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Contents

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A Science Plan

(presented as an ISMASS contribution at the International Glaciological Society Conference in Newcastle-upon-Tyne, UK, July 27-31, 2009)

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Ice Sheet Mass Balance and Sea Level: A Science Plan

by C. J. van der Veen and ISMASS

(presented as an ISMASS contribution at the International Glaciological Society Conference in Newcastle-upon-Tyne, UK, July 27-31, 2009)

Abstract

The dynamic response of ice sheets is currently understood to be due to the coupling of four component processes, each corresponding to a specific region of an ice sheet. They are surface mass balance, ice shelf, basal, and englacial processes. Of these four, only englacial processes have the capacity to transmit stress from one area to another, and as such will play the pivotal role in determining how sea level rise can result from grounded ice moving seaward.

The two least well understood scientific issues relating to englacial processes are presently 1) how horizontal stresses are transferred within ice, and what level of detail in the stress balance is required to adequately capture the transfer, and 2) how well must the ice rheology be represented to predict the dynamical evolution of ice with the desired precision. It should also be noted that description of englacial boundary conditions requires advances in understanding of surface, basal, and shelf processes. Hence model uncertainty will remain high until advances in all four processes are made.

The importance of ice sheet modeling efforts has been magnified by recent reports suggesting that sea level rise remains the most poorly constrained and potentially catastrophic impact of climate change. As such, this document has been prepared to coordinate and focus scientific inquiry in the coming years. First, three scientific questions of great significance are posed. Englacial processes and the closely related numerical schemes for addressing them will be pivotal to advancement on the questions, but the other three component processes will play a role as well. The questions are:

1. Will climate change lead to irreversible (non-linear, rapid) ice-sheet response?
2. Does a rapid change lead to a large mass change?
3. Are observed rapid changes "natural variability" or responses to warming?

In this contribution, the scientific background for each of the questions is presented. This is followed with a "roadmap" for studying the questions that is consistent with the best available data.

1. Introduction

Over the past two decades or so, evidence for active ice sheets – both present-day and in the past – has mounted and the traditional view of ice masses responding sluggishly to external forcings has been replaced by the understanding that large ice sheets can undergo rapid changes. The current generation of whole-ice-sheet models employed to predict the response of the Greenland and Antarctic ice sheets to climate change does not incorporate processes allowing rapid changes in the dynamic parts such as outlet glaciers and ice streams. Instead, these models are based on the shallow ice approximation in which the gravitational driving stress in balanced by drag at the glacier base. While this results in a computationally effective numerical solution scheme that allows for time integrations over longer time scales (e.g. several glacial cycles), the implied ice-sheet behavior is slow and precludes rapid changes as have been observed in both Greenland and Antarctica (for a recent description of these numerical models, see Rutt et al., 2009). Consequently, within the context of impacts of anthropogenically-driven climate change, considerable uncertainty remains regarding the response of the Greenland and Antarctic ice sheets to future warming. As acknowledged by the Intergovernmental Panel on Climate Change, "dynamical processes related to ice flow not included in current models but suggested by recent observations could increase the vulnerability of the ice sheets to warming, increasing future sea level rise." (IPCC, 2007)

Recognizing the potential for rapid ice-sheet change driven by climate change, the Scientific Committee for Antarctic Research (SCAR) established the Ice Sheet Mass Balance and Sea Level (ISMASS) working group to evaluate the mass balance of the Antarctic Ice Sheet. The aim of ISMASS is "to develop a revitalized approach towards the assessment of methods and uncertainties in the estimation of Antarctic Ice Sheet mass balance" (ISMASS, 2004). At that time it was recognized that developing a framework for maximizing the synthesis of data collection and interpretation and model development should be a priority for the glaciological community. In an effort to foster closer collaborations across disciplines, a Workshop on "Improving Ice Sheet Models" was held July 5-7, 2008, prior to the SCAR/IASC Open Science Conference, St. Petersburg, Russia. About 45 scientists from different disciplines (ice-sheet modeling, subglacial geophysics and hydrology, oceanography and atmospheric science) participated in formulating this Science Plan, outlining a community strategy for the next 5-10 years to address current inadequacies in prognostic ice-sheet models.

To address inadequacies in current efforts to model observed rapid changes in ice sheets (outlined in detail in Van der Veen & ISMASS, 2007), the Workshop focused on developing a community strategy on how best to (*i*) improve the physical understanding of ice sheet processes responsible for rapid change; (*ii*) incorporate improved physical understanding into numerical models; (*iii*) assimilate appropriate data into the models for calibration and validation; and (*iv*) develop prognostic whole ice-sheet models that better incorporate non-linear ice-sheet response to environmental forcings (such as change in surface mass balance, loss of buttressing from floating ice shelves and ice tongues, and rising sea level). While the ultimate goal is to fully integrate realistic whole ice-sheet models into coupled climate models, it was deemed important to recognize what can realistically be accomplished over the next decade. Hence, three overarching science questions were formulated and strategies developed how best to address these questions.

The dynamic response of ice sheets is currently understood to be due to coupling of four component processes, each corresponding to a specific region of an ice sheet. They are surface mass balance, ice shelf, basal, and englacial processes. Of these four, only englacial processes have the capacity to transmit stress from one area to another, and as such will play the pivotal role in determining how sea level rise can result from grounded ice moving seaward. The two least understood scientific issues relating to englacial processes are presently how horizontal stresses are transferred within ice and what level of detail in the stress balance is required to adequately capture the transfer, and how well must the ice rheology be represented to predict the dynamical evolution of ice with the desired precision. Description of englacial boundary conditions requires advances in understanding of surface, basal, and shelf processes. Hence, model uncertainty will remain high until advances in all four processes are made. This Science Plan presents a "roadmap" for studying these questions that is consistent with the best available data and modelling approaches.

2. Scientific Questions

2.1. Will climate change lead to irreversible (non-linear, rapid) ice-sheet response?

From a dynamical point of view, irreversible changes in the ice sheets are well describable in terms of hysteresis. Two major examples of this are the grounding-line instability, particularly relevant to Antarctic ice streams, and the ELA-induced bi-stability relevant to the Greenland ice sheet (Huybrechts et al., 2007).

Grounding line instability

Grounding-line instability arises because ice flux at the grounding line is strongly linked to the thickness of the ice, which is determined by the free-water depth. This leads to instability when ice is located on a bed sloping down towards the interior (Thomas, 1979). The grounding-line instability has the potential in West Antarctica to release large amounts of grounded ice into the ocean, with consequent effects on global sea-level.

Other significant factors affecting the ice flux, and thereby the rate of movement of the grounding line, are the force balance at the grounding line, which depends in part on ice-shelf geometry; the viscosity of ice; and the slipperiness of the bed. Because the overall rate of grounding-line motion is determined by the mass flux across the grounding line and the input flux from accumulated snow, long term control on retreat/advance rates and the locations of stable positions are affected by the averaged accumulation in the basin.

The proper computational treatment of grounding-line motion has been a difficult issue in glaciology for several decades, but a new technical implementation has recently emerged based around a boundary layer treatment due to Schoof (2007a). Quite apart from providing a dynamical framework which shows how the flux is related to ice thickness at the grounding line, Schoof's work has allowed the formulation of intercomparison experiments between ice-sheet models representing grounding-line motion, allowing scientists to address and discuss the computational issues involved.

Schoof's work implies that grounding-line retreat can be an unstable phenomenon from a dynamical systems point of view. In particular, the exact course of the retreat has a strong dependence on initial conditions, and a strong sensitivity on the dynamical parameters (ice-shelf back-pressure; ice viscosity; bed slipperiness) as well as the bed topography.

Mass balance/elevation bi-stability

This bi-stability arises because the surface elevation of the modern Greenland ice-sheet lies above the equilibrium line altitude, while the present bedrock is largely below it. If the Greenland ice-sheet were removed under present climatic conditions, it would not regrow. The concern is that if melting increases in Greenland, surface lowering may bring a larger area under the equilibrium line. Continued thinning could subject the saddle area lying between the two main south and north domes to net annual melting. The scientific issue is principally the GCM forcing; the societal issue over the next century is whether the ice-sheet can go beyond the point of no return. This might be strongly conditioned by the behavior of the marine outlet glaciers; rapid retreat of these through climate-driven ice-shelf loss may lead to drawdown and increased ablation of the interior. Associated with this is the possibility of increased ice flow due to basal lubrication by meltwater penetration.

While this issue is important, intercomparisons of direct simulations of the whole Greenland ice-sheet are unfeasible at the moment. Ice dynamical issues related to conditioning by marine outlet glaciers are considered in this document.

Unresolved Matters

One of the major difficulties in modeling the grounding zone has been the complexity of the mechanics, which must allow the stress fields to change from those appropriate to grounded ice to those appropriate for freely floating ice shelves. This remains a difficult technical issue; the analysis of Schoof (2007a; 2007b) considers the case of fast sliding ice where the stress fields in the grounded area are very similar to those in the free-floating shelf. The implication of this is that the transition zone itself does not require a more complex mechanical model than the abutting ice zones.

However, for slow-flowing ice, Nowicki & Wingham (2008) suggest that the situation is more complicated, and that there may not even be a unique relationship between flux and ice thickness at the grounding line. They drew these conclusions from a full mechanical treatment of the grounding zone, solving the full system of mechanical equations using numerical methods. There is no realistic prospect of solving the full system of equations everywhere within an ice sheet, so this implies that it may be necessary to have a nested mechanical model in the grounding zone for a complete treatment. A second issue is how to generalize the boundary layer theory of Schoof (2007b) to three-dimensional models. The generalization will be critical for determining the exact nature of ice stream buttressing effects from ice shelves.

2.2. Does rapid change lead to a large mass change?

An important scientific contribution of space-borne remote sensing has been the observations of rapid changes in Antarctic ice shelves and Greenland outlet glaciers. These observations support historical evidence from ice cores and glacial geomorphology suggesting that glaciers and ice sheets can quickly (over decades) experience changes in dynamics and mass balance. For example, there is strong evidence to support fluctuations in the mass balance of the West Antarctic ice streams over the past several hundred years (Hulbe & Fahnestock, 2007). There is also evidence for centurial changes in the behavior of the glaciers feeding the Brunt Ice Shelf in East Antarctica. Given these observations that rapid change is possible and is presently occurring, a key scientific question is whether observed rapid variations in the coastal environments will lead to sustained changes within the interior ice sheet or will the ice sheets reconfigure into a new quasi-equilibrium state?

Recent velocity changes in some Greenland and Antarctic Peninsula outlet glaciers have complicated temporal signals, including both acceleration and deceleration on time scales of a few years. Two relatively well-documented examples are Helheim Glacier, an eastern Greenland outlet glacier (Howat et al., 2007) and Crane Glacier, a tributary to the former Larsen B Ice Shelf (Hulbe et al., 2008). The cause for change on Helheim Glacier has not yet been determined while the initial perturbation for Crane (and neighbouring) glaciers is the 2002 collapse of the Larsen B ice shelf. The time series for such observations are short (less than a decade in both cases) but they contain valuable information regarding the dynamics of outlet glacier change in response to perturbations at their downstream ends.

2.3. Are observed rapid changes “natural variability” or a response to recent warming?

This considers whether variability observed in ice flows is due to internal dynamics or external forcing. An example of this issue is the question whether changes in many ice streams upstream of the grounding line can be explained by loss of the buttressing ice shelf, or whether additional, internal processes or surface meltwater penetration to the bed are needed to explain the observations.

Background: Jakobshavn Isbræ

Jakobshavn Isbræ has a well documented history of irregular retreat over almost two centuries (Csatho et al., 2008), making it a good test case for addressing this question. After retreating up the fjord, the position of the glacier terminus stabilized from the 1950’s to about 2000 (Sohn et al., 1998). Subsequently, the glacier began to rapidly thin and surface velocities increased. With the completion of recent airborne radio-echo sounding campaigns, there is sufficient ice thickness and surface velocity data to understand better the dynamics of the glacier and to predict whether, like Columbia Glacier in Alaska, Jakobshavn will periodically thin and surge forward after being released by subglacial obstacles or whether the glacier will behave more as it did during the mid and late 20th century wherein the terminus will fluctuate about a quasi-stationary position.

Unresolved Matters

Further complicating factors which need to be considered include the role of side drag along the fjord walls, the restraining effect of the iceberg-rich melange within the fjord itself, and the potential for an influx of oceanic derived heat up the fjord and beneath the ice tongue. An additional interesting issue is specifying boundary conditions on the vertical variation in shear stresses in the case of Jakobshavn Isbræ where a deep, narrow sub-glacial channel is evidently controlling the position and flow of the glacier. Present data need to be used to infer parameters like viscosity, basal slipperiness, and back-pressure. Available data include time series of surface velocity and surface elevation covering the period of relative stability of Jakobshavn and the recent collapse and speed-up. Inversions of these time series can show if and how basal properties are changing over these time periods and to test current understanding of underlying physics and to develop a suite of possible outcomes for future evolution of this glacier.

3. Roadmap for Improvement of Ice Sheet Models

3.1 The Central Role of Inverse Methods

In the context of the questions addressed here, inverse methods primarily relate to the use of surface data – rate of elevation change and upper surface velocities. These data can be used, with ice-sheet, stream or shelf models, to make inferences about the spatial distribution of important flow parameters – for example, the ice rheology, and the rheological properties of the bed. In all the cases we discuss for model initialization, such prior estimation is essential. Time series of such information are even more helpful.

Inverse methods invariably require good estimates of data accuracy in order to properly account for data fidelity and permit these uncertainties to be translated into uncertainties in the outcome. Inverse methods also treat the issue of parameter sensitivity, albeit in a somewhat 'black-box' manner, and significant understanding of issues of research prioritization can be gained through understanding of sensitivity to poorly known parameters. A related issue is one of parameterization, mainly of sub-grid processes, which leads naturally towards encouragement of imaging and other data sources necessary for parameterization.

The question to be asked is simply: what accuracy in the measured data is needed to model the (perhaps unstable) retreat of outlet glaciers and ice streams? Once this is decided, models can then be used to ask to what accuracy the other parameters (such as the flow law hardness parameter) need to be known. It is easy in principle to measure the bed topography, but the other parameters – ice viscosity and basal slipperiness – are more difficult to estimate, and may well be very specific to a particular region. Inverse control methods, using the technique of MacAyeal (1992; 1993) or more recent Bayesian approaches (Berliner et al., 2008), can be used to estimate these from surface data; velocity, surface elevation, and changes in these parameters over the relatively short time period that observations have been made. Inverse modelling will help determine the accuracy with which the material parameters must be measured. Information from other sources – for example, laboratory studies of ice viscosity – can be incorporated.

3.2. The Importance of Model Intercomparison

Model intercomparison experiments have a 13-year history in glaciology, and have proven to be valuable in terms of bringing researchers together for a common purpose, and defining the variability in model output. All intercomparisons have consisted of a well-defined set of experiments, prescribing geometry, boundary conditions, and parameterizations. While such certain model inputs are never found in nature, intercomparisons are attractive to the numerical modeller because they represent a consensus view on exactly what model inputs should be, and free them to practice their forte: model development and analysis.

One aim of this document is to sponsor suites of model intercomparisons addressing the science questions. This raises procedural questions about intercomparisons; if the models make different predictions, how do we discover the cause? A strength of intercomparison is that the well-defined experiments, with a standardized data format, eliminate the possibility that small differences in input data are magnified in model output.

Having established that model inputs are consistent leaves the possibility that model outputs differ because of numerical schemes or the physical description of what is being modelled. One way of addressing this is by encouraging modularization. Here, this implies separate code modules for grounded ice, floating ice, basal processes and surface mass-balance. A truly modular suite of ice-sheet model components would allow interoperability of any set of modules. From the point of view of software this implies a standard set of interfaces. Some progress is already being made in this direction by specifying a standard interface for the mechanical solvers component for grounded and floating ice. There is an opportunity to promote greater modularity in the models by using data formats for intercomparison experiments that require a specific interface for use. Additional modularity can be achieved through the development of ‘community’ or open source ice sheet models. These models would provide a modeller with those components they are lacking, with the relatively low ‘buy in’ cost of using the agreed upon interface.

Model intercomparisons should not be restricted to validation of models against data sets, but also require a broadly ranging set of intercomparisons which allow verification of an algorithm’s ability to solve the governing partial differential equations with appropriate accuracy, and which also investigate the accuracy of different mechanical approximations. Examples of these are the EISMINT suite of intercomparisons from the 1990s, and the more recent suite of ISMIP intercomparisons.

Ultimately, model intercomparison will lead to improved estimates of sea-level rise, as a community of investigators begins the most important intercomparison; whole ice-sheet models of the next 100, 500, and 1000 years. Such an effort will require ice sheet model coupling with other Earth systems components, such as atmospheric and oceanic circulation models. Again, this points to community modelling efforts and modularity as being crucial for advancement.

3.3. Components of Intercomparisons

The standardized sets of data used to drive intercomparison experiments will have to be assembled by a panel of experts that will work together to provide the best available estimates of basal boundary conditions (including material constitution; hydrology including effective pressures; geothermal heat; warming of grounding zone by oceanic effects); high resolution bedrock and surface topography; relevant grounding zones; surface velocity and rate of change.

Additionally, present day surface data (which is rapidly changing and will continue to be monitored) will be used with inverse modelling techniques to estimate parameters like viscosity and basal slipperiness. In principle, such datasets can be extended with a forward model to deduce forcing from events like ice-shelf removal and basal boundary changes, and finally extended to estimate the rate of change of forcing. It will be important that the incomparison exercises that utilize the inverted data have specific experiments that investigate the precise nature of the forcings, and allow for a comparison to the theoretical signatures of change (e.g. shelf removal or bed change signal on upper surface); relation to rate of change of forcing including step changes in ice-shelf geometry.

It would be extremely useful to have time-series of these inversions to show how basal properties are changing over these time periods and to test current understanding of underlying physics and to develop a suite of possible outcomes. While we recognize that time series on appropriate time scales (decades or more) are unlikely to emerge from the key areas for intercomparison, we may be able to make analogies to other regions that are very rapidly changing (days to weeks), such as the Whillans ice plain (Bindschadler et al., 2003), or areas of rapidly discharging subglacial lakes (Fricker et al., 2007). Provided time series data from these areas can be obtained, it will be possible to invert the data to determine how important parameters change in time.

Related to inversions is the problem of model initialization. In particular, this will properly represent rates of change, as well as the thermal history of the previous glacial/interglacial cycle that is stored within the ice. This is particularly important if the current state of the area being studied is unstable. One approach to initialization is given by Arthern & Hindmarsh. (2006). These initialization data should also be provided to the community as part of the intercomparison experiments.

The intercomparisons exercises that are likely to have the greatest relevance to the three scientific questions will be focused on datasets arising from Pine Island Glacier, Jakobshavn Isbrae, all of Greenland, and all of Antarctica.

3.4. Intercomparison Experiments Targeted at Specific Questions

Will climate change lead to irreversible (non-linear, rapid) ice-sheet response?

Intercomparison dataset: Pine Island Glacier (PIG)

A quantitatively accurate model of grounding line retreat is a difficult target to aim for on account of the sensitivity to initial conditions associated with grounding-line instability. Pine Island Glacier has been selected on the basis of its importance for sea level, and the fact that grounding-line retreat will likely take place along a well-defined channel.

Scenarios for predicting the evolution of Pine Island Glacier include: investigating how climate change affects the shelf directly; experiments with prescribed removal of the ice shelf; varying ice dynamical parameters like slipperiness; incorporating a shelf model which responds to ocean warming and melting.

For model validation there may be sufficient historical data to evaluate transient aspects of model performance. For example, positions of the ice shelf terminus, which affects force at the grounding line, are available since the airborne photography missions of Operation High Jump.

Does rapid change lead to large mass change?

Intercomparison dataset: Helheim and Crane glaciers

Broadly speaking, the aim is to use ice-sheet models to investigate the possibility of forcings which produce rapid change but do not produce large mass changes – changes in basal properties such as the Zwally effect (Zwally et al., 2002), or changes in ice-shelf dimensions. In particular, the modelling should be used to investigate the timescales issue by using models to inform about length of time-series of observations necessary to draw meaningful conclusions, and how this is affected by glacier dimensions and dynamics.

Are observed rapid changes "natural variability" or a response to recent warming?

Intercomparison dataset: Jakobshavn Isbræ

Use retreat of this glacier over the past hundred years and evaluate whether removal of the resisting downstream portion causes the observed increase in speed in the upstream region, or whether additional changes in – e.g. basal slipperiness – are needed. The difference between this case and PIG is that the brute force changes to the shelf have already been applied by nature. Finally, the modelling can make predictions about future of the inland area.

4. Ice Shelves

4.1. Background and Motivation

Ice shelves and glacier tongues are the peripheral, floating extensions of the ice sheets, formed under the action of gravity by the seaward flow of ice. Around the coast of the Greenland Ice Sheet, there are a number of fjords through which the ice sheet must flow to reach the ocean and it is through these narrow, channelized regions where the ice meets the ocean and forms ice tongues and ice shelves. The coast of the Antarctic Ice Sheet is more densely populated with ice shelves; nearly half the coastline consists of floating ice. In contrast to the relatively narrow, confined ice fjords that fringe Greenland, the Antarctic coast is dominated by much larger, open expanses of floating ice.

The mass of the ice sheets is largely controlled by the balance between the amount of snow added to the surface, surface melt (which is a small contribution to the mass balance of Antarctica) and the amount of ice lost from the ice shelves. A small amount of mass is also lost from ice sheets by the discharge of subglacial water to the ocean, but this thought to be a small contribution to the mass balance, although the exact amount that reaches the ocean is not known. Mass is lost from ice shelves primarily through two processes: basal melting and iceberg calving. Mass is also added to some ice shelves through refreezing of marine ice on their base.

Ice shelves that are confined to embayments or have pinning points can exert a "back-pressure" on the upstream grounded ice. Changes in the ice shelf configuration (through increased basal melting or iceberg calving) can alter this buttressing, possibly leading to changes in discharge rates from the grounded ice (e.g. DeAngelis & Skvarca, 2003; Rignot et al., 2004a; 2004b). Although the melting of ice shelves does not significantly affect sea level because they are floating, they are coupled through mass and momentum with the grounded ice and can therefore influence the flow of grounded ice across the grounding line, thereby indirectly altering sea level. Recently, melt-water-related disintegration of sections of the Larsen-B Ice Shelf and thinning of glaciers in the Amundsen Sea Embayment (Scambos et al., 2004a; 2004b; Shepherd et al., 2003) revealed that the time-scales of ice shelf change can range from the very short (seconds-months) to much longer (decadal-centuries).

There is a strong thermo-mechanic interaction between ice shelves and sub-ice ocean circulation. The ice shelf draft defines the upper geometric and thermodynamic boundary for the ocean. Basal melting and accretion of marine ice affect ice shelf thickness and temperature profiles, and hence ice shelf flow rates. Accordingly, studying the evolution of ice shelves requires modeling both the thermo-mechanical flow of the shelf and the flow of water in the sub-ice cavity. These two problems are coupled by mass conservation along with the appropriate treatment of heat and mass exchange at the ice-shelf-ocean interface base.

Atmospheric forcing on ice shelves also affects the mass balance. Snow deposition and surface meteorological environment (surface energy balance, and katabatic winds) in part (Rignot et al., 2004b) determine the ice thickness. The surface energy balance affects surface melting – ponding of summer melt-water on the ice shelf surface has been suggested as a contributor to ice shelf disintegration.

Because the flux of grounded ice across the grounding line is sensitive to changes in the peripheral shelves, the mass balance and evolution of the ice sheets is coupled to the evolution of surrounding shelves, although as discussed above, the extent of this coupling remains under debate. Progress in modeling rapid ice sheet evolution will hinge upon advances in modeling of ice shelves and their interaction with the ocean. These models will only be useful for predictions if based on and validated by observations. Therefore, alongside an effort to produce better ice sheet models, there must also be a coordinated effort to acquire appropriate datasets against which to test and validate the models.

4.2. Key Goals and Scientific Questions

An organized, community-wide effort to develop ice-shelf models can lead to an improved understanding of the role of the shelves in the climate system and a predictive capability of their evolution. The key goals to achieve to arrive at such understanding and capability are:

1. To predict the evolution of ice shelves in a warming climate, the physical processes controlling their evolution, and their relationship to climate.
2. To develop an understanding of the impact of ice shelves on ice sheet evolution.
3. To understand and predict the effect of melting ice shelves on ocean circulation and global climate (fresh water, ocean currents).

The key scientific questions to pose in regards to improving ice-shelf models come under three categories, namely, understanding: (1) the physics of ice-shelf processes and how to incorporate these processes into models; (2) the role of ice shelves in the overall mass balance of the ice sheets and freshwater budget of the ocean; and (3) the responses of the ice shelves to changes in climate and the subsequent response of the ice sheet and the ocean. Here we expand on these questions.

4.3. Components of Ice-Shelf Models

Ice-shelf processes

In contrast to the interior of the grounded ice sheet, the absence of friction at the base of ice shelves precludes any local approximate solution for the force balance equations. Early treatments by Weertman (1957), Thomas (1973), Sanderson (1979), Van der Veen (1986) and MacAyeal and Thomas (1986) explored the general consequence of this, essentially in a one-dimensional framework, using a combination of analytical and numerical studies. With the growth in computing capacity, many numerical models for ice shelves have been developed, with a near universal agreement that the shear stresses acting in the vertical plane could be neglected and that the depth-integrated momentum equations (MacAyeal et al., 1986; Morland, 1987) are adequate to describe ice shelf dynamics. This results in a two-dimensional plan-view treatment of the dynamics, with the assumption of local hydrostatic equilibrium further simplifying the description. The major complication, as with the ice sheet case, is the use of a non-linear rheology or constitutive relation for ice flow – usually with a scalar viscosity which depends on strain-rates. This necessitates an iterative approach to the solution scheme. The modeling of the temperature field within the ice shelf remains a three dimensional task, but is a more conventional advection-diffusion problem – essentially as for the grounded the ice sheet.

The assumptions regarding the dynamics appear well supported, as experience has shown that model predictions can be made to match observations of ice velocity well, by `tuning' either an arbitrary scalar ice viscosity, or the rate parameter in a specific ice rheology (typically using a cubic flow relation) (Rommelaere & MacAyeal 1997; Larour et al., 2005; Vieli et al., 2006). Parameter tuning, referred to also as inverse modeling demonstrates considerable variation in flow properties, indicating ice shelf flow is strongly influenced by ice temperatures, and also by other effects. These effects are likely to include local and history dependent material effects, such as anisotropic crystal orientations, presence (or absence) of marine ice, and larger scale structural aspects such as rifts or fracture zones, sutures between merging ice streams, and bands of `weakness' from crevassing/rifting in shear margins. The majority of modeling studies have concentrated on the diagnostic problem of explaining the current state of flow in a given ice shelf. There has been less work on combining the velocity calculations with numerical solution of the prognostic, mass-continuity equation. This may be partly because problems arose in early model intercomparison studies (MacAyeal et al., 1996), but another important issue is that knowledge of basal melt rates is an important component of ice shelf evolution. One major extension has been the addition of basal drag forces to the depth-averaged equations to treat flow in ice shelves and ice streams within a single model – the "shelfy-stream" picture, and inverse modeling techniques have been extended to the estimation of basal drag beneath ice streams (e.g. Joughin et al., 2004; 2006; MacAyeal, 1992).

Basal melting and refreezing affect the temperature profile within the ice shelf. Melting means the loss of warm basal ice, lowering the column average temperature, while accretion adds ice near the in situ freezing point. These effects influence the ice flow rates used in calculating the velocity. Less is known about how marine ice, accreted onto the bottom of ice shelves, affects the mechanical properties of ice shelves. For instance, is it appropriate to use flow parameters derived from meteoric ice to model regions where the thickness has a significant fraction of marine ice? Along the same lines, to what degree does marine ice affect the fracture mechanics of ice shelves? Is it easier or harder to form basal crevasses when marine ice is present? This may have important implications for the stability of ice shelves.

Grounding-line migration

There are two issues associated with accurately representing grounding line migration. They are associated with:

1. *Oceanographic forcing*: There is strong coupling between the basal slope of the ice shelf near the grounding and basal melting near the grounding line. Thus capturing the forcing at the grounding line may require a coupled ocean-ice-shelf model in which the ice-shelf and ocean geometry are both allowed to evolve dynamically.
2. *Numerics*: Numerical representation of grounding line migration remains a topic of concern. Numerical experiments (Vieli & Payne, 2005) showed that models that employed a fixed, Eulerian grid to track grounding line migration suffered from severe numerical artefacts tied to grid-size. Moving grids performed much better, but are much more difficult to employ outside the 1D context for which they have been tested. Adaptive grids provide one avenue that may be able to resolve grounding line migration, but these are still untested and in the development phase. Explicitly tracking sub-grid flux near the grounding line, as is done to track phase boundaries, has also been suggested as a viable alternative. More research is needed to determine the optimal approach.

Following the disintegration of ice shelves in the Antarctic Peninsula, several tributary outlet glaciers were observed to increase their velocity as much as four-fold [Scambos et al, 2004b; Rignot et al., 2004b). In Greenland, the breakup of the Jakobshavn floating tongue was followed by a doubling in speed of the tributary outlet glacier (Joughin et al., 2004; 2008). This provides firm evidence that ice shelf buttressing is an important component of ice-shelf-sheet interaction that needs to be more fully understood. While, buttressing is not (semantically at least) a process, it is an observation that models need to match. To do this, we need to have an improved understanding of **all** of the above-mentioned processes.

Surface melt, hydrological fracturing and ice shelf disintegration

An important component of the mass balance of ice shelves is the surface mass balance. Although for most ice shelves, basal melting makes a much larger contribution to the mass balance, surface melting remains an important process that is not yet readily incorporated into models. One of the reasons why surface melting is important is because of the link between surface melt ponds and hydrologic fracturing. The ability of ponds of surface meltwater to wedge open existing surface fractures appears to be one of the mechanisms by which ice shelves disintegrate (Scambos et al., 2003; Van der Veen, 1998; 2007). The ability to form surface meltponds on ice shelves may depend on whether they have a previously developed drainage system.

Another aspect of ice shelf fracture that needs to be more fully explored is the effect of the formation of crevasses and rifts along the lateral margins of confined ice shelves. The formation and presence of rifts near these margins reduces the effect of lateral shear and this may be an important component in reducing ice shelf buttressing (see below). At present, models often ‘tune’ the flow rate parameter of ice near lateral margins so that models better match observations.

Rifting and Iceberg calving

An important component of the overall mass balance of ice shelves is iceberg calving. As well as a steady incremental “erosion” of the ice shelf front, rifting episodically separates discrete (often large) portions of ice shelves as icebergs, abruptly redefining the boundary of the ice shelf. At present there is no satisfactory model of iceberg calving that can be implemented in models. There are three categories to the approaches that have been used to date:

1. *Calving laws*: In this approach, a mean calving rate is assumed to exist and it is further assumed that the calving rate is a function of one or more internal dynamic and geometric variables (e.g., ice thickness, strain rate, velocity). A calving law is then sought by correlating measurements of iceberg calving rates with measured parameters. This approach has the advantage that it is easy to implement this type of calving law into numerical models. However, there is very little data for ice shelves and most of what exists is for ice shelves in or near steady-states.
2. *Fracture mechanics*: Another approach is to use linear elastic fracture mechanics (LEFM) or a non-linear generalization thereof to model the initiation and propagation of individual fractures within the ice. Laboratory experiments provide measurements of the fracture toughness of ice (Rist et al., 2002), but a first principles calculation of calving rates using LEFM has been elusive so far. To bypass issues of rift propagation Hamman & Sandhager (2003) and Grosfeld & Sandhager (2004) simulated calving of tabular icebergs, by assuming instantaneous rifting events along anomalies in the large scale stress-field of the ice shelf.
3. *Damage mechanics*: Another approach toward modelling iceberg calving is to use a continuum model in which a continuous `damage’ variable is introduced (Pralong et al., 2003). This has been successful in modelling the detachment of hanging glaciers (Pralong et al., 2003) and may ultimately prove to be the most straightforward approach towards incorporating iceberg calving into ice shelf models. This has not yet been done and there are some questions about the appropriateness of the formulation. For instance, `damage’ appears to be approximated as a monotonically increasing function and no allowance is made for the fact that fractures may ‘heal’ over time.

4.4. Oceanographical modelling:

Overview of sub-ice shelf circulation

The ocean circulation beneath an ice shelf is strongly affected by two key properties of seawater. First, the freezing point decreases with pressure, so that seawater of typical salinity freezes at approximately -1.9 °C at the surface, but at approximately -3.0 °C at 1500 m depth. Second, for typical Antarctic temperatures the density of seawater, which is generally given by a highly nonlinear equation of state, is dominated by salinity, so that even very cold fresh water is buoyant.

For the colder regime characteristic of larger ice shelves such as the Filchner-Ronne or Ross, thermal driving is provided by High Salinity Shelf Water (HSSW), which is created by brine rejection during sea ice formation near the ice shelf front. Dense HSSW sinks and flows into the sub-ice shelf cavity at depth, where it is sufficiently warm to cause melting of the ice shelf base despite being near the surface freezing point. Mixing with cold, fresh meltwater produces buoyant Ice Shelf Water (ISW), which ascends the ice shelf base until it reaches a depth at which it is supercooled relative to the local freezing point. Formation of frazil ice in the ISW plume then leads to the accretion of a layer of marine ice at the ice shelf base. Lewis & Perkin (1986) referred to this redistribution of ice through melting and refreezing as an “ice pump”.

A much different regime exists for the ice shelves of the Amundsen Sea embayment, such as Pine Island Glacier (PIG). In this region, the wind-driven circulation forces warm Circumpolar Deep Water (CDW) onto the continental shelf and therefore into sub-ice shelf cavities. Because CDW typically is at temperatures of $+1^oC$, the resulting basal melting is very high – Jenkins et al. (1997) estimated 12 m/yr beneath PIG – and no refreezing occurs. Rather than a redistribution of ice, this circulation regime produces a significant loss of ice, so increases in melting has the potential to induce thinning of floating and grounded ice (e.g., Shepherd et al., 2004).

Sub-ice shelf modeling with static ice shelf geometry

A number of approaches to modeling the ocean circulation in the sub-ice shelf cavity, including the melting/freezing of the ice shelf base, have been taken. These approaches include one-dimensional plume models, two-dimensional planar plume models (in the horizontal plane), two-dimensional overturning models (in the vertical plane), and fully three-dimensional models. In all of these models an implicit assumption that the ocean circulation varies on a much faster time scale than the ice shelf flow means that the ice shelf geometry is held fixed throughout time in such simulations.

Plume models are a category of reduced thermohaline models which treat meltwater as a turbulent, buoyant plume rising along the ice shelf base. In Jenkins (1991), depth-integrated ordinary differential equations for conservation of mass, momentum, heat, and salt were solved along a one-dimensional flowline at the ice shelf base. Thermal driving was obtained by entraining the warmer underlying HSSW into the plume according to a velocity-dependent parameterization. Patterns of basal melting and freezing were found to depend strongly upon the shape of the ice shelf base, with the plume speed increasing in areas of steep basal slope. Jenkins & Bombosch (1995) extended this model to include the formation of frazil ice, leading to more efficient conversion of supercooled water into marine ice (see below). The most recent plume modeling has focused on extension to a two-dimensional model (in the horizontal plane), thus allowing Coriolis effects to be included (Holland & Feltham, 2006).

Hellmer & Olbers (1989) constructed a thermohaline circulation model for a two-dimensional (in the vertical plane) section perpendicular to the ice edge. Following Robin (1979) it was assumed that the circulation parallel to the ice edge was negligible. Application of the model to the Filchner Ice Shelf showed a circulation pattern similar to the predictions of plume models, with HSSW entering the cavity at depth and a thin stream of ISW ascending the ice shelf base. Further studies with this model included modification of the boundary conditions to allow channel flow, as well as application to the Ronne, Amery, Ross, and Pine Island Ice Shelves (Hellmer & Jacobs, 1992; 1995; Hellmer & Olbers, 1991; Hellmer et al., 1998).

The simplified models mentioned above have generally omitted rotational effects, which can be best investigated with a three-dimensional model. These effects were studied by Determann & Gerdes (1994) and Grosfeld et al. (1997) using primitive equation models with a terrain-following vertical coordinate in order to handle the irregularly shaped sub-ice shelf domain. Both studies found that flow in the cavity was primarily barotropic, and hence constrained to follow contours of f/H (where f is the Coriolis parameter and H the thickness of the water column). Due to the sudden change of depth at the ice front, the sub-ice shelf circulation was thus largely isolated from the open ocean, with little inflow of HSSW, resulting in weak vertical overturning and reduced melting relative to the two-dimensional Hellmer and Olbers model. The Determann and Gerdes model has also been applied to investigate the Amery Ice Shelf and its potential response to warming of the Southern Ocean (Williams et al., 2001). Holland & Jenkins (2001) adapted an isopycnic (density) coordinate model for similar studies, finding a pattern of inflow at depth and outflow along the ice shelf base which qualitatively agreed with reduced models and was not obstructed by changes in water column thickness at the ice front. The extent to which the sub-ice shelf cavity communicates with the open ocean thus remains an open question.

Coupled ice shelf - ocean modelling with dynamic ice shelf geometry

Grosfeld & Sandhager (2004) coupled the three-dimensional general circulation model used by Determann & Gerdes (1994) with a two-dimensional ice shelf model. The coupling followed an asynchronous approach, in which the ocean is run for several years to derive basal melting and freezing which are applied to the ice shelf on longer timescales. Formation of marine ice and shifts in basal melting patterns were consistent with the primarily barotropic flow generated by the ocean model. The scale and complexity of this model made it challenging in terms of computing resources. Walker & Holland (2007) developed a simplified two-dimensional vertical-plane model of the coupled ice-shelf – ocean system. Under simulation of oceanic warming, they found that the basal slope of the ice shelf changed significantly near the grounding line, and thus argued that coupled simulations are necessary to properly describe this system.

Frazil ice modelling

Marine ice (consolidated frazil ice) deposits hundreds of meters thick are observed beneath Filchner-Ronne and Amery ice shelves. Explicit frazil modelling is important for marine ice prediction, but has not appeared in full ocean GCMs because frazil evolves rapidly and is computationally expensive. Jenkins & Bombosch (1995) added a prognostic frazil equation to the Jenkins (1991) plume model, showing that frazil increases supercooling uptake efficiency by increasing the surface area over which phase changes occur. Frazil also affected plume buoyancy, creating feedback that focused marine ice formation into smaller areas than basal freezing alone. Smedsrud and Jenkins (2004) extended this to multiple frazil size classes, refining deposition patterns and showing seed crystals growing in suspension before precipitating as their buoyancy passed a threshold. Holland & Feltham (2006) extended this to two horizontal dimensions, finding that Coriolis caused plumes to follow ice draft contours; plumes only rise and grow frazil when confined to do so by grounded ice. In agreement with observation, reasonable marine ice formation could only be achieved when plumes entered inverted 'hollows' in the ice base, as found between inflowing ice streams. Holland & Feltham (2005) investigated vertical frazil variation, finding crystals clustered near the ice shelf base in a balance between buoyant rising and (downward) turbulent mixing, and formulated a frazil deposition condition suitable for use in GCMs.

Ocean tide modelling

The ocean tide is typically the largest single component of short-term variability of ice shelf surface height, and is often the strongest component of sub-ice-shelf currents. Barotropic tide models ranging from fully global to regional solutions for specific ice shelves now provide reasonably accurate estimates of tide-forced surface height variability for the freely floating (hydrostatic) portions of larger ice shelves (King & Padman, 2005). Recent improvement in model skill for tide height derives from assimilation of both *in situ* measurements and satellite altimetry (Padman et al., 2003; 2008) and gravity (Han et al., 2007; Ray, 2008). Accurate empirical models can be developed for high-latitude regions, the Ross and Filchner-Ronne ice shelves, using ICESat laser altimetry (Ray, 2008). However, the explicit inclusion of tides is not appropriate to the long integration times required for climate studies. One goal of studies of tidal contribution to ice shelf thermodynamics is to seek methods by which the tidal contributions can be incorporated via parameterizations of their contribution to the mixing near the ice base. Holland (2008) has described a first attempt to determine the role of tidal mixing close to the grounding line, where most basal melt is believed to occur.

4.5. Requirements for Improvement of Ice Shelf Models

Observations

Much of our current knowledge about ice shelves has come from satellite data (altimetry and InSAR). However, there are gaps (both temporal and spatial) in the current suite of remote sensing observations. There is a major gap coming up in satellite observations, especially SAR, and as a community we need to come up with a measurement strategy to bridge this gap. Some of the key data needs are:

- Sub-ice shelf geometry: bathymetry, ice draft, water column thickness, and basal roughness.
- Ice shelf thickness at the grounding lines by continuing aerial Radar Echo sounding campaigns.
- Temporal variability in basal melt rates (tidal, weather, seasonal, inter-annual, decadal).
- Grounding zone locations.
- Monitoring import of ocean heat (e.g., as Circumpolar Deep Water, MCDW, High Salinity Shelf Water) into the ice shelf cavity,
- Large-scale atmospheric wind pattern changes in the polar oceans.
- Column-averaged ice density distributions for all ice shelves (i.e., to estimate ice thickness from surface elevations).
- Sub-ice shelf hydrography and circulation, especially in the high-melt regions near deep grounding lines.
- Properties of ice mélange in rifts.

Modelling

A number of physical process need to be further developed and implemented into ice shelf models. Such processes need to be first developed and tested in simplified, regional models prior to application in a global climate model. Some of the key questions and model developments needed are:

- The iceberg calving process is presently incorporated in a crude form in ice sheet models. The processes of crack initiation and propagation need to be understood and modeled.
- How to model the composition and mechanical properties of ice mélange inside rifts (and does the mélange matter)?
- How to model the growth, transport and deposition of frazil ice (which is important for refreezing)?
- Are there important mechanical and thermodynamic distinctions between meteoric and marine basal ice?
- What is the contribution of high-frequency processes (e.g., tides) to basal melt/freeze processes and heat distribution through the sub-ice shelf water column?
- What is the contribution of small-scale basal features (i.e., basal crevasses, rifts) to channeling and fate of Ice Shelf Water freshwater plumes?
- The accurate modeling of a mobile grounding zone (mobility due to tides, and longer-term changes in ice thickness).

Deliverables

While the past achievements in observations and modelling of ice shelves are extensive, there remains much to be done. There are some major limitations in our current knowledge and a paucity of observations surrounding ice shelves, which taken together, undermine our ability to predict their evolutions. Most notably lacking are: (1) water masses and ocean circulation near and under ice shelves, (2) changes in these properties, and (3) the bathymetry beneath ice shelves. These issues will not be resolved by the ice shelf modeling community alone, and the community needs to actively promote the acquisition of data that allow a more advanced development of ice shelf models. Without these data, progress in modeling will be fundamentally limited.

Looking forward, improvements in ice shelf modeling are needed in a number of areas. It is perhaps easiest to organize these needs by formulating them in terms of the four boundaries (see Figure 2) of an ice shelf, namely, the ice shelf base, the ice front, the grounding line and the ice shelf surface. Clearly, all are involved and important in determining the evolution of the ice shelf. All of these modeling target boundaries will require, ongoing or new, commensurate observational activities.

1. **Ice shelf base.** Validation of high resolution ice shelf - ocean coupled models against observed past and current melting and freezing rates of ice shelves and tidewater glaciers resulting from ice-ocean interaction.

2. **Ice shelf front**. Reproduce past and current observed changes in the ice shelf front geometry due to calving. Improve ice calving physics. Analyze the relevance of landfast sea ice in possibly stabilizing the ice shelf front.

3. **Grounding line.** Incorporate a treatment of grounding line (GL) dynamics into ice shelf models. Such improvements should mimic recent observed lateral GL migration with tides and changing ice geometry.

4. **Ice shelf surface**. Reproduce past and current spatial and temporal variability in snow accumulation and ablation rates.

5. Surface Mass and Energy Balance

5.1. Introduction

There are two basic approaches to measuring the mass balance of ice sheets. The first is an integrated approach, i.e. a measurement of its mass changes (elevation change or gravity anomaly variations by satellite) without separately determining the input and output fluxes. The second is a component (or flux) approach, in which the input and output fluxes are individually measured. This approach is particularly important when applied to individual drainage systems within the ice sheet. There exists no optimal technique to measure ice sheet mass balance; each of the two approaches has its limitations, assumptions and error terms. Most of these are, in general, independent for the two methods, but both approaches use surface mass balance evaluation at different scales (from seasonal to centuries scale) to determine change in elevation or mass and as input term for the flux approach. Both approaches are important for obtaining not only a simple measurement of mass change, but also an understanding of what is causing that change. Combining the different approaches could greatly reduce independent error terms but is challenging.

Several processes act on snow falling on the surface of an ice sheet and introduce large uncertainties in past, present, and future ice sheet mass balance. Solid atmospheric precipitation (snowfall and diamond dust/clear sky precipitation) is deposited at the surface of the Greenland and Antarctic ice sheets. Wind erosion, wind redistribution, sublimation, melting and other processes during or after the precipitation event lead to a deposition at the surface which is spatially less homogeneous than the original precipitation. Strong katabatic winds cover most coastal areas with comparatively large surface slopes, and wind driven processes (erosion and transport, export into the ocean and atmosphere) represent an important component of surface mass balance at scales ranging from 10 meters to tens of kilometres in these regions.

Major gaps in our knowledge of processes that determine the magnitude of the temporal and spatial variability of snow accumulation prevent us from making best use of advances in technology and model capability to produce a reliable estimate of current surface mass balance, and prediction of future trends. Information about snow surface processes is essential not only for the input term of the mass balance but also for interpreting surface elevation change and gravity anomaly signals, and for improving climate and meteorological models. Improvement of these models requires an iterative process of field survey, model adjustment and verification.

For predicting future evolution of the Greenland and Antarctic ice sheets it is imperative to improve our knowledge of snow accumulation process (precipitation, wind drifting of snow, firnification, refreezing, percolation and melting, etc.) and include these in high-resolution atmosphere-ice sheet models.

5.2. Motivation

Recent remote sensing data from satellite- and airborne missions indicate that disintegration of the Greenland Ice Sheet is presently contributing as much as 0.3 mm yr^{-1} to global sea level rise, and that rate is increasing (Lemke et al*.*, 2007). Support for this statement is provided by different types of observations:

1. Repeat accurate measurements of ice sheet surface elevation change by satellite and airborne laser altimetry (Krabill et al., 2000; 2004; Thomas et al., 2005).
2. Modeling of mass fluxes of Greenland outlet glaciers using Interferometric Satellite Aperture Radar (InSAR) measurements (Rignot & Kanagaratnam, 2006).
3. Measured changes of the gravity field over Greenland by the GRACE satellite mission (Ramillien et al., 2006).

The observed large and rapid mass balance changes reflect a short period of observations. For this reason we need to ensure continuous monitoring of ice mass variability and changes (space and time) for longer periods.

Evaporation

Sublimation processes driven by wind and solar radiation are not negligible but are not explicitly included in numerical weather forecasting and general circulation models. Wind drifting snow is influencing snow accumulation on different spatial scales. Snow is redistributed within the topmost annual snow layer, which causes mixing of water isotopes, by forming sastrugi and small dunes. This process is active on the Antarctic plateau. In areas with strong katabatic winds snow may by eroded and re-deposited and/or sublimate. Strong katabatic winds in slope confluence areas and low pressure systems occur primarily in the coastal regions. Drifting snow forms a new snow accumulation pattern different from the original precipitation pattern. Drifting snow increases the potential for evaporation.

Firnification

A simple steady state firn-densification model by Reeh (2008) accounts for short-term variations in accumulation rate and surface temperature. The study reports on temporal surface elevation- and mass changes at two sites in the percolation zone of the Greenland Ice Sheet in response to various climate histories. A straight-forward translation of observed short-term ice sheet surface-elevation variations into mass changes may be misleading, particularly for the percolation zone, where temperature-driven variations in melting/refreezing rates have a strong impact on near-surface density. In the lower percolation zone, the mass change associated with a temperature anomaly with respect to the mean climate may amount to as much as ten percent of the observed, simultaneous surface elevation change. Moreover, significant surface elevation change may occur even in periods of constant surface climate, and consequently unchanged mass balance, as a delayed response to previous changes in the local surface climate. Further, forcing the model with cyclic temperature variations mimicking fluctuations in West Greenland instrumental temperature records during the past hundred years, shows that surface elevation may increase by as much as 1 m in 5 years for periods with no mass change at all. In the lower percolation zone, temperature-induced density changes rather than fluctuations in accumulation rate are the dominant cause of short-term surface elevation changes. This is in contrast to the situation in the higher percolation zone, where short-term surface-elevation change is dominated by fluctuations in accumulation rate (Reeh, 2008).

Precipitation

Altimetry data (Johannessen et al., 2005; Thomas et al., 2005; Zwally et al., 2005) suggest significant (2–5 cm yr^{-1}) growth of the interior of the Greenland Ice Sheet at elevations above 2000 m from 1992 to 2003/4. This growth may be attributed to increased atmospheric moisture and precipitation and/or shifting storm tracks (Hanna et al., 2006). However, because of the short data spans (about one decade), such studies have yet to provide a more convincing multidecadal perspective on how the Greenland Ice Sheet might be responding to long-term climatic change, most notably the evident global warming since the 1970s (Alley et al., 2007).

Greenland precipitation, downscaled from ECMWF operational analyses and re-analyses (Hanna et al., 2005), shows a significantly increasing trend of 90.9 km^3 yr^{-1} (14.9%), compared with a standard deviation of 69.7 km^3 yr^{-1} (11.4%), for 1958. Additional precipitation, mainly in the form of snow accumulation, therefore largely (80%) offsets increased runoff.

In Antarctica, precipitation in the coastal areas is connected with low pressure systems whereas in the interior clear sky precipitation is significant (up to 50%). Atmospheric models are not able to reproduce clear sky precipitation that may be the dominant part of precipitation on the East Antarctica Plateau. However, it has been shown that single precipitation events are linked with low pressure systems bringing air masses as far south as 75° latitude or even further. These events are stochastically distributed over the year and occur also during the austral winter. Those events are coupled with rising temperatures.

Precipitation and melting are spatially "homogeneous" over tens to hundreds of kilometres, whereas spatial variability arising from post depositional processes at the km scale is one order of magnitude greater than temporal variability at 10s-100s of years. Snow accumulation processes present high temporal variability at annual to decadal scale. While measurements of precipitation have been a routine part of worldwide observations for more than a hundred years, there is still no practical technique that can be used to measure snow precipitation in real time as part of a meteorological measurement program. Thus, knowledge of precipitation and post-depositional processes, seasonality, trends, and spatial variability, is limited. Various difficulties complicate measurements of the surface mass balance, in particular unrepresentative spatial and temporal variability, measurement inaccuracy, and lack of quality control. To be able to predict future trends in ice sheet mass balance our models need to be able to reliably reproduce present-day and recent past patterns (from years to millennium scales) of surface mass balance.

5.3. Requirements for Improvements

Observations

- Continuous assessment of ice velocity, ice thickness, grounding lines positions, firn densification, on multi-year time scales for the entire ice sheet and at monthly intervals for selected fast moving target glaciers.
- Continuous assessment of mass and elevation changes of the ice sheets and surrounding land must be measured in situ at select sites, using repeat geodetic surveys (e.g., GPS–DORIS), to determine the local rate of ice elevation change, and gravimetric measurements for assessing mass change. Local elevation change can be measured using the submergence velocity method ("coffee can") with markers anchored some tens of meters deep in the firn. The simultaneous

knowledge of the vertical velocity and of accumulation rate gives the change in elevation directly. These measurements represent ground-truth for airborne and satellite measurements, and reduce uncertainty caused by temporal variability of snow accumulation at annual scale and variations in depth of the firn layer at decadal/century scale.

- Improvement of regional climate model to capture present day seasonal, inter-annual, and spatial variability (including extreme melt and precipitation events). Regional climate models should be able to reproduce the past 25 years of climate variability at annual resolution, and the last 200 years at decadal resolution. Observations for comparisons include shallow ice cores and satellite data at temporal scales for high-resolution regional climate models.

In spite of significant improvement in spatial coverage in recent years, large regions remain un-surveyed in particular in the coastal areas of Antarctica and Greenland where the spatial and temporal variability is largest. New techniques such as Ground Penetrating Radar (GPR) and GPS must be widely used. Consistency analysis and synthesis of surface mass balance reconstructions from field activities; satellite information, meteorological analyses and climate models, must be carried out for optimal spatial coverage and integration.

Time variability shorter than one year must be assessed at selected sites. Observations of time variability of snow accumulation (e.g., from stake farms and AWS) are needed to improve atmospheric models and the interpretation of satellite altimetry/gravimetric. Observations and models on an interannual to centennial time scale (e.g. ice/firn cores and meteorological time series) are important to detect current and predict future changes.

Deliverables

Continuous monitoring of accumulation requires maintaining stake farms and stake lines at selected locations as well as shallow ice coring covering ideally a 200 year period. The deposits of the Tambora eruption (1816) provide an unambiguous horizon for dating ice cores. Also, radioactive fallout from early 1960s nuclear weapon tests can still be recognized in firn layers, providing a good tool for dating of the past 40-50 years of accumulation. With respect to the high inter-annual variability of accumulation, a 30-year period of observations seems necessary to detect a climate trend. A good tool for determining accumulation over larger geographical areas is snow-radar which averages out small-scale spatial variability.

Continent-wide surface accumulation values at spatial (10 km) and multi-annual (5-30 yr) resolution are required through a variety of different approaches (e.g., extensive GPR and GPS surveys, calibrated by firn cores, satellite based remote sensing, numerical simulation, re-analysis of previous snow accumulation data). Data on the trend of snow accumulation at the century scale (200-500 yr) at selected sites are required. To characterize spatial and temporal variability and covariance, comparisons are required over local (<10 km) and seasonal (<1 yr) scales at selected sites, of precipitation data from atmospheric models, field measurements (AWS and stake farms) and remote sensing observations. Field observations and modelling of atmosphere/cryosphere processes are required to estimate snow redistribution and export to the ocean, sublimation, densification, and metamorphism processes.

Requirements

Ensure that satellite data at all frequencies from international agencies are acquired and made available to ensure comprehensive spatial and temporal coverage for ice velocities of outlet glaciers, altimetry, and gravity.

Snow-radar (GPR) measurements are an excellent tool to detect spatial variability of snow accumulation and to determine mean accumulation rates given that prominent reflection horizons can be dated. To achieve a wider spatial coverage of those measurements the development of airborne snow radars is necessary. These instruments should be applied in particular to profiling in coastal areas and where slopes are large.

One goal of the International Partnership in Ice Core Science, now adopted as a SCAR Expert Group, is to drill ice cores in coastal regions, covering a time span of 2000 years. This period is both long enough to incorporate the "Holocene/Anthropocene transition", and short enough to recover ice cores with very high temporal resolution. The purpose is collect records with resolution ranging from seasonal to annual during the last 50 years (for comparison with atmospheric models), to multi-annual for the last two centuries and decadal resolution at the millennial scale (for reconstruction of natural temporal variability). This goal satisfies the requirement from ice sheet models for improved present day snow accumulation data for model input. Regarding the high inter-annual variability, data from ice cores with long time series can provide reliable average values as well as detect recent trends.

6. Subglacial Hydrology

6.1. Motivation

Water plays a crucial role in the stability of the ice sheets. Changing the basal conditions of an ice sheet, particularly beneath fast flowing ice streams and outlet glaciers, is one possible mechanism to rapidly increase its contribution to sea level rise, through increased ice flow rates in the ice streams.

Until recently, the subglacial hydrodynamics beneath the ice sheets have been considered to be a steady-state system with long residence time for water. Over the last 3-5 years, our knowledge of the hydrology under the Antarctic and Greenland ice sheets has dramatically altered, however. New evidence is emerging for a complex and dynamic subglacial hydrology that has the potential to change the basal conditions of ice sheets on very short time frames (e.g. Fricker et al., 2007; Gray et al., 2005; Joughin et al., 2008; Wingham et al., 2006a; 2006b).

It has long been known that subglacial water exists under the ice sheets. For example, Siegert et al. (2005) documented 145 lakes in Antarctica. However, all the documented lakes were believed to be inactive and subglacial water flow was thought to be a steady trickle. Recent observations have shown that the subglacial water system is much more active and highly variable. In Antarctica, subglacial water volumes can fluctuate and rapid movement of water can occur periodically between active reservoirs via subglacial floods (Fricker et al., 2007; Gray et al., 2005; Wingham et al., 2006a; 2006b). In Greenland, surface melt water can rapidly drain through the ice thickness into the subglacial hydrologic system, causing localized short-lived accelerations (Das et al., 2008) as well as seasonal increase of ice velocity on outlet glaciers and surrounding slow moving regions (Joughin et al., 2008; Zwally

& Jun, 2002). Increasing evidence of these dynamic subglacial hydrologic systems, such as the periodically draining subglacial lakes in Antarctica, injects a new and compelling sense of urgency for gaining a better understanding of subglacial hydrological systems and their impact on both the temporal and spatial evolution of the overlying ice-dynamics.

The distribution and flux of subglacial water and the main processes of subglacial hydrology are not well understood. We have developed a strategy of targeted observational studies closely coordinated with theoretical modeling targeted at evaluating the role of subglacial hydrodynamics. While subglacial water systems are complex, past theoretical and observational studies offer a strong starting point. New efforts are essential to address the recent observations and potential impacts of large water fluxes documented recently, such as rapid draining of large subglacial lakes. These new observations have fundamentally challenged our traditional understanding of subglacial hydrologic systems.

6.2. Key Science Questions

With respect to the subglacial environment, three key questions are identified to focus research efforts, namely:

1. What are the main subglacial processes that affect ice dynamics in a way that could enhance flow rates and lead to rapid sea level rise?
2. What key improvements need to be made to glacial models to incorporate these important processes?
3. What research priorities are needed to gain the understanding required to make these improvements?

6.3. Background

Water melts at the bed of ice sheets due to geothermal heat and heat generated through friction. Similar to mountain glaciers, additional meltwater produced at the surface can be transported through moulins and crevasses to the ice sheet bed. Once at the bed, subglacial meltwater moves down the hydrological gradient, flowing toward the ice sheet margin and forming a large, interconnected subglacial hydrological system. At the bed, subglacial water can move through conduits or pipes, reside in spatially distributed cavities, rest interstitially in subglacial sediments or be captured in subglacial lakes. Each of these water systems has the potential to impact the velocity of the overlying ice. The impact of each subglacial hydraulic system will be a function of the effective basal pressure, which depends on water pressure and ice thickness. When the basal water pressure approaches the overburden pressure across extensive regions, the effective pressure tends to zero and increased ice velocities result (Pfeffer, 2007). While a well-connected conduit system efficiently transports subglacial water at relatively low pressure toward the ice margin and thus does not impact ice velocity very much, subglacial water flowing through a very thin distributed cavity system frequently encounters restrictions and the water tends to be at high pressure, potentially resulting in increased ice velocities. Experimental work also suggests that an increase of water pressure in a till-dominated system could produce a decoupling of the ice sheet from the bed causing an increase in ice sheet velocity.

Changes in subglacial hydrology are closely coupled to the overlying ice sheet. Examples of this tightly coupled system include the drainage of subglacial and supraglacial lakes as well as changes in till thickness. Until recently, the subglacial hydrodynamic system beneath the large ice sheets was considered to be generally static with very long residence times on the order of 50,000 years for water in subglacial lakes. Increasing evidence of dynamic subglacial hydrologic systems provides a sense of urgency for gaining a better understanding of subglacial hydrological systems and their impact on both the temporal and spatial evolution of the overlying ice sheet.

Many areas beneath modern ice sheets are underlain by sediment that will readily deform as pore water pressure becomes significant with respect to ice overburden pressure. The constitutive properties of these sediments must be taken into consideration when developing numerical ice sheet models, yet the chaotic distribution of grain size displayed in the subglacial environment presents a significant challenge. Several studies have determined that a Coulomb-plastic law is most appropriate for modeling subglacial sediment response to applied stress (e.g. Iverson et al., 1998; Tulaczyk et al., 2000a; 2000b).

Ice sheet models that neglect contribution to ice velocity from deformation of subglacial sediment often incorporate a sliding factor at the local ice-bed interface. As a result, temporal changes in ice-stream behavior resulting from changes in sediment advection are not predicted. Such models are inherently incapable of accurately predicting the location of non-topographically controlled ice-stream onsets and, correspondingly, overall ice sheet health. Pollard & DeConto (2003) successfully incorporated a model of deforming sediment into an ice-climate model and found a strong correlation between ice sheet response to climate forcing and bulk sediment transport.

The subglacial bed is one of the most inaccessible places on Earth and forms the least-studied part of the ice sheets. Our lack of knowledge of these remote environments makes the development and testing of theoretical models difficult. Despite significant progress achieved in recent years, Hooke's (1989) conclusions still hold true:

"Further progress in our understanding of the character of glacial drainage systems is being impeded by a lack of observational evidence upon which to base theoretical models. Present models assume rather specific conduit geometries and behaviors; when and if definitive observational evidence becomes available, many of these models may have to be abandoned or extensively modified. Owing to inaccessibility, however, such evidence is not likely to be forthcoming soon. Furthermore, isolated observations may be misleading if they are made under special conditions that are not representative of the system as a whole. Thus remote-sensing techniques such as dye tracing and perhaps geophysical studies are likely to provide the best data available to constrain theoretical and numerical models".

While the advent of remote sensing methods, such as LIDAR and InSAR, can provide insight into subglacial processes through monitoring surface changes caused by subglacial hydrology, any advances in robust ice sheet models must embrace new integrated observational efforts targeted at providing improved constraints on boundary conditions for models at all scales.

6.4. Recommended Studies

Objective: Develop and validate/verify quantitative models of subglacial hydrologic processes and incorporate these into large scale ice sheet models to yield coupled ice sheet – subglacial hydrology models.

Development of prognostic ice sheet models requires a better understanding of physical processes associated with the subglacial environment. Improved hydrological models are needed to provide better boundary conditions for ice sheet models by estimating the rates of water flow, basal melt and freeze-on, sediment transport through subglacial environments, and the spatial and temporal evolution of stress regime as a function of hydrology. Improved understanding of large-scale responses to point-scale processes, such as local changes in sediment rheology caused by hydrological or loading controls, is a fundamental step toward overall improvement of numerical ice sheet models. The ultimate goal is to include a physically-based treatment of basal hydrology in a full thermo-mechanically coupled ice sheet model. Borehole observations (e.g., water chemistry, sediment thickness, ice-water interface conditions, geothermal heat flux) as well as geophysical and remote sensing data (e.g., gravity, magnetics, seismics, radar, altimetry, InSAR) can provide boundary conditions and will be used for assessing the performance of these models.

New observations and coupled ice sheet – subglacial hydrology models will improve the understanding of:

1. The effect of subglacial hydrology on ice dynamics and feedback mechanisms.
2. The influence of subglacially-stored water on ice dynamics.
3. The water budget of different subglacial hydrologic systems.
4. The role of subglacial lakes in the nucleation of fast ice flow. Can subglacial release of large amount of water (e.g., draining of subglacial lakes) “restart” dormant, slow ice streams?
5. The effect of ice sheet mass balance changes on subglacial hydrology, e.g., switch from steady state to rapid subglacial hydrological processes.
6. The interplay between subglacial, englacial and supraglacial water in a changing climate. How do changes in surface melt influence subglacial hydrology (natural vs. anthropogenic effects)?

Regional studies

Determining ice sheet basal properties for assessing the performance of inverse ice sheet models, including:

- Derivation of new, improved subglacial heat flux maps for the Greenland and Antarctic ice sheets from airborne and spaceborne observations;
- Determination of spatial distribution and temporal changes of rheological properties of the bed in selected drainage basins;
- Assembling other data sets, such as improved bed topography/ice thickness.

Local studies

Observations of rapid changes occurring in the subglacial environment to study the influence of subglacial water production and storage on ice dynamics.

By reducing the basal shear stress between the ice sheet and the underlying substrate, the supply and distribution of subglacial water is a modulator of ice velocity in fast flowing regions, where the ice is sliding over either a layer of deforming water-saturated sediments (till) or water. For example, in Antarctica the subglacial water supply and distribution has been proposed as the cause of the episodic acceleration and slow-down of the ice streams draining into the Ross Ice Shelf (e.g. Engelhardt et al., 1990; Joughin et al., 2003; Kamb, 2001). More recently, periodically draining subglacial lakes, potentially modulating ice sheet velocity, have been discovered in both East and West Antarctica (Fricker et al., 2007; Gray et al., 2005; Wingham et al., 2006a; 2006b). Mounting evidence indicates that subglacial lakes and sites of elevated heat flux, characterized by high basal melt, are closely associated with the onset of streaming flow, such as the case of the Northeast Ice Stream in Greenland (Fahnestock et al., 2001) and the Recovery Ice Stream in Antarctica (Bell et al., 2007). Serving as fixed sources of basal lubrication these regions can also become nucleation sites for the initiation of fast flowing ice streams.

It is clear that subglacial lakes and the associated hydrologic systems are crucial components in the dynamic evolution of ice sheets and need to be incorporated into ice sheet models. Moreover, draining subglacial and supraglacial lakes offer the opportunity for studying the response of the subglacial environment to a large transient influx of water and allow us (i) to assess the performance of different inverse modeling techniques and test current understanding of underlying physics, and (ii) to investigate whether rapid changes in subglacial hydrology can trigger rapid, large and potentially irreversible changes in ice dynamics, for example if subglacial release of large amounts of water can “restart” dormant, slow ice streams or trigger the onset of fast (streaming) flow.

Investigating the interplay between subglacial, englacial and supraglacial water in a changing climate. How does increasing surface melt, attributed to climate warming, influence subglacial hydrology and ice dynamics in Greenland?

Parizek and Alley (2004) showed that including the effect of enhanced basal lubrication by surface meltwater increases the rate of ice-sheet discharge and consequent sea-level rise compared to model simulations not including this feedback. However, the effect of surface melt water on future ice sheet behavior cannot be projected with confidence because a clear process-level understanding of englacial water transport is still lacking (Alley et al., 2005). For example (Price et al., 2008) suggest that the velocity increase caused by increased surface melt might be limited by the evolution of the subglacial water system. They also point out that seasonal acceleration of ice flow, observed by Zwally & Jun (2002) and Joughin et al. (2008), does not necessarily imply increased local lubrication, but could be explained by a seasonal doubling of velocity in a well-lubricated, crevassed zone closer to the ice sheet margin, affecting velocities upstream through longitudinal coupling. We propose modeling studies together with extended monitoring of surface elevation and ice velocity changes by remote sensing and GPS observations to investigate (i) the distribution and temporal evolution of water beneath the wet and fractured margins of the Greenland Ice Sheet and on selected outlet glaciers (e.g., on and around Jakobshavn Isbræ and Helheim Glacier in Greenland) and (ii) the impact of subglacial hydrology and englacial water transport on ice sheet mass balance.

Physics of subglacial hydrology: Character and water budget of different subglacial hydrologic systems.

Subglacial water can flow under an ice sheet through an arborescent system of tunnels, linked cavity systems, or in a more or less uniform water film. While a well-connected conduit system efficiently transports the subglacial water at relatively low pressure toward the ice margin and thus does not impact ice velocity much, subglacial water flowing through a very thin distributed cavity system frequently encounters restrictions, and the water tends to be at high pressure potentially resulting in increased ice velocities. Changing between these morphologies can abruptly change ice velocities, causing ice to surge forward or abruptly slow down. Moreover, experimental work also suggests that an increase of water pressure in a till-dominated system could produce a decoupling of the ice sheet from the bed causing an increase in ice sheet velocity.

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