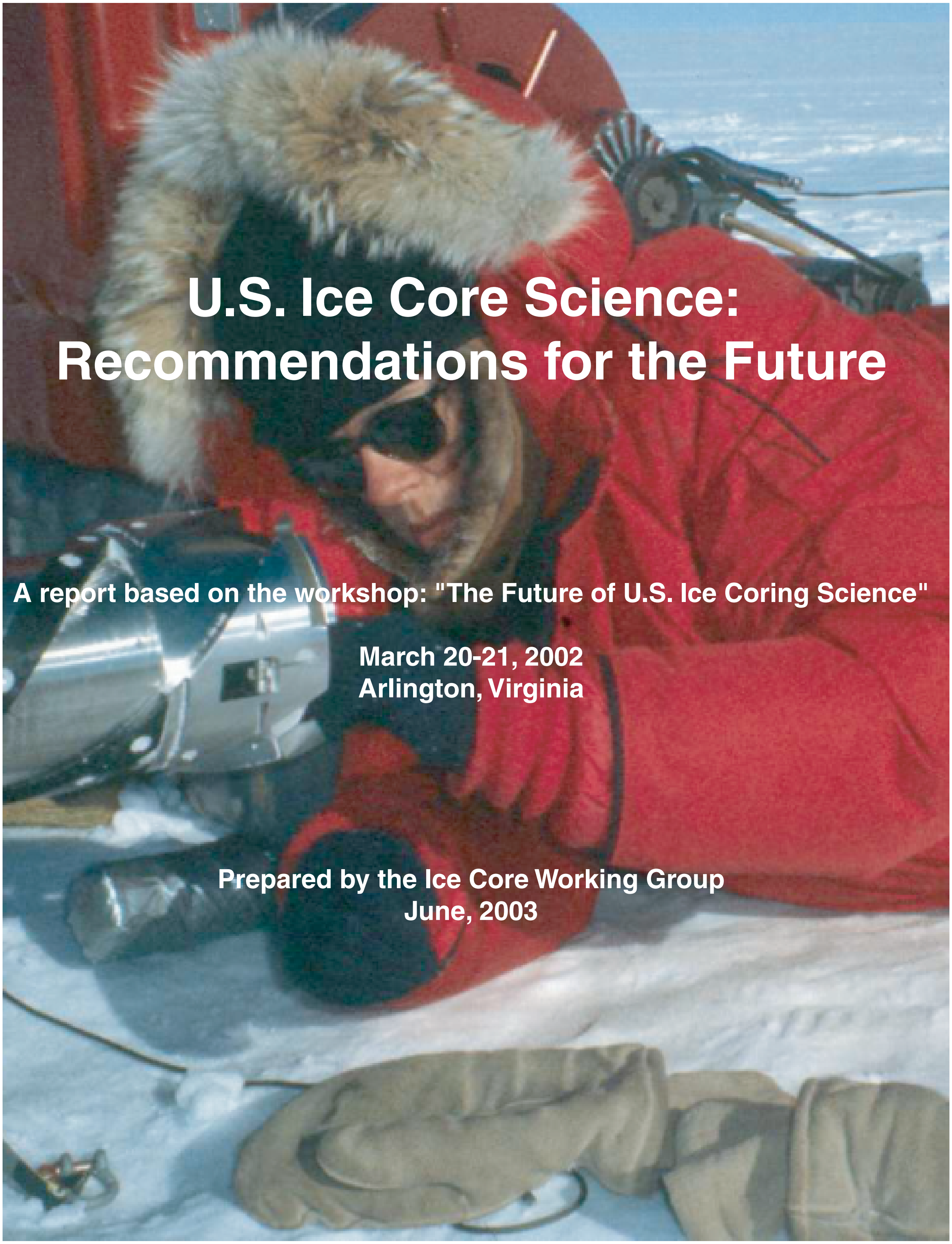

U.S. Ice Core Science: Recommendations for the Future

A report based on the workshop: "The Future of U.S. Ice Coring Science"

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Preface

This report is an outcome of the workshop, “The Future of U.S. Ice Coring Science,” held at the National Science Foundation on March 20-21, 2002, and hosted by the Ice Core Working Group and the NSF Office of Polar Programs. The workshop examined the progress of the U.S. Ice Coring Program since the 1986 National Academy Report, “Recommendations for a U.S. Deep Ice Coring Program,” and developed recommendations for future U.S. ice coring programs. This new report, “U.S. Ice Core Science: Recommendations for the Future,” extends the recommendations of the 1986 NAS report and charts a course for the next decade of ice-core research into global change and polar processes.

Acknowledgements

The March 20-21 Workshop, “Future of U.S. Ice Coring Science” was organized by the Ice Core Working Group and the National Ice Core Laboratory-Science Management Office (NICL-SMO), with assistance from the Office of Polar Programs at the National Science Foundation. The ICWG thanks NSF for hosting the meeting, all of the scientific and technical participants for attending and lending their expertise, and Mark Twickler for organizing it. ICWG would like to particularly acknowledge participants from outside the U.S. ice coring community for devoting their valuable time to this effort, including Wally Broecker (LDEO), Dorthe-Dahl Jensen (University of Copenhagen), Thomas Stocker (University of Berne), Eric Wolff (British Antarctic Survey), and Michael Mann (University of Virginia). ICWG also thanks Julie Palais, NSF Office of Polar Programs, for originally suggesting both this meeting and the review of the 1986 NAS report. Document layout was done by Kristi Donahue and editorial comment by Frank Smith. Cover photo by Kendrick Taylor.

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Executive Summary

Polar ice sheets and tropical ice caps are remarkable archives of climate and environmental change, preserving records of global, local, and regional significance on time scales of months to hundreds of thousands of years. Collecting and analyzing ice core records is a specialized science, requiring deep drilling operations in extreme conditions, careful sample handling, and painstaking data collection over literally miles of ice. Ice core data are influential in a wide variety of disciplines, underpin much of global change research, and continually provide observations that both inform and challenge our understanding of the global Earth system.

The U.S. scientific community has played an important role in ice core research since the first ice coring activities in the IGY. U.S. investigators contributed to the first deep ice cores collected in the late 1960s and participated in subsequent international projects, including the tripartite Russian, French, and U.S. collaboration on the Vostok ice core in East Antarctica and collaborative efforts of the GISP and GISP2 projects.

In 1986, the Polar Research Board of the National Academy of Sciences convened an ad hoc committee to examine U.S. efforts in ice coring. The committee report, "Recommendations for a U.S. Ice Coring Program", recommended a new program of U.S. ice coring. Subsequent projects initiated by U.S. investigators included the GISP2 project in Greenland, probably one of the most influential research projects of modern polar research, deep ice cores at Taylor Dome and Siple Dome in Antarctica, and the U.S. contributions to ITASE (International Trans Antarctic Scientific Expedition) and PARCA (Program for Arctic Regional Climate Assessment) in Greenland.

The scientific payoff from ice coring is significant. Rapid ice accumulation rates and the pristine nature of the ice matrix provide records of past environmental changes available from no other medium. Ice cores record the history of human impacts on greenhouse gases and other aspects of atmospheric chemistry, other atmospheric pollutants, and global temperatures. Ice cores also look further back to times prior to human impacts, providing highly detailed records of climate variations, atmospheric chemistry, and global change over time scales of up to 500,000 years or longer. Studies on both of these time scales provide fundamental data about how the Earth system works and with which to view human impacts. Studies of ice cores also make significant contributions to understanding the dynamics and history of polar ice sheets, including the response of ice sheets to climate change and impacts on sea level. Ice is an archive for trace constituents of all types, including micrometeorites, terrestrial dust, and a wide variety of biogenic compounds. And, polar ice also harbors unique in situ microbial communities, studies of which have just begun.

The future of ice coring science promises a significant increase in the amount of information we can extract from ice core records. Advances in analytical instrumentation for trace elements, isotopes, and biological compounds, in situ borehole logging, new drilling techniques, and a variety of other technical advances will contribute to a much more complete interpretation of ice core results. Investigators from new disciplines, for example the LExEn community, joining the established ice core science community will add to the tremendous payoff from ice coring. New records from critical locations can significantly increase our understanding of key aspects of climate and environmental change on all time scales.

The Ice Core Working Group, a committee of U.S. scientists that makes recommendations about ice coring projects and assists in administrating the National Ice Core Laboratory, met in March of 2002 at the National Science Foundation to discuss the progress of U.S. ice coring programs and future plans. This meeting considered scientific achievements as well as funding, logistical, and administrative issues related to U.S. ice coring programs.

The meeting and subsequent discussions led to the following recommendations for future U.S. U.S. ice coring activities.

1. Reinvigorate U.S. ice coring with a long-term integrated plan for future drilling projects to answer fundamental scientific questions. A draft science plan outlined in this document includes:
   a. A deep ice core in West Antarctica (the inland WAIS core) for high-resolution Antarctic climate studies.
   b. A deep ice core in north Greenland to recover an intact section of the last interglacial period to examine the stability of the Greenland Ice Sheet in warm climates and the dynamics and termination of interglacial climate.
   c. An array of intermediate depth ice cores in both hemispheres to capture climate variability and modes in both hemispheres.
   d. Deep ice cores in Antarctica to extend the ice core paleoclimate record to at least one million years.
   e. A spatial array of records that penetrate the last glacial maximum to examine Earth system history response to large changes in forcing.

2. Rebuild and maintain U.S. capability to collect shallow, intermediate, and deep ice cores in both hemispheres.
   a. Design and construction of a new deep ice coring drill.
   b. Design and construction of a new generation of drilling technology that is easy to deploy for shallow, intermediate, and deep drilling.

3. Support development of improvements in ice core analysis and scientific expertise.
   a. Enhancement of analytical techniques for trace elements and particles.
   b. Development of techniques for trace biogenic gases, and stable isotopic composition of trace biogenic gases.
   c. Development of techniques for small samples for all measurements.
   d. Development of rapid analytical techniques for high-resolution records of greenhouse gases, stable isotopes, greenhouse gas concentrations, and elemental and isotopic composition of major atmospheric gases.
   e. Development and improvement of borehole logging techniques for dust and a variety of other components.
   f. Development of reliable sample handling and laboratory techniques to characterize biological material (living and dead) in polar ice.
   g. Development of improved techniques for physical analysis of ice cores for paleoclimatic and ice-flow studies.

4. Upgrade polar logistics support.
   a. Upgrade logistics support to alleviate current delays in ice-coring projects in Antarctica by increasing aircraft support and over-ice transport.
   b. Maintain Air National Guard and other logistics support in Greenland.

5. Maintain, and expand the National Ice Core Laboratory facility.
   a. Support short-term expansion of storage capacity by implementing denser racking.
   b. Support long-term expansion of NICL freezer space and upgrade of mechanical equipment.

6. Support engineering developments in drilling, logging, and remote sensing that enhance ice core results.

7. Develop and support a stable cadre of drillers, core handlers, and engineers involved in ice coring, including evaluation and improvement of the current relationship between NSF, the scientific community, and the ice coring contractor, with the goal of improving the efficiency of contracted services and developing technology more rapidly.

8. Develop and implement a stable funding strategy for ice coring that maintains continuity of U.S. expertise in acquisition and interpretation of ice core records. This strategy needs to go beyond single campaign style projects to create a longer term commitment to ice coring, analogous to the long term commitment that supports ocean drilling and research ship operations. The ice coring scientific community should initiate this process by creating a long term science plan, then enter into discussions with funding agencies about how to implement this plan. An initial science plan is presented in this document.

Introduction

Cores through polar ice sheets and mountain ice caps provide records of past environmental conditions that are remarkable and unique due to their extremely high temporal resolution and the large number of environmental variables recorded in the ice. Ice core records of environmental change are cornerstones of global change research, providing data necessary for evaluating the behavior of the earth system and our impact on it. The relevance and significance of work on ice cores is underscored by both the pervasiveness of ice core data in the global change literature and the significant public and political attention these data garner. Ice is a truly unique archive, preserving ancient atmosphere, DNA, organisms, and meteorites, recording temperatures, atmospheric dust and aerosols, and human impacts on the environment in detail and scope unequaled by any other medium.

U.S. scientists and engineers have been involved in ice coring and ice core analysis since the International Geophysical Year (IGY) (1957-58), and the U.S. community has produced significant results, notably the highly influential data from the GISP2 project in the early 1990s. U.S ice coring programs have been sporadic, however, with long hiatuses, particularly in recovery and analysis of deep cores, but also in other aspects of the program. Recognizing this fact, the Polar Research Board prepared a report in 1986 entitled "Recommendations for a U.S. Ice Coring Program", which set the stage for a reinvigorated U.S. program, including the GISP2 project and following projects in Antarctica and Greenland. Sixteen years after that report, the Ice Core Working Group, a scientific committee proposed by the NAS report and supported since then by the National Science Foundation, held a meeting to evaluate progress and potential for future U.S. ice coring activities.

This meeting, held in Arlington, VA on March 20 and 21, 2002, outlined the significant achievements of the U.S. Ice Coring Program and identified important new questions, challenges, and opportunities for continued U.S. work on ice cores and related scientific issues. This follow-up report, prepared by the Ice Core Working Group, reaffirms the initial recommendations made by the 1986 NAS report, highlights achievements, challenges, and opportunities since 1986, and makes further recommendations about the future directions of U.S. ice coring science.

History of U.S. Ice Coring

Ice coring activities by U.S. scientists began in the International Geophysical Year (1957-58), and ice core drilling during IGY was primarily a U.S initiative. Early efforts used conventional oil-field technology. Cores of up to 535 m in length were collected in Greenland and Antarctica, but the methods employed were time consuming. Cable-suspended electromechanical drilling, which was more efficient, was developed at the Cold Regions Research and Engineering Laboratory (CRREL) in the 1960s, and today's deep ice coring drills use similar technology. The first of these drills was used in 1966 at Camp Century, Greenland, to collect the first deep ice core (1390 m). In 1968, the same equipment was used to collect the 2164 m Byrd ice core in Antarctica (Figures 1 and 2). Many of these projects were collaborations with European (primarily Danish) polar researchers.

Scientific results from these early cores were very influential, and fostered the development of modern analytical techniques now applied to ice core samples. Many of these cores, archived now for over 30 years, are still providing critical samples to current projects.

The U.S. deep drill was irretrievably stuck at the bottom of the Byrd borehole in 1969 and remains there today. A new electromechanical wire-line drill was designed at CRREL in the 1970s, but never constructed. Following this early period of successful drilling activity, U.S. leadership in deep ice core drilling waned, while Danish, French, Russian and Japanese groups constructed deep ice coring rigs subsequently used in Greenland and Antarctica to collect the Dye 3, Dome C, Vostok and Dome F cores. Meanwhile, U.S. efforts through the 1980s focused on lightweight coring systems for shallow- and intermediate-depth cores, and on a growing collaboration with French and Russian colleagues on retrieval and analysis of the deep Vostok core. Throughout this first generation period of ice coring. U.S. analytical capabilities developed significantly. By the 1980s there were approximately 40 active university and government research laboratories with capabilities in ice core analysis, and a number of important scientific contributions were made by these groups.

In 1986 an ad hoc Panel on Polar Ice Coring, convened by the Polar Research Board's Committee on Glaciology, examined the U.S. scientific capabilities in ice core drilling and analysis and published a report, "Recommendations for a U.S. Ice Coring Program" (ad hoc Panel on Polar Ice Coring, 1986). This panel recommended strengthening and expanding the scope of the U.S. Ice Coring program. Key recommendations included:

1. A commitment of at least 10 years to a program of ice coring and analysis.
2. Drilling and analyzing ice properties and climate parameters of deep, intermediate, and shallow cores in Antarctica and Greenland and at selected low latitude sites.
3. Careful planning of drilling programs to allow appropriate interpretation of ice core records, including collection of multiple cores from each site to allow appropriate interpretation of environmental variability inferred from ice core records.
4. Development and maintenance of state-of-the-art technology for ice coring.
5. Funding of a new U.S. ice coring program through the Office (then Division) of Polar Programs at NSF.
6. Creation of the Ice Core Working Group (ICWG) to provide recommendations to NSF about issues related to ice coring.
7. Management of funding to ensure long-term continuity of the program so that a capable personnel base would be developed and maintained.
8. Coordination of drilling efforts internationally.

This document, and subsequent planning documents from the then newly created ICWG, led to the successful GISP2 program in Greenland in the early 1990s, arguably one of the most influential research project ever undertaken by the U.S. polar community. Following the GISP2 success, two deep cores were collected in Antarctica, the first at Taylor Dome, near McMurdo Station in East Antarctica, and the second at Siple Dome in West Antarctica. The deep ice coring drill designed and constructed for the GISP2 project (5.2-inch drill) was also used at Taylor Dome and Siple Dome. These projects yielded, and continue to yield, important results, but problems with core quality linked to drilling problems limit the results from key sections of the cores. Siple Dome is the first of two cores in the WAISCORES project. Site selection for the second core (usually referred to as the "Inland Site" core) is underway now. This core would provide a very high-resolution record of the last interglacial-glacial cycle and is primarily directed at furthering our understanding of rapid climate change during the last ice age.

In addition to the U.S. deep ice coring projects, several programs have been supported to decipher shorter temporal records from ice cores over large spatial scales. In the Antarctic, the U.S. component of the International Trans-Antarctic Scientific Expedition (US-ITASE) is currently collecting an array of 200-year ice cores from West Antarctica with support from NSF. US-ITASE is a multidisciplinary project involving meteorology, remote sensing, ice coring, and surface glaciology and geophysics to help understand the significance of recent environmental change in West Antarctica.

In Greenland, the ongoing Program for Arctic Regional Climate Assessment (PARCA), with support from NASA, has collected a coordinated series of measurements aimed at assessing the mass balance of the ice sheet. Measurements include more than 80 widely distributed shallow and intermediate ice cores intended primarily to quantify the spatial and temporal variability in net accumulation (Bales et al., 2001; Lamorey et al., 2003). Repeat altimetry surveys show that higher elevations of the Greenland ice sheet are in overall balance (Krabill et al., 2000), with distinct regions of positive and negative mass balance largely explained by short-term variations in snow accumulation (McConnell et al., 2000). Ice core measurements show that temporal variability at annual to decadal time scales is high, particularly in southern Greenland (McConnell et al., 2001), so quantitative understanding of accumulation is critical to interpretation of repeat altimetry surveys. PARCA results show that the lower elevations are experiencing a significant loss of mass.

U.S. involvement in drilling and analyzing low- and mid-latitude glaciers has been restricted to a limited number of U.S. institutions collecting and analyzing cores with cooperation from the country involved. These studies provide extremely important insights into the behavior of the tropical and mid-latitude climate system, and provide important samples of a rapidly vanishing archive of paleoclimate information (Thompson et al., 1997, 2000, 2002; Kang et al., 2000).

The GISP2 and subsequent projects galvanized the U.S. scientific community, and there are now a number of laboratories in the U.S. actively working on ice samples. Expertise for all major measurements typically conducted on ice cores exists in the U.S., and the glacier geophysics community is well integrated in ice coring projects. There is legitimate concern in the community, however, that new investigators are not attracted to the field due to the intermittent nature of coring. This concern is important because there is also clear evidence of major potential for analytical advances that may revolutionize the information obtained from ice coring projects. Some of these potential advances are described further below.

Another milestone in U.S. ice coring was establishment of the National Ice Core Laboratory (NICL) in Denver, Colorado, in 1993, operated jointly by NSF and the U.S. Geological Survey. NICL provides space for long-term archival storage and processing of ice cores, as well as laboratory space for examining cores. NICL actively curates the U.S. ice core sample collection and maintains excellent relationships with the scientific community. After its construction, NICL quickly became an important resource for the scientific community, and it remains an exemplary facility. Maintenance of NICL operations and curation functions in the future is vitally important to the national and international scientific community.

Since its formation in 1986, the ICWG has been active in a variety of roles. ICWG is active in planning U.S. ice coring activities, reviews and makes recommendations on requests for ice core samples, and makes recommendations about operations of the National Ice Core Laboratory. Several past ICWG reports and other planning documents have guided the U.S. program, including:

- "U.S. Ice Core Research Capabilities," 1988 (http://nicl-smo.unh.edu/documents/1988/index.html).
- "U.S. Global Ice Core Research Program, West Antarctica and Beyond," 1989 (http://nicl-smo.unh.edu/documents/1989/index.html).
- "Science plan for WAISCORES Deep Ice Coring in West Antarctica," 1991 (http://nicl-smo.unh.edu/documents/1991/index.html).
- "Ice Core Contributions to Global Change Research," 1998 (http://nicl-smo.unh.edu/documents/1998/index.html).
- "Final Proposal for Preparations for the Inland WAISCORES," 2002 (http://waiscores.dri.edu/DeepDrillingPreparations.pdf).

Of the major projects recommended and endorsed by ICWG, the inland WAIS core remains to be completed. Because the current deep drilling system is not functional and has had serious operational problems in its last two deployments, a new deep drill system has been recommended by NSF's ice coring contractor (Ic eCore Drilling Services (ICDS), University of Wisconsin), and design options are under review.

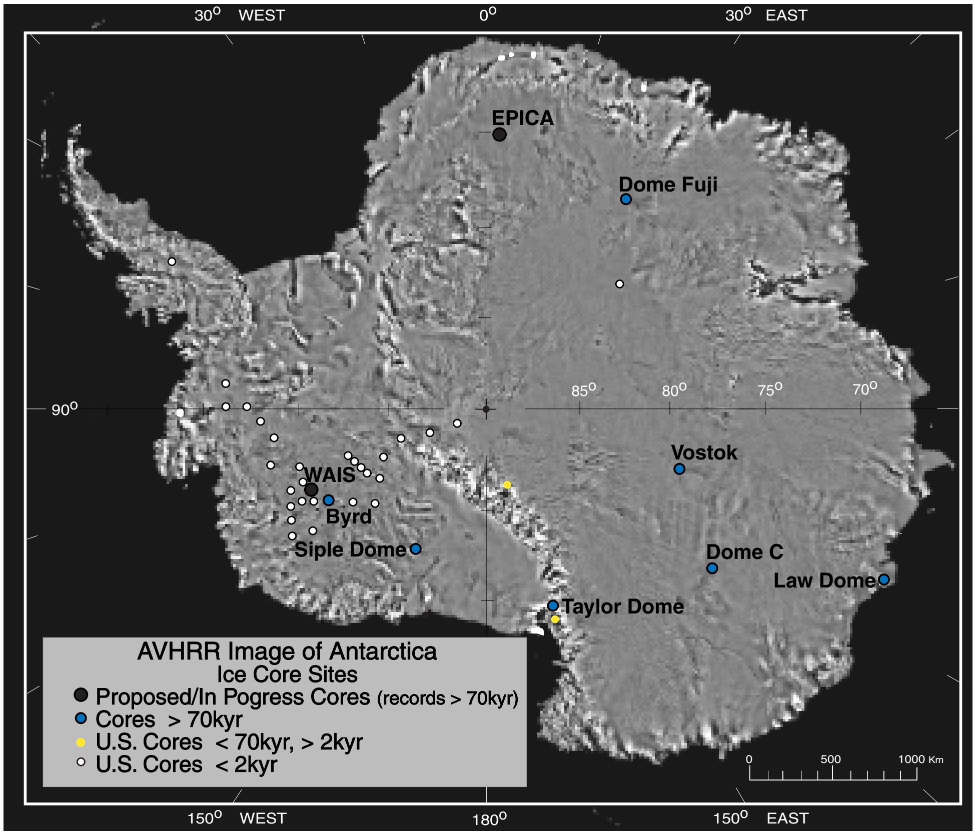

Figure 1. Locations of major ice coring projects in Antarctica.

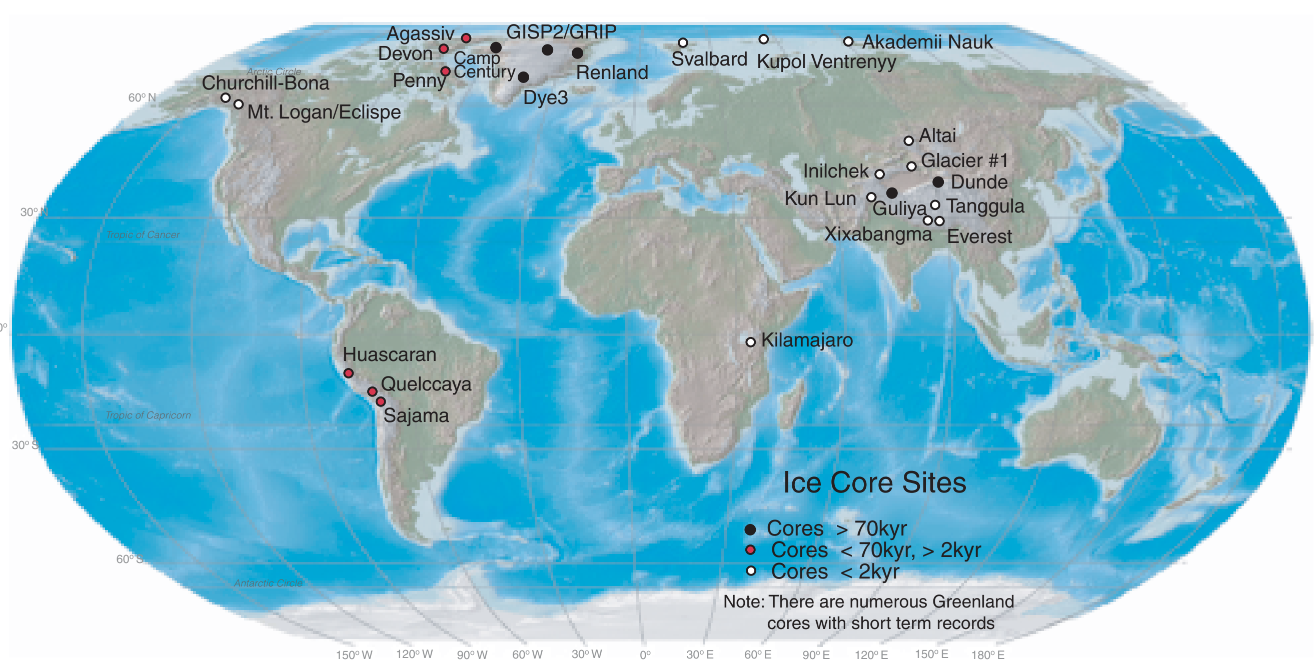

Figure 2. Locations of major ice coring projects outside Antarctica.

Review of Major Scientific Accomplishments, New Questions and New Directions

Studies of polar ice cores over the last 16 years have yielded remarkable results relevant to an impressive range of global and regional scientific problems and have clearly influenced the way we look at global environmental change on many time scales. The major ice coring projects undertaken by the U.S. community over the last 16 years also catalyzed development of important laboratory capabilities, introduced a number of successful new investigators into fields that take advantage of ice core samples and data, and moved the U.S. from being a minor and sporadic player in this field to being a major component of international efforts to understand the earth system. Below we describe major accomplishments of ice coring science, and major unanswered and new questions addressable with continued research. This discussion is divided into five broad categories: climate change and dynamics, history of the atmosphere, ice sheets sea level and glaciology, i life in extreme environments, and other directions and opportunities. There is a great deal of synergy among these topics. This synergy and integration of investigators from diverse disciplines is one of the hallmarks of U.S. and international ice core research.

Climate Change and Dynamics

Ice-core science is central in our understanding of the earth's climate system. By documenting the patterns of climate change that have occurred through unequalled, high-time-resolution, multi-parameter records, ice cores show what climate changes are possible, and why and how climate changes have happened.

Accomplishments

Ice-core records are proving valuable in understanding ice-age cycles, abrupt climate changes, modes of variation of the Holocene climate, and more. The accomplishments to date point to greater discoveries to come.

For ice-age cycles, synchronized ice-core records from north and south polar regions (Blunier and Brook, 2001) confirm the global nature of glacial cooling. Timing of events is tied to features of Earth's orbit that redistribute solar energy, despite the hemispherically distinct character of that forcing. The remarkable result, that southern temperatures have depended more on northern than on southern sunshine (Lorius et al., 1990), is explainable through the modeled effects of atmospheric carbon-dioxide changes (see below) (e.g., Pollard and Thompson, 1997). These carbon-dioxide changes, which are reconstructed from ice cores, have followed northern rather than southern sunshine, for reasons that are not fully explained (e.g., Broecker, 1995). This demonstration of the effects of carbon dioxide on climate over large areas and long times is of considerable importance in assessing future climate changes as humans increase the atmospheric concentration of carbon dioxide.

Whereas long-term, large-region temperature changes have followed carbon-dioxide concentrations closely, changes in smaller regions or over shorter times have been much more complex. The realization that the earth system contains switches, which repeatedly have caused large, rapid, widespread, nearly synchronous changes, is one of the great discoveries of climate science, and rests in large part on ice-core data (e.g., NRC, 2002). Certainly, hints of abrupt climate change were present in paleoclimatic records of many types, and in results from simple models of the climate system, but strong conclusions were prevented by the necessary simplifications of the models and the limited time resolution and other problems with the proxy records.

This changed when long ice-core records were recovered from central Greenland. Because (as discussed below) the ice cores collected accurate indications of local climate (e.g., temperature, snow accumulation; Cuffey and Clow, 1997), regional climate (e.g., wind-blown sea salt (Mayewski et al., 1994), dust with characteristics that allow identification of sources from beyond the ice sheet (Biscaye et al., 1997), and broader conditions (e.g., methane from globally distributed wetlands including in the tropics; Brook et al., 1996), all on the same time scale and with subannual to few-annual resolution, the cores could unambiguously demonstrate that decadal jumps of 1/3 to

1/2 the entire difference between ice-age and modern conditions occurred repeatedly across much of the planet, with centuries of persistence in the new climate state before jumping back (Figure 3). These jumps were of remarkable size-roughly $10^{\circ}C$ in Greenland (Severinghaus et al., 1998). Furthermore, they happened rapidly-decadal to as little as a single year (Alley et al., 1993). Such jumps pose fundamental questions for climate science, and for human responses to climate change.

The clear ice-core demonstration that abrupt climate changes had affected much of the globe then allowed correlation to proxy records from other regions, more accurately than was possible using the independent dating of those records. The "Greenland" cold-dry-windy anomaly pattern was quickly found in widespread regions, from coastal Venezuela to the Arabian Sea, and from African lakes to the California borderlands (e.g., Alley and Clark, 1999). The only major deviation was that Antarctic ice cores record an approximately antiphased behavior, warm when Greenland was cold, and that some other non-ice records from high southern latitudes probably have this same "see-saw" relation to the rest of the planet (e.g., Blunier and Brook, 2001; Alley and Clark, 1999). The see-saw behavior, and the occurrence of some of the abrupt coolings just after strong freshwater input to the North Atlantic, are consistent with models of causation or amplification of abrupt changes through shifts in the oceanic circulation in the North Atlantic (Broecker, 1995). Importantly, freshening of the North Atlantic is linked to abrupt climate change during warm as well as cold times (Alley et al., 1997).

Ice cores provide additional information on causation of abrupt and gradual climate change. Solar and magnetic-field fluctuations are archived in ^{10}Be (Finkel and Nishiizumi, 1997). As discussed in the next section, variations in solar irradiance appear to affect climate (Stuiver et al., 1995; Bond et al., 2001). So far, however, known geomagnetic-field anomalies have not been shown to be associated with climatic anomalies. Meteoritic debris also is archived in ice (e.g., Brook et al., 2000), and thus far the lack of signals at times of abrupt climate change leaves causation within the earth system.

Within the Holocene warm period of the last ~10,000 years and perhaps earlier, modes of variability of the earth system, such as the El Nino/Southern Oscillation (ENSO) and the northern and southern annular modes, have been important for climate changes on interannual to interdecadal time scales. Ice-core data clearly record these oscillations (Barlow et al., 1993; Kreutz et al., 2000).

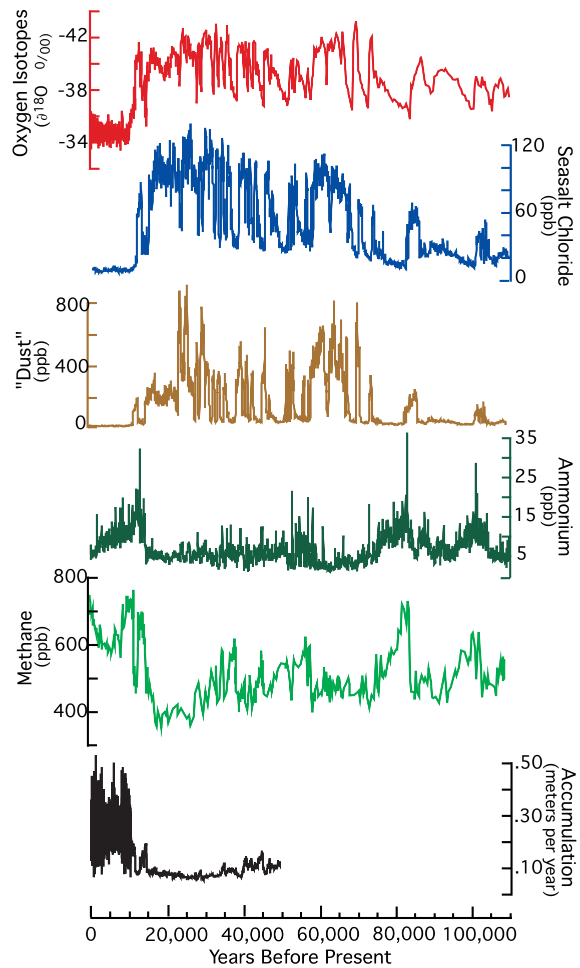

Figure 3. Climate records from GISP2. Oxygen isotope (Stuiver et at., 1995), chemical (Mayewski et al., 1997), methane (Brook et al., 1996) and accumulation records (Cuffey and Clow, 1997) from GISP2 ice core. These represent changes in temperature (oxygen isotopes), sea storminess (excess chloride), aridity (dust), biogenic activity (ammonium), precipitation and temperatures in weland areas (methane) and precipitation on the ice sheet (accumulation).

Future Questions

Despite such impressive results, this glass is clearly only half-full. Far from being a mature science, ice-core research has barely started. Improved analyses of existing cores, and collection of new cores to answer specific questions, will greatly improve understanding of many important problems.

For study of the last ice-age cycle and its abrupt climate changes, only the central Greenland cores (and the ongoing north-central NGRIP analyses) combine high time resolution (subannual to few-annual) and modern multi-parameter climate reconstructions. The highest time-resolution record from the southern hemisphere is not as well resolved as for central Greenland, and the 1968 collection date of that Byrd Station ice core means that it was not analyzed using modern techniques, and that consumption of ice during prior analyses and changes in the ice during storage preclude modern work.

A southern core of comparable "quality" to those from Greenland would improve knowledge of the spatial pattern of abrupt and gradual climate changes, their size, and the details of their phasing; improve estimates of changes in interhemispheric gradients of atmospheric composition (particularly methane); and show more clearly how carbon-dioxide concentrations changed with the abrupt climate jumps. These improved estimates in turn would greatly increase our understanding of causes and consequences of abrupt climate changes, and contribute to our understanding of ice-age cycles.

The flow of ice sheets and glaciers means that the ideal core to answer questions about abrupt climate changes of the ice-age cycle is not the best core to study either Holocene events or events from before the last ice age. Sites that reveal Holocene modes of variability clearly owing to especially high accumulation rate will have ice-age ice buried close to the bed after strong layer thinning, and so are not ideal for study of ice-age events. The optimal accumulation rate and thickness for study of ice-age events in turn produce too much layer thinning to study older events such as northern variability during the previous interglacial or the onset of long duration ice ages about 750,000 years ago. Learning more about the onset of these ice ages, variability during the previous interglacial when northern temperatures were slightly warmer than recently, or the time-evolution of modes of climatic variability will require targeted cores in the north, south, and in mountainous regions.

Biological changes are recorded in ice cores by indicators such as pollen, leaf waxes, spores, cells, and concentrations and isotopic ratios of biologically important gases. Fundamental analytical breakthroughs are now allowing rapid and accurate analysis of such materials at the low concentrations preserved in ice cores. Ice cores thus offer the promise of learning the biological response to the reconstructed climate changes on a common time scale and with high time resolution. Available results to date indicate that the changes in climate have had fundamental impacts on ecosystems. Additional study of these relations is almost certain to provide important insights of broad interest.

Volcanic signals (Zielinski et al., 1994) are quite clear in the ice in acidic fallout, in its electrical signal (Taylor et al., 1993), and in directly identified ash. The relation between large eruptions and short-lived, small cooling is clear (Stuiver et al., 1995). Various authors have suggested that volcanism correlates with rapid climate change. Some models have volcanic eruptions changing climate; others have climate change stimulating eruptions. Recent optical logging evidence, in which the timing of volcanic ash layers in the Siple Dome core is compared with the timing of abrupt changes in dust concentration in the GISP2 core, highlight the potential of future ice cores from both polar regions to track this correlation much further back in time.

More, and higher time resolution, analyses of volcanic and terrestrial dusts, cosmogenic materials, and ice-core chemicals will similarly provide important insights into solar, volcanic, extraterrestrial, and soluble and insoluble aerosol influences on climate. Because many tracers of climate processes are spatially restricted, including dust plumes, the coarse fallout of volcanic eruptions, and many wind-blown biological materials, cores from widespread sites will provide additional insights.

History of the Composition of the Atmosphere

Accomplishments

Accumulation of polar snow and its metamorphism to ice traps small samples of the atmosphere, providing a truly unique and direct record of changes in the composition of the atmosphere. These records are extraordinarily important for understanding natural controls and human impacts on greenhouse gases, biogeochemical processes and changes in source regions. Major contributions include records of greenhouse and anthropogenic gases since the industrial revolution; long records showing how the atmosphere changed with orbital cycles that modify climate on time scales of 10s to 100s of thousands of years; and records revealing the role and response of the atmosphere in abrupt climate change during the last ice age.

Gas measurements in ice cores were pioneered by research groups in France, Switzerland and the U.S. in the late 1970s and 1980s. Studies of major gases (O_2, N_2, Ar) and their isotopes, and measurements of firn air composition, were developed in the late 1980s and early 1990s, especially in Switzerland, France, and the U.S. There are currently 5-6 U.S. labs active in various aspects of ice core gas research. Internationally, there are groups in Bern, Grenoble, Australia, and Japan, and developing programs in China.

The detailed anthropogenic history of the atmosphere is recorded by high-accumulation-rate ice cores in Greenland and Antarctica, and within the firn, the porous snowpack at the surface of the polar ice sheet. Ice core studies reconstruct atmospheric composition prior to the commencement of direct measurements (Figure 4) and convincingly demonstrate that the main greenhouse gases (CO_2, CH_4, and N_2O) increased from the early 19th century to today, in a regular rise clearly attributable to human activities. Recent work illustrates these trends in great detail (Etheridge et al., 1992; 1996; 1998; Machida et al., 1995). Isotopic studies of these gases help to identify details about sources of the concentration increase (Friedli et al., 1986; Sowers et al., 2002). Long ice core records show that modern levels of these three greenhouse gases are highly anomalous in the recent geological record. Current levels of CO_2 (~365 ppm) CH_4 (~1800 ppb) and N_2O (~315 ppb) exceed the highest levels observed in preanthropogenic ice core records by ~85 ppm for CO_2, ~1000 ppb for CH_4, and ~45 ppb for N_2O.

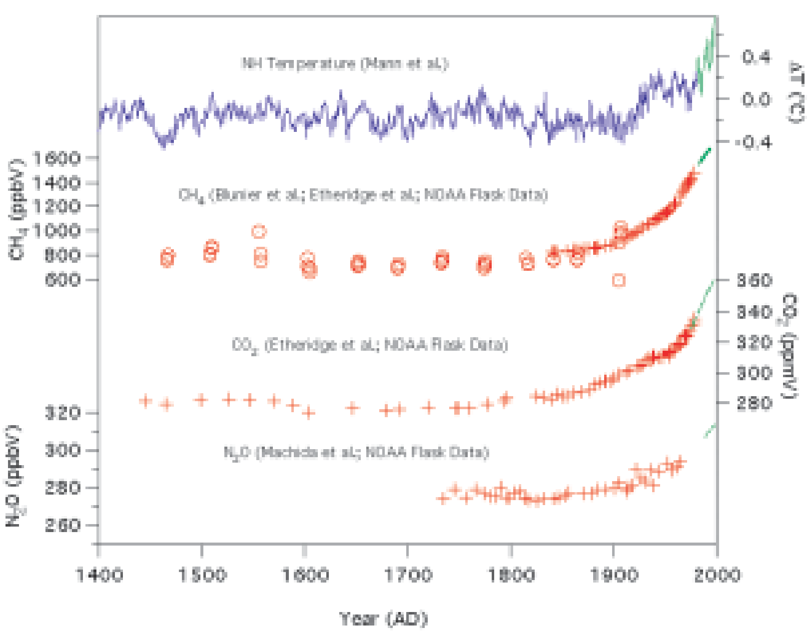

Figure 4. Anthropogenic trends in the major greenhouse gases from ice cores (red) and direct measurements (green), and Northern Hemishphere Temperature reconstruction (blue) and direct mesurements (red). Temperature data from Mann et al. (1999), ice core methane data from Etheridge et al (1993), ice core CO_2 data from Etheridge et al. (1996), ice core N_2O data from Machida et al. (1995). Direct atmospheric gas measurments from NOAA/CMDL (http://www.cmdl.noaa.gov/)

Firn air pumping provides much larger samples of air than are available from ice cores, a trade-off of sample size for a decreased temporal resolution due to air mixing in the firn, and a practical limit of about 100 years of record. Recent firn air studies reconstruct changes in atmospheric oxygen (Bender et al., 1994a; Battle et al., 1996) due to fossil fuel burning, which provides important constraints on oceanic and terrestrial uptake of carbon dioxide. Other studies demonstrate changes in halocarbons and other trace gases (Butler et al., 1999; Sturges et al., 2001a,b) and the stable isotopic composition of methane (Francey et al., 1999; Braunlich, 2001) and N_2O (Sowers et al., 2002). These trends allow us to distinguish human from natural influences on the budgets of these compounds, discriminate among possible sources, and provide a context within which to view future changes.

Studies of atmospheric gases from ice cores spanning the last several hundred thousand years demonstrate the role of the atmosphere in orbital-scale climate change. Records of CO_2 and CH_4 show that major glacial-interglacial cycles are accompanied by changes in these greenhouse gases, with lower levels during glacial periods and higher levels during interglacials (Figure 5; Petit et al., 1999). Greenhouse gas changes are an important part of these orbital cycles; roughly half of the global climate change during an orbital cycle is attributable to them (Raynaud, et al., 1993).

CO_2 changes are thought to be due to changes primarily in the oceanic carbon cycle and partially in the terrestrial carbon cycles, although a universal theory to explain them has not evolved (Sigman and Boyle, 2000). Methane variations are normally attributed to changes in emissions from terrestrial wetlands due to anaerobic bacterial activity (Chappellaz et al., 1990), although this hypothesis has been questioned (Kennet et al., 2002). Less is known about variations in the third most important greenhouse gas, N_2O, but existing records suggest lower values during glacial periods and higher levels during interglacials (Fluckiger et al., 1999; Sowers, 2001).

The timing of climate and CO_2 change has been a major research topic, with most studies suggesting that glacial-interglacial CO_2 and climate change are essentially synchronous, or that CO_2 change lags Antarctic temperature change by several hundred years (Fischer et al., 1999). This conclusion does not diminish the significance of CO_2 in greenhouse forcing; rather, it demonstrated the role of the carbon

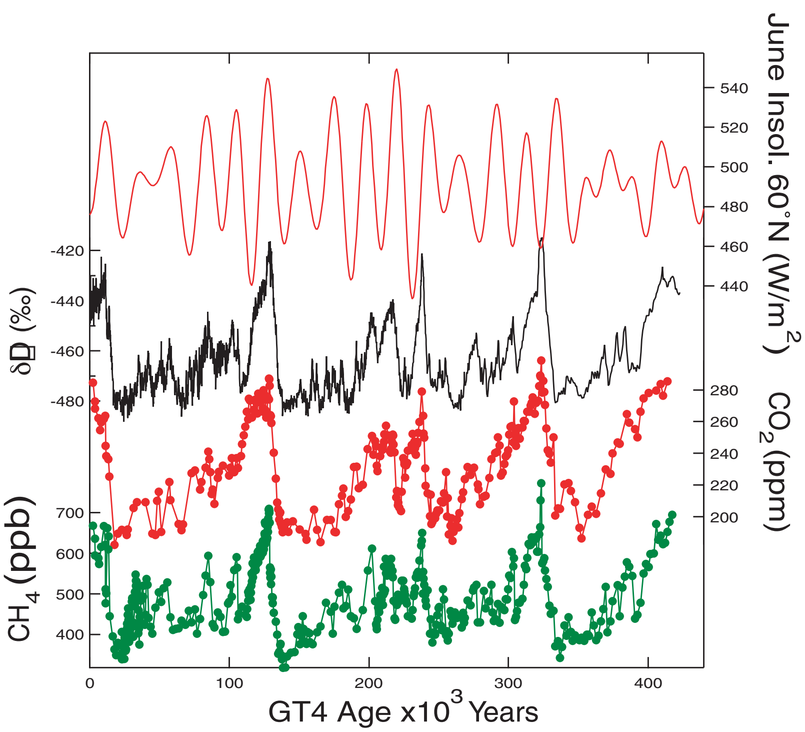

Figure 5. Orbital-scale climate records from the Vostok ice core. CH_4, CO_2, and ∂D from Petit et al. (1999), insolation from Berger and Loutre (1991). GT4 time scale for Vostok from Petit et al.

cycle in amplifying orbital-scale warming trends. Polar asynchrony in climate change at glacial terminations makes it difficult, or perhaps improper, to generalize this conclusion to global glacial-interglacial change. For example, during the last glacial-interglacial transition, the step-warming in Greenland at the Bolling onset lagged the major CO_2 change by several thousand years, although slow warming in Greenland began prior to the major CO_2 change (Alley et al., 2002). Methane variations seem to follow Greenland temperature changes very closely, and although orbital cycles are apparent (Petit et al., 1999) much of the methane record is one of millennial-scale change (Brook et al., 1996; see below). N_2O records are much sparser, but to the extent that a pattern has been identified, it appears to be like that of methane (Sowers, 2001).

Millennial-scale abrupt climate change has been a major focus of the ice core community in the last decade, and there are important atmospheric gas variations on this time scale. Millennial fluctuations in atmospheric methane are now well known (Chappellaz et al., 1993; Brook et al., 1996). Methane increased fairly rapidly, over 1-2 centuries, at the onset of most Dansgaard-Oeschger (D-O) events and appears to slightly lag temperature change (Severinghaus et al., 1998; Severinghaus and Brook, 1999). These methane variations are among a growing body of evidence that the D-O events were widespread phenomena (methane sources are broadly distributed in the northern hemisphere and tropics). Recent high-resolution CO_2 records also show changes on millennial time scales, although these follow a different pattern than methane. During the last deglaciation, rising CO_2 levels were interrupted during the Bølling-Allerod warm period in Greenland, and the onset of the cold Younger Dryas period in Greenland was associated with a resumption of the CO_2 increase (Monnin et al., 2001). These CO_2 changes are similar in timing and sign to Antarctic temperature changes (Figure 6), but the significance of the correspondence with Antarctic or Greenland temperature changes is thus far not clear. On these millennial time scales, the direct radiative effects of changes in CO_2, CH_4 and N_2O were not large enough to have caused major climate changes.

The stable isotopic composition of trace biogenic gases is an important new area of research. Carbon isotopes in CO_2 and CH_4 in ice samples have been measured by several groups (Friedli et al., 1986; Indermühle et al., 1998; Smith et al., 1999; T. Sowers, unpublished). Improvements in analytical precision and sample throughput are still necessary, but these studies are important because they will ultimately help constrain sources and sinks of these gases. Measurements of stable isotopes in N_2O are also possible and provide similar information about that gas (Sowers et al., 2001, 2002)

In addition to the startling discoveries about past changes in greenhouse gases and other bioactive gases, important results have emerged from studies of the major components of air and the noble gases. The isotopic composition $\partial^{18}O$ of oxygen in ice core air is a tracer of the oceanic isotopic composition and provides a way of dating ice cores by correlating with the marine isotope record of sea water oxygen isotopes (Bender et al., 1994b). The $\partial^{17}O$ of oxygen is a new tracer of oceanic productivity that shows significant promise (Luz et al., 1999; Blunier et al., 2002). Stable nitrogen and argon isotopes provide a way to precisely identify the timing of warming, cooling, and accumulation rate changes through the effects of thermal and gravitational fractionation on these species that are preserved in the ice core record (Severinghaus et al., 1998; Severinghaus and Brook, 1999). Studies of elemental ratios of N, O, Ar, and other noble gases provide constraints on gas trapping at the firn/ice transition and the subsequent integrity of the air archive (Bender et al., 1995; Severinghaus et al., 2003).

While the trapped air in glacial ice provides a unique archive of past atmospheres, the snow and ice matrix can also preserve information relevant to the chemical composition of the atmosphere. Analysis of the chemical composition of glacial ice was pioneered in the early 1970s by American and European investigators. Over the past 30 years, with the past decade being the most productive, the chemical analysis of glacier snow and ice has provided significant insight into the relationship between climate change and the atmospheric concentrations of a broad range of chemical species.

Snow forms generally by the condensation of water vapor on an aerosol nuclei. As the snow falls through the atmosphere it scavenges other particles and gaseous compounds and is deposited on the glacier or ice sheet surface. During times of no precipitation, particles and gaseous compounds are also deposited on or interact with the snow surface. Although recent studies have shown that a few of these compounds can be altered after deposition (Domine and Shepson, 2002), the majority of the compounds in snow are quantitatively preserved and subsequently buried, producing a faithful chemical record. Theoretical predictions have suggested that wind-induced interstitial ventilation at the near-surface could affect the aerosol record at low accumulation sites (Cunningham and Waddington, 1993), and modeling and field measurements confirm the existence of ventilation in the near-surface firn (Albert et al., 2000, Albert and Shultz, 2002). Investigations of air-snow transport dynamics on specific chemical signatures in ice core records are in early stages. However, studies in this area have already led to the realization that chemical interactions in the near-surface snow play a large role in tropospheric chemistry, and this is causing a major shift in analysis and modeling in the field of atmospheric chemistry over snow-covered areas (Atmos. Environ., 2002).

Initial scans of ice cores using electrical measurements provides a record of the overall chemistry of the core. Direct current (ECM) and alternating current (DEP) techniques measure the bulk anion and cation composition. These initial measurements of ice cores provide a "roadmap" for investigators to quickly identify signal areas of volcanics, biomass burning, rapid climate changes (Taylor et al., 1993, 1996, 1997). The high resolution (millimeters) of the measurements provide a method for counting annual layers and determining age-depth relationships (Meese et al., 1997)

A number of ice cores provide important records of increased atmospheric pollutants since the industrial revolution. Researchers analyzing ice cores have revealed not only the increase in greenhouse gas concentrations mentioned above, but also changes in a variety of chemical compounds far from pollutant sources. Several studies on the Greenland Ice Sheet during the 1980s documented increases of sulfate and nitrate since the early 19th century as a result of coal

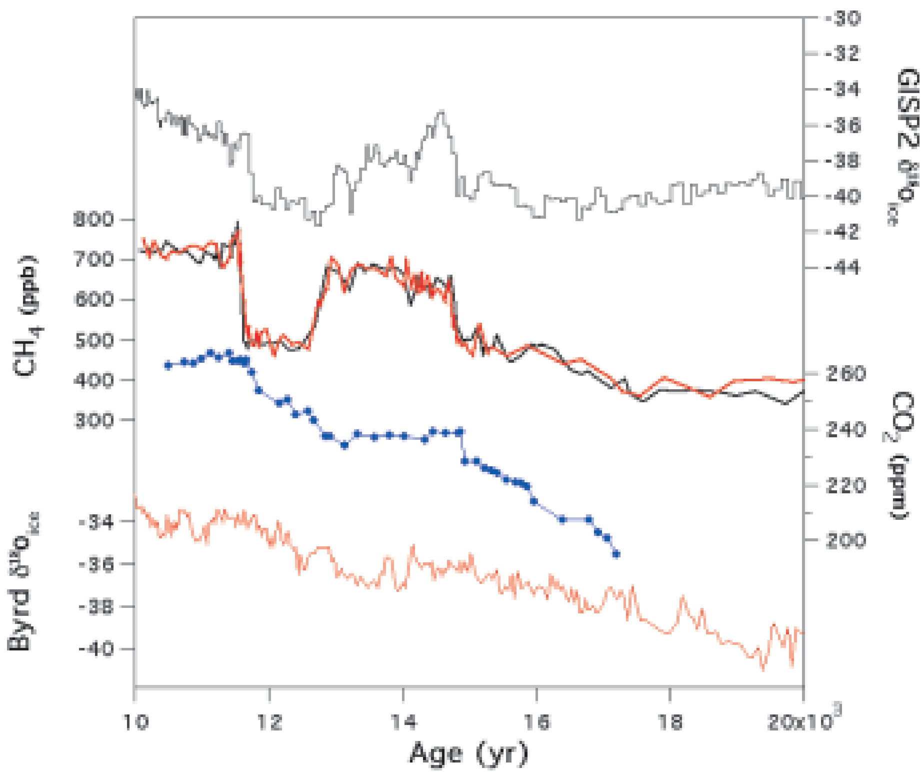

Figure 6. Greenhouse gas and temperature trends across the last glacial-interglacial transition. GISP2 (Greenland) isotope data from Grootes et al. (1993), GISP2 methane data from Brook et al. (2000) (red) and GRIP methane data from Chappellaz et al. (1993, 1997) (black). Siple Dome CO_2 data from Monnin et al. (2001). Byrd isotope chronologyfrom Blunier et al. (1998).

and oil consumption (Neftel et al., 1985; Mayewski et al., 1986). Measurements of heavy metals such as lead and cadmium also show increases during this period (Boutron et al., 1994). Remarkably, many of these anthropogentic species have decreased during the recent decades due to government regulations at the source locations (Boutron et al., 1991; McConnell et al., 2002b).

Polar ice cores are perhaps the best source of the paleovolcanic records that are utilized in the investigation of climate-volcanism connections. Detailed chemical analysis of ice core samples detects sulfate deposits from large explosive volcanic eruptions capable of impacting hemispheric and global climate (Hammer, 1977; Delmas et al., 1985; Zielinski et al., 1996). Deep Greenland ice cores have provided paleovolcanic histories reaching back into the last ice age (Zielinski, 1995; Clausen et al., 1997) and recent results from Antarctica ice cores have extended volcanic records from Antarctica beyond the last millennium (Cole-Dai et al., 2000). On-going and future deep coring projects in Antarctica will undoubtedly yield sulfate-based volcanic records comparable in length and detail to those from the deep Greenland cores.

Long term ice chemistry records have provided important insights into the climate system. Mayewski et al. (1997) used empirical orthogonal function (EOF) analysis on the major ion chemistry time series from GISP2 to develop the Polar Circulation Index (PCI). The PCI measures the relative size and intensity of polar atmospheric circulation. Spectral analysis of the PCI showed direct relationships with the Milankovitch orbital periodicities as well as several other higher frequency periodicities previously noted in climate records.

Ice cores contain information about the aerosol loading of the paleoatmosphere with mineral dust, seasalt, and biogenic sulfates. Aerosol radiative effects include both the direct interaction of particles with solar and terrestrial radiation, and indirect effects by which aerosols modify cloud distributions and radiative properties. Aerosols are a significant component of Earth's current radiation budget (IPCC) and may have played an even larger role during glacial conditions, when the atmospheric burdens of mineral aerosol and seasalt were considerably higher than today. Model simulations of glacial conditions imply significant radiative forcing from mineral dust, and it has been suggested that dust-induced warming may have contributed to the triggering of abrupt climate shifts (Overpeck et al., 1996; Claquin et al., 2003).

Ice core records have also focused attention on the potential role of biogenic sulfate aerosols in climate regulation. The Vostok ice core methanesulfonate record indicates high glacial levels of biogenic sulfate aerosols, leading to speculation that fertilization of the glacial ocean by mineral dust resulted in elevated emissions of dimethylsulfide (DMS) from iron-limited regions of the ocean (Legrand et al., 1991). DMS is the precursor for atmospheric sulfate aerosols, which increase planetary albedo through direct and indirect radiative effects. In contrast to the Vostok record, Greenland ice core records from Renland and Summit do not exhibit a glacial maximum in biogenic sulfate (Hansson and Saltzman, 1993; Legrand et al., 1997; Saltzman et al., 1997). The dramatic difference between the Vostok and Greenland ice core records may reflect differences in the way different oceanic ecosystems responded to changes in dust input and circulation (Moore et al., 2002).

Ice core paleoclimate records have been compared with meteorological/climatological data to evaluate and identify the physical links controlling the glaciochemical climate signals preserved in ice cores. Our confidence in the climate records derived from ice cores has been improved through comparison of ice core records with instrumental data such as meteorological (temperature, precipitation, sea-level pressure), atmospheric chemistry (soluble aerosols, stable isotopes, trace gases), and satellite data. The relationship between ice core major ion chemistry and atmospheric circulation has been investigated for Himalayan ice cores from the Xixabangma and Mt. Everest regions (Kang et al., 2000; Wake et al., 2001). Ice core records have been calibrated to atmospheric variables such as sea-level pressure, and in particular the Amundsen Low (e.g., Kreutz et al., 2000), the Siberian High (Wake et al., 2003) and the North Atlantic Oscillation (Barlow et al., 1993; Appenzeller et al., 1998). Efforts have also been made to link observed changes in sea ice extent with sea-salt deposition on ice caps (Grumet et al., 2001) and to document the timing of sea-salt deposition using major ion profiles in snowpits combined with measured snow accumulation data (Grumet et al., 1998). Analyses of soluble ions in aerosols have been compared with soluble ion concentrations in precipitation in Greenland (e.g., Dibb et al., 1994; Jaffrezo et al., 1994) and in the Himalaya (Shrestha et al., 1997, 2002). Interpretation of ice core records has benefited by the establishment and continued operation of automatic weather stations in remote regions.

Future Questions

Despite the many acknowledged successes, major questions about changes in atmospheric composition on all time scales remain to be answered. The sources and sinks of trace gases are not well understood. There are a large number of important atmospheric species not yet measured in ice due to technical challenges. The response of the biosphere and biogenic gases to climate change, and what governs that response, is not well understood. And, the possible impact of microbial activity on the trace gas record is an emerging question. All of these questions have more than academic significance. Understanding future human impacts on the atmosphere depends on understanding how greenhouse and bioactive gases respond to climate change. The past record is our window into these processes.

Existing work on major greenhouse gases shows that there are several time scales of variability (orbital, millennial, centennial). These variations were due to natural changes in sources but are not captured well for all times or all gasses. One major goal should be to record concentration variations of CO_2, CH_4, and N_2O at high resolution (at least 100 years) over the longest record possible (at least 500,000 years, and hopefully longer). Doing so will require advances in sample handling and analysis to increase throughput, as well as obtaining the long records to analyze, but is completely feasible. Such records would expose the full spectrum of greenhouse gas variability and provide important constraints for models and mechanisms that explain natural greenhouse gas cycles. A recent high quality record of CO_2 from the Dome C ice core from the Bern group (Monnin et al., 2001) illustrates the point. With very high resolution data they showed that CO_2 variations during the last deglaciation closely followed millennial scale trends in Antarctic climate, and are antiposed with millennial trends in Greenland. This new observation is difficult to explain, but is promoting new work on understanding the carbon cycle on this time scale. It is feasible to have records of this quality on all time scales over which ice cores have been collected.

As discussed above, measurement of the isotopic composition of greenhouse gases in ice cores, although still in its infancy, will provide important additional constraints on sources and sinks. Development of techniques that make these measurements routine-so that isotopic measurements are made on the same resolution as concentration measurements-is an important goal for the trace gas community.

The timing of climate change and changes in greenhouse gases is a major issue, both in terms of the greenhouse-climate link and in the use of gas variations as correlation tools for ice core chronology. One limitation on timing is that air is trapped at depth in the firn, causing an age difference between gas and ice. This difference, which must be known to establish greenhouse gas-climate links, is generally not known to better than 100 years except in the Holocene or at sites with very high accumulation rates (Morgan et al., 2002). Further work on understanding the densification process in polar firn, expansion of isotopic and other measurements of major and noble gases that are sensitive to firn properties, and collection of cores from sites with high accumulation rates (minimizing age difference between gas and ice) are necessary to overcome this problem. Because the cause of CO_2 variations is a major ice age puzzle, specific attention should be paid to its variations. One important problem concerns the role of atmospheric dust as a fertilizer of oceanic productivity and CO_2 drawdown. Better ice core records of dust deposition must accompany better records of carbon dioxide.

New work on other chemically active or biogenic gases in ice cores promises to open a new window on understanding the atmosphere (for example, Haan et al, 1996; Haan and Raynaud, 1998; Aydin et al., 2002). Species including methyl chloride, methyl bromide, carbonyl sulfide, carbon monoxide and a number of others, are important players in global atmospheric chemical cycles. These are harder to measure in ice samples because of small sample sizes, but they are important for two reasons. First, anthropogenic activities have heavily impacted the atmosphere over the last few centuries. Establishing the significance of those impacts requires knowing the pre-industrial concentrations of trace species. Firn air studies provide at most 100 years of record, which does not extend back to the beginning of the industrial revolution. Ice core records provide a longer context for understanding human activities. Second, expansion of the suite of trace gas measurements in ice cores over natural climate cycles (of all lengths) will provide a window into biological and chemical processes related to those climate changes. Development of techniques to reliably measure these species is therefore an important goal, one which will undoubtedly provide surprises and breakthroughs equal to those of the first trace gas measurements from ice.

Considerable promise exists in measurements of major and noble gases and their isotopes as well. The Ar/N_2 and O_2/N_2 ratios in central Antarctic ice appear to vary systematically with the amount of sunlight at the ice core site. Because astronomical calculations are exceedingly precise, these gas records hold the promise of improvements in the accuracy of dating the ice (Bender, 2002). Because of the strong temperature dependence of the solubility of the heavy noble gases Kr and Xe, they are expected to vary in their atmospheric concentrations due to the cooling and warming of the ocean over glacial cycles. Ice core records of Kr and Xe may together provide tracers of changes in whole ocean temperature due to the strong temperature dependence of their solubility in seawater. These techniques and others employing the isotopes of noble gases are currently under development.

As better records of the atmosphere are created, attention should also be paid to potential artifacts in the records. Microbial production of trace gases is a possible problem in some situations (Campen et al., 2003). Firn processes and bubble close-off modify the isotopic and elemental composition of gases, and tracers of these processes can be developed from major and noble gas measurements. For example, neon concentrations in firn air are enriched due to size-dependent processes during bubble close-off and may help to correct atmospheric records of O_2/N_2 for this effect (Severinghaus and Battle, 2002).

Chemical measurements in ice cores have traditionally used discrete sampling, with even high-resolution sampling generally limited to 10-12 samples per year and this over limited depth ranges. Research groups around the world, however, have focused in recent years on development of continuous analysis techniques using ice core melters that provide high-resolution analyses at far lower costs. Contamination of the sample stream is minimized by analyzing only melt from the center of a longitudinal ice sample, with the potentially contaminated outer part of the sample discarded. Continuous Flow Analysis (CFA) methods have been developed for a number of soluble chemical species, including Na, Ca, HCHO, H_2O_2, SO_4, NH_4 and NO_3, although detection limits are sometimes high relative to discrete sample analyses using ion chromatography (Röthlisberger et al., 2000). Efforts have also focused on the development of methods that use multiple ion chromatographs that sequentially sample from a continuous stream of melt water from an ice core melter (Traversi et al., 2002). While not strictly continuous, these systems provide high discrete sample depth resolution but at lower cost than traditional discrete methods, while achieving the same thresholds. More recently, a technique has been developed for making continuous, high-resolution measurements of trace elements and isotopes in ice cores. In this method, an ice core melter is coupled to an Inductively Coupled Plasma-Mass Spectrometer and a CFA system, with melt from the inner part of the ice core sample input to both analytical systems in real time. The result is exactly co-registered, very high depth resolution measurements of a broad spectrum of trace elements and isotopes at part-per-billion and part-per-trillion resolution (McConnell et al., 2002a). Since both the soluble and insoluble fractions are analyzed by the mass spectrometer, results include detailed elemental and isotopic information on continental dust and other particles, including volcanic fallout and industrial heavy metal pollution (Figure 7) (McConnell et al., 2002b).

A potentially valuable new ice core geochemical analytical technique involves isotope ratio analysis using inductively coupled plasma mass spectrometry (ICP-MS). One application is the analysis of stable sulfur isotopes (the $^{34}S/^{32}S$ ratio), which may prove useful for discerning sources of sulfur in various sulfur-bearing compounds (Patris et al., 2002). In the past, the precision necessary for sulfur isotope analysis was only possible using traditional gas-source mass spectrometry. However, recent advances in ICP-MS technology now allow a similar precision to be achieved using single-collector magnetic sector instruments. Even better precision will likely be achieved by using multi-collector ICP-MS instruments. The two major advantages of ICP-MS analysis are ease of sample preparation (aqueous solutions can be introduced directly), and significantly higher sample throughput. Another potential application of ICP-MS isotope analysis in ice cores involves stable mercury isotopes. This environmental-science field is evolving rapidly, and will likely cross over to ice cores soon. As is the case for S isotopes, Hg isotopes can now be analyzed with single- or multiple-collector ICP-MS at sufficient precision to investigate natural fractionation mechanisms.

In addition to identifying the number and timing of climate-impacting volcanic eruptions in the past, ice core records offer the opportunity to assess the volcanic impact quantitatively, through estimating atmospheric optical depth variations related to volcanic aerosol mass loadings, which can be derived from sulfate flux or deposition in snow (Zielinski, 1995). Longer and more detailed quantitative ice core records will aid in the development of more robust volcanic forcing parameters in the climate system. Furthermore, investigation of oxygen and sulfur isotopic composition of volcanic sulfate in ice cores is yielding new, significant insights into atmospheric chemical dynamics in response to volcanic perturbations (Cole-Dai et al., 2000; Savarino et al., 2001). Paleo-ozone indicators are also underdevelopment using the isotopic composition of nitrate in ice cores.

Understanding the role of aerosols in paleoclimate forcing and feedback is one of the major challenges facing climate research today. Future research will lead to a better understanding of regional variability in aerosol distributions, and a more complete analysis of the aerosol-borne components of ice cores. In particular, the organic constituents of paleoaerosols in require study. Only a tiny fraction of the organic compounds in ice cores have been identified, and it is clear that organics have a major influence on the radiative properties of aerosols.

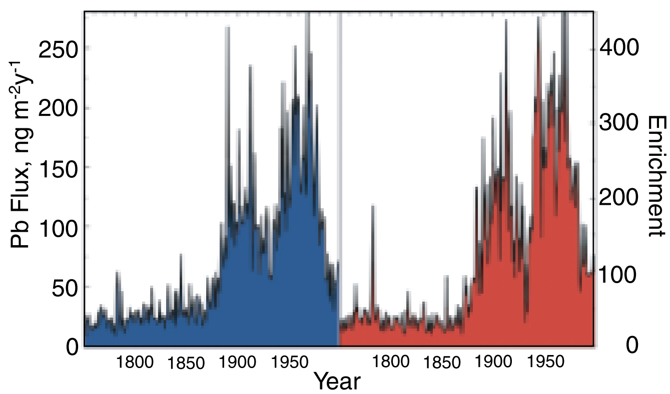

Figure 7. Continuous, high-resolution Pb flux and crustal enrichment since 1750 from a 1999 ice core from Summit Greenland (after McConnell et al., 2002b).

Ice Sheets, Sea Level, and Glaciology

Accomplishments

Understanding the dynamics of the polar ice sheets is fundamental for understanding and predicting global-scale environmental change and its impacts on society. Ice core studies have been an essential and irreplaceable component of ice dynamics research in the past, and will continue to provide a unique and essential perspective for ice dynamics research in the future.

Motivations for Ice Dynamics Studies

How will human societies be affected by climate change? Many discussions of this question focus primarily on the direct impacts of temperature and precipitation changes on populated or farmed regions. This approach is fundamentally inadequate. A substantial fraction of the world's population lives close to sea level and likely will be most affected by sea level changes that are an indirect consequence of climate changes. The polar ice sheets currently contain more than 70 m of sea-level-equivalent water volume (Paterson, 1994). Although it is not likely that this entire volume would be transferred to the oceans over relevant time-scales, a fractionally small volume reduction of the ice sheets is plausible and the resulting sea level rise would likely cause significant displacement of populations and damage to structures. This sensitivity arises from the combination of storm surges, rapid wave-driven erosion and sediment transport, and the very low elevations of many island nations and seaboard regions (such as southern Louisiana).

Climate change is not the only cause of ice sheet changes. Both sea-level rise itself and internal dynamical changes can force significant alteration of ice sheets (Paterson, 1994). A thorough understanding of ice sheet dynamics is absolutely essential for assessing the risks of future sea level rise and for understanding sea level changes revealed by the geologic record. A primary aim of NASA's PARCA program is better understanding of Greenland ice sheet mass balance and its impact on sea level.

Another major motivation for studying the growth and decay of ice sheets is that these changes affect global climate directly by altering the surface radiation balance (ice sheets are good reflectors), and by modifying atmospheric wave structure and circulation (Hartmann, 1994). Indirect effects of ice sheets on climate are also possible. For example, large volumes of water may be stored subglacially and released in giant floods that affect the vertical stability of the ocean and hence ocean circulation and heat transport (Fairbanks, 1989).

For all of these reasons, it is essential that we understand the dynamics of the ice sheets, and especially how they respond to changes of climate and sea level, and how their internal state evolves.

Why are Ice Cores Valuable to Ice Dynamics Research?

Ice coring projects have tremendous value to ice dynamics research because they yield information that is important and is not otherwise available. This information is diverse and varies from place to place, but can be categorized generally as information about:

History of climate forcings. The full response of an ice sheet to an instantaneous change of climate or sea level occurs over time-scales of centuries to tens of millennia (Whillans, 1981; Alley and Whillans, 1984). It is therefore necessary to know climate history on these time-scales in order to understand the current state of the ice sheets and their evolution in the near future. The growth and decay of ice sheets as reconstructed from other geologic records can only be understood if the concurrent climate history is known. Thus all the remarkable information about climate history that is retrieved from ice cores makes a very direct contribution to knowledge of the ice sheets. For example, we know from analyses of several ice cores in Greenland (GRIP, GISP2, Dye 3) that the northeastern part of the Greenland Ice Sheet ought to be thinning currently due to the continued propagation to depth of the climatic warming at the end of the last ice age, eleven thousand years ago (Huybrechts, 1994).

History of ice sheet surface elevations. The response of ice sheets usually involves surface elevation changes, and knowledge of these provides crucial tests for models of ice sheet evolution and relatively direct information about ice volume changes over time. Ice cores yield elevation data through appropriate analyses of air content and stable isotopes. For example, from analyses of the central Greenland GISP2 ice core, we know that the central region of the Greenland ice sheet survived the last interglacial warm climate and did so with an ice thickness only a few hundred meters thinner than the modern one (Raynaud et al., 1997). The Siple Dome ice core has provided evidence that surface elevations have not changed drastically over the past 50 kyr on this ridge between ice streams in West Antarctica, suggesting that the ice stream system was not profoundly different even during the glacial maximum when ice had advanced far into the Ross Sea (analyses in progress by R.B. Alley, J.W.C. White, and others).

Mechanical properties of ice. To understand how the ice sheets are flowing, it is essential that we know how the ice deforms in response to stress. This generalized viscosity is dependent on physical properties of the ice, including temperature, crystal orientation statistics, and possibly crystal size. These quantities are measured by sampling the core and by logging the borehole after core removal. An example of such studies is that ice samples from the Dye 3 borehole have been used in laboratory experiments to show conclusively that crystal orientation is an important control on ice viscosity (Shoji and Langway, 1988). Analyses of thin sections from the GISP2 core revealed that crystals can align themselves in bands of particular orientations that allow these bands to act like normal faults and accommodate the deformation field near ice divides (Alley et al., 1977). Future additions to the arsenal of logging techniques, for example grain-size logging, may well complement thin section analyses.

Flow rate of ice. The actual ice flow rate can be learned by logging and analyzing changes in borehole tilt and length over time after core removal. Such analyses provide both fundamental information on how ice flux is accommodated and crucial tests of our understanding of ice flow. Such information is necessary for improvement of the whole ice sheet models that are used to predict sea level rise contributions. For example, analyses of the Dye 3 borehole and core showed that the Greenland ice sheet has a major layer of soft ice that corresponds to ice deposited during the last ice age (Dahl-Jensen and Gundestrup, 1987). This feature needs to be represented in Greenland ice sheet models to accurately reproduce ice volume. New techniques can be expected to expand our understanding of the flow rate, in particular, of very cold ice, which deforms very slowly. These include plans to use both strain-rate and stress cells (Neil Humphrey, private comm.), optical fibers frozen into ice (Zumberge et al., 2002), and muon tracking with the IceCube neutrino observatory (Dmitry Chirkin, private comm.).

Basal processes. Ice sheet flow is strongly dependent on the nature of the ice/substrate interface. The presence and distribution of water at the interface strongly controls the volume of ice sheets through a lubrication effect; if pressurized water is abundant at the glacier bed, sliding motion can be rapid, the ice flux can be accommodated with relatively low thickness and surface slope, and consequently the ice sheet volume will be relatively small (Paterson, 1994). Likewise, the presence of unconsolidated sediment at the glacier bed will provide additional lubrication in this fashion (Boulton and Hindmarsh, 1987). Ice core studies provide borehole access to the bed, allowing measurement of basal conditions (temperature, water pressure, basal sediment) (e.g., Gow et al., 1997).

Geothermal flux. The geothermal flux has been extensively measured across the earth's surface (including the ocean basins), with the exception of the continental terrain beneath the polar ice sheets. In the extensive Antarctic continent, an area larger than the United States, the geothermal flux is only known for one small region near Ross Island (International Heat Flow Commission, http://www.geo.lsa.umich.edu/IHFC/heatflow.html). Yet the geothermal flux is a major control on the temperature distribution in the ice sheets (and hence the ice flow via the temperature dependence of ice viscosity) and the rate of water production at the bed (and hence the ice flow via the lubrication effect). Ice core analyses that combine borehole temperature data with climate history information provide good estimates of the geothermal flux (Cuffey and Clow, 1997). The importance of geothermal flux information from ice cores was recently demonstrated by the North GRIP project, which identified a remarkable heat flux anomaly in north-central Greenland that is causing basal melt and probably lubricating the enigmatic fast-flowing northeast Greenland ice stream (Fahnestock et al., 2001).

Exposure age. In some cases, rock material recovered from the bottom of ice core boreholes contains a record of the history of glaciation. Specifically, cosmogenic nuclides archive information about the age and duration of the exposure history of the substrate (Ackert et al., 1999). This method can reveal whether or not an ice sheet has disappeared completely from the ice core site at times in the past. This information may provide crucial constraints on the fate of ice sheets during past interglacial climates.

Air-snow transfer. The near-surface snow and firn provide an environment conducive to transport, both from the atmosphere down into the firn, and also from the snow and firn into the atmosphere. Physical and chemical reactions in the near-surface snow and firn depend upon both the nature of the forcing and the properties of the firn itself. An understanding of these interactions, especially at low accumulation sites, may lead to an enhanced understanding of the ice core record. Recent investigations along the ITASE show that snow and firn properties show great variation over West Antarctica, with high accumulation sites showing little post-depositional change in microstructure, while low accumulation sites show large changes (Albert, unpublished data).

Also recently, physiochemical interactions at the snow surface have been found to impact tropospheric chemistry in polar regions; because these interactions typically occur in the top five to ten centimeters of snow (Albert et al., 2002), interactions between snow and some greenhouse gases like ozone are likely to play a role over the large regions of the earth that experience seasonal snow cover.

Why are Ice Dynamics Studies Valuable to Ice Core Paleoclimate Research?

While the contributions of ice core studies to ice dynamics are seminal, it should also be noted that a comprehensive understanding of polar ice sheet dynamics is essential for successful paleoclimatic interpretation of ice cores. Appropriate site selection for new cores relies on knowledge of the ice flow and topography near candidate sites (e.g. Morse et al., 2002; Hempel and Thyssen, 1993), and on whole ice sheet modeling studies that estimate whether the sites of deposition for ice in the core have been reasonably fixed geographically (Letreguilly et al., 1991). Moreover, an understanding of ice flow near the core site (and over time) is necessary to reconstruct snowfall rate histories from analyses of the ice core's age-depth relationship, and to reconstruct temperature histories using borehole temperature measurements. Thus the ice core studies of paleoclimatology and ice dynamics are interdependent and mutually productive (Cuffey and Clow, 1997).

Future Questions

There remain numerous major questions about polar ice sheet dynamics that can and should be addressed by future ice core studies. The most broadly interesting and compelling ones are noted briefly below.

The West Antarctic Ice Sheet (WAIS) is the most poorly understood of the modern ice sheets, and numerical models of it are the most uncertain. There is the potential for the WAIS to contribute significantly to sea level rise over the next several centuries. It is known that the Ross Sea margin of the WAIS has retreated persistently over the past 9 kyr (Conway et al., 1999), and that complicated changes in the Siple Coast ice stream system have occurred in the past several centuries and continue today (Alley and Bindschadler, 2001; Conway et al., 2002; Joughin et al., 2002). Yet we do not know how stable the central core of this ice sheet has been over glacial-interglacial cycles. In particular, we do not know whether the WAIS survived the last interglacial warm climate (Cuffey and Marshall, 2000). There is a strong and urgent need for a deep ice core from central West Antarctica to examine this issue. This core would also provide the first estimate of geothermal heat flux for central West Antarctica, information that is essential for confident modeling of this system.

Unlike the Antarctic ice sheet margins, the southern margin of the Greenland Ice Sheet currently loses mass by rapid surface melt, and this means that increased meltwater production will almost certainly accompany climatic warming in the North Atlantic. Such melt would not only be a major contributor to sea level rise (e.g., DeWolde et al., 1997), but could also affect ocean circulation by altering surface salinity and temperature at the sites of North Atlantic Deep Water formation. The precise connection between climatic warming and surface melt generation in Greenland is not known, and measured recent changes in ice flow rate of the Greenland margin remain enigmatic (Zwally et al., 2002). A well-constrained reconstruction of Greenland climate history and ice sheet response for the last interglacial warm climate period would provide valuable insight about the behavior of the Greenland ice sheet in a warmer climate. Current discourse about the fate of Greenland during this period is contentious (e.g., Cuffey and Marshall, 2000). There is therefore a compelling and immediate need for an ice core from north-central Greenland that provides specific climate and ice surface elevation information from this period.

Future analyses of pairs of long-lived cosmogenic nuclides from oriented bedrock samples (Lal, 1991.) may make it possible to date the initiation of permanent glaciation of Antarctica, which is not known to better than 10^7 years.

Life in Extreme Environments

Accomplishments

New discoveries of microbial life in cold and saline lakes, permanent lake ice and glacial ice are extending the bounds of our known biosphere. The recent description of potential bacterial life in Lake Vostok (Figure 8) (Karl et al., 1999; Priscu et al., 1999) and the discovery of at least 100 other Antarctic subglacial lakes extends the known boundaries for life on Earth even further (Price et al, 2002, Tabacco et al., 2002). A recent review (Priscu and Christner, in press) estimates that there are 1.2 x 1025 prokaryotic cells present in Antarctica's subglacial lakes. If the prokaryotes immured in the Antarctic ice sheet (8.8 x 1025 cells) are also considered, the total number of prokaryotes in the liquid plus solid water phases of Antarctica is 10 x 1025 cells, which equates to 0.003 Pg of carbon (1 Pg = 1015 g). This carbon reservoir is similar to that for all of our planet's freshwater rivers and lakes combined (0.004 Pg; Whitman et al., 1998). The cryospheric carbon reservoir should be considered in future definitions of Earth's biosphere and included in calculations of Earth's carbon balance.

Large numbers of viable microbes are released from glaciers annually through melting and sublimation (Rogers et al., (a) in press). The organisms released range from viruses to prokaryotes and eukaryotes. Among the viruses identified so far are plant pathogens and bacterial phages. Prokaryotes include gram-positives, cyanobacteria, flavobacteria, and purple bacteria. Among the eukaryotes, viable fungi-including basidiomycetes, yeasts and ascomycetes-are common (Ma et al., 1999, 2000). Also found in the ice are single-celled and small multicellular plants and animals. Most of these are unculturable, though some algae have been cultured from ancient ice.

The chronology of the research from the 1970s up to the most recent publications signifies that ice represents a unique ecosystem and preservation matrix that can yield valuable information on microbial longevity, biological molecule preservation, past climates, recent climate change, evolutionary processes, epidemics, origins of life, life on other planets/moons, and other fields of study. With the scores of ice cores that have been collected over the past several decades, we have gained a deeper understanding of the potential benefits from the study of ice. However, it is also clear that, from a biological standpoint, we have only scratched the surface. It is important that future ice-coring projects include biological studies in the planning stages so that appropriate measures can be taken to avoid microbial contamination. Much of the past biological research on ice cores has had to battle contamination problems and has often yielded equivocal results.

While it has been known for nearly a century that laboratory microbes can survive being frozen in ice, the systematic study of microbes in natural ice is still in its infancy. The pioneering work of Sabit Abyzov (Abyzov et al., 1979, 1993, 1998) stimulated interest in this subject starting in the 1970s. Since then, it has become an area of intense research and has gained the interest of scientists and the lay public. In addition to researchers in Moscow and St. Petersburg, Russia, there are excellent laboratories in France, Denmark, Australia, and the USA working on biological projects with ice and permafrost. In the USA, the labs include those located at SUNY ESF, Bowling Green State University, UC Berkeley, Montana State University, and Columbia University. As it relates to the field of astrobiology, the list grows longer, including for example the University of Washington, NASA, JPL, and the University of Connecticut. Many young scientists are becoming interested in biological studies of the cryosphere, and NSF and NASA are seeing more and more proposals focusing on icy ecosystems. The next 10 years should reveal the important biological nature of Earth's glaciers and ice sheets.

Questions Addressable with Future Research

Is there a deep cold biosphere?

There are two equally fascinating components to this

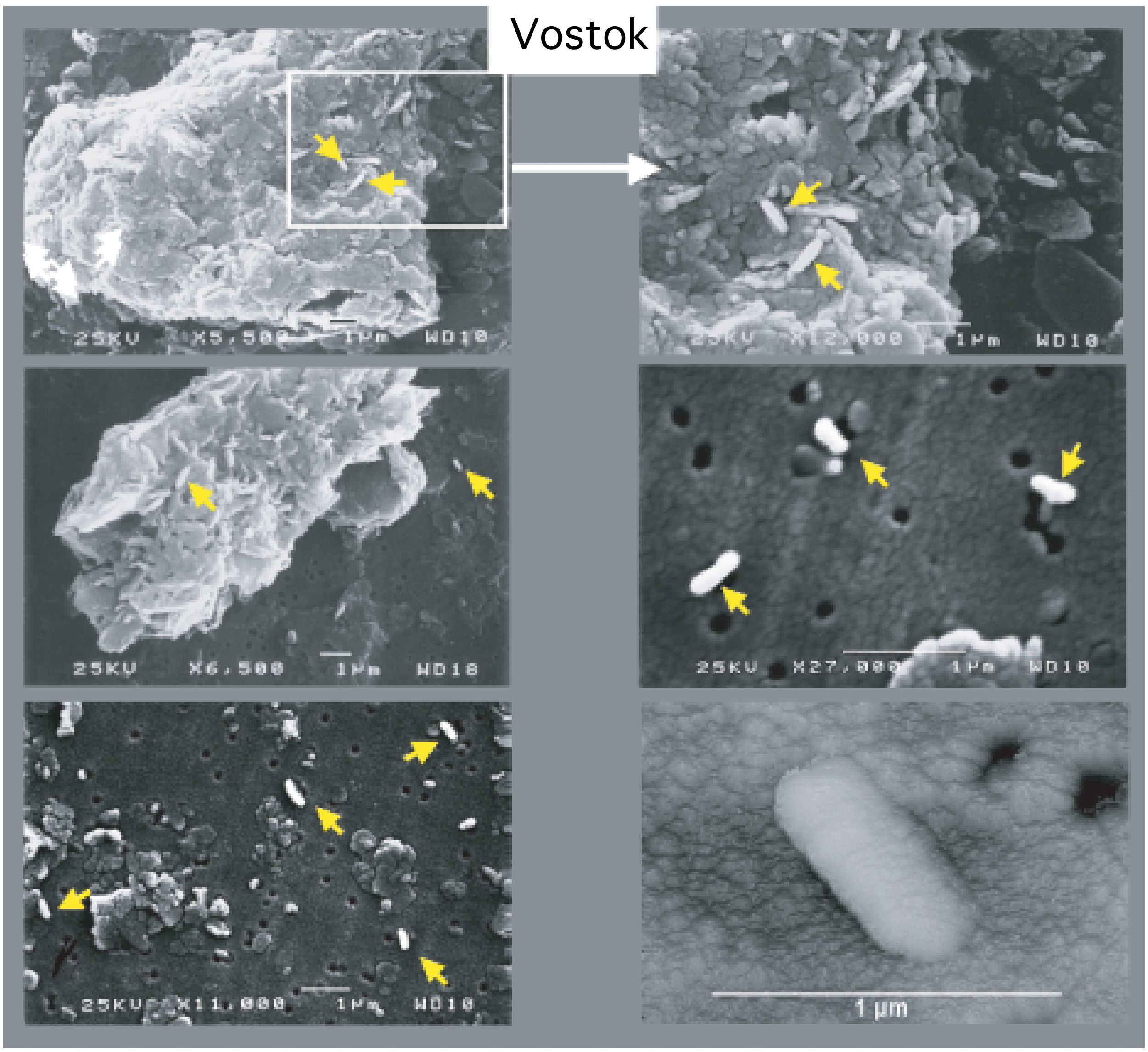

Figure 8: Scanning electron micrographs (upper and lower left panels) of bacteria (denoted by arrows) and associated particulate matter from Vostok accretion ice collected from 3590 m. The lower right panel is an atomic force micrograph of a single 0.8 µm long microbe from the same sample. Note that a majority of the bacteria are attached to particulate matter in the sample. All samples were concentrated on 0.2µm pore size filters. Modified from Priscu et al. (1999).

question. First, there may be an entirely unique ecosystem not only in ice-covered lakes, but in the ice itself. Price (2000) proposed an interesting hypothesis that asks whether there are metabolically active microbes that exist in liquid water veins in solid glacial ice. As ice forms, many solutes, including nutrients, are excluded from the crystal lattice concentrate in liquid veins that do not freeze due to the high concentrations of solutes and the energetics associated with the crystal boundary. Two recent publications support this hypothesis (Fukazawa et al., 1998; Campen et al., 2003). The second possibility is that the organisms in the ice are simply cryo-preserved and are metabolically inactive. Both of these possibilities are important to the field of microbiology, and each has unique properties that are worth thorough investigation. Data from a tropical ice core (Campen et al., 2003) are consistent with ongoing metabolism by a consortium of microorganisms in subfreezing ice.

From a microbial perspective, our planet's zone of habitation ("the biosphere") extends from high into the atmosphere to the inner depths of the earth, where temperatures rise with depth to exceed those assumed possible for known carbon-based life, to the bottom of ice sheets where temperatures rarely exceed $0^{o}C$. Based on information gathered over the last five years, it is clear that the role of permanently cold ecosystems in global ecology must be reassessed and included in formal definitions of Earth's biosphere. As such, Priscu and Christner (in press) have proposed that the earth's cryosphere and associated sub-ice lakes should be included as biospheric components of our planet. Cryosphere is defined here as that portion of the earth's surface where water is in a solid form as snow or ice. Water in its solid form includes sea ice, freshwater ice, snow glaciers, ice sheets and frozen ground.

How long can organisms and biological molecules survive in icy environments?

This question has been asked and partially answered by research on mummies, amber, herbarium samples, halides, and other matrices. Ice may be one of the best preservatives for biological materials. Many biological macromolecules (such as DNA and RNA) are protected from damage by low temperatures, desiccation (i.e., limitation of free water), and neutral pH. These conditions are present in much of the ice on our planet. The answer to the question also has implications when looking for microbes on other planets and moons. To date, viable microbes as well as nucleic acids have been isolated and characterized from ice up to at least 420,000 years old (Priscu et al., 1999) (and some that may be closer to 1 million years old).

Results from some ice cores have shown that there is a gradual decline over time in the number of organisms and nucleic acids. These trends, however, indicate that there would still be 1% remaining after tens of millions to hundreds of millions of years. With a low level of metabolic activity to repair DNA and other molecules, this could be extended considerably (Christner, 2002). If this is the case, then viable microbes and/or their nucleic acids may be preserved on other icy planets and moons.

Basic questions of preservation of organisms and biological macromolecules can be addressed using ice (Willerslev et al., 1999; Ma et al., 2000; Rogers et al. (b), in press). Preservation with no metabolic activity is theoretically possible for hundreds of thousands to a few million years. With a low level of metabolic activity to repair DNA and other molecules, this could be extended considerably. If consortia of microbes are actively metabolizing, then energy supplies may be the limiting factor.

Do pathogenic microbes (fungi, bacteria, and viruses) remain infective in polar ice?

The number and diversity of viable microbes isolated from contemporary and ancient ice cores increases with every new study. Some of the microbes are phylogenetically close to known pathogens. Studies are now underway in at least a few laboratories to identify the prevalence of several human pathogens. Viability is more difficult to assess, but it is theoretically possible to determine whether the viruses remain infectious. These studies to date do show that a large number of pathogenic microbes potentially exist in the ice. Future studies must determine the precise numbers of pathogens being released from glaciers and whether they have an impact on the populations of the same species and/or their hosts.

What is the extent of gene flow from the ancient microbes being released from glaciers into an extant population? Does this gene flow affect host-pathogen relationships? Recycling of microbes and their genomes also has major population and evolutionary implications (Rogers et al. (b), in press). For a given species, the life cycles and population sizes are greater than previously considered. As a practical matter and depending upon the degree of genotype recycling, calculations of evolutionary distances and mutation rates based on contemporary genotypes alone may be inaccurate and misleading. Such distances and rates are valid only within coherent populations, and will be unreliable if ancient genotypes mix with modern ones. Evolutionary theories do not usually consider temporal overlap, especially when the populations are composed of organisms that come from different periods of the geological time scale. The pathogens can emerge from glaciers after decades, centuries, or longer to infect a population of hosts that lack any resistance or immunity to them. There are anecdotal reports of this relating to humans (primarily influenza virus) and marine mammals (primarily caliciviruses), as well as the report of tomato mosaic tobamoviruses (that infect plants) isolated from ice cores (Castello et al., 1999).

There are recent concerns about global warming and its impacts on global ecology. As the earth warms and the ice melts, an increasing number of microbes are released. If ice does contribute significantly to human disease, as well as diseases of other organisms, then an increased rate of melting will lead to an increased risk to the hosts for these pathogens. An important consideration in this respect is an evolutionary one, that of the theory of Genome Recycling. The resurrection of ancient genotypes may swamp mechanisms for resistance and immunity simply by sheer numbers of released microbes, or increased rates of genetic recombination and introgression (by viruses injecting new genes into cellular genomes) may also lead to especially virulent pathogens. Although this idea remains speculative, research results to date cannot exclude these possibilities. It is also worth remembering that rates of melting of old ice, hence supply of old organisms to the environment, were higher during the terminations of ice ages than is occurring today, or than is likely to occur in the future.

Are there outcomes for applied biology?
Some of these ancient microorganisms may be pathogens, gene vectors, and a few may be sources of new and useful compounds or genes for industry or medicine.

What can we learn from subglacial lakes?
While, strictly speaking, exploration of Lake Vostok and other subglacial lakes does not require study of ice cores, the same community of researchers using some of the same analytical techniques and in part some of the same drilling techniques would study samples of overlying ice, water, sediments, and perhaps bedrock from subglacial lakes. Scientific return includes potential discovery of new species of extremophiles hitherto isolated from surface environments, new types of microbial habitats, high geothermal fluxes pointing to an active rift zone, and unusual behavior of clathrate air crystals in the lake, to list but a few examples.

How does the ice relate to ice elsewhere in the Solar System?
As early as 1973, it was suggested that Antarctica could be a surrogate for Martian terrain (Vishniac and Mainzer, 1973; Wharton et al., 1995). Given current technologies, it will soon be possible to search for microorganisms in ancient Martian water-ice matrices, comets, ice on the Jovian moon Europa (and others), and in lunar ice and other frozen substrates.

Examining permanently ice-covered habitats and microorganisms preserved for extended periods within ice is also relevant to astrobiological discussions of past or present life on Mars or in the subsurface ocean of Europa, and to the concept that planetary bodies may not be biologically isolated. We are rapidly reaching a point in our search for the origins of life on Earth that studies must be extended beyond our own planet. Clearly, our efforts will be enhanced if we increase our sample size beyond one. Such remote and seemingly inconsequential frozen environments may harbor as yet undiscovered microbial ecosystems that could shed light on the natural history and evolution of life on a frozen Earth, as well as other icy planets and moons in the solar system.

Other Directions and Opportunities

The study of ice cores has matured to the extent that a "standard" set of physical and chemical properties is now routinely measured and interpreted in ice core records. The potential of the ice core record has in no way been exhausted, however. In addition to the new directions discussed in the sections above, there are a number of important techniques and ideas that hold considerable promise.

Recent Work

One recent area of new activity is in measurements of trace elements in ice, and the isotopic composition of trace constituents. Heavy isotope ratios trace dust sources, providing valuable information about source areas for polar dust (Biscaye et al., 1997). High-resolution measurements of trace elements hold promise for detailed analysis of changes in atmospheric chemistry and circulation (McConnell et al., 2002a). Ir and He measurements may trace variations in extraterrestrial dust flux and its relationship to climate (Kayser et al., 1998; Brook et al., 2000; Karner et al., 2003). Most of these techniques are in their infancy, requiring relatively large samples, difficult processing, and long measurement times. Advances in analytical techniques will undoubtedly overcome these obstacles and allow a much larger suite of measurements-expanding the range of problems addressed with ice samples.

Another area of recent advance is in optical logging of ice core boreholes. Optical loggers remotely detect dust layers (Miocinovic et al., 2001), and additional sensor technology may allow detection of biological material (Bay, pers. comm.). Optical logging has promise in a number of applications, including searching for microbes in ice, rapid analysis of ice sheet stratigraphy, and identification of dust layers of interest to a variety of disciplines.

A number of new techniques for logging of ice core boreholes are under development (Bay et al., 2003b). Optical loggers remotely detect layers of dust and volcanic ash (Miocinovic et al., 2001; Bay et al., 2001). Optical logging has promise in a number of applications, including rapid analysis of ice sheet stratigraphy, identification of volcanic ash, search for solar forcings on decadal, centennial and millennial-scales, and search for causal relationships between volcanism and abrupt climate change. Fluorescence spectra of biomolecules can now be logged in deep ice with an ultraviolet logger (Bay et al., in press) and used to search for microbial life as a function of depth. Sonic and ultrasonic logging offer the potential for determining crystal grain sizes and habits. (G. Lamorey, B. Price, pers. comms.)

The proposed development of a rapid access drill (Clow and Koci, 2002) also has implications for ice coring. This is not strictly speaking an ice coring drill, but a technique to rapidly access the base of an ice sheet. The technique is of interest to ice coring because it can recover short sections of core in regions of ice sheets that are of specific interest, and because it can be used to create boreholes for logging that will help constrain ice sheet stratigraphy, aiding in ice core site selection.

Studies of stratigraphic sections at ice sheet margins in Greenland and Antarctica are an additional area of new activity related to ice coring. Although this is not a truly new area of research, with original work in Greenland starting over 10 years ago (Reeh et al., 1987, 1991), recent work focuses on techniques that use gas records to determine the age of the often deformed marginal sections (Petrenko et al., 2002), opening the possibility of obtaining very large samples of old ice by sampling at the ice margin surface. At this point it seems highly unlikely that these sections will provide continuous samples with the same quality as traditional ice cores (due to ice deformation), but they do hold promise for measurements that require very large samples.

Physical properties of ice cores remain of considerable interest. The thickness of firn, estimated from gravitational fractionation of trapped gases (Sowers et al., 1992), is controlled by temperature and accumulation rate. Additional measurements of the isotopic composition of noble gases and nitrogen will provide data on the physical processes that influence the composition of all gases trapped in ice. Such studies will enhance our ability to reconstruct accurate records of the atmospheric composition and establish the temporal relationship between these changes and climate. Bubble sizes also may provide information on past temperature and accumulation rate (Alley and Fitzpatrick, 1991). Improved digital imagery may enhance the interpretation of annual layers identified visually (Alley et al., 1997), as well as the identification of melt layers (Alley and Anandakrishnan, 1995).

Future Work

A variety of interesting questions may be addressed as the techniques and ideas mentioned in the previous section develop. These include how the flux of extraterrestrial material to the earth varied with time and if there are links to climate or other environmental change; the nature of organic and inorganic extraterrestrial material accreting to the earth; how the transport of impurities to ice varies on subseasonal time scales; how these variations are related to environmental change; and the chemical fingerprints of biogeochemical cycles and climate change. Borehole logging has potential to develop into a major stratigraphic tool that could be employed in access holes to map ice sheet stratigraphy and considerably aid site selection. Other logging techniques may considerably expand the kind of high-resolution data available from ice core boreholes. Ice margin sites can provide large samples of gasses and particles, allowing measurements of tracers-like carbon-14 in atmospheric gasses, pollen, and isotopic composition of dust-that can trace specific atmospheric and climate processes in ways that complement, but are not possible with, traditional ice core methods.

Recommendations for the Future of U.S. Ice Coring

Analysis of ice cores has significantly enriched our understanding of climate and environmental change, and the ICWG believes that ice coring will continue to be a cornerstone of global change research. Many presentations at the March 2002 ICWG meeting and subsequent discussions emphasized how rudimentary our knowledge of past environmental variability really is, and how important it is that we improve our understanding. In response, the ICWG identified an interrelated series of key scientific questions that should be addressed with a continued program of ice coring. ICWG also identified a number of important opportunities for enhancing the quality and nature of environmental information extracted from ice samples, and key challenges and requirements for continuing and improving the U.S. ice coring program.

The scientific questions outlined below all focus on understanding how the earth system behaved at critical time periods in Earth history, up to the present. These questions developed from our understanding that how and why the earth system changes is critical for humanity. This proposed program will require long-term support from funding agencies and the scientific community. This program will provide a framework for planning future field campaigns, developing key analytical capabilities, and attracting new investigators to polar research. The ICWG envisions international collaboration in aspects of the work outlined below, but we believe that the U.S. must also maintain and expand the technical and logistical capability of collecting and analyzing ice cores.

New Multidisciplinary Coring Projects

Rapid Climate Change and West Antarctic Ice Sheet Stability: The Inland WAIS Project

The recognition and description of rapid climate change in the past from the GISP2 core is one of the crowning achievements of the U.S. Ice Coring Program. One of the most fundamental questions in paleoclimate research today concerns the ultimate cause of abrupt climate changes and their future likelihood. A large body of work since GISP2 focuses on the manifestation of rapid climate changes in parts of the world other than Greenland. These studies are attempts to uncover the global fingerprint of rapid climate change, and thereby identify its cause. One of the most significant ice core observations is that there is an asynchrony in abrupt climate change between the northern and southern hemispheres. That is, when Greenland warms rapidly, Antarctica cools, and cold periods in Greenland correspond with Antarctic warmings. Another important observation is that variations in atmospheric carbon dioxide appear to be correlated with millennial-scale Antarctic temperature change. Volcanism may also be linked to abrupt climate change. Patterns such as these tell us something about climate change mechanisms, but existing records do not have the sample resolution or data quality to answer a large number of pressing questions about the behavior of the southern hemisphere climate system. These questions include the relative timing of temperature change in Greenland and Antarctica (for example, did Antarctic changes start before or after antiphase Greenland changes? Is the phasing the same for coolings as for warmings?); the phasing of atmospheric carbon dioxide and temperature change and the detailed nature of millennial-scale variations in carbon dioxide; the behavior of the polar atmospheric circulation; sea ice; the subtropical southern hemisphere ocean circulation; the speed and magnitude of Antarctic temperature change; and a myriad of other aspects of the climate system.

Several decades of work have examined the stability of the West Antarctic Ice Sheet. A number of studies suggest that the WAIS may be unstable, and may respond unexpectedly and possibly catastrophically to recent past changes in climate and sea level and/or future warming and sea level change. This potential instability suggests possible rapid future increases in sea level due to WAIS collapse. During the last interglacial period (about 130 kyr) global sea level probably was ~5 m higher than today, providing a good analog for a possible future world with higher sea level due to global warming. Did the West

Antarctic Ice Sheet collapse at this time? The two deep ice cores in West Antarctica (Siple Dome and Byrd) have not penetrated ice that clearly dates from this period, although current analysis of the bottom of the Siple Dome core may provide some information on the problem.

The questions raised above are addressable with a new deep ice core in inland West Antarctica (referred to as the Inland WAIS Site in other planning documents (ICWG, 1992; Taylor, 2002). The overall objective of this project is to obtain a record of climate and environmental change spanning at least the last 100,000 years, and hopefully into the last interglacial period, with a resolution and accurate layer-counted chronology similar to the GISP2 and GRIP records. The ice coring community believes that this project would have an impact on climate science analogous to that of the GISP2/GRIP programs. Planning for this project is very advanced (the project was proposed in the scientific community in the late 1980s), and the ICWG has consistently endorsed this project as the next major U.S. ice coring activity. Site selection activities have identified prospective drilling sites and are currently continuing (Figure 9). ICWG strongly recommends that this project go forward with a target of beginning drilling in the 2004-05 or 05-06 Antarctic field seasons.

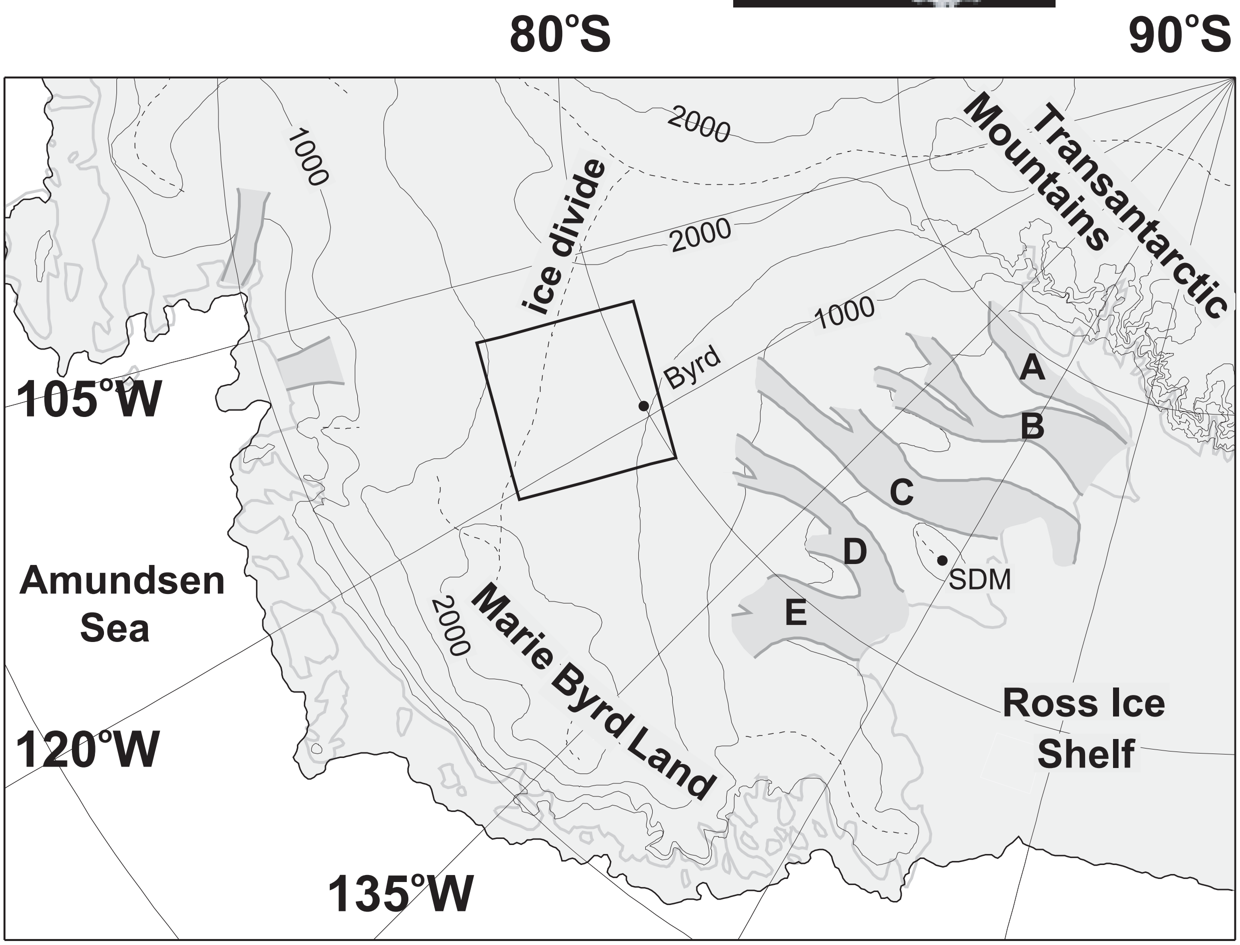

Figure 9: Location of West Antarctic proposed inland WAIS site (black box) Modified from Morse et al., 2002.

The Stability of the Greenland Ice Sheet and the History of the Last Interglacial Period in the Northern Hemisphere: The "GISP3" Project

The remarkable records from GISP2 and GRIP lose continuity at ~ 110,000 years ago, where flow disturbances disrupt the stratigraphy near the bed of the ice sheet. Older ice from the previous interglacial period and before is present, but is not in stratigraphic order. Although the European NGRIP project has also failed to obtain a record from this time period, recent work (Johnsen et al., 2001) suggests that a record including this time period might be recoverable in north Greenland. There are a number of important reasons that a core penetrating that period in Greenland would be extremely useful. First, since the last interglacial is the closest analog to our current climate, we have a vested interest in understanding last-interglacial climate variability in great detail. Second, there is some evidence from marine sediments that the last interglacial ended rather abruptly in the North Atlantic region (Adkins et al., 1998). An abrupt return to glacial conditions has obvious implications (albeit probably in the distant future) for human society. Third, it is possible that the Greenland ice sheet was significantly smaller than the current configuration during the last interglacial, implying a large contribution to sea level at that time (Cuffey and Marshall, 2002). A core to the bed of the ice sheet would establish the minimum age of the ice sheet at the site through stratigraphic studies of the ice and cosmogenic isotope dating of the bedrock below the ice. Furthermore, a new core in Greenland would provide additional sample material for the younger section of the record. This is important because the great scientific interest in abrupt climate change has consumed key intervals of the GISP2 core.

ICWG recommends that the ice coring community start planning activities for a joint U.S.-Danish (and possibly other European collaborators) project (called "GISP3" informally here) to recover an ice core record from the last interglacial period in north Greenland. A workshop open to investigators from all interested countries should be organized to start this process.

Evolution of Climate and Biogeochemistry over the Last Two Millennia: A Network of 2,000-Year Records

Providing a context with which to view current and future climate and environmental change is an important role for paleoclimate studies. The last 2,000 years is a critical period for this effort because climate boundary conditions during that time were similar to those that underlie the present climate system. Unfortunately, instrumental and proxy records provide very detailed data for only the past few centuries at most. Adequate understanding of climate variability and climate trends over the last two millennia requires well-resolved, annually dated records. The polar ice sheets can provide such records and offer the opportunity of developing a spatial network of records, which is critical for examining the complex spatial-temporal variability of climate phenomena that act on this time scale. For example, the long term variability of atmospheric modes-including the North Atlantic Oscillation, the El Niño-Southern Oscillation, and the Antarctic Oscillation-is poorly known, yet critical for understanding climate trends in the polar regions. Recent attention to disintegration of ice shelves in Antarctica, the mass balance of Greenland and Antarctic Ice Sheets, and warming and cooling trends in Antarctica underscores the need to adequately understand natural climate variability in these regions. An international effort to recover a network of 2,000-year ice core records from both hemispheres, and from high altitude sites, and efforts to integrate these records with other kinds of paleoclimate data available on this time scale could immensely improve our understanding of the issues raised here. Such an effort would be analogous to the current ITASE project, but would require equipment and logistics support to collect longer ice cores than ITASE currently recovers. ICWG recommends that planning activities for such an effort be initiated by the scientific community.

Long-Term Evolution of Earth Systems: A One-Million-Year-Old Ice Core

Studies of ocean sediments, ice cores, and other archives document long term cyclicity in Earth's climate that is normally attributed to changes in the geometry of the earth's orbit. Ice core records provide a great deal of information about how the system responds to these changes, and specifically tell us how one of the other major climate forcing factors, the greenhouse gas concentration of the atmosphere, has changed on these time scales. One of the most significant puzzles of paleoclimatology is that the last ~ 700-800,000 years of Earth's history is dominated by a climate cycle of ~ 100,000 years length. Although the orbital eccentricity has a period close to this value, its impact on climate should be quite small, making the "100 kyr problem" one of the most vexing and long-standing issues in paleoclimatology. Equally puzzling is the fact that 700-800,000 years ago the system seemed to switch from a dominant 40,000-year cycle to the 100,000-year cycle, and the switch is not well understood. In addition, a major geomagnetic reversal (Brunes-Matuyama) occurred at 780,000 and an ice core of this age would record impacts of the reversal on cosmogenic isotope production. Long ice core records so far extend to only 500,000 years at most, meaning that important information about greenhouse gases and other atmospheric conditions, available from ice records, is not available during the time of the transition from the "41-kyr world" to the "100-kyr world." This is because current locations of ice core drilling probably do not preserve ice this old at the bed. The consensus of the glaciological community is that there probably are locations in East Antarctica where old records, possibly as old as 1 Ma, exist, and that they could be identified by appropriate site-selection activities. ICWG recommends that the scientific community propose, and NSF support, glaciological investigations related to selecting a site for a one-million-year-old ice core.

Geographic Structure of the Last Glacial-Interglacial Transition: A Spatial Network of Records through the Last Glacial Maximum

The transition from glacial to interglacial conditions that occurred between 20,000 and 10,000 years ago is the most profound global change of the past 100,000 years. Despite this, there are only a few (6-8) ice cores that provide well-dated records of the entire transition. Numerous studies of terrestrial and marine sediments demonstrate significant regional variability in the timing and structure of the glacial-interglacial transition. This variability is important because it is a fingerprint of the processes that acted during this major transition, the origin of which is only partly understood. Understanding the polar regions in the glacial-interglacial transition is important because the polar seas in both hemispheres are the loci of deep ocean water formation, a key element of the global heat budget and climate system, and because of the influence of the ice sheets on deep water formation, sea level, and atmospheric circulation. A network of numerous cores through the glacial-interglacial transition, with a standardized set of measurements and core quality criteria, would provide further insight into how glacial-interglacial transitions work. This insight is of fundamental academic significance, but also important from a practical perspective because the same mechanisms that controlled the glacial-interglacial transition operate today. Creating a network of cores through the glacial-interglacial transition would be a long-term project. One possibility would be an international effort analogous to ITASE, perhaps integrated with other international drilling efforts. A new generation of lightweight intermediate-deep coring equipment would be necessary to accomplish such a project.

Improvement of Ice Coring Capabilities

The existing U.S. 5.2" ice core drill was used in the GISP2, Taylor Dome, and Siple Dome projects. It is currently in need of substantial repair, is quite heavy to deploy, and a recent evaluation of the drilling system recommended replacement (Eustes et al., 2001). As a result, the U.S. is lagging significantly in deep and intermediate ice drilling capabilities and improving this situation must be a high priority. At this writing, the initial design phase for a new ice coring drill is underway, but there is no deployable deep or intermediate ice coring drill. ICWG is very concerned about this issue, and the scientific community is currently involved in the design process for a new drill. Important issues in this process include the cost, logistics burden, and timeline for obtaining a new drill system. A proximal concern of the ICWG is that this drill design and construction process be completed in a timely fashion so that the inland WAIS core is not delayed.

Ice coring is a very specific technical process with only a few expert practitioners globally. Although the U.S. was a leader in early deep ice coring efforts, this expertise has not been maintained. This is an important problem for the U.S. polar community. The reasons for the problem are probably complex, but are at least partially related to how the contract for ice coring support has moved between institutions within the U.S. academic community, a system that does not allow development of long-term expertise in drillers and engineers. Therefore, in addition to regaining the capability to drill a deep ice core, ICWG recommends that NSF and the scientific community seek ways to build and maintain technical expertise in ice coring. As part of this process ICWG recommends that NSF and the scientific community examine and review the current practice of contracting ice coring and drilling services and the management of that contract with the goal of building and maintaining expertise for the long term.

Maintenance and Improvement of Polar Logistics

Ice coring requires significant logistical support. Polar logistics problems, particularly lack of aircraft support in Antarctica, continue to be major stumbling blocks for planning ice coring efforts. ICWG supports OPP's plans to develop heavy traverse capability and possibly heavy traverse re-supply of South Pole Station. This option should also be considered for supporting deep ice coring efforts planned for West Antarctica. ICWG also recommends that a bi-polar ice coring strategy be adopted, with site selection and coring activities concurrently active in both hemispheres. This will allow progress on community goals even when logistics problems develop in Antarctica (or Greenland).

Maintenance and Upgrade of the National Ice Core Laboratory (NICL)

The National Ice Core Laboratory is a very important resource for the ice core community and the scientific community in general. The facility has been operating in excellent fashion for 10 years, but faces some important choices concerning future operations. In the near term, space is an issue. NICL does not have sufficient space to store another deep ice core without rearranging the density of core storage. This rearrangement is feasible and cost effective, and ICWG recently recommended that NICL go forward with increasing the density of racking to accommodate another deep core. A longer-term issue is that much of the NICL mechanical equipment will need replacement in the next 5-7 years, and expansion of freezer space will probably become necessary over the same time frame. Therefore, ICWG has recommended to NSF and NICL that detailed planning for freezer expansions and mechanical upgrades begin now. These plans should also consider issues such as upgrades in facilities to examine and process cores at NICL, remote video and audio links for examining samples from off-site locations, possible additional staff, and other issues important to core curation.

NICL has recently suggested that NICL personnel be involved in future ice coring field operations to insure adequate documentation of cores that are returned to NICL for processing. The ICWG supports this idea.

Development of Analytical Techniques and Capabilities

As indicated in previous sections, there are potential significant breakthroughs in ice core science based on promising new analytical tools for ice core research. Examples of instrumentation recently introduced into ice core analysis include: continuous flow ICPMS, downhole optical dust logger, GC-IRMS for isotopic analysis of individual molecules, flow cytometry, PCR-based DNA analysis, dual-sector GC/MS for trace gas detection, and electrospray MS/MS for detection of organic anions and polar compounds. These and other new developments will lead to substantial improvements in precision, accuracy, and time-resolution of ice core records, and to the utilization of a wide range of previously undetected chemicals and organisms contained in the ice core archives that will provide new insights into paleoclimate and biogeochemical cycling. Development and improvement of analytical techniques applied to ice samples should be a major goal of the U.S. scientific community and should be supported by NSF.

Development of Human Resources

Scientific

Both NSF and the scientific community should continue to support new investigators interested in ice core science. ICWG feels that continuity of support for ice coring is critical for this effort. NSF should encourage meritorious cross-disciplinary proposals that will bring new scientists to ice coring. ICWG should develop more ways of promoting new work on ice core samples (see below for further discussion). One specific suggestion for development of scientific expertise is the creation of an OPP Postdoctoral Fellowship Program focused on new developments in polar science. A competitive post-doc program that would support promising researchers who wish to work in established laboratories could significantly enhance the base of scientific expertise in polar science in the U.S.

Drilling Engineering and Support

A stable cadre of drilling engineers and drillers must be created and maintained. This is a key point for future success and was in fact identified as such in the 1986 NAS report. ICWG believes that the current system of renewing the ice core-drilling contract every 5 years may have resulted in a loss of critical expertise, to the extent that the U.S. cannot field a deep ice core drill at the current time. NSF and the scientific community should work together to create a more stable system of supporting the complex and unique process of drilling and recovering ice cores. A major problem appears to be lack of clear communication and accountability channels between the ice coring contractor, NSF, and the scientific community. More active management (and structures to allow it) of the contractor by NSF and the scientific community is probably part of the solution to the problem. Greater involvement of the scientific community in awarding the contract and constructing its terms is another. A third issue concerns the scope of the responsibilities of the drilling contractor. It might be advantageous to divide some aspects of the current contract into pieces that could be bid on separately, allowing more focused attention to individual projects, for example designing and building a new deep ice coring drill.

However, even with such steps, a contract that moves locations potentially every five years will always create problems for retaining expert personnel. In the long term, other approaches to the problem can be envisioned. One is a transition to an ODP-type model of ice coring, where long-term coring plans are supported essentially continuously, and the drilling services are integrated into the program, with no other responsibilities designated to whomever is providing the drilling expertise. A second solution would be for an academic or research institution in the U.S. to invest resources in building an interdisciplinary center for ice coring science that could sequester sufficient funding to maintain scientific and engineering expertise related to drilling in polar ice sheets. This model is perhaps closer to how our European colleagues operate, and their significant success over the last decade, with relatively small and inexpensively run groups, suggests that this model has merit. A third possibility is an international consortium for ice core drilling, perhaps more like the new IODP. Other solutions could be envisioned. A key aspect of any of them is a structure that promotes direct collaboration of scientists, engineers, and drillers. Another key aspect is that some level of commitment to ice coring is necessary beyond that made to individual campaigns.

A major new future technical challenge for U.S. ice coring is development of "replicate coring", collecting duplicate cores from short stratigraphic sections where additional samples are required. This is particulary important for studies of abrupt climate change, where interest is intense, and intervals of interest are short.

Funding for Ice Coring Activities

The scientific community appreciates the support given to ice coring since IGY; this support has resulted in a large number of seminal scientific contributions. However, hiatuses in ice coring have resulted in recognized problems. The ICWG recommends that funding of U.S. ice coring activities move from a "single campaign" style of operation, where individual coring projects are supported in isolation, to a longer-term strategy of support for the coring program, as discussed above. A strategy for developing this support should be developed by the ICWG and the scientific community. Key elements are a science plan for the long-term program (of the type outlined above) and long-term availability of logistics support.

Role of the Ice Core Working Group

The 1986 NAS report envisioned an ICWG made up of representatives from institutions prominent in ice coring activities that would provide guidance for U.S. ice coring activities and NSF. With the construction of the NICL facility in 1993, ICWG has taken on the additional responsibility of making recommendations about allocating ice core samples and NICL operations. ICWG is currently administered by the NICL Science Management Office. Members are elected to three-year terms, and the chair, who serves a two-year term, is usually chosen from the membership of the committee, although this is not a requirement. The ICWG is currently organized loosely around scientific disciplines, rather than institutions. This mix of expertise is important because of the sample allocation responsibilities of the ICWG. The following areas are currently represented: atmospheric chemistry, biological, gases, geophysics, glaciology, major chemistry, modeling, physical properties, isotopes and technical.

ICWG appears to function well in its current incarnation; however, there are several areas where the function of the committee could be improved.

Communication with NSF and the Drilling Contractor

NSF has been supportive of ICWG and ice coring activities, but there is some concern that community issues are hard to communicate to NSF, in part because there are several programs (including the manager of the drilling contract) within OPP that are involved. Establishing a recognized (both externally and within the foundation) liaison between NSF, ICWG, NICL-SMO, and the ice core drilling contractor could help with this problem. In addition, ICWG has only irregularly reported formally on ice coring issues to NSF and the scientific community. Therefore, we suggest that ICWG implement a policy of writing a brief annual report to NSF after the annual ICWG meeting. (Minutes and summaries of the meetings have been provided regularly, but this report would be a more formal document, drawing attention to outstanding issues). Finally, the ICWG believes it is critical to develop more direct communication between the scientific community and the drilling contractor. The current contractor (ICDS) has an advisory board, but this board reports to ICDS, not to NSF or the scientific community. ICDS is employed by NSF for the benefit of the scientific community, but the lines of authority and responsibility are not clear from the perspective of that community. Although it is difficult to identify precisely where things break down, the problems should be identified and fixed.

Promotion of Ice Coring Science and New Investigators, Technologies, and Data

ICWG has in the past been fairly active in promoting the science of ice coring but has not been very active in specifically fostering development of new investigators and analytical techniques. One possible way to enhance the visibility of ICWG activities and U.S. ice coring science would be to add a scientific agenda to ICWG meetings, perhaps on a biennial basis, providing a venue for U.S. researchers in all areas of ice coring to share scientific ideas. This would have the added benefit of bringing more of the scientific community to the ICWG meetings (which by tradition are open to all investigators). The proceedings of such a meeting could be published in a special volume of a glaciological journal, providing a central place for collecting cutting-edge research on polar ice. Other possibilities for promoting ice coring science include traveling lectureships (like those funded by OPP, Sigma Xi, and AAPG), a regular newsletter, and other more traditional outreach activities.

Structure of the ICWG

Organizing the membership of ICWG entirely around disciplinary areas has advantages, but creates some problems. Because the number of ice core researchers in the U.S. is not large, requiring that all disciplines are represented sometimes means that it is difficult to find experienced people to serve on the committee. One way to solve this problem would be to condense the disciplinary areas and create some "at large" positions on ICWG. This option should be discussed at the next ICWG meeting.

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