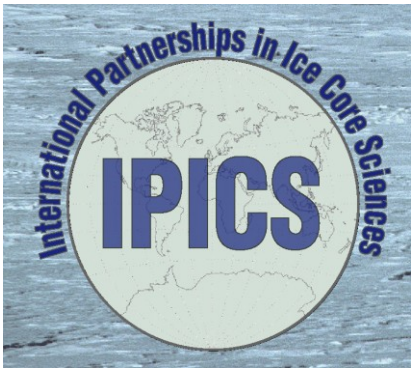
International Partnerships in Ice Core Sciences
(IPICS)

IPICS 40k: Bipolar sequence of climate forcing and response during the last 40 000 years

Science and outline implementation plan
As approved by IPCS SC: 1st September 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 sequence of 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, where rapid climate changes dominate the climate history of the northern hemisphere.

These cores will 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. A specific 40k array working group will be convened by IPICS to perform these tasks. All nations involved in the retrieval and analysis of one of the participating cores, as well as experts on climate modeling and on other climate archives covering this period, will be represented on that team.

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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.
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 are 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.unibe.ch/science/initiatives/ipics/whitepapers.html) that outlines the scientific requirement and some of the issues that must be solved in order to realise 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 realising the goals and of overcoming the technical and organisational impediments to them. The current document is the science and outline implementation plan for the third project "The IPICS 40,000 year network: a bipolar record of climate forcing and response."

2. Motivation and scientific challenge of the IPICS 40k array

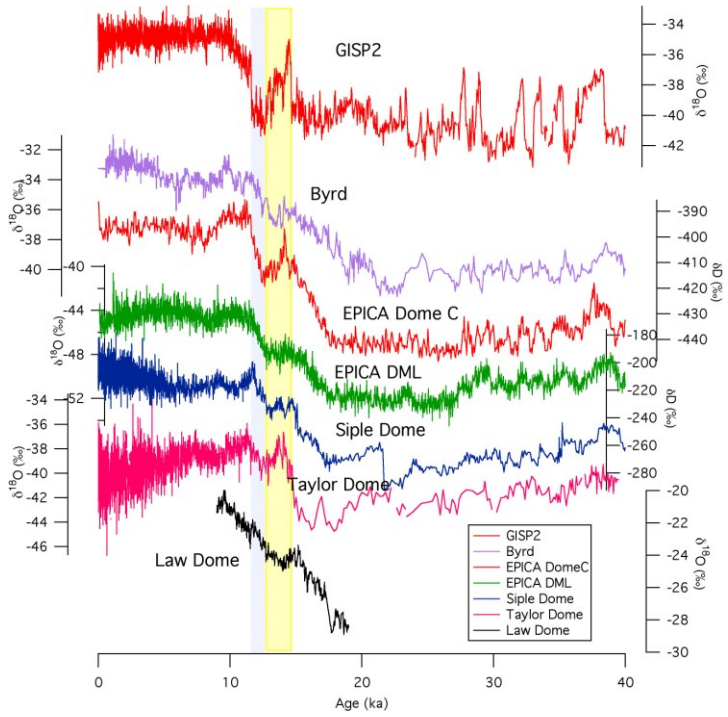

Figure 1. A comparison of climate records from Antarctica and Greenland after CH_4 synchronization. The last 40,000 years is the best documented time period of both the imprint of abrupt shifts in climate in both hemispheres, and the large change from glacial to interglacial conditions.

The last 40, 000 years include the glacial/interglacial transition, our present warm period, the Holocene, as well as a sequence of abrupt swings in climate as recorded in Greenland ice cores and other climate archives. The glacial-interglacial transition is the best-documented global response to very large-scale changes in climate boundary conditions, and the earlier abrupt changes are the best examples of this enigmatic process. In addition, the Holocene was one of the most stable climatic periods, potentially providing the conditions for an outburst of human societal development. The reason for this apparent climate constancy in Holocene climate as well as the linkage between preindustrial climate swings and human development is still a matter of debate. Understanding and simulating these changes are critical challenges for our ability to

model the earth system. To do so we need to understand their spatial and temporal evolution better. Existing data show that the transition and the abrupt changes are characterized by different patterns of long-term warming in the north and south, and related changes in greenhouse gas concentrations, accumulation and ice sheet extent. However, we do not yet fully understand the mechanisms linking the climate of the two hemispheres, the patterns of the regional response in the two polar regions, or the persistence of subdued rapid shifts throughout the Holocene. Ice cores are uniquely placed to provide the contrasting polar elements of climate in very high resolution and provide a suite of measurements (such as greenhouse gases) only avaiable from ice cores.

In particular, we need to:

- Determine spatial patterns in environmental parameters that relate to the ocean surface conditions (e.g., sea ice, marine biological productivity, storm activity).
- Construct the sequence of events (including forcings and responses) through the last glacial-interglacial transition across different geographic areas of both polar regions at the highest resolution possible.
- Synchronize the new records using high-resolution measurements of CH_4, CO_2, volcanic and dust stratigraphies, as well as isotopic compositions of air components.
- Identify climate modes and teleconnection patterns under different climate boundary conditions (orbital forcing, greenhouse gas concentration, land ice masses) by using coupled atmosphere-sea ice-ocean models, possibly in conjunction with regional models.
- Quantify and understand the spatial and temporal evolution of rapid climate changes in both polar regions related to changing thermohaline circulation, an objective of utmost relevance for a future world subject to increased anthropogenic warming.
- Compile high-sensitivity evidence of subdued rapid climate transitions throughout the Holocene.

In addition, we need to understand the response of the Antarctic, Greenland and Arctic ice sheets to climate change. In particular the contribution of the large ice sheets to the glacial/interglacial sea level change, and the temporal evolution over the last 40,000 years, are still a matter of debate. Ice sheet models differ in predictions of the extent and thickness of the major ice sheets at the LGM and their contribution to global sea level during the deglaciation. With the expansion of the ice sheets during the glacial period, some modern coastal ice domes may have merged with the inland ice. Ice cores from these locations can provide basic information (snow accumulation, temperature, altitude, ice sheet extent) reflecting changes in the mass balance of ice caps and ice sheets, which ultimately control long-term sea level evolution, and provide validation of glacial land ice extent in coupled climate models. To achieve these goals we need to:

- Reconstruct accumulation changes at inland and coastal sites subject to different climate evolution and moisture transport.
- Identify changes in ice volume and local ice sheet altitude and, where possible, look for evidence of over-riding of local domes.

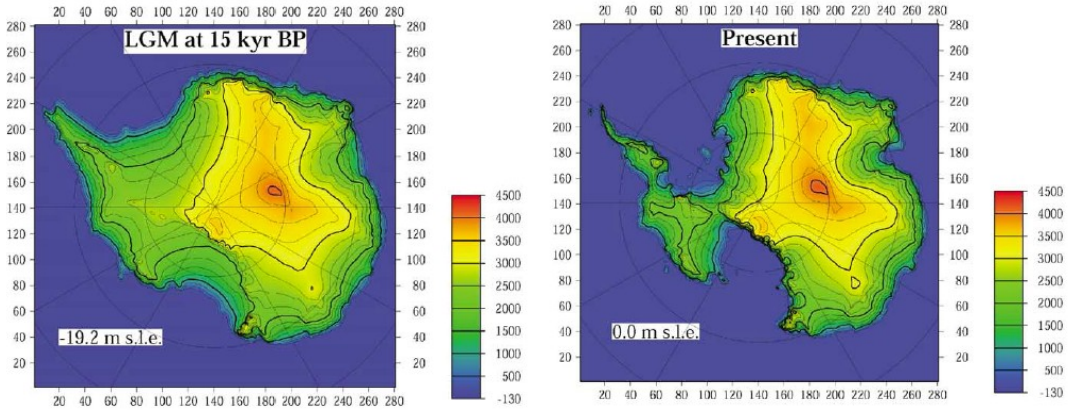

Figure 2. Modelled extent of the Antarctic ice sheet for glacial and present conditions. (From: Huybrechts, 2002, Quat, Sci Rev, 203-231)

3. Meeting the challenge

3.1 Potential drill sites

To document the climate evolution during the last glacial-interglacial transition, during the course of the Holocene and during abrupt climate changes, we need to complete a network of ice core records, covering each major sector of both polar regions, and extending over the last 40,000 years. Although some of the potential records might extend 100 kyrs or more and include the last interglacial, practical limitations confine most of them to a shorter period. The 40,000 year target is important and represents a key feature of potential IPICS 40k drill sites, as it includes the Holocene, the last glacial-interglacial transition, and one of the major Antarctic warming events related to abrupt climate change in the northern hemisphere. To answer the pertinent scientific questions related to Holocene climate stability and variability, additional ice cores may also be required from areas where it is not possible to obtain good records of the glacial-interglacial transition or glacial period such as high accumulation rate areas in both polar regions, as well as incorporating existing ice cores from tropical regions. Other information may be derived from outcropping ice when chronological order is ensured. Inclusion of such additional sampling sites covering the entire Holocene and potentially into the deglaciation is envisaged and should be decided on a case-to-case basis.

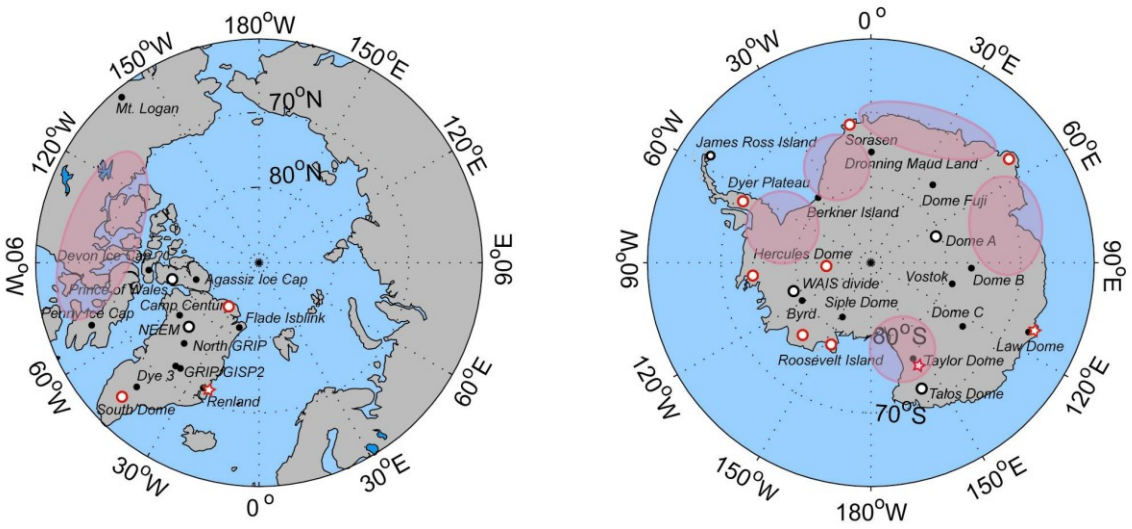

Figure 3. Map of both polar regions indicating drill sites of existing (black dots), ongoing (black open circles) and potential future (red open circles) ice cores covering the entire Holocene, the last deglaciation and beyond. Existing ice core sites with redrilling potential are indicated by red stars. Important areas of interest where potential drill sites are still to be identified are shaded.

Three steps are required to meet the challenge of the IPICS 40k array:

1. Complete drilling and analysis of all currently planned cores.
2. Identify the gaps in the spatial network of ice core sites and assess whether further suitable sites exist and to implement drilling of "gap" sites.
3. Synthesize data from all the sites with the goal to produce a comprehensive picture of the spatial and temporal pattern of major climate change over the last ~40,000 years

To document the spatial and temporal climate variation around the Southern Ocean a circum-Antarctic network of coastal domes is required. In the Arctic an expansion of the study area of glacial/interglacial ice cores from Greenland and the eastern Canadian Arctic into new regions must be explored. Sites in the Russian Arctic and Alaska are of major interest, but have so far failed to provide pre-Holocene ice core records: their potential must be reassessed. Existing ice core records of the appropriate age from non polar, high altitude drill sites should be compiled and integrated in the 40k assessment.

Drilling and scientific investigation of most of these cores will be carried out in smaller national or multinational projects, where logistics and science are shared and coordinated within the respective project partners. Accordingly, for the 40k array project IPICS represents a critical umbrella for scientific and technical exchange and eventually for the synthesis of the records (see below). Many of the cores that would be needed for this network have already been drilled, or are planned in the near future by individual groups (Figure 3). In particular:

- In central East Antarctica several cores already exist.
- In central West Antarctica, US investigators are drilling a deep core during 2006-2010.
- Around the Antarctic coast cores spanning the appropriate period are already available from Taylor Dome, Siple Dome, Law Dome and Berkner Island. For specific questions (such as high resolution greenhouse gas records where snow accumulation rate strongly determine the bubble enclosure characteristics) redrilling of already existing ice cores may be required.
- An Italian led project drilled at Talos Dome during 2005-2008. Additional planned drilling projects at James Ross Island (UK) and the Neumayer hinterland (Germany) may reach the relevant period.
- Inland Greenland is served by a south-north span of cores from Dye 3, Summit and North GRIP. Drilling at the NEEM site, in NW Greenland, starts in summer 2008. The Renland core also spans the period, although new cores from Renland and other coastal ice caps are crucial to get more state-of-the-art information on local climate variations around the Greenland ice sheet.
- A number of cores in the Canadian Arctic Islands (Agassiz Ice Cap, Devon Ice Cap, Penny Ice Cap, Prince of Wales Ice Field) and in Alaska (Mt. Logan) may span at least part of the required period. For some of these sites new cores may also be needed to get more state-of-the-art information.

Although this is already a substantial data base it is far from giving a complete picture of spatiotemporal climate variability (especially for Antarctica) and important information from some strategic drill sites is, therefore, missing completely. Accordingly, additional drill sites are required to fill the gaps.

3.2 Criteria for site selection

To meet the objectives of the 40k array thorough reconnaissance studies around the identified potential drill sites are necessary in most of the cases to choose the best drill site and to ensure that undisturbed climate records over the last glacial/interglacial transition and beyond can be obtained.

The parameters that have to be constrained around potential drill sites include:

- Ice thickness, elevation and basal topography
- Internal radar layers, to assess the likelihood of flow disturbance near the bed and of temporal changes in the dome/ice divide location at the drill site, and to in some cases provide estimates of the time scale
- Ice velocity
- Surface accumulation rate and its spatial variability
- Temperature, including estimates of basal temperature

- Ocean/atmosphere dynamics from local meteorological observations and/or reanalysis data sets (including sea surface temperatures, sea ice variability, atmospheric circulation) in the area of air mass influence on the drill site

4. Common scientific work programme

The most important aspect of the 40k array project is the polewide and global synthesis of the individual records after their completion. This requires coordination of the measured ice core parameters, establishing a master chronology for all sites and quality control of the data sets. Accordingly, IPICS approved ice core projects contributing to the 40k array 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) in decadal resolution. These records provide the base for the synthesis of climate evolution over the last 10-40,000 years
- High-resolution (annual to sub-annual) records of volcanic deposition providing the necessary data for basin wide synchronisation of ice core records such as electric conductivity measurements (ECM) and dielectric profiling (DEP). While quantification of changes in the volcanic sulphate deposition in annual resolution is preferable, in many cases the high sample load required may be prohibitive.
- CH_4 records in decadal to centennial resolution, providing the best tool to synchronize ice core records beyond basins and even across both hemispheres. Where individual project partners are not capable such measurements, collaborations with other IPICS groups will be necessary. Well-resolved ^{10}Be records would also contribute to this most important task, but due to the high costs and workload will only be possible in selected cases. High resolution and precision measurements of $\delta^{18}O$ of O_2 can complement and improve synchronization based on methane, and should be integrated into the 40k project. Based on these records a common IPICS age scale should be established in a joint effort of a designated dating group.
- One of the key goals of the IPICS 40k array is reconstruction of the temporal evolution of ice sheets and domes during the last glacial/interglacial transition. The only direct way to estimate altitude changes is by time-resolved, high precision air content measurements at all drill sites together with an improved understanding of the ´bubble enclosure process. Again partnerships established within IPICS should guarantee that this parameter can be determined at all drill sites.

Obviously, the whole list of ice core parameters that can be measured at each core is much longer, comprising for instance records of other greenhouse gases (CO_2, N_2O), seasonally resolved continuous chemistry analyses, trace elements as well as isotopic measurements on gases. While these parameters are not mandatory for the synthesis to be achieved within IPICS they are still extremely important and all individual projects are

encouraged to widen the spectrum of investigated parameters as much as possible. Accordingly, an unused section of the cores collected for the 40k array project should be archived, and an agreement that provides for sharing samples between nations involved in the 40k project should be developed.

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. Additional sampling programs

While the IPICS 40k array per se is an ice core program, many additional science activities can be perfomed in parallel to the drilling in the field, which provide additional, crucial information for the ice core records. Such programs are for example:

- Atmospheric aerosol sampling during summer seasons or preferably year-round constraining the air/snow transfer of aerosol species.
- Meteorological observations in the field, providing essential information for snow accumulation as well as boundary layer conditions. Together with back trajectory studies this will improve our knowledge on the origin of air masses affecting the drill sites.
- Shallow firn core and pit sample studies to constrain the regional variability in snow and aerosol deposition.
- Studies of snow metamorphism and firnification in snow pits and deep firn cores reaching the firn/ice transition. Among others, this information is important for an improved understanding of the bubble enclosure and thus for the gas record in polar ice cores.
- Deep firn core drillings should also be used for firn air sampling bridging the atmospheric gas record between ice core air bubbles and recent atmospheric observations.
- Temperature profiles and logging of deep drill holes.
- High resolution ice penetrating radar studies around the drill sites which provide information on ice layering, ice flow and bedrock topography. Those data are also the base for high resolution ice flow modelling for drill sites aiding the dating of the ice cores and the interpretation of ice dome changes in the past.

While those additional programs do not have to be inherent parts of the individual drilling projects, IPICS approved projects should search for respective partners and allow access to the drill sites for such additional programs to the IPICS partners as far as logistics allows. Respective agreements to cover the costs and logistics of such additional programs have to be negotiated individually.

6. Data exchange and synthesis

Key aspect of establishing an ice core array of deglacial climate changes is to reconstruct a bipolar history of climate and environmental parameters throughout the last 40,000 years and to pinpoint the coherencies and differences in regional climate evolution. Accordingly, data exchange and data synthesis represent an indispensable part of this 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.). The IPICS 40k committee will formulate a policy with the aim of having all datasets available in a common data format and on a common platform. One possible route would be an agreement with an existing data centre.
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. In addition outside experts from the climate and ice sheet modelling community or those working on other climate archives which are essential for the achievement of the 40k goals will be invited to these groups. The working groups themselves will organize its work plan and details of publication issues.
3. To implement this synthesis regular (at least annual) working meetings of the synthesis group have to be organized.

7. Collaboration and coordination

While each of the drilling projects within the IPCIS 40k array is primarily organized and coordinated independently, the IPICS frame work 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.

Also for the analyses and scientific interpretation of the records IPICS provides the joint expertise of all national ice core groups. Again IPICS is only regarded as an umbrella with all 40k array projects being per se independent but IPICS will foster new collaborations and exchange of all ice core science working groups.

8. 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 40k array project.

In that process a list of all ongoing ice coring activities that l the 40k criteria, and those where planning is in its final stage, has been compiled by the IPICS SC/40k writing team, and will be continuously updated. Based on that list, missing drill sites which will fill the most important gaps have to be identified by the IPICS SC/40k writing team. Identification of gaps should be informed by available information about potential sites, and current understanding of gaps in knowledge about climate variability over the 40 ka time period. A designated core site selection team (including the IPICS 40 k writing team and others) will lead an effort to synthesize and publish a summary of this current understanding as part of the additional site selection. For those missing sites potential consortia have to be found that are able and willing to carry out the ice core drilling and scientific analysis within the time frame envisaged for the IPICS 40 k array project. This requires also the necessary glaciological and geophysical reconnaissance in the respective areas to find an optimal drill site.

To date it is planned to complete the IPICS 40 k drilling activities and the scientific integration by 2015, however, a first integration should be already started on the base of existing ice cores records in 2008/09.

Version:
This version was prepared after comments by the IPICS SC meeting in April 2008, and the edits were accepted by the SC in August 2008. This version is dated 1 September 2008.