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
As approved by IPICS SC: March, 2009

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 ("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. 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. A 2k array working group under the auspices of IPICS will guide and facilitate such integration.

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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 and biogeochemistry. 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. Recognising 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 [Brook and Wolff, 2006]. It has gained recognition or sponsorship from the IGBP Past Global Changes (PAGES) project, and from the Scientific Committee on Antarctic Research (SCAR) (helping to meet the goals of SCAR's Antarctic Climate Evolution (ACE) Programme). It has also been in discussion with 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 21 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 third IPICS meeting, held in Vienna in April 2008, endorsed (subject to minor changes) the current document. 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 during the last 40,000 years.

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

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

Each of these projects has a white paper (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 ring 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 substantial overlap with and 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 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 and climate forcing at annual resolution. Examples include new assessments of surface mass balance on both the Antarctic and Greenland ice sheets, the demonstration that West Antarctica has warmed in the last century (Figure 1),

and the identification of climate regime shifts in the northeast Pacific (Figure 2).

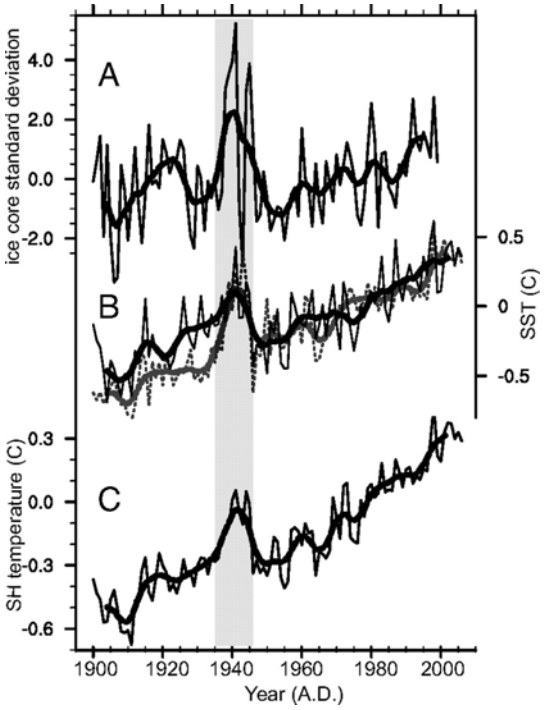

Figure 1 (left). Comparison of West Antarctic ice core stable isotope stack (A) with sea surface temperature (B) and Southern Hemisphere air temperature (C). From Schneider and Steig, *Proceedings of the National Academy of Sciences*, 2009. Note the large response to the exceptional 1940s El Niño event, superimposed on the overall warming trend.

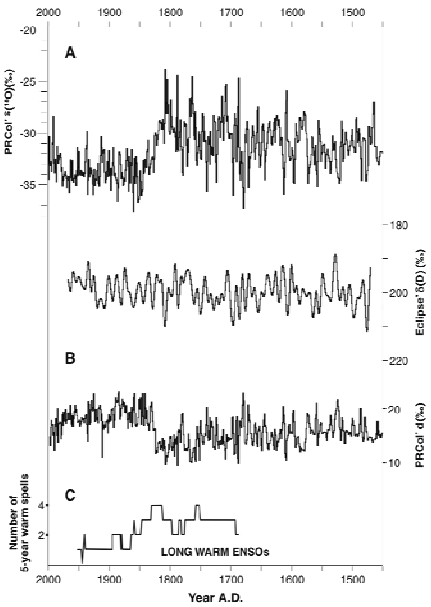

Figure 2 (right). Stable isotopes time series from Mt. Logan (PRCol) and Eclipse Dome, Yukon, Canada, compared with El Niño records of the last ~500 years. After Fisher et al., *Géographie Physique et Quaternaire*, 2004. Note the evidence of significant regime shift in the deuterium excess (*d*) data in about 1850 A.D.

While projects such as ITASE and PARCA 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 nine 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:

1. 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 (Fig. 3). 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.

2. 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 (Fig. 2). 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.

3. 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 $\Delta^{17}O$ of H_2O, indicate considerable promise for quantitative reconstruction of ocean surface humidity, temperature, and sea ice conditions.

4. 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.

5. Precipitation variability and glacier mass balance. Recent work on high resolution ice cores, notably from Antarctica and the northwestern North America, has 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.

6. 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.

7. Biogeochemical understanding. Most trace compounds measured in ice cores, including reactive trace gases, have a residence time in the atmosphere of several days to weeks. They thus show large spatial differences, reflecting the complex interactions between the location of their main sources, their atmospheric chemistry, and the atmosphere dynamics. Examples include carbon monoxide, organic compounds (e.g. black carbon), and isotopic tracers related to the oxidative capacity of the atmosphere (oxygen in nitrate for instance). It is important, wherever the glacier provides a suitable record of such species, to document the inhomogeneities of their spatial distribution in order to better constrain the biogeochemical cycles and their relationships with climate variability.

8. Reconstructions of centennial- to millennial-scale climate variability in the late Holocene. A high-resolution network, integrated with other proxy data will allow spatial and temporal patterns of variability to be better characterized. In particular it should be possible to establish whether climate changes on these timescales are global in extent, and whether they are characterized by patterns of variability similar to those on shorter timescales. This would address a fundamental, longstanding problem in climate science.

9. Improved understanding of the gas occlusion process under a range of temperature and accumulation conditions, and achievement of a greatly increased resolution of the trace gas history in the northern hemisphere and the tropics, to complement the existing records from Antarctica. Among other goals, this would allow for improved assessment of changes in the interhemispheric gradient in gas concentrations and their isotopic signature, with the objective of better identifying sources and sinks.

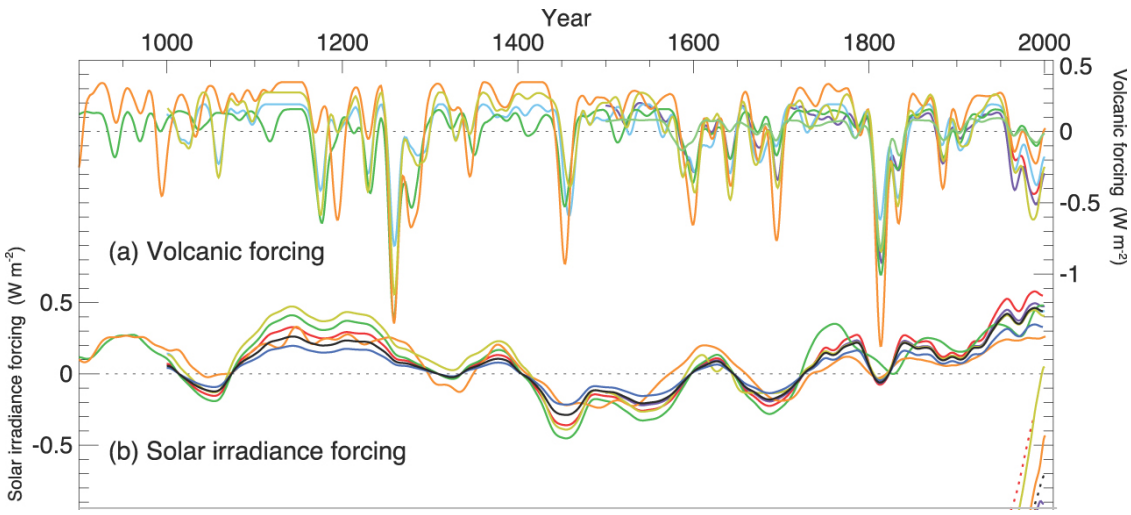

Figure 3. Estimates of solar and volcanic forcing, based mainly on ice core data, used in model simulations for the last 1100 years (Figure 6.13 of IPCC AR4). Improving these

estimates is one goal of IPICS2K.

One particular challenge is the need to collect material from glaciers that are in danger of disappearing, or whose record is likely to be compromised as warming occurs. This applies to some of the non-polar glaciers on Earth. A particular effort will be needed to collect and archive such material as soon as possible, so that the regional information they contain will be available in the future.

3. Meeting the Challenge: Criteria for Site Selection and Successful Implementation

The overarching goal of the IPICS 2k 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 2k array and those sites selected for other purposes (such as the IPICS 40 ka network), requirements for site selection will in general be quite different. For the 2k 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 using volcanic peaks or other unambiguous or other precise temporal markers. 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. 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 six main components for successful implementation of the IPICS 2k Array program:

1. Compilation and assessment of existing high resolution records.
2. Identification of those sites that are most likely to yield highly-resolved, undisturbed records for 2000 years (though shorter records will be valuable where 2000 years cannot be achieved). Sites 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 because of the potential to obtain records of snow accumulation that can be linked to

large-scale precipitation variability. For gas records, sites would need to be chosen that have high accumulation rates, cold temperatures and low impurity concentrations.

3. Examination of the relationship between proposed and existing records and key climate variables of interest, using modeling and statistical studies, and development of improved methods for using variable-resolution records in quantitative reconstruction.
4. Obtaining records from new sites, and new records from previously-drilled sites, to increase overlap with the modern instrumental era.
5. Synthesis of data from all the sites, making it available to the broader community in a readily-usable format.
6. Duplication of records wherever possible, at least over the most recent part of the record where there is overlap with the instrumental record, both for high-volume measurement requirements and to reduce the signal-to-noise ratio through repeat measurements.

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 by 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) will fulfill the criteria for the 2k array. Accordingly, for the 2k 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 2k array, in general there will be important value in revisiting previously drilled sites, due to the 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 goals.
- 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 2k 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 "2k 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, visual stratigraphy, electrical conductivity and/or dielectric properties, ion chemistry including biogenic sulphur and sea salt as well as particulate dust) at the highest achievable resolution, with a strong preference for 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 accurate surface mass balance surface elevation calculations, and ice core physical properties studies.
- High resolution (annual to subannual) records of volcanic deposition, bomb-radioativity (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.
- Where feasible, access to boreholes after drilling is complete should be facilited and encouraged for measurement of borehole temperatures and installation of instrumentation for multi-year borehole temperature monitoring. Access to boreholes will also permit studies of the gas occlusion processes. Physical properties of the ice, especially in the bubble close-off zone, are of interest.
- High frequency radar studies should 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 should be obtained from the same or nearby sites 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 2k 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 obtained. 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 ensure 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 IPCIS 2k array will often be 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.

The next step is to begin compiling and updating a list of all ongoing and near-term planned ice coring activities that fit the 2k criteria. Based on that list, missing drill sites which will fill the most important gaps will be identified by the IPICS SC/2k writing team. Identification of gaps should be informed by available information about potential sites. Although many 2k ice cores will be obtained by small teams, it would be desirable to facilitate greater coordination, including 1) an joint effort to synthesize and publish a summary of current knowledge of the last 2000 years of climate and climate forcing history from an ice core perspective and 2) a joint effort to select and plan for drilling at certain key sites where new international collaborative projects would be most effective. The IPICS SC/2k writing team will work together to begin this process. We recommend that completion of the IPICS 2 k drilling activities and the scientific integration be targeted for 2015.

Version: This version was prepared after comments by the IPICS SC meeting in April 2008, and the edits were accepted by the SC leading to this version dated March 2009.