Interdisciplinary Approaches to Understanding Ocean/Ice-Shelf/Ice-Sheet Interactions

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SUMMARY: The Earth’s major ice sheets are key elements of its global climate system and influence global sea level. The factors that force changes in ice sheet volume are poorly understood and not well represented in current models of global climate dynamics. The IPCC Fourth Assessment Report (Solomon et al., 2007; hereinafter "AR4") projected global sea level rise (SLR) of 18–59 cm by 2100 [AR4, Table TS.6], but included a significant caveat that “the model-based range excludes future rapid dynamical changes in ice flow”. This caveat refers to the possibility that glaciers and ice streams may accelerate, increasing the rate of ice loss from the major Greenland and Antarctic ice sheets to the ocean. At the time of writing AR4, consensus understanding of this process was too poor to even attempt to quantify such dynamic changes.

Since AR4, several studies have observed accelerating mass loss from both the Greenland and West Antarctic ice sheets (GIS and WAIS). These systems hold potential SLR of approximately 7.3 m and 3.3 m, respectively. While current loss rates are still a small fraction of observed total rate of SLR, published post-AR4 projections raise their potential contribution to 21st century sea level rise to >1 m, a level at which major disruption of coastal systems and infrastructure will occur. However, these estimates are largely heuristic; little physical understanding constrains them. Given the societal impact of SLR, there is an urgent need to place these estimates on a more quantitative footing.

The most rapid, recently observed changes in ice sheet mass balance occur around the marine-terminating ice margins, indicating a significant role of ocean variability in controlling dynamic ice loss. It is now clear that collapse of buttressing ice shelves can be followed by rapid glacier acceleration far into the interior of ice sheets. However, the processes influencing ice dynamics at marine margins are still poorly understood. Recent advances have been made in our capabilities to identify the important processes by observing marine ice margins from space and in situ, and by developing paleohistories over a wide range of time scales that place the short-duration of modern observations into the context of natural system variability. Concurrently, the community has significantly improved its ability to model ocean/ice thermodynamic exchanges and grounded glacier response to changing ice shelf structure.

This recent progress leads to an emerging near-term opportunity. Here we document a community vision for a coordinated, interdisciplinary approach that will transform knowledge of these systems. Our over-arching recommendation is that progress will come from comprehensive study of significant systems that illustrate the full dynamic range of the ice-ocean system. The potential near-term societal impact of sea-level rise places these studies at high national and international priority.
1. INTRODUCTION

Developing a physical understanding of ice sheet and glacier mass and dynamic balances is important for the practical problem of projecting sea-level change in a warming world (Solomon et al., 2007; Bindschadler et al., 2011a). Recent observations have shown that mass loss from grounded ice sheets can accelerate rapidly following thinning and/or collapse of adjacent buttressing ice shelves (e.g., Rignot et al., 2004; Scambos et al., 2004; Rignot and Kanagaratnam, 2006; Holland et al., 2008). Ice shelf and glacier front retreat over the last several decades has been observed in several regions, including most of Greenland (Howat and Eddy, 2011), along the Antarctic Peninsula (Cook and Vaughan, 2010), and various glaciers in Alaska (e.g., Post et al., 2011) and Iceland (e.g., Nick et al., 2007). Observations show that ice-shelf mass loss rates through calving and submarine melting can change rapidly on seasonal and shorter time scales in response to shifting environmental conditions including warming of surrounding ocean waters, increases in freshwater entering the sub-ice-shelf cavity from the base of the grounded ice sheet, and variations in the presence and properties of sea ice or mélange\(^1\) in the embayment or fjord adjacent to the ice front.

These observations point to the potential for ice-ocean interactions to be key components of rapid ice-sheet mass change and the associated contribution to global sea level. At this time, however, quantitative understanding of the processes controlling ice-shelf mass balance is not sufficient to support reliable representation of their dynamic effects in predictive models of ice-sheet change. Furthermore, knowledge of longer-term (century-millennial scale) system variability is not sufficient to assess whether recently observed changes (e.g., Fig. 1) fall outside the longer-term norms: for example, satellite measurements are available for at most the last four decades. Consequently, the observed recent ice-sheet mass loss cannot be unambiguously attributed to warming of the past few decades rather than to intrinsic variability of the ice sheets and the coupled climate/ice-sheet system (Holland et al., 2008; Falkner et al., 2011; Post et al., 2011).

An NSF-funded workshop in December 2011 sought to identify the requirements for transformational advances in understanding and modeling of marine-terminating glacier systems that drain the major ice sheets of Greenland and Antarctica. Workshop participants included experts in observational and modeling approaches to describing and understanding the past, present, and future marine margins and inland ice of Greenland and Antarctic Ice Sheets and marine terminating glaciers of Alaska, representatives of NSF's Arctic polar logistics contractor\(^2\), and experts in state-of-the-art and innovative technologies appropriate to the study environment. Presentations described observational studies of modern and paleohistoric conditions at various ice shelves and marine-terminating glacier systems, as well as modeling studies that span the full range of scales from the interaction between floating and grounded ice for individual glaciers to variability of full ice sheets through ice-age cycles. Logistics lessons, and experiences from previous campaigns\(^3\) informed the community about practical aspects of program planning and implementation in hostile polar environments. Representatives of related previous working groups reported on Projecting Future Sea-

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\(^1\) mélange: a mixture of sea ice and icebergs

\(^2\) http://www.polarfield.com/

\(^3\) http://pigiceshelf.nasa.gov/
Level Rise from Land-Ice Loss⁴, Deglaciated Greenland (DEGREE)⁵, and the U.S. CLIVAR Greenland Ice Sheet/Ocean Interactions Working Group⁶. Most of the workshop presentations are available online⁷.

Workshop participants highlighted recent progress in identifying the key processes that influence ocean/ice heat and mass exchange at ice-sheet marine margins. The group concluded that we cannot yet reliably represent critical mass loss processes from ice sheets in prognostic models or sufficiently constrain the paleo-history of specific glacier/ice-shelf systems. **Existing datasets (both modern and paleo) are inadequate** to support development of empirical models of mass-balance processes, or for testing and improving emerging physically based models of ice/ocean interactions in the complex environments typical of ice-sheet marine margins.

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⁵ DEglaciated GREENland (http://geoscience.wisc.edu/geoscience/research/degree-project/)
⁷ http://www-po.coas.oregonstate.edu/research/polar/ocean-ice-workshop/
The fundamental problems with existing datasets are that they lack one or more observational components required to disentangle potential contributions of multiple interacting processes, and they fail to resolve environmental factors and ice system response at the time and space scales of the individual processes. Furthermore, existing resolution (in time and space) of past timing, rates, and extents of change in ice sheets and ice shelves at the scales of individual glacier systems is insufficient to determine whether climate change induces major mass loss events from individual systems that are generally synchronous with neighboring systems.

This report summarizes workshop recommendations for overcoming these limitations (Section 2), provides an extended review of the motivation for placing a high national and international priority on ocean/ice-sheet processes (Section 3), prioritizes strategies for observations (Section 4) and modeling (Section 5), then provides program development guidelines, including criteria for selecting target systems for detailed study (Section 6), and includes an extensive bibliography as an interdisciplinary entry point to the recent literature. Appendices document the details of workshop organization.

2. Principal Findings and Recommendations

- Recent scientific and technical progress in research on various elements of marine-terminating glacial systems and the role of ocean/ice-shelf interaction on the stability of ice sheets provide an **emerging near-term opportunity** for a **coordinated, interdisciplinary approach** that will yield **transformative advances** in scientific understanding of these systems and in capabilities for anticipating and predicting their future behavior.

- **Coordinated programs** will include observational studies of modern processes, documentation of paleo-history on local and regional scales, and development of process and system models.

- Research should focus on two overarching tasks: (a) **obtaining quantitative observations** of the environmental conditions, mass balance, and dynamic changes of specific glacier systems and associated ice sheets sufficient to determine the relative roles of oceanic, atmospheric and glaciological processes; and (b) **developing physically based models** that include critical processes at the ice-sheet marine margins, towards the long-term goal of developing improved prognostic ice sheet and climate models.

- While there is a need for surveys of a wide range of systems aimed at exploring the environmental parameter space affecting the major ice sheets, transformative understanding requires focused acquisition of **comprehensive, interdisciplinary** (ocean, ice, atmosphere; modern and paleo), **synchronous data sets** for **specific systems**.

- Targeted systems should be chosen to **optimize the range of ice/ocean processes that can be studied**, evidence for past change, **a priori** estimation of prospects for future change, and potential for impact of new data on development of ice/ocean process models. The array of target systems selected for detailed study should span a sufficiently wide range of conditions to illustrate how different processes may become important depending on the background climate state. Logistical constraints must also be considered, to make sure that comprehensive study is feasible and cost effective.
• Interactive use of models in development and interpretation of field data should be encouraged. For example, while ice-sheet models presently lack the physical sophistication required to make reliable projections of ice-mass and sea-level change, both process and ice-sheet models are now capable of informing data collection strategies.

• In most cases, the likely target systems will require baseline survey information to constrain key boundary conditions. Particularly critical data sets include seabed and sub-ice bathymetry and topography (including the structure of sills, troughs, and deep channels that connect marine-based systems to ice sheet interiors), the character of sub-ice beds (hard rock versus soft sediment, fluids, and temperatures) and water-column and sedimentary conditions in the neighboring ocean.

• Both detailed spatial analyses in intensive campaigns, and acquisition of long time series of key processes through deployment and servicing of monitoring instruments, will be needed to resolve both spatial structure and temporal variability over scales at which relevant mass-loss processes act. This implies a need for sustained investment in research infrastructure and programs on timescales of years to decades.

• Short-term (years to decades) modern observations of ice-sheet mass change must be interpreted in the context of past changes over much longer time scales (decades to millennia). Paleo data can provide critical constraints on the large-scale dynamics of specific systems or entire ice sheets over these time scales.

• Observational programs will require a combination of robust, established technologies that have been proven in hostile operating environments, along with appropriate investment in advanced and emerging technologies.

• International and inter-agency participation is essential to enhance the measurement and modeling approaches available for comprehensive studies. Active coordination at the federal agency level is needed.

• Mechanisms are needed for ongoing trans-disciplinary communication within the diverse scientific community, to facilitate coordination in a rapidly evolving field.

3. Motivation

The rate of current globally averaged sea level rise (SLR) appears to have nearly doubled over recent decades, and both satellite altimetry and sea-level pressure gauge data support total rate of SLR of 3.3 ± 0.4 mm/year since 1992 (e.g., Rahmstorf, 2007; Church et al., 2011). At this rate, SLR over future decades will significantly impact the nearly 200 million people around the globe that live in coastal flood plains as well as the trillions of dollars of assets lying less than one meter above current sea level (Stern, 2007; Milne et al., 2009).

Three primary factors have contributed to the current rate of SLR: (1) thermal expansion of seawater; (2) melting of small glaciers and ice caps (GICs); and (3) melting of the Greenland and Antarctic ice sheets including their peripheral GICs (Solomon et al., 2007). All three of these effects are expected to continue as the planet warms, although their contributions will vary. In AR4, the estimated relative contributions of these three factors for the period 1993-2003 (sum of ~2.8 mm/year SLR) were given as 60, 30 and 10%, respectively. A recent global synthesis based on GRACE gravity data

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8 GRACE (Gravity Recovery and Climate Experiment) http://www.csr.utexas.edu/grace/
suggests that, for the period 2003-2010 (sum of ~3.2 mm/year SLR); the relative contributions were 55, 15 and 30%, respectively (Jacob et al., 2012). This observation suggests a shift towards a more important role for the Greenland and Antarctic ice sheets. However, this is still considerable debate over the models of glacial isostatic adjustment (GIA) used to correct GRACE mass changes, (Zwally et al., 2011; Thomas et al., 2011) suggesting that further detailed study is needed.

Based on recent observations and well-understood physics, the 2007 IPCC Assessment (AR4) projected SLR this century of 18–59 cm. However, AR4 included a significant caveat that “the model-based range exclud[es] future rapid dynamical changes in ice flow. This caveat refers to the possibility that glaciers and ice streams may accelerate, increasing the rate of ice loss from the major ice sheets (Greenland and Antarctica) to the ocean. Some recent studies suggest these restricted IPCC projections of sea level rise in the next century were too conservative (Wu et al., 2010), and highlight the likelihood that ice sheet melting will become the dominant contributor to sea level rise in the 21st century (Rignot et al., 2011).

The world's remaining inventory of small ice caps and mountain glaciers is equivalent to only 0.6 + 0.07 m of SLR (Radic and Hock, 2010). Meier et al. (2007) estimate a contribution to SLR from this source of 0.1 to 0.25 m by 2100. Thermal expansion of seawater is bounded by the potential for ocean warming. In contrast, the Greenland Ice Sheet (GIS) and Antarctica hold equivalent SLR potential of 7.3 and 56.6 m, respectively (Table 4.1 in Solomon et al., 2007). The larger East Antarctic Ice Sheet (EAIS) is relatively stable, so that Antarctica's potential contribution is expected to come mainly from the more vulnerable West Antarctic Ice Sheet (WAIS). Bamber et al. (2009) estimate that the upper limit on the WAIS contribution to future SLR is 3.3 m. Between them, GIS and WAIS hold >10 m of sea level equivalent, of essentially unknown stability.

Paleoceanographic data and modeling for the previous interglacial period (125-110 ka), when climate conditions were comparable to or slightly warmer than today, imply a sea level rise to 6.6-9.4 m above the current level (Kopp et al., 2009). There is presently no evidence that the massive East Antarctic Ice Sheet was diminished over that time frame; its relative stability may arise because it rests largely on land and has relatively little interaction with the ocean (Mercer, 1978; Bamber et al., 2009). Some sea-level rise during the previous interglacial event may have come from the WAIS (Overpeck, et al., 2006). Nevertheless, if current estimates of the total rise of eustatic sea level above modern levels are correct, volumetric considerations require that loss of ice from Greenland was a major contributor to interglacial events of high sea level (Cuffey and Marshall, 2000; Otto-Bliesner et al., 2006; de Vernal and Hillaire-Marcel, 2008). However, the mechanisms driving such losses from Greenland remain a matter of debate. Recent modeling suggests that atmospheric warming alone is insufficient to account for probable ice losses (van de Berg et al., 2011; Ganopolski and Robinson, 2011), leaving ice-sheet instability and ocean forcing as the most likely causes.

On the time scales of modern observations, the most important individual factor driving the current ice sheet mass losses is hypothesized to be interactions with a warming ocean and changing ocean circulation (Rignot and Jacobs, 2002; Holland et al., 2008; Bindschadler et al., 2011b). This hypothesis is supported by the observation that the most profound recent changes in the Greenland and Antarctic ice sheets result from glacier dynamics at ocean margins (Pritchard et al., 2009). To date, however, evidence regarding ocean-ice sheet interactions is largely indirect, inferred from correlations of
accelerated ice-shelf thinning and subsequent collapse through rapid calving, with conditions in the adjacent ocean. The relationship between ocean temperature and circulation, and basal melt rates, is likely sensitive to a variety of factors such as ice shelf basal topography, water column thickness and the different oceanic processes that can ventilate the cavity (Holland et al., 2008; Little et al., 2009; Mueller et al., 2012; Straneo et al., 2012); however, any mechanism that provides more oceanic heat to an ice-sheet's marine margin is likely to increase mass loss. On longer time scales, sea-level rise from initial melting would increase the attack of the oceans on marine-based ice sheets globally, suggesting the possibility that a large-scale instability may be triggered by an initially regional retreat (Philippon et al., 2006; Weber et al., 2011).

In addition to the global net ice-sheet input of mass to the ocean, the geographic distribution of ice mass fluxes is important because sea level does not rise uniformly but is locally a function of (and in turn influences) ocean circulation patterns and gravimetric adjustments associated with the mass transfer (Wunsch, 2007; Mitrovica et al., 2009; Wu et al., 2010). Spatial variability of ice mass loss also influences long-term glacial isostatic adjustment rates. Large-scale climate impacts of ice sheet melting, such as the influence of meltwater on buoyancy forcing of thermohaline circulation and its attendant impact on global and regional heat transports in the ocean, depend on where freshwater enters the ocean, where it is transported, and the rate at which low-salinity anomalies are dissipated by ocean mixing (Condron and Winsor, 2011). Regional freshwater routing is thought to be a key control of past variations in thermohaline circulation (e.g., Clark et al., 2002; McManus et al., 2004; Carlson et al, 2007; 2008) and may have been a trigger for the end of the last ice age (Liu et al, 2009). Thus, identifying regional effects is critical to understanding ongoing changes and to predicting future behavior of the coupled ocean-ice-climate system (Fichefet et al., 2003; Jongma et al, 2007; Schulz et al., 2007).

4. Observational Objectives and Strategies

4.1 Overview

The importance of numerous specific sets of observations, and of technologies to obtain them, was a focus of much discussion at the workshop. This section briefly calls attention to a number of these specific observational objectives and strategies. The relative importance of these varies between glacial systems, and not all may be relevant to all systems. While this list is intended to give a useable outline of important elements of a science plan, it is not expected or intended to be exhaustive.

4.2 Bathymetry and bed elevation and properties

Detailed knowledge of the geometry and bathymetry of the glacial fjord and adjacent ocean, and the glacier/ice-stream catchment, is required for the formulation of consistent physical models and for the interpretation of ocean observations. Important details include the geometry of topographic highs (sills or ice-proximal moraines) as potential grounding lines seaward of the current ice-shelf front, under the modern floating ice shelf, and under the ice stream, as well as connections to the ice sheet interior. Sills also control the access of relatively warm ocean waters into the embayments constraining ice shelves and tidewater glaciers (Jenkins et al., 2010, Straneo et al., 2010, 2012).

Shipboard multibeam surveys can be used outside the current ice limit, and also (depending on water depth, beam width, and access) may extend a short distance under the calving front of ice shelves. Surveys under floating ice shelves will require active
seismic profiling through the ice and/or deployment of autonomous survey vehicles that can operate under ice either from a nearby ship or by drilling access boreholes through the shelves. Airborne and ground-based radar can provide bed topography for the grounded parts of the ice system. NASA's Operation IceBridge\(^9\) provides an opportunity for targeted airborne surveys. The Center for Remote Sensing of Ice Sheets (CReSIS\(^{10}\)) provides expertise and equipment for both airborne and surface radar remote sensing. Bathymetric channels extending deep into the inland ice may also be mapped by optimizing flight lines for gravity measurements along flow path into the ice sheet rather than in an arbitrary crosscutting grid. Geophysical mapping of the distribution and dynamics of sedimentary cover relative to crystalline rock (Anandakrishnan et al., 1998), and the distribution of subglacial lakes under the grounded ice (Bell et al., 2007; Fricker et al., 2007) will also be important for understanding and modeling the dynamics of the outlet glacier systems.

Regional sea level cannot be assumed to be constant. The sills and channels mapped today, and important to the stability of the ice shelves or marine-terminating glaciers, are still adjusting isostatically to past ice loading. Interpretation of mechanisms of past ice sheet variability also demands knowledge of this crustal variability. Glacial isostatic models are calibrated either by refined histories of ice sheet loading, or data on recent movements in relative sea level (Long et al., 2010). Such measurements are also essential to correct interpretation of modern mass changes recorded by GRACE.

### 4.3 Ice shelf and ice sheet characteristics

The migration of ice shelf and glacier fronts can now be monitored at high spatial resolution (<100 m) over several decades from satellite imagery (Howat and Eddy, 2011). Modern satellite data sets now provide frequent (up to daily), even higher-resolution imagery; the Rapid Ice Sheet Change Observatory (RISCO\(^{11}\)) has been established to provide access to sub-meter imagery and digital elevation models with a repeat time of as little as 24 hours for major outlet glaciers.

Repeated surveys of ice elevation, thickness, and ice shelf draft (referred to as \(h_i\), \(H\) and \(h_d\)) are required for atmosphere, ocean/ice and ice-sheet modeling and for evaluation of mass balance. Satellite and airborne altimetry (e.g., NASA's Operation IceBridge) and airborne and ground-based radar can provide high-resolution maps of \(h_i\) and \(H\), and \(h_d=H-h_i\). Rignot and Steffen (2008) and Luckman et al. (2012) demonstrate the importance of separately mapping these quantities, as ice basal features such as channels may not have a hydrostatically balanced surface expression. Recent studies point to basal crevassing as a significant influence on ice shelf dynamics (e.g., Luckman et al., 2012) and patterns of basal melting and freezing.

Density and temperature profiles through snow, firn, and ice are required to determine the structural and constitutive properties of the ice shelf and to inform the specification of ice-shelf rheology for dynamic modeling studies.

Surface accumulation and loss through ablation and runoff, and its relation to regional atmospheric conditions is required for surface contribution to mass balance. Analysis of data obtained from automatic weather stations (e.g., precipitation, solar insolation, air temperature, albedo) can provide estimates of seasonal melt water production.

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\(^{10}\) CReSIS: [https://www.cresis.ku.edu/about](https://www.cresis.ku.edu/about)

\(^{11}\) RISCO: [http://www.rapidice.org/](http://www.rapidice.org/)
Ice velocity and divergence fields are required for solving the mass balance of ice shelves, and for partitioning that balance between basal melting and calving (Joughin and Padman, 2003; Rignot and Steffen, 2008; Padman et al., 2012). Very high temporal resolution of ice velocity can be obtained with GPS and can reveal anomalous ice dynamics such as stick-slip behavior (e.g., Bindschadler et al., 2003) and tidal contributions to mean glacier flow (Gudmundsson et al., 2011; King et al., 2011), both of which may identify bed and till properties affecting net basal stress. Mapping of ice velocity can also be achieved using satellite and terrestrial synthetic aperture radar interferometry (InSAR) and feature tracking. Terrestrial SAR (interferometry and feature tracking) offers potential for rapid sampling at high spatial resolution, which is especially valuable close to grounding lines and calving fronts.

Ice vertical motion is required on a variety of time scales to determine ice shelf response to tides, ocean variability, and mass balance on seasonal to interannual time scales. High frequencies can be measured with GPS and terrestrial SAR, with repeat measurements on the order of seconds; low frequencies from repeat airborne altimetry and satellites, with repeats of days to years.

Thickness and density of marine ice layer at ice-shelf base should be measured if a marine ice layer is present. Marine ice is thought to increase the structural integrity of ice shelves but cannot, in general, be remotely measured by radar (Holland et al., 2009). We don't expect marine ice on most actively melting ice shelves; however, it can be measured directly through boreholes.

Knowledge of calving events and their relationship to environmental forcing, ice mechanical properties (rheology), and flow interactions with basal topography is required. Comparison of flow velocity fields and ice front migration (e.g., from RISCO) provides calving rates. Calving and rifting events identified this way can be correlated with measured environmental factors and forecast or reanalysis models of atmospheric and ocean state. In situ high-frequency (minutes) observations by time-lapse photography or terrestrial InSAR can provide data on individual calving events, which is especially valuable for the quasi-continuous production of small icebergs at tidewater glacier fronts. Arrays of passive seismic sensors provide continuous time series of fracture events and calving activity. A previous study at an Alaskan tidewater glacier (O’Neel et al., 2007) found the duration of seismic activity in the 1-3 Hz frequency range correlates well with calved iceberg size. Such an automatic detection of iceberg flux would prove useful across disciplines. One example is that iceberg size has implications for freshwater production within the fjord; smaller icebergs melt quicker due to greater surface area.

4.4 Ocean circulation and water properties, including sub-ice-shelf cavity

A combination of long-term observations at selected sites and high-resolution spatial snapshots at multiples times is needed to characterize the ocean state, relevant circulation regimes, and responses of ice. Critical goals of the ocean observation strategy must include determination of ocean heat and salt balances, and the identification of pathways for ocean exchange and their dependences on topographic or other physical controls (Mortensen et al., 2011).

Principal technologies are moorings with current meters and water property sensors, and surveys with CTD and water sampling for geochemical tracers including dissolved trace gases, as well as stable isotopes of oxygen in water and of helium. Surveys must include high along-track resolution of velocity, obtained through deployment of vessel-mounted or lowered acoustic Doppler current profilers (ADCPs). Since fjord circulation
can vary vertically on small scales (e.g., Sutherland and Straneo, 2012), velocity profiling must be capable of resolving these scales, including close to the seabed and surface. Autonomous samplers (floats, gliders, and autonomous underwater vehicles (AUVs) may provide valuable additional information in specific environments. Distinct regions of interest include the sub-ice-shelf cavity, the surrounding fjord or embayment offshore of the glacial termination, and the regional shelf, slope, and open ocean regimes.

Ocean hydrography and circulation within the cavity is key to the ocean/ice thermodynamic exchanges leading to basal melt (and marine ice accretion for some "cold water" ice shelves). This circulation is sensitive to processes such as subglacial freshwater discharge across the grounding line, meltwater plume flow along the ice base and associated compensatory deep inflow, general circulation driven from offshore, and tides. Oceanic data has been acquired under several ice shelves by profilers and moorings deployed through boreholes (e.g., Nicholls et al., 2004). Moorings, telemetering through ARGOS or Iridium, can return multiple years of data at subtidal sampling rate. Rapid surveys of a sub-ice-shelf cavity are possible with AUVs; e.g., Autosub12 under Pine Island Glacier ice shelf (Jenkins et al., 2010).

The use of complementary geochemical tracers is required to fully discriminate and quantify the various water sources. The importance of a seasonal sub-glacial meltwater forcing at the near-GL basal melting, needs to be considered. For sub-ice-shelf data, water samples can be acquired through borehole sampling from the ice shelf surface or by AUVs. Noble (He, Ne, Ar, Kr and Xe) and "ignoble" (e.g., SF6) gases can provide a measure of the relative contribution of the various water sources, as well as the fate of the melt water, such as transport timescale of the ice shelf cavity. Successive surveys can determine changes in transport within the cavity (Hohmann et al., 2002; Loose et al., 2009; Jenkins and Jacobs, 2008).

The distribution of minor (e.g., Ba, Sr) and rare earth elements (REE), and their isotopic signals are also powerful tracers for fluid sources and pathways, which can provide unique answers to the contribution of meltwater flowing from behind the grounding line. For example, the combined use of water and strontium isotopes constrained a submarine groundwater discharge from a mound on the Beaufort Sea continental slope (Pohlman et al., 2011).

The importance of subsurface flow discharge in delivering dissolved nutrients has long been established (e.g. Capone and Slater, 1990). Isotopic fractionation of nitrogen has been proposed as a tracer for nitrate in source waters in Arctic and Southern ocean as well as in groundwater discharge from snowmelt (e.g. Kendall et al., 1995; Sigman et al., 1999).

Because the distribution of minor, REE and nitrogen isotopic signals is preserved to various degrees in the sediment and fossils, understanding the role of sub-glacial meltwater discharge in setting these signals is important to unravel ice-shelf dynamics in the paleo-record. Of significance as well is the use of radionuclide tracers for measuring groundwater discharge on a large time and space scale. Mass balance models using 226Ra (t1/2=1620 years) and 223Ra (t1/2=11.4 days), have been used to calculating the magnitude of groundwater discharge and water residence times along ocean margins worldwide (e.g. Moore, 2006; Hwang, et al. 2005) and may prove valuable in separating surface melt percolating to the ice-shelf base from water that has resided in the till.

Sea ice and mélange in constricted embayments such as fjords can buttress ice flow

12 Autosub: http://www.noc.soton.ac.uk/aui/
(Walter et al., in press) and inhibit calving (Amundson et al., 2010); these processes impose seasonality on glacier processes that may obscure other seasonal processes associated with ocean heat variability and subglacial freshwater flux. Sea-ice concentration has been measured multiple times daily at high latitudes with passive microwave sensors (Special Sensor Microwave Imager, SSM/I\(^{13}\), and until recently the Advanced Microwave Scanning Radiometer – EOS, AMSR-E, which failed on 4 October 2011\(^{14}\), and needs to be replaced). However, these data are coarse relative to fjord-width scales that influence glacier and ice-shelf advance. Alternative sources of sea-ice mélange presence and characteristics can be obtained from the high-resolution visual and radar satellite imagery served by RISCO. Higher-frequency data over a limited domain can be acquired from repeat photography; e.g., monitoring sea-ice/mélange conditions in front of a calving tidewater glacier face\(^{15}\).

Several recently developed or developing technologies are relevant to identified measurement goals. The sub-ice-shelf cavity can be accessed through hot-water drilling (HWD), autonomous underwater vehicles such as Autosub (Jenkins et al., 2010), emerging technology such as tethered hybrid ROV/AUVs\(^{16}\). Novel instrumentation can be installed through boreholes in an ice shelf and telemeter hydrography, currents, and turbulence in near-real time via Argos or Iridium. Helicopter-launched expendable hydrographic profilers may be effective for working in mélange-infested waters. Instrumented marine mammals can provide broad surveys of bathymetry and hydrography (Padman et al., 2010, 2012; Grist et al., 2011). Broad-swath multibeam bathymetry and backscatter mapping is now available on some icebreaking ships such as USCGC Healy and N. B. Palmer.

The application of technologies will balance the opportunities inherent with new systems (such as autonomous vehicles), with the low-risk application of proven technologies (such as instrument installations made possible by HWD).

4.5 Surface fluxes and meteorology

Surface meteorological measurements are required on the ice-shelf and glacier to constrain surface fluxes and estimate ablation, and on larger scales to constrain ice-sheet surface mass and heat balances and to calibrate regional paleo proxy measurements in lake and ice cores. Measurements or reliable regional-model based estimates of surface fluxes over open water and sea ice in the surrounding region are needed to constrain regional ocean models and ocean heat and freshwater balances. Resolution of mesoscale features such as katabatic and orographically intensified boundary layer winds is needed; recent advances in mesoscale atmospheric modeling (Bromwich et al., 2001; Samelson and Barbour, 2008) suggest new opportunities to address the roles of these processes.

The combination of abrupt coastal orography, seasonal or more frequent transitions between landfast and drifting sea ice or open water conditions, and logistically limited access make long-term in situ surface-atmosphere measurements and associated inferences regarding local surface and air-sea fluxes a continuing challenge (Wilkinson et al., 2009). Satellite scatterometer measurements of vector wind stress are complicated by misleading backscatter from frazil ice and are otherwise restricted to

\(^{13}\)http://nsidc.org/daac/projects/passivemicro/ssmi.html
^{14}\)http://weather.msfc.nasa.gov/AMSR/
^{15}\)Video of calving glacier (Jason Amundson, UAS); http://uashome.alaska.edu/~jmamundson/videos/jakobshavn_20080510.mp4
^{16}\)For example, Nereus -- http://www.whoi.edu/page.do?pid=10076
regions of open water, typically with horizontal scales of 25 km or greater. SAR imagery offers higher spatial resolution over open water but no directional information, and suffers from irregular data availability. Obtaining reliable estimates of surface fluxes will thus require detailed attention to regional meteorology and a blend of modeling and observational approaches (Cassano et al., 2001). Recent measurements by unmanned autonomous vehicles (AUVs) flying over Terra Nova Bay, Ross Sea, Antarctica (Knuth et al., 2011) are an example of new technical potential, for rapid surveys of atmospheric conditions.

4.6 Paleo histories

Paleoceanographic observations require sub-seafloor imaging, and coring or drilling, in the immediate region of the glacier terminus (as well potentially through ice shelves). Far-field studies are also needed to address the distribution of water masses in the ocean (both at the sea surface, and in depth transects of the subsurface ocean), and to assess the fate and impact of icebergs, glacial sediment, and meltproducts. Variations in subsurface watermasses are relevant as heat sources to thick ice shelves and marine-terminating glacial margins, and may have global scale connections to the large-scale thermohaline circulation. New isotopic and geochemical proxy data sources will allow for reconstructions of both temperature and salinity histories in the ocean, and these will constrain pathways for freshwater transport and buoyancy forcing, and sea-ice distributions through time (Jennings et al., 2011; Marcott et al., 2011; Belt et al., 2007).

Paleoceanographic records are most useful when they can be placed on a precise chronology. In most cases radiocarbon dating is employed, but such dating requires the presence of suitable carbon-bearing fossils (such as foraminiferal tests or other calcareous shells) and often are sample-size limited. New gas-source accelerator technologies for $^{14}$C-dating allow dating of extremely small samples (Ruff et al., 2007) and this will open new opportunities for chronologic control. Marine $^{14}$C dates are subject to systematic variations associated with local reservoir ages; terrestrial dates (such as in lakes without hard-water effects) are not. An opportunity is emerging to link stratigraphies and chronologies in sediment cores from lakes and in the ocean using high-resolution paleomagnetic variations, which are recorded equally in the marine and terrestrial realms (Stoner et al., 2007).

Past ice-shelf and sea-ice variability remain poorly constrained, but are hypothesized to undergo major catastrophic responses to climate warming (Hulbe et al. 2004) or internal redistribution of heat within the subsurface ocean (Shaffer et al., 2004; Marcott et al., 2011). Sedimentation analogs from larger systems in Antarctica (Anderson et al., 1991) may or may not apply to smaller regional systems such as those in Greenland; regional calibration of proxy data is needed. New opportunities may exist for seafloor sampling of regions recently exposed by large calving or glacial collapse events (Domack et al., 2005), allowing modern calibration of regional sedimentary signatures associated with ice-shelf dynamics. Observations of sedimentary processes under an active ice shelf, while difficult to obtain, would be especially valuable for the interpretation of sedimentary records.

Paleo-atmospheric temperature and precipitation reconstructions can be facilitated through isotopic analysis of layer-counted ice cores or borehole thermometry in regional ice cover (Barrett et al., 2009; Thomas et al., 2008), or by coring of lake sediments in the surrounding region (e.g., Besonen et al., 2008; Axford et al., 2011; D’Andrea et al., 2011). Application of new geochemical and biotic proxies in these settings will provide detailed records of past variability of atmospheric temperature and precipitation.
Integration of such measurements to develop paleo mass balances of the ice surface will benefit from application of data-informed regional climate models.

Insight into glacier variations on land can be obtained by coring of regional ice caps, as well as by cosmogenic isotope exposure dating of bedrock both outboard of current ice limits (Kelly and Lowell, 2009), and potentially by recovery of sub-ice rocks in transects drilled through ice margins.

Development of new paleoceanographic and paleoclimatic records requires access to field sites, for example by ship or aircraft, availability survey technologies (such as mapping, digital imagery, and subsurface reflection geophysics), and specialized coring technologies for ice, lakes, and marine sediments. Multibeam mapping tools are available on US icebreakers. Subsurface imaging tools such as surface-towed multichannel seismic reflection profilers or deep-towed high-resolution imaging systems, are currently more limited on US icebreakers, and some are difficult to deploy in ice-infested waters. New high-resolution mapping and subsurface imaging systems are becoming available on AUVs, and this will open opportunities for site characterization under heavy sea ice or shelf ice. Portable survey systems are needed for efficient exploration of ice-covered lakes. Conventional marine sediment coring is available on US icebreakers, but high sediment fluxes near ice margins point to the need for longer coring or drilling technologies to recover complete sequences. Specialized vessel-mounted drilling systems have been deployed in the Arctic Ocean (Expedition 302 Scientists, 2005; Backman et al., 2006), and sea-floor drilling systems are now being developed with the potential for drilling under sea ice (e.g., the German MeBo system 17). The ANDRILL program supports sub-seafloor drilling from a platform mounted on an ice shelf 18.

5. Modeling Objectives and Strategies

A broad range of coordinated modeling efforts is needed to: synthesize modern and paleo observations; provide context for interpretations; distill and organize quantitative understanding of physical processes; and support development of predictive capabilities. Important elements of a comprehensive modeling program include regional ocean, atmosphere, and climate models, and small-scale physical models of glacial flow and the regional ocean and sea-ice system. Coupled models of glacial flow and ocean circulation can include detailed representations of basal melting and related processes. Ice sheet models should be extended to include representations of marine-terminating glacier dynamics in addition to parameterized sea-level effects. Flexible regional and small-scale models can be used with modified forcing and boundary conditions and geometry to provide dynamical context for paleo reconstructions.

Modeling the modern state: Numerous global-scale ocean and atmospheric modeling products are being developed by the general research community, which can be used to provide quantitative and qualitative contexts for regional modeling. Various atmospheric reanalysis products are now available for use as forcing for smaller-scale modeling, including ERA-Interim 19, NCEP-II 20, ECCO-II 21, and RACMO 22. Sensitivity

18 ANDRILL: http://www.andrill.org/technology/rig
19 ERS-Interim: http://www.ecmwf.int/research/era/do/get/era-interim
20 NCEP-II: http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.html
21 ECCO2: http://ecco2.jpl.nasa.gov/
studies with a regional ocean/ice model point to significant differences in sea ice characteristics and basal melt rates for the Ross Sea and Ross Ice Shelf obtained using different large-scale products for context (S. Springer, pers. comm., 2012). These studies indicate the need for evaluation of available products for a specified regional setting. Recent studies also point to the value of simulations conducted with regional ocean/ice-shelf models forced by or nested in IPCC climate models; for example, such forward simulations have the potential to identify specific ice-shelf-buttressed systems that may presently be stable but could become unstable in decades to centuries (Hellmer et al., in review at Nature). As these large-scale products develop, it is important that researchers focusing on ice-sheet marine margins remain aware of their availability as well as their strengths and weaknesses.

Regional models: For any target system, regional ocean models capable of capturing the dominant heat and freshwater exchange processes active in that system will be essential study components. These may, for example, be forced by the best available reanalysis or forecast atmosphere and ocean model products, and may include various levels of coupling with ice and atmospheric processes. Models such as ROMS23 and MICOM24 include ice-shelf basal melting and sea ice that is dynamically and thermodynamically active (e.g., Dinniman et al., 2007, 2010; Holland et al., 2010). These models can support inclusion of processes normally excluded from global-scale models, such as tides (Makinson et al., 2011; Mueller et al., 2012). However, these models currently include quasi-static ice shelves which rise and fall hydrostatically with the ocean surface but do not change draft or extent; no regional models yet include the ability for ice shelves to evolve with time through net thinning or calving, although such studies are underway (e.g., Goldberg et al. in review). Recent studies point to a rapid response of the ice shelf (time scales of months) and grounded ice sheet (time scales of years) to changes in ice-shelf basal melt rate (Joughin et al., 2010; Little et al., 2012). Asynchronous coupling25 can be used to investigate likely feedbacks between an evolving ice shelf and the ocean and grounded ice sheet, but this is a limited technique in which short-time scale phenomena are not accurately represented. It is a high priority to develop the capability to couple dynamical ice evolution models directly with atmospherically forced ocean models for both modern and paleo applications.

The current generation of regional ocean-ice models also does not represent calving styles and rates and, as a result, cannot predict mélange properties in the ice-front proximate ocean, a potentially major impact on ocean/ice interaction and glacier buttressing in fjord settings. These processes (calving and mélange effects) can be simply represented in modern region models (e.g., by imposing mélange properties rather than developing them prognostically); however, progress needs to be made in the process models. Idealized models are now being run to incorporate the effect on basal melt rate of freshwater fluxes from under the grounded ice sheet (Motyka et al., 2003, 2011), and these should be incorporated into regional models.

Process models: Further development of process models is required to investigate the basic physics of basal melting, calving, mélange effects, freshwater and sediment fluxes from the base of the grounded ice sheet, and coupling of ice dynamics across the grounding line. In the simplest idealized settings, the physics of basal melting is

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23 ROMS (Regional Ocean Modeling System): http://www.myroms.org/
24 MICOM (Miami Isopycnic Coordinate Ocean Model):
25 Asynchronous coupling: model is run with fixed ice shelf to establish "steady-state" basal melt, model geometry is updated off-line, and model is restarted.
relatively well understood; however, it is influenced by complexities of ice basal
topography (e.g., the channels in Petermann (Rignot and Steffen, 2008) and Pine Island
Glacier ice shelf (Bindschadler et al., 2011b)) and by uncertainties in the sensitivity of
basal melt to relative ocean temperature (between linear and quadratic depending on
the source of ocean turbulence). High resolution, non-hydrostatic models can be used to
investigate these smaller scale processes.

Calving is a complex process and is currently represented by many distinct calving
laws (or schemes), although some attempts are now being made to estimate calving
behavior using fracture mechanics. A better understanding of calving is essential for all
levels of models, from regional ocean/ice models, through full-ice-sheet simulations like
the Community Ice Sheet Model CISM\textsuperscript{26}, to paleo reconstructions such as Pollard and
DeConto (2009). Modeling mélange first requires modeling calving mechanisms to
provide the characteristics of the iceberg fragments around which sea ice can
consolidate in winter.

Subglacial freshwater fluxes can be estimated from basal stresses and percolation of
surface-produced freshwater to the glacier base. In theory these production rates can be
modeled; however, their impact on ice-shelf basal melting and sub-ice-shelf and
fjord/embayment circulation depends on channelization under the ice sheet (C. Schoof,
pers. comm., 2011). Nevertheless, it is possible to test the effect in high-resolution
process models, or as input freshwaters "rivers" in regional models.

Discharged sediment plays a role in stabilizing advancing glaciers through creation
of stabilizing moraines (Post et al., 2011). A complex relationship between mass
accumulation, buttressing and varying access of warm ocean waters to the glacier face
leads to a natural cycle of advance and retreat. While some empirical relationships have
been explored to represent this cycling (Post et al., 2011), we cannot yet model it at the
level required for prediction of natural glacier state. Coupled ocean/ice/sediment models
require knowledge of sediment availability (nature of the glacier bed), mobility (both as
till under the glacier and within the water column after discharge at the grounding line),
and details of bathymetry and ice basal topography as constraints on sediment fluxes.

Changes to regional oceanographic conditions and their influence on the geometry,
thermodynamics, and dynamics of floating ice shelves cannot be translated into sea
level rise implications without coupling the changes in the ice stress regime across the
grounding line. Further examination and testing (perhaps using short-timescale
phenomena, e.g., tides) of various approximations to the full stress balance in realistic
geometries are required before parameterizations of buttressing employed in large scale
models (Pollard and DeConto, 2009) are determined to be robust/adequate. Accelerated
ice outflow from a buttressed glacier or ice stream is a negative feedback on ice-shelf
geometry evolution from a changing ocean state; we hypothesize that this feedback can
identify times scales of ocean state perturbations that would have most influence on the
ultimate loss of an ice shelf as a trigger for persistent ice loss from the previously
buttressed ice sheet.

\textit{Paleo-Modeling:} Long transient simulations of major climate changes, such as the
transition from the last global glacial maximum (21 ka) to the present, are still preliminary
(e.g., Timm and Timmermann, 2007; Liu et al., 2009). As these efforts are refined,
however, opportunities will emerge for downscaling with regional models, with
verification and modification from rich regional datasets on past states of the full system.

\textsuperscript{26} CISM: http://oceans11.lanl.gov/trac/CISM
Such regional models, now being run for modern conditions (Lucas-Picher, et al., 2012) highlight the need for dense arrays of validation data, and this will be a challenge for paleo-simulations where data sets will be relatively sparse.

Energy-balance models of surface mass balance of glaciers and ice sheets, forced by atmospheric models, can provide insight into perturbations in ice growth or melting consistent with transient climate simulations (Anslow et al, 2008; Carlson et al., 2012). Models capable of explicitly reconstructing past variations in ice sheets are improving, but remain highly parameterized, especially in their interaction with the ocean via ice shelves (Pollard, 2010). More realistic interfaces with the ocean in such models will in turn require information on both global eustatic sealevel change, and regional isostatic adjustment to model ice loading (Van den Berg et al., 2008).

Close collaboration between modelers working on different features of the target systems is encouraged. For example, understanding the structural requirements of full-ice-sheet models (such as CISM) can guide the development and interpretation of models of various processes (e.g., basal melt, calving, seasonal buttressing by mélange, ice coupling across the grounding line) that must be represented more simply in the large-scale models in order to estimate ice sheet response to ocean change. Conversely, process and regional ocean/ice-shelf models can inform interpretation of paleo data and indicate improvements to paleo models. For example, it is possible to adapt high-resolution regional ocean-ice circulation models, developed for simulation of current conditions, to investigate hypotheses that arise from paleo observations and conceptual models (e.g., Willmott et al., 2007; Marcott et al., 2011). Interactive co-development of large-scale and process-scale models can facilitate sensitivity experiments, and provide guidance in prioritizing which system processes to focus on for most rapid progress in predictive capabilities.

The inclusion of modeling experts in the planning of fieldwork is strongly encouraged so that data collection strategies are informed by recent modeling results, capabilities and deficiencies. Where possible, observational programs should address the modelers' goals of reducing critical quantitative and conceptual uncertainties in their representations of physical processes. Early involvement of modelers in observationally driven programs also improves the likelihood that the resulting datasets will have optimal value in modeling contexts.

6. PROGRAM DEVELOPMENT GUIDELINES

6.1. Site selection guidelines

Workshop discussions of specific glacial systems focused primarily on those in Greenland, Antarctica, and Alaska. Physical processes occurring at the ocean-ice boundary of any marine-terminating glacier may be of general importance, while those involving interaction with large-scale ice sheets will require study of glaciers that drain such ice sheets. The workshop discussions did not focus on the identification of specific marine-terminating glacier systems as optimal prospective subjects for comprehensive study. However, the following characteristics of preferred target systems were identified.

• The primary ice/ocean processes that affect ice-shelf mass changes are known to be active.
• Evidence for prior temporal variability of glacier/ice-shelf mass and extent, at time scales from seasonal to millennial.
• Evidence for short-term variability (interannual and faster) of local forcing of the
marine margins through distal oceanic and local atmospheric drivers, indicative of the presence of a range of forcing states that can be captured by a typical field program.

- Sufficient background data to inform development of observational and modeling programs. This includes geometry, hydrography, atmospheric variability and paleo-history.

- Glacier catchment, embayment and ice shelf size sufficiently large to represent significant ice-sheet drainage, but sufficiently small to allow closure of the ocean heat and freshwater balances through moorings and ship surveys and ice-shelf surveying from the ice surface or airborne/satellite techniques. This constraint focuses attention on systems with potential for significant rates of ice mass loss and relatively complex interactions with the ocean, that can nevertheless be modeled with high-resolution regional models driven by detailed measurements at the model's open boundaries (ocean, atmosphere, and upstream ice sheet).

- Accessible ocean near the ice-shelf grounding line (GL). This constraint recognizes that the largest mass losses from ice shelves typically occur close to the GL (high basal melt, or calving in the case of tidewater glaciers) and that structural changes near the GL have an immediate impact on GL migration and ice-sheet mass change. Obtaining both geometric (seabed, ice base and grounding line) and environmental (ocean and ice) state in this region is critical.

- Workable ice-shelf surface. This constraint recognizes the need to install sensors and carry out surface and airborne surveys of ice state over areas identified as relevant to ice/ocean interactions, from the ice front to the grounding line.

- Access to nearby locations where paleo-history records can be obtained. On land, this would include access to study sites via helicopter, fixed-wing aircraft, or ground transport, the presence of viable paleo archives including regional ice caps and lakes where cores could be recovered, and exposed moraines for analysis of past ice-cap growth and decay. In the ocean, accessibility for conventional or icebreaking vessels capable of handling coring gear and obtaining geophysical surveys, and documented presence of sediments suitable for analysis of past ocean variability.

The recommended comprehensive approach to studying specific archetypal systems requires significant in-field resources, so that logistic constraints may ultimately have a strong influence on system selection. Trade-offs are possible; a limited range of ice/ocean processes can be studied at smaller systems with lower logistic overhead. However, rapid progress toward transformational understanding is likely to require significant logistic effort on more than one target system, such that the array of systems chosen for detailed studies appropriately target processes active at different climate states.

6.2. Other guidelines

- International collaboration should be encouraged, and strongly supported at the funding-agency level. This leverages both logistic and intellectual international resources, and is consistent with one intended legacy of the International Polar Year.

- Fundamental elements of observational programs should be based on existing technologies tested in comparable environments, so that program-critical datasets can be obtained at relatively low risk.
• Opportunities to deploy innovative, higher-risk technologies that have the potential to fundamentally alter our understanding of marine-terminating glacier systems should be encouraged where possible.

• The difficulty of working in remote and logistically challenging environments implies the need for rigorous oversight of project development and risk assessment.

7. ACKNOWLEDGEMENT

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Chidthaisong, J.M. Gregory, G.C. Hegerl, M. Heimann, B. Hewitson, B.J. Hoskins, F.


Appendix

Workshop Organization

The workshop participants, noted below, represented a broad range of fields, including physical and chemical oceanographers, glaciologists, geophysicists, marine geologists, paleoceanographers, quaternary geologists, paleoclimatologists, modeling experts, technologists, and logistics personnel. In each of the two days, talks presented examples of research results and needs, emerging technologies, and logistical considerations for study in harsh environments.

Building on the talks, working groups first addressed within-discipline needs (three-groups; modern observations, paleo observations, and modeling) then, cross-disciplinary opportunities (three groups; Model $\leftrightarrow$ Paleo, Model $\leftrightarrow$ Modern, Paleo $\leftrightarrow$ Modern), and finally the practical realities of fully interdisciplinary study (three groups blended from all disciplines, all addressing this synthesis). The recommendations resulting from these working group interactions form the basis of this report.

![Workshop Organization Diagram]
Workshop Participants.

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Expertise</th>
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<tbody>
<tr>
<td>Mark Abbott</td>
<td>Univ. Pittsburgh</td>
<td>Lake Coring, Paleoclimatology</td>
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<td>Logistics</td>
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<td>Rob DeConto</td>
<td>Univ. Massachusetts</td>
<td>Ice-Sheet Modeling, Paleo</td>
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<tr>
<td>Kim Derry</td>
<td>Polar Field Services</td>
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<td>Larry Mayer</td>
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<td>Univ. Ottawa, Canada</td>
<td>Gravity, Isostacy, Sealevel</td>
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<td>Bill Wiseman</td>
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<td>Observer</td>
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## Workshop Agenda

Interdisciplinary Approaches to Understanding Ocean/Ice-Shelf/Ice-Sheet Interactions  
December 3-4, 2011, Grand Hyatt Hotel, 345 Stockton Street, San Francisco  
Organizers: Alan Mix, Laurie Padman, Roger Samelson

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<th>Duration</th>
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<td>8:00</td>
<td>10</td>
<td>Mix Welcome, meeting logistics</td>
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<tr>
<td>8:10</td>
<td>5</td>
<td>Stoner Ocean Drilling Workshop Report</td>
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<td>8:15</td>
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<td>Straneo CLIVAR WG</td>
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<td>8:20</td>
<td>15</td>
<td>Clark Ice Shelf-Ocean Interaction during glacial time</td>
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<td>8:35</td>
<td>30</td>
<td>Padman Draft plan for interdisciplinary study</td>
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<tr>
<td>9:05</td>
<td>15</td>
<td>Holland Pine Island overview</td>
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<tr>
<td>9:20</td>
<td>15</td>
<td>Steffen Larsen C (LARissa) overview</td>
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<td>9:35</td>
<td>10</td>
<td>Rasmussen Danish studies in Greenland</td>
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<td>9:45</td>
<td></td>
<td>Coffee</td>
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</table>

### Observational Strategies (Padman Chair)

| 10:15 | 10 | Khazendar Satellite obs |
| 10:25 | 10 | Gudmundsen Remote sensing |
| 10:45 | 10 | Loose Chem. Oc. |
| 10:55 | 10 | Jennings Paleoecean records |
| 11:05 | 10 | Pfeiffer/Motyka Glaciers |
| 11:15 | 10 | Hamilton/Straneo Glaciers |
| 11:25 | 10 | Walter Passive seismics |
| 11:35 | 10 | Marcott Moraines: status/opportunities for mapping dating |
| 11:45 | 10 | Axford reconstructing regional climate from lakes |
| 11:55 | 15 | Open discussion |

| 12:10 | 80 | Lunch |
| 13:30 | 10 | Working group assignments |
| 13:40 | 80 | Working Groups I (discipline groups: science goals) |
| 15:00 | 15 | Coffee |
| 15:15 | 75 | Working Groups II (interdisciplinary) |
| 16:30 | 30 | Plenary: review |

### Sunday

| 8:00 | 35 | Plenary: review |

#### Logistics & Technologies

| 8:35 | 30 | PFS Operational capabilities in Greenland |
| 9:05 | 10 | Bowen/Jakuba Hybric ROV opportunities |
| 9:15 | 10 | Chayes Systems on Healy multibeam, etc. |
| 9:25 | 10 | Trehu Active and Passive Seismics, subsurface imaging through ice or water |
| 9:35 | 10 | Abbott Lake coring technologies and operational issues |
| 9:45 | 30 | Coffee |

### Modelling Strategies (Samelson Chair)

| 10:15 | 10 | Milne Paleo-ice sheet modeling |
| 10:25 | 10 | Samelson Regional atmosphere/ocean/sea-ice modeling |
| 10:35 | 10 | Little Coupling models across the GL |
| 10:45 | 10 | Motyka Rapid melt, subglacier meltwater fluxes |
| 10:55 | 65 | open discussion |

| 12:00 | 90 | Lunch |

#### Misc (schedule issues)

| 13:30 | 10 | DeConto Ice sheet modeling: paleo and future |
| 13:40 | 10 | Paden CRISIS |
| 13:50 | 10 | Working Groups III assignments |
| 14:00 | 60 | WG III (tech, model, obs.) |

| 15:00 | 30 | Coffee |
| 15:30 | 60 | Plenary WG summaries (5-10 min each, 1 discussion) |
| 16:30 | 30 | Final discussion Synthesis and recommendations |

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10 February 2012