Ice Drilling Program Office
Long Range Science Plan 2010-2020

Prepared on behalf of the U.S. ice coring and drilling research community by the Ice Drilling Program Office in collaboration with its Science Advisory Board and with input from members of the research community

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Abstract

Our currently changing climate and global environment places urgent needs upon the scientific community to understand Earth's interlinked atmospheric-ocean-cryosphere processes and the relationship of current change to climate change that has occurred in the past. Because glaciers and ice sheets hold unique positions in the climate system and their very formation archives evidence of past change, their study holds a unique place in earth system science. Glacial dynamics are important forces in establishing global sea level. Direct sampling and geophysical probing of glaciers and ice sheets is complex and logistically challenging, and coordinated planning is required in order to address the many important questions. The Ice Drilling Program Office (IDPO) Long Range Science Plan was established by the IDPO and its Science Advisory Board (SAB), in consultation with the broader research community, to articulate the direction of U.S. ice coring and drilling science, and to identify the need for drills and drilling technology as the basis for the accompanying IDDO Long Range Drilling Technology Plan. This document provides a blueprint for research community and funding agency actions and provides the NSF and other funding agencies with information that will enable them to forecast budgets and logistics that will be needed in the coming decade. The scientific needs for ice coring and drilling identified in this document form the basis for an accompanying Ice Drilling Design and Operations (IDDO) Long Range Drilling Technology Plan. That IDDO Plan provides the details of the drills, drilling technology, and drilling expertise that directly responds to the needs articulated in this IDPO Plan. Updated versions of both plans are produced annually in the spring.

Introduction

One of the most pressing environmental issues of our time is the potential that increasing atmospheric concentrations of greenhouse gases (GHG) warming may trigger abrupt climate change, and more broadly, all of the changes that a warming planet will bring. To reduce the uncertainty of future climate and environmental projections, we need to understand the mechanisms of abrupt change and the nonlinear impacts that present warming may have on the cryosphere. These questions cannot be fully answered with existing ice cores; rather, arrays of ice cores must be retrieved to assess environmental change on local, regional, and global scales. Furthermore, the beds of ice sheets and glaciers, and the ice-ocean interface under ice shelves, are well recognized as being critical boundaries for ice dynamics; evaluating conditions there is crucial to being able to predict ice sheet behavior during future GHG emission scenarios. Large uncertainties in sea-level rise projections for the 21st century are associated with the possibility of a rapid dynamical response of the ice sheets to climate change. Subglacial environments also harbor unique, largely unexplored ecosystems. The discovery of subglacial life expands our notion of the habitable zone on Earth and beyond; understanding their evolution and ability to adapt to a sub-ice lifestyle will yield new insight about life in extreme environments. Arrays of access holes will be required to substantially improve our understanding of the dynamics of the Antarctic and Greenland Ice Sheets, and of the underlying subglacial environments.

Past changes are recorded with unparalleled detail in and under the polar ice sheets and temperate glaciers. Detecting climate change from ice core records is a relatively new science that has evolved over the past fifty years. From initial ice coring in Greenland conducted by the U.S. Army, ice coring science has since evolved to include programs in many nations and hundreds of universities around the world (Bentley and Koci, 2007, Langway, 2008). Ice core records have led to many important discoveries, for example the discovery that dramatic changes in climate can occur abruptly, in less than ten years (e.g. NRC, 2002). This discovery has revolutionized climate science and also has important impacts on policy; it established some of the key groundwork leading to the 2007 award of the Nobel Peace Prize to the IPCC for climate science.

Although many important discoveries have already been made through ice coring science, there are many more unanswered questions about Earth's climate processes, including interacting linkages between the northern and southern hemispheres, impact of humans on the atmosphere, atmosphere-ocean-ice relationships, and other issues which can be uniquely addressed by ice coring science. High accumulation sites on glaciers and polar ice sheets contain the highest-resolution natural archive of past environmental conditions. An international meeting sponsored by the U.S. National Science Foundation in 2006 led to the formation of an international group to conduct joint science planning for future projects, the International Partners in Ice Coring Sciences (IPICS), under the leadership of Dr. Ed Brook (Oregon State University) and Dr. Eric Wolff (British Antarctic Society) (Brook and Wolff, 2006). The IPICS white papers describe broad science targets for ice coring: 2k year arrays, 40k year arrays, the last interglacial, and oldest ice (www.pages-igpb.org/ipics/). Because many in the U.S. ice coring community were involved in establishing the IPICS goals, those goals appear below, along with endeavors that are primarily U.S. activities.

Sub-ice environments are mysterious realms that are notoriously difficult to access. Over the past decade or so there have been major advances in our understanding of the subglacial environment revealing new levels of complexity. New studies since the release of the IPCC 2007 report are revealing that nonlinearities in ice dynamics and ice shelf-ocean interactions will likely cause faster sea level rise than predicted in the report; this is a very active area of research with new questions emerging frequently Currently, most of our knowledge about subglacial systems derives from geophysical remote sensing with isolated local data from access holes to the bed, subglacial outflow or sub-ice-shelf cavities. Rigorous inferences about these systems require broader and more detailed data sets, better coverage of different conditions of the systems, and quantitative analyses especially for testing ice sheet models and estimating rates of subglacial weathering. Over the past decade or so, scientists have further recognized that subglacial environments harbor unique microbial ecosystems. An increasing number of reports suggest that microbial communities are metabolically active and thus play a critical role in subglacial weathering. The extent to which microbial activity alters the chemistry of subglacial efflux and the result of that efflux on global processes remains an outstanding question. There is intense scientific and public interest in subglacial environments, particularly in the recently documented, numerous subglacial lakes below the Antarctic Ice Sheet and the unique life forms they may harbor. Subice microorganisms that exist under permanently dark and cold conditions have broadened our understanding of the phylogenetic and metabolic diversity of life on Earth, and may help inform our search for extra-terrestrial life.

Members of the U.S. ice coring and drilling community have led the efforts for these and a multitude of other important findings. U.S. scientific productivity, including both knowledge generation and creation of the next generation of scientists, critically depends upon funding and also upon a mechanism for ensuring continuity and international cooperation in ice coring and ice drilling efforts, along with availability of appropriate drills, drilling expertise, and innovations in drilling technology. This Long Range Science Plan was established by the Ice Drilling Program Office (IDPO), working with its Science Advisory Board (SAB) and with the broader research community, in order to articulate the direction of U.S. ice coring and drilling science, and to provide the foundation upon which the Ice Drilling Program Office –Ice Drilling Design and Operations (IDPO-IDDO) Long Range Drilling Technology Plan can be developed to establish the drills and technology needed to advance the science. These paired plans then provide a blueprint for the ice coring and drilling science community, which enables the community to plan well-coordinated proposals, and also allows NSF to forecast budgets and logistics to facilitate the science. SAB-recommended updates to the IDPO Long Range Science Plan are posted to the Icedrill.org web site each spring, with list-serve invitations for comments and suggestions to enable broad community input. The document is then revised, approved by the SAB, and the final version for the year is posted to the icedrill.org web site in summer.

The science can be described in three categories: climate, ice dynamics and history, and subglacial environment and habitat. The three are described in more detail in the following sections. Science objectives within each category are accompanied by an outline of the science requirements of the associated drilling technology.

I. Climate

Earth's climate is a complicated system involving local, regional, hemispheric, and global phenomena, and it is impossible to understand global climate without understanding components of the system as evidenced by data from a large number of locations and over a range of time scales. Issues articulated by many U.S. scientists were central to the themes in the white papers of the International Partners in Ice Coring Science (IPICS) *(Brook and Wolff, 2006)*, hence a number of the categories below reflect those themes.

1. ~ 200 yr arrays

The broad goal of a 200-year array of ice core records is to establish how the recent atmospheric environment is represented in the upper layers of glaciers and ice sheets. Over the past 200 years, human activities have had a significant impact on atmospheric composition, yet the impacts in polar and remote high latitude and high elevation regions are not fully understood. Shallow ice coring programs have been, and will continue to be done through individual or small-group projects at individual sites (e.g. ice coring in temperate glaciers or in selected areas of Greenland) and internationally-coordinated scientific traverses (e.g. International Trans-Antarctic Science Expedition, Norwegian-USA Traverse of East Antarctica). While shallow coring has been done in a few locations, many more such endeavors are needed in the Arctic, Antarctic, and on temperate glaciers in order to understand whether observed patterns are regional, hemispheric, or global. Through a combination of over-snow science traverses and coordinated individual site efforts, an extensive array of relatively easy to recover ice core records, driven by individual and group proposals, is a mainstay of the ice coring community that will continue with the following objectives: 1) elucidate transfer functions between atmospheric chemistry and snow composition; 2) determine relevant physical and chemical processes related to snow deposition and metamorphism, and their effects on atmospheric chemistry and gas preservation in ice cores; 3) relate snow/firn/ice properties to remotely sensed signals (e.g., borehole, ground and satellite-based measurements), thereby allowing interpolation based on remote sensing data; 4) identify and model post-depositional changes in chemical and physical properties; 5) produce detailed spatial maps of climate and environmental parameters (e.g., temperature, accumulation rate, chemistry); 6) validate local, regional, and global atmospheric models; and 7) investigate the spatial pattern of anthropogenic impacts 8) determine biogeographical patterns of biological material deposition and understand their role in ice core dynamics. Several of these objectives are critical for interpreting longer timescale records detailed in following sections. Studies of these types are often conducted by individuals and small groups on the Greenland and Antarctic ice sheets as well as on temperate glaciers. Requirements for drills to achieve these and other ice coring goals are listed in Table 1.

2. 2k arrays

The time period of the last two millennia is an important focus because it is long enough to allow investigation of climate variability on annual to centennial timescales, yet short enough that relevant climate boundary conditions have not changed appreciably. Existing quantitative reconstructions of the past millennium continue to be debated, in part due to a lack of annual data prior to 1600 AD in many areas and the highly regional nature of many climate processes. A coordinated international effort to recover a spatial array of annually resolved and calibrated 2000 year ice core records (IPICS 2k arrays) has several primary objectives, including: 1) establishing the extent and regional expression of the so-called "Little Ice Age" and "Medieval Warm Period" phenomena; 2) evaluating 20th century warming in the context of the last 2000 years; 3) establishing spatial and temporal patterns of temperature, precipitation, and sea ice extent; 4) quantifying spatial and temporal patterns of important climate forcing mechanisms that are regionally variable (e.g., sulfate, terrestrial dust and associated biological material, black carbon aerosols), and the record of solar variability; and 5) assessing the relative roles of anthropogenic and natural forcing on climate evolution prior to and into the industrial period. New coring associated with this effort would be in the Arctic and Antarctic, and several countries, including the US, are considering new coring associated with the 2k array theme. New US efforts that have been discussed, or are in planning stages include Roosevelt Island in the Ross Sea (the 2 ka record would be part of a deeper core), Detroit Plateau on the Amundsen Coast, and possibly the Aurora Basin in Antarctica. This list is not exclusive, but illustrates the diversity of possibilities.

3. 40k network

The past 40,000 years include the glacial/interglacial transition, our present warm period, the Holocene, as well as a sequence of abrupt swings in climate as recorded in Greenland ice cores and other climate archives. The glacial-interglacial transition is the best-documented global response to very large-scale changes in climate boundary conditions, and the earlier abrupt changes are the best examples of this enigmatic process. The Holocene was one of the most stable climatic periods, potentially providing the conditions for an outburst of human societal development. The reason for this apparent constancy in Holocene climate as well as the linkage between pre-industrial climate swings and human development is still a matter of debate. To understand these phenomena we need to understand their spatial and temporal evolution better. Ice cores are uniquely placed to provide the contrasting polar elements of climate in very high resolution and provide a suite of measurements (such as greenhouse gases) only available from ice cores. In addition, we need to understand the response of the Antarctic, Greenland and Arctic ice sheets to climate change. In particular the contribution of the large ice sheets to the glacial/interglacial sea level change, and the temporal evolution over the last 40,000 years, are still a matter of debate.

Under the auspices of IPICS the international scientific community is developing plans for a network of ice cores covering the last 40,000 years. The specific U.S. contribution to this network (in addition to the WAIS Divide core) has yet to be determined, but is likely to include one or more new ice cores in Antarctica – sites that have been discussed so far include Taylor Dome, Roosevelt Island, Hercules Dome, and South Pole, with the most discussion to date focused on South Pole. The IPICS 40 ka drilling projects may vary in scope and logistical needs, but many are envisioned to be drilling campaigns conducted in one or two seasons with a minimal logistics burden. Site-specific records of climate and environmental change are the primary objective - it will not be necessary to undertake the full suite of measurements possible in an ice core, although clearly such cores can provide material for a variety of future projects depending on interest and resources.

4. High-resolution records of last interglacial

The last interglacial period (~130,000 to 110,000 years ago) was warmer than present due to differences in earth's orbital configuration, and can provide clues about how the earth will behave as human activities continue to force global warming. Critical questions concern the possibility of tipping points of abrupt change in interglacial climates (like today), the evolution of greenhouse gases in warm climates, the possibility of ice sheet collapse (which may be recorded in ice sheets that remained), and changes in ocean circulation during warm climates. Existing ice core records of the last interglacial are almost all from low accumulation sites in Antarctica (e.g. Vostok, Dome C). As a result the detailed behavior of polar climate, greenhouse gases, ice sheet size, and other earth system attributes recorded by ice cores are not well known for this period. The NEEM ice core in Greenland, one of the original IPICS objectives, is now underway, and will hopefully provide an excellent northern hemisphere record of the last interglacial. Within IPICS, discussions about additional records of the last interglacial are just beginning. Likely targets are relatively high accumulation sites in Antarctica where last interglacial ice is likely to be preserved, and possible new sites in Greenland.

Drilling sites are likely to be at remote locations of Antarctica where accumulation is moderate, on order 10 cm/yr. A recent European core at Talos Dome in Antarctica includes the last interglacial period. U.S. community discussions have been considering South Pole and/or Hercules Dome as possible sites, and both seem to be very viable candidates scientifically. At South Pole, borehole logging has shown that the ice likely includes the last interglacial. Some coastal domes like the Renland Ice Cap in Greenland are also possibilities. For these studies as well as those in other categories, because particular depths in the ice are of great interest to a number of investigators, the community needs the capability to do replicate coring off of the main borehole at depths of interest. The NEEM group led by Denmark is also considering this in Greenland.

5. Evidence from the ice sheet prior to 800k yrs

Each time ice cores have extended further back in time they have revealed new facets of climate dynamics. The oldest record now, from the European Project for Ice Coring in

Antarctica (EPICA) core at Dome C, extends back to just over 800 ka and shows that different styles of glacial-interglacial cycle can occur even under superficially similar external forcing. The Dome C site was selected to recover old ice, but not the oldest available ice. Ice is generally believed to have been present continuously in parts of East Antarctica for at least 1.5 million years. Although basal processes may have removed or altered the very oldest ice in many places, it is reasonable to expect that ice older than 800 ka exists in East Antarctica.

The primary reason to seek this older ice is to further understand one of the major puzzles of climate system history – the transition about 1 million years ago from a world dominated by glacial-interglacial cycles lasting about 40ka to one with 100 ka cycles. Numerous questions about this transition, and the earlier time period, including the role of greenhouse gases, the relationship between ice sheet behavior and climate, the relationship between long term late-Cenozoic cooling and climate cyclically, and the persistence of abrupt climate change in earth history, could be addressed with ice core records extending to ~ 1.5 Ma, the current IPICS goal.

There are two complementary, but very different, ways of accessing ice older than 800 ka. The first is drilling at very low accumulation rate sites in East Antarctica, for example at or near Dome A. This has the advantage of recovering a continuous record, which in the younger part, can be compared to other ice cores (an important consideration for drilling at very low accumulation sites where record integrity may be an issue). A variant of this approach would be to destructively drill to a depth corresponding to 800 ka to save time and money, and only recover the older ice. A second method is to exploit blue ice sites where old ice may be outcropping at the surface. Continuous records may be difficult at such sites but access is much easier. Different drilling requirements are needed for the two approaches. At the recent IPICS meeting (Corvallis, OR, 2009) these approaches were discussed, with a strong preference for continuous records, given the potential difficulties of splicing together discontinuous and possible stratigraphically disturbed blue ice or only deep ice records.

Two regions of current attention for sites for oldest ice cores are the Dome A area and the Aurora Subglacial basin. There is a general consensus that several cores will need to be drilled, likely by different national groups and/or international partners, given the potential for stratigraphic disturbance and therefore need for replication. New radar and other data from the ICECAP and AGAP surveys are helping to narrow down site possibilities, but more analysis and modeling is needed to take this further.

Rapid sampling and/or access of the near basal region of the East Antarctic ice sheet would be useful for the oldest ice project, in part because heat flow measurements would be very helpful to understand ice sheet dynamics better and predict where old ice is. This led the IPICS group to discuss the possibility of a “hole maker,” an access tool that would allow heat flow measurements and would be useful for other purposes as well. The need for such a drill is discussed further below.

6. Pre-Quaternary atmosphere
The possibility that very old ice (>1.5 Ma) is preserved in special environments (for example in debris-laden glaciers) in Antarctica is exciting because it would provide a window into the composition of the atmosphere and climate during times when global environmental conditions were very different from today. Such sites will likely range from blue ice locations where drilling issues are essentially identical to those mentioned immediately above, to debris-laden glacier or similar environments, which will require specialized drilling equipment. A drill for dirty ice (Koci drill) exists, and drill development for large samples from clean blue ice is well underway (wide-diameter drill), as described further in the IDDO Long Range Drilling Technology Plan.

7. Large ice volume sampling for changes across climate transitions of rare isotopes, gases, micro-particles, biological materials and other parameters that have not yet been fully exploited in ice core research. Changes in climate and environmental conditions are recorded in ice cores on a variety of time scales; the Dansgaard-Oeschger events of the last ice age are the best known example. Many questions about the nature and origin of these events require access to very large samples of ice for measurements not possible in traditional ice cores, or to continuous samples to fully understand the dynamics of transitions. Examples include the use of ^{14}C of CH_4 to trace methane hydrate destabilization, and nano-diamonds, ^{3}He, and micrometeorites as tracers of extraterrestrial impacts.

Archives for addressing these issues include traditional drilling sites and blue ice sites, but specialized equipment is needed for sampling. In the case of traditional drill sites replicate coring technology is needed to obtain adequate sample sizes, and *in-situ* melting has been suggested as a means of sampling large volumes of air from deep ice core sites. For blue ice sites the large diameter drilling capability discussed above is required. Chain-saw-based quarrying tools like those used in marble quarries might also be considered.

Advances in understanding our climate requires ice cores and samples from many areas, and the requirements for the coring or sampling varies. The following table lists desired characteristics of the drills needed for the areas of science outlined above.

Table 1. Requirements of drills for ice coring Climate research
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	Diam. (cm)	Depth (m)	Drilling fluid	Ambient temp (C)	Transport type	Site occupancy	Int'l aspects
200 yr	< 10	< 400	none	-50	Twin otter / lt traverse	days	Individ contrib
2k array	7-10	100-1000	TBD	-50	Twin otter / lt traverse	days	Individ for IPICS
40k array	10+	1k-3k	TBD	-50	Twin otter	1-2 seasons	Individ or shared
Interglacial	10+	1k-3k	TBD	-50	Herc	Multiple seasons	US only or US-led
<800k yrs (oldest ice)	>10	3.5-4k	TBD	-50	Herc & traverse	Multiple seasons	IPICS
<800k yrs (blue ice)	25	5-20	none	-40	Twin otter	1-2 seasons	US Maybe others
Pre-Quatrny atmosphere	7-25 Rock-ice mix	<40	none	-40	Helicopter	1-2 seasons	US Maybe others
Rare isotopes etc	25 chain saw	<20	none	-40	Helicopter	1-2 seasons	US

II. Ice dynamics and history

The response of glaciers and ice sheets to changing environmental conditions depends both on the forcing and on the properties of the ice, and in particular on the basal conditions. For example fast flowing ice streams and outlet glaciers have slippery beds; in cases where the bed is weak, perturbations at the grounding line propagate inland over short timescales (order of decades), which has the potential for rapid draw-down of inland ice. Depth-age relationships at ice-divides where ice is frozen to the bed can be used as "dipsticks" to determine histories of thinning. The depth-age relationship contains information about past climate and past thinning. For example, a thin annual layer at depth could imply either low accumulation in the past, or ice sheet thinning (e.g. Waddington et al, 2005; Price et al., 2007). Geophysical models and inverse methods can be used to separate the different contributions

1. Bed conditions

The characteristics of the bed beneath an ice sheet exert strong control on the flow, along with other factors such as ice thickness and slope. More direct measurements of basal slip, sediment type and pore pressure are needed to understand the controls on fast flow of ice streams and outlet glaciers. Such measurements are difficult, partly because of problems associated with accessing the bed and keeping boreholes open to deploy sensors in fast moving ice. Further, recent observations suggest a relationship between drainage of subglacial lakes and glacier speed up. More measurements are needed to quantify this relationship.

2. Geothermal flux:
Cucial to estimates of frozen/thawed basal conditions using a coupled thermo-mechanical ice-flow model is the geothermal heat flux. Geothermal flux has been estimated from borehole thermometry at a few locations, but the spatial pattern of the geothermal flux is not well constrained. Rapid access drills that allow installation of heat flux sensors at the base of the ice are needed to make these fundamental measurements that are critical for realistic modeling of thermal conditions at the base of ice sheets.

Calculation of frozen/thawed basal conditions requires a coupled thermo-mechanical ice-flow model. One of the inputs for such models is the geothermal flux, which influences the temperature profile in the ice near the bed. Geothermal flux has been estimated from borehole thermometry at several locations, but the spatial pattern of geothermal flux is not well constrained. Rapid access drills that allow installation of heat flux sensors at the base of the ice are needed to make these basic measurements that are critical for realistic modeling of thermal conditions at the base of ice sheets.

3. Properties of the ice that affect flow
Even in the coldest places on Earth, ice is closer to its melting point than any other naturally-deposited material; the material properties of glacial ice can change dramatically under varying conditions of temperature, age, compression, and flow. Initially deposited as snow with accumulation over many thousands of years, the processes of firnification, transition to ice, and densification create a complicated, layered system with variable density, porosity, and mechanical and thermal properties. Bubbles in the ice impact glacial properties on the small scale, while moulins and cracks evidence complicated internal and basal plumbing on larger scales. All of these aspects impact ice flow. A variety of new technologies and new sensors are becoming available that can facilitate study of the behavior of the ice, which will lead to improvements in that ability to model glacial flow under changing climates. Rapid access drilling to create holes is needed to deploy sensors for making observations from the surface to the bed.

4. Internal layering (tracers of flow history)
Profiling of the ice sheet using radar and seismic methods often reveals internal layers. The pattern of the layers (generally assumed to be isochrones) can be used to interpret the flow history of ice sheets. The history that can be extracted from this layering is much improved if the layers can be dated by tracking them to a dated ice core or borehole. Further, the properties of ice that causes various radar-detected and seismic-detected layers can vary. Ice cores in areas of interest are needed to calibrate radar and seismic data and to derive age-depth relationships. A primary goal of this coring is to rapidly determine the age of ice at depth, without necessarily collecting and dating the overlying core. Such cores would be useful at locations where continuous layers can be traced over to a well-dated site.

5. Ice surface paleo-elevations & land surface paleo-topography
Ice surface elevations around continental mountains and nunataks during past ice sheet maxima and minima, constrain the size of ice sheets, and through modeling, can constrain past extents and volumes. Ice paleo-elevations during interglacials may be estimated by exposure dating of subglacial bedrock where the ice sheet is frozen to its bed. All models that reconstruct ice sheet history rely on bed topography because ice sheets nucleate on highlands. Present models use existing topography because paleo-topography data are lacking. By dating rocks and understanding tectonic and igneous events establishing highlands and basins through Antarctica's history, these models may reproduce more realistic paleo-ice-sheet behavior.

Tectonic processes such as uplift and subsidence significantly influence ice sheet dynamics because elevation influences ice thickness, surface temperature, and accumulation rates and hence whether ice sheets are frozen to, or sliding at their bed. Regional structural basins may be locally forced below sea level or be formed as narrow troughs by rifting processes, pre-existing faults may weaken local rocks to allow easier erosion. Changes in continental elevations with time significantly change bed conditions on tectonic time-scales.

Access boreholes to the ice sheet bed are required to recover short rock and sediment cores for these studies. Locations should be based on best estimates of bedrock geology, bed paleo-topography and plausible ice sheet extents based on models.

6. Processes that control the sub-ice-shelf mass balance
Exploration of sub-ice-shelf ocean cavities and interactions between ice shelves and ocean waters are important for providing data on rates of ice flux, crevassing, especially bottom crevasses, physical properties of the ocean and ocean circulation within ice-shelf cavities. Isolated measurements have and are being gathered from different ice shelves (e.g. Ross and Filchner-Ronne Ice Shelves) but coverage is very sparse and some, including the Ross Ice Shelf, have almost no data available.

Ice shelves are thought to be the sentries of ice sheets; ice sheets at or below sea level may become critically unstable after the ice shelves have disintegrated. Recent work suggests that ocean temperatures control rates at which the ice shelves melt. However, temperatures and ocean-cavity circulation under modern ice shelves are poorly understood. Short-term spatially distributed measurements such as those from moorings, autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs) are needed. Additionally, locally placed long-term observatories are needed to document temporal variability. These projects should be directly related to grounding-zone studies and linked with oceanographic campaigns beyond the ice shelves.

7. Grounding zone processes
The grounding zone is a critical area for ice streams and ice sheet stability, yet grounding zone processes are not well understood. Conceptual geological models of grounding-line

environments have been inferred from stratigraphic successions. Remote sensing studies using satellite observations and geophysical surveys have been conducted at grounding lines of major ice streams, but only one study at a modern grounding line has documented processes. Currently there are no direct observations or measurements of grounding lines and grounding zones associated with the sensitive areas of fast-flowing ice streams.

If we are to increase the reliability of risk assessments of future behavior of ice sheets and their components, measurements are needed to understand: (i) physical and chemical grounding line processes relevant to evaluating ice sheet/ice shelf stability; and (ii) the role of subglacial water and till in areas just up-stream from grounding lines to assess the efficiency and continuity of subglacial drainage and deforming bed systems. Grounding zones may also be sites where discharge of microbial and geochemical weathering products that originated in subglacial, basal, and englacial environments upstream occurs. Discussion of these systems is included in III.2.

Short-term measurements are needed, such as by using moorings, AUVs and ROVs. Transects across grounding lines would be ideal to increase spatial coverage for assessing areal variability. Additionally, locally placed long-term observatories are needed to document temporal variability. These projects should be directly related to ice shelf studies and linked with glacial dynamic campaigns on ice sheets.

Understanding the behavior of glaciers and ice sheets is essential for predictions of changing sea level, and advances in the science of ice dynamics requires drills that create holes through the ice sheet. The following table lists desired characteristics of the drills needed for the science outlined above.

Table 2. Requirements of drills for ice coring Ice Dynamics and History research

	Diam. (cm)	Depth (m)	Core or hole	Ambient temp (C)	Transport type	Site occupancy	Int'l aspects
Bed condtns	8	1k-4k	Hole	-60	twin otter / lt traverse	< 1 season	US & others
Geoth flux	8	1k-4k	Hole	-60	Twin otter / lt traverse	< 1 season	US & others
Flow props	8	< 4k	Hole	-40	Herc / traverse	< 1 season	US & others
Int layering	8-10	< 4k	Hole	-40	Herc / traverse	< 1 season	US & others
Paleo topo	6-10	< 1k	Rock core	-60	Herc / traverse	<1 season	US
Sub-ice shelf	8-76	< 1k	Hole	-40	Herc / traverse	2 weeks	US & others
Grounding zone	8-76	< 1k	Hole	-40	Herc / traverse	2 weeks	US

III. Sub-ice environment

Subglacial environments are the interface between ice, subglacial water, basal sediments, bedrock. This complex system provides habitat for life, records historical environmental conditions in subice sediments and may contain an unaccounted reservoir of carbon and nutrients. Liquid water is known to exist below the Greenland and Antarctic ice sheets as well as temperate glaciers. Important questions remain about the role of subglacial hydrology in ice sheet stability and microbial dynamics and about environmentally-acceptable ways of accessing the sub-ice environment (NRC, 2007).

1. Subglacial basins: sedimentary record

The records of glaciation and its variations in Antarctica are found in scattered terrestrial deposits and sedimentary basins and can be compared with offshore records. New deep geological cores are being collected near the ice sheet margin by the ANDRILL and SHALDRIL programs. Interior subglacial basins also likely contain proxy records of paleoclimate and ice sheet history to complement these records from the continental margins. Three main categories of sedimentary targets are: subglacial lakes, West Antarctic rift basins and East Antarctica epeirogenic basins. Each category may have a variety of origins and histories because of their location relative to the ice sheet margin and magnitude of ice sheet fluctuations. Thus they are probably valuable libraries of past ice sheet and climatic changes.

Subglacial lakes occur throughout the continent, the largest being Subglacial Lake Vostok, which is thought to contain a sedimentary record, as is Subglacial Lake Ellsworth and probably others. In West Antarctica, the stratigraphic record in various basins and probable rifted grabens may contain a mid-late Mesozoic and Cenozoic history of West Antarctic evolution and paleoclimate history. Two low regions within the Wilkes Land sector of East Antarctica (Aurora and Wilkes Subglacial Basins) appear as broad down-warped epeirogenic basins filled by marine and non-marine strata. They may well contain evidence of the much debated past dynamics and paleoclimate of the East Antarctic Ice Sheet.

Access holes are required to recover longer sedimentary rock cores comparable to those from the continental margins. Technological developments are required to integrate geological drilling technologies with those of ice drilling, including clean access. The U.S. Antarctic program complies with the Antarctic Treaty and other treaties to uphold protection of the environment, including activities that involve drilling through the ice. Challenges with this drilling include keeping access holes open for long periods and operating under conditions of differential ice flow movement. Given the pristine nature of Antarctic subglacial environments in particular SCAR has organized an action group to develop a Code of Conduct for the access to "recognize the value of these environments and the need to exercise wise environmental stewardship." The guidelines will be an important consideration in any subglacial access program in Antarctica.

2. Sub-ice microbial ecosystem and biogeochemistry

Subglacial and basal zones, where both water and mineral matter come in contact with ice, sediment or bedrock provide habitat for microbial life. Ice sheets provide reservoirs of microbial cells entombed during atmospheric deposition. The long time-scale of entrapment in ice environments relative to the lifetimes of microbial cells provides an opportunity to explore questions of thermodynamics and substrate availability, rates of evolution and constraints on biodiversity. Microbial cells and their genomic material should also provide valuable information that can be linked to paleoclimatic change; such life forms may be the only biological survivors in areas covered by glaciations for millions of years. Icy systems on Earth also may provide crucial terrestrial analogs for extraterrestrial life surviving and persisting on icy planetary bodies in our solar system, such as Mars, Europa or Ganymede.

The exploration of life within subglacial lakes and their sediment has begun but is still at an early stage of investigation (e.g. SALE program). Of particular interest is the distribution and ecological function of the resident microbes, the extent of biogeochemical weathering, and the genetic diversity of microbial communities in subglacial lakes. Furthermore, the forward motion of thick layers of water-saturated till beneath fast-flowing ice streams may provide a pathway for transportation of subglacial biological and diagenetic materials and weathering products to the surrounding ocean. Some subglacial meltwater is also transported over long-distances within basal drainage systems, which again likely discharge subglacial microbes and their metabolic products into circum-Antarctic seawater. For scientific integrity, these studies must be conducted with clean technology during access and sample acquisition.

3. Geological and tectonic history

Due mainly to the continent being almost entirely covered by ice the geological and tectonic history of Antarctica is far from fully known, yet the continent and its lithospheric plate play important but poorly understood roles in global tectonic architecture. Significant features include: Antarctica is considered aseismic, making it anomalous in comparison with other continents; its plate is surrounded by mid-ocean-ridges and hence should be under compression, yet there are active extensional regimes; the West Antarctic Rift System is one of the largest on Earth, and has unique attributes, with only one rift shoulder and being largely below sea level. Constraints on composition and age of basement rocks of interior East Antarctica would place better constraints on Precambrian provinces and evolution of the Antarctic shield for verifying current models. The state of stress in basement rocks is required for evaluating seismicity and extensional regimes. Drill holes into crustal rocks will allow passive and active seismic experiments for delineating crustal structure.

A significant control on glaciation is continental topography; rising mountains and higher elevations focus snow accumulation and become nivation centers for ice sheets. Sampling bedrock to determine its age is important for reconstructing paleo-topography for glaciological modeling of Antarctic Ice Sheet history. Access boreholes to the ice sheet bed are required to recover short rock and sediment cores for these studies. Locations should be based on best estimates of bedrock geology, bed paleo-topography and plausible ice sheet extents based on models.

4. Subglacial lakes and hydrological system

Subglacial hydrology has been of interest to glacial geologists and glaciologists ever since eskers were recognized as being sediment accumulations from subglacial fluvial conduits. More recently subglacial hydrological systems piqued scientific interest as being important forces in ice dynamics, fast ice flow and surges; subglacial weathering and erosion; sediment transport and jokulhlaup events; hosting microbial ecosystems; and maintaining subglacial lake systems. Transfer of significant volumes of water and sediment occurs through these systems. Due to the difficulties of access, subglacial hydrological systems are difficult to characterize and quantify. Although they are recognized as being critical in terms of ice sheet stability they are difficult to model, one reason being our lack of data on their nature and degree and rates of change that occur.

About 150 subglacial lakes have been already discovered in Antarctica, with Subglacial Lake Vostok being the largest. Of particular importance are studies focusing on spatial variability of life in subglacial lakes, the importance of the degree of hydrological interconnectivity between individual lakes and their influence of the rest of the subglacial hydrological system, as well as the links between lakes and Southern Ocean. These lakes also appear to house important sediment libraries of ice sheet and geological histories, and climate change.

Access holes to sample basal ice, subglacial water, and sediments are required at selected sites over subglacial lakes and other areas of hydrological interest. Hole diameter requirements vary depending on instrumentation required; clean technology is required, with strict environmental review, and the hole may need to be maintained open for days. Differential ice motion may also be a factor.

Access to the complex subglacial environment requires not only a variety of coring and drilling technologies, but in addition the restriction that the drilling must be conducted in a clean, environmentally responsible manner (NRC, 2007). The following table lists desired characteristics of the drills needed for the science of the sub-ice environment.

Table 3. Requirements of drills for Sub-Ice Environment research

	Diam. (cm)	Depth (m)	Core or hole	Ambient temp (C)	Transport type	Site occupancy	Int’l aspects	Environ restrictions
Sediments	10-15	1-3k	Hole	-50	Herc / traverse	weeks	SIeGE / SCAR	Clean access
Biogeochem	3-25	< 4k	Hole	-60	Herc / traverse	weeks	SALE	Clean access
Geology / tectonics	15	< 4k	Hole	-60	Herc / traverse	weeks	SIeGE / Andrill	Clean access
Subglacial hydrology	8-61	< 4k	Hole	-60	Herc / traverse	weeks	SALE	Clean access

IV. Ice as a Scientific Observatory

The polar ice sheets and mid-latitude ice caps can provide both an archive and a natural laboratory for a variety of scientific purposes not directly related to environmental and climate studies. Efforts are already underway, for example at the South Pole, to use ice sheets as targets for high energy neutrinos, as sites for efficient collection of meteorites and micrometeorites, and as extremely quiet platforms for seismic monitoring. Drilling requirements would be developed on a case by case basis and may vary widely, and some applications may make use of existing drills. For example, the hot water drill developed by the Ice Cube project for construction of an astrophysical observatory at South Pole has also permitted a suite of unique climatological and glaciological measurements. Many projects will require fast-access drilling, perhaps with scientific analysis capabilities such as particulate filtration during drilling. These experiments typically do not require recovery of an intact ice core though would benefit from the knowledge gained from cores. Characteristics of the drill have much in common with the projects in Table 2 above.

Science Planning Matrix

Goals to advance the frontiers of the science in ways that enable evidence-based decision-making and that inspire the next generation of scientists are described in the sections above. Community planning for the execution of the science is important for providing coordinated scientific investigations and also for forecasting the accompanying logistical and funding requirements. For each area described above, the following associated matrices identifies the current plans of when the research will be fielded, along with lines indicating timing of drilling technology development, where new technology is needed. Black lettering in the matrix indicates projects that are funded, blue lettering indicates projects that are in the planning phase, and red indicates possible delays in funded projects due to factors other than science or drilling.

Climate

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	2010	2011	2012	2013	2014	2015	2016	2017
Climate								
~ 200 yr investigations								
Hand auger/sidewinder	XXXX XXX	XXXX	XXXX	XXXX	XXXX			
Prairie Dog drill	XXXX XXX	XXXX						
Thermal coring drill	XXXX							
2k array								
badger/eclipse drill	BBBB BBB	BBBB						
4-inch drill	XXXX	XXXX						
40k Network								
40k-WAIS Divide								
possible site renovation delays		rrr	rrr					
DISC drill - coring	DDD							
borehole logging at WAIS		L	L	L				
replicate coring conceptual design								
replicate c. engineering	XXX							
replicate c. prototype & lab tests	XXXXXXX							
replicate c. fabrication	XXXXXX							
replicate coring at WAIS-D		DD	DDD	DD	DD			
40k - Roosevelt Island								
NZ drill - coring	nnn							
Acquisition planning -intermed drill								
intermediate drill cost estimate		XXX						
identify new drilling fluid		XXXXXXXXXX						
intermed drill design adaptation?								
intermed drill fabrication								
intermed drill replicate core fabricatoion?								
40k - South Pole?								
DISC or intermed drill?								
borehole logging								
replicate coring?								
use new drilling fluid								
40k - Herc Dome?								
DISC or intermed drill?								
borehole logging								
replicate coring?								
use new drilling fluid								
High-res records of last interglacial								
NEEM	HHHH	L	L					
Danish H-T drill								
borehole loggin at NEEM	H							
replicate coring?								
Evidence from ice prior to 800k years								
Blue ice - Taylor glacier	XXXX							
10" drill design & fabrication	TTT							
10" drill coring								
IPICS oldest ice								
adapt DISC to cold conditions						DDD D		
DISC drill - coring							DDD	DD
borehole logging								
replicate coring								

Ice Dynamics and History

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	2010	2011	2012	2013	2014	2015	2016	2017
	j f m a m j j a s o n d	j f m a m j j a s o n d	j f m a m j j a s o n d	j f m a m j j a s o n d	j f m a m j j a s o n d	j f m a m j j a s o n d	j f m a m j j a s o n d	j f m a m j j a s o n d
Ice dynamics & history								
Bed conditions								
shot-hole drill	xxxxxxxxx							
hot water drill developments	xx	xxx	xxx					
3" hot water access drill								
Geothermal flux								
Ice properties affecting flow								
Tracers of flow history (internal layering)								
Paleo ice elevation & paleo-topography								
Sub-ice shelf mass balance								
WISSARD		xxx	xxx					
Grounding zone processes		xxx	xxx					
WISSARD		xxx	xxx					

Sub-ice Environment

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	2010	2011	2012	2013	2014	2015	2016	2017
	j f m a m j j a s o n d	j f m a m j j a s o n d	j f m a m j j a s o n d	j f m a m j j a s o n d	j f m a m j j a s o n d	j f m a m j j a s o n d	j f m a m j j a s o n d	j f m a m j j a s o n d
Sub-ice environment		xxx	xxx					
sedimentary record		xxx	xxx					
		xxx	xxx					
microbial ecosystems & biogeochem		xxx	xxx					
		xxx	xxx					
geological & tectonic history		xxx	xxx					
		xxx	xxx					
subglacial lakes & hydrology		xxx	xxx					
		xxx	xxx					

Associated challenges

In addition to planning the science and accompanying drilling technology needed, there are non-scientific challenges that may impact the science or the timing of the field endeavors. The following areas present potential limitations on the amount of field science that the research community would like to conduct. Challenges associated with ice coring and drilling science include:

(1) There is need for an environmentally-acceptable drilling fluid to replace the Isopar K-HCFC 141b mixture that is currently used for drilling at the WAIS Divide sites. This fluid is not environmentally-acceptable for use at future drilling sites, and an appropriate drilling fluid must be identified for upcoming intermediate and deep coring projects. IDPO is working with IDDO to plan budgets for the IDDO task of identifying a suitable replacement drilling fluid in federal fiscal year 2011.

(2) There is limited air logistics access to sites on the Greenland and Antarctic ice sheets, and the approach of the end of the lifetime of the infrastructure supporting the drill at the WAIS Divide site. Science, drilling, infrastructure, and access are all issues that must be continually balanced and assessed through the course of a deep drilling project. IDPO and IDDO has been working with the research community, NSF, and the support contractors in planning that will enable the science to be achieved in a fiscally responsible way.

(3) There is continuing need for ice core storage and archive. Currently cores drilled by the U.S. ice coring program are stored at the National Ice Core Laboratory (NICL) in Denver, an aging facility that will soon reach its full capacity. Upgrading and expanding an ice core storage facility will require a major investment in infrastructure.

Conclusions and Recommendations

The ice coring and drilling community is clearly well posed to make important discoveries that may impact policy decisions regarding environment and climate. Both new discoveries enabled by existing technologies, and new technologies to enable new science visions are needed to achieve the science goals outlined above.

Recommendations for enabling drilling technology

Some of the drills and associated technology needed to achieve the science already exist. However, some existing equipment is in poor repair or is in need of update, while others exist only as elements on a research community wish list. The Science Advisory Board of the Ice Drilling Program Office echoes the sentiment of many in the research community with the following guiding principles for development of drilling technology:

- Planning for drilling technology needs to include consideration of the cost and availability of logistics beginning with the earliest stages of planning and continuing through the process as decisions are made throughout the engineering design and fabrication process.
- Drills and accompanying technology should be developed with an eye for use in a variety of projects in different remote locations.
- Designs should be developed so that the necessary supporting logistics do not impede the execution of the science.

The Science Advisory Board also identifies the following as high-priority investments needed during the coming years for the drilling technology to enable scientific discovery (the following are not prioritized):

1. Maintaining agile coring/drilling capability
2. Two logging winches: 1 km, 4 km
3. Replicate coring capability
4. Purchase or design/construction of an agile intermediate drill
5. Conceptual design for clean access to the ice sheet bed with a fast, narrow hole
6. Conceptual design for upgrades to the DISC drill to enable use in East Antarctica
7. Conceptual design for clean access through the ice sheet with a hole large enough to deploy subglacial rovers

Summary

Glaciers and ice sheets hold unique positions in the climate system and are important because they archive evidence of past change and they are important forces in establishing global sea level. Direct sampling and geophysical probing of glaciers and ice sheets is complex and logistically challenging. This community-based plan, updated annually in the spring, enables research community and funding agency actions regarding ice coring and drilling science, and establishes the need for the accompanying drills, drilling technology, and drilling expertise. Information about the details of each drill and its potential for use is described in a companion plan, the Ice Drilling Design and Operations (IDDO) Long Range Drilling Technology Plan, which is updated yearly and released in July.

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