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Understanding Greenland ice sheet hydrology using an integrated multi-scale approach

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Abstract
Improved understanding of Greenland ice sheet hydrology is critically important for assessing its impact on current and future ice sheet dynamics and global sea level rise. This has motivated the collection and integration of *in situ* observations, model development, and remote sensing efforts to quantify meltwater production, as well as its phase changes, transport, and export. Particularly urgent is a better understanding of albedo feedbacks leading to enhanced surface melt, potential positive feedbacks between ice sheet hydrology and dynamics, and meltwater retention in firn. These processes are not isolated, but must be understood as part of a continuum of processes within an integrated system. This letter describes a systems approach to the study of Greenland ice sheet hydrology, emphasizing component interconnections and feedbacks, and highlighting research and observational needs.

Keywords: ice sheet, hydrology, Greenland

1. The need for treating ice sheet hydrology as an integrated system

The Greenland ice sheet is the largest body of permanent ice and snow cover in the Northern Hemisphere spanning over 1.7 million square kilometers (Bamber *et al* 2001), and is sensitive to changes in regional and global climate. Between 1958 and 2010, Greenland ice sheet mass losses are estimated to have almost tripled, increasing from 110 ± 70 $Gt a^{-1}$ (in 1958, Rignot *et al* 2008) to 263 ± 30 $Gt a^{-1}$ (between 2005 and 2010, Shepherd *et al* 2012). Since 1996, roughly 50–61% of these losses are attributed to ice discharge, with the remainder explained by negative surface mass balance from a combination of precipitation variability, runoff losses, and sublimation fluxes (Rignot *et al* 2008, Van den Broeke *et al* 2009). All these processes are strongly connected to

Greenland ice sheet hydrology and have implications for future sea level rise. Should recent (1992–2009) total mass loss rates of $+21.9 \pm 1$ Gta^{-1} from Greenland ice sheet alone continue, global sea level will rise $+9 \pm 2$ cm by 2050 (Rignot *et al* 2011).

The Greenland ice sheet hydrologic system is complex. Each summer, it becomes activated as meltwater is produced on its surface, evaporates and/or ice sublimates into the atmosphere, percolates into firn layers, and feeds runoff into supraglacial lakes, streams and rivers to the ice sheet's margins (figure 1). Water penetrating firn layers is retained if it refreezes (Pfeffer *et al* 1991, Reeh 1991, Greuell and Konzelmann 1994, Boggild *et al* 2005, Boggild 2007), or stored temporarily until critical saturation for runoff formation is achieved (Pfeffer *et al* 1991). A substantial fraction of surface runoff in the ablation zone may drain into crevasses where it can reach deeper into the ice sheet interior, perhaps even reaching the bed (McGrath *et al* 2011). The remaining runoff flows through supraglacial stream networks into moulins for rapid vertical transport deeper into the ice (McGrath *et al* 2011), or temporarily forms lakes on the ice sheet surface (Echelmeyer *et al* 1991). Supraglacial lakes mostly occur on the western part of the Greenland ice sheet (Sundal *et al* 2009), where some lakes can empty rapidly and refill thus episodically propagating meltwater to the bed (Zwally *et al* 2002, Das *et al* 2008) through the melt season. While it is clear that surface meltwater entering moulins, crevasses, and fractures is routed to the bed through a combination of storage elements and transport pathways, both englacial and subglacial drainage systems are imprecisely known. At the glacier margin, meltwater emerges in proglacial rivers and ice-marginal lakes and discharges into fjords along the entire perimeter of the Greenland ice sheet. During non-melt periods in the winter months, any residual meltwater generally refreezes and marginal discharge is greatly reduced. At this time, winter snow accumulation and redistribution becomes the dominant hydrologic process, but sublimation of blowing snow (Lenaerts *et al* 2012) as well as rainfall and occasional melting events (Rennermalm *et al* 2012a) also take place.

Our current limited understanding of Greenland ice sheet hydrological processes is intertwined with unresolved questions of how present and future climate change may influence ice sheet dynamics and potentially trigger positive hydrology–ice dynamics feedbacks. Dynamic losses are known to occur when greater ice velocities increase calving, retreat, and thinning of ice sheet outlet glaciers. These processes also intensify overall melting rates and volume as more ice flows toward lower elevations, where temperatures are warmer and ablation rates are higher (Parizek and Alley 2004). While the most dramatic ice velocity increases are related to calving at marine outlet glaciers (Moon *et al* 2012), positive velocity anomalies induced by surface melting are particularly prominent for land-terminating glaciers (Joughin 2008, Shepherd *et al* 2009, Bartholomew *et al* 2011a, Sundal *et al* 2011). In order for surface melting to influence ice sheet velocity, meltwater must reach the bed and raise basal water pressure and increase ice-sliding velocities. Theoretical

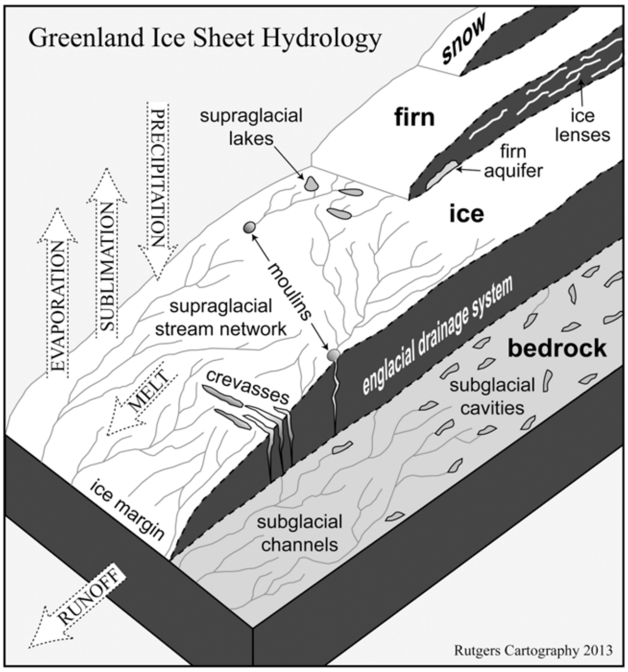

Figure 1. Schematic cross section of Greenland ice sheet hydrology from the ice margin to the interior divide for a land-terminating outlet where snow, firn, and ice layers are shown in a cutaway view to illustrate internal structures. Surface mass balance terms are shown as stippled arrows. Englacial and subglacial features are particularly poorly known.

studies show that rapid fracture propagation to the bed is entirely possible (Van der Veen 2007), and this is supported by observational evidence of marked velocity increases in response to supraglacial lake drainage (Zwally *et al* 2002, Das *et al* 2008) as well as pronounced seasonal velocity variability in moulin-dense regions (Van de Wal *et al* 2008). However, the relationship between velocity and surface melt is not simply linear. In contrast to ice sheet velocities over shorter time periods, annual velocities appear unrelated to ablation rate (Van de Wal *et al* 2008), which suggests the existence of self-regulating mechanisms tied to subglacial drainage network development (Pimentel and Flowers 2010, Schoof 2010, Colgan *et al* 2011, Sundal *et al* 2011).

A central question related to Greenland hydrology is how much meltwater is truly lost to the ocean and thereby ultimately contributes to rising global sea levels. To understand this contribution, four interconnected aspects of the Greenland hydrologic system must be better understood: (1) surface mass balance, (2) meltwater retention, (3) feedbacks between ice sheet hydrology and dynamics, and (4) runoff losses to the ocean at the ice sheet margin. Notwithstanding advances in surface mass balance modeling of the Greenland ice sheet (Mote 2003, Hanna *et al* 2005, Box *et al* 2006, Ettema *et al* 2009, Mernild *et al* 2009, Fettweis *et al* 2012, Fitzgerald *et al* 2012), confidence in mass balance flux magnitudes remains low due to the poorly understood hydrologic system. This includes uncertainties about precipitation inputs (Ettema *et al* 2009, Burgess *et al* 2010), scarcity of *in situ* validation, incomplete and

uncalibrated near-surface air temperature data (Shuman *et al* 2001), and albedo feedbacks from surface melting (Box *et al* 2012). Adding to this uncertainty is limited knowledge about meltwater volumes and fluxes retained in supraglacial lakes and internal glacial storage reservoirs (Sundal *et al* 2009, Rennermalm *et al* 2012a), and meltwater refreezing in firn (Pfeffer *et al* 1991, Forster *et al* 2012, Harper *et al* 2012, Humphrey *et al* 2012). Furthermore, feedback mechanisms between ice sheet hydrology and ice sheet dynamics are being examined with modeling (Phillips *et al* 2010, Schoof 2010, Colgan *et al* 2011, 2012), but require more observational work. Actual meltwater losses can be monitored in rivers and streams, but such observations are sparse especially considering the large number of such streams active during the melt season (Van de Wal and Russell 1994, Mernild and Hasholt 2009, Rennermalm *et al* 2012b), and can only partly be estimated using remotely sensed discharge-fjord sediment area/concentration relationships (Chu *et al* 2009, 2012, McGrath *et al* 2010).

Ice sheet hydrologic elements and processes have many similarities with glaciers and ice caps (consult these comprehensive reviews: Fountain and Walder 1998, Jansson *et al* 2003, Hock 2005, Irvine-Fynn *et al* 2011). However, it is unclear if Greenland ice sheet hydrology can be considered simply an upscaled version of glacier hydrology (Irvine-Fynn *et al* 2011) or whether scale changes produce new and unique behaviors. Similarly, the Greenland ice sheet might not behave as a downscaled Antarctic ice sheet given Greenland's much more active hydrological system. Here, we argue that a better understanding of Greenland ice sheet hydrology can be obtained by bridging gaps between small-scale process studies, large-scale modeling, and satellite remote sensing efforts. This requires higher density and availability of high-resolution satellite remote sensing products, airborne observations, field observations, and scaling studies. To demonstrate these points, we briefly review components and processes of Greenland ice sheet hydrology and how they fit together in an integrated system, identify critical components where progress is urgently needed, and discuss why a multi-scale approach is necessary to gain better understanding of this very large ice sheet in a changing climate.

2. Components of the hydrologic system of the Greenland ice sheet

2.1. Surface mass balance

Surface mass balance refers to the net balance over an annual period between accumulation from precipitation and ablation from runoff production, sublimation and evaporation. Besides its relevance for its sea level rise contribution, it has important impacts on surface energy balance (Tedesco and Steiner 2011), ice sheet thermal state (Phillips *et al* 2010), and ice-flow dynamic processes (Zwally *et al* 2002, Sundal *et al* 2011).

2.1.1. Snow accumulation. With nearly all precipitation falling as snow at this time across Greenland, snow accumulation is the primary input to the ice sheet surface mass (Box *et al* 2006). The general spatial pattern is well established with maximum snow accumulation along parts of the southeast coast and local maxima in northeast and/or northwest corners (Cogley 2004, Hines and Bromwich 2008, Bales *et al* 2009, Burgess *et al* 2010, Linling *et al* 2011). Interannual and high-spatial-resolution accumulation products, however, have low confidence due to scarce availability of *in situ* validation from ice cores, snow pits (Ohmura and Reeh 1991, Mosley-Thompson *et al* 2001, Hawley *et al* 2008), and snow depth observations at automatic weather stations (Bales *et al* 2009). Remotely sensed snow accumulation may eventually alleviate the need for *in situ* observations, but is currently experimental (e.g. Drinkwater *et al* 2001). Shortcomings in snow accumulation estimates propagate to a rather large uncertainty into ice sheet surface mass balance estimates (see section 2.1.2). Additionally, modeling studies show locally important drifting snow processes in southwest Greenland (sublimation) and southeast Greenland (erosion/redistribution) acting to reduce annual accumulation totals, but are currently unconfirmed by observational studies (Lenaerts *et al* 2012).

About 80% of current accumulation variance can be explained by large-scale atmospheric circulation and its interaction with the geometry of the ice sheet (Van der Veen *et al* 2001), and is associated with onshore and upslope flow of moist air strongly correlated with the North Atlantic Oscillation (NAO) (Rogers 2004). Global climate models predict that future circulation changes will enhance the meridional flux over the region, which will increase heat and moisture transport to Greenland (Franco *et al* 2011). This may lead to heavier snowfall and a positive net mass balance on the eastern side of the ice sheet (Kiilsholm 2003), even if the total net effect for all of Greenland is negative (Fettweis *et al* 2012). Additional heat and moisture may stem from enhanced ocean–atmosphere fluxes triggered by reduced sea ice extent and thickness (Serreze *et al* 2009, Screen and Simmonds 2010) as the Arctic Ocean transitions to largely ice free during summer months in the 21st century (Stroeve *et al* 2012). Already under present climate, sea ice variability covaries strongly with ice sheet surface melting in some regions (Rennermalm *et al* 2009). While linkages between sea ice and Greenland ice sheet surface accumulation and ablation are under explored, modeling studies show that sea ice reductions may influence surface climate many 100 km away from the coast (Lawrence *et al* 2008, Higgins and Cassano 2009, 2011).

2.1.2. Surface mass balance estimates. All surface mass balance studies show increasingly negative surface mass balance and larger runoff magnitude since the mid-20th century for Greenland (Mote 2003, Hanna *et al* 2005, Box *et al* 2006, Ettema *et al* 2009, Mernild *et al* 2009, Fettweis *et al* 2012, Fitzgerald *et al* 2012). Between 1961 and 1990, Greenland's total mass balance gains were stable (Van den Broeke *et al* 2009, Hanna *et al* 2011) and approximately balanced by its ice discharge losses (Rignot *et al* 2008). Over roughly that same time interval, the Greenland ice sheet

supplied the surrounding oceans with ∼220–550 (±86) Gta^{-1} ice discharge (assumed equal to surface mass balance) from calving marine-terminating glaciers, and ∼250–264 (±26–45) Gta^{-1} from ice sheet runoff along the ice sheet margin (Hanna *et al* 2005, Fettweis 2007, Ettema *et al* 2009, Van den Broeke *et al* 2009, Mernild and Liston 2012). Since the mid-1990s, velocity has fluctuated significantly for individual outlet glacier (Rignot and Kanagaratnam 2006, Rignot *et al* 2008, Moon *et al* 2012), but increased overall (Moon *et al* 2012) resulting in ice discharge between ∼440 and 600 Gta^{-1} (Rignot *et al* 2008, Van den Broeke *et al* 2009), while ice sheet runoff has steadily increased to ∼400–429 (±57) Gta^{-1} (Fettweis 2007, Ettema *et al* 2009, Mernild and Liston 2012) during 2000–10. Runoff mass losses would have been 100% higher since 1996 if not they had not been offset by increased snowfall and refreezing trends (Van den Broeke *et al* 2009).

The surface energy balance is the main driver for surface mass losses, and is the sum of incoming and outgoing radiative (shortwave and longwave) and turbulent (sensible and latent heat) fluxes modulated by clouds, winds, topography, and other factors (Cuffey and Paterson 2010, Ettema *et al* 2010). Albedo is particularly important because it controls absorption of incoming solar radiation, which is the main surface energy balance component (Van den Broeke *et al* 2008, Tedesco *et al* 2011, Box *et al* 2012). Furthermore, model sensitivity studies show that albedo parameterization is the most important parameter controlling future surface mass balance estimates (Fitzgerald *et al* 2012). In concert with low albedo and high potential for energy release from meltwater refreezing in firn, most melt energy is concentrated near the ice margin, but substantial melt energy can be also found far inland, particularly in southwest Greenland (Ettema *et al* 2010). In the southwest Greenland ablation zone, sensible heat fluxes provides nearly half the melt energy at lower elevations, while net shortwave radiation is the primary driver at higher elevations (Van den Broeke *et al* 2008, 2011) and in most of the ice sheet ablation zone (Ettema *et al* 2010). Between 2000 and 2011, average ice sheet melting season albedo displayed a strong decline indicating its growing importance in driving melt anomalies (Box *et al* 2012). In a future, warmer climate, currently snow covered parts of the percolation zone are likely to expose an underlying darker ice surface resulting in a positive albedo feedback (Box *et al* 2012, Franco *et al* 2012) augmented by enhanced sensible heat advection projected to increase positive melt anomalies especially near the ice sheet margin (Franco *et al* 2012).

Considerable effort needs to be placed on constraining error estimates on reconstructions of past and future surface mass balance components. Surface mass balance estimates are typically made with models of different sophistication levels ranging from positive degree-day models (e.g. Braithwaite 1995), to energy balance models (e.g. Van den Broeke *et al* 2008). Positive degree-day models relating cumulative positive temperatures to surface melting (Braithwaite 1995, Hock 2003) have been useful in providing first order estimates of present and future Greenland ice sheet surface melting (Mote 2003, Box *et al* 2004, 2006, Hanna *et al* 2008). However, energy balance models simulate the actual surface mass balance drivers (Van de Wal and Oerlemans 1994, Van den Broeke *et al* 2008, Van As *et al* 2012), which allows for more detailed investigation of ice sheet hydrology physics, e.g. dependence of firn refreezing on albedo parameterization (Van Angelen *et al* 2012), blowing snow (Lenaerts *et al* 2012), and underlying causes for melt extremes (Tedesco *et al* 2008, 2011).

Model improvements can be made by exploring causes for model disagreement, including initial and boundary conditions, and differences in processes resolved by various models (Fettweis *et al* 2011, Rae *et al* 2012), such as retention in cold snow (Pfeffer *et al* 1991, Greuell and Konzelmann 1994, Janssens and Huybrechts 2000, Boggild *et al* 2005), ice mask extent (Vernon *et al* 2012), parameterization of albedo and topography (Rae *et al* 2012), englacial storage, and snow compaction (Wake *et al* 2009). Increased process understanding of meltwater storage in firn, lakes, englacial and subglacial storages and hydrological drainage networks (see sections 2.2–2.4) will allow time evolution of spatially distributed runoff to be fully integrated into hydrologic runoff-routing models, and water exchange between surface- and en-, and subglacial environments (see section 2.4). A central challenge for model improvements is sparse data availability for ground truth validation from both automatic weather stations (Steffen and Box 2001, Van de Wal *et al* 2005, van As and Fausto 2011) and ablation stakes (Andersen *et al* 2010, Van de Wal *et al* 2012). This is particularly problematic regarding meltwater percolation, refreezing and storage in firn layers (see section 2.2), and point validation of surface energy and mass balance components (see section 4), while spatially distributed high-resolution albedo and surface and basal topography products are becoming increasingly available (see section 4).

Scarcity of *in situ* validation data can be partially overcome by extending the surface mass balance record (e.g. Wake *et al* 2012) to re-evaluate the relationship between surface mass balance and ice dynamics over longer time scales (Hanna *et al* 2011), using remotely sensed surface melt area extent as independent model validation (Fettweis *et al* 2011, Mernild *et al* 2011b) as well as reconciling modeled mass balance losses with temperature anomalies (Hanna *et al* 2011), and total mass loss determined with satellite observations from the Gravity Recovery and Climate Experiment (GRACE) (Velicogna and Wahr 2005, Ramillien *et al* 2006, Wouters *et al* 2008, Van den Broeke *et al* 2009, Chen *et al* 2011, Siemes *et al* 2013). Remotely sensed melt area extent with passive microwave sensors and mass loss determined with GRACE have relatively coarse resolution (25 km and larger) and are thus sufficient for large-scale validation, but offer little insight into surface mass balance processes. Another strategy includes implementing schemes that allow validation with remotely sensed fields, e.g. comparison of albedo determined with remote sensing and modeled as a function of grain size provides insight into grain size model components (Van Angelen *et al* 2012). Perhaps the greatest potential of currently available remotely sensed data products lies in improving initial and boundary

forcing for surface mass balance models. This includes fields of ice albedo (Lenaerts *et al* 2012), and could be extended to include radiation balance components from the Clouds and the Earth's Radiant Energy System (CERES) sensor on NASA's Aqua and Terra missions (Wielicki *et al* 1996, Zhou *et al* 2007), near-surface atmospheric moisture and temperature profiles from the AIRS experiment on NASA's Aqua mission (Susskind *et al* 2003), cloud cover with Moderate-Resolution Imaging Spectroradiometer (MODIS), and cloud properties with CloudSat and the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) (Liu *et al* 2012).

2.2. Surface meltwater retention and refreezing in firn

In the lower reaches of the accumulation zone, referred to as the percolation zone, surface meltwater is produced and can run off or be retained within the snowpack and/or firn such that runoff leaving the ice sheet is less than the total meltwater production. Meltwater retention and refreezing may be quite substantial. Two widely applied surface mass balance models (MAR and RACMO2) estimate annual average refreezing to 202 and 295 Gta^{-1} between 1958 and 2007, which is 45–49% of the total annual melt (see supplemental documentation in Ettema *et al* 2009). For refreezing to occur, meltwater must percolate deeper into available firn pore space. A first estimate puts percolation zone firn meltwater storage capacity between 322 (±44) to 1289 (−252, +388) Gt (Harper *et al* 2012). Adding to these numbers is the recent discovery of widespread perennial water saturated firn aquifers (Forster *et al* 2012). Most runoff is produced in the ablation zone, without significant firn storage capacity, and annual snow fall will replenish firn mass, such that it will take decades to exhaust firn storage capacity (Harper *et al* 2012). A string of recent years with record widespread ice sheet surface melting in 2005 (Hanna *et al* 2008), 2007 (Mote 2007, Tedesco 2007a), 2010 (Box *et al* 2010), and 2012 (Nghiem *et al* 2012) suggest that buffering of meltwater losses by firn storage may grow in importance as surface melting becomes more frequent in the percolation zone. Thus, high priority should be given to further constrain storage capacity, meltwater percolation, and refreezing in firn.

Modeling has the potential to become an important tool in constraining firn storage capacity and meltwater refreezing in firn. However, current surface mass balance model estimates of firn meltwater refreezing of total melt vary widely from 13–23% in simpler models to 45–49% in more comprehensive models (see supplemental documentation in Ettema *et al* 2009). To date, relatively little work has been done in determining a robust refreezing scheme for Greenland, partly due to lack of *in situ* observational data for validation (Bougamont *et al* 2007, Reijmer *et al* 2012). While sensitivity studies show that refreezing parameter uncertainty in a surface mass balance model are smaller than other parameters (i.e., albedo), it still has regional importance (Fitzgerald *et al* 2012). At the same time, more studies are needed to understand the significance of meltwater percolation and refreezing processes.

A key outstanding question is the fate of meltwater as it percolates into firn layers: will meltwater be retained as frozen ice lenses and saturated slush layers, or will it runoff along perched ice lenses and the firn/ice interface? Observational evidence suggests that most meltwater refreezes at depth at higher elevations, while at lower elevations water is more likely to migrate horizontally and escape as runoff (Harper *et al* 2012, Humphrey *et al* 2012). In between, a continuum of processes from complete refreezing and runoff takes place, including: (1) inhomogeneous flow or 'piping'; (2) advancing meltwater front; (3) freezing of meltwater deep into firn (Humphrey *et al* 2012). Meltwater retained in the upper snow and/or firn layers throughout the summer refreeze during winter, forming a high density ice layer that often can be observed in the upper few meters (Braithwaite *et al* 1994, Benson 1962, Humphrey *et al* 2012), and releasing latent energy raising firn temperatures (Pfeffer *et al* 1991, Reeh 1991, Humphrey *et al* 2012). At depths (>10 m), year round presence of liquid water has been inferred from temperature observations (Humphrey *et al* 2012) and confirmed in the field with the recent discovery of extensive perennial firn aquifers (PFA) (Forster *et al* 2012).

The PFA represents a new storage mechanism for the ice sheet, and needs to be considered in ice sheet mass and energy budget calculations and possibly dynamic models as well. Direct evidence of ice sheet liquid water retention in PFA over winter was discovered in April 2011 in southeast Greenland while drilling two ice cores at ∼1600 m elevation (Forster *et al* 2012). The top of the April 2011 PFA was traced by ground penetrating radar to lie between 8 and 25 m (Forster *et al* 2012). Airborne radar data from NASA's Operation IceBridge (OIB) (Koenig *et al* 2010) acquired 11 days prior to the ground observations and high-resolution coupled regional atmosphere–firn model (Van Angelen *et al* 2012) showed that PFAs are concentrated in the south and retained 17 ± 1 Gt of water in April 2011 (Forster *et al* 2012).

2.3. Supraglacial lakes

Supraglacial lakes form during the summer in topographic depressions on the Greenland ice sheet surface, and incise into the surface by roughly doubling ablation rates through lowered surface albedo (Luthje *et al* 2006, Tedesco *et al* 2012). These lakes cover large areas, particularly in southwest Greenland where an average of 61% of the total ice sheet became lake covered between 2005 and 2009 (Selmes *et al* 2011). However, assessments of meltwater volume and fluxes from these lakes are in their infancy, such that the importance of these lakes in terms of net storage and ice sheet dynamic feedbacks (see section 3) is still unknown.

Lake basins may persist from year-to-year or drain episodically (Selmes *et al* 2011, Liang *et al* 2012), and sometimes supply meltwater deep into the ice sheet (Das *et al* 2008). Over the course of the melting season, supraglacial lakes are established in longitudinal bands at increasingly higher elevations (Sundal *et al* 2009, Lampkin 2011). During warmer years, supraglacial lakes drain more frequently and earlier in the melt season, with the lake population extending

to higher elevations over the course of the summer (Liang *et al* 2012). This suggests that recent increases in surface meltwater production (Tedesco *et al* 2008, 2011) may increase the spatial extent, temporal frequency and season of lake drainage events. Assuming this water reaches the bed, this could also influence the spatial pattern of ice sheet velocity (see section 3).

Estimates of lake area and volume can be made with optical satellite imagery (Box and Ski 2007, Sneed and Hamilton 2007), but have only been validated in a relatively small number of studies (Sneed and Hamilton 2007, Tedesco and Steiner 2011). However, there is considerable uncertainty associated with remotely sensed estimates of lake volume because of the assumed impact of optical parameters (e.g., bottom albedo, water attenuation factor) on lake depth retrieval (Box and Ski 2007). One way to improve estimates of the lakes volume and their role in the hydrologic system is through the combination of *in situ* measurements of bathymetry, satellite data and modeling (Banwell *et al* 2012).

2.4. Ice sheet hydrologic network

The Greenland ice sheet hydrologic network is likely to play an important role in regulating feedbacks between hydrology and ice sheet dynamics (see section 3), but also dictates where meltwater and sediment exit the ice sheet to surrounding oceans. Exploration of these features are just beginning, and aside from modeling includes mapping of supraglacial channels using high-resolution remote sensing observations (Yang and Smith 2013) and identification of moulins and englacial structures with ice penetrating ground radar (Catania *et al* 2008, Catania and Neumann 2010).

Modeling hydrological networks allows investigations of connections between meltwater production, input into the subglacial environment, and ice dynamics, but also helps constrain true ice sheet meltwater flux to oceans. Two distinct model types are being developed to better understand the importance of the ice sheet's hydrological connections. The first type of model represents linkages between supra and subglacial hydrology (Flowers and Clarke 2002), which are essential to understand interactions between surface mass balance and ice sheet dynamics (see section 3). Currently, this type of model has only been applied to small parts of the ice sheet (Colgan *et al* 2011) or in idealized experiments (Pimentel and Flowers 2010, Schoof 2010, Hewitt 2011). These first model implementations show how meltwater production and propagation to the bed and seasonal development of the subglacial drainage system are linked to ice sheet velocity speedups, an important unknown in sea level rise projections (see section 3).

The second type of model characterizes large-scale drainage patterns for the entire ice sheet using ice sheet topography datasets, either most simply from the shape of the hydrostatic pressure field by also incorporating basal bedrock topography, (Lewis and Smith 2011), or surface topography combined with a network of linear reservoirs (Liston and Mernild 2012, Mernild and Liston 2012). Linear reservoir modeling can be traced back to classical hydrologic theory (Brutsaert 2005) and has been applied at smaller scales to model meltwater runoff from glaciers (Hock and Noetzli 1997, Klok *et al* 2001, Verbunt *et al* 2003, Hock *et al* 2005) and the Greenland ice sheet (Van de Wal and Russell 1994). The primary benefit of these models is perhaps their capability to examine interannual and melting season network dynamics (Lewis and Smith 2011), and to estimate where and when meltwater exits the ice sheet (Liston and Mernild 2012, Mernild and Liston 2012). However, greater importance of moulins relative to crevasses to transmit meltwater (McGrath *et al* 2011), and strong correlation between late summer ice sheet velocity change and supraglacial channelization patterns (Palmer *et al* 2011) suggest that mapping and modeling drainage network structures at high resolution may be central to understand feedbacks between ice sheet hydrology and dynamics.

2.5. Understanding ice sheet hydrology through analysis of river discharge

River discharge provides direct observations of how much meltwater actually escapes the ice sheet, and has great potential for calibrating and validating surface mass balance models (Mernild *et al* 2011a, Van As *et al* 2012). This can provide information regarding seasonal development of the subglacial drainage system (Bartholomew *et al* 2011b, Bhatia *et al* 2011), capturing catastrophic drainage events (referred to as jökulhlaups) that are a common occurrence in the Greenland proglacial zone (Mernild and Hasholt 2009, Mernild *et al* 2008, Russell *et al* 2011, Russell 1989, 2009), and assessment of meltwater retention (Rennermalm *et al* 2012a). Unfortunately, very few rivers have been and are currently being monitored in Greenland especially as a percentage of the total number (Van de Wal and Russell 1994, Mernild and Hasholt 2009, Rennermalm *et al* 2012b) because of remoteness as well as due to difficulties with measuring discharge in braided, and highly turbid rivers.

Further insight into glacial hydrologic drainage systems is possible using tracers such as radiogenic, cosmogenic isotopes, and stable isotopes of water, naturally occurring elements, and meltwater physicochemical properties. These approaches have long been used for alpine glaciers (Tranter and Raiswell 1991, Theakstone and Knudsen 1996, Tranter *et al* 1996, e.g. Fountain and Walder 1998, Lyons *et al* 2002), and are increasingly being applied to Greenland. For example, variations in electrical conductivity can identify links between subglacial lake drainage and peaks in proglacial river discharge (Bartholomew *et al* 2011b). Stable isotope composition (δ^{18}O, δD) of meltwater runoff may also be useful, because isotopic compositions in snow reflect atmospheric circulation patterns and temperatures, such that isotope composition correlates strongly with elevation and distance from the ocean (Dansgaard 1964, Dansgaard *et al* 1993, Vinther *et al* 2010), and can be used to constrain drainage areas by the ice margin (Reeh and Thompson 1993). Flow paths may be traced using conservative tracers such as Na^+, Cl^-, Ca^{2+}, and Sr^{2+}, which are highly soluble and have low affinity, thus allowing their concentration to be used as an indication of channelized versus distributed drainage systems

(Tranter *et al* 2002), and meltwater storage in non-melting winter months (Wadham 2000). Meltwater source areas and ages may be established with non-conservative isotope tracers such as ^{210}Pb, and ^{7}Be, which have lower solubility and high tendency to adhere to particle surfaces or form colloids. Strontium isotope ratios (^{87}Sr/^{86}Sr) are stable, unique to rocks and minerals, and can identify weathering reactions (Lyons *et al* 2002). ^{87}Sr/^{86}Sr has successfully been used to identify source areas of solutes and sediments for a proglacial stream in Greenland by tracing subglacial erosion areas or differentiating between solute input from atmospheric dust versus bedrock (Hagedorn and Hasholt 2004). Finally, isotopes such as ^{7}Be, and ^{210}Pb provide insights into age of water and dust, and of residence time of surface meltwater within the glacial system. Seasonal variations in the cosmogenic isotope ^{7}Be can quantify contribution of fast flow-dominated surface meltwater, while ^{222}Rn, a uranium decay product in rocks and sediments, may reveal changes from a cavity-dominated to channel-dominated subglacial drainage systems (Bhatia *et al* 2011, Kies *et al* 2011). ^{22}Na is another cosmogenic isotope that, if current limitations are overcome, could become an important method in understanding meltwater flow pathways (currently, analysis of ^{22}Na requires collection of an unfeasible, >500 l, amount of water as well as its transport to a laboratory) (Zhang *et al* 2010).

2.6. Understanding of Greenland ice sheet hydrology with remote sensing techniques

The scarcity of data of direct mass losses such as river discharge data requires other indicators of meltwater runoff to be explored, such as remote sensing techniques. Fjord sediment plumes, visible in remotely sensed images, provide a link between meltwater produced on the ice sheet surface and meltwater released to the ocean (Chu *et al* 2009, McGrath *et al* 2010). Sediments produced as ice move over bedrock are flushed out with meltwater to form buoyant freshwater plumes floating over more dense saline marine water. These plumes are most readily detected downstream of rivers draining land-terminating glaciers, owing to high suspended sediment concentration and minimal obstruction by calving ice. For such rivers, excellent agreement between plume length and discharge demonstrate how this method can capture meltwater variability averaged over a few days (McGrath *et al* 2010). On a larger scale, ice sheet meltwater release from marine-terminating glaciers can also be determined. Comprehensive analysis of remotely sensed sediment fluxes from all of Greenland illustrate highest meltwater losses in Southwest Greenland (Chu *et al* 2012) consistent with the spatial distribution of surface runoff and drainage area configuration (Lewis and Smith 2011). The greatest promise of this method lies perhaps in inferring meltwater discharge variability, as absolute losses require site-specific calibration. However, before this method can be systematically applied, importance of site-specific conditions must be established. This includes braided river plain influence on sediment transport, relationship between fjord geography/bathymetry and salinity, and how glaciological variables such as glacier size, sliding speed, ice flux, erosional susceptibility of bedrock, and meltwater production influence sediment production (Hallet *et al* 1996).

Another unexplored avenue for examining meltwater loss variability is using high-resolution remote sensing observations to assess braided river width. River width, similar to river depth and velocity, can typically be expressed as a power-law function of discharge (Leopold and Maddock 1953). This technique has been applied successfully to Arctic braided river systems (Ashmore and Sauks 2006, Smith *et al* 1996, Smith 1997).

3. Potential feedbacks and linkages between ice sheet hydrology and dynamics

Ice sheet hydrology and dynamics are linked in three ways. First, enhanced ablation along the margin (and perhaps more accumulation in the interior) (see section 2.1.1) increase the ice sheet slope, which is the primary driver of deformational ice sheet movement (Cuffey and Paterson 2010). Second, enhanced meltwater input into the ice sheet can induce cryo-hydrologic warming leading to expanding area of thermal bed conditions (Phillips *et al* 2010) which in turn may increase sliding velocities. Finally, increased meltwater input into the ice sheet hydrologic system could overwhelm subglacial transmission capacities resulting in basal sliding and speed up. All three processes may bring more ice mass to lower elevations with amplified ablation rates resulting in a positive feedback effect. However, this positive feedback effect is brought into question by recent observations and modeling studies suggesting that development of an efficient subglacial meltwater transportation system essentially self-regulates the speedup.

Early models coupling ice sheet dynamics with surface energy balance demonstrate enhanced losses when basal sliding is considered (Van de Wal and Oerlemans 1997). Later modeling studies show that the efficiency of basal sliding is modulated by two processes: (1) englacial water transmission rates (McGrath *et al* 2011), and (2) the state of the subglacial hydrologic system (Pimentel and Flowers 2010, Colgan *et al* 2011). Regarding the first process, it is known that ice velocity may increase five- to ten-fold in response to episodic lake drainage (Hoffman *et al* 2011) for portions of the year, but can also speed up in response to continuous meltwater input (Pimentel and Flowers 2010, Colgan *et al* 2011). Modeling studies suggest that fast meltwater propagation through moulins is more likely to exhaust basal drainage capacity and result in basal sliding than slow flow seeping through crevasses and fractures (McGrath *et al* 2011).

The ice sheet subglacial hydrologic drainage systems can be described as bi-stable systems, where one state is channelized flow that is highly efficient at transporting water, and the alternate state is slow flow through interconnected cavities formed at the ice/bedrock interface, and/or incised bedrock channels with permeable bed sediments (Kamb *et al* 1994, Fountain and Walder 1998, e.g. Cuffey and Paterson 2010, Sundal *et al* 2011). According to this theory, early

melting season subglacial water flows mostly through cavities with low transmission capacity. At this time, large meltwater inputs may overwhelm basal water transport capacity and trigger basal sliding as a result of bed separation and reduced basal friction (Iken and Bindschlader 1986, Anderson 2004, Bartholomaus *et al* 2008). As the melting season progresses, an efficient channelized subglacial drainage system evolves that allows greater meltwater throughput. This explains why ice sheet velocities may decelerate despite further surface melting (Schoof 2010). Observations of seasonal shifts from cavity to channel-dominated flow have been inferred from velocity measurements made with global positioning systems (Bartholomew *et al* 2010), remote sensing (Sundal *et al* 2011), isotope studies (Bhatia *et al* 2011), and shown by modeling studies (Pimentel and Flowers 2010, Colgan *et al* 2011).

Efforts are needed to deepen and expand exploration of linkages between ice sheet hydrology and velocity. While laser and radar altimetry starting in 1994 demonstrated thinning along Greenland's coast and thickening ice in the interior (Krabill *et al* 2000, Thomas *et al* 2006, 2008, Pritchard *et al* 2009, Sørensen *et al* 2011), some estimates of future surface mass losses do not consider amplified ablation due to thinning (Franco *et al* 2012).

4. Toward an integrated multi-scale approach for better understanding of Greenland ice sheet hydrology

A major motivation to study Greenland ice sheet hydrology is its current and likely future impact on global sea levels (Shepherd *et al* 2012). Meltwater flux from the ablation zone escaping at the ice sheet margin are controlled by surface mass balance, meltwater retention, and how much runoff is channeled through networks of supra-, en-, and subglacial cavities and channels. While some supraglacial channels drain at the ice sheet margin into rivers, fjords and lakes, frequent drainage occurs through moulins and crevasses into englacial and subglacial environments. In en- and subglacial environments, additional water is supplied from melting of channel walls. Eventually, meltwater routed through the hydrologic network reaches the ice sheet margin and is delivered to lakes, rivers, and fjords, ultimately reaching the ocean. In addition, meltwater runoff also contributes to raising sea levels augmented by ice discharge at calving glaciers, a type of dynamic loss, modulated by oceanic drivers (e.g. Holland *et al* 2008), and the state of the subglacial system.

Three issues are particularly important to resolve to better constrain future ice sheet hydrologic influence on sea levels. These are: (1) albedo feedbacks; (2) feedbacks between ice sheet hydrology and dynamics; and (3) meltwater retention in firn. Surface albedo plays a fundamental role in both seasonal and long-term ice sheet meltwater export by modulating net solar radiation, the single most important melt driver in the ablation zone (see section 2.1.2). Positive feedback interactions between hydrology and ice dynamics could amplify meltwater losses and are currently not accounted for in model projections (see section 3). Finally, firn meltwater storage has a huge potential to buffer meltwater losses for decades (see section 2.2), and improved confidence in modeling of this process is urgently needed (see section 2.1.2). These three processes' influence on meltwater export to the ocean must be estimated and modeled before accurate projections about future sea level changes from the Greenland ice sheet can be made. However, because these processes do not operate in isolation, but are interconnected through various hydrologic pathways and processes manifested on different spatial scales and configuration, a multi-scale integrated approach is needed.

Ice sheet surface albedo is modulated by all surface hydrologic processes. Over the melting season, all these factors collectively act to darken the ice sheet surface through refreezing in firn (larger grain sizes result in lower albedo), expansion of supraglacial lakes and stream networks, migration of the snow/firn (high albedo) line to higher elevations, and concentration of dust and sediment (low albedo) on the ice surface as they melt out. The only exceptions to melt season albedo reduction are occasional summer snowfall events that lighten the ice sheet surface and increase albedo.

Linkages between hydrology and ice sheet dynamics appear to be modulated by the state of the subglacial drainage system (see section 3), but also by englacial transport system efficiency (see section 2.4). Regardless of the state of the bi-stable subglacial hydrologic network, ice-marginal areas tend to respond faster to surface melting than thicker inland areas, suggesting amplified future dynamic meltwater losses from land-terminating outlet glaciers (Bartholomew *et al* 2011a) as melt intensity and duration increases inland across the ice sheet (Hanna *et al* 2008, Mernild *et al* 2010a), and melts snow to expose darker ice surfaces (Fettweis *et al* 2012).

Firn percolation is intimately linked to the runoff production term of the surface mass balance (see section 2.2). Meltwater percolating into the firn may be retained in pore space, form aquifers, or refreeze as ice lenses (see section 2.2). Firn meltwater volume is controlled by firn storage capacity and surface mass balance. However, only part of the total meltwater production ends up in firn layers with the remainder being routed to the supraglacial hydrological network in lakes, crevasses, streams, and moulins (see section 2.4). Thus, understanding of this process is aided by better-constrained surface mass balance flux partitioning, and meltwater export estimates.

To advance our understanding of these components of the hydrological systems all modes of geophysical exploration are needed, including *in situ* observations, modeling studies, and incorporation of climate reanalysis data, airborne, and remotely sensed datasets. To this end, the cryosphere science community has benefited tremendously from data sharing, for example *in situ* weather station networks on and off the ice sheet, including well established, ongoing efforts such as Danish Meteorological Institute (e.g. Laursen 2010) and Greenland Climate Network's automated weather stations (AWS) (Steffen and Box 2001), and ablation stakes along the so called K-transect in west Greenland (Van de Wal *et al* 2005, e.g. Van den Broeke *et al* 2008, 2011), the

PROMICE network (van As and Fausto 2011), and coastal AWS operated by Danish Meteorological Institute and Asiaq available at National Climate Data Center (National Climate Data Center 2012). Many of these networks provide real time observations, and are often used in surface mass balance modeling efforts as either independent validation (e.g. Ettema *et al* 2009) or forcing inputs (e.g. Mernild *et al* 2010b) (section 2.1.2). *In situ* studies also provide unique datasets that are becoming increasingly available online, for example proglacial river discharge (e.g. Rennermalm *et al* 2012b), surface mass balance (Van de Wal *et al* 2012), and ice cores (Bales *et al* 2001, 2009). All of these help constrain error estimates of surface mass balance components.

At this time, the exact roles and functions of internal and supraglacial hydrologic pathways and water storage remains a knowledge void and scientific frontier, which limits predictive modeling of ice sheets in a changing climate. However, increasingly sophisticated models are being developed and applied to examine details of the hydrologic system, for example, the en- and subglacial drainage system (see section 2.4). Collaborations around model output sharing and comparison are frequently seen (Fettweis *et al* 2011, Rae *et al* 2012, Reijmer *et al* 2012, Vernon *et al* 2012), which helps assessments of forcing data quality, algorithm development and improved representation of processes such as firn refreezing and storage.

Growing availability and diversity of airborne and satellite remote sensing data since the early 1970s are accelerating the subfield of ice sheet hydrology toward new discoveries. Spaceborne passive microwave sensors are instrumental for identifying surface melt timing and extent, (Abdalati and Steffen 2001, Mote 2007, Tedesco 2007b) (section 2.1.2). Total ice sheet mass loss is assessed with the GRACE satellite mission since its launch in 2002 (section 2.1.2). Ice sheet surface properties, including albedo (Hall *et al* 2002, Stroeve *et al* 2006, Hall and Riggs 2007), surface temperature (Hall *et al* 2012), and supraglacial lake distribution (Liang *et al* 2012) are determined using MODIS. High-resolution products from Landsat, Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER), and WorldView among other sensors are used to examine supraglacial lake processes (Box and Ski 2007, Tedesco and Steiner 2011), and even supraglacial streams (Yang and Smith 2013). In Antarctica, subglacial lake changes have been successfully identified with satellite and airborne laser altimetry (Smith *et al* 2009, Scambos *et al* 2011) suggesting that this technology is suitable for Greenland as well. Observations of en- and subglacial properties such as firn aquifers (Forster *et al* 2012), drainage structures (Catania *et al* 2008), layering, and subglacial topography are being facilitated by ground-based ground penetrating radar (GPR) and airborne radars developed and operated by Center of Remote Sensing of Ice Sheets (CreSIS) established by the National Science Foundation at the University of Kansas (Gogineni *et al* 2001, Leuschen *et al* 2010, Paden *et al* 2010), and NASA Operation IceBridge (Koenig *et al* 2010, Studinger *et al* 2010) accessible at the National Snow and Ice Data Center (NASA Operation IceBridge 2012).

Imperative to understanding any ice sheet's hydrologic system is integrating local processes to the scale of the entire ice sheet. To this end, better knowledge of how best these processes should be upscaled is needed. Several promising advances have been made in this direction, including assessing the extent and volume of firn aquifers using ground based and satellite radar observations in combination with surface mass balance models (Forster *et al* 2012) (section 2.2), and mapping supraglacial lakes from multi-temporal satellite data using automated schemes (Sundal *et al* 2009, Liang *et al* 2012) (section 2.3). Newer remote sensing technologies providing very high-resolution images with meter-submeter scale resolution will undoubtedly provide insights into scaling behavior of hydrologic processes such as supraglacial streams and lakes (e.g. Tedesco *et al* 2012, Yang and Smith 2013). One particular upscaling problem is en- and subglacial hydrology due to the inaccessibility of these environments. Scaling and representation of en- and subglacial hydrology will benefit from continued process studies, and advances in modeling of en- and subglacial networks (see section 2.4) in combination with observations of proglacial river discharge with or without tracers (see section 2.5).

5. Conclusions

In this letter, we present a framework for understanding Greenland's meltwater hydrology as an interconnected system of multi-scaled processes. These processes form a set of complex interactions but may be separated into four key hydrologic components necessary to understand this important ice sheet's contributions to present and future global sea level rise: i.e. surface mass balance, meltwater retention, positive feedbacks between hydrology and ice dynamics, and ice sheet margin meltwater losses. Greenland ice sheet hydrology is an exciting, rapidly developing subfield at the nexus of cryospheric and hydrologic science, aided by increased availability of geophysical data as well as new and more capable technologies for remotely sensed observations. Key challenges remain in understanding albedo feedbacks, ice sheet hydrology dynamic feedbacks, and meltwater retention in firn, as well as bridging spatial scales and understanding scaling behavior of small-scale processes, and maintaining consistent observational data sets, both *in situ* and remotely.

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