International Priorities and Challenges in Antarctic Ice Core Science

A Contribution to the COMNAP Antarctic Roadmap Challenges
International Partnerships in Ice Core Sciences (IPICS)

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Introduction

International Partnerships in Ice Core Sciences (IPICS) is a group of scientists, engineers and logistics experts from the leading laboratories and national operators carrying out ice core science. Organized in 2004, the charge of IPICS is to advance the science based on ice coring by promoting international collaboration and exchange of information. IPICS has membership from 23 nations so far, an active steering committee, and organizes an international Open Science Meeting (OSM) every four years. The second OSM will be held in Hobart, Tasmania, in March 2016 (http://ipics2016.org/).

IPICS Priority Projects

IPICS has established five priority projects that require international collaboration and coordination to guarantee success.

The five projects are:

1. The oldest ice core: A 1.5 million year record of climate and greenhouse gases from Antarctica.
2. History and dynamics of the last interglacial period from ice cores.
3. The IPICS 40,000 year network: a bipolar record of climate forcing and response.
4. The IPICS 2k Array: a network of ice core climate and climate forcing records for the last two millennia.
5. Solving ice core drilling technical challenges to advance the science.

Documents describing IPICS and the priority projects can be found on the IPICS web pages at http://www.pages-igbp.org/ini/end-aff/ipics/intro. Brief descriptions of each project are provided here. IPICS is bi-polar, but Antarctic issues and challenges are emphasized here.

1. The Oldest Ice Core

The goal of this signature IPICS project is to substantially extend the length of the ice core record by drilling several new cores in Antarctica. Our motivation is based on the fact that climate scientists have an obligation to provide realistic assessments of how climate will change in the future. Doing so requires accurate models of how the Earth's climate system works and responds to changes. This in turn requires that we understand all the processes that can occur, and how they interact. This knowledge comes only from studying the past. Ice core studies have already revolutionized our view of the Earth system, documenting the recent rise of greenhouse gas concentrations beyond historical norms, the existence of abrupt climate changes, and the tight coupling in the past of climate and greenhouse-gas concentrations. In deep Antarctic ice cores, we can observe that we are currently living in a relatively mild "interglacial" phase within a series of warm/cold oscillations occurring every 100,000 years. These cycles must arise from a strong amplification of weak changes in energy inputs. And we can see that these small changes in input also cause major changes in the partitioning of carbon dioxide and other greenhouse gases between the atmosphere and other reservoirs. However, we still lack understanding of why these processes occur; this means that we still lack crucial knowledge about the natural regulation of carbon dioxide, and about the amplifications that make the climate system so sensitive. Both factors are important as we try to predict the future.

Our oldest ice core now extends over 800,000 years into the past. However, from marine sediments, we know that just before this time the pattern of climate variability was different, with cycles of only 40,000-year length. If we are to understand the state our climate is in now, we need to understand what caused the length of the cycles to change. Studying the interactions of climate and biogeochemistry in this earlier period will allow us to:

- Understand the natural variability that has led us to our current climate
- Assess the likely course our climate would take in the next few centuries to millennia in the absence of human interference.
- See numerous examples of the natural relationship between greenhouse gases and climate, allowing us to deduce the underlying rules that govern the system.
- Test the hypothesis that the change from 40,000 to 100,000 year cycles was caused by a lowering of atmospheric carbon dioxide concentrations.
- Better understand the timescales and processes that control exchange of carbon dioxide (including excess CO_2 from human activities) between reservoirs.

To confront these issues, we have a simple goal: to obtain from Antarctica a reliable ice core record of climate and biogeochemistry extending through several of the 40,000 year cycles and up to the present. In practice this means that we need to obtain a replicated Antarctic ice core record extending at least 1.2 million years, and preferably 1.5 million years, into the past. To meet this challenge we will need to carry out detailed survey and modeling work to identify sites where we can expect to find the oldest ice, to assemble an international team or teams capable of supplying the logistic effort, drilling expertise and intellectual knowledge to obtain the cores and the scientific returns from them, and to drill and analyse two or more cores at different sites to fully validate the records. The "oldest ice" project is gaining a lot of traction, with at least 3 initiatives being planned (multiple cores are needed), and several nations developing rapid access drilling that will assist in site selection. Because this project is exclusively Antarctic, it might warrant particular attention from SCAR, and we have highlighted its importance in previous responses to the SCAR/COMNAP Roadmap exercise. We wish to emphasize here that site selection will need more geophysical surveys likely involving extensive airborne and ground based work, and innovative radar and other technology to resolve internal layers at depth, detect flow disturbances, and assess aspects such as vertical strain rates and basal temperatures, and the likelihood that such surveys would require international collaboration in science and logistics.

2. History and Dynamics of the Last Interglacial Period

As concern about future climate change due to anthropogenic activities grows, it is increasingly important to have a long-term perspective on Earth system feedbacks operating during past warm (interglacial) climate periods. In the ice core record, the last interglacial period (LIG), identified in marine sediment records as marine isotope stage 5E, and in northwest Europe pollen records as the Eemian, is the most accessible interglacial period prior to the well-documented current interglacial, the Holocene. It is also marked by global mean sea level six m (or possibly more) above today's level, reflecting warmer conditions and partial deglaciation of Greenland and Antarctica, providing a benchmark period to assess the response of polar ice sheets to warm climates.

Existing ice core records of the LIG have been very informative but have important limitations. In Antarctica, eight sites (seven deep ice cores and two horizontal cores) include the LIG but additional records with higher resolution, and new records from additional sites, are necessary to characterize regional climate, ice sheet, and environmental change during this important time period.

Specifically, to fully understand the last interglacial and its implications for the future, we need to:

- Characterize the spatio-temporal structures of Antarctic climate and mass balance, including regional variations, and combine the ice core records with surrounding marine records.
- Document changes in atmospheric composition and natural climate forcings linked with solar and volcanic activity during this period.
- Constrain the evolution of the Antarctic ice sheets, and their contributions to global mean sea level under such a warmer climate.
- Relate the processes controlling polar climate and ice sheet variations from the present and the LIG to the predicted scenarios under future global warming.

In order to answer these questions we need to chart the full course of an interglacial from the penultimate glacial termination to the next glacial inception at very high resolution in numerous parameters, including greenhouse gases, and in numerous places, in Greenland, Antarctica, and possibly mountain ice caps. The aim would be to obtain information on forcings and responses at a level comparable to that available for the Holocene.

The Antarctic component of this challenge requires that we determine which Antarctic locations would be most suitable for further constraints on the EAIS and WAIS history, through a combination of modelling studies and remote sensing. Coring in regions sensitive to potential collapse of the West Antarctic Ice Sheet is especially critical. Specific issues for interpreting these new records that will require more research include:

- Improving the quantitative interpretation of ice core records in order to improve dating of LIG layers, deconvolve elevation and temperature signals, and understand post-deposition effects in areas affected by surface melt.
- Integration of ice core information into the climate and ice sheet-modelling framework, which requires developments in data assimilation and proxy modelling.
- Improvement of polar temperature reconstructions for the last interglacial from better understanding of relationships between water stable isotopes and climate, using climate models equipped with water stable isotopes.

To choose new sites in Antarctica a program of combining ice sheet and climate modeling and remote sensing data should be initiated to determine what locations would be most sensitive to changes in WAIS and WAIS history. We anticipate that cores addressing the last interglacial would be collected by individual countries or consortia of countries, within a comprehensive framework created by IPICS. As with the oldest ice project, we highlight here that selecting good sites will require extensive airborne and ground based geophysical work, which can greatly benefit from international scientific and logistical collaboration.

3. The IPICS 40,000 year network: a bipolar record of climate forcing and response.

This initiative uses new and existing ice cores from both polar regions that document the climate evolution over the Holocene, the last glacial/interglacial transition, and the latter part of marine isotope stage 3 (back to 40,000 years before present), where rapid climate changes dominate the climate history of the northern hemisphere. These cores provide essential information on the regional differences in ocean/atmosphere dynamics and the associated environmental changes (such as sea ice coverage, biological productivity etc.) over this time period in unprecedented resolution. Most of these cores are expected to come from smaller ice domes or coastal sites in the Arctic and Antarctic, and therefore will also provide crucial information on the extent and thickness of ice caps under various past climate conditions. Using state-of-the-art analytical tools and chronological control, the synthesis of these records using a master chronology will provide exquisite documentation of changes in the climate system over our current warm period, during the shift from glacial to interglacial conditions and during rapid climate changes of the last ice age. To this end all existing records that fulfill the criteria of this project will be assembled and further missing drill sites will be identified. The gaps in the 40k array will be filled by new intermediate size drilling activities that can be performed by single nation or multinational teams. However, the objectives of this project can only be achieved by a high level of integration of the individual deep ice core drilling projects on an international level and by a synthesis of records based on standardized methods. Publication of high profile papers from the WAIS Divide project has been a recent highlight for IPICS40k; the papers have brought new understanding of millennial scale climate change and carbon dynamics. Several groups are now turning attention to coastal ice domes around Antarctica as recorders of regional environmental change on the 40 ka time-scale.

4. The IPICS 2k Array: a network of ice core climate and climate forcing records for the last two millennia.

This initiative will use a global array of new and existing ice cores that document climate variability and climate forcing changes over the recent past, the last 2000 years ("2k array"). The period of 2000 years is both long enough to incorporate the "Holocene/Anthropocene transition", and short enough to be accessible with ice core records on all continents, including temperate and tropical glaciers, as well as polar ice sheets. Ice cores obtained or studied in the context of the IPICS 2k Array will provide essential information on regional changes in key climate variables such as precipitation, temperature and sea ice cover, as well as changes in climate forcing and biogeochemical cycles. Antarctica is key in this effort because the continent is severely underrepresented in existing compilations for this time period. New ice cores will be obtained from previously visited sites where only low resolution records have been obtained, or where re-visiting is necessary to bring the records up to date with the instrumental record. New cores will also be obtained from areas that have not been the focus of earlier programs, such as smaller ice domes or coastal sites in the Antarctic, and from small glaciers in temperate regions. The overarching goal of the IPICS 2k array is to contribute ice core data at sufficient resolution and dating precision to significantly enhance quantitative climate reconstruction and climate modeling studies, aimed at improved understanding of recent climate variability and change.

To meet this goal, sites that can provide several hundred to 2000 years of highly-resolved, datable ice will be identified. Ice cores will be obtained from these sites and analyzed using state-of-the-art measurements and dating techniques. Quantitative studies will be conducted to evaluate the relationships between the resulting climate proxy records and the relevant climate and climate forcing variables. Finally, the data will be compiled and made accessible to the broader climate research community. The 2k array will be achieved largely through the efforts of small teams. However, the objectives of this project can only be achieved by a high level of integration of the individual projects on an international level and by a synthesis of records based on standardized methods. IPICS2k is now pursued mainly through the PAGES Antarctic2k project (http://www.pages-igbp.org/ini/wg/antarctica2k/intro), which is led by Barbara Stenni, University Ca' Foscari, Venice. There will be a workshop in Venice in September 2015 to plan publications on temperature, accumulation rate and possibly sea ice.

5. Solving ice core drilling technical challenges to advance the science.

IPICS, through the four identified joint projects described in the IPICS white papers, has articulated a suite of requirements for drilling and coring capabilities to support their scientific goals. Although many of these requirements can be met with currently available technology, some will require the extension of current technologies or the development and testing of new ones.

Technical requirements relevant to Antarctic drilling identified in the four proposed IPICS projects fall naturally into two sets – those related to deep-drilling projects (the oldest ice project) and those related to the shallower 40 k and 2k projects. The deep drilling for oldest ice will require improvements in drilling fluids, applying successful strategies for recovering good quality cores through the brittle ice zone, institutionalizing successful approaches to core recovery in warm ice and developing methodologies for obtaining replicate samples. The 40ka and 2ka projects require the identification and standardization of a lightweight, 500 – 1,000 m capable, wet drilling system with simple logistical requirements and short setup and breakdown requirements.

In addition, the need for rapid access drilling and methods of in situ analysis in boreholes to determine age vs. depth relationships and measure geophysical properties like basal heat flow has emerged from discussions about site selection for the oldest ice project.

Many of these challenges have been taken up. Rapid access drilling is being developed by teams in Europe and the US, with testing planned for upcoming field seasons. *In situ* analysis of chemical parameters is also under development in France. (Geophysical logging of boreholes for various properties, also a type of *in situ* analysis, is already well developed). Advanced replicate coring has been successful in the WAIS Divide project. Lightweight, relatively portable drills are now available in several nations, although in some cases could be streamlined further. Active research on drilling fluids continues but the need for a drilling fluid capable of performing well in very cold deep ice remains.