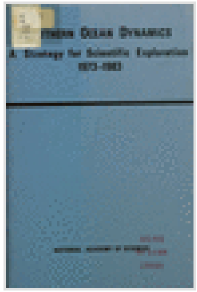

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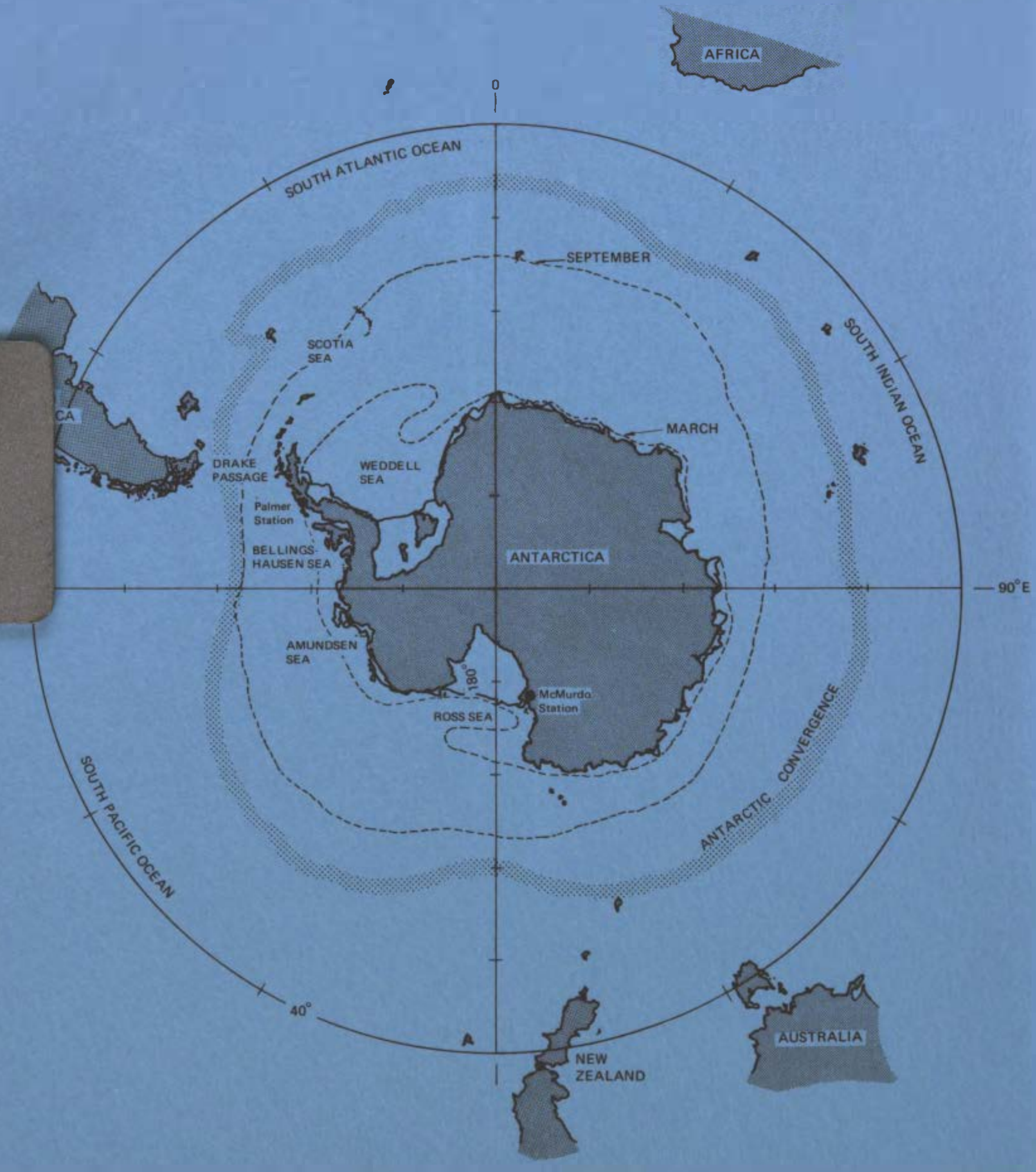

The Southern Ocean Showing the Position of the Antarctic Convergence and V[illegible] of the Pack Ice

SOUTHERN OCEAN DYNAMICS

A Strategy for Scientific Exploration 1973–1983

Ad Hoc Working Group on Antarctic Oceanography
Panel on Oceanography
Committee on Polar Research
National Research Council

NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1974

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The members of the committee selected to undertake this project and prepare this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. Responsibility for the detailed aspects of this report rests with that committee.

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Foreword

The Committee on Polar Research (CPR) was asked by the National Science Foundation (NSF) to undertake a series of discipline-oriented studies on antarctic research. Each was to include a 10-year plan of investigation that was compatible with anticipated logistic, operational, and fiscal constraints. As background, the Committee was provided with a variety of operational and logistical alternatives, along with their estimated costs, that might be developed over the next 10 to 20 years.

In his letter to the Committee, Joseph O. Fletcher, Head of NSF's Office of Polar Programs, stated:

> Our objective in Antarctica is to support the most fruitful scientific program. Our long range operational requirements and logistic plans must be based on clear delineation of scientific problems and identification of the most promising approaches for solving them. We need your help to do this.
>
> For example, a few operational alternatives that depend on evaluation of scientific needs are:
>
> 1. Shall we continue to develop facilities at McMurdo Sound and Christchurch, our bases of operations during the past 15 years, or will future scientific needs call for operational capabilities in areas too far from McMurdo for operational support (such as the Weddell Sea)? If so, we need to start now to prepare for these needs. (For example, the location of Siple Station is determined by its conjugacy to a Canadian station and the proximity of their magnetic field line to the plasmapause—but Siple Station is closer to South America than to McMurdo—where will the next conjugate pair be?)
>
> 2. Should we close down the facilities in the Antarctic Peninsula (Palmer Station and R/V *Hero*), continue activities at the present level, or undertake more ambitious activities there? (R/V *Hero* could probably be more intensively utilized—especially in winter.)
>
> 3. Should we invest in a refit and modernization of the USNS *Eltanin* in 1974 or retire her?
>
> 4. What will be our requirements for icebreaker support in 1980? (This is a question of current urgency.)
>
> 5. Should we continue a pattern of intense summer operations and winter hibernation or develop capabilities for all season operations? What kind of operations? Why?

6. Will our future scientific needs be met by fixed stations and present methods of field party support, or should we actively develop mobile or transportable laboratories, employing vehicles such as the hovercraft?

7. With our operational capability centered at the Ross Sea, a number of programs have developed that are directly related to the presence of the large ice shelf: mass budget and deformation, ice shelf drilling, sub-shelf heat and mass budget, sub-ice-shelf biota, bottom water formation, sediment cores. Do we want eventually to continue these studies in the Ronne Ice Shelf region? If so, when and where?"

In accepting this challenge, the Committee was mindful that the cost of logistic support for implementing polar research is exceptionally high because of the remoteness, inaccessibility, extreme cold, and extended periods of daylight and darkness. Accordingly, the Committee gave considerable emphasis to the acquisition of useful data by automatic stations, to include unmanned geophysical observatories, buoys, aircraft, balloons, rockets, and space vehicles. In developing its reports, the Committee looked upon the antarctic region as an integral part of total global environment and, whenever possible, related its recommendations to the objectives of on-going international worldwide research programs such as the Global Atmospheric Research Program (GARP), the International Decade of Oceanic Exploration (IDOE), and the Deep Sea Drilling Project (DSDP).

The Committee called on each of its discipline-oriented panels to prepare studies as proposed. The outcome is a series of reports, each of which focused on one of the particular disciplines: glaciology, oceanography, meteorology and climatology, geology and solid-earth geophysics, upper-atmosphere physics, and biology. Outside experts were called in as required, and each of the reports was reviewed by concerned groups within the National Academy of Sciences and the National Research Council. This is one of the series of such reports. The Committee intends to review and update these studies periodically, as advances and developments dictate. This approach deviates somewhat from that taken in developing the report, *Polar Research: A Survey* (National Academy of Sciences, Washington, D.C., 1970), which was a more general study that included both polar regions and covered a somewhat shorter time scale.

The Committee on Polar Research is supported by a contract from the Office of Polar Programs, National Science Foundation.

James H. Zumberge, *Chairman*
Committee on Polar Research

Preface

This is the report of a study, convened by the Panel on Oceanography of the Committee on Polar Research, to draft a 10-year plan for scientific exploration of the physical oceanography of the Southern Ocean. To prepare the plan, the Panel established an *ad hoc* Study Group, which submitted an interim report to the Committee in January 1972. The task of the present *ad hoc* Working Group on Antarctic Oceanography was to enlarge on that report and to consider the interaction of such a program with evolving international plans for monitoring the global atmospheric–oceanic circulation during the next 10 years.

This study was conducted during the summer and fall of 1972 at and between two meetings of the Working Group in Boulder, Colorado, and Washington, D.C.; a number of other scientists also participated in the two meetings. An early draft of the report was circulated widely to interested scientists for further comment. This report has undergone critical review by a number of interested groups within the National Academy of Sciences and the National Research Council: the Committee on Science and Public Policy, the U.S. National Committee for the GARP, and the Ocean Science Committee of the Ocean Affairs Board. The comments and help of the latter group are especially appreciated.

The Working Group noted that the present rapid development of new technology is pointing the way toward the solution of global environmental prediction problems. Long-term prediction of climate variability is one such problem requiring the proper monitoring of large-scale physical processes in the polar oceans. This report attempts to show some of the possible first steps toward the establishment of such monitoring in the Southern Ocean.

The Working Group believes that continual planning should be a part of the overall effort to ensure the efficient utilization of available manpower and scientific resources. The recommended program has been organized to consist of a series of well-defined and sharply focused experiments that will permit careful review and efficient management of individual projects. The Working Group believes that its assessment of available resources indicates that the basic experimental sequence is both realistic and feasible. Only rough estimates of costs of such a program are possible. Since the costs will depend strongly on the details of individual experiments, ship and related logistics costs, and the concurrent development of other environmental monitoring programs, cost projections are best left to that group actually carrying out the program. In the Working Group's view, the financial support of a program of Southern Ocean physical oceanography is essential now if the United States is to take a substantive long-term role in global environmental prediction.

The Panel is grateful to all those who participated in the preparation of this report and especially to Louis DeGoes, Executive Secretary of the CPR, and Victor T. Neal, Office of Polar Programs, National Science Foundation, for their contributions to the report's organization and publication.

D. James Baker, Jr., *Chairman*
Panel on Oceanography

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Summary of Principal Recommendations

I. GENERAL

The Working Group, *noting* that the continuing successful development of oceanographic experimental and theoretical capabilities indicates that long-term direct measurements and monitoring are now feasible in the Southern Ocean, and *further noting* that the high logistics costs for polar experiments will require careful planning to ensure efficient use of funds, *recommends* the following:

1. A sequence of sharply focused ocean monitoring and dynamics experiments should be begun as soon as possible in the Southern Ocean for the purpose of contributing to the goal of understanding long-term, large-scale ocean and climate dynamics.
2. The management of such a program should include a continuing effort to review conceptual design, strategy, and interaction among Southern Ocean experiments and to review collaboration between this regional and other global oceanographic and meteorological programs.
3. Since antarctic physical oceanography provides a particularly good opportunity for international collaboration and pooling of effort, the appropriate government agencies should actively seek cooperation of scientists and sponsoring institutions of other nations in planning and carrying out these investigations. The sequence of experiments recommended above could form the U.S. nucleus of a program of International Southern Ocean Studies (ISOS) on ocean dynamics and monitoring in close cooperation with other global environmental monitoring programs.
4. Because of the mutual benefits to be gained, the experimental plan should be developed as soon as possible in order that adequate monitoring systems are operable by 1977. In this way, maximum interaction with the First GARP Global Experiment (FGGE) and its subprogram POLEX-GARP (South) can be achieved.

5. Every effort should be made to find means by which the unfinished circumpolar survey of the physical oceanography of the Southern Ocean can be completed so that the entire region is covered with a network of modern data for physical oceanography.

II. SPECIFIC

The Working Group, *noting* that data should be gathered through an integrated program of manned and unmanned stations and that the development of technology of remote sensing is to be encouraged, *recommends three specific areas of study*:

1. A program emphasizing presently available measurement techniques for the study of the large-scale transient dynamics of the Antarctic Circumpolar Current and its role in the general ocean circulation;
2. A program for direct observation of the processes involved in the formation of Antarctic Bottom Water and the determination of the amounts and variability of this formation;
3. A program to elucidate the structure of the strong frontal zones and their role in the formation of intermediate water masses and to monitor, with existing stations, exchange processes for overall budgets of heat, mass, and momentum in the region.

2

General Objectives and Program Summary

I. INTRODUCTION

As we move closer to an understanding of global environmental phenomena, the important role of the polar regions in long-term atmosphere and ocean dynamics becomes more apparent. An adequate understanding of the physics and dynamics of polar regions is essential to the prediction of global environmental processes that are required for eventual rational management of the earth for the benefit of man.

The goal of this report is to consider the future role of oceanography in the Southern Ocean in light of the above statement. Three general questions are addressed in this chapter: what is the scientific and practical rationale, why is a program being recommended now, and are the existing and projected manpower and scientific resources adequate to carry out the recommended program?

The great distances and high logistics costs involved in mounting programs in the antarctic regions require a strong justification for U.S. participation. For oceanography, we believe that it is appropriate for the United States to give first consideration to matters of global rather than strictly regional significance.

Therefore, the recommended dynamics experiments in the Southern Ocean have two major scientific goals. The first is to use the Southern Ocean as a unique geophysical laboratory for process-oriented studies of the time-dependent dynamics and air–sea interaction of large-scale ocean currents and frontal zones. The second is to use monitoring experiments and theory to understand the role of this part of the ocean in the global ocean–atmosphere circulation, in the global interaction of the sea and the atmosphere, and in the dynamics of climate.

Although we have some understanding of the problems studied in other latitudes, and the grossest features of the circulation can be rationalized, little fundamental progress has been made in actually elucidating the dynamics of processes sufficiently to understand their essential aspects. Both experiment and theory are required to solve these problems. We presently lack both global observational data on the relevant time and space scales and sufficient theoretical understanding.

Global observations are inadequate because it is difficult to make oceanographic measurements: the technology is complex and the time scales relating to energy exchanges are relatively short compared with the global scales. Theories are inadequate because we have not yet been able to isolate essential processes from the many parameters of fluid motions inherent in the conservation equations.

We believe that the proper course for solution of these problems is to plan and execute a set of sharply defined ocean experiments that utilize existing reliable technology. The data from these experiments and from existing data can form a basis for a set of theoretical numerical experiments designed to isolate processes and understand them. The essential role of the theoretical experiments is to provide the feedback between theoretical ideas and the design and interpretation of the field experiments. As a firm understanding of physical processes emerges, their essential aspects can be parameterized into larger models. A balance among monitoring, numerical models, and process-oriented experiments will be required in order properly to couple the ocean to the atmosphere for models that adequately represent long-term climate variability.

The above remarks are general. The specific scientific goals are discussed below.

II. SPECIFIC SCIENTIFIC GOALS

A. OCEAN DYNAMICS

The circumpolar current system—the zonal flow, the meridional flow, and the source of deep water in the Weddell Sea—is the heart of the deep-ocean circulation. The antarctic currents link the world's major oceans, and deep antarctic convection sends both slowly moving water and swifter western boundary currents equatorward. The main thermocline in the ocean is maintained by the resulting gentle upward flow. Processes occurring in the Antarctic affect the global distribution of properties in the oceans; only by exploring these processes and their consequences, first regionally, then globally, can we eventually gain an understanding of the ocean as it operates on climatic time scales. The variability of physical properties and nutrient chemicals is also intimately tied to the circulation. The dynamics of the circumpolar currents are nonlinear and time-dependent and apparently similar to dynamics in temperate latitudes. Therefore, the circumpolar currents will be no easier, and probably more difficult because of logistics, to study than other major current systems.

The geography of the region provides a unique opportunity to monitor certain averaged properties of the circumpolar flow. The current is funneled through the Drake Passage; the total transport here represents the flow that is recirculated around the continent. With the proper set of measurements, one might determine a major ocean current response to large-scale atmospheric forcing. Thus the Drake Passage is a natural geophysical fluid-dynamics laboratory for large ocean currents. In spite of the increased logistics problems, the possible achievements could be a major step in understanding large-scale ocean currents. The specific problems are to measure and understand the vorticity balance and variability of the strong surface flows and the deeper abyssal flows and to understand the interaction of the source flow and the abyssal currents.

There is a strong frontal zone around the Antarctic continent. The processes that maintain this polar front are fundamental in the formation of intermediate water masses. The polar front is closely coupled to the circumpolar current. The specific problems are to delineate the processes occurring at the front and to understand the interaction between the front and the circumpolar current.

B. AIR–SEA INTERACTION

Strong atmospheric cooling of the Weddell Sea water causes it to be the largest source of bottom water in the global ocean. Air–sea interaction also is probably closely related to the circumpolar frontal zones. Processes of heat exchange between the ocean and the atmosphere and of heat redistribution in the Southern Ocean are only very generally known. The specific goals here are to measure, isolate, and understand the air–sea processes responsible for bottom-water formation and to monitor the amount of bottom water formed as a function of time in order to determine its input to the general abyssal circulation. In addition, we need to isolate the air–sea exchange processes at the polar frontal zones in order to parameterize these into large-scale air–sea interaction models. Finally, the requirements of global climate dynamics models include a knowledge of the annual and longer-term trends of separate heat-balance components in the Southern Ocean.

C. SEA–ICE–AIR INTERACTION

The formation and dynamics of sea ice are fundamental to the dynamics of Antarctic Bottom Water formation and to exchange processes and budgets. In an earlier version of this report, a chapter on sea-ice dynamics was included; that chapter is now Appendix D of the report *Guidelines for Antarctic Glaciology* (by the *ad hoc* Glaciology Working Group of the CPR [1974]). The change in location of that chapter in no way diminishes the Working Group's opinion of the fundamental importance of sea–ice–air interactions in polar regions; in fact, the Working Group notes that proper ice-dynamics studies will be an essential part of an Antarctic Bottom Water formation experiment and of the overall budget studies. Certain aspects of ice interaction are included in Chapters 4 and 5 on Antarctic Bottom Water formation and on exchange processes and overall budgets, respectively.

D. ATMOSPHERIC DYNAMICS

The Global Atmospheric Research Program (GARP) has set specific requirements for atmospheric measurements in the southern hemisphere during the First Global GARP Experiment (FGGE) scheduled for 1977. The first goal of this program is the improvement of short-term atmospheric prediction. The related meteorological requirements include measurement of sea-surface temperature [because the sensible heat transfer to and from the oceans is a major heat source (or sink) for the atmosphere] and atmospheric pressure. This requirement will involve obtaining measurements from drifting buoys and input from oceanographers to see that the information obtained will be of maximum value to both disciplines. The specific quantity of interest to oceanographers here is Lagrangian information, i.e., paths of surface currents around the continent.

The second goal of the program is the understanding of the physical basis of climate. This longer-term atmospheric prediction capability requires information on the motions and thermal structure of the upper ocean layer. Thus a second quantity of interest is heat-storage information along the path of the drifting buoys. This could be obtained, for example, by measurement of near-surface temperature profiles.

III. ULTIMATE PRACTICAL GOALS

Studies on the physical oceanography of the Southern Ocean can contribute significantly to our understanding of four areas of global societal concern. They are (1) weather and climate modification; (2) an ecologically efficient long-term use of the region's fisheries; (3) an ecologically sound strategy for the disposal of waste and radioactive by-products; and (4) the improved prediction of local weather, sea, and ice conditions.

The National Academy of Sciences report on weather and climate modification [Committee on Atmospheric Sciences, 1973] states that "concern for man's impact on the worldwide climate has been sharply increased by the exponentially growing capacity to utilize global resources to produce goods and services—a capacity that within decades may begin to approximate the natural forces influencing the atmosphere and the ocean. Alterations to the atmosphere are assuming a place of prominence in worldwide concern over the human environment." The polar regions play a major role in climatic variability. Through polar meteorological experiments like POLEX (a subprogram of GARP), interaction experiments like AIDJEX, and oceanographic experiments like the ones recommended here, oceanographers and meteorologists hope to define more clearly the role of the polar regions in oceanic and atmospheric climate.

Biological productivity is high in the Southern Ocean. The large regions of summer plankton growth at high latitudes, brought on by the long days of sunlight, are a source of food for animals from small krill to large whales. The monitoring of the physical oceanographic environment will be a necessary adjunct if man is to harvest efficiently but not exhaust the renewable organic resources of this richly productive region.

The disposal of waste and radioactive by-products is a major environmental concern today. If the practice of dumping such by-products in the ocean were to be seriously advocated, an ecologically sound strategy would be required. Such a strategy awaits our understanding of the deep circulation of the ocean. The Southern Ocean plays a major role in the abyssal circulation, which is in turn responsible for the distribution of materials in the deep ocean. Overturning rates and processes must be understood and monitored before we can predict the residence times for these man-made pollutants.

Finally, understanding of the physical environmental processes in the atmosphere and ocean surrounding the Antarctic continent could eventually lead to an economically and ecologically sound development of the region. With improved local weather, ice, and sea condition predictions, and improvement in navigational aids, a rational development of the potential resources of the continent and its ocean can be planned.

IV. HISTORICAL BACKGROUND

A clear view of the next steps in physical oceanography programs in the Southern Ocean and their time frame is now emerging from recent scientific literature and a number of international meetings. The region has revealed a variety of strong, transient dynamical phenomena involved in the formation of large water masses and abyssal circulation. Vigorous exchanges of heat and momentum with the atmosphere suggest the importance of southern hemisphere air–sea interactions in the global atmospheric circulation.

In November 1970, the coordination group on the Southern Ocean of the International Oceanographic Commission (IOC) noted that significant progress had been made in describing the hydrography of the Southern Ocean and in delineating the gross exchanges of physical properties with the adjacent parts of the World Ocean. They noted that data required for proper understanding of phenomena, however, were still lacking. Especially emphasized was the serious lack of data on (1) variability in the distribution of properties and of the large-scale circulation, (2) the direct measurements of deep-water movements in the Southern Ocean, (3) the origin and dynamics of frontal zones, and (4) the formation of water masses. They noted that winter data in particular are needed and that the heat budget should be refined on the basis of direct measurements. Furthermore, the concept of an integrated global observing program is currently being extended to the IGOSS by the IOC. The IGOSS pilot project is now under way with the ultimate objective of providing comprehensive monitoring of the oceans and atmosphere through an integrated system involving the common use of facilities, sensors, and platforms such as ocean buoys, ships, and space satellites.

The U.S. contribution to this advancement of knowledge of antarctic oceanography has been substantial. The collection of a network of modern data in the Southern Ocean carried out from the USNS *Eltanin* from 1962 to 1972 has provided a firm but incomplete base for future research there in a number of oceanographic disciplines. *The Working Group notes that the termination, due to budgetary limitations, of the USNS* Eltanin *program in 1972, before its circumpolar survey was completed, is the cause of the incomplete data base and* recommends *that every effort be made to complete the survey, either from the* Eltanin *or from some other ship.*

The existing data base and recent developments in ocean engineering do, however, allow us to consider now a new phase of observation: long-term monitoring of the dynamics and specific experiments designed to probe the basic physics and interaction processes. We *recommend* in the chapters that follow a series of experiments designed to explore in depth three major areas: the dynamics of the Antarctic Circumpolar Current; the mechanisms and variability of Antarctic Bottom Water formation; and the role of exchange processes in strong frontal zones and overall budgets.

The steady advances in experimental and theoretical oceanography achieved during the past decade have provided a pool of sophisticated yet reliable instrumentation and expertise that can be applied to any ocean. With the use of these techniques, scientists are beginning to be able to ask and answer the relevant dynamical questions.

Some of the recommended experiments can be done with existing technology, and these should be implemented as soon as reasonably possible in order to minimize ever-rising support costs. Others will require development of automatic data buoys and other remote technology. In view of the importance of such technology in long-term monitoring, pilot experiments and development should begin as soon as possible.

The plans for GARP also show the need for prompt inception of this program of exploration. It is clear that the goals of the oceanographic studies are closely related to ultimate goals of GARP. The second objective of GARP is to study those physical processes in the atmosphere that are essential for an understanding of the factors that determine the statistical properties of the general circulation of the atmosphere, which would lead to better understanding of the physical basis of climate. Knowledge of ocean circulation and its interaction with the atmosphere will be an essential input to this objective. The Polar Experiment subprograms POLEX-GARP (North) and POLEX-GARP (South) of FGGE will require monitoring of oceanic dynamical processes, but the detailed experiments have not yet been defined.

The Working Group emphasizes the opportunities for fruitful simultaneous experimentation with FGGE and POLEX-GARP (South) in 1977 and urges that an experimental plan be developed as soon as possible so that scientific interaction can be achieved and adequate monitoring systems made operable by then.

Finally, we turn to the question of logistics and resource allocation. Can a program be structured so that it is scientifically sound but does not stretch the available resources (manpower, equipment, and funds) beyond their projected limits? We believe that it is possible to do so provided that the activities are a sequence of well-defined, sharply focused experiments rather than a parallel broad effort toward a diffuse and ill-defined goal. Activities in several areas can be carried forward simultaneously, but expensive field programs should be staggered so that the project as a whole remains of manageable size.

Therefore, we *recommend that a sequence of sharply focused ocean monitoring and dynamics experiments be begun as soon as possible in the Southern Ocean for the purpose of contributing to the goal of understanding long-term, large-scale ocean and climate dynamics.*

In order to do this, continual review and planning must be part of the scientific management of the program. Therefore, we *recommend that the management of such a program include a continuing effort to review conceptual design, strategy, and interaction among Southern Ocean experiments and on collaboration between this regional and other global oceanographic and meteorological programs.*

We note that the international interest in antarctic oceanography suggests that these experiments could be done together with national oceanography organizations of other countries. The existing international cooperation of several countries in antarctic research is a firm basis for this collaboration, which would maximize the information flow. Therefore, we *recommend that the National Science Foundation actively seek cooperation of scientists and sponsoring institutions of other nations in planning and carrying out these investigations.*

Such a sequence of experiments could form the U.S. nucleus of a program of International Southern Ocean Studies (ISOS) on ocean dynamics and monitoring. This program could contribute directly to research in physical oceanography and climate variation sponsored by the International Decade of Oceanographic Exploration (IDOE), the Division of Environmental Sciences (DES), and the Research Applied to National Needs (RANN) program. Monitoring should be carried out in cooperation with the Intergovernmental Oceanographic Commission's (IOC) Integrated Global Ocean Station System (IGOSS), the United Nations Environmental Program (UNEP) "Earthwatch," and other such international global programs.

V. PROGRAM SUMMARY

We have recommended the planning of a sequence of ocean dynamics and monitoring experiments in the Southern Ocean with maximum interaction with the FGGE. The specific areas of study for these experiments is discussed in detail in the following chapters.

In summary, the Working Group, *noting* that data should be gathered through an integrated program of manned and unmanned stations and that the development of technology of remote sensing is to be encouraged, *recommends* three specific areas of study:

1. A program emphasizing presently available measurement techniques for the study of the large-scale transient dynamics of the Antarctic Circumpolar Current and its role in the general ocean circulation;
2. A program for direct observation of the processes involved in the formation of Antarctic Bottom Water and the determination of the amounts and variability of this formation;
3. A program to elucidate the structure of the strong frontal zones and their role in the formation of intermediate water masses and to monitor, with existing stations, exchange processes for overall budgets of heat, mass, and momentum in the region.

A summary time-phased chart is shown in Table 2.1.

As noted above, we do not recommend here a specific program in Sea Ice Dynamics. This subject is already covered in Appendix D of the report

TABLE 2.1

RECOMMENDED GENERAL PROGRAM STRUCTURE

	Activity	Time Frame 1973 - 1976	1976 - 1979	1979 - 1982
		CONTINUAL PLANNING AND REVIEW	CONTINUAL PLANNING AND REVIEW	
OCEANOGRAPHY	Dynamics of the Circumpolar Current	Begin Field Experiment →	Monitoring	Merge into International Climate Research Effort
	Antarctic Bottom Water Formation	Begin Field Experiment →	Monitoring	
	Exchange Processes and Overall Budgets	Begin Field Experiment →	Monitoring	
OTHER	GARP PLANNING	GARP PLANNING	GARP PLANNING	
		AIDJEX		
		POLEX →	→	
			FGGE	

Antarctic Glaciology, Guidelines for U.S. Program Planning, 1973–1983, by the *ad hoc* Glaciology Working Group of the CPR (National Academy of Sciences, 1974). The interaction of oceanography with sea ice is discussed in Chapter 5.

3

Dynamics of the Circumpolar Current

I. PRINCIPAL RECOMMENDATIONS

1. We *recommend* the initiation of planning for a measurement program, emphasizing presently available techniques, to study the large-scale, transient dynamics of the Antarctic Circumpolar Current (ACC) and its role in the general ocean circulation. The program can be divided into two parts: a set of specific experiments designed to explore features, heat balances, and energy sources and a continuing effort to monitor the important vector and scalar fields in the regions of the current. The elements of such a program would include the following:

(a) Direct measurements with moored instruments, e.g., current meters, capable of long-term (at least one year) records;

(b) The use of continuous vertical profiling instruments and bottom-mounted instruments capable of measuring average properties of the flow (pressure gauges, electromagnetic field recorders, and acoustic sounders); and

(c) Lagrangian studies with drogues and middepth floats to determine the path and, together with surface measurements, to establish unambiguous tracers for the ACC. A pilot experiment is recommended, to be carried out in collaboration with FGGE planning.

2. We *recommend* a feasibility study on the measurement of absolute dynamic topography on an east–west section from the South Sandwich Trench to the western end of the Drake Passage.

3. We *recommend* that the development of remote-sensing techniques, e.g., satellite measurements, and instrument deployment by aircraft be strongly encouraged.

4. We *recommend* the encouragement of realistic theoretical and laboratory models of joint theoretical–observational experiments on the Antarctic Circumpolar Current.

II. INTRODUCTION

Although it is the major current system of the world, the ACC is one of the least known. It appears to be broader (sometimes showing a biaxial nature) and is longer than any other temperate current; its transport is primarily zonal. The vertical shear is less than in other currents, and there appear to be both strong barotropic and baroclinic contributions to the transport. It is closely associated with the Polar Front Zone, yet the actual dynamical interaction is not understood. The associated meridional (cross-stream) fluxes may play a crucial role in determining the budgets of heat, salt, and dissolved oxygen in the world ocean.

The immediate scientific goal is to establish the space and time scales for a kinematic description of the flow as a base for dynamical studies. The ultimate scientific goal is to understand the dynamical role of this region in the general oceanic and atmospheric circulation. Achievement of the first goal is still remote; even the dynamics of such well-studied currents as the Gulf Stream are elusive. The final practical goal will be the establishment of a monitoring network in the current as part of a global environmental prediction program.

III. BRIEF HISTORY

The early results, primarily based on hydrographic data [Sverdrup *et al.*, 1942], suggest that the current is broad, has a transport equal to that of other major currents (at least 100×10^6 m^3/s), and extends to the bottom, where it is deflected by at least five different ridge systems as it flows around the Antarctic continent.

A chart of sea-surface topography prepared from available historical data by Gordon and Bye [1972] is shown in Figure 3.1. The width and intensity of this averaged current was found to vary greatly; constrictions occur south of New Zealand, at the Drake Passage, and near 145° W; the flow is relatively diffuse over the southeast and southwest Pacific basins. Wavelike patterns suggestive of the nonlinear, time-dependent dynamics seen in other currents at temperate latitudes appear to the lee of New Zealand and at 145° W. (From other data, an apparent strong interaction with the bottom was observed by Gordon [1971, 1972] near the Macquarie Ridge, where a large loop is formed by the current.) The variations in the sea-surface slope across the Drake Passage were found to be nearly the same as the maximum variation of 38 cm observed by McKee [1971] using monthly mean-sea-level records at the opposing coastlines (Punta Arenas and the Argentine Islands).

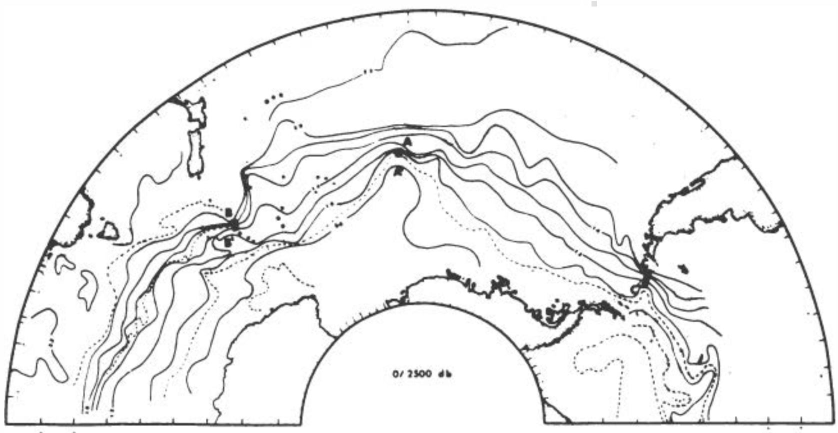


FIGURE 3.1 Sea-surface dynamic-height anomaly relative to the 2500-dbar level. The depths less than 3000 m are stippled. There are approximately 1000 data points from which the dynamic height isobaths are constructed. These data are spread smoothly over the entire region shown and have denser spacing in the Drake Passage–Scotia Sea region and lesser density between 170° W and 170° E north of 60° S. The few data points available east of the Campbell Plateau are shown to indicate the marginal control of the dynamic isobaths in that vicinity. [A. L. Gordon and J. A. T. Bye, *J. Geophys. Res. 77,* 5994, 1972. Copyright by American Geophysical Union.]

We note that a 38-cm difference would drive a barotropic current of transport 20×10^6 m^3/s here. Thus, long-term transport changes of almost a factor of 2 are suggested.

A number of recent attempts to measure the transport have combined direct current measurements with hydrography. Reid and Nowlin [1971] found from a section across the Drake Passage that the relative pressure field was consistent with earlier measurements of the Soviet research ship *Ob* and British RRS *Discovery* and concluded that when the data are treated in the same way, three various sets of historical data (two from the *Discovery*, one from the *Ob*) and their own show remarkably similar results: a geostrophic transport relative to the bottom varying from 90 to 110×10^6 m^3/s. They found a transport relative to the greatest depths sampled to be 110×10^6 m^3/s. Their absolute transport, based on bottom-current-meter records of 24 to 125 hours' duration was greater: 240×10^6 m^3/s. One year later, Callahan [1971] used hydrographic stations and bottom-current meters along a section from Australia to Antarctica (132° E). He found an absolute transport of 230×10^6 m^3/s, based on current-meter records of 25 to 50 h. In addition, Callahan's hydrography revealed narrow horizontal scales in the relative current: at 51° S the eastward flow was divided by a narrow slow countercurrent to the west, over the Indian–Antarctic Ridge. This feature also appeared at 115° E and 140° E. Figure 3.2 shows his 132° E section.

A remarkable result was obtained by Foster [1972] from hydrography and four vertical arrays of current meters across the Drake Passage in February 1970. In agreement with previous results, he found a net eastward geostrophic transport of 72 × 10^6 m^3/s relative to the 3000-dbar level. However, a relative transport estimate based on variable reference level yielded a value of 5 × 10^6 m^3/s to the *west*, and the absolute transport obtained from the overall current-meter mean (10 days) was 15 × 10^6 m^3/s to the west. Although near-zero transports have been inferred by Ostapoff [1960, 1961] by the variable-reference-level technique, this is the first estimate based on direct measurements of a significant westerly transport through the Drake Passage.

On the basis of these observations, it is clear that the fundamental vorticity balance of the current involves contributions from several terms: wind stress, bottom topography, curvature, and time dependence.

A number of theoretical studies, both analytical and numerical, have been made on the dynamics of the current and its interaction with the general abyssal circulation. Sverdrup *et al.* [1942] noted that the current was

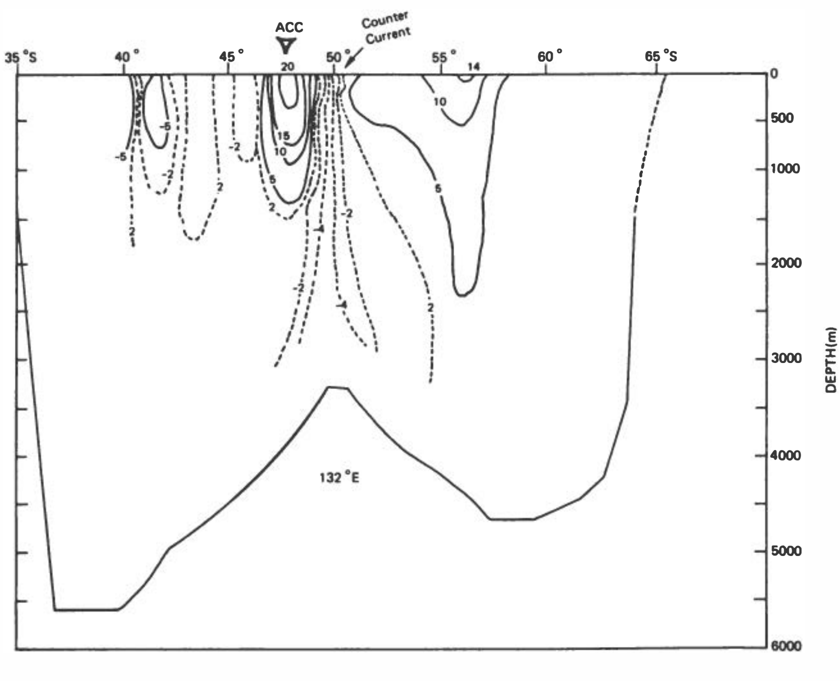


FIGURE 3.2 Zonal component of absolute velocity (in centimeters/second, positive east) at 132° E. Vertical exaggeration is 500 [J. E. Callahan, *J. Geophys. Res. 76,* 5860, 1971. Copyright by American Geophysical Union.]

deflected by the bottom ridge systems in a direction consistent with Ekman theory and inferred that the current must penetrate to the bottom. They also suggested that lateral friction balanced the wind stress.

After the qualitative success of linear β-plane analysis in explaining the major features of tropical and midlatitude ocean circulation, Munk and Palmén [1951] inquired into the vorticity balance of the ACC. They discovered that the eastward current that would be produced by the observed surface wind stress is much stronger than observed, unless an unrealistically high value is assigned to frictional dissipation. They suggested that the retarding pressure of submarine ridges balances the stress exerted by the surface wind and that the easterly relative flow is caused by deep water in the Antarctic Ocean drifting toward the axis of the rotating earth. Later, Stommel [1951] suggested that since nowhere in the Antarctic Ocean is there a continuous latitude with a depth greater than 1000 m, zonal theories of the current must be modified to take account of possible zonal pressure gradients. He assumed that all dissipation takes place in the Drake Passage region and found that the ACC could be qualitatively explained as a wind-driven current regime. Kamenkovich [1962] and Schulman [1970] also demonstrated the strong effects of topography, and Devine [1972] showed the importance of baroclinicity to the path of the current in the Drake Passage. Gill [1968], following the work of Stommel, pointed out the possible importance of northward (turbulent) momentum flux in the vorticity balance.

The numerical model of Gill and Bryan [1971], a circulation driven by imposed wind stress and temperature distributions, showed the interesting result that the force due to pressure difference across the bottom topography of a model Drake Passage was in the same direction as the wind force and was larger. Observations show that the water on the Atlantic side of the Drake Passage is colder than that on the Pacific side; thus, this “driving” pressure gradient may be real. A knowledge of absolute dynamic topography on an east–west section from the South Sandwich Trench to the western end of the Drake Passage would be required for a calculation of this difference in the real ocean.

The ACC can be regarded as a baroclinic zonal jet and as such might be expected to show baroclinic waves, which could result in large meanders. However, Bowen and Stommel [1971] found from RRS *Discovery* stations between April 1938 and March 1939 that the position of the isotherms was notably steady. The deep flow in the region of 0 to 20° E did not move more than 160 km and perhaps moved much less. Thus, wave disturbances such as one might expect to find in a major zonal baroclinic current apparently do not exist, at least not in the relative flow.

The ACC interacts with other phenomena in the region. Crease [1964] has pointed out that existing ACC theories are too simple, i.e., the proper description of the dynamics of the flow must contain a description of the Antarctic Convergence. Sverdrup *et al.* [1942] noted that the isobaric surfaces change slope abruptly at the Convergence. Gordon [1968] has pointed out that the westward flow produced by water discharge around the continent (a mechanism proposed by Barcilon [1966]) may result in summer speed-up of the east wind drift, interior to the ACC. Conclusive evidence is not yet available. One study has deduced the transport of the ACC with a global model utilizing advection and diffusion in an idealized World Ocean Basin. The study reports a wide variation in ACC transport as a function of longitude, a conclusion that could be tested.

Most recently, Thompson [1971] noted that propagating Rossby waves carrying momentum up-gradient into the weak current will cause baroclinic currents to be sharper where deeper water lies on the left, and he has used this fact to explain qualitatively Callahan's observations that the ACC is sharpest on the steeper slope of the Indian–Antarctic Ridge. Thompson suggests that concentrated currents might also be found at the northern end of the Albatross Cordillera (170° W to 140° W at 60° S) and also at the northern flank of the Atlantic–Indian Ridge near 50° S from 5° W to 30° E.

In summary, the overall vorticity balance of the current is complex, involving contributions from several forms. Estimates of total transport vary widely, although according to Gordon [1967] relative geostrophic transports seem to vary little in the Drake Passage where repeated observations have been made. Wind-driven theories of transport yield plausible values. Linear theory, as in the case of other ocean currents, reveals some of the main qualitative features but does not adequately account for time-dependence and effects of bottom topography.

Nonlinear effects, including curvature and the coupling of wind and thermal driving, have not been adequately investigated. The interaction between the current and other observed features, e.g., the Polar Front, is still not clear; and the role of the region in the global oceanic and atmospheric circulation is yet to be determined.

IV. RECOMMENDED PROGRAM

We recommend *the initiation of planning for a measurement program, emphasizing presently available techniques, to study the kinematics and dynamics of this region. The program can be divided into two parts: a program of specific experiments designed to explore features, test balances, and* *energy sources and a continuous effort to monitor the important vector and scalar fields in the regions of the current.*

The first step is to establish firmly the time and space scales of the motion and the driving fluxes. Although we have a rudimentary idea of the spatial structure of the current in some regions, its time-dependence is practically unknown. The dynamics may be distinctly different within different regions and time periods. Therefore, monitoring programs and special experiments must be designed to cover this diversity of dynamic characteristics. For example, the dynamical effect of bottom topography is complex, and the driving fluxes vary strongly with season. Experiments must be designed to yield accurate estimates of the various terms in the conservation equations if adequate theoretical models are to be devised.

A series of recommendations for the elements of a possible set of dynamics experiments is presented below. These recommendations involve techniques that are being increasingly applied to other parts of the world ocean. If we are to extend our knowledge of antarctic oceanography, we must apply these techniques in the Southern Ocean now.

A. ELEMENTS OF A LONG-TERM MONITORING PROGRAM

1. Flow Tracking and Surface Indicators

The technology exists for the satellite tracking of surface and subsurface drogues. Such measurements have been of particular importance in local vorticity studies in the Gulf Stream and the Kuroshio Current. The flow patterns thus measured in conjunction with other properties of the current can reveal the relative importance of the bottom topography, time-dependence, curvature, and planetary–vorticity terms in the vorticity-conservation equation. Deep drogues will be important in these studies, as will bottom-moored current-meter arrays. However, the Lagrangian studies themselves are important because they give a picture of the near-surface flow, which is unobtainable any other way. Moreover, they could provide useful atmospheric and sea-surface data for meteorology, e.g., the FGGE. If such surface-drifting buoys can be made to withstand the severe seas and winds of the region, they could be used for such tracking in the ACC.

One of the outgrowths of these studies should be the establishment of surface indicators for the current. For the Gulf Stream, the position of the 15 °C isotherm at 200 m has proved a reliable indicator for tracking meanders and eddies. The indicator for the ACC could be a sharp surface-temperature gradient, the position of the 1 °C isotherm at 2000 m, a visible change in surface chemistry, or some other feature. *We note that Lagrangian studies* *with drogues and middepth floats could be used to determine the path and, together with surface measurements, to establish unambiguous tracers for the* ACC *and* recommend *that a pilot experiment be attempted when the technology is adequate. Such an experiment should be carried out in collaboration with* FGGE *planning.*

2 Cross Sections, Profiles, and Time Series

We have pointed out that the data on relative geostrophic transport through the Drake Passage are remarkably similar (or can be made to be so by using consistent reference levels) but that the data do not agree when referred to available direct current-meter measurements. One step is clear: more closely spaced and longer time series of current meter and other direct measurements of current profiles are needed. Moreover, each of the geographical regions that have different dynamics must be studied.

We *recommend* that direct measurements of current and temperature initially be made in the current with moored arrays of a few instruments capable of at least four-month and preferably one-year records. The choice between a linear and a two-dimensional array is to be determined by experience with moored arrays in other strong currents, e.g., the Gulf Stream. Later, more elaborate arrays could be supplemented by continuous vertical profiling instruments and bottom-mounted instruments (e.g., pressure gauges, electromagnetic-field recorders, and acoustic sounders capable of monitoring average properties of the flow). Four distinct dynamic areas suggested for study are listed, and a schematic diagram of possible instrument deployment (for the Drake Passage) is shown in Figure 3.3. This general arrangement could be used in any of the regions discussed below. For logistic ease, the first of each of these studies should be carried out, or begun and finished, during austral summers. To keep the experimental activity within reasonable bounds, the different regions should be attempted in sequence.

Drake Passage–A Constraining Narrows To extend the time series of previous records, first consideration should be given to long-term measurements with a few instruments. Later, a more elaborate array including five strings of current meters might be distributed as pictured in Figure 3.3 with one at the convergence near the most rapid flow. Bottom-current meters should be placed close to South America in order not to miss any deep flow. Bottom-pressure gauges up either side of the passage as pictured would allow the measurement of the time-dependent behavior of several isobars and thus permit a vertical resolution of the directly measured pressure field.

Flat Basin "Flat" here means that topographic effects on local vorticity are minimized. A possible region is the Southeast Pacific Basin, along

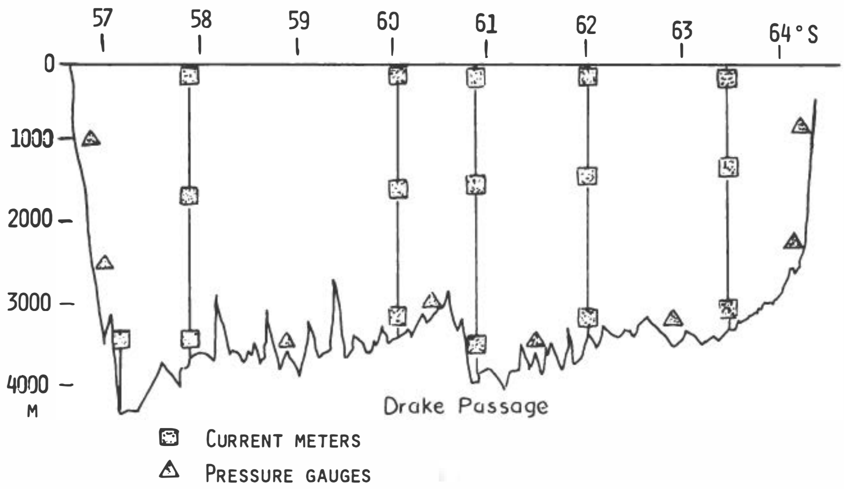


FIGURE 3.3 Recommended eventual arrangement of instruments across the Drake Passage; the first long-term moorings would involve fewer instruments.

100° W. A cross section of velocity profiles would be required before the moorings are set out in order to determine the spatial separation of the moorings. The density field should be monitored as often as possible across the section.

East–West Ridge (e.g., Indian–Antarctic Ridge at 132° E) Here the bottom is parallel to the flow, and the vorticity balance probably is different. Indeed, the measurements of Callahan [1971] show a westerly countercurrent along the ridge, and the work of Thompson [1971] emphasizes the importance of time-dependent flow there.

North–South Ridge (e.g., the Macquarie Ridge of the Campbell Plateau at 140° W) In this region, the current crosses a north–south ridge and then appears to undergo a series of meanders. The flow path exhibits meanders that are superficially similar to those observed in the Gulf Stream or Kuroshio and would best be studied by the combination of techniques used in those areas. Accurate studies of meanders and local vorticity balance require both bottom current-meter arrays and path tracking by ship or airplane. To monitor the transport adequately, a two-dimensional array of moorings would be required.

B. A SPECIFIC EXPERIMENT

The determination of the magnitude and sign of the downstream pressure gradient across any of the many ridges that the current passes over would be an important step in determining the role of these submarine ridges in either driving or opposing the ACC. In view of its importance in resolving the question of pressure gradients across the submarine ridges in the ACC, *we* recommend *a feasibility study on the measurement of absolute dynamic topography on an east–west section from the South Sandwich Trench to the western end of Drake Passage.*

C. THE POLAR FRONT AND THE ANTARCTIC CIRCUMPOLAR CURRENT

The relation of the ACC and surface-temperature gradients as tracers was discussed briefly earlier. The relation of the ACC to the Polar Front Zone is a more difficult problem to solve. This zone, where a fluid mass with polar characteristics abuts one with subpolar properties, is variable and complex. Some data in this area show a convergence process, some a divergence. Still other data show so complicated a structure that no simple circulation model is obvious. The mechanism responsible for the formation of the zone and its interaction with the ACC and other dynamical processes in the Antarctic Ocean are not understood.

An adequate study of the zone and its interaction with the ACC would require a detailed plan. *We* recommend *that such a plan be developed utilizing the data available from other experiments and then carried out, if logistically feasible.*

The ACC affects the general oceanic circulation through the flow of mass and momentum into or from the antarctic region. This cross-stream transport is basic to our understanding of the larger role of the ACC. We note that, wherever possible, data sections along east–west lines should be encouraged. Knowledge of cross-stream momentum flux could shed some light on the vorticity balance. For example, Gill [1968] has pointed out that an alternative to lateral friction in the vorticity balance is a northward momentum flux. To obtain a balance, mean values of the flux $\overline{\rho uv}$ of about 100 dyne/cm^2 are required. Assuming that the principal part of $\overline{uv}$ is due to the fluctuations of u and v about their mean values, the magnitude of the fluctuations would need to be at least 10 cm/s, that is, of the same order as the mean velocity. A time series of current-meter records from an array is one way of (crudely) estimating this momentum flux.

3. We *recommend* the development of realistic theoretical and laboratory models of Antarctic Bottom Water formation.

Eddy transports can be found in principle by monitoring temperature and salinity simultaneously with velocity and then estimating the divergence of the fluxes $\overline{v'T'}$ and $\overline{v'S'}$. The present techniques are not accurate enough for this measurement. As the techniques improve, they should be attempted in sections in the current.

D. DEVELOPMENT OF NEW TECHNOLOGY

The Working Group notes that in most instances it will not be necessary to develop new technology, i.e., sensors and data-acquisition systems and their associated moorings for the Antarctic. Aside from the straightforward extension of sensor ranges and necessary strengthening against ice and heavy weather, the development of sensors carried on in other oceans by other programs appears to be adequate.

TABLE 3.1

RECOMMENDED PROGRAM STRUCTURE
Dynamics of the Circumpolar Current
Experiments and Goals

Proposed Experiments and Theory	Specific Goals
Monitoring Experiments	
* Long-term Eulerian variability from moored current and temperature measurements	Understand space-time variability for determination of eddy fluxes of energy, heat and momentum.
* Transport variability in Drake Passage from integrating techniques	Use unique geography of enclosed flow to establish response and index to large-scale atmospheric forcing of ocean currents.
* Surface flow paths from drifting buoys	Synoptic view for direct gross estimates of energy budgets.
* Surface temperature and properties from remote sensing	
Technique Development	
* Aircraft deployment of deep moorings	Substantial reduction of logistics costs for long-term measurements.
Theory	
* Review of existing theory against background of survey data	Feedback to experimental design.
* Application of non-linear time-dependent jet dynamics to ACC	Rationalize existing and incoming data with basic conservation laws.
* Laboratory models of specific ACC dynamical processes	Assist analytical and numerical models in detailed study of specific processes.

However, it is important to encourage the development of technology that promises to reduce logistics costs. A maximum use of satellite data would be a good example of time saving. The deployment of instrumentation by aircraft rather than ships also promises to be highly cost-effective. Therefore, we recommend *that the development of remote sensing techniques,* e.g., *satellite measurements, and instrument deployment by aircraft be strongly encouraged.*

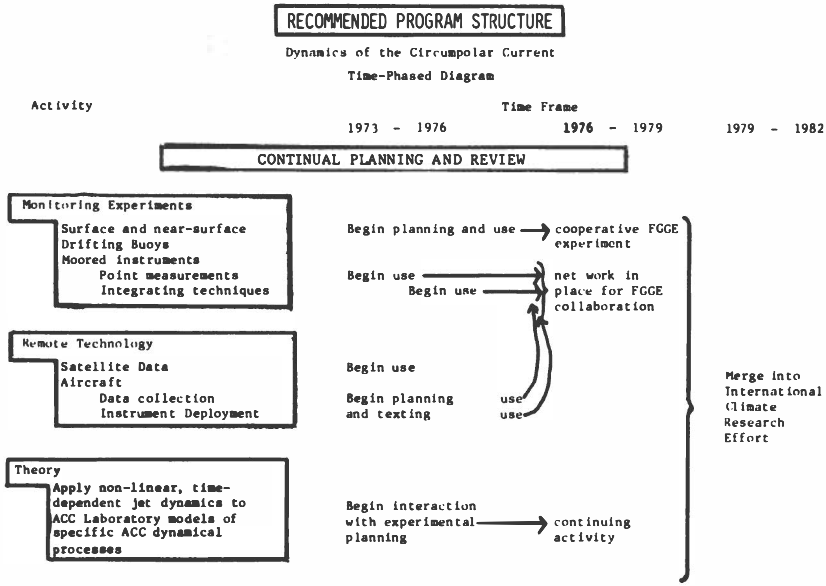
E. REALISTIC THEORETICAL MODELS

The success of local vorticity studies on western boundary currents and the similarity of ACC paths to Gulf Stream and Kuroshio paths suggests that a similar approach could be applied with success to the ACC. *We* recommend *the encouragement of construction of realistic theoretical and laboratory models of the ACC and joint theoretical-observational experiments on the ACC.*

F. SUMMARY OF RECOMMENDED PROGRAM

Tables 3.1 and 3.2 summarize the experiments and goals and show how the recommended program would fit into a ten-year time scale.

TABLE 3.2



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4

Antarctic Bottom Water Formation

I. PRINCIPAL RECOMMENDATIONS

1. We *recommend* the initiation of planning for a program of direct observations of various processes for simultaneous test of several hypotheses on the formation of Antarctic Bottom Water in the Weddell Sea. The elements of the initial program should include:

(a) A study of the distribution and variation of the ice cover in the Weddell Sea;

(b) A study of the hydrography of the Weddell Sea—we note that because of the technological problems imposed by the heavy ice cover, considerable planning and preliminary field work will be required for comprehensive observations;

(c) A study of the currents in the Weddell Sea in conjunction with the hydrographic work;

(d) Studies of the bottom topography of the Weddell Sea, to be carried out in conjunction with the hydrographic work—all ships traversing the Weddell Sea area should be outfitted with accurate positioning and depth-sounding equipment;

(e) An effort to obtain measurements from a nuclear submarine under the ice and the strong support of development of automatic data systems and mobile surface-effect-type laboratories for use in the Antarctic.

2. We *recommend* the continuation and completion, in order to identify other bottom-water-formation areas, of the unfinished circumpolar hydrographic survey carried out by the USNS *Eltanin* through 1972. Emphasis should be placed on coverage of areas not already studied (e.g., continental margins), and atlases of the data should be compiled. Summer icebreaker studies in any continental margin areas, e.g., Weddell Sea, Ross Sea, or Adelie coast, and efforts to gain any winter data anywhere on hydrography, chemistry, meteorology, and ice cover should be supported.

3. We *recommend* the development of realistic theoretical and laboratory models of Antarctic Bottom Water formation.

II. INTRODUCTION

Water-mass analysis shows that the bottom water over a large portion of the world ocean has its origin in the waters surrounding Antarctica. The mechanism of formation of this Antarctic Bottom Water (AABW) has been discussed for many years and is one of the chief unsolved problems of antarctic oceanography. The principal questions are the following: What physical mechanisms produce Antarctic Bottom Water? Where are the potential formation areas? How much is formed? When does the formation occur? What is the interaction of the bottom water with other phenomena in the Southern Ocean?

III. BRIEF HISTORY

The formation of cold, high-salinity water by the freezing of ice at the surface in the winter was first suggested by Brennecke [1921] and Mosby [1934]. They noted that the resultant cold surface water, whose salinity has been increased, could mix with the deeper, warmer, and saltier water at the edge of the Continental Shelf and sink to the bottom. Later analysis of water masses in the Southern Ocean [Deacon, 1937; Wüst, 1938] suggested that the major portion of the AABW forms in the Weddell Sea. The absolute rate at which the bottom water is formed has not been determined directly, but estimates of the mean annual production range from 10×10^6 to 50×10^6 m^3/s, with the lower values [Stommel and Arons, 1960] being more generally accepted but not directly tested. More recent studies have supported the lower estimates [Gill, 1973; Mosby, in press; Warren, 1971; Warren and Voorhis, 1970; Wright, 1970]. The most recent evidence also shows that the Weddell Sea is not the sole source of AABW and that not all bottom water has the same characteristics as the Weddell Sea variety. For example, Jacobs *et al*. [1970] and Gordon [1971a, 1971b] have discovered saltier bottom water that probably comes from the Ross Sea, and Gordon and Tchernia [1972] show a third source of AABW near the Adelie coast. The "Adelie" water has exactly the same characteristics as the Weddell Sea bottom water. Moreover, Gordon [in press] showed that shelf water at the freezing point with salinity sufficiently high to form AABW also occurs in the regions of the Shackleton and Amery ice shelves. However, the Weddell Sea appears to be the major source of AABW, and much of this water enters the rest of the World Ocean, where it has strong influence on the temperature and density of abyssal waters and on sedimentary processes.

A number of physical processes that may play a role in the formation of bottom water have been proposed. Fofonoff [1956] suggested that the characteristics of the deep water may be determined primarily by the equation of state of seawater, just as the temperature distribution of deep water in lakes is determined primarily by the physical properties of water rather than the energy exchanges across the surface of the lake. He made use of the fact that when two water types of different temperatures and salinities are mixed together, the increase in density brought about by the small decrease in volume yields a mixture that is denser than either type. The mixture therefore sinks. He suggested that AABW is such a mixture of warm deep water and water from the Continental Shelf. He noted that since unmixed shelf water has not been observed at great depths, bottom water is formed principally in shallow water. Formation of bottom water may also occur when the coastal-current water is cooled as it flows along and beneath the vast ice shelves in the southern Weddell Sea [Seabrooke *et al.*, 1971]. This cooled coastal-current water would then mix with warm deep water to form AABW. However, this process appears to require the loss of more heat than can be conducted through the ice [Foster, 1972; Gill, 1973]. Gordon [1971a] has suggested that the cold shelf ice may play a role in allowing the shelf water to attain sufficient density for bottom-water formation. In this way, the shelf ice influences the shelf water produced by sea ice.

A double-diffusive mechanism (salt-fingering) has been proposed as still another physical process for formation of AABW [Gill and Turner, 1969]. This process can occur in a fluid whose density variations result from the distribution of two components with different molecular diffusivities. The motion is driven by drawing on the potential energy in the field of the component with a destabilizing gradient. The mechanism can be active when the surface water is considerably less dense than the deeper water, can be driven by melting of surface ice, and can operate in the summer. Gill and Turner suggest a current down the slope, carrying colder, fresher water to the bottom, under the warmer saltier water. The existence of such a bottom current in the summer is a testable prediction of this thermohaline mechanism.

Although all of these mechanisms are plausible, none has been critically tested, and the most generally accepted remains the freezing of the sea surface, originally suggested by Brennecke and Mosby. Moreover, we note that although primary production of the cold saline shelf water may occur in winter, it is possible that escape of this water to the deep ocean may not be confined to the winter. Gill [1973] has shown how there can be a net brine release over the Continental Shelf area because the pack ice is continually being blown offshore, and he suggests that bottom water is produced throughout the year, since there is always a supply of dense water from the Continental Shelf. He notes that the western part of the Weddell Sea is particularly important in the production process.

IV. RECOMMENDED PROGRAM

A. GENERAL SURVEY DATA REQUIRED

Using data collected by various national programs up to 1960 and by the USNS *Eltanin* from 1962 to 1972, oceanographers have begun to formulate the questions previously mentioned. However, the survey data are insufficient for resolution of any of these questions, and the nature of a broad survey precludes detailed studies of local areas. Moreover, we still have no winter data on water properties in potential sinking regions because ships cannot penetrate the ice.

To extend the present survey data as efficiently as possible, we make the following three *general* recommendations for surveys of hydrography, bathymetry, chemistry, meteorology, and ice cover:

1. *To identify other bottom-water-formation areas, the hydrographic survey carried out by the* Eltanin *through 1972 should be continued and completed, with emphasis on coverage of areas not already studied (e.g., continental margins), and atlases of the data should be compiled.*
2. *Summer icebreaker studies in any continental margin areas–e.g., Weddell Sea, Ross Sea, or Adelie coast–should be supported.*
3. *Efforts to gain any winter data anywhere on hydrography, chemistry, meteorology, and ice cover should be supported.*

B. DATA REQUIRED FOR TEST OF HYPOTHESES

At the conclusion of the general survey work, it will be necessary to turn to the collection of data for tests of the specific hypotheses of AABW formation. We divide the general problem into two parts here: the formation of cold, high-salinity water in general; its mixing with and escape from the surrounding water masses.

A test of the idea that sea-ice formation leads to the formation of denser water will first require knowledge of the physical and chemical properties of the ice, the rates of its formation, and its movement due to wind. The geographic distribution and thickness of the ice must be determined. Second, the hydrographic properties of the water under the ice must be known, and the rate of formation of cold, high-salinity water must be monitored by measuring both the vertical and horizontal circulation of local waters.

The effect of freezing ice shelves on seawater density requires all these data, as well as the distribution of freezing and melting at the shelves.

Cooling of the surface due to katabatic flow of air down the cold slopes of the Antarctic continent can also form high-density surface water. Such effects have been directly observed off the coast of France in the Mediterranean during the mistral, where deep mixing occurs in selected regions down to a depth of 2100 m [Médoc Group, 1970]. An experiment similar to the one in the Mediterranean would be valuable for the study of AABW formation, but it would be more complex, because of the effect of ice at the surface. The distribution of polynyas and leads and the hydrographic properties of the water under the ice, as well as the rates of formation of the dense water and its horizontal and vertical circulation, must be monitored in regions of preferred cold air flow.

A number of direct measurements are required for tests of mixing and escape of AABW. To test the theories based on (a) mixing and sinking in proportion to production rate of dense shelf water, (b) mixing and sinking due to the nonlinear equation of state, and (c) mixing and sinking due to the salt-finger mechanism, we require detailed (microstructure) measurements of temperature, salinity, and chemistry and direct velocity (horizontal and vertical) measurements. Hypotheses that depend on change of outside constraints will, of course, require direct measurement of those constraints, e.g., possible interaction between the wind and the density field associated with deep geostrophic currents [Gordon and Tchernia, 1972; Killworth, 1973].

Finally, the question of the movement of the AABW away from the source regions must be considered. The question resolves into two parts: the movements and their dynamics; mixing with other water masses. We need to know the geographic distribution of currents and bottom-water characteristics (temperature, salinity, oxygen, silicate) and the transports and dynamics of these flows (geostrophic or nongeostrophic). The question of mixing will be attacked through physical and chemical measurements of microstructure and fluxes.

C. SPECIFIC PROGRAM FOR THE WEDDELL SEA

We recommend *a plan for simultaneous test in the Weddell Sea of several hypotheses on the formation of bottom water.*

Until the International Weddell Sea Oceanographic Expedition (IWSOE) of 1968, the oceanographic data in the Weddell Sea were largely confined to the outer edges, mainly in the northern and eastern parts, with the exception of the few stations obtained during the drift of the German ship *Deutschland* across the central part of the Weddell Sea in 1912. In the southern summer of 1968, the USCGC *Glacier* was able to penetrate the central and southwestern parts of the Weddell Sea and to obtain a number of hydrographic stations in these regions. The only winter hydrographic stations are still those obtained by the *Deutschland* in 1912, and, unfortunately, the winter data are probably the most important to the understanding of AABW formation.

To understand the formation of AABW as it occurs here, we need to know the heat and salt budgets, the location and intensity of the sinking of surface waters and the subsequent subsurface currents, and the type of mixing processes involved. Understanding the budgets requires in turn a knowledge of the air–ice–sea interactions at the surface of the ocean, of the temperature and salinity structure in the entire Weddell Sea, and of the incoming and outgoing currents. An understanding of air–ice–sea interactions in the Weddell Sea is extremely important, since in the presence of open leads and polynyas, heat exchange is greatly increased. Consequently, the rate of freezing in these areas may be several orders of magnitude greater than in areas where the ice is a meter or more thick. Thus we must also know how the distribution of ice cover changes in time throughout the Weddell Sea.

The hydrography of the Weddell Sea should be determined with a varying spatial resolution. Since the geostrophic constraint causes any subsurface flow of AABW to move largely around the Weddell Sea parallel to the contours, hydrographic sections would be most strategically located normally to the general bottom contours. An idealized plan for the location of hydrographic stations is seen in Figure 4.1. The region in the vicinity of the shelf break, approximately the 600-m contour, is of special interest, as it is here that the warmer deeper water may mix with the shelf water. The summer measurements by the *Glacier* showed that there was a frontal structure here, but the stations were spaced too far apart to resolve the details. It is also important that measurements of the temperature and salinity microstructure of the top 200–300 m be made over the deeper parts of the Weddell Sea, as this is the region in which surface water mixes with the warmer deeper water. All these measurements are needed in both summer and winter and ideally would be carried out at about 3-month intervals. Existing winter data furnish only a rough indication of what may take place during the freezing season.

Relative values of the transport of water in the Weddell Sea can be calculated from hydrographic data using the geostrophic equations, but absolute values can be obtained only from current measurements over a long enough period. A successful strategy might be to combine hydrographic stations with measurements of the bottom currents, especially those into the Weddell Sea in the east between about 25° W and 30° W, and the subsurface currents along the Continental Shelf. Bottom-current measurements and hydrographic data at selected stations in the hydrographic plan of Figure 4.1 would provide these data; such measurements ideally should be made over periods long enough to allow short-time effects to be filtered out.

The bathymetry of the entire Weddell Sea area, especially the western

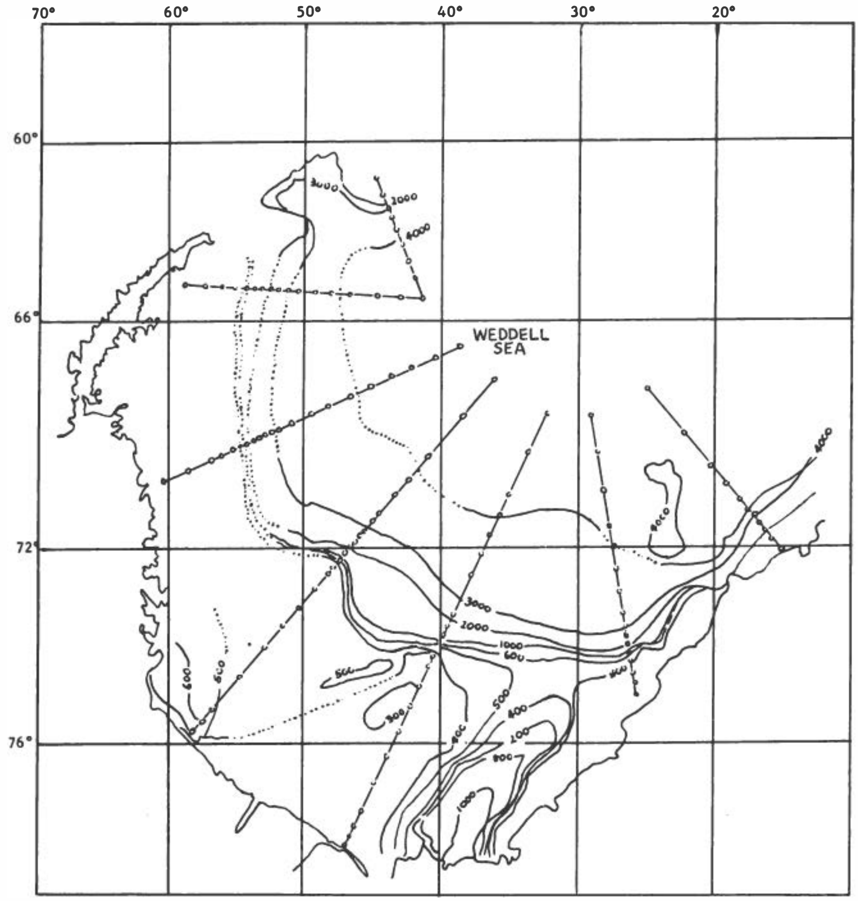


FIGURE 4.1 Idealized plan for a hydrographic survey in the Weddell Sea.

and southwestern shelves, needs to be known in much greater detail. The bottom topography of the Continental Shelf is of particular interest, since the flow of water along the shelf may be partially controlled by the configuration of the bottom contours. Of perhaps even greater importance is the bottom typography of the Continental Slope, since the flow of AABW or its precursor could take place largely along the slope, and the presence of large canyons on the slope could lead to a concentration of flow in density currents down these canyons.

Our recommendations for a field program in the Weddell Sea are the following:

Ice Cover. We recommend *that a program to study the distribution* *and variation of the ice cover in the Weddell Sea be initiated as soon as possible.* The first step would be the study of all the pertinent satellite photographs. Visual observations are not practical for complete year-round coverage, since the southern part of the Weddell Sea is dark in winter, and the entire region is commonly covered with clouds. We do not know whether the winter ice cover is broken by leads that are too small to be resolved by satellites; therefore, we suggest a program of remote sensing of the ice cover by aircraft. Both side-looking radar and passive microwave radiometers have the advantage of being all-weather instruments and thus may be ideal for antarctic work. We suggest regular monthly flights over the Weddell Sea. At present, it is possible to fly C-130-type aircraft from Ushuaia, Argentina, down the western part of the Weddell Sea across the southeastern part and back over the central part. If refueling were possible at a base on the Antarctic Peninsula, the coverage could be increased.

The net transport of ice from the Weddell Sea shelf region should also be monitored to allow the calculation of the net amount of salt release during bottom-water formation. This monitoring could be done by satellite coverage.

Hydrography. We recommend *that a program to study the hydrography of the Weddell Sea be initiated as soon as possible, noting that because of the technological problems imposed by the heavy ice cover, considerable planning and preliminary field work will be required for comprehensive observations.* In addition, the results of the ice cover program may have a considerable effect on the plans for the hydrographic work. At present, the most effective hydrographic program would be one that made use of a nuclear submarine. STD's are already available for use from submerged nuclear submarines, and it would be possible to obtain a rapid survey of the temperature and salinity structure of the entire Weddell Sea at any time of the year. A somewhat less desirable method, which would probably provide only part of the needed data, is the use of present-day icebreakers. Even in the summer, it is not possible for icebreakers to penetrate the central and western parts of the Weddell Sea, except during unusual ice conditions like those encountered during the summer of 1968 by the *Glacier*. If it appears that a large polynya in the southeastern Weddell Sea remains open during the winter, it might be desirable to have an icebreaker in this area to study the air–ice–sea interactions under winter conditions.

Also technically feasible at present would be a manned station drifting across the Weddell Sea during the winter, as did the *Deutschland* and the *Endurance*. The least demanding drifting station would be an icebreaker with a skeleton crew. Such an icebreaker would have some mobility to search for the regions of bottom formation, which might be quite small.

Unmanned automatic data buoys that are tracked and interrogated by satellites could provide winter hydrographic data. The successor to IRLS, the

TWERLE system, will probably be operational in 1974, but the development of suitable salinity sensors has yet to be accomplished. Helicopters operating from icebreakers or shore stations also might provide platforms for obtaining hydrographic data in ice-covered regions, but operations under winter conditions remain untried. Unmanned submersibles are being tested in the Arctic and could provide a means to extend hydrographic data under ice cover; however, at present their range is still short, less than 50 km. Finally, the development of a mobile surface-effect-type laboratory that could operate on both ice and water could produce the ideal platform for year-round work in the Weddell Sea. Unfortunately, surface-effect-type vehicles for operation on rough ice surfaces are still in the early stages of development, and it may be many years before they can be used safely in Antarctica. *We* recommend *that every effort be made to obtain measurements from a nuclear submarine under the ice and that the development of automatic data systems and mobile surface-effect-type laboratories for use in the Antarctic be strongly supported.*

Currents. We recommend *a program to study the currents in the Weddell Sea in conjunction with the hydrographic work.* At present, it would be possible to make current measurements from an icebreaker during the summer in the eastern Weddell Sea in the relatively ice-free region at about 20° W using bottom-current meters and hydrographic stations. It might also be possible to retrieve current meters left over the winter in this region. In the remainder of the Weddell Sea, the year-round close ice cover will probably prevent retrieval of current meters using conventional techniques. The development of acoustically interrogated bottom-current meters might provide a means of obtaining long records of currents without the necessity of retrieval. This method would be most feasible in the northwestern parts of the Weddell Sea, where helicopters from land stations on the Antarctic Peninsula could emplace and interrogate the instruments through holes in the ice. Some of the testing of current-metering devices could be carried out in the more accessible Ross Sea region.

Bathymetry. We recommend *that studies of the bottom topography of the Weddell Sea also be carried out in conjunction with the hydrographic work and that all ships traversing the Weddell Sea area be outfitted with accurate positioning and depth-sounding equipment.* Again, the most efficient means for determining bathymetry under ice cover would be a nuclear submarine. However, since the bathymetry does not change with the seasons, summertime penetrations by icebreakers could cover most of the Weddell Sea. The region just east of the Larsen Ice Shelf, which has so far been impenetrable, might require spot soundings through the ice by helicopters.

Related Studies. In addition to these four main programs concerned with studying AABW formation, some other related programs should be considered. As mentioned earlier, the general hydrographic study of the seas around Antarctica carried out by the *Eltanin* from 1962 to 1972 should be continued to determine the extent of AABW formation in regions other than the Weddell Sea. In addition, the work on the abyssal circulation to determine the transport of AABW northward away from Antarctica should be continued, with direct current measurements emphasized. Finally, if the studies of the oceanography under the Ross Ice Shelf that are planned in conjunction with the Ross Ice Shelf Drilling Project show that the ice shelf can modify the surrounding waters in a quantitatively important manner, then similar studies should be carried out under the Filchner Ice Shelf.

It is clear from property distributions that some bottom water is formed in the Ross Sea, although at a much lower rate than in the Weddell Sea. Summer and winter hydrographic stations on the Continental Slope there would give a better idea of the source of this water and might suggest how to deploy current meters to measure the formation rate directly. The work in the Weddell Sea is given first priority here.

D. DEVELOPMENT OF NEW TECHNOLOGY

The Working Group notes that the existing point measurements of water velocity and temperature are probably not adequate for long-term monitoring of the variability and amounts of bottom-water formation. Some kinds of averaging techniques, e.g., electromagnetic or acoustic, will probably be required and are being developed as part of other oceanographic experiments such as NORPAX and MODE. We do not feel that special development will be required for the Southern Ocean processes but wish to encourage the use of the new averaging techniques there as they become reliable enough for that environment.

E. THEORETICAL AND LABORATORY WORK

We *recommend* that the development of realistic theoretical and laboratory models of AABW formation be encouraged.

F. SUMMARY OF RECOMMENDED PROGRAM

Tables 4.1 and 4.2 summarize the experiments and goals and show how the recommended program would fit into a ten-year time scale.

TABLE 4.1

RECOMMENDED PROGRAM STRUCTURE

Antarctic Bottom Water Formation

Experiments and Goals

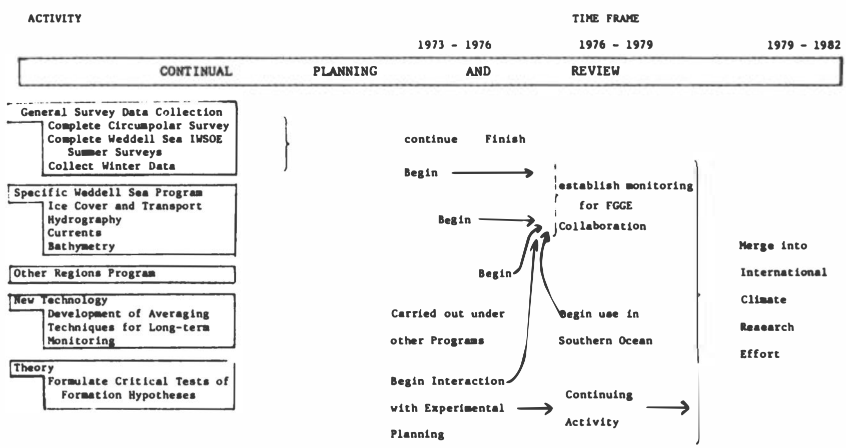
Proposed Experiments and Theory	Specific Goals
Survey	
* Complete Weddell Sea summer hydrography.	Collect data for model formulation and test of hypotheses.
* Collect winter data under ice pack.	Determine "climate" of Antarctic Bottom Water through knowledge of * Properties of water masses * Rate of renewal of deep circulation
Monitoring Experiments	
* Long-term variability of bottom velocity and temperature near continental margins.	Determine relation between water-mass formation and ocean-atmosphere exchanges for parameterization into global circulation models.
Theory	
* Formulate critical tests of Antarctic bottom water formation hypotheses.	

TABLE 4.2

RECOMMENDED PROGRAM STRUCTURE

Antarctic Bottom Water Formation

Time-Phased Diagram



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5

Exchange Processes and Overall Budgets

I. PRINCIPAL RECOMMENDATIONS

The Working Group, *noting* that determination of the budgets of heat, momentum, salt, and other materials is crucial to understanding the role of the Southern Ocean in global oceanic and atmospheric dynamics, and *further noting* that such determination will require measurements of the exchange processes by direct or indirect means in areas of strong interaction, e.g., frontal zones, makes the following recommendations:

1. We *recommend* the initiation of planning for a program of measurement of exchange processes in the Southern Ocean. Such planning should draw heavily on satellite observations and on the development of measurement techniques and understanding of exchange processes generated by other programs, e.g., NORPAX, CUEA, or JASIN, in other oceans.
2. We *recommend* that the initial elements of a measurement program include

(a) A detailed survey designed to yield the structure (thermal, haline, alkalinity, CO_2, and nutrient distribution) of the Polar Front and other frontal areas in various positions and at various times;

(b) Estimation of fluxes occurring within gyres and near continental margins to assess the interaction of Antarctic Surface Water south of the Antarctic Circumpolar Current with warmer, saltier deep water.

3. We *recommend* emphasis on the collection of data during the winter, especially below and within the sea-ice fields, noting that other seasonal data are also critical in refinement of budget studies in the continental margin and open ocean, and that hydrographic and meteorological measurements in the regions of glacial ice be made in conjunction with the various existing and proposed ice-shelf projects.
4. We *recommend* a continuing program for monitoring standard meteorological variables during all survey programs. This monitoring function

could eventually be performed by untended data stations and remote-sensing systems.

II. INTRODUCTION

In this chapter, we present a general discussion of exchange processes in the Southern Ocean and regions important to the overall budgets.

It is clear that understanding the role of the Southern Ocean in the global long-term atmospheric and oceanic climate will require certain monitoring of large-scale exchange processes. It is equally clear that the determination of the magnitude and variability of large-scale energy and property exchanges in any region of the world ocean requires a complex, expensive, and long-term effort.

In our recommendations, we have noted that careful and continual planning will be required so that an efficient program can be carried out with maximum use of results from other studies of exchange processes in other oceans. We have listed the initial elements of a possible program.

The divergent wind drift and intense thermohaline alterations of the surface waters around Antarctica set up a meridional circulation pattern that carries great quantities of heat, salt, and water from the northern abyssal waters into the Southern Ocean. This water upwells and is altered to cold antarctic water masses, which subsequently spread northward. The sea–air exchanges of heat, salt, and momentum and the exchange of properties between water masses in this region are vigorous, and they are only poorly understood. Of special global interest is the exchange of material across the sea–air interface, which couples the ocean with the atmosphere. The Antarctic is of particular significance because, through these waters, the abyssal waters of the world can interact directly with the atmosphere.

Based on current understanding of antarctic oceanography, we can outline the procedures that are needed for better definition of the budgets or balances of heat, salt, and mass. Areas of interaction between definable bodies of water whose boundaries are marked by relatively large gradients of temperature and/or salinity are fundamental; primary among these are the frontal zones, continental margins, the main pycnocline, and the large cyclonic gyres. Special attention must be placed on the thermohaline activity below melting, stable, and growing sea-ice covers and within the ice-free areas; the antarctic pack-ice field is characterized by both phenomena. The interaction of glacial ice with seawater is clearly of local importance and could be of large-scale importance. The key to all the budget studies is better determination of all the fluxes of heat, salt, and momentum and of the influence of various environmental parameters on these fluxes. Such determination is crucial to the understanding of the role of the Southern Ocean in global oceanic and atmospheric dynamics.

Therefore, we recommend *the initiation of planning for a program of measurement of exchange processes in the Southern Ocean.*

The Working Group notes that it is not feasible at this time to mount a special and large measurement program for this purpose. Extensive efforts are being made in other programs (e.g., NORPAX, JASIN, or CUEA) to determine reliable and accurate techniques for the monitoring of energy and property exchange. Additionally, satellite data from the region have not yet been fully utilized for such studies. To conserve resources, *we* recommend *that planning for a program of measurement of exchange processes in the Southern Ocean draw heavily on satellite observations and on the development of measurement techniques and understanding generated by other programs in other oceans.* In this way, studies in the Southern Ocean can proceed concurrently with studies in other oceans without a requirement for special development.

The initial elements of a measurement program must be descriptive: the determination of the magnitude and variability of heat, salt, momentum, and other exchanges. Later elements will include use of the data to elucidate the actual transfer mechanisms accomplishing the fluxes.

III. BRIEF OVERVIEW

A. MERIDIONAL CIRCULATION AND AIR–SEA INTERACTION

The thermohaline interaction of the sea with ice and the atmosphere, coupled with the relatively low stability of the surface water, produces deep-reaching convection in a number of zones in the Southern Ocean. Major regions of sinking occur at the continental margins and frontal zones in the deep ocean. The deepest convection occurs in the production of Antarctic Bottom Water (AABW); at the Polar Front Zone, convection extends to about 1 km in production of Antarctic Intermediate Water (AAIW). Figure 5.1 shows a schematic representation of water mass interaction in the Southern Ocean [Gordon, 1971c].

The southward-migrating and upwelling Circumpolar Deep Water (CDW) tends to compensate for the sinking northward-migrating antarctic water mass. The CDW carries toward the sea surface the heat and salt needed to balance sea–air exchange, and it recycles nutrients to maintain the antarctic surface water as a fertile area for plankton blooms.

The antarctic convection pattern extends by lateral migration below the main thermocline of the world ocean. The northward flow of AABW occurs mainly in deep western boundary flows, and the AAIW represents a layer separating the thermocline waters from the abyssal waters. The AAIW migrates slowly northward in a nearly sheetlike pattern into the South Pacific and Atlantic [Mosby, 1934].

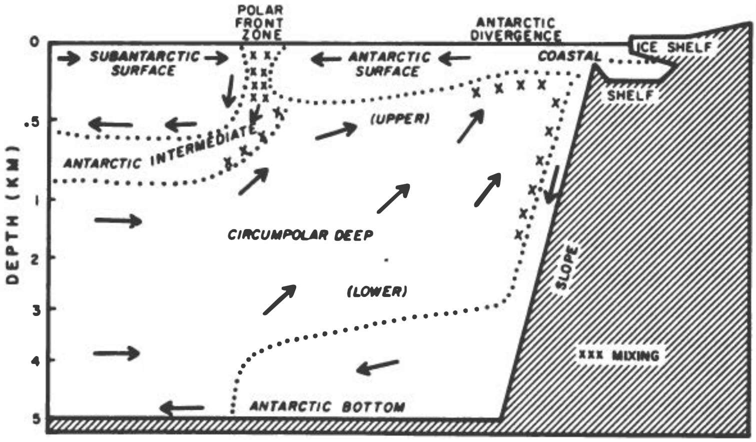

FIGURE 5.1 Water mass distribution on a north–south plane with inferred flow pattern. [A. Gordon, AAAS Pub. No. 93, p. 612. Copyright 1971 by the American Association for the Advancement of Science.]

The water composing the two antarctic water masses eventually flows back to the south in each ocean, with important additions of relatively salty but warmer water from the North Atlantic Ocean. The North Atlantic Deep Water (NADW) warms the abyssal waters, since it is warmer than the average abyssal water temperature. This flow of NADW, lower in oxygen but higher in nutrients as a result of oxidation of organic material below the thermocline, is incorporated into the CDW and eventually upwells to begin the process again. The NADW is of special importance in adding salt and heat to abyssal water and to the Southern Ocean.

The overturning of abyssal waters in the Southern Ocean thus maintains the abyssal layer as an oxygen-rich, cold environment and provides a "breathing" or recycling mechanism for the abyssal waters.

B. APPROXIMATE BUDGETS

Unambiguous direct measurement of the transfers of ocean properties due to meridional circulation is not now possible, because the flux per unit area is too small. For example, the approximate magnitude of the meridional volume flux of deep water, $50 \times 10^6\ m^3/s$, yields an average meridional velocity of 1 cm/s over the deeper half of the Southern Ocean, a value that is at the limit of present direct current measurements. Local variations in space and time may be large enough to measure directly, but the mean fluxes and residence times of water or materials must at present be estimated by a combination of direct and indirect methods.

1. Heat Budget of the Abyssal Water

The heat extracted annually by the atmosphere must be balanced by a southward and upward flux of heat within the water column. The heat transfer from sea to air (estimated from the 1966 USSR *Antarctic Atlas*) is about 10^{14} cal/s for the ocean south of the southernmost extremity of the Polar Front Zone. The heat loss is balanced by the production of cold AABW. It is possible to estimate, from flux arguments, the production rate of AABW. Assuming that the average potential temperature of the abyssal waters (defined as those below the intermediate water masses) of the World Ocean is 1.7 °C; that heat is added by the introduction of warmer water, geothermal heating, and downward diffusion of heat across the thermocline; and that all heat is removed by sea-air losses in the antarctic region, Gordon [1973] finds that the thermal balance for all abyssal waters suggests a production rate of AABW of 38×10^6 m^3/s.

2. Salt Budget of Antarctic Surface Water

The net annual input of fresh surface water, derived from the excess of precipitation over evaporation and continental runoff, must be balanced by an upwelling of salty water to maintain the mean salinity. Superimposed on the annual values is the strong seasonal influence of the waxing and waning of sea ice.

A summer salt balance study [Gordon, 1971b] of the upper 100 m of water from the Antarctic Continental Shelf to the southern extremes of the Polar Front Zone (roughly an area of 20×10^6 km^2) indicates that a seasonal surface salinity variation of 0.1‰ requires upwelling of approximately 60×10^6 m^3/s [Gordon, 1971c], in rough agreement with the mean Ekman divergence for this region. An annual average upwelling of 60×10^6 m^3/s would transfer 14–19 kcal cm^{-2} yr^{-1} into the surface water. This agrees with the estimated annual average of 15 kcal cm^{-2} yr^{-1} heat exchange across the sea–air interface.

In the winter, the salt budget is more complicated, because salt is removed from the surface water during production of AABW. By assuming that the 60×10^6 m^3/s of deep-water upwelling continues at this rate all year, that the low-salinity water lost at the Polar Front removes excess surface water but not salt from the surface layer, and that the average salinity of the sinking cold saline shelf water is 34.65‰, it is possible to construct an annual salt balance of the surface water [Gordon and Taylor, 1973]. The estimates from the salt balance yield the loss rate from the upper 100 m. It is

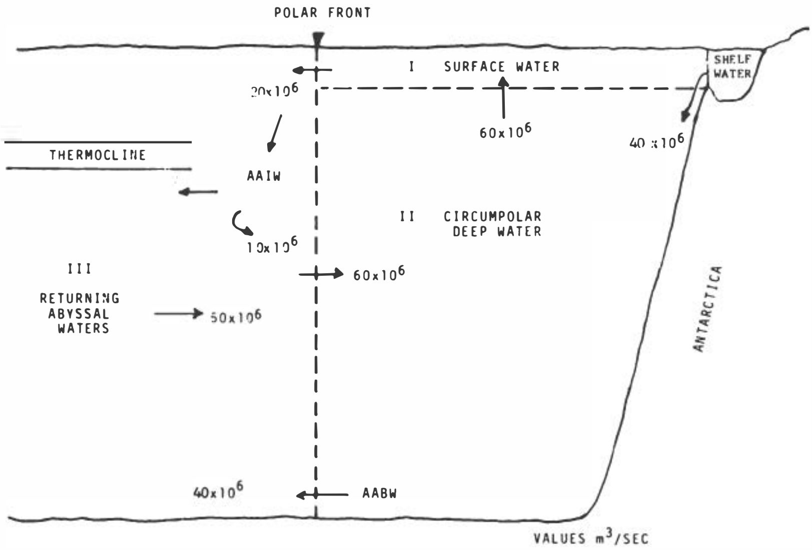

FIGURE 5.2 Volume transport for "average" circumpolar north–south plane. Values from Gordon [1971b, in press] and Gordon and Taylor [1973].

not possible to extrapolate to the production rate of AABW and AAIW, because we do not yet know how the volume transport changes as these waters mix with the deeper waters, but some estimates can be made.

Figure 5.2 shows in schematic fashion the average circumpolar meridional volume flux obtained from the foregoing estimates of heat and salt budgets. The 10×10^6 m^3/s value for returning AAIW is determined here from conservation of mass, and the 60×10^6 m^3/s of deep water passing southward below the Polar Front Zone is also approximate. All the numbers are, of necessity, somewhat speculative; moreover, we remain ignorant of the processes within boxes I and II and of the processes accomplishing the heat and salt fluxes across the interface of these boxes. The values are annual circumpolar averages; large variations in time and space could drastically alter the picture.

IV. RECOMMENDED PROGRAM

The primary aim of the budget studies is to determine the magnitude and variability of the local exchanges. These data will be used together with information from other experiments to elucidate the characteristics and dynamics of the transfer mechanisms responsible for the interactions and, finally, the influence of the Southern Ocean on global atmospheric and ocean circulation.

A. GENERAL SURVEY DATA

Measurements should be made in those regions where vertical and meridional fluxes of heat and salt are most active:

1. Frontal Zones

There are many areas in the Southern Ocean across which marked changes are observed in water characteristics. The most commonly known of these antarctic fronts are the Antarctic Polar Front (Antarctic Convergence) and the Antarctic Divergence.

The *Polar Front* has received most attention, since it is the formation zone of AAIW and it appears to be coincidental with the axis of the Antarctic Circumpolar Current. It is the zone separating the antarctic and subantarctic surface water masses. We know surprisingly little of the relation of the Polar Front to climatic-meteorological features and bottom topography, although Wyrtki [1961] has attempted to relate the structure of the front to the position of the maximum west wind with some success. The Polar Front is clearly related to the Antarctic Circumpolar Current; it is the thermohaline structure associated with the geostrophic flow of the current. In the Pacific sector of antarctic waters, the thermal structure of the front often displays a complex cellular structure [Wexler, 1959; Gordon, 1971a], as shown in Figure 5.3. These cells of warm water undergo rapid heat loss to the atmosphere and may have relevance to large-scale heat budgets and AAIW formation.

We recommend *a detailed survey designed to yield more information on the structure (thermal, haline, alkalinity, CO_2, and nutrient distribution) of the Polar Front at various positions and times so that a determination can be made of its importance relative to other frontal areas in exchange processes.*

Other frontal zones exist about which little is known. The principal ones are the *Australasian Subantarctic Front* [Burling, 1961], which occurs about 300 km north of the Polar Front in the Indian Ocean sector of antarctic waters; and the *Weddell-Scotia Confluence* [Gordon, 1967], which marks the boundary of the Weddell Gyre water (cold and relatively fresh) with the water flowing through the Drake Passage (warmer and saltier). The Confluence extends from the Antarctic Peninsula across the central Scotia Sea to

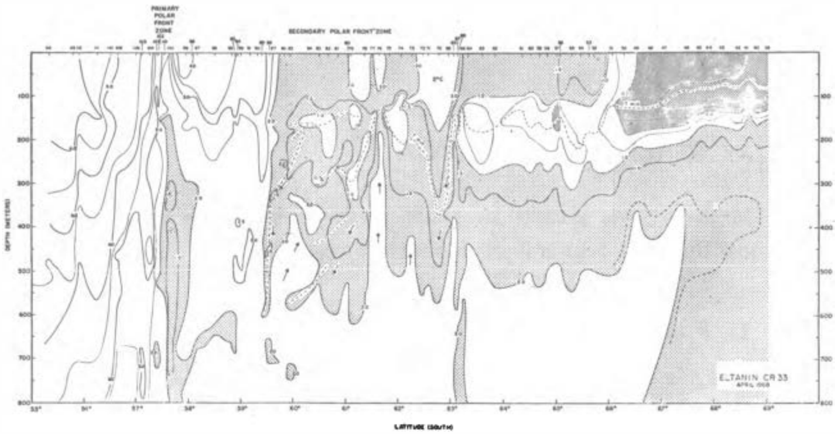

FIGURE 5.3 Double polar front structure often observed in the thermal structure in the Pacific sector [Gordon, 1971a].

about 20° E. The vertical exchange in the Confluence zone appears to be large, since there is some indication that the oxygen within the zone is higher at all depths than on either side. In addition to the possible relevance of this zone to vertical transfer of heat and salt, its position at the surface has a marked effect on climate. The climate of the South Sandwich Islands, which are south of the Confluence, is truly polar, but that of South Georgia, north of the Confluence, is more nearly subpolar; yet both groups are south of the Polar Front Zone. It appears that long-term movements of the Confluence could produce meridional shifting of the climatic belts. A northward shift would bring colder water (and air) farther north and probably would bring more sea ice. *We* recommend *that each of these other frontal areas be studied to determine their relative importance in exchange processes.*

2. Cyclonic Gyres

The circulation pattern around Antarctica is marked by a series of large cyclonic gyres. The major gyres occur in the Weddell and Ross Sea areas; however, minor cells exist in the Bellingshausen and Amundsen Seas and the Amery Ice Shelf region. Within these gyres, the core layers, which bear an inverse relationship to the sea-surface topography, reach their shallowest levels and so may attain maximum interaction with the atmosphere. The recirculation of water within these gyres yields long residence times and may account for their colder, fresher (but denser) characteristics. The processes occurring within the gyres and the interaction with the water to the north may be important elements in vertical and meridional transfers.

3. Continental Margins

On approaching the Continental Slope from the deep ocean, the "warm-salty" deep water changes abruptly. The water on the floor of the Continental Slope has properties closer to those of AABW than to those of deep water. The origin of the cold, but relatively fresh, water over the Continental Slope does not easily fit into the schematic model shown earlier [Gordon and Tchernia, 1972]. It is possible that deep convection may occur that does not reach the sea floor. What is the magnitude of such convection, and what role does it play in larger-scale vertical transfer of heat and salt?

We recommend *an assessment of the role of transfer processes occurring within gyres and near continental margins; the initial step should be a study of existing data.*

4. Sea Ice

The establishment of firm budget models requires not only more information on the thermohaline structure and velocity field on a variety of scales but also accurate estimates of the sea–air exchange and a better understanding of the influence of a changing ice cover on the ocean. A sea-ice dynamics program is recommended in the 1974 CPR report *Antarctic Glaciology: Guidelines for U.S. Program Planning, 1973–1983*, Chapter 2 and Appendix D; we support that recommendation. The foregoing report also contains specific recommendations for the study of water properties beneath sea and glacial ice. Therefore, the following comments are brief and general.

The extensive ice cover of Antarctica is further augmented by the highly important waxing and waning of the effective edge of the continent due to sea-ice fluctuations. Records of antarctic sea ice indicate two crucial phenomena: the first is the very large year-to-year variation in ice cover, over which are superimposed the strong seasonal oscillations; the second is the extensive ice-free regions that form near the continent early in the melting season, or possibly throughout the entire year, and that separate the open-ocean sea ice from near-coastal sea and glacial ice.

The significance of these two features becomes evident on comparing the thermal characteristics of the ice-covered water with those of the ice-free water. The ice acts as an effective barrier to ocean–atmosphere exchange of radiation, sensible and latent; i.e., it adds a continental aspect to the atmospheric climate. What is the effect of a growing, stable, or melting ice cover on the underlying water column? This effect depends on the season and the rate of growth or melting of the sea ice. The ice insulates the water from heat gains or losses, but the water-column temperature structure will vary under the ice, since other transfer mechanisms, such as deep upwelling, may be present under the ice cover. The average temperature of the water column below a stable or melting sea-ice cover may increase with time as more circumpolar deep water is advected into the region and upwells or mixes vertically. The upwelling or vertical mixing of warmer deep water may account for the accelerated ice melting that is observed in many areas in early spring. Warming can occur even with a slowly growing ice cover when the density (at freezing) of the surface layer is increased by salinity injection and vertical mixing with the deeper warm layers increases. We know little of the meridional and vertical transfer of heat in the antarctic region, especially below the sea-ice and glacial-ice covers; the thermohaline "history" of subice water column for growing and melting ice cover is thus of primary importance to budget studies and understanding of the sea-ice fluctuations.

Sea ice also influences the haline component of the water column. The freezing-point brine ejected by the sea ice into the underlying water, already at or near the freezing point, results in thermohaline-induced convection that may reach directly to the deep ocean floor.

Sea-ice formation is most active in the winter. Since lowered stability induces greater vertical flux, the water column below the forming sea ice and in the ice-free regions near Antarctica must receive attention in winter. A much-enhanced sea–air interaction occurs north of the ice fields and might be of primary concern to AAIW formation and the intensity of the Polar Front and circumpolar current.

In summer and winter, the deep water upwells into the surface layer. We know little of how this upwelling proceeds, since the pycnocline is strong in every place sampled in summer and winter. The mechanisms responsible for the upward flux of the CDW into the surface layer are not know. Since this flux is not accomplished solely by diffusion (the vertical advection induced by the Ekman divergence accounts for most of the necessary flux), it appears that a balance exists between the upwelling of CDW and downward erosion of the top of the CDW layer; that is, the pycnocline is eroding into the upwelling CDW. This process may be imbalanced locally. It is expected that a deepening would occur during periods of strong winds when mechanical stirring of the surface layer is strong and that shallowing would occur during calms and under stable or melting ice fields. Therefore, observations of the pycnocline should be made under a variety of environmental conditions, perhaps in each segment of a cyclone in each season.

We recommend *collection of data during the winter, especially below and within the sea-ice fields, noting that other seasonal data are also critical in refinement of the budget studies in the continental margins and open ocean.*

5. Glacial Ice

The interaction of the seawater with glacial ice, especially along the bottom of the ice shelf, is not understood. However, we do know that the elevated pressure at this interface decreases the freezing point of seawater below the sea-surface value, so that the water in contact with the bottom of the ice shelf would have very low temperatures. The occurrence of temperatures as low as −2.26 °C near the Filchner Ice Shelf and −2.13 °C in the Ross Sea (0.2–0.3 °C below the surface freezing point) suggests that some of this water spreads northward into the open-shelf region. We can only speculate about the process occurring at the water–glacial–ice contact and about the vigor of the process in regard to the interaction with the "open" ocean.

We recommend *that hydrographic and meteorological measurements on the effect of glacial ice be carried out in conjunction with the various existing and proposed shelf projects and that laboratory studies of freezing-point depression as a function of pressure be supported.*

6. Meteorology

The presence of a permanent continental ice cap reaching to the edges of the Antarctic continent allows the polar high-pressure area to extend over the continental margins of Antarctica, producing in the coastal region a general easterly airflow that is often marked by strong katabatic winds. The coastal easterlies vary with season, with maxima at both solstices, and are bounded at the north by a climatic low-pressure trough. North of this trough are the climatic westerlies. The wind field is not steady, but rather appears to be a series of cyclones and anticyclones migrating eastward about Antarctica. The cyclones generally approach the continent by a few routine paths.

The heat and water exchange between sea and air varies strongly with position within a cyclone [Zillman, 1972]. Climatic means have been calculated, but they are subject to error, since the exchange can be strongly time-dependent. The neglect of the resultant nonlinearity could produce large errors in the climatic sea–air transfer determination.

We recommend *a continuing program for monitoring standard meteorological variables during all survey programs. This monitoring function could eventually be assumed by untended data stations and remote-sensing systems.*

B. LONG-TERM MONITORING

Other than the monitoring that can be carried out with data from existing weather stations and supply ships, we do not make a specific recommendation for a long-term monitoring network. That plan must await the development of techniques and systems currently being tested in other oceans. However, we anticipate that the planning for such a special network might possibly begin before 1977. The technology that might be used in such a network is discussed in the next section.

C. TECHNOLOGY FOR LONG-TERM MONITORING

Data can be collected either by the manual use of sensors, i.e., measurements from ships or vehicles that can maneuver on the ice fields to obtain hydrographic data through the ice and in ice-free pockets, or by remote sensing from satellite or aircraft. The first method allows flexibility in experimental procedures, and the second allows data gathering for long periods and in regions and seasons when no manned vessel or vehicle can be present. From the manned vessels or vehicles, traditional measurements should be carried out in the entire water column, with particular emphasis on the upper kilometer. Attention to the microstructure and middle-scale structure is necessary, especially in ice fields. Since measurements in the ice fields should be made over the annual history of the ice cover, a combination of ships and over-the-ice vehicles will be needed.

Unmanned stations of various types—drifting, moored with a surface float, or "locked" in the ice—might be used to obtain long-term measurement of meteorological parameters at a number of distances from the sea (or ice) surface, as well as measurements of the water temperature and salinity at a number of levels in the water column. Such measurements can be used to monitor the near-surface heat storage, to refine the sea-air heat flux, and, by observing drift of the buoys or by measuring the current from the moored systems, to determine the response of the ocean to the wind.

Subsurface moored buoys can be used to obtain long-term thermohaline and current measurements below the sea ice. It is possible that buoys frozen into the pack ice fields would be more useful, since they could give meteorological data and relay information to satellites.

Supply aircraft flying between New Zealand and McMurdo should routinely measure sea temperature with infrared thermometers. Although cloud cover would often negate such data, enough "holes" can be found to at least study the clear-sky periods. Microradiowave frequency can also be used to obtain crude temperature data through the cloud cover but would, more significantly, yield sea-ice configuration information. Satellite observation of the oceans' irradiance should also be carried out.

D. SUMMARY OF RECOMMENDED PROGRAM

Tables 5.1 and 5.2 summarize the experiments and goals and show how the recommended program would fit into a ten-year time scale.

TABLE 5.1

Recommended Program Structure

Exchange Processes and Overall Budgets

Experiments and Goals

Proposed Experiments and Theory	Specific Goals
Monitoring Experiments	
* Ice cover variability from microwave imagery from satellites.	Measure energy exchange between ocean and atmosphere.
* Heat storage in upper layers from temperature profiles reported by drifters.	Reduce logistics costs of long-term data collection.
* Surface temperature and properties by remote sensing.	Relate ocean-atmosphere heat exchanges to subsurface water mass formation and atmospheric circulation variability.
* Long-term variability of the front from remote sensing.	
Survey	
* Collect planning data across frontal zones.	Isolate and understand exchange processes, e.g., determine relation between subsurface water-mass formation and ocean-atmosphere heat exchanges, for parameterization into global circulation models.
* Organize collection of upper layer data from supply and weather ships.	
Theory	
* Refine existing overall energy budgets with new and incoming data	
* Use input from CUE, NORPAX, and JASIN to formulate upper layer models relevant to Southern Ocean.	
* Review and formulate adequate frontal-zone models.	

TABLE 5.2

RECOMMENDED PROGRAM STRUCTURE

Exchange Processes and Overall Budgets

Time-Phased Diagram

CONTINUAL PLANNING AND REVIEW

Activity	Time Frame 1973 - 1976	1976 - 1979	1979 - 1982
Monitoring Experiments			
• Ice cover variability (satellite)	Begin →	Establish monitoring for FGGE collaboration	Merge into Internationl Climate Research Effort
• Surface Temperature and properties (satellite)	Begin →		
• Heat storage in upper layers (drifters)	Begin →		
• Long-term variability of front (satellite)	Begin →		
Survey			
• Collect planning data across frontal zones	Begin →		
• Detailed frontal survey	Begin →		
• Collect supply and weather ship data	Begin →		
Theory			
• Refine existing budgets with new and incoming data • Use input from other experiments to formulate Southern Ocean models • Review and formulate adequate frontal zone models	Begin →		

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Appendix A
Abbreviations Used in this Report

AABW	Antarctic Bottom Water
AAIW	Antarctic Intermediate Water
ACC	Antarctic Circumpolar Current
AIDJEX	Arctic Ice Dynamics Joint Experiment
CDW	Circumpolar Deep Water
CPR	Committee on Polar Research
CUEA	Coastal Upwelling Ecosystems Analysis (IDOE program)
DES	Division of Environmental Sciences (NSF)
FGGE	First Global GARP Experiment
GARP	Global Atmospheric Research Program
IDOE	International Decade of Oceanographic Exploration
IGOSS	Integrated Global Ocean Station System
IOC	Intergovernmental Oceanographic Commission
IRLS	Interrogation Recording and Location System
ISOS	International Southern Ocean Studies
IWSOE	International Weddell Sea Oceanographic Expedition
JASIN	Joint Air-Sea Interaction Experiment
MODE	Mid-Ocean Dynamics Experiment
NADW	North Atlantic Deep Water
NORPAX	North Pacific Experiment (IDOE-ONR program)
ONR	Office of Naval Research
POLEX-North	Polar Experiment—Northern Hemisphere
POLEX-South	Polar Experiment—Southern Hemisphere
RANN	Research Applied to National Needs (NSF)
TWERLE	Tropical Wind Energy and Reference Level Experiment
UNEP	United Nations Environmental Program