NASA Conference Publication 3115, Vol. 1

West Antarctic Ice Sheet Initiative

Volume 1: Science and Implementation Plan

Proceedings of a workshop held at
Goddard Space Flight Center
Greenbelt, Maryland
October 16–18, 1990

NASA

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West Antarctic Ice Sheet Initiative

Volume 1: Science and Implementation Plan

Edited by
Robert A. Bindschadler
NASA Goddard Space Flight Center
Greenbelt, Maryland

Proceedings of a workshop cosponsored by the National Aeronautics and Space Administration, Washington, D.C., and the National Science Foundation, Washington, D.C., and held at Goddard Space Flight Center
Greenbelt, Maryland
October 16–18, 1990

NASA
National Aeronautics and Space Administration
Office of Management
Scientific and Technical Information Division
1991

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Note: Discipline Reviews appear in Volume 2 of this report

PREFACE

The West Antarctic Ice Sheet Initiative (WAIS) began under the name of SeaRISE (Sea-level Response to Ice Sheet Evolution) and was conceived at a workshop held January 23-25, 1990 in College Park, Maryland. SeaRISE was recommended to the National Science Foundation's Division of Polar Programs as a necessary initiative to assess accurately the potential of marine ice sheets to change sea level rapidly. The report of that workshop (NASA Conference Publication 3075) established the scientific rationale for this multidisciplinary investigation. The Division of Polar Programs accepted the concept of SeaRISE and proposed it as an initiative for funding to the Global Geosciences Directorate. At the same time, they requested that the scope of the initiative be more clearly defined by the scientific community.

This document fulfills that request by presenting the Science and Implementation Plan of WAIS. The program has been renamed to eliminate any possible confusion with attempts to actually measure global sea level change and to indicate more directly the area where studies will be focused. The plan was formulated at a workshop held October 16-18, 1990 at NASA/Goddard Space Flight Center. Antarctic Earth scientists, spanning all disciplines relevant to understanding the physical environment of Antarctica, attended the two workshops.

The October workshop began with a series of review papers on various aspects of Antarctic research, included as Volume 2 of this report. Oral presentation of these papers underscored the couplings that exist between the ice, ocean, atmosphere, and land in the Antarctic, and the need for WAIS (or SeaRISE) to be a multidisciplinary program.

Volume 1 contains the Science and Implementation Plan created by the participants who identified specific investigations necessary to attain the WAIS goal of predicting the future contributions of marine ice sheets to rapid changes in global sea level. Significant cross-fertilization was achieved between discipline subgroups to address physical processes that couple the ice, ocean, land and atmosphere. Required funding levels for the investigations were determined and a recommended schedule was formulated which phased investigations over 5 years such that both annual funding and logistic requirements were held relatively constant.

Other nations have expressed keen interest in the WAIS project and its goals. The United Kingdom, Norway, Australia, and Sweden were able to answer the invitation for workshop observers that was extended to all SCAR (Scientific Committee on Antarctic Research) nations.

WORKSHOP PARTICIPANTS

WAIS Working Group Members:

Richard Alley /The Pennsylvania State University
John Anderson /Rice University
Robert Bindschadler(Chair) /NASA-Goddard Space Flight Center
Don Blankenship /The Ohio State University
Hal Borns /University of Maine
David Bromwich /The Ohio State University
Pieter Grootes /University of Washington
Barclay Kamb /California Institute of Technology
Douglas MacAyeal /University of Chicago

Other Participants:

Paul Berkman /The Ohio State University
Parker Calkin /State University of New York-Buffalo
George Denton /University of Maine
Gene Domack /Hamilton College
Herman Engelhardt /California Institute of Technology
Jim Fastook /University of Maine
Jane Ferrigno /U.S. Geological Survey
Bernhard Lettau /National Science Foundation
Stan Jacobs /Lamont-Doherty Geological Observatory
Tom Kellogg /University of Maine
Larry Lawver /Institute for Geophysics
Paul Mayewski /University of New Hampshire
Julie Palais /National Science Foundation
Michael Ram /University of Buffalo
Charlie Raymond /University of Washington
Vin Saxena /North Carolina State University
Reed Scherer /The Ohio State University
Simon Stephenson /National Science Foundation
Dietz Warnke /California State University
Ian Whillans /The Ohio State University
Don Wiesnet /National Geographic Society
Herman Zimmerman /National Science Foundation

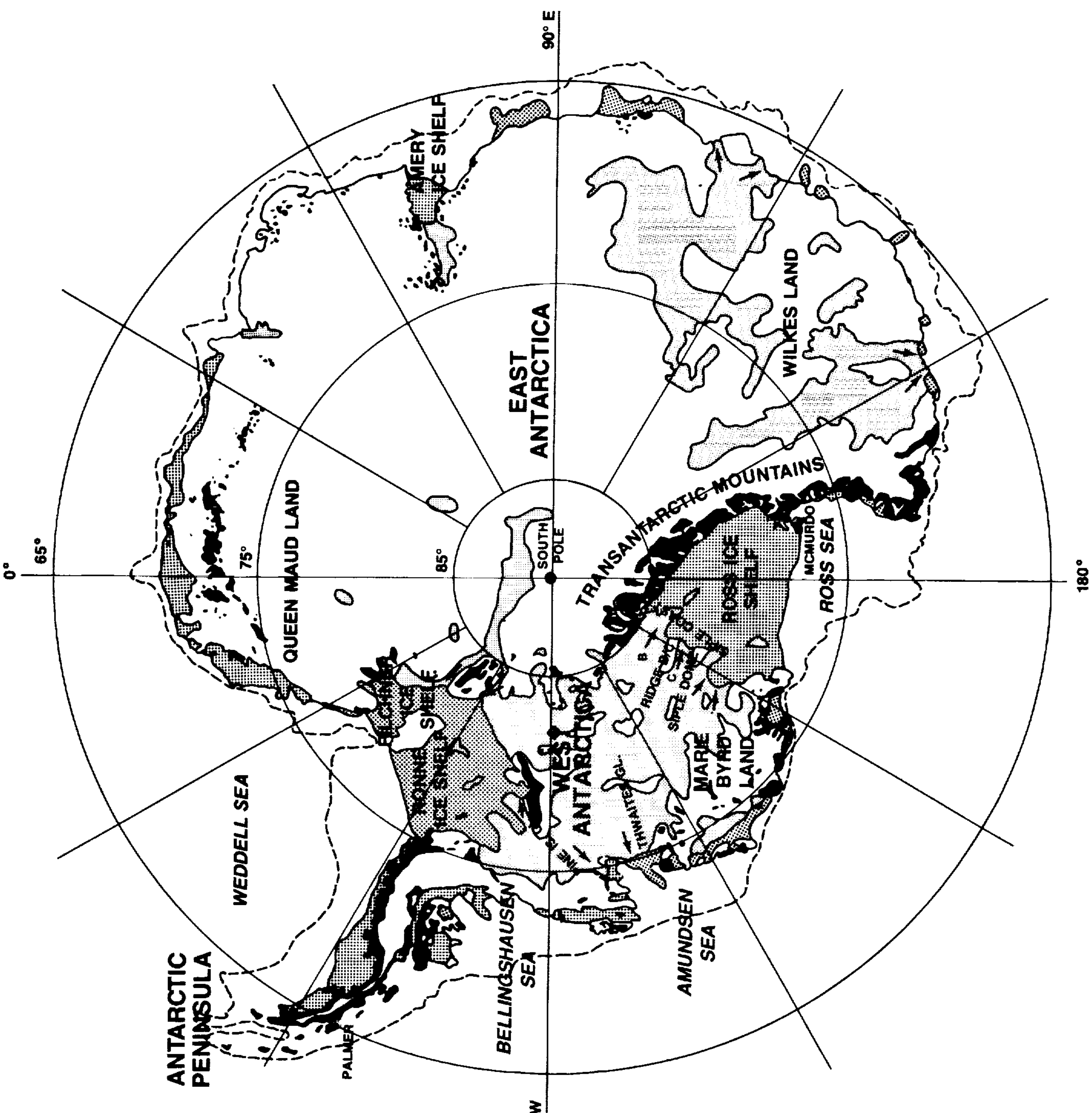
International Observers:

Chris Doake /United Kingdom
Elisabeth Isaksson /Sweden
Joe Jacka /Australia
Olav Orheim /Norway

Note: Full addresses for the participants are listed in Appendix B.

ACKNOWLEDGEMENTS

All workshop participants are thanked for their contributions to this report. Many others also provided valuable input. Financial support was provided by the National Science Foundation/Division of Polar Programs (NSF/DPP) under grant DPP-9017562.



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QUEEN MAUD LAND
AMERY ICE SHELF
WILKES LAND
TRANSANTARCTIC MOUNTAINS
ROSS ICE SHELF
MCMURDO
ROSS SEA
SIPLE DOME
MARIE BYRD LAND
AMUNDSEN SEA
BELLINGSHAUSEN SEA
WEDDELL SEA
ANTARCTIC PENINSULA
PALMER

Map of Antarctica showing locations of most features mentioned in this report. Light-shaded areas indicate portions of ice sheet grounded on bedrock more than 500 meters below sea level and represent the major portions of marine ice sheet. Arrows represent major ice streams which drain the marine ice-sheet regions. Heavily-shaded areas show ice shelves that buttress ice flow and beneath which ocean circulation is an important process of mass exchange. Solid areas represent exposed rock where glacial geology is possible. The dashed line represents the edge of the continental shelf and defines the region between the ice-sheet margin and the shelf edge where ocean stations and sediment cores can contribute information on the present and past behavior of the ice sheet. Solid circles show the location of stations mentioned in the text.

1. EXECUTIVE SUMMARY

The West Antarctic Ice Sheet Initiative (WAIS), formerly called SeaRISE, addresses concern about the future behavior of the West Antarctic ice sheet and the possibility that this ice sheet could collapse, rapidly raising global sea level. The West Antarctic ice sheet is the largest remaining marine ice sheet (those that are grounded well below sea level). It contains enough ice to raise global sea level 6 meters, and has been measured recently to be undergoing rapid and dramatic change in particular regions.

Whether these changes are manifestations of impending collapse is not known but these discoveries compel scientists to gain a fuller understanding of the nature of marine ice sheet flow. This potential for collapse stems from the marine ice sheets' inherent instability to grounding-line retreat and from the capability of their fast-flowing internal ice streams to rapidly disperse the ice into the surrounding oceans. Because the flow of a marine ice sheet is strongly affected by its environment and, in turn, the configuration of the ice sheet strongly influences its environment, the research program must take into consideration the coupled atmosphere-ocean-cryosphere-lithosphere system.

Within WAIS, investigations in glaciology, meteorology, oceanography and geology are linked together by focusing on the single goal of predicting the future behavior of the West Antarctic ice sheet and, in so doing, assessing its potential to collapse and rapidly raise sea level. To make such a prediction requires an understanding of the current state, history, internal dynamics, and mutual interactions within the polar atmosphere-ocean-cryosphere-lithosphere environmental system and its coupling to global climate.

Much of the supporting research needed to develop this understanding is multidisciplinary in nature, as will be the incorporation of the results into numerical models of ice flow capable of recreating past configurations of the West Antarctic ice sheet. The essential role of WAIS is to foster and guide the multidisciplinary approach and to see to it that disciplinary components are well integrated into ice-flow models.

Elements of the needed research program are expressed in terms of specific tasks which must be undertaken to answer key questions to achieve the initiative's goal. In condensed form, these questions are:

* What are the current local and regional mass balances of the ice sheet and how are they realized by input from the atmosphere and output via the ice-sheet flow system and the ocean?

* What are the physical controls on the motion and areal extent of the ice streams, and how are these coupled to climatic factors and incorporated into the complete dynamics of the ice-sheet/ice-shelf system?

* How has the configuration of the West Antarctic ice sheet responded to climatic changes over the past glacial/interglacial cycle and has it undergone episodic rapid mass wasting?

* What controls precipitation over the ice sheet in the context of global atmospheric circulation, and climate change?

* How will climate change affect the ocean state and distributions of sea ice around Antarctica, with consequent effect on precipitation over the ice sheet?

* What is the mass-exchange interaction between the ice shelves and the underlying ocean water and how will this be affected by climate change, with resulting change in mass balance of the ice-shelf/ice-sheet system?

Once these questions can be answered in sufficient detail and with sufficient reliability, it will become possible to model the coupled atmosphere-ocean-cryosphere-lithosphere system and to test the modeling against a known history of ice-sheet evolution. Successful modeling will then provide the basis for predicting future evolution.

A head start on some aspects of WAIS within individual disciplines is already underway in current or proposed projects and programs involving the West Antarctic ice sheet: the Siple Coast Project, the Antarctic Geophysical Initiative, the Global Ice Core Research Program, the Filchner-Ronne Ice Shelf Programme, the International Geosphere-Biosphere Program, the International Trans-Antarctic Scientific Expedition, various satellite remote-sensing missions, and research programs of other nations. The unique role of the WAIS initiative is to unite these various elements, together with consciously multidisciplinary projects not yet launched, in support of the important goal of predicting the future of the West Antarctic ice sheet.

The needed research tools are largely in hand, so that the feasibility of reaching the supporting objectives is assured. Attainment of the ultimate goal is therefore possible. The execution of WAIS would consist of an initial 5-year study of the Ross Embayment region of West Antarctica while reconnaissance data were collected elsewhere in West Antarctica and possibly in other marine ice-sheet areas in East Antarctica and Greenland. A recommended schedule of investigations has been drafted which spreads the logistic and financial support evenly over the 5-year period. This would be followed by a second study phase, also lasting approximately 5 years, concentrating on those areas of West Antarctica that indicate particular susceptibility to collapse.

2. CLIMATIC IMPORTANCE OF ICE SHEETS

Polar ice sheets are an active component of the global climate system. This is particularly true in the Southern Hemisphere where the Antarctic ice sheet is strongly coupled to both the ocean and the atmosphere. The fierce katabatic winds generated by radiative cooling over the ice sheet force a continental-scale atmospheric circulation that couples with atmospheric behavior in mid-latitudes and even in the tropics. The formation of sea ice around the continent, promoted by the outward flow of cold air, generates cold, saline shelf water which evolves into bottom water that spreads into all ocean basins and strongly influences the global oceanic circulation. Because of such couplings, assessing the future ice-sheet behavior and its effect on and response to global climate change is a problem that requires understanding feedbacks far more complex than a shift in the relative areas of net accumulation and net melting driven by changes in local temperature.

The most immediate influence of the ice sheets on the climate is their direct modulation of sea level. Because they contain enough water to raise sea level 70 meters, even a small change in ice-sheet volume would have major economic and ecological impacts on coastal areas worldwide. The severity of such impacts will increase with the rapidity of the change. The most rapid rises in sea level yet inferred occurred during the climatic warming at the end of the last ice age when the seas rose at rates exceeding 25 mm/a during two distinct periods: more than ten times the rate sustained over the last century. These episodes are believed to coincide with periods when the North American ice sheet was rapidly discharging ice into the ocean, a process referred to as ice-sheet "collapse." Whether there are any modern ice sheets that will react in a similar way to either anticipated climatic warming or as a delayed internal instability triggered by past climatic fluctuations is an unanswered question.

3. MARINE ICE SHEET INSTABILITY

There is a class of ice sheets believed to be inherently unstable and prone to collapse. Termed "marine ice sheets," they are characterized by being grounded on beds well below sea level. They go afloat around their peripheries at the grounding line and contribute to large floating ice shelves which continue to thin as ice moves towards the margin. The potential instability arises in cases where the bed becomes progressively deeper inland from the grounding line. If ice at the grounding line thins, the grounding line would have to retreat inland. Unless the ice at the new grounding line can be supported, for example by a "buttressing" effect of the floating ice shelf beyond the grounding line, it will thin more rapidly in the deeper water causing even further grounding-line retreat. This process of retreat will continue at an ever-increasing rate, progressively dispersing more and more ice into the ocean. This process is what is meant by the term "ice-sheet collapse."

Ice streams, large river-like currents of ice flowing through the ice sheets at speeds one to two orders of magnitude faster than the general ice flow, greatly increase the potential swiftness of ice-sheet collapse by rapidly transporting ice from the interior of the ice sheet to the margin. Understanding the nature of ice-stream formation and evolution is central to understanding the nature of ice-sheet collapse. Any process that initiates a retreat of the grounding line could be a possible trigger of collapse. Possible triggers include rising sea level and thinning ice shelves caused by increased subshelf melting or enhanced calving. Possible safety latches are increased ice-shelf grounding caused by increased advection from ice streams, and basal freezing caused by altered subshelf circulation.

Although the concept of marine ice-sheet instability and collapse was originally a theoretical one, results of recent Antarctic field work support the assumptions and reasoning on which it is based. A closely related concept, the potential for unstable retreat of tidewater glaciers, has been verified by the onset of a dramatic retreat of Columbia Glacier, Alaska, which has continued for the last 10 years. Also, evidence from glacial geology and paleoclimatology now points to collapse of major portions of the North American ice sheet at the end of the last ice age. The collapsing portions were marine in character and were subject to the instability conditions noted above.

4. THE WEST ANTARCTIC ICE SHEET INITIATIVE

The urgent concern with the West Antarctic ice sheet centers on the question of whether the atmosphere and ocean system is coupled to the ice sheets in such a way that a climatic warming from present conditions is likely to trigger, or that past climatic changes have already triggered, the collapse mechanism in existing marine ice sheets. The most direct and important impact of this process would be a rapid rise in sea level. Processes in the ice, ocean, atmosphere and subglacial bed all may be involved. For this reason, the collection of investigations to answer this concern must be multidisciplinary.

4.1 Goal and Objectives

The goal of the West Antarctic Ice Sheet Initiative (WAIS) is to predict the future behavior and potential for collapse of the West Antarctic ice sheet.

This goal will be achieved by the creation of numerical models capable of simulating the complex environmental system of ice sheet, polar atmosphere, polar oceans and Earth's crust. The development of such models and their success in accurately simulating the West Antarctic ice sheet requires the collection and analysis of a wealth of diverse types of data. The required investigations will be directed toward a number of supporting objectives.

The objectives of WAIS are to understand the current state, internal dynamics, interactions, and history of this environmental system.

Each of the WAIS objectives stated above is intended to provide a necessary element of an accurate numerical model of marine ice sheet evolution that is sensitive to the forcings and interactions of the surrounding environment. Information on the **current state** provides the initial conditions of the model. **Internal dynamics** refers to the governing equations of the model required to properly account for the flow of the ice. **Interactions** between the ice and the remainder of the environmental system must be understood to account for feedbacks, both positive and negative, that will dynamically change the forcings on the ice sheet. Finally, data on the **history** of this environmental system are needed to test the model and supply essential memory to the model when predictive runs are attempted.

4.2 A Multidisciplinary Project

WAIS is an ambitious project. The attainment of the WAIS objectives requires input from scientists in many disciplines. While the first two objectives of WAIS are principally the domain of glaciologists, the latter two can be addressed by scientists from many disciplines. The ice sheet shares boundaries with the atmosphere, oceans and underlying rock, and all exert important controls on the eventual behavior of the ice sheet. The major atmospheric forcings are temperature and snow accumulation. Meteorologists must be active in WAIS to reach a sufficient understanding of atmospheric processes so that WAIS models of the ice sheet can simulate variation of these parameters for specified model scenarios. Oceanic heat flux and salinity control basal melting and freezing of ice shelves. Oceanographers must be supported to conduct investigations to supply estimates of current mass exchange beneath ice shelves and how it might change in the future. Finally, subglacial heat flux, erodibility, and permeability are critical in the production of basal lubricant. Geologists must be involved in WAIS to quantify these parameters and the possible changes in them with changing ice conditions.

The need to develop an accurate history of the West Antarctic ice sheet, its paleo-environment, and its configuration will involve specialists from many disciplines. Time series of air temperatures and accumulation rates are important data to collect as well as time series of ice-sheet thickness and extent. The former will be provided by analyses of ice cores while the latter will be provided by geologists working in the areas of exposed rock, on sub-ice sediments, and offshore on the continental shelf.

4.3 Scientific Focus: A Single Goal

WAIS is a complex project whose success requires maintaining a sharp scientific focus on its single goal so that investigators from many disciplines can work together and arrive at a common understanding of the ice-sheet environment. This focus on a multidisciplinary goal will encourage open communication amongst scientists and efficient use of field logistics. To utilize funding support effectively, each investigation must have a clear connection to and substantially contribute to this goal. A management plan to coalesce the efforts of many separate investigations toward this common goal is presented in Section 8.

4.4 Geographic Focus: West Antarctica

Another way in which effective use of resources is to be maintained is by limiting the geographic scope of the investigations to West Antarctica. This ice sheet is the largest surviving marine ice sheet in the world, containing enough grounded ice to raise sea level 6 meters. Its deep, basin-shaped bedrock floor has the geometry appropriate for instability. It is believed by some to have collapsed and disappeared during the last interglacial period about 125,000 years ago. Recent studies of sub-ice sediments support this view. More certain is the fact that during the last glacial maximum this ice sheet was much larger, extending in places to the edge of the continental shelf. In the last 18,000 years it has retreated to a position well back of that maximal stand but its current rate of change is unknown. We do not know whether the West Antarctic ice sheet is continuing to retreat, has reached some state of equilibrium, or is readvancing.

Measurements of net mass balance in separate regions of the ice sheet indicate a complex pattern of growth and wastage, but only a small portion of the total ice sheet has been measured. Direct indications of currently unstable behavior have recently been discovered in the form of rapid changes taking place along the Siple Coast (see Map). In the Ross Embayment (the region stretching from the ice divide across Ice Streams A-E and the Ross Ice Shelf to the northern limit of the Ross Sea), the presence of active ice streams may be a manifestation of collapse already underway. Recent measurements and modeling of the ocean circulation on the continental shelf indicate relatively high melting rates near the grounding lines of the large ice shelves. Additionally, the current absence of substantial ice shelves that could buttress the Pine Island and Thwaites Glaciers could cause a forthcoming collapse of that part of the ice sheet.

The initial investigations of WAIS concentrate on the Ross Embayment sector of West Antarctica because of its large data base, simpler logistics, and physiographic setting typical of marine ice sheets. Reconnaissance investigations of all of West Antarctica also will be undertaken to avoid missing dramatic behavior outside the Ross Embayment sector. The meteorological analysis will also need to extend over the full West Antarctic ice sheet to capture the important mesoscale phenomena. Eventually, to produce a complete prediction of the potential contribution of all marine-ice-sheet regions to rapid sea-level rise, areas outside of West Antarctica will need to be considered. These would include regions such as Wilkes Land in East Antarctica where substantial portions of the ice sheet are marine (see Map), and Jakobshavns Glacier in Greenland that drains about 10 percent of the Greenland ice sheet through a deep channel whose floor is well below sea level.

4.5 Duration: A Phased Approach

This plan includes specific projects needed to address WAIS objectives in the Ross Embayment over a 5-year period. By itself, such a program cannot be expected to attain the sophisticated modeling necessary to achieve the WAIS goal. Rather, this 5-year period is to be viewed as Phase I of a longer term project extending 10 and perhaps 15 years. By the end of Phase I the essential field data necessary to predict the future of the ice sheet in the Ross Embayment will be in hand but not the analysis of these data and development of numerical ice-flow models which depend on the analysis. Five years is felt to be a minimum duration for Phase-I activities, assuming adequate logistics and science project support.

Near the end of Phase I, there will be a need to reassess the most practical course for subsequent investigations. If reconnaissance data of other areas of West Antarctica identify regions of greater concern, investigations can be shifted to those locations. Alternatively, if the Ross Embayment is shown to be the most active region, necessary follow-up studies will be proposed there. At this time, it is impossible to predict which case is more likely.

5. SCIENCE PLAN

In this report, the key scientific questions identified during the earlier SeaRISE workshop (NASA Conference Publication 3075) are reexamined and elaborated upon. Broad tasks required to answer those key questions and specific investigations to carry out those tasks are identified. Within some disciplines, the questions have been revised to reflect either a shift in emphasis or an improved statement of the critical issues.

The numerous feedbacks and interactions that are part of the Antarctic environment will necessitate many multidisciplinary investigations. Assignment of such investigations to any single discipline is arbitrary and not intended to preclude interdisciplinary collaborations. In some cases, joint investigations are mentioned in more than one discipline.

5.1 Glaciology

5.1.1 Ice Dynamics

1) What is the present distribution of surface-elevation change, and what is the net mass balance of the West Antarctic ice sheet?

Overall net mass balance is the most basic measure of ice-sheet health. Local net mass balances indicate the pattern of mass redistribution and can assist in interpreting the cause of any imbalances. There are two principal techniques used to measure mass balance: direct measurement of elevation change, and calculation of thickness change based on measured volume fluxes.

While repeat measurement of elevation can be done at isolated points with either GPS positioning or conventional surveying (where fixed points are visible), satellite altimetry is much preferred. Satellites provide the broad spatial coverage necessary to assess the behavior of large ice sheets. Coverage of West Antarctica with a radar altimeter will begin with the ERS-1 satellite scheduled for launch in 1991 but data will be limited to the area north of 82°S. Further, it is expected that a 5-year data set will be required before reliable indications of elevation change are obtained. Thus, these data will have little impact on Phase-I activities in WAIS but will certainly play a role in subsequent studies. Reduction and analysis of these data in the U.S. will most probably be funded by NASA.

Laser altimeters provide the same capability to directly measure elevation change, but will not be included on space platforms until the late 1990s. Laser altimetry from aircraft is available but suitably configured aircraft cannot operate in Antarctica at this time.

A problem with elevation measurements is that they are not a direct measure of ice thickness or volume change. Changes in firn density, or changes in bed elevation due to either changing till thickness or tectonic motions also cause surface elevation change. Thus, geophysical, geological and glaciological studies will be needed in areas of changing surface elevation to interpret the degree to which such changes represent changes in ice volume.

The second method for calculating net mass balance avoids this difficulty, although it requires much more field work. This method sums mass fluxes into and out of any given region to calculate the rate of change of ice volume there. This method has already been applied in West Antarctica. The basic data required are the ice thickness and velocity across vertical sections in the ice, the accumulation at the upper surface and the basal melt or accretion at the base. The basal term is usually small (except on ice shelves) and the surface accumulation data come primarily from analysis of shallow surface cores where peaks in radioactivity indicate stratigraphic horizons corresponding to the years 1955 and 1964 when there was an increase in the testing of nuclear bombs in the atmosphere. Ice thickness data are collected by radio echo soundings, usually from an airborne platform, while the velocity data come from a variety of sources, including conventional surveys, satellite surveying techniques, aerial photogrammetry, and, most recently, repeat satellite imagery.

The detailed study of mass balance distribution of Ice Streams D and E has already been planned as part of the Siple Coast Project (see Section 6.1.1). The method employed will be similar to that used on Ice Stream B where the flux across a series of transverse gates is determined, but more velocities will be measured by using repeat satellite imagery.

The net mass balance of the entire West Antarctic ice sheet can be measured by the mass flux method but requires similar remote sensing data. Velocity data will be obtained by sequential satellite imagery. The USGS already holds many of the necessary images as part of an image acquisition and analysis program of major Antarctic outlet glaciers. Approximately 20 additional Landsat TM images should be acquired as early as possible to determine velocities along the entire perimeter of West Antarctica. Ice thicknesses will need to be measured by airborne radar sounding at the locations where velocities are measured and as close to the grounding lines as possible. These radio-echo sounding flights would cover approximately 3000 km and be located predominantly along the Amundsen and Bellingshausen coasts. Finally, accumulation-rate data are needed. Present coverage is sparse, but to improve this data set markedly would require a major commitment of resources. Passive-microwave data already available may help in interpolating the detailed pattern between surface measurements. The new mass flux data will permit a major improvement to the estimation of the net mass balance of West Antarctica.

Accumulation rates in these areas are known only roughly. Large local variations discovered in the past make it imperative that improvements be made to this data set. Such improvements are expected from the meteorological studies of WAIS (see Section 5.2). Similarly, the basal mass gain or loss is concentrated under the ice shelves, and the mass budget there is a primary concern of the WAIS oceanographers. Its description can be found in Section 5.3.

Although WAIS is focused on the West Antarctic ice sheet, reconnaissance of other marine ice-sheet regions should not be overlooked. Wilkes Land in East Antarctica is such a region (see Map). Positioned farther north than most of West Antarctica, it is an excellent region for a program of monitoring surface elevation using satellite altimetry.

2) What are the physical controls on the motion and areal extent of ice streams?

In order to answer this question, three distinct aspects of ice-stream mechanics need to be understood:

- the mechanics of rapid basal motion, and its role in determining the positions of ice streams;
- shear-margin mechanics and its effect on the lateral extent of ice streams; and
- the mechanics of ice-stream buttressing by ice shelves.

The research needed to address these topics is identified below.

2a) Basal Mechanics

Recent work has shown that physical conditions at the base of Ice Stream B are favorable for the occurrence of rapid basal motion either by basal sliding or by deformation of subsole till. The presence of deformable subsole till in a layer a few meters thick has been demonstrated. Active till deformation accommodating ice-stream motion is highly probable.

To formulate the mechanics of rapid basal motion so that a numerical model can adequately predict ice-stream behavior, the following research tasks need to be accomplished. (1) The till flow law, the basal sliding law, and the individual contributions of till deformation and basal sliding to ice-stream motion need to be determined observationally at several representative locations in the ice-stream system. (2) The thickness of the till layer needs to be measured and mapped throughout the Ross Embayment to the extent feasible. (3) Hydraulic characteristics of the basal water system under the ice streams need to be determined and the physical control(s) on these characteristics must be ascertained. (4) The results of (1) through (3) need to be integrated into a quantitative model of the basal mechanics of ice streams. (5) With this as a basis, the transition at the head of the ice streams from non-streaming sheet flow to streaming flow needs to be mechanically modeled so the headward extent of ice-streaming can be related to environmental variables.

Task (1) requires borehole geophysical work at the base of the ice streams, combined with laboratory testing of till samples obtained by coring. Also required at each site is the local ice-surface velocity by either satellite geodesy or repeat imagery. Task (2) requires high-resolution seismic profiling, combined with spot checks of till thickness at borehole sites. Task (3) addresses the key controlling variable in ice-stream mechanics, the basal water pressure; because this parameter is not detectable by remote-sensing methods, borehole geophysics is again required. Tasks (4) and (5) are mainly interpretative and computational.

Tasks (1) and (3) will be essentially completed at one site by the beginning of the WAIS project. The remaining sites can be completed at the rate of one per year, so that six sites can be completed by the end of Phase I. This should provide an adequate sampling of different conditions. During this phase, Task (2) is best done by running seismic lines out from borehole sites. Additional geographic coverage can be obtained in Phase II. Tasks (1) through (3) require substantial LC-130 support. Once on-site, surface transport can be used to move the drill rig distances of up to 20 kilometers as may be needed in the vicinity of some sites. Tasks (4) and (5) need ongoing attention throughout the program, as field data accumulate.

2b) Shear Margin Mechanics

Although most of the resistive drag supporting the ice streams against gravity is located at the bed, the side drag across the margins can be significant at places. Also, the mechanics of the marginal shear zones determines where the lateral edges of the ice stream are established and, therefore, the ice-stream width, discharge and mass balance.

To get the information needed to quantify these aspects of shear zone mechanics and to incorporate them into an overall model of ice-stream behavior, the following investigations are needed: (1) mapping of shear zones by satellite imagery, comparative studies of different shear zones based on the imagery, and search for evidence of past or current changes in position of the zones; (2)

search for relations between location of margins and features of basal topography; (3) on-the-ground study of selected shear margins to reveal detailed flow patterns and their evolution with time if the shear margins are currently migrating; (4) determination of the flow law of ice in the shear zones, which is thought to differ from the standard flow law (ice in the shear zone being weaker); (5) formulation of detailed marginal-shear-zone mechanics, including the patterns of crevassing and the physical mechanism by which the lateral position of the marginal shear zones is controlled.

Task (1) will use satellite imagery collected by the American series of Landsat imagers and, at latitudes higher than 82.6°S, from the French SPOT series. Task (2) requires airborne radio-echo sounding in addition to imagery. Task (3) can be carried out with standard flow velocity measuring techniques using strain grids plus satellite geodesy at selected points. Task (4) requires ice coring to retrieve deep ice samples from the shear zones for mechanical testing (flow-law determination), and for structural and fabric studies aimed at revealing the mechanism of anomalous rheology. Task (5) involves computational interpretation and hopefully, the development of a quantitative theory of marginal shear zones.

The imagery required for (1) will require only a modest number of SPOT images (5-10) to augment the larger collection required for the net mass balance and basal mechanics studies already mentioned. For (2), more detailed radio-echo sounding data will be needed at locations where anomalous marginal features appear on the imagery. A number of locations on Ice Streams D and E have already been identified and will be included in the radio-echo sounding flights already proposed. Tasks (3) and (4) would require a dedicated field camp at the margin. A minimum of two sites would be required--each begun in separate years and each revisited at least once to collect strain data.

2c) Buttressing Mechanics

The strength of the connection between the ocean and the ice sheet rests on how effectively resistance to ice-shelf flow is transmitted upstream to the grounded ice. For many years, the buttressing effect of ice shelves has been held to be the primary resistance to ice-sheet collapse. A major opportunity exists in the Ross Embayment region to examine this critical point. The Crary Ice Rise, the largest ice rise in the Ross Ice Shelf, is changing rapidly and large changes are occurring just upstream in the mouth of Ice Stream B. A detailed data base of the nature of flow around this ice rise and in the ice-stream mouth has been collected and analysis has begun under the Siple Coast Project. Further, satellite imagery has revealed contorted features that indicate strongly transient flow.

WAIS can accomplish an improved understanding of buttressing mechanics thorough the following investigations: (1) monitoring the changing deformation in this area; (2) developing mechanical models that adequately represent the flow of ice shelves past ice rises and over ice rumples; (3) mapping the full set of contorted flowbands providing a history of the flow on the ice shelf; and (4) incorporating the models of (2) into simulations that adequately simulate the history indicated by (3).

Task (1) can be achieved primarily through periodic acquisition of SPOT imagery and through surface field teams remeasuring existing stations left from previous years.
Task (2) is an interpretative task building on the data of (1). Task (3) again relies on satellite imagery, while (4) is computational in nature.

Many SPOT images of the Crary Ice Rise/Ice Stream B mouth area have already been purchased. Five additional scenes are needed to fill existing gaps. Six SPOT images provide complete coverage of Crary Ice Rise and should be collected twice: once early and once late in Phase I. The five sites in the mouth of Ice Stream B should be remeasured once during Phase I by a surface team travelling by snowmobile. Additional mapping of the ice shelf might be possible with lower resolution Defense Meteorological Satellite Program (DMSP) imagery at lower cost than Landsat or SPOT.

3) How will the volume of grounded ice change over the next decades to several centuries?

The answer to this question rests on the development of numerical models that adequately incorporate the physical processes and interactions identified by other WAIS investigations. Such models provide the only means to answer this question and must be fully time-dependent. The models should include heat-flow to define material properties throughout the ice column and subglacial stratum, and meteorological calculations to account for varying accumulation rates as the ice-sheet configuration changes with time.

These models must be validated by demonstrating that they can represent known past configurations as well as depict transient events identified by the analyses of field data. The analyses of field data and satellite data will provide the initial conditions, the boundary conditions, and the ice-sheet configurations for such validation experiments. Appropriate input to the model might span the period from the last glacial maximum to the present. To be credible, any model must be able to accurately reproduce this period.

With a validated model, predictions about the future behavior of the ice sheet and its effects on sea level will be made. Again, initial conditions (the present configuration and net mass balance) and environmental data (accumulation rate, oceanic circulation) will be required, as well as a means to change these environmental parameters. In the absence of a model capable of calculating changes in these environmental parameters, a series of scenarios might be provided by the relevant experts to adequately bracket the ranges of possible future situations. Model predictions for these various scenarios will encompass the range of possible future ice-sheet configurations and its effects on global sea level. Experiments that bracket likely ice-sheet response are desirable, in any case, to address political concerns centered on issues such as greenhouse warming, where even the best global climate models can only indicate a range of probable future climates.

This task is exclusively computational and requires no field work of its own. The breadth of the task is extensive and complex and should not be postponed until all analysis of field data is completed. Enough is already known about possible ice dynamic mechanisms that fruitful model development is possible. Also, because of the eventual complexity of such a model, and the variety of numerical methods which might be employed within the model, it is advisable that this task be undertaken by more than a single investigator or group.

5.1.2 Ice Cores

The analysis of ice cores is most useful to WAIS in providing a record of the past environmental forcing at the ice-sheet surface: snowfall and temperature. Proxy records of surface elevation derived from ice cores also indicate aspects of the ice-sheet response to these and other forcings. Finally, ice cores and the boreholes left by their recovery allow temperature, ice property, and basal studies that help ice dynamicists in their physical description of ice flow and help determine the specific nature of the boundary conditions for the numerical flow models.

1) Did the West Antarctic ice sheet collapse during the previous interglacial?

This is still a major, open question and determining that it did or did not happen will go far toward assessing the potential for future West Antarctic ice sheet collapse. Ice-core analysis may be able to answer this question. The task is to date basal ice removed from a portion of the ice sheet that occupies a marine basin. Dating can be accomplished through correlating isotopic or other records to dated sub-ice, continental shelf and deep-sea sedimentary records, through ice-flow modeling, or through newer methods utilizing cosmogenic isotopes. If the basal ice is older than the Sangamon interglacial (approximately 125,000 years), then the ice sheet did not disappear at that location. Spatial extension of the stratigraphy at such a location, through radar sounding of the surrounding area, would enlarge the region where ice could be inferred to have existed during the Sangamon. The other side of the question; e.g., proving disappearance, is more difficult to establish because the absence of ice of this age does not discount the possibility that it had existed but was subsequently melted from the bottom of the ice sheet.

Fulfilling this task demands an ice core drilled to a submarine bed at a site in interior West Antarctica that preferably, is characterized by a low geothermal heat flux and a high accumulation rate because these characteristics help produce a colder bed. A location on the Ross Sea/Pine Island Bay ice divide is a potential site. To calculate most accurately the rate of loss of old ice by basal melting, a temperature profile in the ice should be measured as well as the geothermal gradient and thermal properties in the bed. These factors should be used in ice-flow models.

2) What were the major changes that occurred in the atmosphere over the West Antarctic ice sheet over the last glacial/interglacial cycle?

Climatologists are gaining valuable experience in answering this kind of question by analyses of air samples extracted from ice cores recovered from the Greenland ice sheet and elsewhere. The air at each depth provides a sample of a past atmosphere which can be analyzed for a variety of chemical and isotopic constituents, while particulate and chemical studies can be conducted on the surrounding ice. Atmospheric temperature and accumulation rate, two very important parameters for the ice-flow modeling, can be determined from these data. In addition, the chemical composition and particulate concentration can be used to infer patterns and changes in patterns of atmospheric circulation, making them useful for testing the predictions of atmospheric numerical models.

Interpretation of the resulting climatic information is simpler where the core site is more stable. An ice divide in the interior is preferable. Local changes in ice-sheet configuration could induce changes in local meteorological patterns, thereby complicating the interpretation. Atmospheric circulation simulations using different possible ice-sheet configurations would assist in the identification of the preferred sites to answer this question. As with (1), high accumulation and interior siting are also beneficial.

3) What has been the changing configuration of the West Antarctic ice sheet from the last glacial maximum to the present?

The best information to answer this question would be a history of ice-sheet elevation at a number of points on the ice sheet. Measurements of the total gas content of the air trapped in the cores provide a measure of atmospheric pressure that existed when the air cavities were sealed. If atmospheric circulation has remained stable, this pressure can be converted to a surface elevation. Interpretations of deviations in total gas content suffer from the ambiguity of whether elevation, atmospheric circulation, or both varied. The degree of ambiguity can be reduced by sampling the ice sheet at a number of locations. Thus, more sites provide a valuable measure of the pattern of elevation change as well as less ambiguity for each measurement.

Sampling is desired in central regions and in more dynamic, marginal areas. A record of elevation since the last glacial maximum can be obtained by drilling to only a few hundred meters depth in some places, so it is feasible to expect to collect several of these cores without expending major logistic resources. Possible sites include Ridge B/C and just upstream of present-day ice streams. The ice-core record of former surface elevations will be compared with the geological record obtained from nunataks and coastal mountains (see Section 5.4.1).

4) What are the physical properties that affect ice flow and have variations in these properties distorted the surface of known age?

Ice cores provide various data related to the flow nature of the ice. Crystal size, fabric and temperature all influence the effective viscosity of the ice and represent the integrated deformation and temperature history of the ice. These data are useful in constraining flow models that attempt to reproduce the history of the ice sheet. Electrical properties are perhaps the best data to correlate with the existence of internal radar-reflecting layers. Such layers are believed to represent isochrones.

Many of the most important data here are collected in the borehole once the core is removed, and many of these data will be directly relevant to other disciplines working within WAIS. Repeat inclinometry (for deformation and mass-balance calculations), sonic logging (for ice fabrics), and basal water pressure all should be measured. To assist the geologists, subglacial coring should be undertaken.

Location of core sites is critical, especially for the deeper boreholes that might require more than one field season to complete. Core sites should be chosen only after a vigorous site-selection program, centered around airborne radar surveys followed by ice-flow modeling and, if possible, snowpit studies, installation of automatic weather stations, and atmospheric modeling. Limited, single-investigator coring to 200 m or less (dry drilling) would help characterize the regional variability of paleoclimatic records and would answer specific dynamical questions.

Paleoclimatic cores would be chosen to increase coverage that now is limited to J9, Ridge B/C, Dominion Range, Siple Station, Byrd Station,and the planned McMurdo Dome cores. Dynamics questions might include the extent of dynamic softening and strain heating on ice streams and at their margins.

A reasonable field schedule would be to finish radar surveys of the upper Ross Embayment region (begun as part of the Siple Coast Project) in the 1992-93 field season, drill Ridge B/C or Siple Dome in 1993-94 while conducting surface surveys inland, and then drill a deep core inland during the following three seasons. Dry cores can be fitted around this schedule as needed. The logistics burden of the deep-core effort could be reduced if some scientific analyses were transferred to the new U.S. Ice-Core Repository. The balance of field and laboratory analyses needs careful consideration. About one-third of the expected core analyses are tied to WAIS objectives, with the remainder addressing broader questions of global biogeochemical cycles. Thus, WAIS should contribute perhaps a third of the total costs of the deep-drilling operation.

5.2 Meteorology

The major meteorological controls on the ice sheet are accumulation rate and surface temperature. Thus, the broad goal of the meteorological component of WAIS is to understand the spatial patterns and temporal variability of precipitation (nearly equal to accumulation on large spatial scales) and temperature over the West Antarctic ice sheet as consequences of the coupling between the atmospheric circulation and the ice-sheet topography. These key environmental upper boundary conditions on the ice sheet will be described for both preset and altered ice-sheet conditions for input into glaciological ice-flow models. Atmospheric numerical models will be important for understanding changes to the atmospheric circulation (and resulting accumulation and temperature patterns) through the glacial-interglacial cycle as it will be reconstructed by WAIS investigators, and for calculating future scenarios of atmospheric circulation used in predicting future ice-sheet behavior.

1) What is the magnitude and interannual variability of moisture transport onto the West Antarctic ice sheet?

The atmospheric transport of water vapor across the coastline yields the snowfall that nourishes the ice sheet. Knowledge of the moisture transport in the West Antarctic sector is poor due to lack of data and little recent analysis.

Particular tasks that must be accomplished to answer the above question are: 1) analysis of past regional radiosonde records (particularly from Byrd Station) to extract moisture fluxes at the limited number of sampling sites; 2) development of methods to derive moisture fluxes from existing satellite remote-sensing data, particularly focusing upon the difficulties associated with underlying pack-ice and ice-sheet surfaces; 3) continuing analysis of broad-scale atmospheric numerical diagnoses (e.g., from the European Centre for Medium-Range Weather Forecasting) to ensure that all available observations are being incorporated; and 4) an expansion of the in-situ data-collection network including automatic weather stations (AWSs) on the ice sheet and offshore islands, and deployment of free-drifting buoys in the oceans.

Only task (4) requires field work. It is proposed to deploy two new AWS sites each year during the 5 years of Phase I, in addition to servicing previously established sites. This should be sufficient to establish a synoptic-scale array on the ice sheet. WAIS ice-coring activities could benefit significantly from an AWS placed at each coring site for year-round atmospheric observations. The measured variables could include snow accumulation from an array of acoustic snow-height sensors, and perhaps some simple, automated analyses of snow chemistry.

It is assumed that the World Climate Research Program will succeed in establishing the proposed International Antarctic Drifting Buoy Project to monitor the synoptic-scale atmospheric circulation over the ocean areas surrounding Antarctica. Additionally, it is anticipated that considerable assistance with the remote-sensing research and diagnosis of atmospheric numerical analyses from groups already active in this research will be possible. With Phase I of WAIS establishing the tools needed to describe the moisture flux, Phase-II analyses can concentrate on evaluating flux characteristics and broad-scale controls.

2) What are the important synoptic processes that affect the moisture flux and what is the variability of each process?

Cyclonic activity controls the patterns and variability of moisture flux across the edge of the ice sheet, but very little is known about the basic processes. The long-term (15-20 year) climatology of synoptic systems (primarily cyclones) over high latitudes of the South Pacific Ocean should be established from synoptic analyses that have satisfactorily incorporated all available observations (e.g., the satellite measurements routinely being recorded at McMurdo and Palmer Stations). Particular emphasis should be placed upon establishing the patterns of variability and the associations between the sea-ice and cyclone occurrence. Satellite and available in-situ data need to be evaluated for the frequency and characteristics of these synoptic influences on the West Antarctic ice sheet.

It may be possible to supplement such investigations by tracing snow strata to map the amounts and extents of snowfall produced by major storms over the ice sheet. Continued investigations of mesoscale cyclone formation, tracks, etc. are needed on seasonal and interannual time scales to resolve their role in snowfall over the ice sheet. Once again, satellite and available in-situ observations will provide the key data.

No additional field work is required beyond the expansion of the AWS and ocean-buoy network described in the previous section. It is expected that analyses of these data will extend through Phase II of WAIS as the data base expands.

3) What are the patterns of large-scale variability in the atmospheric circulation?

Synoptic processes express broader scale atmospheric, oceanic and ice-sheet conditions. An understanding is needed of the dominant, large-scale patterns of variability and how these processes interact. Examples of this variability on weekly and seasonal time scales are atmospheric blocking, and links with tropical convection and sea-ice variations. Emphasis is placed here on the interannual, global-scale El Nino Southern Oscillation (ENSO) events, which as studies have indicated, may be strongly manifested in West Antarctica. Synoptic analyses can interact effectively with ice-core studies of ENSO-related depositional events. The South Pacific Cloud Band (SPCB) should be studied as a possible major candidate for transmitting the ENSO and higher frequency tropical impulses to high latitudes of the South Pacific Ocean.

Satellite and synoptic analyses are the primary sources of data. Analyses of existing and new data are required but field work is not needed. Continuing work in Phase II of WAIS is anticipated.

4) How would the important atmospheric processes change under altered boundary conditions?

This question must be answered to provide ice-flow models with scenarios of past and future atmospheric forcings on the ice sheet. A coordinated observational and modeling effort is required with the purpose of understanding the relationship between the nature and variability of moisture fluxes and extratropical cyclones. The modeling studies require as input the topography of the ice sheet, the atmospheric composition and the oceanic surface conditions (sea-surface temperature and sea-ice distributions), illustrating once again the close links between the various disciplines.

Currently, two modeling strategies exist for simulating atmospheric processes. Regional (or mesoscale) models use relatively short time integrations (few days to approximately 1 week) to understand fine-scale details of atmospheric processes, such as the evolution of cyclones and related synoptic and mesoscale processes. General Circulation Models (GCMs) are used for longer term integrations of a month or so to applications involving geologic time scales. Both modeling strategies must be employed in WAIS. Regional modeling efforts should be focused on the synoptic-scale environment, assessing the patterns of moisture transport on a case-study basis using data from available observational networks. These case studies then will be used to refine the parameterization schemes in GCM simulations.

In addition, physical processes not currently represented in the GCM simulations need to be incorporated. As an example, existing GCMs do not explicitly resolve the katabatic wind regime, but recent studies have indicated that the katabatic wind regime may play a central role in the evolution of the circumpolar vortex which, in turn, affects the flux of moisture onto the continent through the interaction of the circumpolar vortex with extratropical cyclones.

No field work is required for the modeling activities. Substantial opportunities exist for interaction with the WAIS activities of other disciplines to understand the nature of the glacial-interglacial cycle for large ice-sheet changes. Refined GCMs will be required for this purpose. Use of GCMS for predictive purposes will require coupling of atmospheric and oceanic simulations, and could be a topic for Phase II of WAIS.

5) What are the mechanisms by which the snow is actually generated?

This process is important in understanding how the atmosphere is affected by the ice sheet, but has never been studied observationally. Investigation of the detailed atmospheric dynamics associated with invasions of moist air into West Antarctica is needed along with an evaluation of the accompanying cloud microphysical and chemical processes which govern cloud and precipitation formation. These studies will feed into theoretical and modeling studies of topographically-forced snowfall.

Ice-core interpretation will be considerably enhanced by improved knowledge of the physics governing the parameters measured in ice cores, particularly stable isotopes and chemical constituents. Opportunities for cooperation with the ice-core drilling should include simultaneous measurements in the air and on the ice sheet.

A well-instrumented research aircraft, like the NCAR Electra or equivalent, is needed for these investigations. To minimize the transit time from the base airfield and to maximize the measurement time of the aircraft, it will probably be necessary to establish a suitable airstrip in West Antarctica, and to operate the aircraft from this remote location at least part of the time. The success of using blue-ice runways for other aircraft elsewhere in Antarctica may open the door for this logistic requirement. It is recommended that these aircraft campaigns be conducted during the first three field seasons of WAIS.

5.3 Oceanography

The principal link between the ocean and the ice sheet rests with the water that circulates under the large ice shelves of West Antarctica. An increase in the amount of heat being transported beneath and transferred to these ice shelves leading to a reduction in their ability to buttress the inland ice is often suggested as the likely mechanism by which a climatic warming could trigger an ice-sheet collapse. Predicting the validity of this hypothesis requires a better understanding of how sub-ice water circulation and heat transport work today, and an understanding of how warmer oceanic waters would be incorporated into the subshelf circulation. The oceanographic studies of WAIS will focus on these coupled questions and will provide numerous opportunities for interdisciplinary investigations.

1) What are the connections between the waters of the open ocean and those on the continental shelf?

It is through the exchange of water at the continental shelf edge that the global ocean directly influences the ice-sheet environment. The edge of the Antarctic continental shelf is one of the primary ventilation sites in the world ocean. There, deep water evolves into surface and shelf waters which interact with the atmosphere and sea ice, as well as with the ice margin and the undersides of the ice shelves. Heat and salt are vigorously exchanged in coastal polynyas and by deep vertical convection near the continental shelf break. Bottom waters formed near Antarctica account for more than half of the abyssal ocean volume.

To understand the transport of fresh water and salt across the continental shelf requires oceanographic measurements of salinity, temperature, chemical tracers, and currents on appropriate temporal and spatial scales at representative locations. Time-series observations should extend over several seasonal cycles, encompassing the residence time for waters on the continental shelf. Satellite measurements of ice distribution and movement will help oceanographers to understand the forcings and interannual variability and to identify sites where air-sea interactions are highest. Efforts to model the ocean circulation on the continental shelf should focus upon regional differences in and sensitivity to changing wind fields and fresh water, salt and temperature fluxes.

2) What is the spatial pattern and temporal variability of ocean interaction with the ice shelves of West Antarctica?

Most of the ice in West Antarctica feeds large ice shelves that float over warmer sea water. An increase in sub-ice-shelf melting has long been believed to be a likely trigger for marine ice-sheet collapse (see Section 3). Modeling experiments have shown that changes in ocean thermohaline characteristics could produce shifts in the strength of the sub-ice circulations, which now appear to cause relatively high melt rates near the ice-shelf grounding lines. Because the seawater freezing point falls with increasing pressure, melting rates are highest where the ice-sheet drafts and grounding lines are deepest. These melting rates could increase if the grounding lines retreated into deeper basins. In addition, order-of-magnitude differences have been reported between the basal melting and freezing rates beneath different ice shelves. Where the sub-ice-shelf circulation is dominated by cold, dense, high-salinity shelf water as in the Ross Sea, average basal melt rates may be as low as 15-25 cm/yr. Where "warm" circumpolar deep water floods the continental shelf as in the Bellingshausen Sea, basal melt rates are as high as 2 m/yr. It has yet to be determined how quickly future climate change might alter the ocean characteristics or circulation near Antarctica, possibly shifting the present distribution of high-melting and low-melting regimes.

Field measurements and modeling efforts should focus upon these two different regimes, beginning in the Ross Embayment which has more extensive hydrographic and cryographic data bases. A transect should be occupied along the axis of the cold Ice Shelf Water circulation cell, extending from the ice shelf grounding line to the deep ocean. Along this transect a series of holes drilled through the Ross Ice Shelf would provide access to the sub-ice cavity for chemical analyses of water samples, for deployment of remote-recording expendable instruments. These holes could also be used for collection of sub-ice sediments, whose analysis provides information on the history of the ice sheet (see Section 5.4.2).

Measurements near the grounding lines in both deep-water and shallow-water environments should attempt to differentiate between meltwaters derived from the ice shelf and from the grounded ice sheet. Coordinated time-series measurements near the ice front should focus upon the factors that cause high melt rates in that region, and upon the variability of Ice Shelf Water (ISW) outflow. Present-generation oceanographic equipment must be tested in the sub-ice environment, and may require repackaging if ice-hole diameters are small (<25 cm.). Continued development of drilling technology should focus upon the provision of larger diameter holes at lower energy cost and the rapid retrieval of crystallographically and stratigraphically unaltered ice cores from the basal regions of an ice shelf.

In contrast to the relatively well-studied Ross Sea, the Amundsen-Bellingshausen ocean circulation is an enigma. Aside from the anomalously warm water on the shelf there, this region often displays strong sensitivity in models of climate change and may be an area of recent ice-shelf retreat. Marine geologists have identified sites there where larger ice shelves existed within the past few thousand years. The scarcity of relevant data makes a detailed survey of this region imperative. Historically, this shelf has been difficult to penetrate due to perennial sea-ice cover, but that should no longer present a major obstacle to modern icebreakers. Maximum synoptic value of these data will be achieved if it is coordinated with the planned focus on the South Pacific-Antarctic by the World Ocean Circulation Experiment (WOCE) program in 1991-93.

3) What will be the spatial and temporal patterns of climatically induced changes in the sea ice and ocean of the Southern Hemisphere?

The impact of these processes of air-sea-ice interaction on sea level will depend upon the response of the Southern Ocean and its sea-ice cover to global warming. If the ocean near Antarctica becomes warmer by direct uptake of heat from the atmosphere or by decreased vertical heat flux from the deep water to the atmosphere, then more ocean heat may be transported onto the continental shelf and beneath the ice shelves. If sea-ice production decreases near Antarctica, then less-dense shelf water may be formed, facilitating access of that warmer water to the ice shelves. Some general circulation models (GCMs) are now yielding less warming than earlier predicted in the Southern Hemisphere atmosphere, but more warming in the Southern Hemisphere ocean over the next several decades.

Investigation of this question will necessitate modeling, measuring and monitoring the spatial and temporal variability of the continental margin sea-ice cover and ocean circulation. Models that couple the deep-ocean, continental-shelf and sub-ice-shelf circulations must be sensitive to observed ranges of water properties, current velocities, sea-ice distributions and basal mass balances. Existing oceanographic data bases and paleoclimatic indicators need to be assembled and analyzed in the context of present-day seasonal, interannual and regional variability and past sea level changes. Methods need to be developed to extract sea-ice thickness and motion from satellite data and to verify these parameters via moored and drifting instruments, sea-ice cores, or aerial observations. Particular attention should be focused upon the identification of coastal regions of potentially high salt or meltwater flux or high sensitivity to climatic perturbations.

4) What are the relationships between the northern limit of sea ice or between the leads and polynyas in the sea ice and regional accumulation rates on the ice sheet?

A separate mode by which the ocean affects the ice sheet is by providing the moisture which the atmosphere delivers as snow. Much of this accumulation is apparently delivered in winter storms when the open ocean lies hundreds of kilometers from the continent but the zonal range of source areas is not well defined. Leads and polynyas in the otherwise-solid sea-ice cover are also important local sources of moisture. Additionally, polynyas increase the flux of heat and perhaps aerosols to the atmosphere, increasing the ability of the air to hold moisture and raise accumulation rates over the ice sheet. Parameterization of this effect will be necessary in full-scale numerical models of the West Antarctic environment.

To determine the seminal relationships between these interactions, data of sea-ice concentrations, weather patterns, and accumulation rates are required. Extended time series of sea-ice concentrations are now available from satellite-based passive microwave sensors but the accuracy of concentration estimates needs to be improved. Weather patterns can be derived from satellite image data but supplemental data from automatic weather stations (AWSs) installed near the locations of perennial coastal polynyas would provide much-needed detail. These AWSs should be instrumented to measure accumulation to augment a record of past accumulation rates and their spatial pattern obtained from a set of shallow firn cores acquired at typical coastal sites.

The oceanographic projects that are essential to the realization of WAIS objectives offer numerous opportunities for interdisciplinary cooperation. These would include potential interactions with: 1) modelers trying to simulate the global-scale coupled ocean-atmosphere circulations and the ice-sheet response to global change; 2) meteorologists concerned with the sources of moisture to the ice sheet, the annual cycles of ocean surface temperature and the siting of AWSs; 3) remote-sensing specialists trying to document spatial and temporal changes in the ice sheet or sea-ice distribution and movement; 4) glaciologists interested in regional variability in ice-shelf mass balance, internal characteristics, velocity, thickness and crevasse distribution; 5) geologists in need of environmental data to interpret sediment cores or to correlate with evidence for recent changes in sea level; and 6) climatologists focused on the sea ice and ice-sheet mass balance, in particular, upon the more rapidly changing coastal zone.

5.4 Geology and Geophysics

1a) What was the configuration of the West Antarctic ice sheet during the last glacial maximum?

1b) What is the configuration of the West Antarctic ice sheet during an extreme glacial minimum?

1c) Has the West Antarctic ice sheet undergone rapid, episodic mass wasting in the recent geologic past?

These questions are linked by the fact that the data to answer them consist of dated marginal positions of the ice sheet--be they on land, on the sea floor, or subglacial. Each topic is treated separately below.

5.4.1 Terrestrial Geology

Drift sheets, end moraines, erratics, striations, glacial fluvial features, trimlines of weathering and strand features provide reliable evidence upon which to reconstruct past configurations of the West Antarctic ice sheet. From these features, the boundaries of the ice sheet--both areal and vertical--and the flow direction can be determined. When tied to specific time intervals by relative and numerical dating methods (e.g., AMS and conventional radiocarbon, cosmogenic methods), these data will allow the development of chronologies defining ice-sheet growth and decay. In addition, they will provide bounds for the determination of rates of advance and retreat. Time resolution of suitable numerical dating methods is a few hundred years.

The broad study areas for these investigations are the east flank of the Transantarctic Mountains and the nunataks and coastal mountains of Marie Byrd Land and Ellsworth Land. The Transantarctic Mountains have already received a great deal of study, but gaps must be filled and the results integrated with existing data. These gaps are included in the regions from Cape Adare to Coulman Island, Coulman Island to McMurdo Sound, and McMurdo Sound to Darwin Glacier. Investigations should also be extended southward into the Reedy Glacier area. In this area, the record can be directly integrated with the past and present activity of Ice Stream A of the West Antarctic ice sheet. Previous studies in the southern Transantarctic Mountains have been hampered by lack of a reliable dating method; recent improvements in cosmogenic dating promise to make studies there more profitable.

The chronology of ice surface and marginal change, combined with data developed from marine geology studies, will reveal whether episodes of rapid and episodic ice wastage occurred. The data from any such episodes can then be compared with the global sea level record. Ultimately, these data will provide the critical historical record of the transient behavior of the ice sheet essential for the control and calibration of ice-sheet numerical models. In addition, the chronologies will be useful in testing the consistency between interpretations derived from the ice core, ice dynamics, and marine geology components of WAIS.

5.4.2 Marine Geology and Geophysics

The geologic record also extends to the ocean-covered areas of the continental shelf where the ice sheets deposit material and rework this material when they advance over it. The structure and stratigraphy of this sediment furnish a record of glacial and glacial-marine conditions at the time of deposition and possible clues to the role that subglacial water may play in the dynamics of ice-stream motion. By dating the core material using geochemical and paleonotological techniques and by evaluating the relative composition and character of the sediments, the age of key units, and therefore the rates and patterns of ice-sheet retreat, can be inferred. Paleontological techniques also provide information on the bottom water characteristics (e.g. temperature, bathymetry, and proximity to grounded ice), upper water mass characteristics (e.g. presence or absence of glacial ice, salinity, light, mixing, and primary productivity), and terrestrial palynology (e.g. vegetation characteristics and pollen spores).

The specific tasks that must be accomplished to answer the above questions are: 1) an analysis of existing high-resolution seismic data and piston cores from the Ross Sea; 2) a mapping of the sea-floor stratigraphy using multi-beam bottom imaging instruments; 3) a refinement of the location and dating sequence of significant geologic features found in (2); 4) an overall synthesis of data and interpretation; and 5) an extension of these methods to the areas beyond the Ross Sea, specifically Pine Island Bay, underneath the Ross Ice Shelf, and possibly the Wilkes Land continental shelf.

Task (1) will be undertaken initially to assess these existing data and to define better those areas where field studies should be conducted. Seismic analyses will concentrate on defining those areas where seismic facies and morphological features imply former grounding-line positions. This work will be hampered by a paucity of high-quality records; existing data consist mainly of relatively short and discontinuous sparker records.

Many piston cores have been acquired from the Ross Sea continental shelf, mainly during Eltanin and Glacier cruises. These cores contain a valuable record of the late Pleistocene-Holocene glacial setting on the shelf. Detailed sedimentological studies of these cores are needed to define former grounding-line positions and the paleodrainage divides of former ice sheets, and to study the nature of ice-sheet retreat from the shelf. Studies also are needed to evaluate methods of age-dating these sediments and for extraction of information of water mass characteristics and terrestrial palynology listed above. This work is expected to occupy investigators for the first year of WAIS.

In the second year, mapping of the sea floor using multibeam bottom imaging instruments (task 2) will provide a wealth of information about the subglacial environment during the last glacial maximum. This work, done in conjunction with high-resolution seismic profiling, will result in a three-dimensional reconstruction of the glacial sediments and the thin veneer of Holocene sediments that blanket the Ross Sea continental shelf. These sediments record the most recent expansion of the West Antarctic ice sheet and its retreat from the shelf.

Information gained the first 2 years of the project will be used to design experiments to identify the geological setting (e.g., bedforms, subglacial meltwater channels, sediment properties) associated with former grounding-line positions on the shelf, and to examine the history of ice-sheet retreat from the shelf. Field work for task (3) will commence in the third year of WAIS, and will concentrate on detailed mapping of these areas using deep tow side-scan sonar and high-resolution seismic profiling. Sediment cores will be acquired from specific environments the succeeding year. One or more of the transects will extend from the continental slope to the ice-shelf edge and within paleodrainage divides of specific ice streams (based on provenance studies of tills conducted during the previous two years' studies). Age dating of the contact between subglacial and glacial marine sediments in these cores will rely on the most current radiometric dating methods (i.e., Tandem Accelerator Mass Spectrometer: TAMS) and, hopefully, will provide a record of the timing and rate of ice-sheet retreat from the shelf. Along with these data, paleontological studies of the sediment will contribute to a characterization of the environment during the interglacial and retreat phases.

The final year of Phase I will be devoted to task (4), which is exclusively interpretative. If there have been problems in any of the prior data-collection seasons, additional field work may be required but it is not part of this plan.

The additional areas indicated under task (5) include Pine Island Bay, underneath the Ross Ice Shelf, and the Wilkes Land continental shelf. Pine Island

Bay is an area of particular interest due to the absence of ice shelves in the mouths of the two major outlet ice streams. Marine geologic and geophysical studies of the bay combined with the oceanographic studies recommended (see Section 5.3) should provide insight into the history of ice-sheet advance and retreat in this unique setting and possible causes. It is anticipated that one field season will be sufficient to collect the necessary seismic data and cores needed to address the questions concerning the history of this area during and since the last glacial maximum. The timing of this study would be coordinated with oceanographic and meteorological interests in the region and may be deferred until Phase II.

The modern analog for the depositional environment of an extended West Antarctic ice sheet is located underneath the Ross Ice Shelf at the grounding line of the ice streams. Sediment cores recovered from beneath a series of access holes drilled through the ice shelf will provide an unprecedented view of how the sediment structures evolve. Seismic work at each drill site will give the stratigraphic context of each core, assisting in the generation of a single, continuous record from the grounding line to the edge of the continental shelf. This data set will enable a better interpretation of the dynamics and history of the ice sheet, the depositional mechanism and the role of water in the formation of these deposits.

The continental shelf along portions of the Wilkes Land margin represents the terminal drainage for two large marine-based ice drainage systems which appear to be relatively stable. This contrast to the West Antarctic condition would provide information on those factors which contribute to this stability. The precise timing (within a few hundred years) of recession of the ice sheet can be determined because of the presence of: a well-defined terminal moraine system; a high-resolution post-glacial marine sequence; and a relict subglacial morphology, fluted surfaces, etc. The age, composition, and distribution of these features need to be evaluated through a program of high-resolution seismic profiling, side-scan sonar surveys, and coring.

5.4.3 Subglacial Geology and Geophysics

To understand the minimum extent of the ice sheet (question 1b, above), data must be collected from beneath the present-day ice sheet. Holes through the ice can be drilled rapidly using hot-water systems permitting frequent access to the bed either underneath the ice shelf or underneath the grounded ice sheet. Collected cores will be examined in detail for sediment physical properties, composition and texture. Sedimentological, micropaleontological and geochemical analyses will be performed to constrain the environment of deposition, to establish the age of these deposits, and to help determine the southernmost extent of the grounding line during past interglacials. These data will be correlated with similar information derived from marine sediments collected on the continental shelf or under the ice shelves to provide a broader view of the history of the ice margin. Cores acquired within the present zone of ice-sheet grounding will be used to test models relating bed conditions to ice-sheet stability. The actual timing involved in drilling at these sites will rely on coordination with glaciological and oceanographic studies.

Subglacial geophysical investigations will also be directed at answering a much different question than the trio of questions listed at the beginning of this section.

2) What are the geologic controls on the flow of a marine ice sheet?

The answer to this question requires geophysical techniques to study the geologic setting of the ice sheet. For this study, the subglacial lithology, distribution of geothermal flux, and tectonic activity all must be considered. There is evidence that the positions of the ice streams are controlled by the subglacial lithology and perhaps by the thermal regime. If their rapid motion is caused by a deforming subglacial till made weak by pressurized subglacial water, then the ice streams must be located near a rapidly erodible source of sediment as well as in a region characterized by basal melting. It is known that the West Antarctic lithosphere is characterized by recent volcanism and associated high geothermal flux but few details exist on the spatial pattern of these characteristics.

Most of the subglacial and englacial geophysical data of the West Antarctic ice sheet and its underlying bed that are needed for WAIS will be collected either by projects already planned, such as Antarctic Geophysical Initiative (AGI) (see Section 6.1.2), or by collaborations with WAIS investigators in ice dynamics, ice coring, or marine geology. This method of providing ancillary data for glaciological studies in the Siple Coast Project (Section 6.1.1) proved effective and established the broad geophysical data base upon which subsequent measurements during WAIS will be able to build.

Early in the WAIS program, a regional mapping of the ice-sheet configuration and bed-type needs to be accomplished in the region of the catchments of Ice Streams B, C, D and E. Understanding the correlation of lithospheric boundaries and subglacial morphology with changes in the dynamic regime between the ice divide and the ice streams of this portion of the West Antarctic ice sheet is critical to understanding its evolution, but insufficient data exist. Two seasons (1991/92 and 1992/93) of airborne radar soundings combined with airborne gravity and magnetics should be flown in cooperation with transects being undertaken by the AGI program.

As an adjunct to this aerogeophysical program, a sequence of radar transects to measure the thickness of Ice Streams D and E across a number of gates distributed along their lengths needs to be undertaken (in 1992/93) (see Section 5.1.1). When combined with surface velocities derived from satellite imagery, these radar data will yield the critical net mass balance needed to assess the current state of Ice Streams D and E and to serve as initial conditions to numerical models.

A detailed aerogeophysical survey will also be required in the vicinity of the proposed deep ice-drilling site on the divide between the Pine Island and Ross Embayments. The surface, bed and internal-layer morphology supplied by these studies are necessary boundary conditions for the ice-flow modeling of the age-depth relation needed to understand the history of the West Antarctic ice sheet and date any ice cores from the ice sheet. Additionally, any indications of lithospheric properties that might coincide with high geothermal flux and a shortened core record can be evaluated before drilling begins. These data can be obtained in conjunction with the aerogeophysical efforts in support of ice dynamics and subglacial geology in the catchments of Ice Streams D and E and over the Byrd subglacial basin that were described above (for 1992/93).

Understanding the water and sediment budget as well as the ice rheology in the region at the onset of ice streaming flow is critical to understanding the dynamics of the ice sheet and our ability to model it. Because of this, geophysical investigations of the bed character, bed morphology and ice fabric using both ground radar and seismological techniques need to be undertaken in the area near the onset of fast flow. These studies should begin immediately after completion of the aerogeophysical program described above.

Determining the current state of the West Antarctic ice sheet will require measuring the ice thickness of the outlet glaciers along the coast of Marie Byrd Land. Again, satellite-image-derived velocities can be combined with these data to determine the current mass outflow in these coastal areas to compare with independently derived estimates of the iceberg calving rate. Reconnaissance work of a similar nature in the marine potions of Wilkes Land is also advisable.

6. RELATED RESEARCH PROGRAMS

6.1 Domestic Programs

Much of the research necessary for the attainment of the WAIS objectives is already being supported or planned under the auspices of active domestic programs. The WAIS program provides a framework that connects portions of these independent activities, along with new investigations, and focuses them sharply so that a multidisciplinary question of possible major global importance is answered.

Reports describing each of these projects have already been written. What is given here is only a brief description to identify how each project relates to the WAIS program.

6.1.1 Siple Coast Project

The Siple Coast Project (SCP) is a glaciological study concentrating on the Ross Embayment sector of the West Antarctic ice sheet (SCP Steering Committee, 1988). It began in 1983 and aims to determine the current mass balance, to identify the physical controls on ice flow, and to predict the future behavior of the ice in this region. While the first two goals are well in hand, it has become increasingly apparent that the prediction of the future of a marine ice sheet is not solely a glaciological problem. It requires an understanding of the complex nature of interaction between the ice, the underlying lithosphere, the ocean and the atmosphere; WAIS is designed to provide this understanding.

The SCP also has discovered the significant changes in the ice sheet that form the urgent basis for WAIS. Along with the discovery of major mass imbalances and changes in ice velocities, SCP investigators have revealed the existence of a thick, extensive subglacial layer with mechanical properties that are probably responsible for the rapid motion of the ice streams.

According to the SCP Science Plan (SCP Steering Committee, 1988), major field activities are expected to terminate by 1994. Due to the strong overlap in the goals of the SCP and WAIS, concluding SCP investigations can be considered as initial WAIS investigations.

6.1.2 Antarctic Geophysical Initiative

The Antarctic Geophysical Initiative (AGI) is a 10-year program begun in 1990 and focusing on Antarctica's tectonic evolution and its role in paleoenvironmental change that culminated in the Cenozoic glaciation (Workshop

Report on the Antarctic Lithosphere, 1988). The initial thrust of this program also will be in West Antarctica. All of the geophysical data collected as part of the AGI will contribute to the objectives of WAIS and, similarly, the geological and geophysical undertakings of WAIS will contribute to a better understanding of both the tectonic evolution and paleoenvironmental history of West Antarctica. It is expected that the similar geological, geophysical and geographical foci of AGI and WAIS will result in close cooperation.

6.1.3 Global Ice-Core Research Program

The Ice-Core Working Group (ICWG) has identified the West Antarctic ice sheet as the location for a deep and intermediate coring program following the completion of the Greenland Ice Sheet Project-2 (GISP2) hole (ICWG, 1989). The primary goals of the West Antarctic phase of this program are: to determine the response of the West Antarctic ice sheet to the warmth of the last interglacial; to reconstruct a high-resolution, multiparameter history of the ice sheet and the overlying atmosphere; and to elucidate the interaction between climate, ice-sheet size, and sea level. Comparison of this record with that from GISP2 should allow assessment of the critical timing and phase relationships of global environmental changes affecting both Greenland and Antarctica.

The location of the deep core is being proposed along the ice divide in West Antarctica, a region where interests from the AGI and WAIS merge. The site selection for the planned deep and intermediate cores will clearly draw heavily on the wealth of data already collected by the SCP and eventually by the AGI and WAIS. The requirement of the coring program to know basal topography, current net balance, and 10-meter temperatures can be satisfied with SCP and AGI data. Additional requirements include confirmation of a frozen bed, local ice flow and meteorological sensitivity at the drill site. The first and third of these requirements are addressed by WAIS.

The ICWG and WAIS both seek to understand interactions between the ice sheet and its environment. Ice cores from several of the West Antarctic ice-sheet localities (e.g., Ridge B/C and Siple Dome) recommended by the ICWG initiative contribute directly to WAIS. It is likely that a close cooperation will develop between the two programs.

6.2 International Programs

The WAIS goal and objectives are not only of domestic interest. Many other nations have active research programs in West Antarctica and are concerned about the future of this ice sheet. Thus, much of the research of Antarctic scientists in other countries is directly relevant to WAIS. Major international programs with overlapping interests to WAIS are described below. These programs afford WAIS investigators opportunities for sharing of results and for initiating collaborative research. We recommend that such collaborations be undertaken as deemed appropriate and desirable by individual WAIS investigators.

6.2.1 Filchner-Ronne Ice Shelf Programme

Many nations have been active in West Antarctic research and are concerned about the future behavior of this ice sheet. The Working Group on Glaciology of the Scientific Committee on Antarctic Research (SCAR) has recommended that "an increased effort be put into field work as well as numerical simulation studies on ice shelves and associated oceanographic systems, in particular the Filchner/Ronne Ice Shelf and the southern Weddell Sea" (FRISP Newsletter, 1990). The Filchner-Ronne Ice Shelf Programme (FRISP) was initiated in 1973 shortly after this recommendation and representatives of countries such as Argentina, Germany, Great Britain, Norway, Sweden, the U.S., and the USSR have agreed to cooperate in studying the glaciological regime of the ice shelf. While the research of the FRISP is limited to glaciological and oceanographic studies, the geographical region of interest includes a major portion of West Antarctica, and close cooperation with these scientists will be actively pursued by WAIS scientists.

6.2.2 Glaciology of the Antarctic Peninsula

There are also a number of countries conducting research in the Antarctic Peninsula under the Glaciology of the Antarctic Peninsula (GAP) program. The record of past ice-sheet configuration, oceanographic characteristics, and atmospheric circulation patterns produced by GAP researchers will be of obvious relevance to WAIS investigations. WAIS will maintain open communication with GAP researchers to keep them informed of planned WAIS investigations and important results, and to facilitate collaborations between investigators that will benefit each program.

6.2.3 International Geosphere-Biosphere Program

The International Geosphere Biosphere Program (IGBP) attempts to link together the research of many nations into a comprehensive study of the entire Earth climate system. The Scientific Committee on Antarctic Research (SCAR) recently identified a number of research tasks that "must be included in an Antarctic component of the IGBP" (SCAR, 1989). The list contains recommendations for studies of sea-ice/ocean/atmosphere interactions, the interaction of the Antarctic ice sheet and sea level, and the Antarctic paleoenvironmental record. All of these are elements of WAIS and indicate the very useful contribution to the IGBP by WAIS.

6.2.4 International Trans-Antarctic Scientific Expedition

As proposed, the broad aim of the International Trans-Antarctic Scientific Expedition (ITASE) is to establish how the present-day atmospheric environment is represented in the upper layers of the Antarctic ice sheet. The key scientific problems to be addressed include: the spatial representativeness of several environmentally-related parameters measured in ice cores on a time scale of approximately the last 100 years; establishment of a basis for assessing recent environmental change in Antarctica; documentation of variations in the transport processes over the ice sheet; refinement of mass balance of the ice sheet; the linking of AWS data to data from air-sampling stations; and establishment of ground-truth for future remote-sensing experiments. These objectives overlap with many of the WAIS objectives and key questions.

The primary product of ITASE would be a continental-scale map of several environmental parameters. This would serve as useful input into WAIS models. ITASE data would come from a series of 20-meter-long surface cores collected every 50-100 km along traverse routes distributed throughout the continent. Logistics support will be developed from an international pool but several legs may depend on the logistic capabilities of one country. Many member countries of the International Ice Core Forum have taken part in the formulation of ITASE and it will be offered to SCAR for consideration as part of the IGBP. Ideally, the US component of ITASE would be heavily weighted in West Antarctica and would benefit from close scientific and logistic cooperation with WAIS activities.

6.2.5 Ice-Sheet Research with ERS-1

Satellite remote sensing greatly improves the ability of scientists to study large regions of the Earth. In the polar regions, satellite data have been used to study surface morphologies of ice and rock, ice flow, meteorological phenomena, ocean currents, and the behavior of the sea-ice cover, to name only a few of the many possible applications. The European Space Agency's ERS-1 satellite will have an orbit which extends southward to 82^{o}S, covering a substantial portion of West Antarctica. Ice-Sheet Research with ERS-1 (ISRERS-1) is an international collection of glaciologists who plan a wide range of studies using the radar altimeter, the synthetic aperture radar (SAR), and the thermal sensor on the ERS-1 satellite scheduled for launch in 1991. Altimetry will provide an accurate data base of surface elevation against which future altimetric surveys (perhaps with laser altimeters) can be compared to discover regions experiencing rapid thickness change. The synthetic aperture radar data from ERS-1 will not extend over much of West Antarctica because of the north-looking view of the sensor but will provide preliminary data to glaciologists, oceanographers, and geologists. Analyses of these data will help determine the potential for using future SARs which will cover more of West Antarctica.

7. IMPLEMENTATION PLAN

7.1 Feasibility

None of the critical research contemplated for WAIS requires major technical advances, although improvements on many fronts such as isotopic dating, finer resolution sonar, and more efficient drilling, obviously would benefit the research. The necessary capabilities are currently available in the United States. With the recent demonstration of ice-drilling capability for both recovery of core and bed access, as well as the emphasis on new geophysical platforms, any part of the West Antarctic can be investigated either directly or remotely. Satellite and airborne remote-sensor data collected from current or planned instruments will expedite the collection of reconnaissance data. The laboratory capabilities also exist, as do the computers and modeling expertise to utilize them.

7.2 Schedule and Logistics

WAIS will make efficient use of logistic support through a coordination of the diverse field activities. Activities by different investigators, but in the same regions, will be executed together to the extent possible. Such coordination provides greater return for expensive support such as Twin Otter aircraft or helicopters in regions far from McMurdo Station. This coordination will be encouraged by the WAIS Working Group but individual investigators will work directly with the Polar Operations Section of the National Science Foundation/Division of Polar Programs.

The Working Group has taken the required investigations identified in the Science Plan (Section 5) and formulated a recommended schedule for Phase I (see Table 1). This schedule incorporates the majority of Ross Sea Embayment investigations into a 5-year period beginning with the 1992-93 field season.

While a number of factors could force modifications to the recommended schedule, investigators contemplating involvement in WAIS are encouraged to adhere to the schedule as much as possible. The phasing of investigations in the schedule is intended to increase the scientific return and to maintain relatively constant logistics and funding requirements. Investigations that provide information and analyses critical to the locating of subsequent studies are scheduled early.

Table 1. WAIS Implementation Plan	Funding ($M) (1990 Dollars) 92	93	94	95	96	97	Logistics 92	93	94	95	96	97
1. Ice Dynamics												
1) Mass Balance: (see also 5c Radar)												
Siple Coast	.2	.3						ℓ,t				
Amundsen Coast	.1	.1	.1	.1	.1				ℓ,t			
Wilkes Land		.05		.05								
2) Physical Controls												
a) Basal Mechanics (see also 5c Seismic)												
Borehole Geophysics	.45	.45	.45	.45	.45		L	L	L	L	L	
Ice Flow	.15	.15	.15	.15	.15		ℓ	ℓ	ℓ	ℓ	ℓ	
b) Shear Margin Mechanics	.2	.1	.2	.2				ℓ		ℓ	ℓ	
c) Buttressing Mechanics	.1	.1	.1		.1		ℓ	ℓ			ℓ	
3) Ice Flow Models	.2	.2	.2	.2	.2							
Subtotals	1.2	1.5	1.15	1.1	1.25							
2. Ice Coring												
1) Site Surveys (see also 5c Radar)	.2	.2					ℓ,t	ℓ,t				
2) Core (Ridge B/C or Siple Dome)		.8						𝓛				
3) Deep Core (1/3 Cost Support)			1.0	1.0	1.0				𝓛	𝓛	𝓛	
Subtotals	.2	1.0	1.0	1.0	1.0							
3. Meteorology												
1) Moisture Flux Analysis	.15	.15	.15	.15	.15							
AWS Deployments	.15	.15	.15	.15	.15		ℓ,t	ℓ,t	ℓ,t	ℓ,t	ℓ,t	
2) Synoptic Process Studies	.1	.1	.1	.15	.15							
3) Large-Scale Variability	.1	.1	.1	.15	.15							
4) Scenario Modeling	.2	.2	.2	.2	.2							
5) Snow Formation	.3	.3	.3	.2	.2		A	A	A			
Subtotals	1.0	1.0	1.0	1.0	1.0							
4. Oceanography												
1) Ocean/Continental Shelf Interaction	.2	.2	.2	.3	.3		S		s		S	
2) Sub-Ice-Shelf Interaction												
Ross Sector	.65	.55	.5	.4	.4							
Amundsen/Bellingshausen Sector			.3	.3	.2				𝓈			
3) Climatic Response of Ocean & Sea-Ice	.15	.15	.1	.1	.1		s		s		s	
4) Accumulation/Sea-Ice Relationship	.2	.2	.1	.1	.1							
Subtotals	1.2	1.1	1.2	1.2	1.1							

5. Geology										
a) Terrestrial Geology										
Cape Adare to Coulman Island	.18					ℓ,t/s				
Coulman Island to McMurdo		.18					ℓ,t/s			
McMurdo to Darwin Glacier			.18					ℓ,t		
Reedy Glacier Area		.18	.18				ℓ,t	ℓ,t		
S.W. Marie Byrd Land	.18	.18				ℓ,t	ℓ,t/s			
Exec. Comm. & Ames Ranges			.18					ℓ,t/s		
James, Hudson & Walker Mountains				.18					ℓ,t/s	
Pine Island & Thwaites Glaciers Area				.18	.18					ℓ,t/s
Subtotals	.36	.54	.54	.36	.18					
b) Marine Geology & Geophysics										
Analysis of Existing Data	.3									
Seafloor Mapping of Ross Sea		.75					𝓈			
Detailed Shelf Transects			.75					𝓈		
Coring & Shallow Drilling				.75					𝓈	
Data Analysis					.5					
Pine Island Bay Survey					.25				S	
Sub-Ross Ice Shelf Survey				.1				ℓ		
Subtotals	.3	.75	.75	.85	.75					
c) Subglacial Geology & Geophysics										
Radar Surveys										
Catchment B/C	.1					ℓ,t				
Ice Streams D&E	.25	.1				ℓ,t				
Core Site Survey	.1					ℓ,t				
Pine Island	.2	.1				ℓ,t				
Ice Stream B		.1								
Marie Byrd Land Coast			.25	.35	.1			L,t	L,t	
Wilkes Land					.25					L,t
Seismic Surveys		.25	.1				L			
Subtotals	.65	.55	.35	.35	.35					
Totals	4.9	6.4	6.0	5.9	5.6	28	31	32	21	20
Grand Total			28.8							

Logistics Code:

- A – Meterologic Research Aircraft
- ℓ, L, 𝓛 – LC-130 Aircraft
- s, S, 𝓈 – Research Vessel (Ship)
- t, T, – Twin Otter Aircraft (Possibly Helicopters for Terrestrial Geology)

Assigned Values
Light (< 1Month) = 1
Moderate (1-2 Months) = 2
Heavy (> 2 Months) = 3
Logistics Totals Reflect Assigned Values

7.3 Funding

Table 1 also presents the funding schedule required to complete all Phase-I investigations. As formulated, this schedule maintains a nearly uniform annual funding level of between $5 and $6 million with a total Phase-I cost of $28.8 million. All funding estimates are given in terms of 1990 dollars. The WAIS initiative proposal made by the Division of Polar Programs (DPP) within the National Science Foundation (NSF) has requested monies to support the WAIS initiative, however, some investigations may be supported by NSF/DPP core funds. These decisions will be made by NSF/DPP.

The goal and objectives of WAIS fall well within the research interests of many other agencies; e.g., NASA, NOAA and USGS, which are active in global change and Antarctic studies. It is possible that some of these agencies may become involved in WAIS and contribute funds to support particular WAIS research tasks. The WAIS Working Group will work with NSF to enlist the interest of these agencies in WAIS and to garner additional funding, if needed.

7.4 Opportunities for New Researchers

WAIS will involve many investigators, large field campaigns, and substantial funding. In relevant disciplines where the population of currently active Antarctic investigators is small, there is an opportunity for other interested scientists to become involved in an Antarctic research project with direct relevance to global concerns. Scientists currently involved in Antarctic research can benefit by involving colleagues with relevant expertise in collaborative proposals.

8. MANAGEMENT PLAN

The focal point of WAIS within the science community is the WAIS Working Group. Presently, it is composed of eight scientists including at least one person in each of the relevant fields (see page vi). To date, the primary role of the Working Group members has been to promote the concept of WAIS within their respective communities and to complete the traditional set of planning documents describing the project.

Ultimate management authority of WAIS will come from NSF/DPP and is likely to involve three different program offices: the Polar Glaciology Program, the Polar Earth Sciences Program and the Polar Oceans and Climate Program. Once scientific investigations begin, the management structure of WAIS will be reviewed by the Working Group and NSF/DPP. It is possible that a sharper interface between the scientists and NSF/DPP utilizing a single point-of-contact for both groups will be deemed more effective.

The initiation of WAIS proposals, funding and field work will follow an "Announcement of Opportunity" issued by NSF/DPP in January 1991. The announcement provides general information about the nature of the WAIS program and requests prospective proposers to submit a letter of intent to NSF/DPP by March 15, 1991, briefly describing the intended investigation. This WAIS Science and Implementation Plan serves as a more in-depth description of the WAIS program to be used in the writing of actual proposals, which would be due by the normal June 1 deadline for Antarctic research.

Copies of the letter of intent will be passed on to the WAIS Working Group which will identify any gaps in a complete WAIS program in April 1991. If gaps exist, the participation of appropriate scientists to fill those gaps will be encouraged. The WAIS Working Group will also review the intended investigations and provide suggestions to the investigators in both method and schedule to help produce a set of final proposals that matches the recommended schedule of investigations as closely as possible. This oversight function of the Working Group is intended to enhance the scientific return of WAIS and to help maintain a sharp scientific focus. It will constitute neither an acceptance nor a rejection of either particular investigators or their proposals.

The Working Group will not advise, recommend, or participate in any funding decisions. Proposals received by NSF/DPP will undergo merit review in a manner to be determined by NSF. Principal Investigators of accepted FY92 proposals will become responsible for coordination and implementation of the WAIS program. The membership of the WAIS Working Group will be modified, if necessary, to include predominantly active WAIS investigators. While continuing to serve as the "conscience" of the project, the Working Group will shift to a role of insuring coordination of and communication between all WAIS investigators and of working with NSF/DPP at the interagency and international levels. It is anticipated that a WAIS symposium will be held each year to present results and that the WAIS Working Group will need to meet at least one additional time each year to maintain the course of the project.

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Appendix A: Supporting Statements from Scientific Panel Reports

Concern about ice-sheet collapse raising sea level is not new. Research on this critical subject has been identified and endorsed by many panels of distinguished Earth scientists. By taking a multidisciplinary approach, WAIS satisfies many separate research elements ranked as priority research by these panels. What follows are statements supporting the WAIS goal excerpted from these reports.

A.1 Our Changing Planet: The FY 1990 Research Plan. The U.S. Global Change Research Program, Interagency Committee on Earth Sciences, 1989

"High Priority Research Needs:

Ice Sheet Mass Balance. The most important area of research in the cryosphere is to determine the mass balance of the ice sheets...and determine how their respective mass balances are changing...because of the linkage of negative mass balance in glaciers to rising sea level [p. 36]...

Sea Ice and the Oceans. The dynamics and thermodynamics of the interaction between sea ice and the ocean and the influence of sea ice on both ocean circulation and climate require further study [p.36]...

Ice-Ocean-Atmosphere Coupling. Much improved models are needed to link climate change to glacier mass balance changes and changes in sea level, so that the glacial component of sea-level change can be predicted. In addition, second generation, three-dimensional ice-sheet models, which include thermodynamics, ocean coupling, and feedback effects of solid Earth deformation, are needed to simulate the present state of the polar ice sheets and to predict the response of ice sheets to climate change. A better model of a marine-based ice sheet, such as the West Antarctic ice sheet, is needed to produce a coupled glacier ice-ocean-atmosphere model [p. 39]."

A.2 Earth System Science, A Closer View, Earth Systems Sciences Committee, NASA Advisory Council, 1988

"Interactive ocean-atmosphere-ice models..." are identified as an important research focus for studying the Earth system on time scales of decades to centuries (p. 152).

The following parameters are listed as providing a fundamental description of the Earth (Tables 9.1A and 9.1B):

Importance	Parameter
Essential	Ice Volume and Extent
High	Sea Level
Substantial	Ice-Sheet Surface Elevation
	Ice-Sheet Volume Changes

A.3 The Role of Antarctica in Global Change, Scientific Priorities for the International Geosphere-Biosphere Program (IGBP), Scientific Committee on Antarctic Research (SCAR) Steering Committee for the IGBP, (1989)

"Tasks that must be included in an Antarctic component of the IGBP include:

To monitor the rate and extent of change in the Antarctic sea ice, atmosphere, ocean and biota, and study their interactions;

To establish a system to measure changes in Antarctic snow accumulation and ice flow likely to affect ice mass balance and sea level;

To clarify further the past global environmental changes using deep ice cores and sediment records from Antarctica." (p. 5)

A.4 Glaciers, Ice Sheet, and Sea Level: Effects of a CO_2-Induced Climatic Change, Committee on Glaciology, Polar Research Board, National Research Council, 1985

"The physics of the dynamic response of the ice sheets to variations in climate is known in general terms, but some processes are not well understood or have not yet been incorporated fully in numerical models. Major gaps in understanding concern basal sliding, the coupling of ice streams with the ice sheets in which they are embedded, and what determines the position of the seaward (calving) face of ice shelves [p. 3]...

In the case of the West Antarctic Ice Sheet, the situation is further complicated by the possibly delicate stability of the interaction between ice streams and ice shelves. If melting from the base of ice shelves were to increase markedly, the effect on ice streams could be far more important than the expected minor increase in surface melting and runoff. [p. 4]"

A.5 Environment of West Antarctica: Potential CO_2-Induced Changes, Committee on Glaciology, Polar Research Board, National Research Council, 1984

"It has been suggested that a rapid reduction of the ice mass of West Antarctica leading to a drastic rise in sea level might occur as a consequence of CO_2-induced warming.

The existing West Antarctic environment is inadequately described by the available observations. This conclusion holds both for the general atmospheric and oceanic circulations and for their specific manifestations: the mass and energy balances of the inland ice sheet, the ice shelves, and the surrounding sea ice. [p. 1]...

This rise in sea level [caused by a rise in CO_2] will be relatively manageable in the next century unless, as some scientists have suggested, the warming triggers a rapid reduction in the ice mass of the West Antarctic Ice Sheet. In order to assess the possibility that this would happen, two kinds of studies are required. First, the external climate factors that influence the West Antarctic Ice Sheet--mainly precipitation, summer temperature, and oceanic heat flux--need to be known. Second, the dynamic response of the ice sheet/ice stream/ice shelf system to changes in this external forcing needs to be understood. [p. 4]"

A.6 U.S. Research in Antarctica in 2000 A.D. and Beyond, A Preliminary Assessment, Polar Research Board, National Research Council, 1986

"OUTLOOK BEYOND 2000 A.D.
...the scientific priorities for antarctic research will most likely reflect the global issues of pollution, climate change habitability, resources, geotectonics, and other large-scale problems.

Examples of just a few of the many specific global questions that may be addressed include the following:

* The stability of the West Antarctic Ice Sheet in the face of the anticipated global warming...

* The role of the Antarctic in forcing the global atmosphere and ocean...

* The intensity of the antarctic-driven forcing system, the parameters that control it, and its fluctuations with time. [pp. 13-14]...

Glaciology's recent exciting discoveries and advances are expected to continue with regard to understanding the role of ice in climate, documenting the climate of the past, determining the stability of the ice sheets, and assessing the potential future impact of the antarctic ice sheet on sea level. [p. 21]"

A.7 <u>Antarctic Solid-Earth Sciences Research: A Guide to the Next Decade and Beyond</u>, Ad Hoc Committee on Antarctic Geosciences, Polar Research Board, National Research Council, 1986

"The following are the most important broad topical problems...that we recommend be investigated during the next decade of Antarctic geoscience research:...

Category A: Antarctic Problems with Global Implications. [p. 8]...

3. The reconstruction of a more detailed history of the Antarctic Ice Sheet and the definition of the physical , geological, and biological responses to it on both the regional and global scale [p. 9]."

APPENDIX B: Addresses of Workshop Participants

Dr. Richard Alley
306 Deike Bldg.
Earth Sys. Sci. Center
University Park, PA 16802
(814) 863-1700
FAX: 814-865-3191

Dr. John B. Anderson
Dept. of Geology & Geophysics
Rice University
Houston, TX 77251
(713) 527-4884
FAX: 713-285-5214

Dr. Paul Berkman
125 South Oval Mall
The Ohio State University
Columbus, OH 43210
(614) 292-6639
FAX: 614-292-4697

Dr. Robert Bindschadler
NASA/Goddard Space Flight Center
Code 971
Greenbelt, MD 20771
(301) 286-7611
FAX: 301-286-2717

Dr. Don Blankenship
125 South Oval Mall
The Ohio State University
Columbus, OH 43210
(614) 292-3471/6531
FAX: 614-292-4697

Dr. Harold Borns
304 Boardman Hall
University of Maine
Orono, ME 04469
(207) 581-2196
FAX: 207-581-2202

Dr. David Bromwich
125 South Oval Mall
The Ohio State University
Columbus, OH 43210
(614) 292-6692
FAX: 614-292-4697

Dr. Parker E. Calkin
Geology SUNY Buffalo
4240 Ridge Lea Road
Buffalo, NY 14260
(716) 831-2460/3051
FAX: 716-831-2010

Dr. Curt H. Davis
Remote Sensing Lab./ Univ. of KS
2291 Irving Hill Road
Lawrence, KS 66045
(913) 864-7794
FAX: 913-864-7789

Dr. George Denton
Institute of Quaternary Studies
University of Maine
Orono, ME 04469
(207) 581-2193
FAX: 207-581-2202

Dr. C.S.M. Doake
British Antarctic Survey
High Cross
Madingley Road
Cambridge CB3 0ET
United Kingdom

Dr. Eugene W. Domack
Geology Department
Hamilton College
Clinton, NY 13323
(315) 859-4711
FAX: 315-859-4185

Dr. Hermann Engelhardt
Div. of Geo. & Planetary Sciences
California Institute of Technology
Pasadena, CA 91125
(818) 356-3720

Dr. James Fastook
223 Neville/Computer Science
University of Maine
Orono, ME 04469
(207) 581-3927

Ms. Jane Ferrigno
USGS
927 National Center
Reston, VA 22092
(703) 648-6360
FAX: 703-648-4227

Dr. Pieter M. Grootes
Quaternary Isotope Lab AJ-20
University of Washington
Seattle, WA 98195
(206) 543-3191
FAX: 206-543-3836

Dr. Elisabeth Isaksson
Institute for Quaternary Studies
Boardman Hall
University of Maine
Orono, ME 04469

Dr. Joe Jacka
Thayer School of Engineering
Dartmouth College
Hanover, NH 03755
(603) 646-1843

Mr. Stan Jacobs
Lamont Observatory
Palisades, NY 10964
(914) 359-2900/326
FAX: 914-365-0718

Dr. Barclay Kamb
Div. of Geo. & Planetary Sciences
California Institute of Technology
Pasadena, CA 91125
(818) 356-3720

Dr. Thomas Kellogg
Institute of Quaternary Studies
University of Maine
Orono, ME 04469
(207) 581-2190

Dr. Lawrence Lawver
Institute for Geophysics
8701 Mopac Boulevard
Austin, TX 78759-8345
(512) 471-0433
FAX: 512-471-8844

Dr. Douglas MacAyeal
University of Chicago
5734 S. Ellis Avenue
Chicago, IL 60637
(312) 702-8027

Dr. Paul Mayewski
University of New Hampshire
EOS/SERB
Durham, NH 03824
(603) 862-3146
FAX: 603-862-2124

Dr. Olav Orheim
Norsk Polarinstitutt
Postboks 158
Rolfstangveien 12
N-1330 Oslo Lufthavn
Norway

Dr. Julie M. Palais
Div. of Polar Programs
National Science Foundation
Washington, DC 20550
(202) 357-7894
FAX: 202-357-9422

Dr. Michael Ram
Dept. of Physics/ Univ. of Buffalo
239 Fronczak Hall
Amherst, NY 14260
(716) 636-2539
FAX: 716-626-2507

Dr. Charles Raymond
Geophysics Program AK-50
University of Washington
Seattle, WA 98195
(206) 543-4914
FAX: 206-543-0489

Dr. Vin K. Saxena
Prof. of Meteorology, Box 8208
North Carolina State University
Raleigh, NC 27695-8208
(919) 737-7290
FAX: 919-737-7802

Dr. Reed Scherer
125 South Oval Mall
Byrd Polar Research Center
Columbus, OH 43210
(614) 292-2605
FAX: 614-292-4697

Mr. Simon Stephenson
Div. of Polar Programs/NSF
1800 G Street, N.W.
Washington, DC 20550
(202) 357-7808
FAX: 202-357-9422

Dr. D.A. "Dietz" Warnke
Dept. of Geological Sciences
California State University
Hayward, CA 94542
(415) 881-3425
FAX: 415-727-2035

Dr. Ian Whillans
Byrd Polar Research Center
The Ohio State University
Columbus, OH 43210
(614) 292-2033
FAX: 614-292-4697

Dr. Don Wiesnet
National Geographic Society
601 McKinney St., N.E.
Vienna, VA 22180
(703) 938-9829
FAX: 703-938-0312

Dr. Herman Zimmerman
Div. of Polar Programs/NSF
1800 G Street, N.W.
Washington, DC 20550
(202) 357-7894
FAX: 202-357-9422

NASA
National Aeronautics and Space Administration

Report Documentation Page

1. Report No. NASA CP-3115, Vol. 1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle West Antarctic Ice Sheet Initiative Volume 1: Science and Implementation Plan		5. Report Date April 1991 6. Performing Organization Code 971
7. Author(s) Robert A. Bindschadler, Editor		8. Performing Organization Report No. 91A01040 10. Work Unit No.
9. Performing Organization Name and Address NASA Goddard Space Flight Center Greenbelt, Maryland 20771		11. Contract or Grant No. 13. Type of Report and Period Covered Conference Publication
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546-0001		14. Sponsoring Agency Code

15. Supplementary Notes

The WAIS workshop was cosponsored by NASA and the National Science Foundation, Washington, D.C.

16. Abstract

This report describes the Science and Implementation Plan of the West Antarctic Ice Sheet Initiative (WAIS). The goal of this initiative is the prediction of the future behavior of this ice sheet and an assessment of its potential to collapse, rapidly raising global sea level. The multidisciplinary nature of WAIS reflects the complexity of the polar ice sheet environment. The project builds upon past and current polar studies in many fields and meshes with future programs of both the U.S. and other countries. Important tasks in each discipline are described and a coordinated schedule by which the majority of these tasks can be accomplished in 5 years is presented. The companion report (Volume 2) contains seven discipline review papers on the state of our knowledge of Antarctica and opinions on how that knowledge must be increased to attain the WAIS goal.

This initiative was discussed in an earlier report under the name of SeaRISE (NASA CP-3075).

17. Key Words (Suggested by Author(s)) Antarctica, Sea Level, Ice Sheet, Climate, SeaRISE	18. Distribution Statement Unclassified - Unlimited Subject Category 42

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages 59	22. Price A04

NASA FORM 1626 OCT 86