US GLOBAL ICE CORE RESEARCH PROGRAM

WEST ANTARCTICA AND BEYOND

By
ICE CORE WORKING GROUP

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Foreword

The plan "The US Global Ice Core Research Program: West Antarctica and Beyond" was developed over the past year by the Ice Core Working Group (ICWG) on behalf of the US ice core research community.

The ICWG was established following the recommendations of the "ad hoc Panel on Polar Ice Coring" established by the Committee on Glaciology of the Polar Research Board (National Academy Press, Washington, 1986). The ICWG was to "provide the scientific direction and the driving force" to a new Ice Coring and Analysis Program (ICAP) to be funded and managed by the Division of Polar Programs of the National Science Foundation (Recommendations for Implementation", p. 7-8 and p. 31).

The "Global Ice Core Research Program" provides an outline for US ice core research during the next decade based on the inventory of the research priorities and capabilities of the US ice core research community (Report "US Ice Core Research Capabilities", ICWG., University of New Hampshire, 1987) and on the conclusions of a Workshop on US Ice Core Research (13-17 June, 1988, "Compiled Reports of the US Ice Core Research Workshop", ICWG., University of New Hampshire). Specific scientific goals for the ice core projects outlined in the plan have to be defined by the group of PI's that will do the research.

For the ice core research community the long range research goals provide a scientific focus that will facilitate scientific exchange and collaboration both within the community and with other disciplines.

The development of a long-range ice core research plan by the community will enable NSF, the lead agency in the funding of ice core research, to institute a long-range funding and management plan for ice core research. This is essential for the efficient use of logistics and ice core drilling capability in support of the research as well as for an efficient use of the ice core analysis capacity of US laboratories.

A coordinated research effort over the next decade will greatly improve our understanding of the dynamics of climate and global change as well as of the dynamics and stability of the Polar ice masses.

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1. Executive Summary

Developing to its full potential the paleoenvironmental information contained in the ice masses of the world requires a long-range program in which expertise from many different fields is focused on a common goal.

The US ice core research community proposes that the US drill several deep and intermediate cores in Antarctica and Greenland during the 1990s with the first deep core in West Antarctica. The relative timing of the changes in various core parameters in cores from the Arctic and the Antarctic will help us understand the dynamics of climate and global change. The West Antarctic core should reveal the response of the West Antarctic ice sheet to the warm interglacial climate about 125.,000 years ago.

Expanded drilling and analyses of shallow cores in polar regions and at lower latitudes must complement the bipolar drilling program in order to document spatial variability in environmental change and to generate transfer functions to translate the long paleoenvironmental records from the Arctic and Antarctic into changes at lower latitudes.

To attain these scientific goals in a timely manner the Ice Core Working

Group recommends that:

- NSF/DPP adopts a long-range ice core research plan and takes an active role in the realization of this plan by creating the infrastructure needed for vigorous and flexible ice core research.

- NSF/DPP manages and actively seeks funds to support the long-range ice core research program to ensure fair and open access for all members of the scientific community.

- NSF/DPP supports key non-core studies that are directly related to ice cores and are necessary to ensure proper site selection and interpretation of core data.

- NSF/DPP, together with other programs and agencies, encourages the development of innovative techniques for ice sampling and analysis that may improve the quality and/or reduce the cost of paleoenvironmental information from ice cores.

- NSF/DPP encourages scientists to optimize the data retrieval from all ice cores by analysis and interpretation of many different core parameters in multidisciplinary collaborations.

- A database for rapid drill site selection as well as a database of the results of core analysis be collected and made available via the World Data Center.

- Unused core sections be curated in a US ice core storage facility and be made readily available for additional studies to US investigators and investigators of countries with which the US has scientific collaboration and exchange of sample materials and research data.

2. Global Environmental Change

Our natural environment has changed on a global scale in the past and will change in the future. Such environmental changes may negatively affect many areas of the world. Changes in the near future may result both from natural climate variability (which over the last few million years has been responsible for a sequence of cold and warm periods of variable intensity (glacials/interglacials; stadials/interstadials)) and from man-caused changes in atmospheric composition (especially of greenhouse gases like carbon dioxide ($C0_2$), methane (CH_4)

and nitrous oxide (N_20)) and vegetation which may trigger climate changes of similar magnitude. If the adverse effects of such changes are to be reduced by long-range planning and policy, then the large-scale environmental changes that may be expected over the next several decades to centuries need to be predicted with considerably more accuracy and detail than is possible today. We therefore need to understand the complex interactions between insolation, atmosphere, ocean, biosphere, and cryosphere that determine climate.

Important new information on the dynamics of major climatic change has been obtained over the past years from ice cores and deep sea sediment cores. It is now well established that major changes in global climate occurred almost simultaneously in both hemispheres. Such changes were accompanied by large changes in the concentration of the radiatively active gases $C0_2$ and CH_4 in the atmosphere. The concentration Of $C0_2$ in air trapped in ice from the last glacial maximum was 30% lower than in Holocene ice, while CH_4 was 50% lower. During periods of maximum glaciation, more vigorous atmospheric circulation is indicated by deuterium excess and by increased concentrations of dust and ions in the ice.

Deep sea sediments record the major changes in global ice volume in the oxygen isotopic composition of benthic foraminifera. These sediments also show evidence of changes in ocean circulation and nutrient distribution. Somewhat more detailed information on global ice volume changes during the last 160,000 years is available from cores drilled into Holocene and Pleistocene coral reefs.

The new data, however, also bring out the limitations of our current understanding of global climate change.

Deep sea sediment records as well as the Vostok ice core record show clear periodicities at 20 ka, 40 ka, and 100 ka which correspond to those of variations in the earth's orbital parameters and provide support for the Milankovitch theory that variations in insolation caused by orbital changes are responsible for the glacial-interglacial/stadial-interstadial climate changes. Enigmatically, insolation forcing is out of phase between the two hemispheres while climate change is not. Moreover, most of the climatic variability over the last million years occurs with a 100,000 year period, but most of the insolation variability occurs with 20,000 and 40,000 year periods.

The role of greenhouse gases like $C0_2$ and CH_4 in providing a positive feedback in climate change and synchronizing the response of both hemispheres has been widely discussed. Yet $C0_2$ and CH_4 increase in phase with increasing temperature but show a different phase response to cooling; CH_4 follows temperature directly (at the resolution of available data), but $C0_2$ lags. The exact phase relationship between temperature change and $C0_2/CH_4$ change as well as the degree of amplification of temperature changes by positive feedbacks, e.g. from greenhouse gases and albedo, is still unknown. More precise data on past changes in temperature and atmospheric composition are needed.

Several ocean models show how increased productivity in high latitude southern oceans could have produced the observed C02 lowering during glacial times. Yet the Greenland Dye-3 core shows several episodes where climate and C02 concentration seem to have changed by more than half of the full glacial-interglacial difference over a very short time interval (Dansgaard/Oeschger events). If real (and not artifacts of ice deformation near the bed) such rapid changes cannot be produced by current ocean uptake models. Further questions arise from the fact that the rapid changes found in Greenland cores seem to be absent in the Antarctic ice, and from the fact that the increase in 813C in deep sea sediment predicted by the C02 uptake models has not been observed.

Carefully collected data from ice cores from both the Arctic and Antarctic and from lower latitudes as well as from strategically located ocean sediment cores and terrestrial records are needed to help answer these questions and to elucidate the ocean-atmosphere-cryosphere-biosphere interactions and to reconstruct global environmental change due to natural causes on time scales of decades to 105 years. This knowledge will improve the estimate of current man-made climate change and allow more accurate prediction of changes to be expected over the next decades to centuries.

3. Archives of Ice

The polar ice sheets and high altitude ice masses preserve in their coldest areas a highly detailed record of climatic conditions and atmospheric composition at and around the time of snow deposition (Appendix A). In some areas of Greenland and Antarctica it may be possible to retrieve ice up to one million years old. This will give access to a global change record spanning several complete glacial-interglacial cycles. This record will provide a crucial test for the various atmospheric and oceanic general circulation models that should be able to describe the different glacial and interglacial climates in the past as well as the transitions between them. The outcome of this test of the past determines how wen we can expect the models to predict future climate change. For these reasons ice core research has received highest priority both in US Antarctic research plans (US Research in Antarctica in 2000 A.D. and Beyond, Polar Research Board, 1986) and in global change research plans (Global Change in the Geosphere-Biosphere, Initial Priorities for an IGBP, US Committee for an International Geosphere-Biosphere Program, 1986).

The paleoenvironmental information stored in ice may be influenced by local conditions during snow deposition and firnification and/or by the flow history of the ice. Thus reconstruction of global climate in the past requires an array of well distributed ice cores, including deep, intermediate, and shallow cores from the Antarctic, the Arctic, and low-latitude sites. Because of the large variety of paleoenvironmental indicators present in the ice and the importance of obtaining precise information on the relative timing of changes in those indicators, ice cores should be analyzed for multiple parameters, usually by multiple investigators.

The low-latitude records, though unable to match the great length and high resolution in the last glacial period of polar cores, are valuable because they complete the global coverage of past atmospheric and climatic changes. They will facilitate integration of data on the paleoenvironmentfrom ice cores with those from a host of other low-latitude studies on peat bogs, lake sediments, loess, and other terrestrial deposits. Most low-latitude ice masses are warming and retreating today which lends special urgency to low-latitude studies.

4. US Ice Core Research Plan

US ice core research, encompassing a wide spectrum of capabilities (ICWG report, 1987), can fill important gaps in our knowledge of past and present environmental conditions. Below we present specific research objectives that address the important problems discussed above. An outline of a long-range plan to realize these objectives follows. This plan may require modification during execution based on results obtained by early studies and by our sister disciplines (e.g. ice dynamics, oceanography, atmospheric sciences, climate modeling), but should prove useful for guiding and encouraging ice core research.

4.1 Specific Objectives

a. Recover a long (up to 10^6 years), detailed record of natural climate and paleoenvironmental changes in both hemispheres.

Such a record will identify the major components of climate change (e.g. Milankovitch cycles) over several full glacial-interglacial cycles as wen as the fine structure of climate variability on a time scale of decades to millennia that is superimposed on the long-term variations under glacial and interglacial climate conditions. Comparison with the long ocean-sediment records and coral records may reveal ocean-atmosphere-cryosphere interaction.

b. Recover high-resolution records of the Holocene and the last interglacial transition from as many distinct geographical locations as possible.

Records with annual resolution will provide well dated and highly detailed histories of environmental change over decades to millennia. Time scales for the younger part of long records that lack annual resolution may be established by correlation with these high-resolution records. Accurate chronologies are needed to compare the timing of changes in ice cores, ocean cores, and terrestrial deposits from both hemispheres.

c. Determine cause and effect relationships between changes in climate and changes in atmospheric composition.

These may be determined from lag/lead phase relationships between changes in $\delta^{18}0/\delta D$ and the concentration in the ice Of $C0_2$, CH_4, 0_2, dust, major cations and anions, trace elements, cosmogenic isotopes, and other constituents. Of special interest are the rapid glacial to interglacial warmings, but also the Younger Dryas climate episode and the apparently rapid Dansgaard/Oeschger climate events documented in Greenland. Study of the "Little Ice Age" and other recent Holocene climate oscillations is important to understand perturbations of the interglacial climate and offers the best calibration of ice core records with instrumental and historical records.

d. Determine changes in global biogeochemical cycles, (e.g. carbon, oxygen, sulfur, and water) due to natural causes.

The carbon cycle can be monitored in the ice mainly by measuring $C0_2$, CH_4, and CO concentrations and isotopes in air trapped in the ice. The concentration of these gases affects the radiative properties of the atmosphere. Their $^{13}C/^{12}C$ ratio also indicates redistribution of carbon between atmosphere, ocean and biosphere. Sulfur (as $S0_4^{2-}$ or $CH_3SO_3^-$) and its isotopic composition provide records of volcanic activity, meridional transport (in conjunction with major cations), and ocean productivity of dimethylsulfide (DMS). DMS is produced by phytoplankton in the surface ocean and is released into the atmosphere via gas exchange. In the atmosphere DMS is oxidized to sulfur dioxide, methanesulfonate, and ultimately, sulfate. The sulfate aerosol is the principal source of cloud condensation nuclei over the oceans and may play a major role in controlling the planetary albedo and, through it, global climate.

e. Determine natural changes in global tropospheric chemistry.

Global tropospheric chemistry may be affected by changes in the oxidative capacity of the atmosphere; most significantly by changes in OH, 0_3 and NO_x. Measurements of CH_3Cl (methylchloride), H_2 (hydrogen), and of light hydrocarbons (C_2-C_4) are needed as indicators of possible changes in OH concentration.

f. Examine natural changes in global biogeochemical cycles of toxic species.

Toxic chemical species of many types are produced by human activities and may pose environmental hazards. Examples include heavy metals, hydrocarbons, and inorganic and organic acids. Many of these species also have natural sources. It is important to understand natural variations in environmental levels and in biogeochemical cycling of these species to provide a baseline to which current pollution can be compared.

g. Elucidate the interaction between climate, ice sheet size, and sea level.

The focus is here on the West Antarctic ice sheet because much of its bedrock is below sea level. This ice sheet may be prone to sudden decay as has been documented for the Laurentide ice sheet. The approximately 6m of sea level rise resulting from a collapse of the West Antarctic ice sheet would flood coastal areas around the world.

h. Improve our understanding of anthropogenic influence on global biogeochemical cycles and climate.

As the dynamics of natural biogeochemical cycling and natural variations in climate are unraveled from the ice core records, anthropogenic effects can be better defined. For example, comparing concentrations of certain chemical species in pre-industrial and modem ice will help determine the extent to which anthropogenic sources have perturbed natural biogeochemical cycling of these species and/or climate. This information is vital as input to models that predict ecosystem effects and climate change, and for helping decision-makers choose control strategies to limit pollutant emissions.

Properties that need to be measured to reach the objectives outlined above are listed in Appendix B.

4.2 Global Array of Ice Cores

Long ice core records ($>10^5$ years) are limited to the polar regions. Obtaining a long core requires multi-season drilling and major logistics operations. To optimize the scientific return on such a large investment in time and money, the drill site has to be chosen carefully based on surface accumulation rates, firnification conditions, surface and bedrock topography, and ice flow. Systematic airborne ice radar sounding must first identify potential core sites. Such work must be done with careful long-range planning, because currently only one radar system exists which is capable of penetrating several thousand meters of ice and available flight time is very limited. Surface-based ice radar sounding and atmospheric sampling, snow pits, and shallow cores at those sites must then confirm and add detail to the airborne radar survey data and determine the quality of the paleoenvironmental information that can be expected from each site. Thus several years of site selection research must precede drilling of a deep core.

Shallow and intermediate (10-1000 m; 10^2 - 10^4 yr) ice cores should be obtained in polar regions but also at various low latitude/high altitude sites. Drilling of these cores is logistically easier because it can generally be accomplished in one season by a relatively small group. However, site selection for shallow and intermediate cores requires, just like the long cores, several years of field studies preceding the drilling.

Radar surveying is not such a limiting factor here since more than one radar system is available that will penetrate to depths of several hundred to a thousand meters, and in thicker ice the cores end sufficiently far above bedrock that bedrock topography is only a minor factor in site selection. Major difficulties for the low latitude programs are the development of support and collaboration for the research project in the countries where the ice is located, and the search for a suitable ice mass in a climatically and topographically highly variable terrain. Study of the gases trapped in the ice is especially difficult because it requires transport of frozen core samples from a remote site.

As our understanding of the global ocean-atmosphere-cryosphere-biosphere interactions that shape global environmental change increases over the coming years, new questions that may be answered by ice core analysis will arise. To maintain a lively and fruitful interaction between ice core research and other areas of global change research, we must be able to obtain cores suitable to answer specific questions without the long delays for site selection discussed above. Since the characteristics of the core most suited to settle a specific question depend on that question, drill site selection without delay requires that an existing database be available consisting of - systematic airborne radar surveys and surface studies of several areas. The database could be shared with other fields, e.g. the radar bedrock data with geophysics and tectonics, the ice surface data with meteorology and climate modelling.

The Arctic and the Antarctic, research programs are organizationally and logistically independent. Parallel programs for ice core research in these areas can therefore be developed. Simultaneous ice core research in both the Arctic and the Antarctic will allow rapid identification of global environmental changes recorded by core features in both polar regions. Our plan for ice core drilling and research is based on the assumption that research in the Arctic and the Antarctic will proceed in parallel. This will require (internal) management of the analytical capacity of the various research groups involved as well as coordination of the Arctic and Antarctic programs so that major drilling and sampling years in both areas do not coincide. Polar intermediate and shallow cores as well as lower latitude cores can be obtained in a single season and can be fitted into the long-range deep drilling schedule as needed. The intermediate and shallow cores address the spatial variability in the paleoenvironmental record from ice cores and are an integral part of the long-range U.S. ice core research plan.

4.2.1 Long Paleoenvironmental Records: Antarctica.

The emphasis for the US Antarctic ice core program should be on West Antarctica. This was the consensus of the 1988 University of New Hampshire Ice Core Research Workshop. There are several reasons for this choice:

- The stability of the West Antarctic ice sheet under a projected global greenhouse warming is unknown. The sea level rise that would result from a collapse is a major factor of uncertainty in the evaluation of the effects of a greenhouse warming. A core in West Antarctica that contains ice from the previous interglacial and the preceding glacial period will answer crucial questions on a possible collapse of the West Antarctic ice sheet during the warm interglacial period about 125,000 years ago.

A long Antarctic core record with a resolution comparable to the GISP-2/GRIP records now being collected at the summit of the Greenland ice sheet is needed.

This will allow detailed interhemispheric comparison of the critical timing and phase relationship of climatic and atmospheric changes. Although East Antarctica has provided excellent ice core records, e.g. Vostok and Dome C, the accumulation and, therefore, the resolution near the centers of outflow on the East Antarctic plateau is an order of magnitude lower than in Greenland. The northern flow divide area of West Antarctica has a suitable accumulation rate and may preserve a seasonal record as indicated by the results obtained at Siple Station.

- The West Antarctic ice core record(s) will complement the data on configuration, mass balance and ice flow obtained under the US Siple Coast Project. The Siple Coast Project will benefit from the identification of marker horizons in the ice and from the physical properties measured along the core and in the bore hole as well as from data on past ice sheet size and climatic forcing. The understanding of ice flow in the area, obtained by the Siple Coast Project, is of crucial importance for the interpretation of the core record.

- The Solid Earth Geophysics Initiative planned to start in 1990 involves extensive radar. Surveying of the bedrock under the West Antarctic ice sheet. The data gathered by this project will provide an invaluable database for drill site selection in West Antarctica. Conversely, core data on the chemical composition and physical properties of the ice as wen as access to bedrock provided by a deep core, will benefit the Geophysics program.

- The planned program Cenozoic Paleoclimates will benefit from access to subglacial strata provided by deep and intermediate core holes.

- An ice core program in West Antarctica, where the US has a long ongoing research program, complements programs in East Antarctica where research by the USSR, France, Australia, and Japan has produced valuable records, and in the Antarctic Peninsula where Great Britain focuses its Antarctic research.

A disadvantage of West Antarctica is the uncertainty whether a long (>10^5 yr) record can be recovered. This depends on the stability of the ice sheet during the previous warm interglacial period and on the geothermal flux from the underlying bedrock. Model calculations indicate that for a heat flux near the low end of the normal range most of the West Antarctic ice sheet win be frozen to its bed so we can retrieve a long record, but with a flux at the high end the ice will be melting at the bed. Radar is an imperfect but highly useful sensor for basal melting and data should be collected in potential drill areas to look for melting.

The deep core part of the West Antarctic ice core research project should start with an airborne ice radar survey to determine the general bedrock topography and whether the ice is locally frozen to the bed or melting. Paleoenvironmental records with minimum disturbance due to ice flow can be expected along the ice divides and from ice domes. For West Antarctica these are the Ross Sea-Pine Island Bay and the Pine Island Bay-Weddell Sea divides, the area between Mt. Woollard and the Whitmore Mountains, the area between the Whitmore Mountains and Hercules Dome, Hercules Dome, Siple Dome and Dome BC (Appendix C). For Siple Dome and Dome BC radar survey data are already available. The Ross Sea-Pine Island Bay and Pine Island Bay-Weddell Sea divides are interesting because they have a high accumulation rate (20-30 cm/yr) and are partly over bedrock plateaus which promises simple ice flow near the bottom. These areas are the first choice for the first Antarctic deep core project and should be the starting point for the ice radar survey. Integration of this ice radar survey with the planned Geophysics ice radar activities is feasible and should be undertaken.

More detailed ice radar sounding and study of the preservation of environmental information in snow pits and shallow cores should start at sites found promising in a first analysis of the airborne ice radar data the field season following airborne surveying. Site selection for deep and intermediate drilling can then be based on the field data and the scientific questions to be answered by the core (possibly at a workshop organized by the ICWG). If the airborne ice radar survey is field season 1, then drilling could start in field season 4. This long lead time makes it obvious that airborne ice radar and surface-based surveys of potential core areas should continue for other sites after the first core site has been selected, to provide a database for future site selection for a second Antarctic deep core. Potential goals for a second deep core could be to obtain a very long paleoenvironmental record, or to document the disappearance and regrowth of the West Antarctic ice sheet in case the first core in West Antarctica failed to obtain ice older than about 100,000 years. A core through e.g. Hercules Dome, situated in East Antarctica where the East Antarctic ice sheet adjoins the West Antarctic ice sheet, may be expected to show significant changes in ice flow and surface elevation in case the adjacent West Antarctic ice disappeared. A decision on the second core should be based on the preliminary results of the first West Antarctic core as well as on the information provided and the questions raised by global change research in general and by other deep and intermediate ice cores in particular.

Optimum use of the existing US ice core research and ice core drilling capabilities could be obtained if Antarctic deep drilling could start one or two years after completion of the drilling of the Greenland Summit deep core of the GISP-2 program. This would target the 1994-95 Antarctic field season to start deep drilling in West Antarctica.

Intermediate and shallow Antarctic core projects may be completed within a single field season. These can be developed and proposed by a single PI. Drilling at McMurdo Dome has been proposed for 1991-92. Two other sites with potential for an intermediate (- 1000 m) core are Dome BC and Siple Dome between ice streams B and C, and between C and D respectively. These cores tie in directly with the Siple Coast Project. A core through such a local outflow center will be a sensitive indicator of changes in ice thickness and flow in the West Antarctic ice sheet along this part of the Siple Coast. The core records can be compared with those of nearby Byrd Station and J-9 to evaluate spatial variability.

The full range of important paleoenvironmental indicators should be analyzed in the intermediate and shallow cores. This optimizes use of the environmental information contained in the cores and promotes comparison between different cores. Analysis of a wide range of core properties can be accomplished by a collaboration initiated by the PI or by DPP inviting suitable proposals to complement analyses already proposed. One or two intermediate and/or shallow core projects in West Antarctica should precede the first deep drilling project. This will augment the database available to interpret a deep long record and also build experience in Antarctic deep drilling thereby increasing its chances of success.

4.2.2 Long Paleoenvironmental Records: <u>Greenland</u>

Summit: The first field season of the GISP-2 deep core project in the summit region of the Greenland ice sheet was summer 1989. Deep drilling is projected for the summers 1990-1992. In collaboration with a multinational European project called GRIP two cores to bedrock will be obtained and analyzed independently. These records will constitute the longest time series available from ice sheets in the Northern Hemisphere (expected length >200,000 years). Frequent intercalibration of the analysis techniques will result in two independent records of paleoenvironmental conditions that are directly comparable and that will be interpreted jointly. The goal of the GISP-2 project is to obtain a long and detailed multiparameter record of environmental conditions in central Greenland with minimum complications from ice flow. The record will show natural variations with periods in the range of 1 to 10^5 years. The detailed multiparameter record will improve the interpretation of the rapid changes in climate and atmospheric composition observed in the Dye-3 core. It may also provide better understanding of the role of the North Atlantic, source area of the North Atlantic Deep Water, in the global climate system.

The GISP-2 project is funded by the NSF and a large group of investigators is measuring various core properties. Due to budgetary restrictions the analysis of a number of important core parameters could not yet be funded. It is important that the omissions in the core analysis be filled to gain the full scientific return from the drilling of this core. Bore hole studies over several seasons after completion of the drilling project should be encouraged. These will provide direct measurements of the differential movement of -the ice at different heights above bedrock, data invaluable for ice flow modelling.

North: After completion of the GISP-2 project and a first West Antarctic deep core, a deep core program in the northern part of Greenland is important to complement the data obtained from the Dye-3 core and expected from the summit cores. Comparison of results from the three sites will show the varying relative influence of the Arctic and the North Atlantic oceans on the local climate.

Within the framework of international collaboration between the United States and European countries plans should be made for airborne ice radar surveying and surface reconnaissance of the northern part of the Greenland ice sheet during the drilling of the Summit cores. This should identify sites at or near the flow divide with a relatively simple bedrock topography, temperatures low enough to preclude summer melting and an accumulation rate and ice thickness that provide good resolution in the upper part of the core as well as a long time record. It is desirable to continue US-European collaboration, established for GISP2/GRIP, in a North Greenland project.

Preliminary field operations for a drilling project in North Greenland could begin after completion of the GISP-2 drilling with deep drilling starting after the West Antarctic deep core. Participation in the North Greenland Project should be decided by review of individual P.I. research proposals submitted to NSF/DPP. The GISP-2 project could serve as an organizational model, to be amended later based on experience.

The GISP-2 and the North Greenland deep core projects should be complemented by intermediate and shallow drilling programs to obtain two or more cores down flow lines on either side of the divide towards the margin. These cores will provide information on glacial-interglacial changes in ice sheet configuration and ice flow. A continued US-European collaboration will make it possible to study simultaneously the eastern and the western Greenland drainage and thus to obtain rapidly a database useful for the interpretation of the paleoenvironmental records from the divide areas. Analysis of the intermediate and shallow cores should include most of the properties analyzed in the deep cores.

Long-range Antarctic and Arctic ice core research needs active participation by DPP and other NSF programs. The long lead times needed for proper site selection and the large logistics demands necessitate collection of a database for site selection and logistics planning for regular and systematic drilling beyond specific core projects already identified. DPP can facilitate and stimulate both in its contacts with the research community and its contractor PICO. The interdisciplinary focus of ice core research asks for continuous interaction with the various other fields of global change research to decide which questions are most important and can best be answered by ice core research. Drilling of cores so identified can then be initiated without a long delay for reconnaissance and without unforeseen logistics demands. Participation in the deep cores and other community-developed core projects should be decided by review of individual PI proposals. This should guarantee fair access to the projects for the whole glaciological research community.

Because the quality of the paleoenvironmental interpretation of ice core records depends on the comparison with other core properties and other core records, i.e. on the available ice core database, preliminary analysis of cores should be completed within two years of completion of the drilling. After that time the results should be made available to the community to aid in the interpretation of other records. Property data should be exchanged freely between participants in a single core analysis project.

4.2.3 Paleoenvironmental Records at Lower Latitudes: Intermediate and shallow depth cores.

Ice masses suitable for paleoenvironmental studies are found in a number of non-polar, high-altitude regions of the earth. These are important to extend our knowledge of spatial changes in paleoenvironmental information recorded in ice cores and to provide a link between ice core records and paleoenvironmental indicators preserved nearby at lower elevations in tree rings, peat bogs, lake sediments, loess, etc. Potentially useable ice masses are found on the arctic islands of Canada (Ellesmere, Devon, Baffin Island), Norway (Svalbard), and the USSR (Novaya Zemlya, Severnaya Zemlya, Franz Josef Land), in the high mountain ranges along the Pacific Coast of the Americas (especially in the Alaska Range, Wrangell Mountains-St. Elias Mountains, and the Andes), and in the high areas of central Asia (Tibetan Plateau, Himalaya, Karakoram Range). These areas provide north-south transects in the region 70-140OW and 60-1000E. In addition glaciers on Mt. Kenya and Mt. Kilimanjaro, in New Guinea, and on the South Island of New Zealand deserve attention.

In general a core through these lower latitude ice masses can be obtained in one season by a relatively small group using a light, dry-hole drill. Examples are the successful programs on Quelccaya, Peru, and Dunde, China. This does not create a heavy logistics demand. Development of a low-latitude ice core site should therefore preferably be done by an individual PI or group of PI's. In their dealings with authorities and colleagues of the country where the site is located they should, where needed, receive strong support from the ice core research community, NSF, and the US government. NSF should strive to facilitate free exchange of science and samples for such projects under the International Geosphere-Biosphere Project. This independent, individual approach will stimulate parallel efforts in different parts of the world and thereby speed the development of a global ice core database.

Once it has been established that an ice mass contains a useful paleoenvironmental record and a drill site has been identified, the PI who developed the site must complement the analytical capabilities of his/her own group by collaboration with other PI's as needed to ensure that the full set of valuable paleoenvironmental indicators in the core is measured in a timely manner. After two years the core data should be made generally. available to aid in the interpretation of other core records, just as those of polar cores. Special emphasis is to be placed on logistical support to preserve core/sample quality during transport to the laboratories.

4.3 Complementary Studies

The plans for ice core research presented above focus on ice core studies. Yet the discussion shows that selecting a good site to obtain a long paleoenvironmental record alone requires the collaboration of at least three different glaciology fields. Ice radar sounding of surface and bed topography and of internal layering and surface studies of accumulation, strain, and temperature should be distilled by ice flow modeling into a site choice. Involvement of several other disciplines and specialties is needed if the ice core records are to be exploited to the full potential of their paleoenvironmental information. Such involvement should be stimulated by multidisciplinary workshops and by making ice core data available via the World Data Center for cross-correlation with other paleoenvironmental records and joint interpretation. Collaboration is needed with, e.g. atmospheric scientists, oceanographers, geologists, and modelers.

4.3.1 Atmospheric Sciences:

All constituents found in ice cores originally came from the atmosphere. The amounts of these constituents in the core are dependent upon emissions at the sources, atmospheric transport from source regions to the glaciers, and deposition onto the surface. Changes that occur after deposition are also important.

Reconstruction of global climate and environmental conditions in the past from the ice core record requires that we understand each of these steps. In order to gain this understanding we must determine the present conditions and processes. Data on atmospheric emissions world-wide are available from numerous studies and should be collected. Atmospheric circulation patterns that affect the ice coring site should be determined to identify the most important source regions and transport pathways. Measurements of airborne concentrations and deposition rates of chemical species on a year-round basis must be made to define the atmosphere-to-snow transfer processes specific to the site of interest. These measurements should include air sampling as well as collection of fresh snow, older surface snow, and snowpit samples for detailed analysis. Year-round meteorological data at the site must be collected to define these transfer processes. Finally, processes that may redistribute constituents in the snowpack, such as meltwater percolation and diffusion of gases, should be studied at the ice coring site. Interpretation of changes in aerosol content and changes in the concentration of radiatively active gases in air trapped in the core in terms of their influence on global climate needs further study. Specifically, we need to determine the effect that an increase in the atmospheric concentrations of cloud condensation nuclei, indicated by increased sulfate concentrations in ice from glacial periods, has on cloud albedo and cloud distribution.

4.3.2 Oceanography:

Detailed correlation and interpretation of ice core and deep sea sediment records will reveal the way in which climatic and atmospheric changes express themselves in the two records.

Ocean sediment cores around Antarctica can provide a record of past fluctuations in sea ice -extent and ice discharge. Of special interest are indications of patterns of periodically increased discharge as reported from Indian Ocean cores, and the areal extent of such patterns. If episodic discharge were documented, it would have major consequences for our understanding and modeling of mass balance, ice flow and ice sheet shape.

4.3.3 Terrestrial Records:

Especially at lower latitudes it- may be possible to study pollen and other paleoindicators both in the ice and in deposits such as lake sediments, peat bogs, and loess. This can provide a very reliable way to correlate ice core records with other terrestrial paleoenvironmental records. If time series from ice cores can be correlated with radiocarbon dated records from other nearby environments then ice core chronologies can be improved. Involvement of e.g. palynologists and limnologists in certain parts of the ice core paleoenvironmental project should be stimulated.

4.3.4 Modeling:

The interaction between atmospheric climate, ocean circulation, ice sheet size and flow, and biospheric activity, and the effect of the different response times of these systems on global change need to be determined. Ice core data can make a significant contribution to the required database. Regular interaction with modelers of climate and ocean circulation is needed for an efficient use of ice core paleoenvironmental data in testing atmospheric and oceanic global circulation models. Interaction will also help identify for the ice core research community questions and modeling uncertainties that need to be eliminated by new or better paleoenvironmental data.

4.4 Summary

US ice core research can make important -contributions to our understanding of global change. A long-range ice core research plan for the next decade comprises:

- a deep core in West Antarctica; drilling to start around 1994-95,
- at least two intermediate and several shallow cores in West Antarctica,
- a second deep core and additional intermediate and shallow cores in Antarctica after completion of the drilling of the first deep core,
- one deep and several intermediate and shallow cores in Greenland after completion of GISP-2 drilling, and
- coordinated retrieval and analysis of other polar and lower latitude cores.

None of the actual cores are identified in this plan because W the available data are insufficient for a proper site selection, and (ii) due to rapid progress in global change research a site selected now, based on today's scientific questions may no longer be the most desirable site in two or three years when final site selection is made. For the first (West Antarctic) deep core site selection is focused on the cross hatched divide area in Appendix D.

NSF/DPP should provide for two key ingredients for the successful realization of the plan, namely accumulation of a database on potential drill site areas that will allow selection of a drill site without additional delay for field surveys, and a logistics and drilling operation that can support ice core drilling in the Arctic, the Antarctic, and at lower latitudes and produce good quality cores to bedrock independent of the ice thickness. In addition DPP will need the funds to support the multiparameter laboratory analyses that retrieve the paleoenvironmental information from the ice cores.

5. **Recommendations**

Developing to its full potential the paleoenvironmental information contained in the ice masses of the world requires a long-range program in which expertise from many different fields is focused on a common goal.

To reach this goal, the Ice Core Working Group recommends that:

- NSF/DPP adopts a long-range ice core research plan and takes an active role in the realization of this plan by creating the infrastructure needed for vigorous and flexible ice core research.

- NSF/DPP manages and actively seeks funds to support the long-range ice core research program to ensure fair and open access for all members of the scientific community.

- NSF/DPP supports key non-core studies that are directly related to ice cores and are necessary to ensure proper site selection and interpretation of core data.

- NSF/DPP, together with other programs and agencies, encourages the development of innovative techniques for ice sampling and analysis that may improve the quality and/or reduce the cost of paleoenvironmental information from ice cores.

- NSF/DPP encourages scientists to optimize the data retrieval from all ice cores by analysis and interpretation of many different core parameters in multidisciplinary collaborations.

- A database for rapid drill site selection as well as a database of the results of core analysis be collected and made available via the World Data Center.

- Unused core sections be curated in a US ice core storage facility and be made readily available for additional studies to US investigators and investigators of countries with which the US has scientific collaboration and exchange of sample materials and research data.

Appendix A

Global Change Components That Can be Documented Using Ice Core Records

- Global Climate

  e.g.,
  - greenhouse gases
  - aerosols
  - atmospheric temperature
  - stratosphere/ troposphere exchange
  - air mass sources
  - precipitation patterns

- Global Ice

  e.g.,
  - distribution of glaciers, snow, and sea ice
  - ice volume and sea level
  - glacier dynamics and ice properties

- Biogeochemical Cycles (C, N, S, etc.)

  e.g.,
  - biogenic gases
  - marine aerosols
  - continental aerosols
  - atmospheric interconversions

- Anthropogenically Derived Material

  e.g.,
  - radiatively active gases and aerosols
  - inorganic and organic pollutants

- Geologic and Extraterrestrial Activity

  e.g.,
  - volcanic activity
  - geomagnetic field
  - solar activity
  - extraterrestrial fluxes

Appendix B

Properties to be measured in ice core research and the environmental information they provide.

I Gas Content

Total gas content	paleo-elevation of the ice surface
$C0_2$ concentration	greenhouse gas increases with temperature; positive feedback
CH_4 and other trace gases like N_20, CH_3Cl and light hydrocarbons	greenhouse gases like $C0_2$ as well as indicators of the oxidizing capacity of the atmosphere
0_2/Ar and N_2/Ar ratios	fractionation of gases trapped in the ice; Dole effect

II Stable Isotopes

a) in gases

$^{13}C/^{12}C$ in CO_2	relative size carbon reservoirs
$^{18}0/^{16}O$ in O_2	02 cycle and global stratigraphic marker
^{15}N / ^{14}N in N_2	isotope fractionation of gases trapped in the ice
$^{13}C/^{12}C$ and D/H in CH_4	source distribution atmospheric CH_4
$^{15}N/^{14}N$ and $^{18}0/^{16}0$ in N_20	source distribution atmospheric N_20

b) in ice

D/H and $^{18}0/^{16}0$ in ice	primary paleoclimate indicators, deuterium excess d

III Cosmogenic Isotopes

$^{14}C/C$ in $C0_2$	dating up to 30 to 40 ka
^{1O}Be, ^{26}AJ, ^{36}Cl concentrations	cosmic ray production rate; accumulation rate
^{8l}Kr/Kr in trapped air	dating old ice

IV Chemistry

Major anions and cations	mass balance and seasonality; volcanic events; atmospheric circulation; sea ice extent; biogeochemical cycling
trace metals (Pb, Ir)	natural sources of trace metals and their variability
organic compounds	biogeochemical. Cycling
H_20_2	atmospheric chemistry, seasonality

V Particulate concentrations
atmospheric circulation, global dust sources, volcanic events

VI Electroconductivity:
chemical horizons, seasonality

VII Physical:
mechanical and stratigraphic continuity, layer thickness, borehole studies ice flow modeling

VIII Atmospheric studies:
transfer functions for isotopes, ions, and particulates from atmosphere to ice