A Research Program for Projecting Sea-Level Rise from Land-ice Loss

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Executive Summary

The enormous impacts of future sea-level rise on socio-economic infrastructure, coastal habitats and ecosystems of the U.S. and other countries with similarly high population density and extensive coastal development require immediate attention. Population densities in coastal regions and on islands are about three times higher than the global average, with approximately 145 million people living within one meter of present sea level. Thus even a small increase in sea level will be disruptive through coastal erosion, increased susceptibility to storm surges and resulting flooding, groundwater contamination by salt intrusion, loss of coastal wetlands, and other issues. Accurate projections of the likely magnitude and rate of future sea-level rise are essential for international efforts aimed at mitigating climate change, as well as for local, regional, and national governments as they plan to adapt to committed climate change and sea-level rise while protecting environmental resources and sustaining economic growth.

Among the various components that contribute to sea-level change, increased loss of land ice (glaciers, ice caps, and ice sheets in contact with a subglacial bed) is expected to progressively become the dominant source of future sea-level rise. However, quantifying the response of land ice to climate change represents a major scientific challenge, leading to the central question addressed in this Report:

What will be the future mass balance of land ice and its contribution to regional and global changes in sea level?

This Report presents key strategies intended to guide future sponsored research by the National Science Foundation and other interested agencies on a concerted effort to address this central question. Ultimately, accurate projections of future land-ice loss require the use of numerical models that must adequately represent various processes influencing the current state of land ice in order to successfully simulate its response to external forcing and internal feedbacks. This Report identifies a series of scientific questions that must be addressed in order to achieve this overall objective. Each question is described in terms of existing data followed by implementation strategies, which include discussion of barriers (where they exist), required new observations and technologies, and analysis methods. The ordering of the questions follows a logical progression beginning with the first four which address the need to know the current status of the various components of land ice and researching the direct effects of environmental forcings on the atmospheric, marine, and subglacial interfaces of land ice. At the same time, the fifth question recognizes the need to identify and project the essential aspects of global climate that may impact land ice. This information then serves as the basis for projecting land-ice loss, as addressed by the sixth and seventh questions on the possible upper limits based on past configurations of land ice or by imposing dynamic limits on ice flow. Finally, the eighth question emphasizes the need to rigorously quantify the uncertainty in our projections of land-ice loss. Strong research linkages exist among these questions, and parallel and follow-on efforts that coordinate and synthesize the results from all eight questions will significantly improve our ability to make credible projections of land-ice contributions to regional and global sea-level changes. The success of this effort will require a sustained and long-term commitment involving dedicated partnerships between the U.S. National Science Foundation and other funding agencies with similar or parallel interests in support of sea-level research.

Background

Warmer climates reduce the amount of land ice and increase sea level. In recent years the land-ice contribution has increased and gained in importance relative to other components of sea-level change. Earlier attempts by the Intergovernmental Panel on Climate Change (IPCC) to quantify this contribution relied on large-scale models that did not allow for the possibility of a rapid dynamic response of land ice. The most recent IPCC Fourth Assessment Report (AR4) report stated that without a deeper understanding of the dynamic response of ice sheets, neither a best estimate nor an upper bound of future sea level is possible [*Meehl et al.*, 2007]. Since release of that report in 2007, several new and independent analyses have attempted to reduce the uncertainty in current estimates of land-ice loss. At this time, new observations have determined that mass loss from glaciers and ice caps is equivalent to 1.1-1.4 mm a^{-1} sea-level rise [*Cogley*, 2009; *Meier et al.*, 2007] and that the Antarctic and Greenland ice sheets is each contributing about 0.4-0.8 mm a^{-1}, and that these rates have accelerated over recent decades [*Rignot et al.*, 2008a; *van den Broeke et al.*, 2009; *Velicogna*, 2009].

In Antarctica, the most important regions for net mass loss are in West Antarctica. The largest net mass losses are documented in the Amundsen Sea embayment [*Pritchard et al.*, 2009; *Thomas et al.*, 2004], followed by the Antarctic Peninsula. For a few specific recent events, a rapid increase in loss of grounded ice follows the abrupt removal of the adjacent ice shelf or floating ice tongue [*Joughin et al.*, 2004; *Rignot et al.*, 2004; *T A Scambos et al.*, 2004], confirming the idea that the floating ice features buttress the glaciers and ice streams behind them. These are the regions of Antarctica where atmospheric warming is most rapid [*Steig et al.*, 2009], and ice shelves have recently collapsed or are rapidly thinning [*Cook and Vaughan*, 2010].

In the Northern Hemisphere, nearly the entire Greenland ice sheet is showing signs of net loss with the most pronounced changes underway in the southern half of the ice sheet [*Joughin et al.*, 2010; *Luthcke et al.*, 2006; *Pritchard et al.*, 2009; *Rignot et al.*, 2008b]. Losses concentrated around the margins are partially offset by increased accumulation in the high-altitude interior ice sheet. For both Greenland and Antarctica, some uncertainty in directly measured mass-loss rates remains because satellite-based gravity data require substantial corrections for the spatial variability of glacial isostatic rebound, which is only now improving through high-precision Global Positioning System (GPS) measurements of vertical bedrock motions [*Wu et al.*, 2010].

Given the facts that nearly a third of humans on the planet live within the coastal region [*Anthoff et al.*, 2006], that the frequency of high-water events is increasing in nearly all populated coastal regions [*Menendez and Woodworth*, 2010], and that many existing and planned future mega cities will be coastal, there is an urgent need to project future sea level. Increased loss of land ice is expected to progressively dominate other contributions to future sea level increase. Both the magnitude of future sea level and its rate of change are important. This Report presents key strategies intended to guide future sponsored research by the National Science Foundation and other interested agencies on a concerted effort to improve projections of future magnitude and rates of land-ice loss.

Objective

The research program described in this report addresses the specific question:

What will be the future mass balance of land ice and its contribution to regional and global changes in sea level?

Land ice refers to all ice contacting a subglacial bed, either in or out of ocean waters. The term draws a direct distinction with sea-ice. It explicitly includes mountain glaciers, ice caps and ice sheets and implicitly includes floating ice shelves connected to ice sheets or glaciers because ice shelves are directly fed by flow from the land-based features. Recent observations confirm a direct dynamic connection between glaciers or ice sheets and ice shelves [*Joughin et al.*, 2004; *Rignot et al.*, 2004; *T A Scambos et al.*, 2004]).

The question above makes explicit the connection between land-ice loss and sea-level rise; however, the focus of this report is on projecting future land-ice loss. Not all lost land ice will immediately affect sea level: some of the released water must travel within rivers or aquifers, and some may be retained on land in reservoirs [*Chao et al.*, 2008].

Land-ice loss causes immediate gravitational, isostatic and rotational adjustments associated with the transfer of grounded ice into the world's oceans, leading to a non-uniform (non-eustatic) redistribution of water, commonly referred to as the global sea-level "fingerprint" [*Milne et al.*, 2009; *Mitrovica et al.*, 2001; *Tamisiea et al.*, 2003]. Identifying the sources of land-ice loss (and possible regions of land-ice-mass gain) and their associated fingerprints is thus essential to determine what coasts will experience local sea-level change either above or below the global mean. This will be critical information for planners and policy makers. The question, however, is not intended to include analysis of local rates of subsidence, not because they are unimportant, but because they are not directly related to projecting land-ice loss.

Ultimately, accurate projections of future land-ice loss require the use of numerical models that can adequately represent the current state of land ice and successfully simulate the response of land ice to external forcings and internal feedbacks. This leads to a series of scientific tasks that must be addressed to achieve the overall objective. In this report, these are presented in the following section as a set of research questions. Each is described in terms of existing data followed by implementation strategies, which include discussion of barriers (where they exist), required new observations and technologies, and analysis methods. The ordering of the questions follows a logical progression from needing to know the current status of the various components of land ice; researching the direct effects of environmental forcings on the atmospheric, marine, and subglacial interfaces of land ice; identifying and projecting the essential aspects of global climate that impact land ice; projecting possible upper limits on land-ice loss based on past configurations of land ice or by imposing dynamic limits on ice flow; and then rigorously quantifying the uncertainty in our projections of land-ice loss.

Research Questions

1. What is the ongoing rate of change in mass for all glaciers and ice sheets and what are the major contributing components to the mass change?

Relation to Objective

Recent assessments have shown an increase in the rate of mass loss from glaciers and ice sheets around the planet over the last decade. It is critical to examine these mass changes and expand investigations into poorly studied areas in order to develop observation strategies and inform models tasked with projecting the future contributions of glaciers and ice sheets to sea level. Important questions to address are:

- What is the spatial variability of ongoing mass changes?
- What is the temporal variability of ongoing mass changes?
- What trends are apparent in the mass changes?
- How well can the individual components of the mass balance, such as accumulation, surface melt, runoff and ice calving be constrained?

Existing Data

Satellite and airborne remote sensing measurements (for example, interferometric synthetic aperture radar (InSAR), sub-pixel correlation of optical imagery, altimetry and gravity (GRACE)) provide regional views of ice-sheet and glacier velocities, elevation changes and mass changes. Regional climate modeling combined with ice-discharge estimates at flux-gates is also a useful means to assess mass changes and discriminate the relative contributions of ice discharge and the individual components of the climatically-driven mass balance.

Global assessments of net mass changes for glaciers and ice caps (G&IC) are scarce. These syntheses depend largely on the extrapolation of time series derived from ground-based observations. These labor intensive studies are of varying length and quality and are collected from about 300 (mostly small) glaciers that represent only about 0.1% of the estimated ~160,000 glaciers on the planet [*Bahr and Dyurgerov*, 1999]. Regional trends in mass balance are currently estimated by scaling up mass-balance measurements from small study glaciers [*Kaser et al.*, 2006], but this approach is subject to large uncertainties, and the number of glaciers instrumented and studied in this manner has decreased in recent years due to lack of resources, adding to these uncertainties.

There is a fundamental lack of basic information about many glaciers around the planet. Critical variables such as the area, area-elevation distribution and volume are largely unknown. International databases such as the World Glacier Inventory (WGI) archive location, area and maximum/minimum elevation of individual glaciers but do not provide data suitable for deriving mass changes. The Global Land Ice Measurements from Space (GLIMS) database at the U.S. National Snow and Ice Data Center provides glacier outlines for approximately one-third to one-half of all glacierized areas, but these parameters are of varying quality and resolution and many have not been updated to reflect recent changes.

Implementation

Required observations

It is essential that remote sensing observations, including altimetry, InSAR, and GRACE, are continued in order to provide continuous time series of the ongoing mass change of all land ice. Methods need to be developed or refined to resolve the large discrepancies between existing mass-balance assessments of the ice sheets, and different approaches should be cross-validated and integrated to exploit the strengths of each method. New observations such as *in situ* continuous GPS networks and airborne gravity measurements in support of improving estimates of glacial isostatic adjustment are needed to constrain gravimetry and altimetry based mass-balance estimates. Altimetry derived mass-balance estimates require better models of firn compaction. InSAR and optically derived estimates of ice discharge need more detailed observations of grounding line locations and especially ice thicknesses. Regional climate models need further development to reconcile disagreement between estimates of the individual components of the climatically driven mass balance among various models. Strategies need to be developed to integrate surface mass-balance models into climate models and to compare model output with observations.

For assessing and projecting the contribution of G&IC to future sea level, it is important that global glacier inventories are made more complete, with a special emphasis on regions that are major contributors to sea-level change. Key variables required include additional information on the boundaries and area of individual glaciers, their hypsometry and the fraction of G&IC draining into marine-terminating outlets. Efficient tools such as automated classification techniques need to be developed to obtain regional coverage even if this is at the expense of higher precision. Up-scaled inventories and projections are at present entirely dependent upon poorly validated power-law scaling relationships [*Bahr et al.*, 1997]. Representative direct thickness measurements from airborne radio-echo sounding, for example, are required to validate scaling techniques.

Existing mass-balance time series obtained from *in situ* observations and repeat surface elevation surveys must be continued, but new observations, especially from larger ice caps, are essential in order to assess mass changes and inform mass-balance models. Seasonal *in situ* measurements are needed to constrain mass-balance models since they provide insight into the temporal variability of mass changes and their controls. Existing data sets need to be compiled and assimilated and methods developed to obtain global-scale mass changes from the sparse existing data. Such assimilation will inform observation strategies, such as assessing minimum sampling densities. It is important to assess the role of mass loss by iceberg calving in total mass changes of G&IC as a base from which to develop models that incorporate the dynamic component of mass loss into global-scale mass-balance modeling. Observations of velocity and ice thickness at flux gates of major marine-terminating glaciers are required. It is noted that not all mass lost from land-based ice will reach the oceans, so it is necessary to ascertain the portion of glacier mass loss that does not contribute to sea-level rise. In general, remote sensing methods and modeling must play a much stronger role in the future to capture G&IC mass balance rates more efficiently and completely.

Because some assessments of ice-sheet mass balance include some or all of the mass loss from G&IC's peripheral to the Greenland and Antarctic ice sheets, it is important to correct for double-counting of mass loss from Greenland and Antarctica in global assessments of all ice masses to sea-level rise.

2. How do surface processes and their spatial and temporal variability affect the mass balance and behavior of land ice?

Relation to Objective

Surface processes directly control rates of glacier accumulation and ablation, and are therefore a key component of mass-balance monitoring and modeling. Beyond their direct impacts on surface mass balance, snow and other surface processes have an indirect impact on ice dynamics by controlling the quantity of meltwater that reaches the bed or contributes to ice shelf breakup. Moreover, understanding surface processes and structure are important for accurate interpretation of satellite and airborne measurements of ice surfaces, and the interpretation of climate signals recorded in ice cores.

Overview of Processes

Processes acting at the air/snow or air/ice interfaces and within the atmospheric boundary layer govern the exchange of energy and mass across these boundaries, and subsequently control the surface mass balance of land ice. These processes include radiative, conductive and convective energy exchanges that drive changes in the phases of water, as well as mechanical processes such as blowing snow and meltwater transport that redistribute mass and energy across and within the ice. The primary atmospheric drivers of surface balance are the nature and distribution of clouds, and the dynamic (wind) and thermodynamic (heat and vapor content) characteristics of the air. These characteristics and their temporal evolution govern how much precipitation arrives at the surface in the form of snow accumulation, how much snow and ice melts, and the rates and extent to which snow is transported or metamorphosed to ice. Surface and near-surface processes also play important roles in ice mass balance, since surface characteristics, such as the ice crystal grain size, surface water content or roughness feed back to atmospheric processes. These surface characteristics and processes can increase the receipt of radiation due to changes in surface albedo, or alter turbulent energy exchanges due to variations in surface roughness. Processes occurring within the near-surface snow or ice layers further influence mass and energy exchanges, for example through the formation of superimposed ice.

Existing Data

Observations of surface processes require the continued maintenance and expansion of existing observing systems, particularly satellites and meteorological observations from stations. Existing *in situ* observations include the Greenland and Antarctic Automated Weather Station (AWS) networks, and weather stations on or near glaciers and ice caps. Satellite observations of surface processes include optical imaging of snow-cover extent, active and passive microwave measurements of snow accumulation, passive microwave measurements of melt extent, thermal imaging of snow-surface temperatures, and multispectral imaging of snow and ice albedo. In addition, the atmospheric models necessary to interpolate / extrapolate measurements of surface processes from local to regional scales rely heavily on satellite observations of the atmosphere. Numerous short-duration *in situ* observational programs have contributed information on processes of snow accumulation, metamorphism and melt at specific sites. Existing surface accumulation data from radar surveys and firn and ice cores on the ice sheets has been used in developing downscaled regional atmospheric models of accumulation, which should continue to be refined and validated against new field data as it is collected. Four polar cloud observation sites exist in the Arctic, along with two in the Antarctic, providing important information not only on clouds but on atmospheric boundary layer processes over ice that are obscured from satellite observation due to clouds.

Implementation

There are modeling and observational barriers to improving our understanding of surface processes on land ice. Quantifying snowfall and the proportion remaining as snow accumulation is presently one of the greatest challenges to existing mass-balance observational programs. Cloud cover and type are important parameters for predicting receipt of radiation at the surface, but are not adequately represented in large-scale atmospheric models. Ground-based observations of clouds and precipitation are difficult to automate and presently require manned stations. Remotely deployable cloud instruments are in development, but their widespread use has been hampered by power constraints and cost. Weather and climate models do not resolve local atmospheric variability for glaciated valleys in rugged mountain ranges or ice sheet outlet glaciers, and reasonable downscaling methods require local data, particularly for such basic parameters as temperature and pressure. These local measurements are difficult to acquire because most glaciated regions are remote and have few or no weather stations. In addition, the complex terrain of these regions often produces regional climates with much higher spatial variability than seen in satellite observations or models of the atmosphere. In high precipitation or melt regions on glaciers and ice sheets, there are serious engineering barriers to the collection of atmospheric data for assimilation into models, since the position of fixed-height weather instruments with respect to the snow / ice surface may vary seasonally by several meters. Direct measurement of melt, water content at depth in the snowpack, meltwater movement over and into ice, and superimposed ice formation currently require *in situ* observations.

Required observations

Research needs for a better understanding of snow accumulation on land ice and its susceptibility to future climate changes require high-quality temporally resolved information on the processes governing the current spatial distribution and magnitude of accumulation. Like accumulation, the melting of snow or ice surfaces is forced by atmospheric processes, but the movement of meltwater over and into ice is largely governed by ice topography and crevassing, which are largely surface expressions of ice dynamics. Melt is also a surface boundary condition for ice dynamics, since the englacial and subglacial transmission of that water and its heat may result in increased bed lubrication and a decrease of the ice's viscosity. Climatological data on both accumulation and melt extent and frequency on glaciers and ice sheets is needed in combination with atmospheric forcing data to refine and validate models of ice-surface processes. Required observations include:

- Measurements of snow accumulation and snow and ice melt on glaciers and ice sheets. Existing observational networks must be combined and integrated with new techniques to routinely produce spatially distributed maps of snow accumulation and melt extent, as determined from ground, airborne and satellite measurements. Firn and ice cores will provide critical temporal information, particularly near ice-sheet coastlines and on maritime glaciers where surface observations are difficult to calibrate due to the high magnitudes and variability of precipitation.
- Atmospheric measurements of clouds, radiative and turbulent fluxes, and precipitation. Of particular importance are new observations in coastal / maritime locations with heavy cloud cover and large amounts of precipitation. Observational transects from high-precipitation regions towards drier continental interiors, more radiation measurements, and more vertical soundings are necessary to improve cloud cover and atmospheric boundary layer simulations. Other suggestions include radiosonde launches from seasonal field camps on the ice sheets, and the development of low-cost temperature and pressure logging and transmitting stations for widespread deployment in glaciated mountain ranges with poor data coverage.
- Measurements of snowpack processes and characteristics including snow grain size and crystal habit or specific surface area, density, and temperature are needed at a wide range of locations to improve models of snow processes and of surface energy balance over snow and ice. These measurements and improvements to snowpack models will also allow better quantification and modeling of firn densification and compaction, critical to the interpretation of geodetic measurements of glacier and ice-sheet mass changes.

New Technologies

- Development of measurement techniques to quantify the relation between precipitation and accumulation, particularly the sublimation of blowing snow. This may be an important mechanism of precipitation recycling over snow and ice surfaces, but models and estimates are currently unconstrained by data.
- Development of means to examine the routing of meltwater and its transformation into superimposed ice or other forms of internal accumulation. Lack of such information may be a significant source of error in mass-balance assessments of glaciers and coastal ice-sheet outlets. Ice layers found in firn cores are evidence of past surface melt, but the conditions under which they form, and their influence on other surface measurements, are poorly constrained.

Analysis Methods

The observations identified above would enable development of more reliable and comprehensive models of surface processes in order to improve projections of future sea level. Advances in surface balance modeling can be made by developing parameterizations for use in atmospheric models, and by finding appropriate means to assimilate new observations into models and atmospheric reanalyses. Specific improvements include the representation of clouds, radiative and turbulent exchange with snow and ice surfaces, precipitation and winds. These processes are typically heterogeneous on length scales shorter than atmospheric model grid cells, requiring parameterization or nested models, which must then be evaluated against observational data covering an appropriately large area. Substantial interaction between the observation and modeling communities is needed to ensure that the observations required to improve models are effectively made, and that the observations that are made are effectively used. For example, the atmospheric modeling and data assimilation communities should be involved in site selection for new atmospheric measurements, even if the primary purpose of those measurements is for surface process studies. Few atmospheric observations are made over earth's ice surfaces, so it is critical that any new observation sites provide the maximum possible value to both local and global atmospheric modelers, as well as to researchers studying ice surface processes.

3. What are the geometry, character, behavior and evolution of the ice/bed interface, and what are their impacts on ice flow?

Relation to Objective

Conditions and processes at the ice/bed interface are a first-order control on ice flow speed, and therefore understanding of these conditions and processes is essential to assessing the potential response of glaciers and ice sheets to external forcing [*Clarke*, 2005]. Important questions to address are:

- What is the shape of the bed, including basal topography and roughness at scales relevant to controlling ice flow?
- What is the thermal and hydrologic character of the bed, including the basal temperature, geothermal heat flux, and basal hydrologic system, insofar as these influence the position of shear margins and the locations of frozen and unfrozen regions?
- What is the behavior of the ice/bed interface and what processes control that behavior, including, hydrology, till and basal ice rheology, roughness, basal debris and its friction, and how can these processes be parameterized for use in ice-flow models?
- How does the configuration and temporal evolution of the subglacial hydrologic system influence ice motion?

Existing Data

Our knowledge of the subglacial environment has increased through a combination of field and remote-sensing observations, significantly improving our understanding of how subglacial conditions regulate the fast motion of glaciers and ice sheets. However, both scientific and practical considerations have necessitated that these observations be made at a local to regional scale, leaving the basal environment under-sampled. For example, the bed topography of some small glaciers and key marine-terminating regions of ice sheets, such as Jakobshavn Isbrae and Pine Island/Thwaites Glaciers [*Holt et al.*, 2006; *Vaughan et al.*, 2006], are particularly well mapped, but vast regions of the Greenland and Antarctic ice sheets and other glaciated regions, including most large Alaskan tidewater glaciers, have few or no comparable data. Likewise, borehole studies providing insight to basal temperature and hydrologic conditions and their fundamental control on rapid basal motion remain sparse [*N Iverson et al.*, 1995; *Kamb*, 2001].

Implementation

Required observations

New observations are required to improve our understanding of the role of subglacial environments in regulating ice-sheet dynamics. One of the most significant observational requirements is improved resolution of bed topography and roughness at scales guided by the needs of numerical ice-flow models – 100s to 1000s of meters at the grounding line to 10s of km in the interior [*Jezek et al.*, 2009; *Jezek et al.*, 2011]. Inverse and adjoint solutions for these models should guide where bed topography measurements are needed to better constrain ice-flow models. Information about basal character, including gravity and gravity anomalies, basal temperature, basal hydrology, and till depth, is needed at a similar resolution as bed topography. In addition, our current poor understanding of rheology at the ice/bed interface, especially deformation of till and basal ice, could be improved through laboratory experiments coordinated with measurements of surface motion, borehole instrumentation, subglacial sampling, and geophysical inversions [*N R Iverson et al.*, 2007; *Sane et al.*, 2008].

Frequent and spatially extensive InSAR measurements of surface velocity are needed to fully utilize these new bed observations. Coupling surface velocity with known bed conditions will allow for the inversion of basal conditions over large spatial areas [*D MacAyeal et al.*, 1995]. Repeat surveys will allow examination of changes in flow speed that result from changes in boundary conditions and any associated changes in basal conditions.

Active seismic observations cannot be applied everywhere, but should be coupled to the adjoint solutions to improve understanding of the results through distinguishing lakes, soft beds (and their characteristics), and hard beds [*Blankenship et al.*, 1986]. Passive seismic observations reveal the locations of sticky spots, detect stick-slip behavior that should be included in flow modeling, and monitor outburst flooding affecting lubrication over short times [*Anandakrishnan and Bentley,* 1993].

Highly crevassed regions and the vast scale of glaciated regions means that some important geophysical data cannot be measured everywhere, including in some essential regions. Nevertheless, adjoint solutions or other “inversions” from ice thickness, surface slope and ice velocity using the relatively better-known rheology of ice will be required to accurately incorporate basal lubrication. Repeated application of this approach to regions that are changing will allow more complete estimation of the “flow law” over a wider range of subglacial conditions. Viscoelastic and plastic, rather than purely viscous, models will be needed for interpretation of changes caused by tidal forcing or other rapid forcing [*Gudmundsson*, 2007]. Observationally, repeated velocity determinations must be coupled to thickness and other data to be most useful.

New technologies

Technological advances are required to fill the observational gaps associated with the subglacial environment. Ongoing advances in the radar depth sounding of glaciers and ice sheets are a promising avenue for increased constraints on the nature of the subglacial environment. For example, high-resolution (<10 m) 2-D observations of basal topography and basal roughness may be potentially observed using ice-penetrating SAR. In addition, cost-effective, long-distance aircraft (i.e. V5, Global Hawk) are needed to make expanded coverage practical. Additional priorities for technological advances should focus on increasing knowledge of physical conditions at the bed. For example, the development of more cost effective drilling techniques would permit increased observations of basal temperature and relevant hydrologic variables as well as of subglacial material properties. It is also likely that new laboratory experiments aimed at elucidating basal physics would provide useful guidance for field observations of subglacial processes. Continued improvement of seismic techniques will be valuable. New techniques are needed to improve our ability to observe changes in the basal hydrologic system as they relate to changes in ice velocity.

Improved ability to determine surface-velocity fields is also essential, including sub-daily data to capture response to tidal forcing, outburst or lake-drainage floods, and other short-period events, but also capturing velocity changes and driving-stress changes as the ice sheets respond to forcing over years and longer.

Analysis methods

The integration of new and existing observations with numerical ice-flow models is the most direct path towards improved knowledge of basal motion. For example, the inversion of high-resolution bed topography with observations of surface velocity can be used to resolve spatial variations in basal drag. The results of these modeling studies can then be used to set priorities for campaigns collecting local observations of subglacial conditions (i.e. seismic studies for discriminating hard- versus soft-bed sliding). However, to better understand the evolution of the ice/bed interface, repeat measurements of ice flow and basal behavior are needed, particularly following a perturbation to the glacier stresses (*e.g.*, ice-shelf collapse, grounding line retreat, lake drainage). These perturbations will provide natural experiments to resolve changes in basal friction and/or flow. Viscoelastic and plastic models will be needed to accurately model the response to fast perturbations. In addition, continued advances are needed in our understanding of subglacial water-flow and its influence on ice motion. Most theoretical and process-scale models of subglacial hydrology are currently not coupled to dynamic ice flow models. As a result, ice flow models generally implement “static” basal boundary conditions rather than boundary conditions that co-evolve realistically along with the subglacial hydrology. Thus, the development of subglacial hydrologic models that can be coupled with dynamic ice-flow models will be a fundamental improvement in our ability to predict future land-ice contributions to sea level rise.

4. What are the most significant ocean/ice interactions that govern the thermodynamic and dynamic behavior of marine-terminating land ice?

Relation to Objective

Recent observations show that the most rapid acceleration of land-ice mass loss occurs in marine-terminating glaciers and ice streams draining ice-sheet catchment basins through floating ice shelves and tongues that have recently experienced large changes in ice extent and/or thickness [*D H Holland et al.*, 2008; *Joughin et al.*, 2010; *Pritchard et al.*, 2009; *Rignot et al.*, 2010; *Shepherd et al.*, 2003; 2004]). The favored hypothesis at this time is that in addition to direct floating land-ice mass-loss associated with basal melting and calving, reduction in the extent of floating land ice can reduce the forces buttressing the grounded ice, leading to rapid dynamic thinning of the glaciers and ice streams. However, losses may also be assisted through rapid disintegration of ice shelves triggered by surface melting [*D R MacAyeal et al.*, 2003; *T Scambos et al.*, 2003; *T Scambos et al.*, 2009] and ocean waves [*Massom et al.*, 2010].

Given that oceans likely play a significant role in land-ice mass loss, then understanding changes in ocean heat content and circulation on local-to-global scales (c.f. Question 5) is required. Recent measurements indicate that the average temperature of the global upper ocean is increasing [*Lyman et al.*, 2010] with changes of up to 0.4°C from 1969 to 2008, averaged over 0-700 m depth and partial ocean basin scales [*Levitus et al.*, 2009]. While the impact of this warming would be significant for specific land-ice marine margins, more rapid changes in the ocean heat provided to the margins can occur through changes in circulation of warm ocean currents, which can change water temperatures by several degrees on time scales from seasonal to a few years; see, *e.g.*, [*D M Holland et al.*, 2008] for Greenland case studies.

However, most evidence linking ocean forcing with land ice response is indirect. Few direct measurements of basal melting have been made; iceberg calving laws are still rudimentary and primarily based on the few observations of iceberg calving rates that exist; and detailed, long-term datasets required to unambiguously separate ocean-induced thermodynamic changes in the ice shelves and tongues from other changes induced upstream of the grounding line are lacking. For most settings insufficient information exists on ocean circulation and hydrography to correlate remotely sensed changes in land-ice thickness and extent with ocean temporal and spatial variability. Even the sign of the response of land-ice mass change to projected ocean warming is uncertain for specific environments because of complex feedbacks between the ocean, land-ice, sea ice, and atmosphere; *e.g.*, [*Nicholls*, 1997].

Currently, ocean interactions with the land ice are parameterized within numerical models, with the assumption that these models and parameterizations are representing the most important physics of the ocean/ice system [*Holland and Jenkins*, 1999]. Adequate model performance is only possible through tuning of parameters to provide acceptable representation of the few observed characteristics of the system. The need for tuning implies that empirical parameterizations may fail when extrapolated beyond the climate state for which they were derived and warns against using models for projections of future land-ice loss through ocean effects. It is not even currently possible to determine whether the glacial environments presently experiencing the most sensitivity to environmental change will be the dominant contributors to land-ice mass loss over decadal to century time scales.

Thus, while ocean-related effects clearly contribute significantly to recent land-ice mass loss, predicting future ice loss depends on progress in several areas including: advances in observations and measurement technologies; representation of key processes in numerical models and improved computational techniques; and collaborative research merging skills in oceanography and atmospheric sciences, ice dynamics, thermodynamics and mechanics, and the geological setting.

Implementation

Required Observations

The primary requirement at this time is for observations targeted at unambiguously determining the ocean/land-ice interactions that must be accurately represented in climate models. While some progress can be made with reanalyses of existing data sets, there is a need for new exploratory measurements aimed at identifying previously unexpected processes, and focused, multidisciplinary measurement programs.

Reanalyses

The primary determination of marine-glacial environments chosen for detailed study is based on recently observed rapid changes in land-ice distribution near marine margins. However, the community has not yet quantified the probability of specific environments contributing significantly to decade-to-century land-ice loss. One approach is a concerted effort to classify the wide range of environments experienced by marine terminating land ice. The objective would be to reduce the large number and complex range of environments to a manageable set for detailed conceptual and numerical modeling studies, which could be used to determine priorities for new data sets. Classification would be based on factors such as relative contributions of various processes to the overall mass and force balances. It is plausible that these analyses would identify presently inactive systems that would be activated in projected future climate states. Research should consider the possibility that some systems may be stabilized by feedbacks for some range of variability in background climate state through processes such as decreased formation of dense High Salinity Shelf Water [*Nicholls*, 1997], increased marine ice accretion on ice-shelf bases, increased ice-shelf basal melting [*Gagliardini et al.*, 2010], sea-level fall adjacent to retreating marine-based margins [*Gomez et al.*, 2010], and increased surface accumulation offsetting losses by basal melt.

The main impediment to this reanalysis is the fractured state of relevant databases. Many research groups now serve partial data sets but coordination of these data sets is not always ideal for researching complex environments. For example, modeling initialization and validation requires detailed, constantly updated geometric information (time-varying seabed, ice base, ice-surface topography, and ice-shelf extent), along with oceanic and atmospheric observations or simulations. Multiple data sets exist for each of these components, but no single site serves all available data interpolated to common epochs and in a consistent format.

Progress also requires interdisciplinary collaboration. Mass and force balances and uncovering the processes that govern them for marine-terminating land ice require input from oceanographers, atmospheric scientists, glaciologists and geologists. There is now sufficient evidence to confirm that strong feedbacks exist between these components of the climate system. Interdisciplinary research should be fostered through: (*i*) improved institutional mechanisms for funding such research, including Ph.D. student and postdoctoral opportunities; and (*ii*) focused, multidisciplinary workshops.

Required new measurements

Based on what is presently known, the following measurements are needed for initializing models and assessing the performance of specific model components. Brackets list known, applicable technologies.

- Ice-shelf cavity, fjord bathymetry, and floating ice thickness, including time series (active source seismology, gravimetry, radar, laser altimetry, AUV and ROV, instrumented marine mammals).
- Ice structural, dynamic and thermodynamic properties: density, temperature; surface water content; ice velocity; shear margin structure; marine ice content and crevasse geometry (InSAR, altimetry, visual imagery, passive microwave, surface radar, boreholes).
- Calving (passive seismic, time lapse photography, Global Positioning System (GPS), satellite imagery including optical, high res SAR, upward looking acoustic Doppler).
- Grounding zone characterization: mapping (laser altimetry, MODIS break-in-slope, radar interferometry) and time-dependent ice front mapping (MODIS, Landsat); ice thickness and bedrock features (ground penetrating radar); migration (strain gauges; GPS, satellite imagery); direct subglacial and ice-shelf cavity measurements (basal debris and subglacial till properties, grounding-zone wedge sediment properties, subglacial water and hydrographic measurements); direct subglacial and ice-shelf cavity sampling (sediment and ice cores, water samples).
- Meteorological forcing including temperature, radiation balance, wind stress, relative humidity and precipitation (satellite microwave atmospheric sounding and scatterometer, AWS, regional modeling)
- Multi-year to decadal time series of ocean currents and hydrography in and near the ice shelf cavity (through-ice and near-ice-front moorings, acoustics, tracer hydrography) or tidewater glacier front (near front moorings); synoptic snapshots of hydrography and currents (AUVs, acoustically navigated gliders); hydrographic observations aimed at a range of scales to capture processes of ice-ocean interaction
- Adjacent ocean shelf bathymetry and hydrography and sea-ice conditions (swath mapping, autonomous gliders, instrumented marine mammals, radar and visual satellite sea ice imagery)

New technologies

Recent innovative approaches to obtaining measurements near the ice-sheets' marine margins demonstrate the value in transitioning these technologies to more routine application. Autonomous underwater vehicles such as Autosub [*Jenkins et al.*, 2010; *Nicholls et al.*, 2006]) are presently high-risk but high-reward endeavors. Direct measurements of basal melt by phase-sensitive radar provide a definitive test of basal melt rates [*Corr et al.*, 2002; *Jenkins et al.*, 2006]). Radar studies across grounding lines can also detect basal melt, although only for regions that are logistically accessible and relatively uncrevassed [*Catania et al.*, 2010]). Instrumented marine mammals provide the ability to map ocean hydrography [*Nicholls et al.*, 2008] and bathymetry [*Padman et al.*, 2010] offshore of ice fronts. Approximate sub-ice-shelf bathymetry can be inferred from inversion of airborne gravity data from the IceBridge program (pers. comm., J. Cochran, 2010).

Newer exploration technologies must also be fostered, driven by the scientific needs for new data. Methods already applied in other ocean regions should be tested and adapted to the complex and harsh environments around land-ice termini. These methods include "remote" sensing of ocean temperature, salinity and circulation in the marine margins through acoustics, and monitoring ice behavior through acoustics, seismology, GPS and satellite velocity mapping. For some "mature" technologies such as GPS, the novel requirement is for sustained operations over-winter and for multiple years, since recent modeling suggests large seasonal and interannual variability in both the ice and ocean. Tracer hydrography and the new and emerging generation of chemical sensors should prove invaluable to understanding processes and scaling very local observations. As with other remotely sensed data, ground-truthing data are important and thus there is a need to have subglacial access ice drilling to obtain direct samples and measurements to constrain the data from the areally important coverage from remote sensing.

Modeling

The community requires access to coupled ocean/ice models with sufficient resolution to resolve the grounding zone and the calving fronts. An adaptive-mesh model is being developed in the U.K., but significant progress could be made with structural grid models currently applied to oceanic domains without ice shelves; *e.g.* FVCOM. In addition, modeling efforts should focus on (1) process-scale modeling and validation, (2) developing parameterizations from successful process-scale models for use in larger scale models, and (3) testing and validating large-scale coupled ocean/ice models. To the extent possible, models should be developed as a "community" resource, taking advantage of multiple users testing different explicit and parameterized schemes for specific processes. While modeling efforts that identify high-variability environments (*e.g.*, Amundsen Sea Embayment) will provide confidence in parameterizations, modeling should also seek to identify other regions that may become active with a sufficient change in background climate state.

5. What are the key aspects of distant climate that impact land ice and how are they likely to change?

Relation to Objective

The distant, or external, climate system is here defined as the properties of the atmosphere and oceans surrounding and enveloping the land ice, properties which are set for the most part by the global climate system. Changes in land ice are ultimately determined by distant climate forcing, driven by factors such as variations in solar heat flux, volcanic aerosols, greenhouse gases, to mention a few. It is through distant climate forcing and natural internal variability of the climate system that the properties of the atmosphere and oceans that envelope the ice sheets are set. The external climate system brings the heat and moisture to the ice sheets through global pathways and mechanisms that are not yet fully understood. The focus here is distinctly different than for Questions 2 and 4, already discussed above, in that it centers on how the global system *delivers* interannual and longer timescale variability of heat and moisture to the surface and the floating base of the ice sheets whereas Questions 2 and 4 focus on how the ice sheets respond to such changes. While the evolution of land ice itself has an effect on the external climate system, in the present context the principal concern is with the effects of the external system on land ice. Development of ice-sheet models is occurring at an accelerating pace [*Lipscomb and al.*, 2009; *Little and al.*, 2007], with observations of key processes beginning to be transformed into parameterizations suitable for eventual use in prognostic models (again, see Questions 2 and 4 above). However, without a concomitant understanding of the global to polar-scale mechanisms governing the variations in heat and moisture transport to the land ice, establishing robust projections of land-ice contributions to future sea level will not be possible.

Existing Data

A number of aspects of the atmospheric, oceanic, and sea-ice components of the global climate system have significant variability in the polar regions on a range of time and space scales. The aspects include, but are not limited to: phenomena known as the North Atlantic Oscillation [*Hurrell*, 1995] and the Southern Annular Mode [*Thompson and Wallace*, 2000], which involve the variation in intensity of the westerly winds in each hemisphere; variations in the Meridional Overturning Circulation [*Lozier et al.*, 2010]; changes in sea-ice cover over the Arctic Ocean [*Serreze et al.*, 2007] and Southern Ocean [*Gille*, 2002]; and changes in the pathways and intensity of the North Atlantic Current [*Hakkinen and Rhines*, 2004] and the Antarctic Circumpolar Current [*Böning et al.*, 2008] and their associated warm-water branches. From a number of lines of inquiry, including recent observations and paleo-records, as well as numerical modeling results, it is known that these aspects of the climate are vulnerable to large change in the future.

On longer time scales (millennial and beyond), the direct influence of atmospheric heating can have a dramatic influence on ice-sheet behavior [*Ridley et al.*, 2005]. On shorter time scales (decadal to centennial), however, it is believed that changes in warm, subsurface waters near the ice sheets can rapidly bring heat to the marine periphery of an ice sheet and cause ice drawdown [*D M Holland et al.*, 2008]. Abrupt changes in ocean circulation pathways are thought to be controlled by abrupt atmospheric transitions, and possibly mediated by a changing sea-ice cover. All such changes near the ice sheets are controlled by changes in hemispheric to global scale processes occurring far away from the ice sheets.

The past may serve as prologue to future behavior in this context, and knowledge of paleo-records may help frame the mechanisms and amplitudes of variability of global- to polar-scale atmospheric and oceanic variability, and the connectivity between the two scales. The instrumented record of the 20th century may also provide some further insights, particularly in attempting to separate natural from anthropogenic forced climate change in the environments surrounding the land ice. Further examination of atmospheric reanalysis, ocean-state estimation, and sea-ice records will likely be informative. This needs to be done within the context of defining the mean state of transport of heat and moisture to land ice as forced by atmospheric and oceanic process far away from the ice sheets themselves, and quantifying the variations about that mean. Such study would also reveal what observations we need to sustain, and which ones may be missing at present.

Implementation

Required observations

Historically, the high-latitudes have generally lagged other regions of Earth in terms of basic observations of processes and sustained larger-scale observations. To gain adequate insight into the forcing of the land ice by the external climate system and connections between low and mid-latitude climate and that at high latitudes, large spatial-scale observations of the atmosphere, sea ice, and oceans in the polar and extra-polar regions are required. The largest gap in the observational data set resides with the subsurface ocean. Currently adequate mappings do not exist of the regions where warm waters are, how they vary, and how the variations relate to changes in the atmospheric and sea-ice cover states.

Analysis methods

With extensive, large-scale observations of the state of the polar and extra-polar atmospheres, oceans, and sea-ice covers, integration of those observations into comprehensive numerical models can begin; this should allow such models to replicate observed behavior. This would include both the mean state and the variations on the mean. Such models can ultimately be used to project the likely variations to occur in the external climate system over the coming century, which in turn will be critical to projecting the land-ice contribution to sea-level change.

6. What do paleorecords tell us about the fate of contemporary land ice and the rate at which it can change?

Relation to objective

The response of land ice to warmer climates in the past is known from records of sea-level change, marine and terrestrial sedimentation around former ice sheet and glacier margins, and from chemical and isotopic evidence preserved in ice cores. Extending and interpreting the evidence from these, and new kinds of paleorecords, will provide valuable information on the relationship between climate forcing and changes in land ice volume, and place bounds on possible future changes. Paleorecords can address both the magnitude of land ice loss, and potential rates of change related to ice dynamics. Guiding questions for extension of the paleo record are:

- What were the configurations of the Greenland and Antarctic ice sheets at times of higher sea level in the past?
- What do paleorecords tell us about past rates of unstable ice sheet collapse and sea level rise?
- What climatic conditions led to reduced land ice cover at times in the past relevant to projected future climate?

In addressing these questions, highest priority should be given to determining the interglacial configurations – geographic extent and thickness – of ice sheets that existed under conditions similar to those expected in the next few centuries of a warming world. Because society's ability to adapt depends so heavily on rates of change, emphasis should also be given to paleorecords that help constrain the stability or instability, and potential rates of collapse, of present-day marine sections of the polar ice sheets.

Existing data

There is a large body of data on past land ice extent and sea level change, but much information remains to be mined, and additional data to be gathered from existing ice cores, sedimentary records and glaciated terrain. Several promising new lines of evidence exist, but will require technological development to access samples. Interpretation of the data will benefit from parallel developments in ice-sheet, climate, and glacio-isostatic modeling.

During the last interglacial (Eemian) period, approximately 125,000 years ago, global sea level is estimated to have peaked at least ~ 6.6 m higher than present, with contributions originating from northern and southern hemisphere sources [*Kopp et al.*, 2009]. Ice-sheet models suggest a smaller Greenland ice sheet at the time [*Cuffey and Marshall*, 2000]. Direct evidence for collapse of the critical marine-based West Antarctic ice sheet (WAIS) comes from marine microfossils and atmospherically-derived cosmogenic isotopes in subglacial sediment, which show that the deep subglacial basins now covered by the ice sheet were open to marine sedimentation at least once within the past 0.75 Myr [*Scherer et al.*, 1998]. However, the timing and duration of this event remains uncertain, and a major challenge is to establish whether the ice sheet collapsed once, or repeatedly, and the climatic regimes responsible for such collapses. Sediment cores collected by the ANDRILL MIS project in the Ross Sea show repeated rapid transitions from glacial till to marine sediment, which are interpreted as evidence of, but do not directly demonstrate, marine ice-sheet instability of the WAIS during Pliocene time [*Naish et al.*, 2009; *Pollard and DeConto*, 2009]. The Antarctic Climate Evolution (ACE) Research Program of SCAR is coordinating plans to recover similar records in the future through ANDRILL and other geological drilling projects.

Sea-level records, especially well-dated coral-based records from the last glacial termination ~ 21,000 to 5,000 years ago, provide detailed evidence of periods of rapid land-ice loss when global sea level may have risen by meters on centennial timescales [*Bard et al.*, 2010; *Fairbanks*, 1989]. The rates and magnitude of these changes varied geographically, due to factors such as the gravitational effect of the changing distribution of ice and water, isostatic rebound, and shoreline geometry. Analysis of the resulting sea level "fingerprint" provides a powerful means of identifying the ice sheet sources contributing to rapid sea-level rise [*Bassett et al.*, 2005; *Clark et al.*, 2002], and should be used as a framework for interpreting past changes in land ice distribution as more precise, detailed and widespread sea level records are obtained in future.

Implementation

Required observations

Existing efforts in glacial and marine geology, and paleoclimatology, should be supported to better define the extent of land ice during previous interglacial periods and to determine rates of change during glacial terminations. This work should be carried out in close collaboration with ice-sheet and climate modeling efforts, including development and validation of next-generation models. Ongoing work to better define local sea-level changes leading up to the present and past interglacials, and to expand the geographic coverage of these records, should also be supported.

New methodologies and sampling technology

In addition to existing approaches, several new methodologies could substantially improve constraints on the extent of the Greenland and West Antarctic ice sheets during past interglacial periods. These require access to samples of ice and rock from within and beneath the existing ice sheets, hence the development of rapid-access ice-drilling technology, as described below.

There is great potential for determining the thickness and dimensions of the Eemian West Antarctic ice sheet from chemical tracers and the isotopic composition of surviving Eemian ice. Total air content trapped in ice, chemical signatures (MSA, sulfate), and isotopic indicators such as deuterium excess provide powerful constraints on ice sheet surface elevation and proximity to the ocean at the time of deposition and subsequent gas trapping. Hence analysis of Eemian ice from locations such as Hercules Dome or similar sites flanking West Antarctica would provide a test for WAIS collapse during this period: Low-altitude, coastal signatures such as high gas content would indicate collapse, marine incursion and draw-down of adjacent domes. Conversely, “continental interior” signatures would provide evidence of WAIS survival and an ice sheet configuration similar to the present day. The main challenges to this approach are locating and recovering the necessary samples of Eemian ice. Radar surveys could be used to trace reflectors from ice core sites in East Antarctica to prospective sampling sites flanking the West Antarctic ice sheet. In the subsurface, established techniques for optical logging of dust content [*Bay et al.*, 2001] would be used to pinpoint the Eemian interval for sampling. New drilling technology is required for rapid access to deep ice with sufficiently wide geographic coverage. The mineral exploration industry has well-established techniques that should be considered. A light, low-cost, and easily transportable system for rapid hole cutting using a hydraulic motor driven by circulation of a non-freezing fluid is preferrable to hot-water based drilling, to prevent thermal disturbance of samples during drilling and recovery. Temperature measurements should also be made in the borehole. Substantial scientific synergy could be realized from borehole temperature measurements, because ice-sheet temperature profiles are sensitive indicators of basal heat flux and past elevation change of the ice sheet, if climate histories are independently known. Coring capability would be required only for collection of sample material at selected depths (i.e. during the Eemian).

Cosmogenic nuclide measurements on rock samples from beneath existing ice sheets also hold promise for determining the extent, timing and duration of past ice-free conditions. Cosmic rays penetrate only a few meters into exposed ice or rock, but produce a variety of rare long-lived and stable nuclides. These accumulate in rock surfaces during times when ice sheets are absent; their occurrence in subglacial rock surfaces would provide definitive evidence of former ice-free conditions. By measuring combinations of nuclides with different half-lives, in surfaces at varying depths, it should be possible to build up a picture of former ice-sheet extent for comparison with paleoclimate records. Short bedrock cores have been recovered from the bed beneath ice-core sites such as GISP2, but are not well placed to address the question of ice-sheet response to interglacial climates. However, strategically placed access holes such as in the geological basins below the WAIS can allow recovery of subglacial sediment and rock that can also constrain last-interglacial ice-sheet dynamics and history, as shown by the unplanned study of [*Scherer et al.*, 1998]. Subglacial bedrock sampling would also require a rapid-access drilling capability to obtain reasonable geographic coverage beneath the Greenland and West Antarctic ice sheets. Because the cosmogenic nuclide signal is only produced within the topmost few meters of rock, and can be removed by subsequent glacial erosion, the most prospective sampling sites are shallow subglacial mountains and ridges within a few hundred meters of the surface, where cold, protective ice remains frozen to the bed. Hot-water drilling, followed by coring to a few meters depth using existing downhole sampling technology would be adequate for this type of sampling. Stratigraphic cores of several meters length from subglacial geological basins can also provide important data on past ice dynamics.

Although not a perfect analog, the processes involved in past climate change and land-ice loss are relevant to understanding the climate and ice-sheet responses relevant for future change. Interpretation of the data with ice-sheet and climate models provides a means of testing the local versus remote transient responses to the forcings of past periods of rapid sea-level rise and land-ice loss. Our modeling capabilities need to be improved to include two-way coupling between high-resolution climate (atmosphere, ocean, land surface and sea ice) models and higher-order Greenland and Antarctic ice sheet models. We need to validate for climate conditions relevant for future change whether these coupled models melt the land ice in the right places and at the right rate. Coupled climate-ice sheet models should be used to assess the magnitudes of the positive and negative feedbacks in the system that could accelerate or delay future land-ice loss. In parallel with these modeling activities, a concerted effort should be implemented to synthesize and standardize existing paleo data that can be used for model validation as well as provide improved insights into past ice-sheet behavior.

7. What are the probable upper limits of the magnitude and rate of land-ice contributions to sea-level change on decadal to millennial time scales?

Relation to Overarching Theme

One of the most pressing deficiencies in understanding of land-ice contributions to sea-level rise is the lack of “reasonable” upper limits on the extent to which land ice can feasibly contribute to sea-level rise in the coming centuries. Such information is essential for development of adaptation strategies for future sea-level rise. Inability to provide such upper limits was emphasized by the IPCC AR4, which stated that at present “understanding of [large changes in ice-sheet dynamic] effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea level rise” (IPCC, 2007, p. 14).

As a result, a major research focus is required to determine appropriate upper limits to these contributions – not in the most extreme of unlikely conditions, but within the expected range of possible future climates. One strategy to probe potential limits of ice sheet response is to impose climate forcings that are extreme, but still plausible, and assess the response of land ice to these scenarios.

Existing Data

Data that have revealed limitations in understanding ice-sheet processes include detailed satellite, airborne and *in situ* observations of outlet-glacier and ice-stream flow rates, surface-elevation changes, retreating ice fronts, ice-sheet grounding line retreats, and drainage of surface melt to the subglacial bed. These data, along with other complementary data observations, also contribute to understanding and quantifying the potential impacts of these changes on mountain glaciers and ice caps as well. Such complementary observations include ice thickness of grounded and floating ice and its internal structure from ice-penetrating radar, bed topography, and bathymetry of fjords into which outlet glaciers discharge.

Implementation

While existing data have expanded the knowledge of processes critical to ice-sheet stability, they fall far short of what is needed to make further progress. Thus, the main barrier to progress is the amount of data and the lack of prognostic knowledge of key physical processes (e.g. basal sliding) that ultimately limit discharge from land ice into the ocean. Although some of the necessary observational tools already exist, the spatial resolution of parameters such as bed topography, and the temporal resolution of velocity fields and detailed surface elevation changes, limit quantitative assessments of vulnerabilities to rapid change. The absence of sustained (annual to decadal and multidecadal scale) systematic measurements of velocity and elevation changes through the full cycles of forcing and response also contribute to these limitations. Another barrier is a lack of full understanding of a number of the physical processes that control ice flow (particularly at the ice/bedrock and ice/ocean interfaces) as well as instability of ice shelves and outlet glaciers and conditions that enable their rapid disintegration. Progress continues to be made on this front, but some of the observational information needed to fully develop and validate these models is lacking. A final barrier is the current lack of an ability to define worst-case forcing scenarios. In summary, there is a complete absence of models with the appropriate physics that are adequately constrained by observations (*e.g.*, bed topography) and driven with well-defined forcings. The limits to land-ice contributions to sea-level rise are intimately linked to both the current state of the ice sheet and the extent to which they may be perturbed by future forcings. In this sense, the probable upper limits require knowledge of both current land-ice states and future climate conditions. Probable climate forcing needs to be determined locally, at ice/ocean and ice/air interfaces, and globally.

Required observations

For the most part, observational technology to make the necessary measurements already exists, but the major challenge is building and deploying those tools to obtain measurements with sufficient spatial and temporal accuracy. Overall, observations needed include: (1) bed elevation/bathymetry of major outlet glaciers extending from the edge of the continental shelf to glacier termini to the ice divides with sufficient resolution for ice-sheet models, (2) surface elevation and changes through time, (3) surface velocity, (4) basal conditions (*e.g.*, water pressure, geothermal heat flux, bed roughness, till properties), (5) grounding line position and movement, including sediment composition for its influence on grounding line stability, (6) ice-shelf thickness and internal structure (*e.g.* level of fracturing), and (7) oceanographic measurements in the ice-shelf cavities to determine melt rates (e.g., temperature, salinity, heat flux and their spatial and temporal variations). These all are targeted at understanding ice responses to today's conditions, as well as informing models of future behavior.

Analysis methods

Determining the potential upper limits of land-ice loss requires credible models that are validated by observations of present and past behavior in relation to past and present forcings to which that behavior is (or was) a response. In a broad sense, there is a need for sensitivity experiments at the regional to continental scale with appropriate model physics. For example, the impacts of perturbations at an outlet glacier calving front need to be understood locally (*e.g.* what happens to the ice near the grounding line), regionally (*e.g.* how does the perturbation propagate upglacier), and over the whole ice sheet or catchment basin (*e.g.*, how does drawdown in a catchment influence neighboring catchments). Achieving this requires an understanding of the conditions and processes at the ice/ocean and ice/bed interfaces, as well as an understanding of how the associated forcings – water temperature structure under the ice shelves, delivery of water to the ice bed, etc. – might change. In the near term, such models require the ice, bed and ocean characteristics, quantification and understanding of model uncertainties, and associated improvements in models as observations are made and these uncertainties are understood, all of which are also discussed elsewhere in this report. Initial efforts will need to focus on basin scales, but should evolve to ice-sheet scales as the models continue to improve.

Finally, a crucial component of this research involves quantitatively identifying forcing scenarios along with their associated probability. At present, the tools necessary to do this do not exist within glaciology. There may, however, be techniques developed outside the traditional glacier and land-ice observation and modeling approaches that can inform this approach. For example, applications of statistical methods may lead to a probability distribution for critical parameters that may be a valuable tool for quantifying uncertainty.

8. How confident are our estimates of land-ice contributions to sea-level rise inferred from observations and models?

Relation to Objective

A fundamental question tied to any estimate of future ice-sheet contributions to sea-level change is "how confident can we be in those estimates?" Related questions are:

- Given current observations, what uncertainties can be assigned to present-day ice-sheet changes;
- How large are the uncertainties in sea-level projections stemming from ice-sheet and coupled ice-climate models;
- What are useful measures of "projection skill" and how can these measures be improved;
- What observations would ideally be required (and are feasible) to reduce uncertainties in our estimates?

Existing Understanding

Any model used for prediction whether statistical or dynamical, relies on a set of input parameters from which the model is evolved. These input parameters are often uncertain, because they reflect subgrid-scale closures, difficult-to-observe quantities, and unknown surface, lateral, or basal forcings, or because they parameterize structural uncertainties in the model formulation. Traditional approaches to assess model sensitivities and uncertainties rely on choosing a single set of "best" values for model input parameters, running the model forward with those values, and treating the resulting model output fields as predictions. However, due to model nonlinearity, the mean of the input distribution does not, in general, yield the mean of the output distribution, and thus this approach is of limited use. Moreover, such approaches prevent rigorous assessment of uncertainties, which require the computation of probability distributions for model outputs. These model output distributions are needed by policy planners because such distributions contain more comprehensive and useful information than any single "best prediction".

Types of uncertainty

Uncertainty encountered in any climate modeling experiment generally falls into one of four types:

1. Numerical model uncertainty introduced into any model output field as a result of an imperfect or incomplete numerical description of the system of equations being solved (*e.g.*, discretization or truncation error, subgrid-scale parameterizations, downscaling, etc.).
2. Structural model uncertainty (*e.g.*, imperfect understanding of the flow "law" for ice or trying to simulate ice-stream flow with a model governed by shallow-ice approximation dynamics).
3. Parameter uncertainty associated with the value of a model "parameter" (in the broader sense), which may vary spatially or temporally (*e.g.*, the value and spatial distribution of the sliding coefficient in a linear-friction sliding law or boundary conditions).
4. Data uncertainty associated with observations being used as model constraints (*e.g.* for formal data assimilation or model inversion) or as a model input (*e.g.*, ice-sheet geometry).

In general, the effects of model, structural, and parameter uncertainty are cumulative, and cannot be easily separated when comparing model output to observations.

Methods

Techniques of uncertainty quantification (UQ) may be categorized into three classes: (1) statistical or deterministic inverse problems, (2) forward propagation of uncertainties, and (3) optimal design or control under uncertainty. The inverse problem consists of inferring statistical uncertainties to model input parameters (*e.g.* the value of the exponent n in Glen's flow "law", basal sliding, initial conditions, etc.) through a formal comparison between observations and model output, which takes into account observation (and representation) errors, and an inversion procedure that maps from observation space to parameter space. The forward problem consists of propagating those inferred parameter uncertainties through the forward (or "predictive") model in order to assign uncertainties to model output fields (*e.g.*, ice-sheet mass loss). The optimal control problem consists of defining an objective/target function in terms of statistics of an output quantity (*e.g.* sea level), a model that maps control variables (*e.g.* CO_2 emissions) to a probability density function (PDF) of the output, and a procedure to infer optimal values for the control values that minimize the objective/target (*e.g.* what is the limit on CO_2 emissions (control) required to keep the rate of sea-level rise (model output) below some desired value?).

Conventional approaches to solving the above classes usually involve some form of Monte Carlo sampling. However, such methods quickly become prohibitive as the dimension of the parameter space and the complexity of the model increase.

Implementation

Challenges and limitations

For very large parameter spaces (*e.g.*, for three-dimensional parameter fields, typical grid dimensions are $\sim 10^6$ or more) such as those that will exist for a coupled, higher order ice-sheet model with complex physics, many formal approaches are intractable, even with the best current or anticipated high-performance computing (HPC) resources. Therefore, successful implementation of UQ tools within ice or ice-climate models will require existing or novel approaches that can handle large parameter spaces through a combination of "smart" approximations that are tailored to the ice sheet problem at hand. A unified modeling approach is essential, and some combination of stochastic and deterministic methods will likely be needed.

Regardless of the type or combination of approaches taken when implementing UQ in coupled ice-climate models, any approach will require access to HPC architectures and methodologies. For this reason, partnerships with HPC centers (*e.g.*, within NSF's TeraGrid, DoE, NASA) and personnel are expected to be crucial in order for this effort to succeed. It is worthwhile to note that both the NSF and DoE have recently funded projects that are focused on initial steps towards implementing UQ in existing ice-sheet models.

In the following, a framework for applying UQ tools to ice-climate models is presented. While it assumes a particular approach to the problems noted above, any alternative approach would likely proceed in a similar manner. The following generic steps would be applied following the "validation pyramid" approach. That is, process-scale sub-models are approached and understood first (*e.g.* a basal processes sub-model), then larger scale models containing those sub-models are approached (*e.g.* the whole-ice-sheet model), and finally, coupled models are approached (*e.g.* a coupled ice-sheet/ocean-circulation model). The application of this framework to large-scale, many-parameter ice-climate models represents a formidable challenge requiring a sustained program of research.

A framework for end-to-end quantification of uncertainties

In the first stage, uncertainties in input model parameters are inferred from (1) observational data and their uncertainties, (2) the governing model dynamics and physics, and (3) additional constraints on the parameters. Solution of this *stochastic inverse problem* yields a probability density function (PDF) on the model parameters. For small numbers of parameters, variants of existing Markov chain Monte Carlo (MCMC) methods can be used to sample the resulting PDF to yield mean, covariance, and higher moments. For large numbers of parameters, MCMC is prohibitive, so one must resort to approximations (*e.g.* reduced ice sheet forward model, response surface approximation, or approximation of the covariance locally as an inverse of the Hessian matrix of the weighted data misfit function).

In the next stage, the joint PDFs describing the uncertainty in the model input parameters, determined in the first stage, are propagated through the forward model, to yield model outputs in the form of PDFs. Solution of this stochastic forward problem will result in output predictions from ice sheet models that are accompanied by rigorous uncertainty estimates. When the number of parameters is small, conventional Monte Carlo sampling methods can be used to propagate uncertainties through the forward model. For larger numbers of parameters, alternate strategies will be required. These include more clever sampling strategies specifically tailored to the problem structure, as well as methods that directly approximate the output PDF.

Analysis of model output and associated uncertainties would address issues of consistency, plausibility, practical consequences, etc. The inferred uncertainties in the model parameters are a measure of how well the parameters are constrained by the available observations. Critical assessment of inferred parameter PDFs may also lead one to refute the model due to remaining systematic misfits (*e.g.*, the model is missing some important physics, or an inadequate set of equations is being solved). The proposed inverse and forward UQ framework can be deployed to determine where additional observations are needed to better constrain uncertain model parameters, and thus to further reduce the uncertainty in model output. This concept of “quantitative observing system design” directly addresses the question of “how do we reduce uncertainties in projections?”

As an illustration of end-to-end UQ, consider a forward model that computes ice velocities and ice-shelf basal melt rates but has uncertain sub-shelf melt parameters a and b. Given observed velocities, solution of the stochastic inverse problem yields a joint PDF for parameters a and b. This joint PDF is then propagated through the forward model to yield joint PDFs of outputs of interest (*e.g.* ice-mass loss). Finally, the resulting uncertainties in predictions of ice-mass loss are the basis for solution of a stochastic optimization problem to design new observational experiments that will reduce this prediction uncertainty by placing further constraints on uncertain model input parameters.

Synthesis

Among the various components that contribute to sea-level change, increased loss of land ice (glaciers, ice caps, and ice sheets in contact with a subglacial bed) is expected to progressively become the dominant source of sea-level rise over the course of the 21st century and beyond. Quantifying the response of land ice to climate change, however, represents a major scientific challenge largely because numerical models used for projecting land-ice loss are limited by a poor understanding of processes that influence the current state of land ice. This Report addresses this challenge by developing a multidisciplinary research strategy centered on addressing eight research questions that will improve our ability to make credible projections of future land-ice loss. Ultimately, the success of this concerted effort will require a sustained and long-term commitment involving dedicated partnerships between the U.S. National Science Foundation and other funding agencies with similar or parallel interests in support of sea-level research.

Each research question is framed in terms of existing data followed by implementation strategies, which include required new observations and technologies and analysis methods. The ordering of the questions follows a logical progression, beginning with the first question which addresses the need to know the current status of the various components of land ice. The next three questions identify strategies aimed at improving our understanding of the direct effects of environmental forcings on the atmospheric, subglacial, and marine interfaces that influence land-ice behavior. Question 5 addresses the need to identify the key elements of the global climate system that impact land ice today and to evaluate whether these elements will change in the future. This information then serves as the basis for projecting land-ice loss, as addressed by the sixth and seventh questions on the possible upper limits based on past configurations of land ice or by imposing dynamic limits on ice flow. Specifically, Question 6 is aimed at improving constraints on past changes in the rates and amounts of land-ice loss in order to provide a perspective on the rate at which contemporary land ice can change as well as a target for model validation. Question 7 identifies the importance of providing "reasonable" upper limits on the extent to which land ice can feasibly contribute to sea-level rise in the coming centuries, acknowledging that such an assessment was lacking in the IPCC AR4 but is essential for development of adaptation strategies for future sea-level rise. Finally, Question 8 emphasizes the need to rigorously quantify the uncertainty in our projections of land-ice loss.

These eight questions represent distinct facets of the overall objective of projecting the land-ice contribution to future sea level. Answering each question is a required component of achieving this objective, but the integration and synthesis of the knowledge and insights gained in pursuing each question is a necessary final step that is critical to successfully apply the results of this program into credible projections of land-ice loss. Many overlaps between questions regarding researching key processes, obtaining critical data sets, and constructing and/or testing representative models were identified in the individual sections above, but integration and synthesis is not automatic.

There is an explicit need for "crossover" research that straddles two or more questions. Often this type of research makes very efficient use of logistic resources and leads to new, productive collaborations and interactions between disciplinary communities within polar research. One clear example of such a synergistic research study would be one that links the production of surface meltwater with its effect on subglacial conditions and the subsequent interaction of that water with the adjacent ocean (in the case of a tidewater outlet glacier). Through each question's shared relevance to the overall goal of projecting the land-ice contribution to future sea level, the questions are linked and achievement of the single goal requires progress in answering each question.

This penultimate synthesis, combining all the new knowledge within each question toward the single objective, is perhaps the most challenging aspect of all. Within this framework, it requires a coordinated effort to draw together all that has been achieved in addressing each question. It cannot be expected to be static, rather it must be malleable and able to incorporate new insights and understandings quickly. One obvious aspect of this coordination would involve the allocation of logistic resources. Another aspect is based in the intellectual exercise of scientific inquiry; discovery and insight have the greatest benefit to all when they are discussed and shared openly. There are examples where focused scientific objectives can spawn a unique and vibrant research community (*e.g.*, the West Antarctic Ice Sheet initiative: WAIS). Deliberate fostering of a new research community explicitly focused on the objective of projecting the land-ice contribution to future sea level would deliver additional benefits to research focused on any of the specific questions identified in this report and would provide a valuable framework for periodic syntheses of the best projection of future sea level the scientific community can deliver.

Such a framework and the community it attracts also provide an accessible, credible and up-to-date point of contact for those community planners and policy makers for whom the issue of future sea level is a very practical matter. Presently, this interface exists in a very scattered fashion although the urgent need for it has been expressed many times and is widely recognized.

Partnerships

NSF will be a central player in the pursuit of projecting the land ice contribution to future sea level, but it will not be the sole participant. There are many ongoing programs supported by NSF, other Federal agencies and other countries that are highly relevant. An exhaustive list is not given here, but cooperation with these other players is of obvious benefit to achieving credible projections of future sea level. It is hoped that the common goal with these other activities and research agencies will lead to more effective support as funding agencies are able to leverage their investments and more efficient research as new collaborations and joint programs are initiated.

Epilogue

The organizers of this workshop would like to make a few final observations to the sponsors of this workshop.

The breadth of disciplines included and the diversity of the attendees at the workshop offered opportunities for new relationships to begin. We feel that the participants made full use of the multidisciplinary environment. An enormous amount of new information was exchanged and participants left with new awareness of additional facets of the very complex issue of projecting future land-ice loss. We feel the participants will become ambassadors of the need for a comprehensive, multi-faceted approach to this complex scientific issue. We expect that some of the new relationships will result in new collaborations combining disciplinary approaches that have not been previously joined.

An attempt to rank the themes failed to reach a consensus result, a fact that reinforces the importance of each theme and the need to integrate them into a comprehensive research goal. Thus, what this report offers is a statement of the necessary dimensions of a research strategy for projecting future land-ice loss and its contribution to future sea level. This is an essential and necessary first step. What remains to be done, and the workshop had insufficient time to accomplish, is a recommended integration of specific elements of each theme into a single research strategy. We suggest that that such a goal be addressed in a future workshop.

We gratefully acknowledge NSF's support for this workshop and hope that this report is of use in effectively advancing the need to accelerate research in the critical issue of projecting future land-ice loss and its contribution to future regional and global sea-level change. We also recognize that many federal agencies are engaged in facets of this research and ultimately the federal government must serve the needs of stakeholders affected by this important issue. We recommend that the concept of an interagency sea-level research office be pursued collaboratively among NSF, NASA, NOAA, DoE, DoD and other relevant agencies as a means of enacting a single, coordinated and sustained approach to this issue.

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References

Anandakrishnan, S., and C. Bentley (1993), Micro-earthquakes beneath Ice STreams B and C, West Antarctica: observations and implications, *jg*, *39*, 455-461.

Anthoff, D., R. J. Nicholls, R. S. J. Tol, and A. T. Vafeidis (2006), Global and regional exposure to large rises in sea-level: a sensitivity analysis*Rep.*, 31 pp.

Bahr, D. B., and M. Dyurgerov (1999), Characteristic mass-balance scaling with valley glacier size, *Journal of Glaciology*, *45*(149), 17-21.

Bahr, D. B., M. F. Meier, and S. D. Peckham (1997), The physical basis of glacier volume-area scaling, *Journal of Geophysical Research-Solid Earth*, *102*(B9), 20355-20362.

Bard, E., B. Hamelin, and D. Delanghe-Sabatier (2010), Deglacial meltwater pulse 1B and Younger Dryas sea levels revisited with boreholes at Tahiti, *Science*, *327*(5970), 1235-1237.

Bassett, S. E., G. A. Milne, J. X. Mitrovica, and P. U. Clark (2005), Ice sheet and solid earth influences on far-field sea-level histories, *Science*, *309*(5736), 925-928.

Bay, R. C., P. B. Price, G. D. Clow, and A. J. Gow (2001), Climate logging with a new rapid optical technique at Siple Dome, *Geophysical Research Letters*, *28*(24), 4635-4638.

Blankenship, D., C. Bentley, S. Rooney, and R. Alley (1986), Seismic measurements reveal a saturated porous layer beneath an active Antarcitc ice stream, *n*, *322*, 54-57.

Böning, C. W., A. Dispert, M. Visbeck, S. R. Rintoul, and F. U. Schwarzkopf (2008), The response of the Antarctic Circumpolar Current to recent climate change, *Nature Geoscience*, *1*(12), 864-869.

Catania, G., C. Hulbe, and H. Conway (2010), Grounding-line basal melt rates determined using radar-derived internal stratigraphy, *Journal of Glaciology*, *56*(197), 545-554.

Chao, B. F., Y. H. Wu, and Y. S. Li (2008), Impact of artificial reservoir water impoundment on global sea level, *Science*, *320*(5873), 212-214.

Clark, P. U., J. X. Mitrovica, G. A. Milne, and M. E. Tamisiea (2002), Sea-level fingerprinting as a direct test for the source of global meltwater pulse IA, *Science*, *295*, 2438-2441.

Clarke, G. K. C. (2005), Subglacial processes, *Annual Review of Earth and Planetary Sciences*, *33*, 247-276.

Cogley, J. G. (2009), Geodetic and direct mass-balance measurements: comparison and joint analysis, *Annals of Glaciology*, *50*(50), 96-100.

Cook, A. J., and D. G. Vaughan (2010), Overview of areal changes of the ice shelves on the Antarctic Peninsula over the past 50 years, *The Cryosphere*, *4*, 77-98, doi:10.5194/tc-5194-5177-2010.

Corr, H. F. J., A. Jenkins, K. W. Nicholls, and C. S. M. Doake (2002), Precise measurement of changes in ice-shelf thickness by phase-sensitive radar to determine basal melt rates, *Geophysical Research Letters*, *28*(8), 1232, doi:1210.1029/2001GL014618.

Cuffey, K. M., and S. J. Marshall (2000), Substantial contribution to sea-level rise during the last interglacial from the Greenland ice sheet, *Nature*, *404*(6778), 591-594.

Fairbanks, R. G. (1989), A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation, *n*, *342*, 637-642.

Gagliardini, O., G. Durand, T. Zwinger, R. C. A. Hindmarsh, and E. Le Meur (2010), Coupling of ice-shelf melting and buttressing is a key process in ice-sheets dynamics, *Geophysical Research Letters*, *37*.

Gille, S. T. (2002), Warming of the Southern Ocean since the 1950s, *Science*, *295*(5558), 1275-1277.

Gomez, N., J. X. Mitrovica, P. Huybers, and P. U. Clark (2010), Sea level as a stabilizing factor for marine-ice-sheet grounding lines, *Nature Geoscience*, *3*(12), 850-853.

Gudmundsson, G. H. (2007), Tides and the flow of Rutford ice stream, west Antarctica, *Journal of Geophysical Research-Earth Surface*, *112*(F4).

Hakkinen, S., and P. B. Rhines (2004), Decline of subpolar North Atlantic circulation during the 1990s, *Science*, *304*(5670), 555-559.

Holland, D. H., R. H. Thomas, B. De Young, M. H. Ribergaard, and B. Lyberth (2008), Acceleration of Jakobshavn Isbrae triggered by warn subsurface ocean waters, *Nature Geoscience*, *1*, doi:10.1038/ngeo1316.

Holland, D. M., and A. Jenkins (1999), Modeling thermodynamic ice-ocean interactions at the base of an ice shelf, *Journal of Physical Oceanography*, *29*(8), 1787-1800.

Holland, D. M., R. H. Thomas, B. De Young, M. H. Ribergaard, and B. Lyberth (2008), Acceleration of Jakobshavn Isbrae triggered by warm subsurface ocean waters, *Nature Geoscience*, *1*(10), 659-664.

Holt, J. W., D. D. Blankenship, D. L. Morse, D. A. Young, M. E. Peters, S. D. Kempf, T. G. Richter, D. G. Vaughan, and H. F. J. Corr (2006), New boundary conditions for the West Antarctic Ice Sheet: Subglacial topography of the Thwaites and Smith glacier catchments, *Geophysical Research Letters*, *33*(9).

Hurrell, J. W. (1995), Decadal trends in the North Atlantic oscillation: Regional temperatures and precipitation, *Science*, *269*(5224), 676-679.

Iverson, N., B. Hanson, R. Hooke, and P. Jansson (1995), Flow mechanism of glaciers on soft beds, *s*, *267*, 80-81.

Iverson, N. R., T. S. Hooyer, U. H. Fischer, D. Cohen, P. L. Moore, M. Jackson, G. Lappegard, and J. Kohler (2007), Soft-bed experiments beneath Engabreen, Norway: regelation infiltration, basal slip and bed deformation, *Journal of Glaciology*, *53*(182), 323-340.

Jenkins, A., H. F. J. Corr, K. W. Nicholls, C. L. Stewart, and C. S. M. Doake (2006), Interactions between ice and ocean observed with phase-sensitive radar near an Antarctic ice-shelf grounding line, *Journal of Glaciology*, *52*(178), 325-346.

Jenkins, A., P. Dutrieux, S. S. Jacobs, S. D. McPhail, J. R. Perrett, A. T. Webb, and D. White (2010), Observations beneath Pine Island Glacier in West Antarctica and implications for its retreat, *Nature Geoscience*, *3*, 468-472.

Jezek, K., P. Gogineni, X. Wu, E. Rodriguez, F. Rodriguez, and A. Freeman (2009), Global ice sheet mapping observatory: Airborne experiments, *Proceedings IEEE Radar Conference*, 1-4.

Jezek, K., X. Wu, P. Gogineni, E. Rodriguez, A. Freeman, F. Rodriguez, and C. D. Clark (2011), Radar images of the bed of the Greenland Ice Sheet, *Geophysical Research Letters*, *in press*.

Joughin, I., W. Abdalati, and M. Fahnestock (2004), Large fluctuations in speed on Greenland's Jakobshavn Isbrae glacier, *Nature*, *432*(7017), 608-610.

Joughin, I., B. E. Smith, I. M. Howat, T. Scamblos, and T. Moon (2010), Greenland flow variability from ice-sheet-wide velocity mapping, *J. Glaciol,*, *56*(197), 415-430.

Kamb, B. (2001), Basal zone of the West Antarctic ice streams and its role in lubrication of the rapid motion, in *The West Antarctic Ice Sheet: behavior and environment*, edited, pp. 157-199, American Geophysical Union, Washington, D.C.

Kaser, G., J. G. Cogley, M. B. Dyurgerov, M. F. Meier, and A. Ohmura (2006), Mass balance of glaciers and ice caps: Consensus estimates for 1961-2004, *Geophysical Research Letters*, *33*(19).

Kopp, R. E., F. J. Simons, J. X. Mitrovica, A. C. Maloof, and M. Oppenheimer (2009), Probabilistic assessment of sea level during the last interglacial stage, *Nature*, *462*(7275), 863-U851.

Levitus, S., J. I. Antonov, T. P. Boyer, R. A. Locarnini, H. E. Garcia, and A. V. Mishonov (2009), Global ocean heat content 1955-2008 in light of recently revealed instrumentation problems, *Geophysical Research Letters*, *36*.

Lipscomb, W., and e. al. (2009), A community ice-sheet model for sea level prediction, *EOS Transactions*, *90*, 23.

Little, C., and e. al. (2007), Towards a new generation of ice sheet models, *EOS Transactions*, *88*, 578-579.

Lozier, M. S., V. Roussenov, M. S. C. Reed, and R. G. Williams (2010), Opposing decadal changes for the North Atlantic meridional overturning circulation, *Nature Geoscience*, *3*(10), 728-734.

Luthcke, S. B., H. J. Zwally, W. Abdalati, D. D. Rowlands, R. D. Ray, R. S. Nerem, F. G. Lemoine, J. J. McCarthy, and D. S. Chinn (2006), Recent Greenland ice mass loss by drainage system from satellite gravity observations, *Science*, *314*, 1286-1289; doi: 1210.1126/science.1130776.

Lyman, J. M., S. A. Good, V. V. Gouretski, M. Ishii, G. C. Johnson, M. D. Palmer, D. M. Smith, and J. K. Willis (2010), Robust warming of the global upper ocean, *Nature*, *465*(7296), 334-337.

MacAyeal, D., R. Bindschadler, and T. Scambos (1995), Basal friction of ice stream E, West Antarctica, *jg*, *41*, 247-261.

MacAyeal, D. R., T. A. Scambos, C. L. Hulbe, and M. A. Fahnestock (2003), Catastrophic ice-shelf break-up by an ice-shelf-fragment-capsize mechanism, *Journal of Glaciology*, *49*(164), 22-36.

Massom, R. A., A. B. Giles, H. A. Fricker, R. C. Warner, B. Legrésy, G. Hyland, N. Young, and A. D. Fraser (2010), Examining the interaction between multi-year landfast sea ice and the Mertz Glacier Tongue, East Antarctica: Another factor in ice sheet stability?, *Journal of Glaciology*, in press.

Meehl, G. A., et al. (2007), Global climate projections, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller, pp. 748-845, Cambridge University Press, Cambridge, UK.

Meier, M. F., M. B. Dyurgerov, U. K. Rick, S. O'Neel, W. T. Pfeffer, R. S. Anderson, S. P. Anderson, and A. F. Glazovsky (2007), Glaciers dominate Eustatic sea-level rise in the 21st century, *Science*, *317*(5841), 1064-1067.

Menendez, M., and P. L. Woodworth (2010), Changes in extreme high water levels based on a quasi-global tide-gauge data set, *Journal of Geophysical Research-Oceans*, *115*.

Milne, G. A., W. R. Gehrels, C. W. Hughes, and M. E. Tamisiea (2009), Identifying the causes of sea-level change, *Nature Geoscience*, *2*(7), 471-478.

Mitrovica, J. X., M. E. Tamisiea, J. L. Davis, and G. A. Milne (2001), Recent mass balance of polar ice sheets inferred from patterns of global sea-level change, *Nature*, *409*(6823), 1026-1029.

Naish, T., et al. (2009), Obliquity-paced Pliocene West Antarctic ice sheet oscillations, *Nature*, *458*(7236), 322-U384.

Nicholls, K. W. (1997), Predicted reduction in basal melt rates of an Antarctic ice shelf in a warmer climate, *Nature*, *388*(6641), 460-462.

Nicholls, K. W., L. Boehme, M. Biuw, and M. A. Fedak (2008), Wintertime ocean conditions over the southern Weddell Sea continental shelf, Antarctica, *Geophysical Research Letters*, *35*(21).

Nicholls, K. W., et al. (2006), Measurements beneath an Anarctic ice shelf using an autonomous underwater vehicle, *Geophysical Research Letters*, *33*(L08612), doi:10.1029/2006GL025998.

Padman, L., D. P. Costa, S. T. Bolmer, M. E. Goebel, L. A. Huckstadt, A. Jenkins, B. I. McDonald, and D. R. Shoosmith (2010), Seals map bathymetry of the Antarctic continental shelf, *Geophysical Research Letters*, *37*.

Pollard, D., and R. M. DeConto (2009), Modelling West Antarctic ice sheet growth and collapse through the past five million years, *Nature*, *458*(7236), 329-U389.

Pritchard, H. D., R. J. Athern, D. G. Vaughan, and L. A. Edwards (2009), Extensive dynamic thinning on the margins of the Greenland and Antarctic ice sheets, *Nature*, doi:10.1038/nature08471.

Ridley, J. K., P. Huybrechts, J. M. Gregory, and J. A. Lowe (2005), Elimination of the Greenland ice sheet in a high CO2 climate, *Journal of Climate*, *18*(17), 3409-3427.

Rignot, E., M. Koppes, and I. Velicogna (2010), Rapid submarine melting of the calving faces of the West Greenland glaciers, *Nature Geoscience*, doi:10.1038/NGEO1765.

Rignot, E., J. E. Box, E. Burgess, and E. Hanna (2008a), Mass balance of the Greenland ice sheet from 1958 to 2007, *Geophysical Research Letters*, *35*, L20502, doi:20510.21029/22008GL035417.

Rignot, E., G. Casassa, P. Gogineni, W. Krabill, A. Rivera, and R. Thomas (2004), Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf, *Geophysical Research Letters*, *31*(18), -.

Rignot, E., J. L. Bamber, M. R. van der Broeke, C. Davis, Y. Li, W. J. van der Berg, and E. van Meijgaard (2008b), Recent Antarctic ice mass loss from radar interferometry and regional climate modeling, *Nat. Geosci.*, *1*, doi:10.1038/ngeo1102.

Sane, S. M., C. S. Desai, J. W. Jenson, D. N. Contractor, A. E. Carlson, and P. U. Clark (2008), Disturbed State constitutive modeling of two Pleistocene tills, *Quaternary Science Reviews*, *27*(3-4), 267-283.

Scambos, T., C. Hulbe, and M. Fahnestock (2003), Climate-induced ice shelf disintegration in the Antarctic Peninsula, in *Antarctic Peninsula Climate Variability; Historical and Paleoenvironmental Perspectives*, edited by E. A. Domack, pp. 79-92, American Geophysical Union, Washington, D.C.

Scambos, T., H. A. Fricker, C. C. Liu, J. Bohlander, J. Fastook, A. Sargent, R. Massom, and A. M. Wu (2009), Ice shelf disintegration by plate bending and hydro-fracture: Satellite observations and model results of the 2008 Wilkins ice shelf break-ups, *Earth and Planetary Science Letters*, *280*(1-4), 51-60.

Scambos, T. A., J. A. Bohlander, C. A. Shuman, and P. Skvarca (2004), Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica, *Geophysical Research Letters*, *31*(18), -.

Scherer, R. P., A. Aldahan, S. Tulaczyk, G. Possnert, H. Engelhardt, and B. Kamb (1998), Pleistocene collapse of the West Antarctic Ice Sheet, *Science*, *281*, 82-86.

Serreze, M. C., M. M. Holland, and J. Stroeve (2007), Perspectives on the Arctic's shrinking sea-ice cover, *Science*, *315*(5818), 1533-1536.

Shepherd, A., D. Wingham, T. Payne, and P. Skvarca (2003), Larsen Ice Shelf has progressively thinned, *Science*, *303*(5646).

Shepherd, A., D. Wingham, T. Payne, and P. Skvarca (2004), Correction and Clarification to "Larsen Ice Shelf has progressively thinned", *Science*, *303*, 1612.

Steig, E. J., D. P. Ruhterford, M. E. Mann, J. C. Comiso, and D. T. Shindell (2009), Warming of the Antarctic ice sheet surface since the 1957 International Geophysical Year, *Nature*, *457*, 459-462.

Tamisiea, M. E., J. X. Mitrovica, J. L. Davis, and G. A. Milne (2003), Long wavelength sea level and solid surface perturbations driven by polar ice mass variations: Fingerprinting Greenland and Antarctic ice sheet flux, *Space Science Reviews*, *108*(1-2), 81-93.

Thomas, R., et al. (2004), Accelerated sea-level rise from West Antarctica, *Science*, *306*(255), doi:10.1126/science.1099650.

Thompson, D. W. J., and J. M. Wallace (2000), Annular modes in the extratropical circulation. Part I: Month-to-month variability, *Journal of Climate*, *13*(5), 1000-1016.

van den Broeke, M., J. Bamber, J. Ettema, E. Rignot, E. Schrama, J. W. van de Berg, E. van Meijgaard, I. Velicogna, and B. Wouters (2009), Partitioning recent Greenland mass loss, *Science*, *326*, doi:10.1126/science.1178176.

Vaughan, D. G., H. F. J. Corr, F. Ferraccioli, N. Frearson, A. O'Hare, D. Mach, J. W. Holt, D. D. Blankenship, D. L. Morse, and D. A. Young (2006), New boundary conditions for the West Antarctic ice sheet: Subglacial topography beneath Pine Island Glacier, *Geophysical Research Letters*, *33*(9).

Velicogna, I. (2009), Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE, *Geophy. Res. Lett.*, *36*(L19503), doi:10.1029/2009GL040222.

Wu, X. P., M. B. Heflin, H. Schotman, B. L. A. Vermeersen, D. A. Dong, R. S. Gross, E. R. Ivins, A. Moore, and S. E. Owen (2010), Simultaneous estimation of global present-day water transport and glacial isostatic adjustment, *Nature Geoscience*, *3*(9), 642-646.

Appendix A: Workshop Structure and Execution

This "Projecting Future Land-Ice Loss" workshop was supported by grant (1036804) from the National Science Foundation Office of Polar Programs Interdisciplinary Science program. It was organized by the grantee, Peter Clark (Oregon State University) in collaboration with Robert Bindschadler (University of Maryland Baltimore County and NASA-Emeritus) and David Holland (New York University). These three scientists comprised the Executive Committee. Prior to the workshop, a Science Steering Committee was also established (see **Appendix B**) to assist in the selection of workshop participants and in anticipation of needing a small group of writers to complete the workshop report.

The Executive Committee also invited a number of other U.S. scientists to attend to ensure diversity of many characteristics: scientific expertise; time in career, and gender. Care also was taken to select scientists who had a broad view of their discipline, credibility within that discipline, and an ability to recognize merit in scientific endeavors beyond their discipline. Designated and invited participants filled roughly half of the intended 40 participant positions. The remaining available positions were announced through a broad call to the community that invited other scientists interested in addressing the workshop goal to express their interest in attending by submitting a statement of what they would be able to contribute to the workshop. These applications were reviewed by the Executive Committee and decisions made to create a final list of about 20 attendees, bringing the total to roughly 40. Due to some last minute cancellations, 37 people attended (**Appendix B**).

The four-day workshop began with welcomes from the host and representatives of the sponsoring and other interested federal agencies (NSF, NASA and DoE). Participants introduced themselves and the general structure of the workshop was described. The first day consisted of a series of 30-minute overview presentations that captured the relevant knowledge and status in a variety of areas: ice sheets; glaciers; paleoclimate, geology; oceans; model uncertainty; etc. A 12-minute presentation on each topic was given by an expert in the field followed by an 18-minute discussion of the topic led by another expert in that field. Many presenters followed the guidance of offering possible science questions as input to breakout group work that would follow the next day.

The second day began with a few more overviews followed by some shorter presentations that afforded everyone the opportunity to express what they felt were relevant processes, ideas or technologies for the group to consider in formulating its research strategy. Following lunch, four breakout groups met independently, each with the same task of defining no more than 8 science questions that captured the necessary research for projecting future land-ice loss. The Executive Committee had defined the interdisciplinary composition of these breakout groups the night before. The reports of each group to the plenary at the end of the day expressed more similarity than difference; however the differences were key to refining the scope of each question. That evening, the Executive Committee along with a fourth member (to include a member of each group), caucused to cluster related questions. Eight emerging research themes were identified, each with from 2 to 5 questions from the individual groups, along with three additional questions that could not be linked with any other questions.

The third day began with a presentation of the preliminary themes. A new set of four reconstituted breakout groups were formed to examine the preliminary themes using the original wordings of the questions produced the previous day. The task for each group was to either validate or redefine these themes and identify a representative from their group to "own" that theme. Groups were free to split a theme, if appropriate and to present the rationale for their recommended action to the full group. When the plenary was held at the end of the morning, the theme refinements were presented. Most themes were quickly validated, but there were some disagreements which had to be ironed out to a consensual position so the meeting could move forward. There was little contention on how to incorporate the three single questions into existing themes.

With organization of the emerging program structure nucleating around the 8 emerging themes, the "owners" of each theme were instructed to meet together and given the tasks of rewording the theme question and beginning to write two paragraphs—one that clarified the theme and a second that justified its connection to the overall objective: "Projecting Future Land-Ice Loss". These presentations were made to a plenary session, again for group validation, before the afternoon concluded. Some questions were raised in the plenary session, but all were relatively minor. The end of the day was approached by these same theme groups meeting to start discussion on what specific research activities would be involved in addressing their specific theme questions.

The final day continued the work of each theme group defining their recommended research agenda. A late-morning plenary was called to allow each group to present its thoughts on their research agenda. Each theme group gave attention to the following topics: existing data; barriers (such as technological developments); required new observations; and analysis methodologies to be utilized. The concern that a very broad collective research agenda would be less valuable than a few high-priority requirements, led to the instruction to the audience to challenge broad research agendas so that the highest priority activities were clear.

Near the end of the workshop, the organizers requested that each theme group supply its question, paragraphs on clarification and justification, and a 1-2 page description of high-priority research activities. The broader timetable is to complete a draft of the report, circulated to the workshop attendees, and delivered to NSF by the end of September. Subsequently, the report draft will be open to the polar research community for their comment and feedback and a Town Hall meeting will be held at the Fall AGU meeting in December 2010 for final comments. After these comments are made, a final report will be prepared and delivered to NSF by February, 2011.

Appendix B: Participants

Executive Committee
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Science Steering Committee
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