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Carbon Dioxide Effects Research and Assessment Program

Environmental and Societal Consequences of a Possible CO_2-Induced Climate Change:

Volume II, Part I

Response of the West Antarctic Ice Sheet
to CO_2-Induced Climatic Warming

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Environmental and Societal Consequences of a Possible CO_2-Induced Climate Change:

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Response of the West Antarctic Ice Sheet
to CO_2-Induced Climatic Warming

by

Prof. Charles Bentley
University of Wisconsin

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for the U.S. Department of Energy

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NOTE

The paper which follows was commissioned as part of the project to produce A Research Agenda on Environmental and Societal Consequences of a Possible CO2-Induced Climate Change. Volume I (published December 1980 by the U.S. Department of Energy, publication DOE/EV/10019-01) summarizes the project's recommendations, and is based on the work of nearly 500 authors, co-authors, workshop participants, other experts consulted, and reviewers.

The papers commissioned as part of this project are:

1. Response of the West Antarctic Ice Sheet to CO2-Induced Climatic Warming: A Research Plan: Charles F. Bentley

2. Arctic Sea Ice Research in Support of Studying the Potential Effects of a CO2-Induced Global Warming: N. Untersteiner

3. Influence of Short-Term Climatic Fluctuations on Permafrost Terrain: Jerry Brown and John T. Andrews

4. Potential Effects on Ocean Dynamics of an Increase in Atmospheric Carbon Dioxide: Some Scientific Issues and Research Approaches: Michael McCartney and Henry Lansford

5. Effect of Increased CO2 on Ocean Biota: Osmund Holm-Hansen

6. Effects of Increased CO2 on Photosynthesis and Agricultural Productivity: Donald N. Baker, L. Hartwell Allen, Jr. and Jerry R. Lambert

7. Direct Effects of Increased Concentration of Atmospheric Carbon Dioxide on Managed Forests: Larry W. Tombaugh, Donald I. Dickmann and Douglas G. Sprugel

8. Impacts of Rising Atmospheric Carbon Dioxide Levels on Agricultural Growing Seasons and Crop Water Use Efficiencies: James E. Newman

9. Alleviation of Environmental Stress on Renewable Resource Productivity: Gordon S. Howell

10. Effects on Agricultural Plant Pests: Dean L. Haynes

11. Effects of Climate Change on Animal Agriculture: H. Allen Tucker

12. Response of "Unmanaged" Ecosystems: Boyd R. Strain and Thomas V. Armentano

13. Ecological Consequences of a CO2-Induced Climatic Change on Forest Ecosystems: W. Carter Johnson and David M. Sharpe

14. Research Needed to Determine the Present Carbon Balance of Northern Ecosystems and the Potential Effect of Carbon Dioxide Induced Climate Change: Philip C. Miller

15. Effects of CO2-Induced Climate Change on Freshwater Ecosystems: Charles C. Coutant

16. Research Issues in Grazinglands Under Changing Climate: Dennis F. Pendleton and George M. Van Dyne

17. The Use of Paleoclimatic Data in Understanding and Possibly Predicting How CO2-Induced Climatic Change May Affect the Natural Biosphere: Thompson Webb III

18. Climate Change and Agricultural Production in Non-Industrialized Countries: Lloyd Slater

19. CO2 and Climate Change: Anthropological Perspectives: William I. Torry

20. Responding to CO2-Induced Climate Change: Opportunities for Research: Richard A. Warrick and William E. Riebsame

21. Climate and Society in History: Theodore K. Rabb

22. Research on Political Institutions and Their Response to the Problem of Increasing CO2 in the Atmosphere: Dean E. Mann

23. International, Legal and Institutional Implications of an Increase in Carbon Dioxide: Edith Brown Weiss

24. Psychological Dimensions of Climatic Change: Baruch Fischhoff and Lita Furby

25. Interdisciplinary Research and Integration: The CO2 Problem: Robert S. Chen

26. Effects of Climate Change on Health: Melinda Meade

27. Theoretical and Empirical Aspects of Optimal Control Strategies: William D. Nordhaus

28. A Conceptual Framework for Research About the Likelihood of a "Greenhouse Effect": Mancur Olson

29. Adaptive Aproaches to the CO2 Problem: Roger G. Noll

30. Planning for Climate Change: Dennis Epple and Lester Lave

Contributed Paper: The Potential Response of Antarctic Sea Ice to Climatic Change Induced by Atmospheric CO2 Increases: S. F. Ackley

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I. INTRODUCTION

A. Nature of the Problem

In recent years there has been a rapidly increasing interest in the possibility that the West Antarctic ice sheet (that part of the Antarctic ice sheet that lies on the Pacific side of the Transantarctic Mountain range) may shrink rapidly in the near future. The West Antarctic ice sheet is in principle more vulnerable than the East Antarctic or Greenland ice sheets because most of its rock bed lies far below sea level. Simplified theoretical analyses suggest that such an ice sheet has no stable position between an extension all the way to the edge of the continental shelf, and complete disappearance. Such analyses, however, ignore such factors as the probable stabilizing influence of the confining borders and grounded areas of the ice shelves that fringe the grounded part of the ice sheet (called the "inland ice sheet") along most of its perimeter, and changes in the snow precipitation rate as the size of the ice sheet changes.

Models put forward within the last decade have suggested, partly from theory and partly by analogy with the Laurentide ice sheet which formerly covered much of North America, that if the West Antarctic ice sheet once starts to shrink rapidly, it could disappear completely in only a few centuries or even less. Concern about the possible vulnerability of the West Antarctic ice sheet has been emphasized by recent estimates of future climatic warming due to CO_2 build-up in the atmosphere. A recent report by the Climate Research Board of the National Research Council reviews several predictions made using global circulation models and finds them all to imply that a doubling of the CO_2 in the atmosphere, a level that may very well be reached before the middle of the 21st century, would cause a polar heating of 4° to 8°C. In view of the limited realism of the models, polar scientists must view these predictions with some reserve and press for more sophisticated models that predict changes in the polar environment, including the ocean, more realistically. Nevertheless, the general urgency of the CO_2 problem has made it imperative to pay serious attention to the currently available, state-of-the-art, predictions.

The serious consequences of the $\sim$ 6 m sea level rise that would occur in the event of a major shrinkage of the West Antarctic ice sheet would include flooding of all existing port facilities and other low-lying coastal structures, most of the world's beaches, extensive sections of the heavily farmed and densely populated river deltas of the world, and large areas of many of the major cities of the world, which are concentrated along coast lines.

However, there is widespread disagreement about both the past and the future behavior of the West Antarctic ice sheet; the "disaster" model of rapid shrinkage is regarded as unconvincing by many glaciologists. Some point out that in historical times, during which oceanic tide gauges have been in operation, the ice sheet has not been melting at a rate corresponding to its complete disappearance in 200 years, because the rate of sea level rise that would be implied is an order of magnitude greater than that observed. Others argue that warming will affect a marine ice sheet little until a critical threshold is surpassed, after which shrinkage may be rapid. According to this argument, during the present interglacial temperatures have remained below the critical level. During the last interglacial about 125,000 years ago, however, temperatures for a time were higher than during the present interglacial and may have exceeded the critical level: sea level was probably about 6 m higher than at present, and a likely explanation (although not the only one) is the disappearance of the West Antarctic ice at that time.

Disputed though it may be, the possibility of a rapid shrinkage is great enough to demand further research. Before predictions can be made the current state of the ice sheet must first be determined. This can be accomplished effectively for the whole ice sheet only by a monitoring program that depends heavily on accurate determination of surface elevations by radar and laser altimeters carried in satellites in polar or near-polar orbits. Ground-based measurements in selected areas are also required to learn why any observed changes are occurring. Another essential line of approach is to continue to examine what has happened in the past, with increasing emphasis on the detailed records of the current and last interglacial ages. This can be done by collecting and examining ice cores from critical locations on the inland ice sheet and the ice shelves, especially "pinning points" within the ice shelves and isolated domes in the inland ice where the ice is moving very slowly, from continued examination of the glacial geologic record, and from detailed examination of past and present flow patterns within the ice sheets, as revealed by radar probing of the internal characteristics of the ice.

Such a program would help us greatly in understanding how the ice sheets may currently be changing, but it is a much more difficult problem to predict what will happen in the future: observed characteristics of the ice sheet must be incorporated into a model that can then be used with different climatic inputs, particularly man-made changes in atmospheric conditions that have not occurred in the past. The short-term consequences of a CO_2-induced warming and of associated changes in the polar environment (cloudiness, precipitation, ocean heat flux), will be manifested first in changes in the seasonal ice forms (snow, southern sea ice), and in surface melting and warming of the ice sheet. Long-term consequences must be inferred from theoretical considerations and, by analogy with the past, obtained from geological evidence of ice extent and sea levels during previous warm periods and from the climatic record stored in the ice sheets themselves.

A concern in both the short-term and long-term contexts is that climate change today, whether natural or man-made, may lead to large and irreversible changes in the future, even if the climate change itself were reversed. Much of the solution of the problem will have to rely heavily on theoretical studies and numerical modeling. The problem is exceedingly difficult. The ice sheet is a complex dynamic system whose response to warming involves glaciological processes not yet fully understood: above all, the movement and storage of water in large ice masses and the alteration between, or combination of, internal-deformation flow and sliding on the underlying rock. Furthermore, any response to atmospheric temperature changes must also involve modifications in precipitation patterns due to changes in atmospheric circulation and sea ice cover around the continent and, perhaps most important and difficult to analyze, the effect of warmer ocean water in contact with the ice, especially at the underside of the great ice shelves.

Still another uncertainty is introduced when one considers that the West Antarctic ice sheet straddles a large and volcanically active intracontinental rift system, rather than the stable cratonic environment that is assumed in most modeling. Regional heat flow values could be as much as twice those used in modeling the basal melting or basal sliding characteristics of the Laurentide ice sheet, and these higher values may influence the vulnerability of the ice sheet to external factors. Eruptions in Quaternary time are known to have produced large meltwater lakes within the ice sheet, with as yet undetermined effects on its stability, and studies of tephra layers in ice cores have revealed a correlation between volcanic eruptions and periods of climatic cooling. All of these factors require additional study, and they should be seriously considered when the behavior of the West Antarctic ice sheet is being debated.

B. Approach to the Problem

In the following discussion we approach the problem in two ways, first with a discussion of the research problems involved and second with a presentation of specific projects to be undertaken to solve those problems. The research problem approach in turn is designed specifically to answer the question of what the response of the West Antarctic ice sheet to a CO_2-induced climatic warming will be, and is organized according to the following basic questions: (1) how fast is the ice mass changing now, and why? (2) How will the boundary conditions that affect the ice sheet, that is, the heat and mass exchanges at the boundaries, respond to an atmospheric temperature change; how are those boundary conditions changing now? (3) What will be the response of the ice sheet to changes in boundary conditions? (4) What can be learned by analogy with what has happened in the past?

To answer the last question, continued examination of the geological and biological records of both the present and last interglacials is needed, on land and ocean sediments, and from all latitudes. We need to know if the ice of West Antarctica disintegrated during the last interglacial about 125,000 years ago or at any other time, and if it did, what the climatic, oceanic and glaciological conditions were at the time of disintegration. The Hypsithermal intervals (warmest parts) of both the present and the last interglacials were warmer than today, but whereas the West Antarctic ice sheet may have disappeared during the last interglacial, it has survived the present one: during the recent Hypsithermal interval (which probably culminated before 10,000 years ago in Antarctica) the Ross Ice Shelf barrier apparently continued to recede at the same rate as before, implying that rising eustatic sea level remained the sole cause. We need to know how much warmer than today the Hypsithermal intervals of both the last and the present interglacials were: this will give us some idea of how much Antarctic warming can occur before the level critical to the future of the West Antarctic ice sheet is reached, and whether this critical level could be reached by man's release of CO_2 into the atmosphere.

The first three questions involve studies of ice dynamics to obtain an adequate understanding of climatic changes due to CO_2 warming and the effect of these changes on the balance between accumulation and losses of ice from the West Antarctic ice sheet. It is more rigorous and complex than the historical approach, to which it promises to provide greater depth, and requires: (1) an adequate knowledge of the present physical state of the ice sheet, i.e. its surface and bedrock form, mass balance, temperature, flow, and crystal fabric, and similar knowledge of the surrounding ice shelves which form the termination of, and perhaps stabilize, the inland ice sheet; (2) sufficient knowledge of the mechanisms governing the nourishment, flow and losses from the ice sheet to give a reliable estimate of the effects of any given change in climate: this involves a full understanding of the dynamics of both the grounded ice sheet and the surrounding ice shelves and their interaction; (3) a program that monitors the West Antarctic ice sheet in order to give an early warning of any impending change of sea level.

II. PRESENT CHANGES IN MASS

A. Satellite Monitoring

Changes in volume of the West Antarctic ice sheet (and of all of Antarctica) are best measured from satellites which yield information for the whole continent rapidly, are accurate in their determination of position, and in some aspects, are very precise in their measurements. They involve no expensive and difficult field work on the ground. However, satellite measurements can only yield information about what is happening; to understand why (necessary for prediction) field work on the ground in selected areas is essential. In particular, changes in the mean density of the firn layer overlying the solid ice must be known to relate volumetric changes to changes in mass.

Complementary ground-truth stations on the ice surface, and theoretical studies, must be considered essential and integral parts of a program of measurements from satellites. In any region where changes in volume are detected, unless the changes are large, a program to determine changes in mean density of the upper layers of the ice sheet should be initiated; theoretical examination of the changes to be expected in response to changes in surface temperature and mass balance should also be undertaken. The importance of ground measurements and theoretical analyses for the interpretation of microwave brightness temperatures is discussed below (§II.C.1).

1. Surface elevations can be measured very effectively by altimeter from a satellite in polar orbit. Other methods are either less accurate or less well suited to monitoring changes in elevation, or both. Initial mapping of the ice sheets is needed for studies of ice dynamics because the surface slope is used to calculate the shear stress at the bed of the ice and the direction of ice flow. Remapping after several years or less can reveal significant changes of surface level anywhere over the whole continent with acceptable accuracy. Monitoring elevation change is potentially the most important technique available for rapidly determining volumetric change. In any region where precise leveling has already been carried out on the surface, the initial satellite altimeter map would give the elevation changes immediately.

The accuracy to be expected from a radar altimeter is about ± 1 m, the limitation arising from the size of the footprint combined with the effect of irregularities in the surface. This accuracy is excellent for mapping the surface elevation and is sufficient for revealing any gross imbalance within the lifetime of one satellite. For example, if the ice sheet were shrinking at a rate corresponding to total disappearance in 200 years, the average elevation change would be 10 m or so per year. Nearly everywhere, however, the present lowering rate must be much less than that. Therefore, a laser altimeter should be placed in orbit as soon as possible in order to monitor surface elevations to an accuracy of 0.1 m (the improved accuracy comes from the much smaller footprint of the laser system). This will permit monitoring of significant elevation changes (> a few tenths of a meter per year) within the lifetime of a single satellite. We strongly support proposals for the inclusion of a laser altimeter on the NOSS satellite.

2. Ice sheet boundaries. Perhaps the most noticeable changes in the ice sheet will occur at its margins. Although marginal changes can be expected due to normal variations in calving, the margins should be monitored continuously using imagery from Landsat and its successors to detect changes that warrant more thorough study. Since they are not subject to the irregular calving of large icebergs, ice walls (where the ice margin is aground) may be particularly sensitive indicators of possible changes in the balance of ice sheets. Particular attention should also be paid to detecting changes taking place at the mouths of ice streams because such changes could propagate rapidly inland.

Satellite altimetry also provides the accuracy needed for locating the change of slope marking most present-day grounding lines (the margins of regions where grounded ice rests on a bed below sea level) and the size, shape, and location of crevasse zones (see Section II.B).

3. Ice thickness. Eventually it may be possible to measure ice thickness by radar sounding from satellites, but the capability does not currently exist nor can its development be expected before the late 1980's, at best.

B. Study of Grounding Lines and Other Glacial Features

Certain currently observable features readily reflect mass changes. The positions of grounding lines are particularly sensitive to change; the shape and position of crevasse fields, the location of the calving margins, and even surface textures would also respond to major changes in mass. Although these features are also influenced by other effects, such as drift snow, tides, and kinematic waves in ice transport, they nevertheless should be monitored using existing satellites; observed changes could lead to a verification program either on or near the surface or by future, sophisticated, satellites. Grounding lines between the inland ice and the ice shelf, and at the margins of ice rises (fully grounded areas with nearly stationary ice) and ice rumples (weakly or partially grounded areas where the ice is shoved across its bed) within the ice shelves, are especially important.

1. Inland ice margins. The positions of grounding lines must first be determined. Where the change in surface slope is not abrupt enough to define a grounding line, airborne and surface radar programs can be devised to locate it by studying changes in ice thickness, the presence of bottom crevasses, and the presence of debris entrained in the ice. In some places, such as the Ross Ice Shelf and the Antarctic Peninsula, existing photographs may be useful. Once the exact positions of grounding lines are known, they should be monitored yearly at selected points where they can be clearly defined by tide meters.

The most critical sites are on ice streams because beneath them the bedrock slope is low, so that the position of the grounding line is particularly sensitive to changes in ice thickness.

2. Ice rises and ice rumples. Crevasse patterns defining ice rumples should be monitored by aerial photography at intervals of a few years to detect changes in the degree of pinning. If sea level and/or ice thickness are changing, ice rumples would be either incipient or former ice rises. Pinning points are believed to play a key role in the dynamics of ice shelves. Particular attention should be paid to ice rumples in ice shelves that survive close to their climatic limit (10-m temperatures near 0°C) because these should be the first to respond to climatic change. The velocity of flow over ice rumples, which should be sensitive to small changes in ice thickness, also should be monitored by Doppler satellite positioning repeated yearly.

Careful searches for smaller ice rises which may not have significant surface topography should be carried out by airborne radar sounding. Local surface studies would then be needed to verify their presence and to study the local mass balance in a search for evidence of an increasing or decreasing size.

C. Components in the Total Mass Balance

Changes in surface elevation can only reveal a net mass imbalance upstream; for real understanding it is vital to measure separately the contributing mass input and output terms. The techniques required for this work have been available for some time but few measurements have been made in the U.S. program. Adequate logistic support is essential.

1. Surface mass balance. Surface stations should be spaced 50-100 km apart over the entire drainage basin of any system under study. Measurements at those stations should include the determination of surface mass balance by shallow core drilling to a depth below an appropriate radioactive fallout horizon. These same surface stations would serve for measurement of other quantities, such as 10-m temperatures, temperature-depth gradients, strain rates, ice movement rates, gravity, ice thickness, and a range of core properties that may change quickly after the core has been brought to the surface.

Detailed surface mass balance measurements may be needed only on the first drainage basin to be studied. Using the ground truth available from one such detailed survey, careful correlation should be made with the brightness temperatures indicated by multispectral passive microwave scanners flown in satellites. The brightness temperature depends upon the physical temperature and on the emissivity of the surface, which in turn is a function of the accumulation rate and other climatic factors such as wind. A few theoretical studies of the interrelationships between these parameters have been made, but many more are needed. A combination of theoretical analyses and ground truth measurements should then permit satisfactory separation of causes so that accurate extrapolation of surface mass balance rates can be made using the microwave data.

2. Ice thickness. To calculate mass flux, ice thickness must be known as well as surface velocity. The thicknesses of the Ross Ice Shelf and the adjacent parts of the West Antarctic inland ice are already reasonably well known. The Ross Sea drainage basin could therefore be studied without extensive further ice thickness measurements. Study of the other drainage basins, however, would require additional mapping by airborne radar sounding.

3. Ice velocity. The principal means of measurement of ice velocity is positioning by Doppler satellite technique, which yields an accuracy of a few meters. This technique requires re-occupation of measuring stations. Re-occupation could be avoided by emplacing a network of laser reflectors whose positions could be monitored from a laser ranging system mounted in a satellite.

In some places where there are identifiable features in the ice surface, such as crevasses, aerial photogrammetry or satellite imagery can give good velocity determinations.

4. Basal mass balance on the underside of ice shelves. Melting or freezing on the underside of the large ice shelves is an important but little-known component of the total mass balance. In principle, the most versatile method of exploring the lower boundary of ice shelves is airborne radar sounding. More has been inferred about the bottom mass balance of ice shelves from airborne remote sensing than from any direct measurements at the ice/water interface, because it is impracticable to make direct measurements at more than a few isolated points, whereas airborne remote sensing can reveal characteristics of the ice/water interface over thousands of kilometers in a day.

Such airborne measurements, however, require direct observations for proper interpretation. The first effective data came from borehole and core studies at J9 on the Ross Ice Shelf in the 1978-79 summer, where sea ice accreted to the bottom of the ice shelf was found. More such measurements are badly needed, together with detailed studies of mass exchange processes beneath ice shelves. A transect of boreholes across an ice shelf, from barrier to grounding line, could provide data necessary for interpreting radar reflections. Bottom melt/freeze rates could be determined from a combination of instruments embedded in frozen-up boreholes and hanging in the water below, with recorders on the ice surface. Temperature sensors beneath the ice shelf should be placed not only near the ice-water boundary but throughout the water column down to the sea bed and at least some of the instruments should be designed for long-term monitoring (see §III.C.4). Some logistic problems of drilling and instrument development are involved, but the program is vital for the advancement of our knowledge of conditions beneath ice shelves.

The amount of melting and freezing must ultimately be understood in terms of oceanographic measurements. For this purpose modern oceanographic stations (i.e. with closely-spaced, high resolution, continuously-recording instruments for measuring conductivity and temperature vs. depth) should be established across an entire ice-shelf front.

In the Ross Sea, and more recently along the Wilkes Land coast, tongues of warm water have been observed penetrating at intermediate depths from the continental margin to the base of floating glacial ice. Simultaneously, regions of water with temperatures below the sea-surface freezing point extend northward from the ice shelves. These features are believed to result from melting at the ice shelf base. The horizontal extent of the warm and cold cores suggests that they are active throughout the year and are independent of present-day sea surface processes. The vertical position of these cores in the water column indicates that the relative depths of the continental shelf break and ice shelf base may influence the circulation/heat flux across the continental shelf. Additional oceanographic stations are needed along ice shelf barriers to determine the extent and variability of these currents. Measurements of the isotopes ^{39}Ar, ^{85}Kr and ^{14}C on water samples taken from underneath the Ross Ice Shelf through bore holes, and from along the Ross Ice Shelf barrier, could give valuable information on the origin and age of the water. Modeling work is also required to determine whether monitoring of specific water masses by bottom-moored current meters and thermistor arrays could determine the major component of heat flux to the region beneath the shelf.

D. Sea Level Changes

The measurements described in Section II.C would provide the data needed to calculate total mass balance. Another way of determining that figure for the entire Antarctic ice sheet is the measurement of sea level change. Geophysical analyses show that sea level at any point on the earth is determined by an interaction between ice loads and their gravitational effect, water loads, and a deformable earth. Ice sheet changes result in generally latitudinal zones of time-varying vertical movement of the land. Because of that complicated response of the earth to changes of surface loading, and because ice melting from Arctic ice masses may also affect sea level, an extensive network of tide-gauge measurements covering the margins of the entire world ocean is required. Measurements along the Antarctic coast alone would not suffice to determine quantitative ice volume change, because they would be strongly affected by the isostatic response of the earth to thinning or thickening of the marginal Antarctic ice, and to the gravitational changes associated with the changing ice mass.

Just for those reasons, however, tide gauge studies in Antarctica are potentially an important way of using sea level data to detect whether thinning or thickening of the marginal Antarctic ice is taking place. Unfortunately, a preliminary check with the U.S. National Ocean Survey suggests that only two tide gauges in Antarctica have been manned for as long as one year, and that only one is presently in operation -- the British Antarctic Survey station in the Argentine Islands (65°S) that has been in continuous operation for over 20 years. The only other tidal measurements were at Cape Armitage (Ross Island) in 1902! Other observations have been made for just a few months or days, scattered in time and space.

If parts of the Antarctic ice margin are indeed thinning, this should be detectable in only a few years of new observations. Useful data might be obtained by the releveling of points that were tied in to tide gauges by old expeditions. Routine and continuing tidal observations should be established at as many Antarctic coastal stations as possible.

III. BOUNDARY CONDITIONS AND THEIR RESPONSE TO ATMOSPHERIC TEMPERATURE CHANGE

A. Present Values

The boundary conditions that affect the behavior of the West Antarctic ice sheet and which will change in response to CO_2-induced temperature changes are those that determine the mass balance at the surface and at the interface between the ice shelf and the ocean. Measurement of the present values of these boundary conditions has already been referred to in II.C above. The mass balance rate at the ice-water interface in turn depends upon ocean temperature and circulation.

B. Response to Atmospheric Temperature Change

1. Ocean temperature and sea ice cover. The response of the ocean and its sea-ice cover to atmospheric temperature change is critically important and must therefore be mentioned even though it is outside the principal competencies of the authors of this report. Antarctic sea ice is discussed in a separate report by S.F. Ackley: "The potential response of Antarctic sea ice to climatic change induced by atmospheric CO_2 increases" (see Appendix D of the Steering Group report). It is completely impossible to estimate how boundary conditions on the ice sheet vary without considering the ocean. We simply give two examples.

(a) Observations frequently show a sharp subsurface feature, the "Antarctic Slope Front", over the upper continental slope near a well-developed coastal current. The front and current form a hydrodynamic boundary between cold, heavy water on the shelf and warmer (by $\sim 3°C$), lighter water offshore. This feature may be very important in determining the extent of the ice sheet during a glacial maximum. We need to understand better what oceanographic, atmospheric and/or cryogenic factors now maintain this boundary, how it might change as a result of climatic warming, and what might be the impact on the ice shelves if they came to be bathed in water 3°C warmer than at present.

(b) Precipitation rates on the ice sheet depend upon the extent of the Antarctic pack ice because ice cover drastically reduces moisture transfer to the atmosphere. The winter flux of heat and moisture to the atmosphere must be high within the huge polynya that is sometimes found in the Weddell Sea, and which might serve as an analogue for a less extensive sea ice cover in response to climatic warming. Further, if the Antarctic surface water is indeed a CO_2 source and not a sink, as some investigators now believe, decreasing the mean ice cover could vent additional CO_2 to the global atmosphere. This effect should be considered among the feedback mechanisms in modeling CO_2-induced warming in Antarctica.

2. Surface temperature on the ice sheet will change directly as the atmosphere temperature changes. Secular trends in mean annual temperature will be felt at a depth of a few meters, with a lag of only a few years or less. However, only if summer temperatures reached 0°C over substantial areas of the ice sheet would there be a significant impact on the surface mass balance.

3. The surface balance rate poses more complicated problems. Any atmospheric warming could, if other factors such as atmospheric circulation patterns remained unchanged, be accompanied by an increase of precipitation resulting from an increased capacity of the air to carry moisture from the ice-free regions of the Southern Ocean and an increase in the area free of sea ice surrounding the Antarctic continent. These processes have received little attention in recent work on modeling regional features of the general circulation of the atmosphere. Consequently, it is important to use Global Circulation Models (GCMs) to study the present regional climatic regimes of the Southern Hemisphere, taking the best possible account of Antarctic topography and the katabatic wind system. The sensitivity of these models to changes in sea surface temperature and sea ice cover should be examined in terms of the Antarctic mass balance. Satellite data can be used to specify the sea ice cover and to monitor its changes. Further studies of stable isotopes in precipitation could be useful for the identification of the origin of the moisture.

Experimental modeling work should continue at all times in parallel with the installation of automatic weather stations, the continued operation of radiosonde stations, and the availability of satellite imagery to encourage more glacio-meteorological studies.

4. Water temperatures and melt/freeze rates beneath ice shelves. The importance of these factors in determining the mass balance and therefore the rate of volume change of the ice sheet has been pointed out in Section II.C.4. Unfortunately, very little is known about how these factors would change in response to changes in ocean temperature, even if these could be predicted. This point is a critical weakness in our present ability to predict quantitatively the response of the West Antarctic ice sheet to CO_2-induced temperature change. Theoretical studies of ocean circulation and interaction with the underside of an ice shelf are badly needed.

At present, melting along the seaward vertical faces of the ice shelves (the "barriers") is probably quantitatively unimportant compared to bottom melting. In a period of warmer ocean surfaces, however, melting along the barrier might become significant, if near-surface water was much warmer than water circulating beneath the ice shelf, or if that circulation was weak.

The recent interest in icebergs has spawned several laboratory, field, and theoretical studies of how glacial ice melts in seawater. This has been useful, but has concentrated on the vertical walls and on seawater temperatures far above the freezing point. More relevant to Antarctica would be similar studies at near-freezing temperatures and of processes at the ice "ceilings" affecting currents flowing beneath the ice shelves.

C. Present Changes in Boundary Conditions

Regular monitoring of the physical state of the West Antarctic ice sheet and surrounding ice shelves should give early warning of changes that could result in rapid shrinkage of the ice sheet.

1. Ocean temperatures and circulation, which may constitute the main threat to the ice shelves around West Antarctica, can be monitored by anchored buoys recording temperature, salinity, and currents at a series of sites off the fronts of ice shelves. Buoys of this type have been developed so that records can be recovered annually during the southern summer. A program of this type would also enhance our understanding of the processes of bottom melting. Oceanographic stations almost anywhere along the margin would help to reveal the extent and variability of the Antarctic slope front.

2. Surface temperatures (i.e. ice or firn temperatures at a depth of $\sim$ 10 m), provide the most direct evidence of the onset of climatic warming, and are simple to monitor. Furthermore, the form of the temperature-depth curve in any borehole indicates the broad trend of temperature changes with time at that location. Climatic records from Antarctic stations over the past 25 years provide evidence of the natural variability of mean annual temperature. The U.S. at present maintains two continuously-operated inland stations (South Pole and Siple stations). Routine measurements should be taken at these sites of 10-m temperatures and seasonal accumulation. Up to now such data have not been obtained. In addition, temperatures need to be monitored in boreholes of moderate depth at selected sites on the ice sheet. The temperature profiles obtained would immediately show if any significant warming had taken place over the past thirty years, and if the effect is larger in polar regions than at lower latitudes where more abundant statistics are available.

3. Surface mass balance. Satellite monitoring of brightness temperatures by passive microwave sensors should provide a powerful tool for monitoring changes in surface conditions. Changes attributable to physical temperature and surface accumulation rates should be deducible with the aid of observations from a relatively small number of ground truth stations (see §II.C.1).

Annual measurement of accumulation on stake networks at each site listed for temperature profile measurements should be made. Even though annual variability would obscure any but a very large secular trend over a reasonable period of measurement (i.e. 10 years), the record would be vital for interpretation of brightness temperatures.

4. Mass balance at the ice-water interface should be monitored by the instruments described in §II.C.4. The installations could be at the same ice shelf sites used for monitoring surface temperature and accumulation changes (see §III.C.2).

Long-term changes in the ocean heat flux beneath ice shelves should be monitored by conventional oceanographic observations off the ice fronts.

IV. RESPONSE TO CHANGES IN BOUNDARY CONDITIONS

Shrinkage of the West Antarctic ice sheet can proceed only if ice is transported outward from its central regions into the bordering oceans faster than it is replenished by accumulation processes. The speed of ice movement and its response to changed boundary conditions and an evolving surface profile are thus of central importance.

Although it is known that motion occurs by a combination of internal deformation and basal sliding, the rates of neither process can be predicted with confidence. The internal deformation is affected by structure and temperature variations with depth, which can be examined by core drilling at a limited number of locations, in combination with additional laboratory experimentation on the effect of texture and fabric on the flow law of ice. More serious is the lack of physical understanding of the basal sliding process and of practical and effective observational means to study it. In Antarctica it is both feasible and important to establish the basal temperatures which would determine where sliding could take place. To understand the sliding process, however, it will be necessary to rely on knowledge gathered on glaciers where the bed is more accessible and operating conditions are easier.

A major consideration is the possibility of extremely rapid sliding such as occurs periodically in surge-type glaciers. Surge-like speeds would be needed to cause the disappearance of the West Antarctic ice sheet on the time scale of one century. It is known that high speeds exist continuously in certain outlet glaciers and ice streams in Antarctica and Greenland. Could other parts of this ice sheet be thrown into a state of fast motion by changing boundary conditions? Although again a clear understanding of the physical controls and the conditions required for rapid sliding are best sought outside the Antarctic, the evidence for what has happened and is now happening must be sought in Antarctica itself. First, where does rapid sliding (high speed) occur now and what are the special conditions that might be responsible? In some cases a rough answer may be apparent -- for example, in the outlet glaciers where an immense flux must be transported through a confined valley. In other cases it is more subtle; for example, why do ice streams exist and why are they where they are? Second, is the pattern of fast motion changing, or has it been changing? An answer to this can be sought in the ice stratigraphy revealed by coring, in the ice thickness distribution on the ice shelves, in the current constancy or variability of velocity in fast-moving zones, and in the state of balance on a drainage basin scale. If one finds evidence for surge-like changes in major drainage basins, then the possibility of rapid collapse under changed conditions becomes much more real.

Because of the need to know the internal physical characteristics of the ice sheet that control its deformation, we strongly recommend that efficient ice core drilling systems and ice core handling operations be developed for obtaining cores to bed at many locations. Of prime interest are a number of cores along an ice stream. Other locations of interest include isolated ice domes, ice rises, and the ice shelves. The existing borehole at Byrd Station should not be ignored: inclinometer surveys already made should be analyzed and, if possible, a new survey taken; the physical properties of the basal ice zone should be studied for clues to the interaction between the ice sheet and its bed.

Drilling programs can also be used as ground truth in radar surveys from which the continuity of features in the ice sheets can be studied. Since internal radar reflections in ice sheets are indicative of both past and ongoing processes, they may reveal the effects of past changes in boundary conditions.

Ultimately any prediction of future changes in the West Antarctic ice sheet must involve numerical modeling. Models can simulate present ice dynamics, rates of change, and past variations of the ice sheet, and can be checked against observed data when they are obtained. Progressive improvement in the models results from applying them to different regions and testing the results. The successful modeling of past and present changes should be regarded as a prerequisite to the prediction of future changes. When reasonable success has been obtained, then some confidence in the future predictions is warranted.

V. THE RECORD OF THE PAST

A. Ice Drilling and Core Studies

There is a remarkable record of past environmental conditions preserved in the depositional stratigraphy of ice sheets. Stable isotopic ratios of the ice itself which are related to past temperatures are the best known records, but there are others too: total gas content, reflecting former surface elevations; atmospheric composition, including especially the CO_2 level; precipiation rates; and impurities that may record such events as volcanic eruptions or changes in the source for the precipitated moisture. The record can be very detailed (in places it may be possible to study separate years) and very long (possibly some 10^5 years in West Antarctica, more in East Antarctica). These records can be used to establish base-line climatic conditions before anthropogenic effects, to test if there has been a past natural analogue for climatic changes expected in the near future, and to continue study of the relationship between volcanic eruptions and climatic change.

One point should be emphasized because of the intrinsic value of ice core studies to climatic history: the quality of the record from polar ice for geochemical studies cannot be matched by any other type of coring. Ice coring at suitable locations in East Antarctica will indicate past climatic change over at least 200,000 years, which spans the last interglacial, and possibly several times longer. It can also provide the most detailed record of the past atmospheric composition that is possible with present techniques: that record is very important to mankind because it provides a clue about what changes may be expected during the present interglacial. Additionally, ice cores in West Antarctica are likely to provide the best record of volcanic eruptions, their relationship to climatic change, and the dispersal patterns of tephra.

1. Study of existing ice cores. Ice cores to various depths exist for a number of locations in Antarctica and elsewhere, and many studies remain to be done. For example, CO_2 variations as reported in older experiments should be re-examined in light of recent improvements on the extraction and measurements of the CO_2 content of air trapped in the ice cores. Measurements of CO_2 concentration in ice cores can now be made to a precision of $\pm$ 10 ppm. CO_2 variations are global so only a few carefully-selected cores from dry accumulation zones (zones in which there is no summer melt, principally in Greenland and Antarctica) need be studied to reconstruct the atmospheric CO_2-concentration history. Other studies that can profitably be made on existing cores include closer investigations of gas content, of structural features, and how volcanic events may be recorded. Many cores, unfortunately, are in poor condition because of relaxation, cracking, and recrystallization; studies on these cores especially should be carried out as soon as possible before further deterioration.

2. Shallow coring. It would be very useful to measure isotopic variations and snow accumulation changes along shallow cores to compare systematic variations (if any) in these parameters with the instrumental CO_2 record, which shows a small (20 ppm) but persistent increase in atmospheric CO_2 over the past 20 years. Drilling to 20 m or so is a relatively easy task; for much of Antarctica coring to 20-30 m would furnish stable isotope, chemical, and accumulation profiles extending back 100 years or more. (Because of the permeable nature of the firn, year-by-year variations in CO_2 concentrations could not be measured on such cores.) Ice temperatures also should be precisely determined in all drill holes extending that far back in time as an indicator of any recent climatic change. Other core features that may reflect environmental changes also should be investigated along with how the firnification process affects the record preserved in ice cores.

A systematic shallow coring program can be used to describe the geographical variations in core properties that are associated with changes in the surface environment. This is important for interpreting the record preserved in older ice.

3. Intermediate drilling. Drills for coring to 1000 m or so now exist and could be used to obtain ice samples for measuring CO_2 records in conjunction with isotopic ratio and accumulation profiles. At most locations in West Antarctica, coring to 1000 m depth would reach material deposited at the height of the last glaciation ($\sim$ 20,000 years B.P.). Studies of these cores should include measurements of the entrapped CO_2 to confirm the strong suggestion from studies on four existing cores that a marked increase in CO_2 concentration occurred near the start of the present interglacial. Studies of salts and insolubles, including microparticles, should also be conducted on the same core so that any associated atmospheric circulation changes can be detected. In areas of very low accumulation in East Antarctica drilling to 500 m would reach ice dating from the glacial-interglacial transition.

4. Deep drilling. The only ice likely to have survived a past deglaciation in West Antarctica (if it occurred) would be that associated with persistent domes or ice rises. At such locations, the bottom ice might be old enough to allow the proposed 125,000 B.P. sea-level rise to be evaluated in terms of the climatic record in the core, including any association with atmospheric CO_2 levels. On the other hand, the absence of old ice might imply (depending on the flow regime) that the ice sheet was not present during the last interglacial.

In East Antarctica, and in central Greenland as well, ice 125,000 years old would be expected to occur at depths of 3000 m or less. Unfortunately, no drill capable of penetrating cold ice to these depths is currently available. However, there are good prospects that such a drill will become available in the next two or three years.

5. Dating. For both intermediate and deep drilling maximum advantage should be taken of new accelerator-based techniques that have been and are being developed which are capable of dating ice up to 50,000 years old on samples of ∿ 20 kg (from ^{14}C) and up to several hundred thousand years old on samples of 1 kg (from $^{36}Cl/^{10}Be$). Dating of cores drilled in the interior of ice sheets as well as along flow lines from ice streams in the marginal areas would be most useful to understanding the dynamics and history of the West and East Antarctic ice sheets.

6. Radar sounding. Recent studies indicate that fluctuations in the state of the Ross Ice Shelf occurring over the past 1500 years are detectable by detailed radar studies. Specific radar experiments should be planned to relate information between drill sites, to study the record of past changes preserved within the ice, and to investigate whether or not fluctuations in the inland ice sheet and other bounding ice shelves are also preserved. Radar studies of this kind might provide the quickest estimate of changes in the ice sheet in the very recent past.

B. Sea Level and Ocean Volume Studies

Studies of past heights of the sea are aimed principally at determining, and understanding the cause of, the detailed record of sea levels above 0 m in the last interglacial, including their amplitudes, timing, rates of change, durations, and accompanying temperatures, and at evaluating the contribution of Antarctica to the sea level record of the present interglacial, especially in the last 5,000 years or so.

1. The last interglacial. Some detailed studies on rising coasts have suggested that the 6 m sea level may represent two stands at about 135,000 yrs B.P. and 120,000 yrs B.P., the climate being cooler during the second stand. It has also been claimed that a third stand above 0 m may exist at about 95,000 yrs B.P., although this claim has been vigorously contested. To some investigators, high stands with cool water suggest Antarctic surges. The reality and characteristics of these three putative sea stands are already being studied by standard geological techniques, but these studies should be intensified and perhaps coordinated. Observations in stable areas are needed also.

Another approach to deducing volumetric changes of the Antarctic ice sheet during the last interglacial is by analyzing corals or tests of marine microfauna of that age, in order to reconstruct the oxygen isotopic composition of the interglacial ocean. If the West Antarctic ice sheet had melted, all of it would have affected the composition of ocean water, whereas only about half would have contributed to the rise in sea level. Even so, oxygen isotopic analyses made so far contain too much noise for accurate reconstruction of ice volume during the last interglacial. Any improvement in the oxygen isotopic record of the last interglacial ocean would be very valuable.

2. The present interglacial. Sea level curves, mostly from the Northern Hemisphere, show that sea level has changed no more than a few meters in the last 5,000 years. To understand the Antarctic component of sea level change (a resolution of half a meter may be possible), many more curves from the Southern Hemisphere are needed, especially for the last 5,000 years.

(a) As many studies as possible are needed from the margins of Antarctica itself. Almost no studies have been made away from McMurdo Sound, except for a few stations on the Antarctic Peninsula. But scattered reports and photographs show that many of the peninsulas and islets around Antarctica exhibit a "marine limit" of wave-washed rock, probably reflecting emergence after the last deglaciation. Many of these localities must have shells, etc., which could be used to date the emergence -- e.g. abundant raised shells have been reported in the area of Davis Station and at Vestfold Hills on the East Antarctic coast. If these localities could be visited in the course of normal ship and helicopter operations, vital information could be gathered in only one day or so at each point.

(b) It is particularly important to have studies along north-south transects: on the coasts of Argentina, southern Africa, Australia, and especially on the numerous sub-Antarctic islands; locations should be as close as possible to tide gauge stations. Lake shore tilt observations should be made where possible.

C. The Geologic Record

Four different aspects of the history of the West Antarctic ice sheet can be examined in the geologic record.

1. Reconstruction at the last glacial maximum. Currently there are two fundamentally different published reconstructions of the configuration of West Antarctic ice during the late Wisconsin maximum. The first, based on data from glacial-geologic studies in the Transantarctic Mountains and the McMurdo Sound regions and from Ross Sea sediment cores, depicts extensive grounded ice in the Ross Sea and, by extrapolation, in the Weddell and Amundsen Seas as well. This model, which is supported by some of the glaciological and geophysical studies, implies that the grounding lines of the West Antarctic ice sheet have a history of large fluctuations. The second model, based on other glaciological and geophysical studies, shows grounding of only local domes in the Ross Sea, with very little expansion of the Siple Coast grounding line. The glacial-geologic evidence is strong because the deposits show where and, to the extent that dating is adequate, when ice was present; data from both marine and terrestrial deposits are internally consistent. At present it is widely accepted that the West Antarctic grounding lines were far advanced from their present positions during the Pleistocene, but the thickness of the advanced ice sheet is uncertain even in the Ross Sea region. Further progress in this reconstruction awaits more glaciological information and an adequate model.

Glacial-geologic work should be carried out in other sectors of West Antarctica, not only to provide information on the history of the ice sheet, but to serve as a check on glaciological and geophysical inferences, which usually involve assumptions concerning the behavior of ice or the rheology of the earth.

2. Recession during the present interglacial. Sediment cores from the Ross Sea contain a till overlain by marine sediments that were deposited after retreat of the grounded ice. Radiocarbon dating at the base of the marine sediments in a suite of cores from the Ross Sea can provide a detailed record on the timing of grounding line retreat. A similar approach should work for other sectors around the West Antarctic ice sheet.

3. The last interglacial. Glacial geologists and marine geologists can test the validity of the hypothesis that the West Antarctic ice sheet collapsed during the last interglacial by examining the sea level history contained in the oxygen-isotopic record of deep-sea cores, by study of uplifted coral reefs, by analyses of sediment cores with high sedimentation rates from just north of Antarctic continental shelves, and by searching for deposits in Antarctica that formed during the last interglacial.

4. The older record. Because West Antarctica is volcanically active, geologists have been provided with an additional tool to help interpret glacial history. Volcanic eruptions that take place beneath an ice sheet produce distinctive black to yellow pyroclastic deposits referred to as hyaloclastites. The Cenozoic volcanic province in Marie Byrd Land, along the Pacific coast of West Antarctica, is characterized by unusually thick and extensive hyaloclastite deposits that can be dated by K-Ar and fission track analyses. Older deposits record the antiquity, approximate thickness, and geographic extent of the pre-Quaternary ice sheet. Hyaloclastites less than one million years old have been only moderately affected by erosion and tectonic displacement, and they can, therefore, be used to help reconstruct fluctuations in ice level during Quaternary time. Studies to date indicate with considerable certainty that ice levels were roughly 2,000 m above the present level during at least two separate intervals in Quaternary time; additional field work may also help clarify the characteristics of the ice sheet during the last interglacial.

VI. A PROJECT APPROACH

In the preceding sections we discussed the research problems that need to be solved in order to predict the future of the West Antarctic ice sheet. In this section we outline some specific projects that should be carried out. As elsewhere, the concentration on ice sheet studies themselves reflect only the scope of this particular report; we emphasize again the extreme importance of research related to the surrounding ocean and its sea ice cover and their interactions with the atmosphere and the ice sheet.

In developing research plans for Antarctica (and complementary plans for Greenland) it is important to keep in mind the value of international collaboration. The benefit of joint experiments through cooperation both between organizations and between individual scientists has been manifest in the past; notable examples include work with Danish, French, and Swiss laboratories on ice core analysis, with groups from the United Kingdom and Denmark on airborne radar sounding of the ice sheet, with Soviet glaciologists on coring through the Ross Ice Shelf, and with many scientists from New Zealand on a variety of projects in the Ross Sea area. Particularly to be considered for the future (in addition to the above) are collaborative efforts with the Antarctic expeditions of the Federal Republic of Germany as their rapidly expanding plans for the Weddell Sea sector develop, and with FRG, Japan, New Zealand, Norway, the United Kingdom, and others, who may be undertaking (or continuing) oceanographic research in the waters surrounding West Antarctica.

Also worth emphasis is the importance of data analysis programs after completion of field work, particularly, but not only, on ice cores. Further study of existing cores has been recommended above; it is equally vital that sufficient attention be paid to thorough analysis of cores recovered in the future. The same holds true for data of other sorts, such as satellite imagery, radar sounding records, oceanographic data, and extensive near-surface glaciological studies. When field programs are so expensive, complete data analysis is particularly cost effective.

Another important point relates to drilling projects, particularly coring to intermediate and large depths. Both in the preceding sections of this report, and in the projects outlined below, drilling programs are largely separated according to two purposes -- studies of ice dynamics and examination of the record of the past. Conceptually these aspects may be rather different, but in practice they must be combined. Core drilling, particularly to bedrock, is very expensive and time-consuming; sites for drilling must be selected so as to satisfy, to the greatest extent possible, the needs of both research objectives.

A. Satellite Studies

Maximum advantage should be taken of present and future satellites. The most important experiment is the determination of rates of change of surface elevations, since this can answer directly the question of present-day changes in the ice volume (§ II.A.1). Observations of the positions of grounding lines and other glacial features, and of their changes, are valuable for identifying critical regions for ground-based studies of ice dynamics (Section II.B). Monitoring of mean annual brightness temperatures for studies of surface mass balance changes is also a very important experiment that can be carried out with existing hardware (§ II.C.1). For future development, the capability of laser ranging to targets on the ice surface that would make possible a network of velocity measurements without repeated re-occupations on the surface would be of very great value (§ II.C.3).

B. Drainage Basin Studies

Most of the West Antarctic ice sheet can be conveniently subdivided into a number of major drainage basins which are of interest to the question of mass balance and dynamics. These basins can have different states of mass balance and can react differently to external changes.

The major regions in order of importance for study are as follows:

1. The Amundsen Sea drainage basin;

2. The Ross Sea drainage basin;

3. The Bellingshausen Sea drainage basin;

4. The Weddell Sea drainage basin.

The Amundsen Sea drainage basin has top priority because, lacking an extensive ice shelf, it may be especially vulnerable to rapid change and therefore is of primary importance in investigating an incipient rapid shrinkage of the West Antarctic ice sheet. The Ross Sea drainage system contains a large ice shelf which may be the key to ice sheet vulnerability to temperature changes; the dynamics of the ice sheet can soonest be understood there because it has been by far the most intensely studied to date. Little is known about the Bellingshausen Sea system; it is small and remote from the major part of the West Antarctic ice sheet, and is unlikely to play a major role in the dynamics of the ice sheet. Nevertheless, this drainage system should be studied; since it is generally warmer for the same elevation than other parts of the West Antarctic ice sheet. Effects of climatic warming on the warmer, more northerly regions of the ice sheet should be carried out to study those phenomena which may commence earlier there than where the ice sheet is colder.

The Weddell Sea drainage basin may be just as important as the Ross Sea basin, but has lowest priority partly because much less work has already been done there and it is remote from logistic support bases, but primarily because substantial work in this area probably will be done in the 1980's by the West German Antarctic Expeditions.

1. Amundsen Sea drainage basin. A field program for the Amundsen Sea drainage basin should have the following elements:

(a) The present-day grounding lines of Thwaites and Pine Island Glaciers should be located accurately. Radio-echo sounding provides a crude location, but a tiltmeter should locate the grounding line to within a fraction of the ice thickness.

(b) The ice discharge velocity and flux across those grounding lines should be measured accurately. Aerial photogrammetry using Landsat imagery will give a good initial velocity grid over both ice streams, and this can be updated every few years. Islands and nunataks in the Pine Island Bay region provide fixed control points for accurate measurements of surface velocity and strain rates.

(c) Surface and bed topography must be mapped in the Amundsen Sea sector of West Antarctica so that the ice drainage systems of Thwaites and Pine Island Glaciers can be accurately determined, and boundary conditions for numerical modeling experiments can be established, including subglacial meltwater.

(d) A grid of data stations should be established on the surface over the drainage basin. Snow accumulation rates and surface temperatures must be found for the Thwaites and Pine Island Glacier drainage systems in particular.

(e) A corehole to bedrock should be drilled through the low ice-divide saddle between the Amundsen and Weddell Sea drainage basins to determine whether the ice divide saddle has recently lowered and/or migrated.

(f) Precise elevation profiles should be completed along flowlines of Thwaites and Pine Island Glaciers from their grounding lines to their respective saddles on the ice divide. The Thwaites Glacier level profile should connect with the USGS-Ohio State Byrd Station strain network. The profiles could best be completed by laser or radar satellite altimetry (preferably the former). If that is not possible, a precise leveling traverse on the surface is required. They could then be used as base lines against which to measure elevations obtained later from satellite altimetry.

(g) Satellite imagery (reflectivity and microwave emissivity) should be used to look for expansion of what appear on Landsat photographs to be ablation zones on Thwaites and Pine Island Glaciers as indicators of response to climatic warming. If expansion is detected, and is correlated with an increase in ice crevassing and discharge velocity (also monitored by Landsat) for these ice streams, then actual surface ablation rates should be measured in the field and correlated with grounding line retreat rates. This would be a long-term component of the study.

(h) Sediment cores should be obtained to determine the former extent and the retreat history of grounded ice in the Amundsen Sea sector. This work should be coordinated with glacial geologic studies in the Pine Island Bay region.

(i) The studies of glacial and volcanic geology described below (paragraph I) both have important objectives in the Amundsen Sea region. These studies should be carried out concurrently with the glaciological investigations both to provide interaction between all the various disciplines involved in studies of the ice sheet, and for logistic cost-effectiveness.

2. Ross Sea drainage basin. The program in the Ross Sea drainage basin should be similar to that in the Amundsen Sea drainage basin. Much of the bedrock topography has already been mapped. The emphasis should be on Ice Streams B and C because Ice Stream B is one of the most active, whereas there is reason to believe that Ice Stream C may recently have become substantially less active. Existing data suggest that the contrasting behavior of these ice streams is inconsistent with steady state. To solve this problem we need contemporary surface mass balance measurements along flow lines from the ice divide to the ice shelf with supporting velocity and strain rate data. Radar flights should be extended to study in more detail the record of ice processes preserved within the ice. Coreholes to bedrock should be drilled along Ice Streams B and C, on the Siple Coast ice dome in between those ice streams, on Crary Ice Rise, and on Roosevelt Island. We also propose two flow-line studies involving coring to a depth of 150 m on the Ross Ice Shelf downstream from Ice Streams B and C. Ice temperatures should be determined precisely in all drill holes as an indicator of any recent climatic change. At some of those locations holes should be drilled through the ice shelf and temperature sensors placed not only in the ice shelf but also throughout the water column to the sea bed.

C. Deep Drilling in the East Antarctic Ice Sheet

A large program of core drilling has been recommended for inclusion in the studies of the Amundsen Sea and Ross Sea drainage basins. In addition, it is of great importance to complete at least one core hole to bedrock in East Antarctica; the area or areas should be carefully selected to minimize the difficulties of interpretation of the record in the lower-most part of the core. The reasons for coring in East Antarctica were discussed in Section V.A.

D. Establishing Monitoring Stations

Monitoring of a number of parameters has already been discussed under satellite studies and drainage basin studies. Of particular additional importance is monitoring ocean changes with a series of anchored buoys (§ III.C.1). Emphasis here should be on the Ross and Amundsen Seas in connection with the corresponding drainage basin programs on the ice sheet.

A program is proposed to monitor temperatures in five 300-m deep boreholes (§ III.C.2), and to make repeated measurements of surface mass balance at the same location (§ III.C.3). One monitoring station would be situated in the center of the Ross Ice Shelf, one on the Filchner Ice Shelf, one at Byrd Station, one on the inland ice sheet (preferably a local ice divide) in northern Marie Byrd Land, and one at the South Pole for comparison with the good temperature record at that station. The holes could be drilled and temperature profiles measured in one summer; changes could be monitored by freezing in a vertical string of sensors for future remeasurement. The technique recommended for surface mass balance is to measure changes of surface level against a large number of stakes spread over a suitable network.

E. Glacial Geology

1. Amundsen Sea project. A systematic set of continental-shelf sediment cores should be obtained from the outer edge of the Amundsen Sea to the ice edge in Pine Island Bay. These cores would allow the former extent of grounded ice to be determined and might permit ^{14}C dating of the time of ice recession to its present limits. Concurrently, glacial geologic studies should be made of ice-free areas on the Pine Island Bay region. Both projects could be carried out from an icebreaker.

2. Ross and Weddell Sea project. Collection and study of continental-shelf sediment cores from the Ross and Weddell Seas should continue, especially in view of the very encouraging results that have been obtained so far. The results will delimit the maximum extent of grounded ice in these two seas during the last glaciation and will show the chronology and pattern of the following ice recession. Icebreakers are required for this project.

3. Southern Transantarctic Mountains project. Glacial deposits in several areas (such as the Beardmore and Reedy Glacier areas) should be studied in detail by glacial geologists and soil scientists. The results will be important for reconstruction of late Wisconsin-age ice configuration and may allow ^{14}C dating of the recession of the Siple Coast grounding line to its present position. Helicopter support is needed for this project.

4. Interior nunatak project. Studies of the Ellsworth and Thiel Mountains have shown that the late Wisconsin-age configuration of interior West Antarctica domes can be determined by glacial geologic techniques. These studies should be continued by examination of the Whitmore Mountains, Mt. Woollard, Mt. Moore, the Noah Hills, the Martin Hills, the Stewart Hills, the Pensacola Mountains, and the mountains of Marie Byrd Land. A Twin-Otter or similar light, fixed-wing aircraft will be needed for this study.

5. McMurdo Sound project. Extensive glacial geologic and pedologic studies of glacial deposits should continue in the McMurdo Sound area, because these deposits form the type section for Antarctica and have afforded the most precise dating of fluctuations of the West Antarctic ice sheet. This project will require helicopter studies.

F. Sea Level and Ocean Volume Studies

Accurate knowledge of the course of changes in sea level and ocean volume during the last interglacial is the key to reconstructing the history of the West Antarctic ice sheet at that time. That, and reconstruction of the climate immediately before and during the interval of high sea level, is essential to any prediction of what may happen during a future CO_2-induced warming.

Work should continue on raised coral reef complexes, similar to that already carried out in Barbados and in New Guinea and adjacent islands, to determine the fine structure of sea level change and its timing during the interval 140,000-115,000 yrs B.P. Improvement in radiometric dating techniques is most desirable. Oxygen isotopic studies should be continued both on coral reefs and on deep-sea cores with high sedimentation rates, for the same time interval (§ V.B.1).

A program of study of past sea levels around the margin of Antarctica and meridionally along the other southern hemisphere continents should be initiated (§ V.B.1). To study present-day changes tide gauge stations should be established wherever possible along the Antarctic coast, and the potential usefulness of re-determining the heights above sea level of tide gauge sites from former expeditions should be investigated. Whenever possible tide gauges should be placed where there is glacial geologic evidence of post-glacial sea level changes (Section II.D).

G. Numerical Modeling and Theoretical Studies

Numerical modeling and other theoretical studies must be strongly encouraged. Particularly important are the use of general circulation models applied to the southern regions to study inter-relationships between ocean temperature, sea ice extent, carbon dioxide, and the mass balance on the Antarctic surface, and studies of the response of ice sheets to changes in boundary conditions, of the interaction between ocean currents and ice shelves, of the response of ocean surface temperature and circulation to changes in atmospheric temperature, and of the processes controlling the sliding of the glacier or ice sheet on its bed. Quite apart from being indispensable at the planning and evaluation stages of a systematic research program, modeling and theoretical studies are highly cost-effective and can be launched more rapidly than the field programs that they complement.

The main obstacles to a program of modeling and theoretical studies of the response of the West Antarctic ice sheet to CO_2 are created by the limited number of interested workers and by the lack of essential information. Removal of the latter obstacle is adequately covered by the rest of this program; the former suggests above all a need for the coordination of all relevant work to ensure that results, and especially projections, represent a consensus clearly identifying the boundary between knowledge and speculation.

Solution of the problem of CO_2 and West Antarctica requires three specific modeling projects:

Regional changes in the precipitation, summer temperatures, and ocean heat flux of West Antarctica to be expected from increased atmospheric CO_2 concentrations. This calls for a focusing of the CO_2-related experiments of atmospheric and oceanic modelers on the climatic elements most relevant for assessing the reaction of the West Antarctic ice sheet. These modelers need to cooperate with polar glaciologists to improve current simulations of the existing polar climate as a prelude for predicting a concrete CO_2 scenario for West Antarctica.

Temperature changes in the large ice shelves and in the main ice sheet of West Antarctica in response to projected CO_2-induced changes in the regional environment. This represents a fairly complex but tractable problem in the thermodynamics of inhomogeneous moving media with internal heat generation (including re-freezing of meltwater below the ice sheet surface and basal melting or freezing on the ice shelves). The results will replace current qualitative "vulnerability" estimates by quantitative changes to be expected in the internal temperature fields of the ice sheets.

The dynamic behavior of different West Antarctic drainage basins in the projected CO_2 scenario. These model calculations should first address the Ross Sea sector, where the West Antarctic ice sheet ends in a thoroughly studied floating ice shelf, and the Amundsen Sea sector, which features no ice shelf at present. The well-explored Lambert Glacier-Amery Ice Shelf system currently exemplifies the conditions that might be created by increasing CO_2 in the higher latitudes of the Ross Sea sector and should therefore also be modeled, to serve as a checkable analogue. A crucial test for all such models will be their capability of simulating the growth of the present ice sheet configuration as a steady or transient state, starting from bedrock or from some proto-type ice sheet free to develop in a number of ways.

All these model experiments will, of course, gain increasing realism from the results of the various field programs suggested in this research plan. However, since the modeling can take account of present uncertainties by permitting key parameters to vary over their uncertainty ranges, a systematic modeling program along the lines here described will provide the earliest-possible concrete answers to what increasing CO_2 concentrations might do to the West Antarctic ice sheet. Moreover these answers can be qualified by error estimates and be sharpened progressively as more field results become available.

H. Airborne Radar

We believe that the most effective way to collect data over large portions of the ice sheet is with radar sounding. These data yield crucial information about ice thickness, mass balance, grounding lines and pinning points and past changes in the ice sheet. To obtain improved information about the internal characteristics of the ice sheet a digital radar that not only records profiles but amplitude and phase data as well should be developed as a fundamental part of these investigations. A digital system would also permit much more efficient handling of data than do present systems.

I. Volcanic Geology

The Quaternary volcanoes in the Amundsen Sea sector are the primary objective of desirable future studies of the volcanic record of glacial history in Marie Byrd Land. Stratigraphic and chronologic studies of Quaternary hyaloclastite sequences and of subaerial lava flows should be made. The specific objective is to determine as precisely as possible the age and duration of volcanic activity in each of four large Quaternary volcanoes (Mt. Murphy, Mt. Takahe, Mt. Siple, and Toney Mountain), and the position of ice level during each volcanic episode. Mt. Takahe is of special interest because it is composed of hyaloclastites that are apparently less than 250,000 years old, and may provide information about ice levels during the last interglacial (§ V.C.4).

VII. PRIORITIES

Projects and parts of projects are divided into three groups. There is no priority ordering within groups.

Top:

- Satellite altimetry
- Satellite monitoring of Antarctic sea ice distribution
- Amundsen Sea drainage basin study
- Interaction between ice shelves and oceans
- Grounding line studies (including ice rumples)
- Drilling on ice rises and ice domes
- Deep drilling in East Antarctica
- World-wide sea level and ocean volume changes - last interglacial
- Ocean, sea ice, and precipitation modeling using global circulation models
- Numerical modeling of ice sheet response
- Technique for surface mass balance from satellites
- Radar profiling of ice shelves for bottom balance rate
- Basal mass balance on ice shelves
- Oceanographic monitoring along barrier
- Instrumental emplacement deep in ice shelf for bottom balance rates
- Marine coring for evidence from last interglacial and Holocene retreat record
- Tide gauge studies

Second:

- Ross Sea drainage basin study
- Satellite studies of ice margins
- Ice thickness mapping
- Development of laser ranging capabilities
- Marine coring for evidence of extent of last major ice advance

Third:

- Weddell Sea drainage basin study
- Bellingshausen Sea drainage basin study
- Study of existing cores
- Shallow coring
- Antarctic Holocene sea level changes
- Monitoring temperature change
- Monitoring accumulation rates on stake networks

VIII. SOME SPECIFIC LOGISTICAL CONSIDERATIONS

A. Logistic Support for Ground Programs

The drainage basin studies lie at the very heart of the investigation of the West Antarctic ice sheet and its response to climate change. These studies in turn involve extensive measurements on the surface or at relatively closely spaced stations. Techniques for making the measurements are largely available, but the necessary supporting vehicles do not exist. It is essential that the U.S. program have available suitable surface vehicles or economic, light-weight aircraft, such as the Twin Otter, and if at all possible both. Adequate logistic support is essential for successful execution of the study of the West Antarctic ice sheet.

B. Deep Drilling Equipment

High priority has been given to a program of drilling to bedrock in East Antarctica. Unfortunately, no drill capable of penetrating cold ice to depths greater than 1000 m (depths below which drilling fluid becomes essential to prevent hole closure) is currently available. Although such a drill may be developed by Denmark, France, or the Soviet Union in the next few years, the U.S. program would benefit greatly if such a drill were developed in the United States. Furthermore, deep drilling equipment for penetrating to bedrock in the West Antarctic inland ice, where the temperatures are much higher, and through the Ross Ice Shelf in routine and rapid fashion, are urgently needed.

C. Airborne Radar System

Several aspects of the program require airborne radar sounding. Plans, currently in abeyance, for the development of a digitally-recording modern radar system to be installed in a C-130 aircraft should be activated at the earliest opportunity.

D. Base in Pine Island Bay

Work in the Amundsen Sea sector has been hindered in the past by higher priority given to other projects, by the long distance from the main station at McMurdo Sound and by the frequency of unsuitable weather. Consideration should be given to establishing a new base by sea in the Pine Island Bay area, and to the use of economical light aircraft (Twin Otter) for this work. This is not a new idea -- position papers on this subject have been prepared by J.O. Fletcher and are available from the Polar Research Board.

E. Systems for Studying the Lower Boundary of Ice Shelves

An essential part of the study on bottom balance rates on ice shelves is the proposal to install instruments within and beneath the ice for short-term, and, if possible, long-term monitoring. To be feasible the placement project should be a small portable operation supplied by helicopter from an icebreaker at the barrier or carried out entirely by Twin Otter or helicopter should be developed. It would be important to be able to complete several holes, perhaps even as many as 10 or a dozen, in a single season. This involves a program of instrumental development and methodology for rapid emplacement. Consideration should be given as to whether it is more practical to emplace the instruments in boreholes or to employ robot meltsondes such as have been used in Greenland, but not yet successfully in Antarctica.

F. Laser Ranging System

As mentioned previously, a program for the development of self-cleaning laser reflectors that could be emplaced on the ice surface and that would maintain themselves without being revisited would make it possible to monitor ice movement using available techniques with a laser-ranging system in a satellite in polar orbit. Although this is not a solution for the short term, it is of great importance for a long-term program.

G. Satellite Receiving Station

The absence of a recording system on planned operational earth resources satellites means that there will be no imagery at all for Antarctica through most of the 1980's unless a receiving station can be set up in Antarctica. The importance of the satellite imagery to the program proposed here makes it essential that a south polar recording station be established.

H. Ocean-Sediment Coring Winch

Sediment coring in the Weddell and Amundsen Seas requires a suitably-equipped icebreaker. We strongly recommend that a coring winch be installed on one of the new Polar Class icebreakers.

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