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

July 2010

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LONG RANGE SCIENCE PLAN 2010-2020
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Cover photo: Karl Kreutz, an associate professor at the University of Maine, carefully measures each section of an ice core as it comes out of the drill on the Clarke Glacier in the McMurdo Dry Valleys, Antarctica. Kreutz's research group took a 160-meter core sample to study the regional climate from the past 2,000 years. Credit: Emily Stone, National Science Foundation

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Executive Summary

The impact of human activity on the climate of our planet is a critical issue confronting society. Ice cores are a unique source of paleoclimatic information that place the present climate in the context of longer term climate changes. Existing ice cores have provided a wealth of knowledge about climate change, however it is increasingly clear that arrays of ice cores are needed to assess environmental change on local, regional, and global scales. Ice cores provide critical data for developing and testing global climate models. Furthermore, the societal need for accurate predictions of future sea level rise requires improved understanding of glacier and ice sheet dynamics. This involves geophysical probing of glaciers and ice sheets, with particular emphasis on poorly understood basal processes. The drilling needed to achieve these science goals is both technically and logistically challenging, and coordinated science/technology/logistics planning is required in order to effectively develop and deliver the required ice drilling capabilities. This 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 drills and drilling technology required to enable the science. The companion plan, the Ice Drilling Design and Operations (IDDO) Long Range Drilling Technology Plan, identifies current drills, their usefulness and limitations, and discusses new drills and associated technology that need to be developed in order to move forward on the goals of this Long Range Science Plan. The Science Advisory Board recommends that sufficient funding be planned by the NSF to enable the following science targets and specific drilling technologies in the coming years.

Recommended science targets

This report discusses broad science goals across a number of areas where ice coring and drilling are needed. The Science Advisory Board recommends that areas of emphasis now and in the near future include the following:

1. Strong support should continue for individual and small group ice coring projects in Greenland, Antarctica, and temperate glaciers for the 200 year, 2k arrays, and blue ice drilling for ice older than 800k. There are many driving issues, and the agile nature of the drilling allows the community to respond to new questions in a timely fashion.
2. Ice cores should be drilled at South Pole and Hercules Dome to address questions about climate evolution in the last 40,000 years and the last interglacial period.
3. Drilling the main core at WAIS Divide should be completed, and replicate coring and borehole logging science should be planned and conducted in a way that optimizes the science output while minimizing the cost spent on site infrastructure repairs.
4. Planning and site selection for projects that will collect the oldest ice should continue. It is recognized that actual drilling is five years or more in the future.
5. Borehole studies for ice dynamics and climate history are important and use of existing boreholes should be pursued until a logistically favorable rapid access drill is developed. Borehole observatories should be established at several key sites where well-studied ice

cores have been retrieved to enable multidisciplinary studies of paleoclimate and ice dynamics.

6. The WISSARD project is a first step toward understanding ice-ocean interactions, and planning should be initiated for follow-up investigations on aspects of ice dynamics and ocean-ice interactions critical to understanding ice sheet stability.
7. Clean access and sampling technologies and methods should be developed to permit future investigation of sensitive ecosystems in subglacial environments.

Recommended logistical principles

Some of the drills and associated technology needed to achieve the science already exists, but may need repair or update. Other needed equipment exists only conceptually, as needs identified in this plan. The Science Advisory Board recommends the following guiding principles for development of drilling technology:

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

Recommended drilling technology investments

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

1. Maintain quality agile coring/drilling capability
2. Obtain two logging winches: 1 km and 4 km, with first priority on 1 km winch acquisition
3. Develop replicate coring capability
4. Purchase or construct an agile intermediate-depth ice coring drill
5. Develop a design for rapid access through the ice sheet with a narrow hole
6. Identify needed upgrades to the DISC drill to enable use in East Antarctica
7. Develop a design for clean access through the ice sheet with a hole large enough to deploy subglacial rovers
8. Identify an appropriate drilling fluid to be utilized at in situ temperatures below -30C.

Introduction

This Long Range Science Plan was developed by the Ice Drilling Program Office (IDPO) and its Science Advisory Board (SAB), in consultation with the greater research community, to provide a blueprint for research community planning and in order to provide the National Science Foundation and other funding agencies with information that will enable them to forecast budgets and logistics for science reliant on ice coring and drilling in the coming decade. The companion plan, the Long Range Drilling Technology Plan, developed by the Ice Drilling Design and Operations (IDPO) group, in collaboration with the IDPO, provides the details of the drills, drilling technology, and drilling expertise that directly respond to the needs articulated in this Long Range Science Plan. Updated versions of both plans are produced annually in the spring.

One of the most pressing environmental issues of our time is the potential that warming due to increasing atmospheric concentrations of greenhouse gases may trigger abrupt climate change, and more broadly, all of the changes that a warming planet will bring. To reduce the uncertainty of future climatic and environmental projections, we need to understand the mechanisms of abrupt change and the nonlinear impacts that present warming may have on the cryosphere. Ice cores yield a vital paleoclimatic record, but 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 in these boundary zones is crucial to being able to predict ice sheet behavior during future greenhouse gas 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 its 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 Intergovernmental Panel on Climate Change (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 linkages between the northern and southern hemispheres, impact of humans on the atmosphere, atmosphere-ocean-ice relationships, and other issues that can be uniquely addressed by ice coring science. High accumulation sites on glaciers and polar ice sheets contain high resolution natural archive of past environmental conditions. An international meeting sponsored by the U.S. National Science Foundation in 2004 led to the formation of an international group to conduct joint science planning for future projects, the International Partnerships in Ice Core Sciences (IPICS), under the leadership of Dr. Ed Brook (Oregon State University) and Dr. Eric Wolff (British Antarctic Survey) (Brook and Wolff, 2006). The IPICS white papers described broad science targets for ice coring: 2k-year arrays, 40k-year arrays, the last interglacial, and oldest ice (www.pages-igbp.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.

Subglacial 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. 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, enhanced 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 effect of that efflux on global processes remain outstanding questions. 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. Microorganisms that exist under permanently dark and cold subglacial conditions have broadened our understanding of the phylogenetic and metabolic diversity of life on Earth, and may help inform our search for extraterrestrial 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 training 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, to articulate the direction of U.S. ice coring and drilling science, and to provide the foundation upon which the Ice Drilling Design and Operations (IDDO) Long Range Drilling Technology Plan is 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 while allowing the National Science Foundation (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 website each spring, with listserv 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 website in summer.

The science can be described in four categories: climate, ice dynamics and history, sub-ice environment, and ice as a scientific observatory. The four are described in more detail in the following sections. Science objectives within each category are accompanied by an outline of the science requirements for the associated drilling technology. Finally, science planning matrices are presented that show the envisioned timing of the field efforts and associated actions for the development of new drilling technology, so that the technology will be ready when needed by the science.

I. Climate

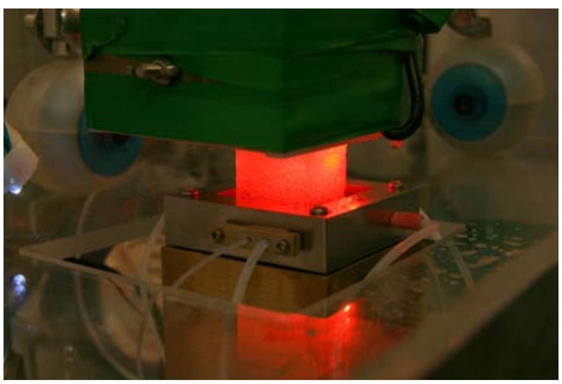
Earth's climate is a complicated system involving local, regional, hemispheric, and global phenomena. It is impossible to understand global climate without understanding both individual components of the system and the system as a whole, as evidenced by data from a large number of locations and over a range of time scales. Issues articulated by many U.S. scientists (e.g. ICWG, 2003) were central to the themes in the white papers of the International Partnerships in Ice Core Sciences (IPICS) (Brook and Wolff, 2006), hence a number of the categories below reflect those themes.

1. ~ 200-year 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-U.S. Scientific Traverse of East Antarctica). While shallow coring has been done in a few locations, many more such endeavors are needed in the Arctic and 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; 7) investigate the spatial pattern of anthropogenic impacts; and 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. The agile drills required for 200 year arrays and some of the 2k array sites exist in various states of repair in the current U.S. inventory. They are used often, and should be maintained in top form so that agile drills in the inventory are all functional and can be quickly readied for deployment to the field. Requirements for drills to achieve these and other ice coring goals are listed in Table 1 at the end of this section. The Long Range Drilling Technology Plan describes the agile drills in detail and discusses their current condition.



This image is of an ice core sample sitting on a melter head in an ultra-trace chemistry laboratory. Records taken from a Greenland ice core showed pollution from coal burning in North America and Europe that traveled through the atmosphere and deposited in the Arctic Region was higher 100 years ago, contrary to the expectation that pollution was at a peak in the 1960s and '70s. Credit: *Joseph McConnell, Desert Research Institute*

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 2,000-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 2,000 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 United States, are considering new coring associated with the 2k array theme. New U.S. or U.S/International efforts that have been discussed or are in planning stages include Roosevelt Island in the Ross Sea (the 2,000 year record would be part of a deeper core), Detroit Plateau on the Amundsen Coast, and possibly the Aurora Basin in Antarctica or a high accumulation rate site in Greenland. This list is not exclusive, but illustrates the diversity of possibilities.

3. 40k network

The past 40,000 years include the glacial/interglacial transition and 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 is one of the more 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 resolve their spatial and temporal evolution. Ice cores are uniquely placed to provide the contrasting polar elements of climate in very high resolution as well as a suite of measurements (such as greenhouse gase concentrations). In addition, we need to understand the response of the Antarctic, Greenland, and other 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 matters 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 South Pole, Hercules Dome, and Taylor Dome, with the most discussion to date focused on South Pole. Planning for drilling by New Zealand with U.S. science collaboration is moving forward for a site on Roosevelt Island, as a contribution to the network. The IPICS 40k 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.

For this science it is important that IDPO/IDDO acquire for the U.S. community an intermediate depth coring drill, capable of drilling to 1,000 m or more with minimal logistical burden. As discussed in the IDDO Long Range Drilling Technology Plan, current agile drills in the inventory have a maximum depth of several hundred meters. The only other drill in the inventory is the DISC drill, which can reach 4,000 m; however it is logistically heavy and requires multiple seasons for deployment and drilling. An intermediate depth drill that can reach 1,000 m would facilitate discoveries for the 40k array and also other ice coring goals.

The bubbles visible in this piece from an Antarctic ice core contain carbon dioxide and other gases that were trapped in the ice when formed many thousands of years ago. Ice cores provide the only natural archive of ancient air. Credit: *Oregon State University*

4. High-resolution records of the last interglacial

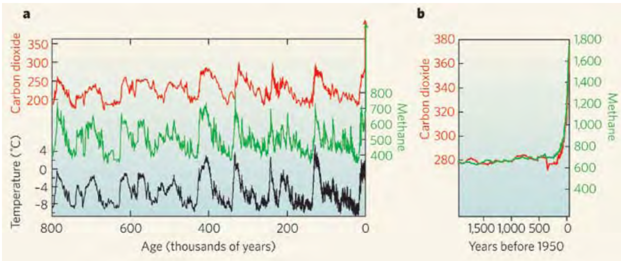
The last interglacial period (~130,000 to 110,000 years ago) was warmer than present due to differences in Earth's orbital configuration, and can provide clues about how the Earth will behave as human activities continue to force global warming. Critical questions concern the possibility of tipping points 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 North Greenland Eemian Ice Drilling (NEEM) ice core in Greenland, one of the original IPICS objectives, is now under way, and we hope will 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 in Antarctica where accumulation is moderate, on the order of 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, such as 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. A conceptual design for replicate coring has been developed by IDDO, and is currently being implemented with the DISC drill, as discussed in the Long Range Drilling Technology Plan. The NEEM group led by Denmark is also considering some form of replicate coring in Greenland.

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

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 40 ka 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 cyclicity; 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.



The 100,000-year 'sawtooth' variability in carbon dioxide, methane, and temperature undergoes a change about 450,000 years ago, with the amplitude of variation greater since that point than it was before. Concentrations of greenhouse gases in the modern atmosphere are highly anomalous with respect to natural greenhouse-gas variations (present-day concentrations are around 380 p.p.m. for carbon dioxide and 1,800 p.p.b. for methane). Figure from Brook, 2008, Paleoclimate: Windows on the Greenhouse, *Nature* 453, 291-292.

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 drill destructively (i.e., without producing core) 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 such as Taylor Glacier (Aciego et al., 2009) and Mt Moulton (Dunbar et al., 2008) 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 possibly stratigraphically disturbed blue ice or only deep ice records.

Two regions of current attention for sites of 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 the need for replication. New and ongoing radar, laser altimetry, gravity and magnetic data from ICECAP and Antarctica’s Gamburtsev Province (AGAP) airborne surveys are helping identify potential sites, but additional observations and model calculations are needed. Planning needs to be put in place in order to upgrade the DISC drill, described in detail in the Long Range Drilling Technology Plan, for drilling in the very cold conditions found in East Antarctica.

Rapid sampling of and/or access to the near basal region of the East Antarctic ice sheet would be useful for the oldest ice project, in part because temperature and heat flow measurements would be very helpful for better understanding ice sheet dynamics and predicting where old ice occurs. This led the IPICS group to discuss the possibility of a “hole maker,” an access tool that would allow temperature and 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 glaciers or similar environments, which will require specialized drilling equipment. A drill for dirty ice (Koci drill) exists, and drill development of a drill for wide-diameter samples from clean blue ice is well under way ("blue ice" drill), as described further in the IDDO Long Range Drilling Technology Plan.

7. Large ice volume sampling for changes across climate transitions

Rare isotopes, gases, micro-particles, biological materials, and other parameters that have not yet been fully exploited in ice core research offer new opportunities if large volumes of ice can be made available. 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 the ^{14}C concentration of trapped 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 new large-diameter blue ice drill mentioned above is required. Chainsaw-based quarrying tools such as those used in marble quarries might also be considered.

Summary

Advances in understanding our climate require arrays of ice cores with depths ranging from tens of meters to 4 km, and the requirements for the coring or sampling vary. Agile drills currently at IDDO need to be repaired and maintained in good condition so that they are ready for a variety of projects. Acquisition of an intermediate depth drill that can drill to approximately 1,000 m depth in one season while minimizing logistical requirements is also a priority. Development of the replicate coring capability for the DISC drill and creating a large-diameter drill for blue ice areas should be accomplished in the coming year. A conceptual design for upgrading the DISC drill for the cold conditions of East Antarctica should be planned. In addition, because the HCFC-141-b component of the current drilling fluid is being phased out, there is need to identify a replacement drilling fluid that is suitable for the cold conditions of East Antarctica. The following information in Table 1 lists desired characteristics of the drills needed for the areas of science outlined above, and more information on each type of drill is given in the IDDO Long Range Drilling Technology Plan.

Table 1. Requirements of drills for ice coring: Climate Research

	Diam. (cm)	Depth (m)	Drilling fluid	Ambient temp (C)	Transport type	Site occupancy	Int'l aspects
200 yr	7-10	<400	none	-50	Twin otter/ lt traverse	Days/weeks	Individual contrib
2k array	7-10	100-1,000	TBD	-50	Twin otter/ lt traverse	Weeks/month	Individual for IPICS
40k array	10+	1-3k	TBD	-50	Twin otter/ Herc	1-2 seasons	Individual or shared
Interglacial	10+	1-3k	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-Quaternary 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

The IDDO Long Range Drilling Technology Plan discusses in detail a variety of drill systems, many of which exist and several that need to be developed, which fulfill the needs articulated above. Detailed comments on the current status, technical issues, and plans for each type of drilling system are presented in that document. Appendix 1 of the Long Range Drilling Technology Plan matches specific drill systems with the science endeavor, and Appendix 2 of the Drilling Technology Plan gives the timing of development and field projects.

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, 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. Ice core data — including records of accumulation rate history, ice fabric measurements, and inferred surface elevation changes based on atmospheric measurements from bubbles in ice cores — are important contributors to ice dynamics studies. 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). 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, and access drills that can rapidly access the bed while minimizing logistics are needed to facilitate this science. Such drills do not yet exist for deep ice.

2. Geothermal flux

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 are easily portable and drill to the bed in less than one field season would allow installation of temperature and heat flux sensors at the base of the ice. These basic measurements are critical for realistic modeling of thermal conditions at the base of ice sheets.

3. Rheological properties of ice

Rheological properties of ice depend strongly on temperature, impurities, and texture, including grain size and fabric (e.g. Cuffey and Paterson, 2010). Improved understanding of the controls on the rheology is needed to develop realistic models of deformation of ice sheets, which are needed to help develop depth-age relationships in ice cores, and also to establish past, present and future responses to possible environmental changes. Sensors that measure depth profiles of temperature, fabric, optical stratigraphy and tilt in boreholes are now available. Rapid-access drills that can drill through ice up to 4 km thick are needed to deploy these sensors.

4. Internal layering (tracers of flow history)

Profiling of ice sheets 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 the layer pattern is much improved if the layers can be dated by tracking them to a dated ice core or borehole. Further, knowledge of the various causes of radar-detected and seismic-detected layers is needed to fully exploit these remote sensing methods. A system to rapidly access the ice sheet and then extract ice cores from selected depths in the ice sheet would allow for analyses of ice properties at depths of special interest; such a drill does not yet exist but should be considered.

5. Ice surface paleo-elevations and land surface paleo-topography

Trimlines, moraine limits and exposure-age dating provide geologic constraints on past ice thickness around protruding continental mountains and nunataks (e.g. Todd et al., 2010; Bentley et al., 2010; Stone et al., 2003). Mapping paleo-elevations during past interglacials is more problematic, but exposure-age dating of subglacial bedrock at locations where the ice sheet is thin and frozen to its bed would help constrain ice-sheet extents during past interglacials.

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, 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 been 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 buttress discharge from 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. Access holes large enough for deploying subglacial rovers are needed for measurements to improve understanding. 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

Grounding zones are critical areas 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 (Anandankrishnan et al., 2007; Alley et al., 2007). 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, access holes are needed for measurements 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 upstream 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 Section III.2.

In common with Section II.6, short-term measurements by moorings, AUVs, and ROVs are needed. Transects across grounding lines would be ideal to increase spatial coverage for assessing areal variability. Also in common with Section II.6, locally placed long-term observatories are needed to document temporal variability. Grounding line projects should be directly related to ice shelf studies and linked with glacial dynamic campaigns on ice sheets.

Remote sensing techniques such as seismic imaging and radio echo sounding can complement the in-situ measurements of bed conditions and englacial properties. Such remote sensing techniques (in particular seismic imaging) require shallow holes for emplacing sources. The capability for producing large numbers of shallow holes (25-100m depth, 5-10cm diameter) is present within IDDO with the Rapid Air Movement Drill, and that capability should be maintained and improved. Increasing the speed of drilling while continuing to reduce the size and power consumption of the shot hole drills will be important. The Rapid Air Movement Drill is discussed in more detail in the Long Range Drilling Technology Plan.

Summary

Understanding the behavior of glaciers and ice sheets and the study of ice dynamics are essential for predictions of changing sea level; advances in the science of ice dynamics require drills that create access holes into and through the ice sheet. Table 2 below lists desired characteristics of drills needed to create holes in ice sheets for the study of ice dynamics and history. The IDDO Long Range Drilling Technology Plan discusses in detail drills, a few of which exist, for making holes in ice sheets. Significant future planning and development will be needed to develop capability for making deep rapid-access holes, as discussed in the Long Range Drilling Technology Plan.

Table 2. Requirements of drills for Ice Dynamics and History Research

	Diam. (cm)	Depth (m)	Core or hole	Ambient temp (C)	Transport type	Site occupancy	Int'l Aspects
Bed conditions	8	1-4k	Hole	-60	twin otter/ lt traverse/ Herc*/trav*	<1 season	US & others
Geothermal flux	5-8	1-4k	Hole	-60	Twin otter/ lt traverse/ Herc*/trav*	<1 season	US & others
Rheological properties	8	<4k	Hole	-40	Herc/ traverse	<1 season	US & others
Internal layering	8-10	<4k	Hole	-40	Herc/ traverse	<1 season	US & others
Paleo-topography	6-10	<1k	Rock core	-60	Herc/ traverse	<1 season	US
Sub-ice shelf	8-75	<1k	Hole	-40	Herc/ traverse	2 weeks	US & others
Grounding zone	8-75	<1k	Hole	-40	Herc/ traverse	2 weeks	US
Seismic imaging	5-10	~ 100 m	Hole	-40	Twin otter	Hours/days	US

* Depending on depth of hole

III. Sub-ice Environment

Subglacial environments are the interfaces between ice, subglacial water, basal sediments, and bedrock. This complex system provides habitat for life, records historical environmental conditions in subglacial 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 Antarctic Drilling Project (ANDRILL) and Shallow Drilling on the Antarctic Continental Margin (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 differing locations relative to the ice sheet margin and magnitudes of ice sheet fluctuations. Thus, they may provide valuable archives 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 does 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, the Scientific Committee on Antarctic Research (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 ecosystems 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 timescale 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., the Subglacial Antarctic Lake Environment, or SALE, program). Of particular interest is the distribution and ecological function of the resident microbes, the extent to which biogeochemical weathering occurs, and the genetic diversity of microbial communities in subglacial lakes and sediments. 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. Access holes through the ice are needed for this science, and, for scientific and environmental integrity, these studies must be conducted with clean technology both during access and sample acquisition.

3. Geological and tectonic history

The massive Antarctic ice sheet makes subsurface access difficult, hence the geological and tectonic history of Antarctica is far from fully known. The continent and its lithospheric plate play important but poorly understood roles in global tectonic architecture, leading to contradictory current impressions. Antarctica is considered aseismic, but if so, it would be unique among all of the 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 currently known attributes are unique, 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 through the ice 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 systems

Subglacial hydrology has been of interest to glacial geologists and glaciologists ever since eskers were recognized as being sediment accumulations from subglacial fluvial conduits. Measurements to quantify current subglacial hydrological systems are important for understanding ice dynamics, weathering and erosion of subglacial rock, sediment transport and jokulhlaup events, microbial ecosystems, and maintaining systems of subglacial lakes.

Transfer of significant volumes of water and sediment occurs through these systems. Due to the difficulties of access, subglacial hydrological systems have not been well characterized, and the lack of quantitative data makes it very difficult to model ice sheet stability.

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

Summary

Drills to create access holes are needed to sample basal ice, subglacial water, and sediments at selected sites over subglacial lakes and other areas of hydrological interest. Hole diameter requirements vary depending on instrumentation needed; 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. A priority development is a conceptual design for a drill that can provide clean access holes that are large enough to deploy subglacial rovers; this design should strive to keep supporting logistical requirements to a reasonably low level.

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). Table 3 below lists desired characteristics of the drills needed to create clean access holes for the science of the sub-ice environment. The Long Range Drilling Technology Plan discusses the drills in more detail, including prospects for development of a fast access drill with relatively low accompanying logistical requirements.

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	8-60	<4k	Hole	-60	Herc/ traverse	weeks	SALE	Clean access

The IDDO Long Range Drilling Technology Plan shows, in Appendix 1, the hot water and mechanical rapid-access drills that could provide clean access holes for the projects described above. Clean mechanical rapid-access drills do not currently exist, and need conceptual and engineering development. It is currently envisioned (Appendix 2 of the Drilling Technology Plan) that development on that type of system may begin in 2012, pending availability of funding.

IV. Ice as a Scientific Observatory

The polar ice sheets and mid-latitude ice caps archive evidence of past climate and also serve a variety of endeavors that use the ice as a platform for science. Borehole access to the interior of the ice sheet enables wide-ranging observations, from astronomy using cosmic particles to tracking of glacial flow.

1. Ice sheet as a platform for astrophysics

Efforts are under way at the South Pole to use the ice sheet as a target for high-energy neutrinos traveling to Earth from cosmic sources. The Ice Cube telescope is a powerful tool that may reveal new physical processes associated with the enigmatic origin of the highest energy particles in nature. Arrays of smaller boreholes promise to yield future opportunities for astrophysics research from ice sheets.

Glaciers and ice sheets serve as platforms for efficient collection of meteorites and micrometeorites. Micrometeorites yield clues to the birth and evolution of the solar system. Some are visible to the human eye on the surface of some blue ice areas, while others may be swept up inside melted water wells created in the ice at established field stations.

A Digital Optical Module (DOM) is lowered into a hole in the ice at Amundsen-Scott South Pole Station as part of the IceCube project. IceCube will search for neutrinos from distant astrophysical sources. Photograph Credit: Ethan Dicks, National Science Foundation.

2. Ice sheet as a platform for geophysical studies

The Global Seismographic Network includes seismic monitoring stations for earthquakes and other events around the world, including on ice sheets. The ice sheets serve as extremely quiet platforms for seismic monitoring. The South Pole Remote Earth Science and Seismological Observatory has seismic equipment installed approximately 300 m deep in boreholes. Similar observations will occur in boreholes on the Greenland Ice Sheet.

3. Ice sheet as an archive of recent past atmospheric composition

In very cold areas of ice sheets where snow rarely melts, many decades of snowfall create a porous network of old snow, called firn, in the top many tens of meters of the ice sheet. The firn serves as an archive of atmospheric composition, with the oldest air existing at depth. Sampling firn air from various depths in boreholes drilled in the ice sheet enables, for example, observation of the extent of anthropogenic emissions and patterns of increase or decrease.

4. Borehole logging for paleoclimate information

New geophysical and climate studies can be achieved using recently developed, state of the art sensors, lowered into well-maintained boreholes that were originally drilled for retrieval of ice cores for climate studies. The boreholes serve as enduring scientific observatories. They enable analyses that complement study of the ice core and that are difficult or impossible to obtain by other methods. Repeated measurements, for example of optical and radio properties and temperature enable observations of changes over time. Methods for repairing several key deep boreholes need to be developed.

5. Borehole logging for ice dynamics studies

The formation process of the ice sheet creates layers that may evolve and deform over time as the ice sheet flows across an uneven terrain. Borehole observations enable improved modeling of ice sheet behavior and studies of ice sheet stability.

Summary

Ice sheets are platforms for a wide range of scientific observations that span many areas of science. Some of the areas of this science, for example firn air studies and seismic monitoring, have been possible because the coring drills that are needed to make the holes already exist. Other areas, including borehole logging science for paleoclimate and glacial dynamics, are at an early stage because there currently is not a drill that can quickly, and with minimum logistical requirements, drill a borehole through several kilometers of ice. Unlike core sampling, borehole logging is nondestructive, continuous, and immune to core damage or drill depth errors and permits study of a large volume of ice *in situ*. A rapid access drill for creating narrow holes needs to be designed that is not logistically intensive, and logging winches for intermediate depths (1 km) and deep depths (4 km) need to be acquired in order to enable scientific discoveries made through borehole logging. Characteristics of the drills needed to make the boreholes have common requirements with those for the projects in Table 2 above. Maintenance and improvement of agile drills for relatively shallow coring, as well as perspectives on development of deep rapid access drills, are discussed in more detail in the companion plan, the IDDO Long Range Drilling Technology Plan.

Science Planning Matrices

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 associated matrices shown below identify the current plans for the timing of the field research. In cases where new drilling technology is needed, the steps are identified for development that is needed leading up to deployment of the drills.

In the Climate matrix (Table 4) below, a potential delay in drilling at WAIS Divide has become evident, due to probable needed maintenance of surface infrastructure at the site. The potential delay and delayed drilling actions are represented in the matrix in red letters, mostly affecting the timing of replicate coring proposed at that site. It is not possible to accurately forecast this situation at this time; updated planning will occur over time as the situation evolves.

Planning for U.S. drilling as part of the Climate 40k networks is a topic of current ice coring community discussion as of the writing of this report. Strong cases are being made to drill both at South Pole and Hercules Dome, but the community has not yet come to final consensus on whether the drilling will occur first at South Pole or first at Hercules Dome. The planning matrix shows both South Pole and Hercules Dome, and tentatively lists South Pole as the first to be drilled. It is anticipated that continued discussion will lead to final planning decisions in fall of 2010.

In the Planning Matrices below, 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 that are due to factors other than science or drilling.

Table 4: Climate Planning Matrix

	2010				2011				2012				2013				2014				2015				2016				2017				2018			
Climate	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
~ 200 yr investigations																																				
Hand auger/sidewinder		x	x	x	x	x	x	x	x	x	x			x	x			x	x																	
Prairie Dog drill		x	x	x	x	x	x	x	x																											
Thermal coring drill		x	x																																	
2k array																																				
badger/eclipse drill		b	b	b	b	b	b																													
4-inch drill		4	4			4	4																													
40k Network																																				
40k-WAIS Divide																																				
possible site renovation delays								r	r																											
DISC drill - coring				D	D																															
borehole logging at WAIS								L				L				L				L	L															
replicate coring conceptual design																																				
replicate c. engineering	x	x	x	x																																
replicate c. prototype & lab tests			x	x	x																															
replicate c. fabrication				x	x	x				x	x																									
replicate coring at WAIS-D								D	D			D	D			D	D																			
40k - Roosevelt Island																																				
NZ drill - coring				N	N																															
Acquisition planning -intermediate drill																																				
establish science requirements			x	x																																
int drill feasibility & cost estimate					x	x	x																													
int drill design/adaptation								x	x	x																										
int drill fabrication								x	x	x	x	x																								
int drill field test & prep for deployment												x	x	x	x																					
Acquisition planning -new drilling fluid																																				
establish science requirements					x	x																														
identify new drilling fluid							x	x	x	x	x																									
40k - South Pole? (Or Herc Dome)																																				
Intermediate drill coring																I	I																			
borehole logging																				L	L															
replicate coring?																																				
40k - Herc Dome? (Or South Pole)																																				
Intermediate drill coring																				I	I			I	I											
borehole logging																												L	L							
replicate coring?																																				
High-res records of last interglacial																																				
NEEM																																				
Danish H-T drill		H	H																																	
borehole logging						L				L																										
Evidence from ice prior to 800k years																																				
Blue ice - Taylor glacier																																				
Blue Ice drill design & fabrication	x	x	x																																	
Blue Ice drill coring				B	B			B	B																											
IPICS oldest ice																																				
adapt DISC to cold conditions															x	x	x	x	x	x	x	x	x													
DISC drill - coring																								D	D			D	D							

The letters denoting specific drills are: b: badger-eclipse; 4: 4-inch drill; D: DISC drill; N: NZ drill; H: Hans-Tausen drill; B: blue ice drill; L: borehole logging; I: intermediate drill.

Table 5: Ice Dynamics and History Planning Matrix

	2010				2011				2012				2013				2014				2015				2016				2017				2018			
Ice Dynamics & History	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Development - hot water access drill																																				
subglac hot water drill development	x	x	x	x	x	x	x	x	x	x	x																									
Development - mech rapid access drill																																				
establish science requirements						x	x	x																												
conceptual design										x	x	x	x	x																						
engineering												x	x	x	x																					
prototype & lab tests													x	x	x	x																				
fabrication														x	x	x	x																			
Bed conditions																																				
Geothermal flux																																				
Ice properties affecting flow																																				
Tracers of flow history (layering)																																				
Paleo ice elevation & topography																																				
Sub-ice shelf mass balance																																				
WISSARD												x	x			x	x																			
Grounding zone processes																																				
WISSARD												x	x			x	x																			
Seismic imaging												x	x			x	x																			

While the ice dynamics community has identified a number of important science topics to pursue, progress in many areas is held back by the lack of a rapid-access drill that is logistically acceptable for work in the deep field. Hence, planning for development of such a drill is planned in the coming years, pending availability of funding. This is also the case for some of the science themes in the Sub-Ice Environment Matrix below.

Table 6: Sub-ice Environment Planning Matrix

	2010				2011				2012				2013				2014				2015				2016				2017				2018			
Sub-Ice Environment	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Sedimentary record																																				
Microbial ecosystems & biogeochem																																				
WISSARD												x	x			x	x																			
Geologic& tectonic history																																				
Subglacial lakes & hydrology																																				
WISSARD												x	x			x	x																			

Table 7: Ice as a Scientific Observatory Planning Matrix

	2010				2011				2012				2013				2014				2015				2016				2017				2018			
Ice as a Scientific Observatory	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Ice - a platform for planetary science																x	x																			
Observations from existing boreholes																																				
Conceptual design for borehole repair				x	x	x																														
Assessment of existing boreholes						x	x	x	x	x	x	x	x																							
Borehole repair							x																													
Siple Dome																																				
Borehole logging												L	L																							

Members of the physics community who are interested in using the ice as a platform for neutrino detection are currently testing the Rapid Air Movement drill for use at South Pole. If the drill proves successful in meeting their goals, then a plan may evolve for future drilling in that category.

The borehole logging community is a strong proponent for repairing the GISP2 and other deep boreholes to enable continued observation of the interior of the ice sheet for a variety of science goals, as discussed in the Observatory section of the report. Identification of methods to repair borehole casing and identifying which boreholes need maintenance are activities that will need attention in the coming year, as indicated in the matrix. A proposal is currently pending at NSF for a borehole logging science project using the existing Siple Dome borehole.

Associated Logistical Challenges

In addition to planning the science and the associated drilling technology, there are non-scientific challenges that may impact the timing of the field endeavors. The following areas present potential limitations on the amount of field science that can be done to address urgent issues of climate and environment. Challenges associated with ice coring and drilling science include:

(1) Drilling ice cores deeper than approximately 300 m necessitates use of a drilling fluid mixture that has a density similar to ice to prevent borehole closure. In addition, the fluid mixture must have a viscosity that is low enough to permit passage of the drill sonde through the fluid many times during the drilling process. One of the current mixture components, HCFC-141b, is being phased out as a result of the Montreal Protocol, and will not be available for future drill sites. A new replacement must be identified with a reasonably low viscosity for the very cold temperatures of East Antarctica, and the fluid must be appropriate for the analytical methods used in the scientific analysis of ice core chemistry. A fluid used at the NEEM coring site in Greenland satisfies the criteria for sites of moderate temperature, but its properties are not favorable for drilling in the very cold conditions encountered in East Antarctica. IDPO/IDDO investigations will begin in FFY2011, as discussed further in the Long Range Drilling Technology Plan.

(2) There is limited air logistics access to sites on the Greenland and Antarctic ice sheets. With multiple science communities requesting flights, time at the field site must be carefully planned and established to optimize scientific productivity. Currently the surface infrastructure supporting the DISC drill at the WAIS Divide site is nearing the end of it lifetime and will need extensive repair in the coming several years. Conducting field science and ice core drilling while attempting to minimize logistical requirements requires constant vigilance and planning. IDPO and IDDO have been working with the research community, NSF, and the support contractors in planning revised time schedules that will enable the science to be achieved in a fiscally responsible way.

(3) The ice core storage facility for U.S. science is in dire need of repair and expansion. Cores drilled by the U.S. ice coring program are stored at the National Ice Core Laboratory in Denver, an aging facility that will soon reach its full capacity. Upgrading and expanding the ice core storage facility will require a major NSF investment in infrastructure.

(4) The community's desire to maintain key boreholes as long-term observatories is a new concept. GISP2 remains one of the most influential and widely cited records in paleoclimatology; a well-maintained borehole would spawn new discoveries fostered by borehole logging science. Recently, differential GPS indicated that the borehole casing is sinking faster than would be expected from steady ice flow divergence. Follow-up borehole video revealed that the casing is collapsing and already not navigable by most logging instruments. The GISP2 casing needs to be repaired and maintained for current and future science, as do the casings of the boreholes at Siple Dome and Taylor Dome. As discussed in the IDDO Long Range Drilling Technology Plan, preservation of existing ice core boreholes is a new endeavor; planning and evaluation will need to occur in order to identify a strategy for repair and maintenance of the major boreholes. Action on this item is urgent yet there is not funding to address this issue. As discussed in the IDDO Long Range Drilling Technology Plan, pending availability of funding, borehole repair could begin in 2011.

Conclusions and Recommendations

In the formation of this IDPO Long Range Science Plan, the members of IDPO and the Science Advisory Board have interacted with members of the broader research community to articulate the issues driving ice coring and drilling science, to examine which science endeavors can be addressed with existing drilling equipment, and to identify developments in drills and drilling technology that are needed to fill voids in drilling capability. The ice coring and drilling community is clearly well poised 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 in this document. The Science Advisory Board recommends the following science targets, principles for developing new drilling capabilities, and specific drilling technologies needed in the coming years, and urges NSF to plan future financial resources that can accommodate at least the following elements.

Recommended science targets

This report discusses broad science goals across a number of areas where ice coring and drilling are needed. The Science Advisory Board recommends that areas of emphasis now and in the near future include the following:

1. Strong support should continue for individual and small group ice coring projects in Greenland, Antarctica, and temperate glaciers for the 200 year, 2k arrays, and blue ice drilling for ice older than 800k. There are many driving issues, and the agile nature of the drilling allows the community to respond to new questions in a timely fashion.
2. Ice cores should be drilled at South Pole and Hercules Dome to address questions about climate evolution in the last 40,000 years and the last interglacial period.
3. Drilling the main core at WAIS Divide should be completed, and replicate coring and borehole logging science should be planned and conducted in a way that optimizes the science output while minimizing the cost spent on site infrastructure repairs.
4. Planning and site selection for projects that will collect the oldest ice should continue. It is recognized that actual drilling is at least five years or more in the future.
5. Borehole studies for ice dynamics and climate history are important and use of existing boreholes should be pursued until a logistically favorable rapid access drill is developed. Borehole observatories should be established at several key sites where well-studied ice cores have been retrieved to enable multidisciplinary studies of paleoclimate and ice dynamics.
6. The WISSARD project is a first step toward understanding ice-ocean interactions, and planning should be initiated for follow-up investigations on aspects of ice dynamics and ocean-ice interactions critical to understanding ice sheet stability.
7. Clean access and sampling technologies and methods should be developed to permit future investigation of sensitive ecosystems in subglacial environments.

Recommended logistical principles

Some of the drills and associated technology needed to achieve the science already exist. However, some of the existing equipment is in poor repair or is in need of update, while other equipment exists only as ideas on a research community planning list. The Science Advisory Board recommends the following guiding principles for development of drilling technology:

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

Recommended drilling technology investments

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

1. Maintain quality agile coring/drilling capability
2. Obtain two logging winches: 1 km and 4 km, with first priority on 1 km winch acquisition
3. Develop replicate coring capability
4. Purchase or construct an agile intermediate-depth ice coring drill
5. Develop a design for rapid access through the ice sheet with a narrow hole
6. Identify needed upgrades to the DISC drill to enable use in East Antarctica
7. Develop a design for clean access through the ice sheet with a hole large enough to deploy subglacial rovers
8. Identify an appropriate drilling fluid to be utilized at in situ temperatures below -30C.

Glaciers and ice sheets hold unique positions in the climate system and are important because they archive evidence of past change and are vital factors in establishing global sea level. Ice coring and geophysical probing of glaciers and ice sheets is technically 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. Both this Science Plan and the Drilling Technology Plan are updated yearly and released in July.

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Acronyms

AGAP: Antarctica's Gamburtsev Province

ANDRILL: Antarctic Drilling Project

AUV: Autonomous Underwater Vehicle

DISC: Deep Ice Sheet Coring

EPICA: European Project for Ice Coring in Antarctica

GISP2: Greenland Ice Sheet Program II

HCFC: Hydrochlorofluorocarbon

ICECAP: A project name, not an acronym

IDDO: Ice Drilling Design and Operations

IDPO: Ice Drilling Program Office

IPCC: Intergovernmental Panel on Climate Change

IPICS: International Partnerships in Ice Core Sciences

NEEM: North Greenland Eemian Ice Drilling

NRC: National Research Council

NSF: National Science Foundation

ROV: Remotely Operated Vehicle

SAB: Science Advisory Board

SALE: Subglacial Antarctic Lake Environment

SCAR: Scientific Committee on Antarctic Research

SHALDRIL: Shallow Drilling on the Antarctic Continental Margin

SIeGE: Sub-Ice Geological Exploration

WAIS: West Antarctic Ice Sheet

WISSARD: Whillans Ice Sheet Subglacial Access Research Drilling