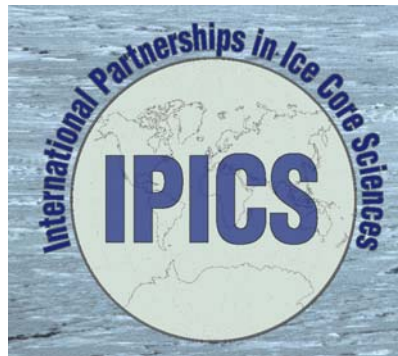


**International Partnerships in Ice Core Sciences
(IPICS)**

**The IPICS 2000 Year Array: ice core contributions to
quantitative assessment of recent climate forcing and climate
variability.**

*Science and coordination plan
April 2008*



Executive summary

The international ice core community has, under the auspices of International Partnerships in Ice Core Sciences (IPICS), defined four priority projects for the next decade or more. One of these is the study of 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 (“2 k 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 possibly sea ice cover, as well as changes in climate forcing. 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 2 k 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 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 2 k 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. A specific 2 k Array working group will be installed by IPICS to guide and facilitate such integration.

Contents

To be completed later

1. Introduction - the IPICS priority projects

Ice cores have revolutionized our view of the Earth system, and have become a cornerstone of research into climate. For example, they provided the first clear evidence that abrupt climate changes have occurred, and they have shown that greenhouse gases and climate have been tightly linked over the last 800,000 years. Ice cores have provided much of our information about how greenhouse gases and other pollutants have increased in recent times, as well as highly resolved information on polar climate variability. Ice core studies have already made a huge contribution to societally-relevant and global-scale issues, such as furthering our understanding of climate change, and by tracking the extent of global pollution.

However, much more still needs to be done, especially to meet the challenge of understanding how the Earth's combined biogeochemical/climate system works, and how it will respond to the change in atmospheric composition currently taking place. Recognizing this, all the major ice coring nations have combined to define an agenda for future research.

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. It has gained recognition or sponsorship from the IGBP Past Global Changes (PAGES) project, from the Scientific Committee on Antarctic Research (SCAR) (helping to meet the goals of SCAR's Antarctic Climate Evolution (ACE) Programme), and from the IUGG's International Association of Cryospheric Sciences (IACS).

At the first IPICS meeting, in Washington, DC in 2004, participants identified several high priority international scientific projects to be undertaken over the next decade or more. At the second IPICS meeting, in Brussels, Belgium, in October 2005, these projects were further defined, and routes to implementation were discussed. The 2005 meeting also placed IPICS on a more formal footing. It now has an international steering committee including representatives of 20 nations. It was agreed that the next step is to form planning groups around each of the scientific projects; an additional international group of drillers and engineers has been organized.

The priority projects are:

1. The oldest ice core: A 1.5 million year record of climate and greenhouse gases from Antarctica.
2. The last interglacial and beyond: A northwest Greenland deep ice core drilling project.

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

The technical and drilling group is developing plans around the title “Ice core drilling technical challenges”.

Each of these projects has a white paper (available at the IPICS web site at <http://www.pages-igbp.org/ipics/whitepapers.html>) that outlines the scientific requirement and some of the issues that must be solved in order to realize the science goals. This needs to be expanded into a science plan that explains in more detail the scientific rationale and targets behind each project. In some cases, it is also necessary at this stage to define an outline implementation plan that discusses ways of realizing the goals and of overcoming the technical and organizational impediments to them. The current document is the science and outline implementation plan for the fourth project: “The IPICS 2000 Year Array: ice core contributions to quantitative assessment of recent climate forcing and climate variability.”

2. Motivation and scientific challenge of the IPICS 2k Array

One of the major contributions of paleoclimatology is the production of high resolution (annual to decadal) data of sufficient quality to be used in climate change detection and attribution studies, in quantitative studies of climate variability and in determination of changes in climate forcing. Important examples include: the network of tree rings records that are the foundation of the well-known reconstructions of past temperature over the last millennium; and records of cosmogenic isotopes from ice cores, used to determine past changes in solar forcing. Such records are fundamental to the study of climate on the timescales (decadal to century) that are of the greatest interest to climate dynamics studies, which are hampered by the relatively short period of direct instrumental climate observations. The timescales made accessible by these records are also of the greatest relevance to the formulation of climate policy, in the context of anthropogenic climate change. Yet the number of records that can contribute directly to the quantitative assessment of climate change and climate variability on these timescales remains quite limited. More records are needed at high temporal resolution and with precise dating, and obtained recently enough to allow for direct comparison with instrumental records. Additionally, further refinement and development of techniques is needed, to take advantage of the different types of data available from different paleoclimate archives. A particular challenge is the integration of records that are dominated by high frequency signals (e.g. tree rings) with those that are dominated by lower frequencies, or whose effective frequency resolution changes through the record (e.g. ice cores).

Ice core records are best known for the unprecedented picture they have provided of climate and climate forcing on long timescales – millennial and longer. Yet the potential also exists for much greater use of ice cores in studies of more recent and higher-

frequency climate variability. In the last decade, several initiatives have focused on obtaining ice cores records with significant spatial density: these include the multinational ITASE (“International TransAntarctic Scientific Expedition”) in Antarctica, the PARCA (“Program for Arctic Regional Climate Assessment”) program in Greenland, and the collection of multiple cores in the Andes, Northwestern North America, and Asia. Results from these projects have demonstrated the utility of multiple ice core records in quantitative reconstruction of climate at annual resolution. Examples include new assessments of surface mass balance on both the Antarctic and Greenland ice sheets, the first demonstration that Antarctica has warmed in the last century, and the identification of pre-industrial climate regime shifts in the northeast Pacific.

While projects such as ITASE have generally focused on the very recent past (last 100-200 years), they provide the necessary first step in identifying those sites, and those techniques, which are most promising for extending ice core records to longer timescales, while retaining high resolution information. The ice core research community is thus well positioned to contribute important new paleoclimate observations, as well as determinations of past climate forcing changes, that are required for improved understanding of recent climate variability and climate change. The purpose of the 2000-year array (“2k Array”) initiative is to provide the framework to ensure that this potential is realized.

The choice of 2000 years as a target time period for focused ice core studies is motivated by several factors. First, this time period captures the transition from agricultural to industrial societies, and the attendant changes in the land surface and the composition of the atmosphere. Second, 2000 years represents a sufficient number of different realizations of climate to capture a statistically meaningful sampling of natural variability on decadal to century scales. Third, 2000 years is a short enough time period to be realistically achieved at most potential ice core drilling locations, including small glaciers and ice caps outside the polar regions. The target interval of 2000 years thus allows for significant expansion of the spatial coverage of ice core records, without compromising the high temporal resolution necessary for quantitative studies at decadal or shorter timescales. Finally, 2000 years is the time period that has been targeted by many recent studies using other paleoclimate archives, such as tree rings and corals.

There are at least seven areas where an expanded and improved network of ice core records, covering the last 2000 years, can provide unique information, not available from other paleoclimate archives:

- Solar forcing. Virtually all modeling studies use the record of ^{10}Be , from a single core at the South Pole, as the basis of solar forcing estimates prior to the ~400-year records of sunspots. This record needs to be improved with multiple records of equal or better resolution, from different latitudes, to separate meteorological noise from solar forcing changes. Cosmogenic isotopes will be prohibitively expensive to measure at all sites, but it is essential that multiple records from several key sites be obtained.

- Aerosol forcing. High resolution ice core records, combined with advanced modeling studies continue to improve our ability to use ice core records to obtain quantitative records of past changes in soot, dust, and aerosols. New isotopic techniques provide the opportunity to examine changes in sources, in atmospheric photochemical reactions, and to identify the stratospheric vs. tropospheric influence of specific volcanic eruptions.
- Sea ice and sea surface temperature change. Recent comparisons between sea ice extent and records of sea-ice related geochemistry such as methanesulfonic acid, and the development of new proxies such as the $\Delta^{17}\text{O}$ of H_2O , indicate considerable promise for quantitative reconstruction of ocean surface humidity, temperature, and sea ice conditions.
- Temperature variability and change. Improved understanding, through model simulations and shallow ice core networks, of the controls on stable isotope concentrations has contributed to the increasingly quantitative use of this traditional proxy as a measure of past temperature variability.
- Precipitation variability and glacier mass balance. Recent work on high resolution ice cores, notably from Antarctica and the northwestern North America, have demonstrated the utility of ice core snow accumulation records in reconstructing past changes in precipitation, which are tied to large scale atmospheric circulation change. Additionally measurements of both snow accumulation and density provide important information on ice sheet and glacier and ice sheet mass balance.
- Atmosphere dynamics. Aerosol and isotope tracers in ice cores are intimately linked to long-range atmospheric transport. The potential of high resolution records of such tracers should be exploited to reconstruct patterns of atmospheric variability and possible regime shifts.
- The Little Ice Age/Medieval Warm period. Remarkably, it remains uncertain to what extent the putative Little Ice Age was a globally colder event. Multiple, 2000-year ice core records from Antarctica could establish the pattern, extent, and sign of LIA-related changes, addressing a fundamental, longstanding problem in climate science.

3. Meeting the Challenge: Criteria for Site Selection

The overarching goal of the IPICS 2 k Array is to contribute ice core data of sufficient quality to significantly enhance quantitative climate reconstruction and climate modeling studies, aimed at improved understanding of recent climate variability and change. To meet this goal, we will need to identify sites worldwide that can provide 2000 years of highly-resolved, precisely-datable ice; we will need to obtain and analyze cores from these sites, and we will need to demonstrate that the records obtained can be linked quantitatively to relevant climate and climate forcing variables.

Although there is overlap between ice cores sites appropriate for 2 k Array and those sites selected for other purposes (such as the IPICS 40 kyr network), requirements for site selection will in general be quite different. For the 2 k Array, it is essential that records be datable at a precision of at worst a few years, and ideally at the subannual scale. This requirement stems from the need to demonstrate quantitative relationships between the ice core proxy data and key climate or climate forcing variables of interest, such as temperature or solar irradiance. In cases where annual-scale resolution is not achievable, it may be possible to use lower resolution information, as long as it can be tied quantitatively to higher-resolution records. For example, at many sites diffusion will preclude annual resolution of water stable isotope ratios at depth in the core, yet calibration against the instrumental temperature record will still be possible over the most recent few decades. In this example, if an independent method is used for dating (e.g. identification of seasonal cycles in dust, sulfate, and other species with little mobility in the ice on century timescales, the multi-year average isotope record will still be useable. It will also be important, due to the presence of significant high frequency noise, that multiple records be obtained wherever possible. Results from multiple-coring efforts show that in general less than 50% of the interannual variance is shared among ice core records. Extracting the common signal using methods such as compositing (stacking) or multiple linear regression is required if quantitative comparison with the target variable (climate or climate proxy) is to be achieved. . Use of volcano-derived chemical markers should be used as much as possible to refine synchronization of multiple cores, as should high-frequency radar stratigraphy.

We identify five main components to the successful implementation of the IPICS 2k Array program:

1. To compile and assess existing high resolution records.
2. To identify those sites that are most likely to yield highly-resolved, undisturbed records to 2000 years. Sites with that lie in climate “centers of action”, with strong interannual variability, should be emphasized, to improve signal-to-noise-ratios for the reconstruction of teleconnection patterns. Sites that are marginal for soluble ions and gas records, due to warm ice temperatures, should nevertheless be considered seriously because of the potential to obtain records of snow accumulation that can be linked to large-scale precipitation variability.
3. To examine the relationship between proposed and existing records and key climate variables of interest, using modeling and statistical studies, and to develop improved methods for using variable-resolution records in quantitative reconstruction.
4. To obtain records from new sites, and to obtain new records from previously-drilled sites, to increase overlap with the modern instrumental era.
5. To synthesize data from all the sites, and to make it available to the broader community in a readily-usable format.

Drilling and scientific investigation of most of these cores will be carried out in smaller national projects, where logistics and science are shared and coordinated within the respective project partners. There will also be overlap with existing multinational efforts, since the upper few hundred meters of various deep cores (e.g. the U.S.-based WAIS

Divide core, the EPICA cores) will fulfill the criteria for the 2 k Array. Accordingly, for the 2 k Array project, IPICS largely represents an umbrella for scientific and technical exchange and eventually for the synthesis of the records (see below). Although cores have been obtained at many of the sites that would be needed for the IPICS 2 k Array, in general there will be important value in revisiting previously drilled sites, due to need to overlap with the instrumental record, and due to the importance of having multiple cores to reduce noise. Some particular geographic areas are notable because of their obvious potential; this should not be considered a comprehensive list:

- Central West Antarctica and the Antarctic Peninsula. High resolution records could be obtained at sites identified by the ITASE program of ~200-year cores. Logistics could be leveraged with ongoing US and British projects in these areas.
- Coastal domes in both East and West Antarctica and in Greenland have significant potential due to high accumulation rates. It is noted that in general cores from central East Antarctica will not provide the necessary resolution for IPICS 2 k Array.
- Additional, duplicate cores from high altitude cores from tropical and temperate latitudes should be obtained at the most promising sites.
- Many cores in the Arctic were drilled more than 20 years ago. These sites should be revisited to update the records to the present.

4. Common scientific work programme

The most important aspects of the 2 k Array is the achievement of a uniformly high quality set of data. It will be essential that the stated precision of dating be well documented and justified, and that original, raw data be available. This will require coordination of the measured ice core parameters as well as quality control of the data sets.

Efforts should be made to involve scientists from outside the ice core research community, to take greatest advantage of the relevant expertise. In particular, the expertise in the tree-ring research community should be taken advantage of, in developing and applying statistical methods for high-resolution reconstruction of past climate. It will also be desirable to expand the use of tracer-enabled general circulation models.

Different ice core sites will require different measurements, and it will not necessarily be fruitful to lay out specific requirements for formal recognition of an appropriate “2 k Array” project. However, it is recommended that, at a minimum, most such projects should include:

- Continuous records of the “standard” climate proxies (stable water isotope, ion chemistry including biogenic sulphur and sea salt as well as particulate dust) at the highest achievable resolution, in most cases at least annual. Records of dust concentration, organic tracers of biomass, and industrial

pollutant aerosol concentrations should also be obtained wherever possible. Density measurements should be at the highest possible resolution and precision, to contribute to satellite-based studies, and to accurate surface mass balance calculations.

- High resolution (annual to subannual) records of volcanic deposition, bomb-radioactivity (beta-decay, ^{36}Cl and ^{210}Pb), providing the necessary data for synchronisation of ice core records.
- Precise measurements of density and vertical strain, to allow for correction of layer thickness measurements to annual snow accumulation rates. Vertical strain estimates, supported by surface velocity and strain rate measurements and ice flow modeling, will be particularly important in non-polar sites, where ice 2000 years old may be in the lower 1/3 of the core, where deformation due to flow becomes significant.
- High frequency radar studies should be routinely be used to aid with synchronization of ice core timescales, to identify areas with low spatial variability in snow accumulation, and to create spatial maps of accumulation through time.
- Multiple cores from the same or nearby sites to to aid in separating signal from noise.
- Standardized procedures for archiving; where possible, additional cores should be drilled for archival purposes.

Individual projects participating in the IPICS 2 k Array are requested to archive a sufficient amount of ice and make it available for other IPICS groups to measure additional parameters after the standard climate records of the respective core have been published. It is noted that some areas are in danger of being lost as ice coring sites due to regional warming. Such areas should receive the highest priority.

IPICS will organize regular intercalibration of analytical methods to insure that records from different cores, generated in different labs, can be compared with a high degree of accuracy.

5. Data exchange and synthesis

Data exchange and data synthesis represent an indispensable part of the IPICS challenge. This requires:

1. Free flow of data between IPICS partners. To ensure intellectual rights data must become available to other IPICS partners for internal use and must become publicly available after publication on an international data bases (such as PANGAEA, world data centers, Journal web pages etc.). IPICS will provide a common data format and data platform to ensure efficient data exchange, or arrange with an existing international data base group to manage IPICS data.

2. Synthesis studies after data sets of all required locations have become available to the

IPICS members. To this end special working groups will be established within IPICS and all data sets have to be provided for this synthesis. All data groups providing data and additional specialists become members of the working group and co-authors of the synthesis papers. The working groups themselves will organize its work plan and details of publication issues.

3. To implement synthesis, regular (at least annual) working meetings of the synthesis group have to be organized.

6. Collaboration and coordination

While each of the drilling projects within the IPICS 2 k Array is primarily organized and coordinated independently, the IPICS framework provides an ideal stage for an overarching coordination of logistics and drilling activities. Accordingly, updates on ongoing and planned ice core drilling activities should be given by each group either during IPICS steering committee meetings or in annual IPICS status reports to fuel the discussion of potential collaboration and logistic synergies as well as in using drill equipment of other groups or joint drill development. Especially, for the drilling issues the established IPICS drilling group is expected to organize efficient information exchange and collaboration.

7. Next steps

This plan has been written by the sub-group of the IPICS SC that was asked to compile the main scientific objectives and integration plan for the 2k Array project: Eric J. Steig, Hubertus Fischer, David Fisher, Massimo Frezzotti, Joseph R. McConnell, Valérie Masson-Delmotte, Tas van Ommen, Eric Wolff.

The next step for this science and implementation is its formal endorsement by the IPICS SC. In that process a list of all ongoing ice coring activities that fulfill the 2 k Array criteria and those where planning is in its final stage should be compiled by the IPICS SC/2k writing team. The addition of meteorological and tracer-modeling components should be considered as a formal part of the IPICS 2 k Array. It is noted that a variety of atmospheric models equipped with the explicit modeling of stable isotopes have now been run over the past century, and provide new and important opportunities for model validation and the possibility of climate reconstruction using forward calculations with physical models and formal inverse procedures.

Finally, it is recommended that the IPICS SC consider invited a few key scientists from outside the ice core community be added to the SC for this project, to help with the goal of fully integrating the ice core results into broader climate change community.

Version:

This version is a first draft for discussion, dated April 9th, 2008. It has so far been created and edited by a small sub-group of the IPICS SC, and is now available for

discussion and comment by the entire IPICS SC. It may be updated in the coming months, but will remain a draft until adopted by the next formal meeting of the IPICS SC.