Antarctic ice sheet variations to geothermal heat flux. *Glob. Planet. Change* 49 (1–2), 63–74.

Popov, S.V. and Masolov, V.N. 2007. Forty-seven new subglacial lakes in the 0-1108 E sector of East Antarctica. *J. Glaciol.* 53 (181), 289–297.

Price, S.F., Payne, A.J., Catania, G.A., and Neumann, T.A., 2008. Seasonal acceleration of inland ice via longitudinal coupling to marginal ice. *J. Glaciol.* 54 (185), 213–219.

Ramillien, G., Lombard, A., Cazenave, A., Ivins, E.R., Llubes, M., Remy, F., and Biancale, R., 2006. Interannual variations of the mass balance of teh Antarctica and Greenland ice shets from GRACE. *Glob. Planet. Change.* 53 (3), 198–208.

Ridley, J.K., Huybrechts, P., Gregory, J.M., and Lowe, J.A., 2005. Elimination of the Greenland Ice Sheet in a high CO_2 climate. *J. Clim.* 18 (17), 3409–3427.

Rignot, E., and Kanagaratnam, P., 2006. Changes in the velocity structure of the Greenland Ice Sheet. *Science.* 311 (5763), 986–990.

Rignot, E.J., Gogineni, S.P., Krabill, W.B., and Ekholm, S., 1997. North and Northeast Greenland ice discharge from satellite radar interferometry. *Science.* 276, 934–937.

Rignot, E., Box, J.E., Burgess, E., and Hanna, E., 2008. Mass balance of the Greenland ice sheet from 1958 to 2007. *Geophys. Res. Lett.* 35 L20502, doi:10.1029/2008GL035417.

Rippin, D.M., bamber, J.L., Siegert, M.J., Vaughan, D.G., and Corr, H.F.J., 2003. Basal topography and ice flow in the bailey/Slessor region of East Antarctica. *J. Geophys. Res.* 108, doi:10.1029/2003JF000039.

Rooney, S.T., Blankenship, D.D., and Bentley, C.R., 1987a. Seismic refraction measurement of crustal structure in West Antarctica. In: *McKenzie, G.D., (ed.), Gondwana Six: Structure, Tectonics, and Geophysics. American Geophysical Union, Washington, DC. Geophysical Monograph.* 40, 1–7.

Rooney, S.T., Blankenship, D.D., Alley, R.B., and Bentley, C.R., 1987b. Till beneath Ice Stream B. 2. Structure and continuity. *J. Geophys. Res.* 92 (B9), 8913–8920.

Rooney, S.T., Blankenship, D.D., Alley, R.B., and Bentley, C.R., 1988. Seismic.reflection profiling of a widespread till beneath Ice Stream B,West Antarctica. (Abstract) *Ann. Glaciol.* 11, 210.

Royston-Bishop, G., Priscu, J.C., Tranter, M., Christner, B., Siegert, M.J., and Lee, V., 2005. Incorporation of particulates into accreted ice above subglacial Vostok lake, Antarctica, *J. Glaciol.* 40, 145–150.

Röthlisberger, H., 1972. Water pressure in intra- and subglacial channels. *J. Glaciol.*, 11 (62), 177–203.

Röthlisberger H., and Lang, H., 1987. Glacier hydrology. In: *Gurnell, A., (ed.), Glacio-fluvial sediment transfer.* London: Wiley. 207–284.

Sawagaki, T. and Hirakawa, K., 1997. Erosion of bedrock by subglacial meltwater, Soya Coast, East Antarctica. *Geogr. Ann.* 79A, 223–238.

Sayag, R., and Tziperman, E., 2008. Spontaneous generation of pure ice streams via flow instability: Role of longitudinal shear stresses and subglacial till. *J. Geophys. Res.* 113 (B05411), doi:10.1029/2007JB005228.

Sayag, R., and Tziperman, E., 2009. Spatiotemporal dynamics of ice streams due to a triple-valued sliding law. *J. Fluid Mech.* 640 483–505. doi:10.1017/S0022112009991406.

Schneider, T., 2000. Hydrological processes in the wet-snow zone of glaciers: a review. *Z. Gletscherkd. Glazialgeol.* 36 (1), 89–105.

Sergienko, O.V., MacAyeal, D.R., and Bindschadler, R.A., 2007. Causes of sudden, short-term changes in ice-stream surface elevation. *Geophys. Res. Lett.* 34, L22503, doi:10.1029/2007GL031775.

Shaw, J., 2002. The meltwater hypothesis for subglacial bedforms. *Quat. Int.* 90, 5–22.

Shepherd, A., Wingham, D.J., Mansley, J.A.D., Corr, H.F.J., 2001. Inland thinning of Pine Island Glacier, West Antarctica. *Science.* 291 (5505), 862–864.

Shepherd, A., Hubbard, A., Nienow, P., King, M., McMillan, M., Joughin, I., 2009. Greenland ice sheet motion coupled with daily melting in late summer. *Geophys. Res. Lett.* 36, L01501, doi:10.1029/2008GL035759.

Shoemaker, E.M., 1986. Subglacial hydrology for an ice sheet resting on a deformable aquifer. *J. Glaciol.* 32 (110), 20–30.

Shoemaker, E.M., 2003. Effects of bed depressions upon floods from subglacial lakes. *Glob. Planet. Change.* 35 (3–4), 175–184.

Siegert, M.J., 2005. Lakes beneath the ice sheet: The occurence, analysis and future exploration of Lake Vostok and other Antarctic subglacial lakes. *Annu. Rev. Earth Planet. Sci.* 33 (1) 215–245.

Siegert, M.J., and Bamber, J.L., 2000. Subglacial water at the heads of Antarctic ice stream tributaries. *J. Glaciol.* 46 (155), 702–703.

Siegert, M.J., and Glasser, N.F., 1997. Convergent flow of ice within the Astrolabe subglacial basin, Terre Adélie, East Antarctica: an hypothesis derived from numerical modelling experiments. *Polar Res.* 16 (1), 63–72.

Siegert, M.J., Dowdeswell, J.A., Gorman, M.R., and McIntyre, N.F., 1996. An inventory of Antarctic subglacial lakes. *Antarct. Sci.* 18 (3), 281–286.

Siegert, M.J., Kwok, R., Mayer, C., and Hubbard, B., 2000. Water exchange between the subglacial Lake Vostok and the overlying ice sheet. *Nature.* 403 (6770), 643–646.

Siegert, M.J., Ellis-Evans, J.C., Tranter, M., Mayer, C., Petit, J.-R., Salamatin, A., and Priscu, J.C., 2001. Physical, chemical and biological processes in Lake Vostok and other Antarctic subglacial lakes. *Nature.* 414 (6864), 603–609.

Siegert, M.J. and Fisher, D.A., 2002. A terestrial analogy to Martian "accublation zones" revealed by airborne ice-penetrating radar from the East Antarctic ice

sheet. *Icarus*. 157, 264–267.
Siegert, M.J., Hindmarsh, R.C.A. and Hamilton, G.S., 2003. Evidence for a large surface ablation zone in central East Antarctica during the last Ice Age. *Quat. Res.* 59, 114–131.
Siegert, M.J., Carter, S., Tabacco, I., Popov, S., and Blankenship, D., 2005. A revised inventory of Antarctic subglacial lakes. *Antarct. Sci.* 17, 453–460.
Siegert, M.J., Taylor, J., and Payne, A.J., 2005a. Spectral roughness of subglacial topography and implications for former ice-sheet dynamics in East Antarctica. *Glob. Planet. Change*. 45, 249–263.
Siegert, M.J., Carter, S., Tabacco, I., Popov, S., and Blankenship, D.D., 2005b. A revised inventory of Antarctic subglacial lakes. *Antarct. Sci.* 17 (3), 453–460.
Six, D., Letréguilly, A., and Reynaud, L., 2001. Greenland ice sheet mass-balance distribution: a variance analysis of existing field data. *J. Glaciol.* 47 (158), 441–451.
Smith, B.E., Fricker, H.A., Joughin, I.R., and Tulaczyk, S., 2009. An inventory of active subglacial lakes in Antarctica detected by ICESat (2003–2008). *J. Glaciol.* 55 (192), 573–593.
Sneed, W.A., and Hamilton, G.S., 2007. Evolution of melt pond volume on the surface of the Greenland Ice Sheet. *Geophys. Res. Lett.* 34 (L03501), doi:10.1029/2006GL028697.
Souchez, R., Petit, J.-R., Jouzel, J., de Angelis, M., and Tison, J.-L., 2003. Reassessing Lake Vostok's behaviour from existing and new ice core data. *Earth Planet. Sci. Lett.* 217 (1–2), 163–170.
Stearns, L.A., Smith, B.E., and Hamilton, G.S., 2008. Increased flow speed on a large East Antarctic outlet glacier caused by subglacial floods. *Nature Geosci.* 1, 827–831.
Steffen, K., Nghiem, S.V., Huff, R., and Neumann, G., 2004. The melt anomaly of 2002 on the Greenland Ice Sheet from active and passive microwave satellite observations, *Geophys. Res. Lett.* 31 (20), L2040210.1029/2004GL020444.
Studinger, M., Bell, R.E., and Tikku, A.A. 2004. Estimating the depth and shape of Lake Vostok's water cavity from aerogravity data. *Geophys. Res. Lett.* 31 (12), L12401, doi:10.1029/2004GL019801.
Sundal, A.V., Shepherd, A., Nienow, P., Hanna, E., Palmer, S., and Huybrechts, P., 2009. Evolution of supra-glacial lakes across the Greenland Ice Sheet. *Remote Sens. Env.* 113 (10), 2164–2171.
Tabacco, I.E., Cianfarra, P., Forieri, A., Salvini, F., and Zirizotti, A., 2006. Physiography and tectonic setting of the subglacial lake district between Vostok and Belgica subglacial highlands (Antarctica). *Geophys. J. Int.* 165 (3), 1029–1040.
Thoma, M., Mayer, C., and Grosfeld, 2008. Sensitivity of subglacial Lake Vostok's flow regime on environmental parameters. *Earth Planet. Sci. Lett.* 269 (1–2), 242–247.
Thomsen, H.H., Thorning, L., and Braithwaite, R., 1986. Vurdering af de gletscher-hydrologiske forhold på inlandsisen ved Paakitsup Akuliarusersua, Ilulisat/Jakobshavn. Arbejdsnotat. *Grønl. Geol. Unders.* 15/12 1986.
Thomsen, H.H., Thorning, L., and Braithwaite, R., 1989. Glacier-hydrological conditions on the inland ice north-east of Jakobshavn/Ilulisat, West Greenland. *Grønl. Geol. Unders. Rapport.* 138.
Thomsen, H.H., Thorning, L., and Olesen, O.B., 1989. Applied glacier research

for planning hydro-electric power, Ilulissat/Jakobshavn, West Greenland. *Ann. Glaciol.* 13, 257–261.

Thomsen, H.H., Braithwaite, R.J., Weidick, A., and Olesen, O.B., 1993. Evaluation of hydropower potential for possible future industrial use Nuuk area, West Greenland. *Rapp. Grønl. Geol. Unders.* 159, 59–62.

Thomsen, H.H., Olesen, O.B., Braithwaite, R.J., and Bøggild, C.E., 1991. Ice drilling and mass balance at Pâkitsoq, Jakobshavn, central West Greenland. *Rapp. Grønl. Geol. Unders.* 152, 50–53.

Tsai, V.C., and Ekström, G., 2007. Analysis of glacial earthquakes. *J. Geophys. Res.* 112, F03022 doi:10.1029/2006JF000596.

Tsai, V.C., Rice, J.R., and Fahnestock, M., 2008. Possible mechanisms for glacial earthquakes. *J. Geophys. Res.* 113, F03014, doi:10.1029/2007JF000944.

Tulaczyk, S., Kamb, W.B., and Engelhardt, H.F., 2000. Basal mechanics of Ice Stream B, West Antarctica 2. Undrained plastic bed model. *J. Geophys. Res.*, 105 (B1), 483–494.

Uppala, S.M., KÅllberg1, P.W.,Simmons, A.J., Andrae, U., Da Costa Bechtold, S.V., Fiorino, M., Gibson, J.K., Haseler, J,. Hernandez, A., Kelly, G.A., Li, X., Onogi, K., Saarinen, S., Sokka, N., Allan, R.P., Andersson, E., Arpe, K., Balmaseda, M.A., Beljaars, A.C.M., Van De Berg, L., Bidlot, J., Bormann, N., Caires, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M., Fuentes, M., Hagemann, S., Hólm, E., Hoskins, B.J., Isaksen, L., Janssen, P.A.E.M., Jenne, R., Mcnally, A.P:, Mahfouf, J.-F., Morcrette, J.-J., Rayner, N.A., Saunders, R.W., Simon, P., Ster, A., Trenberth, K.E., Untch, A., Vasiljevic, D., Viterbo, P., Woollen, J., 2005. The ERA-40 re-analysis. *Q. J. R. Meteorol. Soc.* 131 (162), 2961–3012. doi:10.1256/qj.04.176.

Vaughan, D.G., Bamber, J.L., Giovinetto, M., Russell, J., and Cooper, A.P.R., 1999. Reassessment of net surface mass balance in Antacrtica. *J. Clim.* , 933–946.

Vaughan, D.G., Rivera, A., Woodward, J., Corr, H.F.J., Wendt, J., and Zamora, R., 2007. Topographic and hydrological controls on subglacial Lake Ellsworth, West Antarctica. *Geophys. Res. Lett.* 34 (L18501), doi:10.1029/2007GL030769.

van der Veen, C.J., 1998a. Fracture mechanics approach to penetration of surface crevasses on glaciers. *Cold Reg. Sci. Technol.* 27 (1), 31–47.

van der Veen, C.J., 1998b. Fracture mechanics approach to penetration of bottom crevasses on glaciers. *Cold Reg. Sci. Technol.* 27 (3), 213–223.

van der Veen, C.J., 2007. Fracture propagation as a means of rapidly transferring surface meltwater to the base of glaciers. *Geophys. Res. Lett.* 34, L01501, doi:10.1029/2006GL028385.

van der Veen, C.J., Leftwich, T., von Frese, R., Csatho, B.M., and Li, J., 2007. Subglacial topography and geothermal heat flux: Potential interactions with drainage of the Greenland ice sheet. *Geophys. Res. Lett.* 34, L12501, doi:10.1029/2007GL030046.

Velicogna, I., and Wahr, J., 2006. Acceleration of Greenland ice mass loss in spring 2004. *Nature.* 443, 329–331.

Waddington, E.D., 1987. Geothermal heat flux beneath ice sheets. In: *Waddington, E.D. and Walder, J.S., (Eds.): The physical basis of ice sheet modelling. IAHS Publ.* 170, 217–226.

van de Wal, R.S.W., 1996. Mass-balance modelling of the Greenland ice sheet: a comparison of an energy-balance model and a degree-day model. *Ann. Glaciol.*

23, 36–45.
van de Wal, R.S.W., Greuell, W., van den Broecke, M.R., Reijmer, C.H., and Oerlemans, J., 2005. Surface mass balance observationc and automatic weather station data along a transect near Kangerlussuaq, West Greenland. *Ann. Glaciol.* 42, 311–316.
van de Wal, R.S.W., Boot, W., van den Broecke, M.R., Smeets, C.J.P.P., Reijmer, C.H., Donker, J.J.A., and Oerlemans, J., 2008. Large and rapid melt-induced velocity changes in the ablation zone of the Greenland ice sheet. *Science*. 321, 111–113.
Weertman, J., 1972. General theory of water flow at the base of a glacier or ice sheet. *Rev. Geophys. Space Phys.* 10 (1), 287–333.
Weertman, J., 1973. Can a water-filled crevasse reach the bottom surface of a glacier?. In: *IUGG-IAHS Symposium on the Hydrology of Glaciers, Cambridge, 7–13 September, 1969. IAHS Publ.* 95, 139–145.
Wendt, A., Dietrich, R., Wendt, J., Fritsche, M., Lukin, V., Yuskevich, A., Kokhanov, A., Senatorov,A., Shibuya, K., and Doi, K., 2005. The response of the subglacial Lake Vostk, Antarctica, to tidal and atmospheric pressure forcing. *Geophys. J. Int.* 161 (1), 41–49.
Wendt, J., Dietrich, R., Fritsche, M., Wendt, A., Yuskevich, A., Kokhanov, A., Senatorov, A., Lukin, V., Shibuya, K., and Doi, K., 2006. geodetic observations of ice flow velocities over the southern part of subglacial Lake Vostok, Antarctica, andn their glaciological implications. *Geophys. J. Int.* 166 (3), 991–998.
Wiens, D.A., Anandakrishnan, S., Winberry, J.P., and King, M.A., 2008. Simultaneous teleseismic and geodetic observations of the stick-slip motion of an Antarctic ice stream. *Nature*. 453 (7196), 770–775.
Wingham, D.J., Siegert, M.J., Shepherd, A., and Muir, A.S., 2006. Rapid discharge connects Antarctic subglacial lakes. *Nature*. 440 (7087), 1033–1036.
Wingham, D.J., Wallis, D.W., and Shepherd, A., 2009. Spatial and temporal evolution of Pine Island Glacier thinning. *Geophys. Res. Lett.* 36 L17501, doi:10.1029/2009GL039126.
Wientjes, I.G.M. and Oerlemans, J., 2010. An explanation for the dark region in the western melt zone of the Greenland ice sheet. *The Cryosphere*. 4, 261–268.
Wouters, B., Chambers, D., and Schrama, E.J.G., 2008. GRACE observe small-scale mass loss in Greenland. *Geophys. Res. Lett.* 35, L20501, doi:10.1029/2008GL034816.
Zwally, H.J., Abdalati, W., Herring, T., Larson, K., Saba, J., and Steffen, K., 2002. Surface melt-induced acceleration of Greenland ice-sheet flow. *Science*. 297 (5579), 218–222.