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Polar Research—A Strategy

Physical Oceanography and Tracer Chemistry of the Southern Ocean

Ad Hoc Committee on Antarctic Physical and Chemical Oceanography
Polar Research Board
Commission on Physical Sciences, Mathematics, and Resources
National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Foreword

This document is one of a series, *Polar Research—A Strategy*, issued by the Polar Research Board that identifies needs and develops strategies for polar research. These studies are expected to be sufficiently searching to guide polar research over the next two decades. The setting of priorities is particularly important in times of financial stress, and it is hoped that these studies will assist decision makers in government and nongovernment organizations concerned with the polar regions.

There are seven other reports in the series:

1. *An Evaluation of Antarctic Marine Ecosystem Research;*
2. *Study of the Upper Atmosphere and Near-Earth Space in Polar Regions: Scientific Status and Recommendations for Future Directions;*
3. *Polar Biomedical Research: An Assessment,* with an Appendix, *Polar Medicine—A Literature Review;*
4. *Snow and Ice Research: An Assessment;*
5. *Permafrost Research: An Assessment of Future Needs;*
6. *Polar Regions and Climatic Change*;
7. *Antarctic Solid-Earth Sciences Research: A Guide for the Next Decade and Beyond.*

Work continues on studies on arctic marine science, arctic geosciences, and arctic social sciences, with further studies to be initiated during the coming year.

The recommendations contained in this report are the result of the deliberations of the committee with regard to the charge:

1. review and assess the principal problems in antarctic physical and chemical oceanography;
2. evaluate the implications of these problems on a global scale; and
3. recommend future directions for research.

The Polar Research Board greatly appreciates the work of Arnold Gordon, chairman of the Ad Hoc Committee on Antarctic Physical and Chemical Oceanography, and of the members of this committee as well as the many contributors in the conduct of the study and the preparation of this report.

Gunter E. Weller
Chairman
Polar Research Board

Preface

Through decades of exploration and research, a basic appreciation and a general understanding of the Southern Ocean system have been attained. Specific advances in technology and scientific understanding of the Southern Ocean during the last decade have set the stage for the next level of scientific investigation. Effective field and modeling projects can be designed to address fundamental issues of Southern Ocean circulation, mixing, water mass formation, coupling with the atmosphere and ice, and influence on the biology and seafloor.

These endeavors must be viewed in global perspective. The Southern Ocean is an important element in the global system in two respects: (1) it is the primary route of interocean exchange, and (2) it is the primary site of water mass modification, which drives much of the thermohaline circulation of world ocean.

Polar oceanography is essential to an understanding of global climate dynamics, which are of tremendous economic consequence. Knowledge of the climatic roles of the polar oceans requires statistically validated monitoring that can be done most efficiently with the aid of satellite-borne sensors and by satellite data relay and satellite tracking of drifting buoys and mooring arrays.

This report considers technical and scientific developments and research questions in studies of the Southern Ocean since its predecessor, *Southern Ocean Dynamics—A Strategy for Scientific Exploration 1973-1983* (National Research Council, 1974) was published. The summary lists key research questions in Southern Ocean oceanography. Chapter 1 describes how Southern Ocean research has evolved to provide the basis for timely research toward more directed objectives. Chapter 2 recommends four research programs, encompassing many of the specific recommendations that follow.

Appendix A provides the scientific background and Reference/Bibliography list for this report for: air-sea-ice interaction; the Antarctic Circumpolar Current; water mass conversion; chemical tracer oceanography; and numerical modeling of the

Southern Ocean. Further reviews appear in: Gordon, 1983; Killworth, 1983; Hellmer and Bersch, 1985; Nowlin and Klinck, 1986; Gordon and Owens, 1987 and Scientific Committee of Oceanographic Research (SCOR) Working Group 74, 1985. Appendix B describes the satellite-based observation systems expected to be active during the next decade. Appendix C is a list of relevant reports published during 1981-1987.

The scientific issues are not limited to the responsibilities and interests of any one agency or country. Economy, efficiency, and timeliness in addressing the global scientific issues inherent in polar oceanography require consideration of all possible arrangements for ensuring and expediting needed satellite coverage for alternative sensing, measurement, and data-relay technology in the absence of sufficient satellite coverage.

The focus of the recommendations deals with the circulation and mixing of the Southern Ocean. This is the primary concern of physical oceanography. However, the study of circulation and mixing greatly benefits from measurement of various chemical parameters, which are aptly referred to as tracers. Therefore, the subject of tracer chemistry is included within this report. In addition, a discussion of the importance of the Southern Ocean to global climate nutrients and CO_2 is included in Appendix A.

Figure i (from Gordon and Molinelli, 1982) shows the bottom topography and regional names of the Southern Ocean.

General Circulation of the Southern Ocean: Status and Recommendations for Research (SCOR Working Group 74; International Council of Scientific Unions, 1985) is contemporaneous with this report and consistent in its recommendations. Another valuable resource is the report of the World Ocean Circulation Experiment (WOCE) Core Project 2 Southern Ocean Planning Meeting (World Meteorological Office (WMO) Report, 1987). The WOCE Implementation plan for Core 2 will be published in 1988.

I thank the committee members and contributors for stimulating discussions and contributions to the Report. Other contributors include Joey Comiso (NASA); Lou Gordon (Oregon State University); Tom Whitworth (Texas A&M University); and Taro Takahashi and S. Jacobs (Lamont-Doherty Geological Observatory).

Arnold L. Gordon
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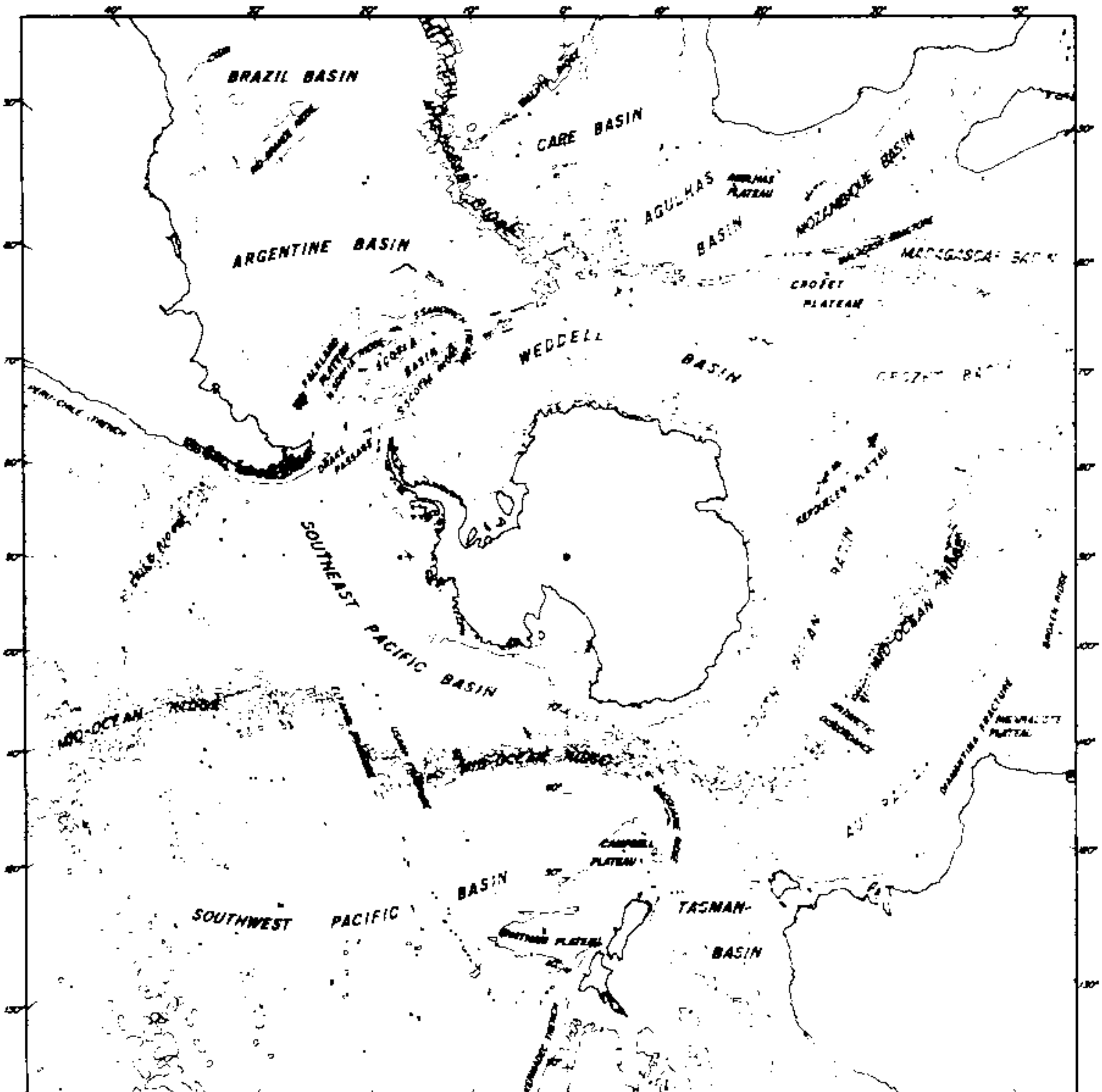

FIGURE i Bottom topography and nomenclature of the Southern Ocean. Source: Gordon and Molinelli (1982).

Executive Summary

The success of Southern Ocean research since 1974 and the concurrent development of satellite-based oceanographic technology and more powerful computers for numerical modeling point the way to a new generation of programs in the Antarctic. *Southern Ocean Dynamics—A Strategy for Scientific Exploration 1973-1983* (National Research Council, 1974), by the Polar Research Board's Ad Hoc Working Group on Antarctic Oceanography, outlined a series of recommendations for research on Southern Ocean circulation, bottom water formation, and exchange processes. Many of the recommended studies have been carried out, and knowledge of the region has expanded significantly. The studies proposed in 1974 were largely based on new current meter technology and conductivity-temperature-depth (CTD) instrumentation that had been used effectively in lower latitudes. The next stage of Southern Ocean research can take advantage of further developments in satellite and oceanographic technology.

Satellite scanning, at several wavelengths, and satellite data telemetry systems, such as drifter tracking, greatly augmented Southern Ocean field observations through the 1970s. Notable work included the use of SEASAT satellite altimeter for study of sea level variability (Cheney et al., 1983); NIMBUS passive microwave radiometer for detection of sea-ice cover (Zwally et al., 1983; Sturman and Anderson, 1985); and the ARGOS-tracked drifters set out as part of the First Global Atmospheric Research Program (GARP) Global Experiment (Hofmann, 1985; Patterson, 1985). July-October 1978 SEASAT observations led to the first extensive data set on synoptic distribution of wave height and wind stress in the Southern Hemisphere (Mognard et al., 1983). Altimeter data were sufficient to resolve low-frequency, large-scale changes of sea level during this period (Fu and Chelton, 1984, 1985). SEASAT synthetic aperture radar (SAR) has been used for study of sea-ice movements (Curlander, et al., 1985).

All-weather altimeter and microwave data and cloud-opaque infrared measurements showed the enormous potential of satellite-based remote sensing to provide a global synoptic view of the ocean. The return is far greater than is available only through point measurements from moorings and ships. However, the combination of ground-based and satellite data greatly expands the quantitative value of each. Indeed, surface observations are required for proper interpretations of satellite data. Drifting buoys in combination with satellite relay of sensor and trajectory data are an equally important technology. Ship navigation is also critically dependent on satellites in cloud covered Southern Ocean regions.

SEASAT altimetry has been used to determine mean sea surface elevation, and to reveal features of the ocean bottom where no ship tracks are available. Passive microwave radiometers have yielded the first significant time series of antarctic sea-ice cover, for the period from 1973 to the present. The seasonal signal dominates the areal cover, but interannual variations amount to 30 percent of the annual mean (Zwally et al., 1983; Sturman and Anderson, 1985). Relationships are probable between sea-ice variability and global climate issues, such as the Southern Oscillation and carbon dioxide-induced warming, but their interconnections are unknown.

With 60 years of classical hydrographic measurements and a decade of application of new technologies such as current meters, CTDs, expendable bathythermographs (XBTs), drifters, geochemical tracers, and bottom pressure gauges, much of the basic-scale structure of the Southern Ocean thermohaline and chemical field is sufficiently known to pose specific questions about the hydrodynamics. A full understanding of Southern Ocean processes and of their global impact cannot be obtained without year-round measurements of Southern Ocean structure, in particular the region covered by winter sea ice.

The application of geochemical tracer techniques in the Southern Ocean would enhance the physical studies recommended above. Of special interest are dissolved atmospheric chlorofluoromethanes, carbon dioxide, low-level radioisotopes, and high-precision measurements of the stable isotopes. The latter are of particular relevance in antarctic oceanography for the studies of exchange processes between seawater and glacial ice and the roles of freezing and evaporation in the alteration of surface water salinity.

Studies of air-sea gas exchange, the dynamics of surface ocean biological activity and upwelling processes in relation to global carbon dioxide and climate concerns are of major importance (Sarmiento and Toggweiler, 1984). Gas and water vapor exchange processes under winter sea ice are critical to the degree of ventilation of nascent bottom waters. Nutrient budgets and recycling rates, as functions of season and location, are closely coupled to the chemistry, biology, and physical oceanography and thus to the global carbon cycle. The dynamics of the dissolved biogenic silica cycle is unique and of primary importance to the Southern Ocean ecosystem.

RESEARCH QUESTIONS

The influence of Southern Ocean processes extends far beyond the Antarctic. Major interdisciplinary concern is now focused on this region because of its potential importance in the stability of the global circulation and climate, the uptake of substances from the atmosphere, the stability of the Antarctic ice sheet, and the distribution and apparent variability of the biota. Understanding the Southern Ocean depends in turn on answers to several basic questions:

- How do local and large-scale couplings of the ocean-atmosphere system determine sea-ice distribution?

- What are the energy, thermal, freshwater, momentum, and vorticity budgets of the Southern Ocean? How and where is momentum dissipated? What is the total heat loss and freshwater gain south of the Antarctic Circumpolar Current?

- What ventilation (water mass modification) processes dominate the deep-ocean and continental margin regimes of Antarctica? What are their rates and relative importance?

- What are the dynamic and thermodynamic characteristics of the subpolar gyres and of the vigorous Weddell Gyre, specifically?

- What are the basic dynamics of the Antarctic Circumpolar Current: Is the circumpolar geometry of the Southern Ocean responsible for unique dynamics? How does the Antarctic Circumpolar Current interact with the subtropical and subpolar gyres? What are the driving mechanisms and eddy transports of heat, water, and buoyancy across the Atlantic Circumpolar Current?

Progress will depend on the availability of adequate funding and efficient research platforms and finding investigators who can carefully design and execute the field work and analyze the data.

The U.S. effort in Southern Ocean studies should be coordinated with that of other nations within the World Ocean Circulation Experiment (WOCE) Core Project 2, the Southern Ocean.

RECOMMENDED RESEARCH, 1988-2000

Southern Ocean research during the remainder of the century cannot address all questions, but rather should address specific elements of the above questions. The objectives outlined here are in accord with a growing consensus that the Southern Ocean regime plays a key role in the world climate system.

The research will stress an integrated application of numerical modeling with satellite telemetry, tracking, and remote sensing, in addition to the use of arrays of instrumented drifters and moorings anchored to the sea ice and seafloor, and CTD/tracer chemistry observations.

The need for long-term monitoring systems is clear, but basic spatial structures, primarily in winter, are not yet sufficiently resolved for effective design of the monitoring arrays. Thermohaline and tracer chemistry observations are essential to the research procedure. Acoustical methods such as sound fixing and ranging (SOFAR and RAFOS techniques), Doppler profiling, inverted echo sounders, and tomography must be adapted to the polar environment. The effectiveness of ice camps should be assessed for application in the Southern Ocean.

The committee recommends that the next phase of Southern Ocean research address the following topics (no priority order is implied): the Antarctic Circumpolar Current, sea-ice zone, subpolar gyres, and continental margin.

Antarctic Circumpolar Current

Sensing by satellite altimeter and scatterometer can provide a synoptic circumpolar view of sea level variability and of the surface wind stress field. These measurements are essential for further progress in understanding the Antarctic Circumpolar Current's global-scale characteristics. In addition, well-coordinated field observations, including those from arrays of drifting and moored instrumented arrays and some repeated CTD and XBT sections, are needed to assess the subsurface characteristics and obtain meridional heat and freshwater fluxes across the circumpolar belt. Moorings should be sited in areas of both intense eddy activity and low eddy activity, as well as within the Drake Passage.

Sea-Ice Zone

Information pertinent to ocean-atmosphere exchange rates is most deficient within the sea-ice cover. Knowledge of the dynamics and thermodynamics of the sea-ice cover and of the seasonal evolution of the mixed layer is essential to an understanding of ocean-atmosphere coupling. Satellite infrared, microwave, SAR (active and passive), tracking, and telemetry-relay technology should be key factors in advancing this research. A program of field measurements, coordinated with satellite observations, would maximize the utility of the satellite data for application to a broad range of objectives. A quantitative understanding of the role of the sea-ice cover in the heat-water-momentum budget of the Southern Ocean may require arrays of ice-strengthened, long-term drifters equipped with meteorological and oceanographic sensors (thermistor-conductivity chains).

Subpolar Gyres

The subpolar gyres transfer heat, momentum, and a host of chemical and biological substances between the Antarctic Circumpolar Current and the antarctic continental margin. Additionally, they are the sites of intense water mass modification. The largest in terms of size and transport is the Weddell Gyre, believed to be responsible for the bulk of abyssal ocean ventilation. However, the general lack of data, particularly during its sea-ice-covered phase, means that its role in heat, water, mass, and gas exchange budgets has been only roughly estimated. These issues, and in particular the nature of the western boundary current, need to be resolved. The Weddell Gyre should be the focus of the deep-ocean research directed at the area south of the Antarctic Circumpolar Current. Gyres north of the Ross Sea and east of Kerguelen and their coupling should be studied as well. Instrumented drifting and moored arrays, acoustical methods for monitoring ocean circulation, and CTD/tracer chemistry would play significant roles in field experiments. Sea ice study from satellites and perhaps with the array of drifters mentioned in the sea-ice zone recommendations should be coordinated with gyre research.

Continental Margin

Exchange of ocean properties across and along the shelf-slope front may be fundamental to the formation rates of antarctic bottom water, the dissipation of circumpolar deep-water characteristics, and glacial ice stability. Studies of glacial ice mass balance offer opportunities for collaboration between glaciologists and oceanographers. Detailed shelf-slope interaction studies such as those conducted in lower latitudes should be carried out in the unique Southern Ocean environment. In particular, the circumpolar variability in oceanic heat transport onto the continental shelf, and salt and ice fluxes off the shelf, needs to be understood. Arrays of current meters, thermistor-conductivity chains, and acoustical Doppler profiler moorings across the shelf-slope frontal zone are recommended.

Southern Ocean studies are clearly an international effort. The United States must be a vital player in this effort. To do so requires a technological and manpower commitment. While satellite-based technology is clearly an essential part of the new technology, emphasis on effective ships, with significant ice capabilities, is still key to the detailed field observational program, from which quantitative results can be generated. The manpower requirements may be met by providing sufficient educational and research opportunities for graduate-level students, perhaps as a separately funded grant.

1
Evolution of Southern Ocean Oceanography

New technology, developments in numerical modeling, a reasonably good water mass and circulation structural picture from decades of surveys, and the global importance of the Southern Ocean all argue for focusing a coordinated program on research that is more complex and global than previously attempted. Understanding of the special role of this region (see Figure i) in ocean circulation, climatic variability, mixing and transport of gases and chemicals, and ecosystem maintenance could thereby be substantially advanced. The increased international interest in the Southern Ocean, as demonstrated in the developing WOCE Core Project 2, holds out the hope that real advances will be made in coming decades.

Southern Ocean Dynamics—A Strategy for Scientific Exploration 1973-1983 (National Research Council, 1974) recommended studies of circulation, bottom-water formation, exchange processes, and overall budgets of the Southern Ocean. Many of the recommended studies were carried out, based on technology that had first been used effectively at lower latitudes. The success of these studies and the concurrent development of satellite measurement and new modeling techniques now point the way to a new generation of programs in the Antarctic.

Understanding of the Southern Ocean has evolved significantly in the last 30 years. These advances were made possible by circumpolar and regional surveys and more recently by projects focused on specific elements or processes within the Southern Ocean. The vastness of the Southern Ocean and its remoteness from supply ports require collaboration and maximum use of satellites and remote-sensing instrument arrays. Recent advances in Southern Ocean studies reflect both international collaboration and new technology.

The 1957-1958 International Geophysical Year (IGY) programs included an extensive Southern Ocean component and marked the beginning of renewed interest in the region. The IGY data set is a comprehensive, nearly synoptic (taken over three consecutive austral summers) representation, but data lie mostly along supply routes to the antarctic stations. While not uniformly distributed, the data do permit time-variability studies for 3 years and comparison with *Discovery* observations of the 1930s. Extensive use of newly available technology for bathythermography was important to the success of IGY oceanography. The mechanical bathythermograph provided high spatial resolution of the thermal structure of frontal zones and indicated eddies within the Polar Front zone. Since then, antarctic research and supply ships have continued to obtain thermal data from the upper 250 m, extending a valuable, albeit spatially and temporally incomplete, time series.

Subsequent availability and use of expendable bathythermographs resulted in more accurate temperature profiles to deeper levels (nominally, 450 m). These probes have been a key factor in the studies of the Southern Ocean frontal zonation structure. In the late 1970s, this technology also made possible the greater exploitation of ships of opportunity, in order to obtain a set of repeated lines along various routes in the Southern Ocean.

From 1962 to 1972, the *USNS Eltanin* obtained a comprehensive, multidisciplinary data set over 80 percent of the Southern Ocean area. Part of the southwest Indian Ocean was surveyed in 1974 by the *Conrad.* From 1974 to 1979 the *Eltanin*, renamed the *Islas Orcadas* and operated by Argentina, extended the circumpolar survey through the South Atlantic. The existence of the *Eltanin* and other Southern Ocean research programs of the 1960 to 1980 period encouraged numerous oceanographers to enter polar science, and placed the United States in a leadership role in this field. The hydrographic data greatly enhanced the picture of thermohaline stratification, water masses, fronts, and currents in the circumpolar belt and continental margins of Antarctica. These data allowed more accurate mapping and volumetric determination of temperature/salinity (T/S) modes of water masses (e.g., Worthington, 1981). This, in turn, generated new concepts regarding water mass formation processes and rates. Additional sites of bottom-water formation were located, as was evidence for deep convection in the Weddell Gyre. The *Eltanin* and *Islas Orcadas* hydrographic data are a primary component of the *Southern Ocean Atlas* (Gordon and Baker 1982; Gordon and Molinelli 1982).

In the evolution of observational technology during that period, continuous, in situ measurement of the thermohaline stratification by the CTD replaced the use of serial hydrographic stations. These new systems improved the resolution of vertical stratification by up to three orders of magnitude, thus allowing detection of relatively intense fine structure in the frontal zones and near the continental margin. Station time decreased, providing the opportunity for improving the horizontal spatial resolutions. The application of tracer geochemistry advanced concurrently with the increase of substances exploitable as tracers (e.g., stable oxygen isotopes, tritium, carbon-14, and, recently, chlorofluoromethanes). Geochemical techniques provide an integrated view of the effects of glacial ice-ocean and ocean-atmosphere exchange processes on a variety of spatial and temporal scales.

Several expeditions surveyed the western segment of the Weddell Gyre (a cyclonic flowing circulation feature south of approximately 56° in the Atlantic sector of the Southern Ocean) in the summers of the late 1960s and 1970s. This work and similar observations from icebreakers in the Ross Sea provided the oceanographic data within the fringes of the summer and multiyear sea-ice fields. It did much to refine concepts of formation and production rates of antarctic bottom water, the intensity of the Weddell Gyre, the continental margin fronts, and ocean-glacial ice interactions.

A joint US-USSR program aboard the Soviet ship *Somov* (Gordon and Sarukhanyan, 1982) in October and November of 1981 took oceanographic data from well within the sea-ice cover, near its time of maximum extent. The *Somov* data, along the Greenwich Meridian, reveal conditions of the ice-covered ocean after the cumulative effects of an austral winter. The data led to improved estimates of deep to surface water heat flux and provided the basis for a concept of polynya generation and maintenance (collected reprints are published by Ackley and Murphy, 1986). The 1986 Winter Weddell Sea Project aboard *Polarstern* has provided further insight into winter processes. Preliminary inspection of the data indicated very large heat flux estimates in the vicinity of Maud Rise.

Still, conditions under the extensive seasonal sea-ice cover around Antarctica remain the largest unknown in the oceanography of the Southern Ocean. Observations within the sea-ice cover are still in the early survey phase, and further water property observations are needed.

The International Southern Ocean Studies, in the early 1970s, focused on the Antarctic Circumpolar Current at the Drake Passage, and with some observations southeast of New Zealand. This work found strong coupling between winds and currents, a multifilament structure with associated frontal zones, and active eddy generation, which accomplishes significant meridional heat flux. It also established the mean and variable baroclinic and barotropic transport of the Antarctic Circumpolar Current. The 1978-1979 First GARP Global Experiment (the Global Weather Experiment) included satellite tracking of drifting buoys to study circumpolar circulation.

Satellites have contributed greatly to knowledge of the Southern Ocean. Passive microwave data are used, without cloud interference, to map sea-ice characteristics and the annual advance and retreat (Figure 1). Sea-ice movements can be observed directly from satellite with SAR imagery. In cloud-free conditions remote sensing in the visible light region of the electromagnetic spectrum and in the infrared helps define locations and variability of frontal zones. The seasonal signal is obvious but the microwave data also reveal interannual variability (Figure 2). The brief SEASAT mission, in 1979, demonstrated the potential utility of its scatterometer for sea-level winds and its altimeter for sea-surface elevation (Figure 3). From its three months of data, a circumpolar mapping of low frequency surface variability within the Antarctic Circumpolar Current showed coherence only over very large (basin) scales (Figure 4). Satellites have also been used for tracking drifting buoys and some equipment with air-pressure sensors. These trajectories provide estimates of mean and eddy energy levels (Figures 5 and 6).

With some exceptions (e.g., winter period observations), Southern Ocean research is moving into a post-survey phase in which new oceanographic technology,

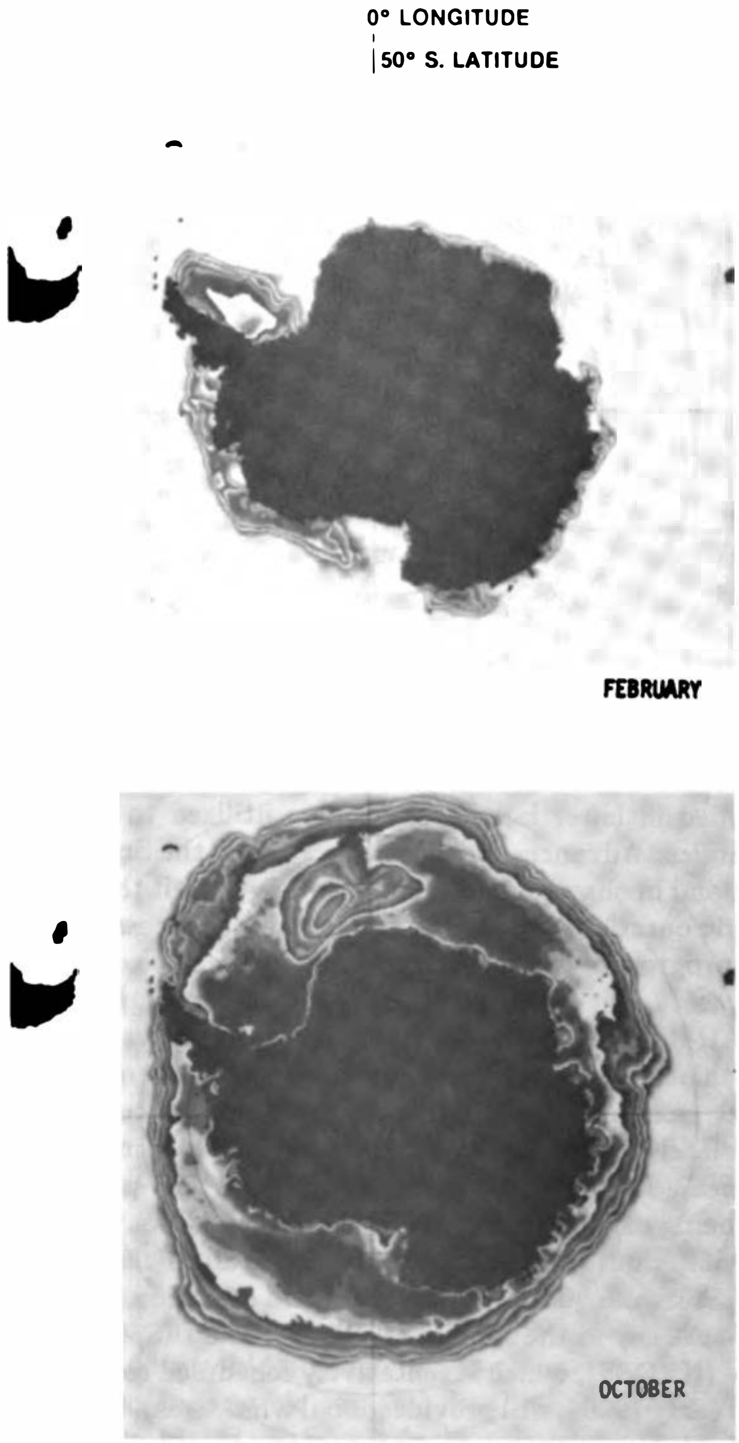

FIGURE 1 Southern Ocean ice concentration—in percent derived from the single-frequency radiometer on Nimbus-5. The months of minimum (February) and maximum (October) ice extent are shown. In each case data are averaged over the indicated month and then over the years 1973-1976. The October results show a large area of low mean concentration near the Greenwich Meridian. This feature is called the Weddell polynya; it was observed in 1974-1976 but not in 1973. Source: Zwally, et al. (1984).

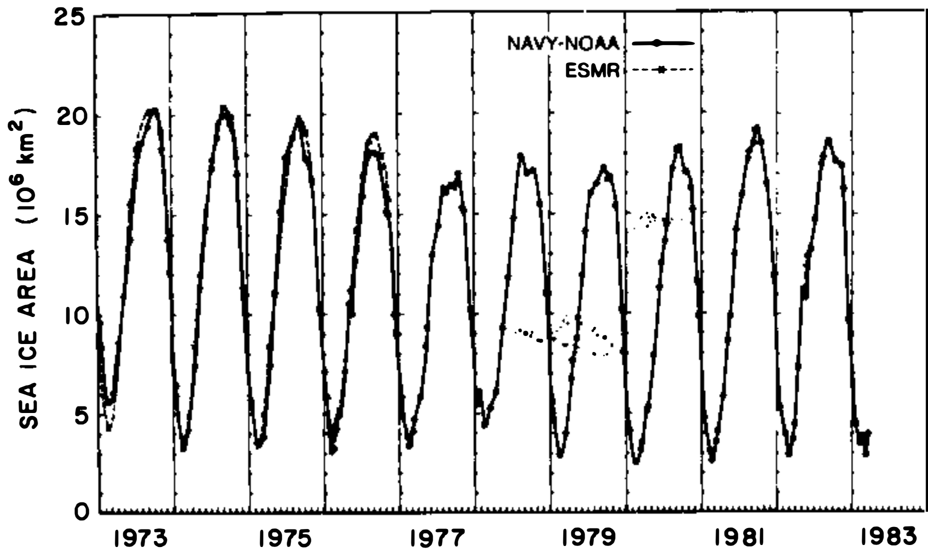

FIGURE 2 **Interannual variability of sea-ice cover. The total area containing sea ice was estimated from satellite passive-microwave measurements. Superimposed on the annual cycle, there was a significant decrease in sea ice extent during the late 1970's. There has been some recovery in recent years, but not to the high values of the early 70's. Extended observations are needed to reveal the causes of these long-term changes in sea ice extent and their relationship to climate. Source: Zwally, et al. (1983).**

successfully applied in lower latitudes, is being utilized to study Southern Ocean circulation dynamics. Advances in basic knowledge of the Southern Ocean, in circulation modeling, and in observation technology now permit the design of experiments to address specific questions bearing on fundamental processes.

Substantial progress on these questions depends on the combined application of new technology, including satellites, drifting buoys, and improved acoustical methods (e.g., SOFAR/RAFOS floats and tomographic arrays), and the use of data generated from this technology in new general circulation models that will be available on the next generation of computers. Methods successful in lower latitudes must be appropriately modified and applied to the Southern Ocean.

Southern Ocean studies will constitute an important part of the WOCE Core Project 2, now being organized as part of the World Climate Research Program, a successor to GARP. Southern Ocean circulation studies carried out in the WOCE framework will assure adequate participation and scientific impact.

Satellites are the key to the success of WOCE. The U.S. Naval Research Oceanographic Satellite (NROSS), which is tentatively scheduled to fly a three-year mission beginning in the early 1990s, will provide global wind stress, sea state, and SEASAT-quality altimetry for time-dependent studies of fronts and eddies. It will also carry a microwave imager for measurements of ice edge position, believed to be an important parameter of climate variability. At the time of this writing elements of NROSS has been cancelled, however the scatterometer may be placed aboard another satellite.

The European Space Agency's ERS-1 and the National Space Development Agency of Japan's J-ERS-l satellites will provide similar data with contemporaneous

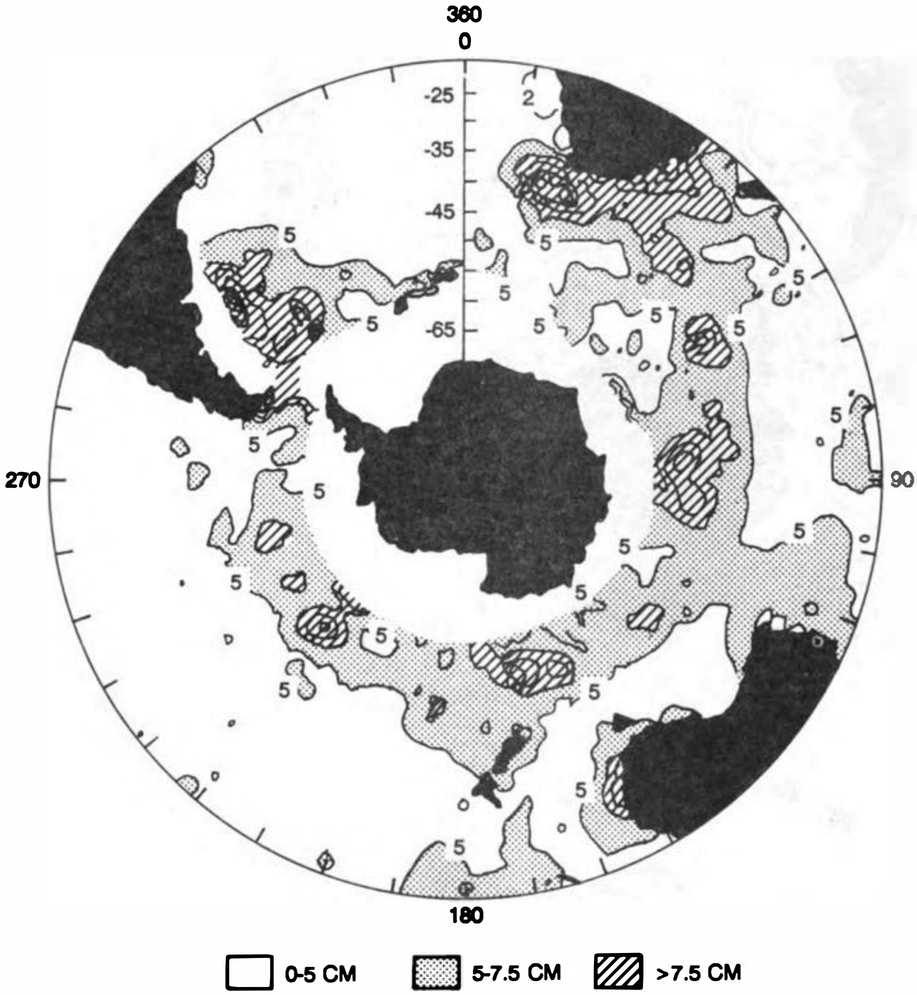

FIGURE 3 SEASAT altimeter mesoscale variability, June to September 1978. Source: R. Cheney, NOAA (1983).

global coverage. They will have SAR, ideally suited for the study of sea ice and ocean surface roughness. Neither of these satellites is capable of providing the precision altimetry necessary to infer ocean circulation.

Financial and technical setbacks mean uncertain launch schedules and possibly years of delay. Research plans, logistical support, and funding agencies must be flexible enough to respond to changes in satellite schedules. Field work not critically dependent on satellite data could proceed in any case.

A major goal of oceanographic research in the Southern Ocean should be to delineate currents on a global scale. Only in this way can researchers begin to establish the magnitude of the terms in the conservation equations, to understand the ocean-atmosphere response and feedback, and to provide information needed for biological studies. The Ocean Topography Experiment (TOPEX-Poseidon), a 3-year, precision altimeter experiment planned for launch in late 1991, is designed as a major improvement over SEASAT altimetry. TOPEX altimetric data will be

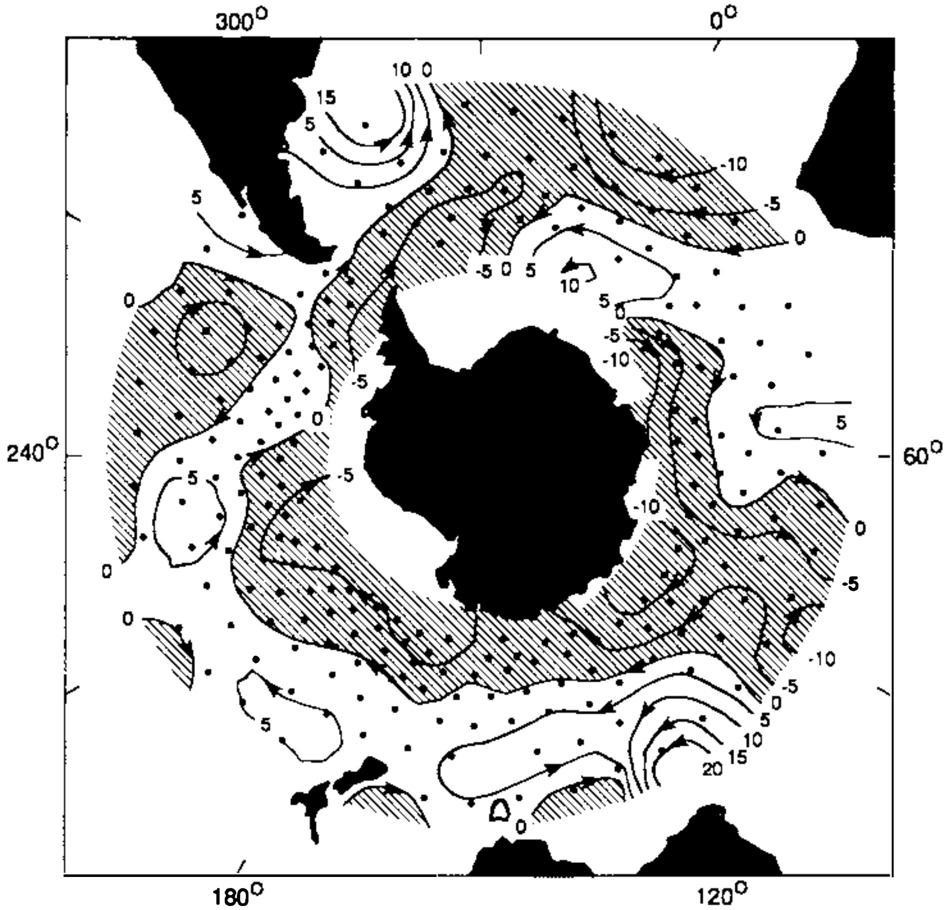

FIGURE 4 Low frequency, basin scale sea-level variation from SEASAT, July to October 1978. Units are in centimeters. Source: Fu and Chelton (1984).

used for the first global-scale synoptic measurements of ocean currents, but its orbit is optimized for tropical and mid-latitudes, and thus will reach only to 63.4° latitude north and south. The lower-accuracy NROSS (status uncertain) and ERS-1 data obtained poleward of 63.4°, can be used to extend the TOPEX data set to higher latitudes.

The potential of satellites for Southern Ocean biogeochemical issues is less clear. NIMBUS-7 has provided imagery at a variety of visible-light and infrared wavelengths showing great promise in some regions (e.g., Gulf Stream and California coastal waters) for defining chlorophyll concentrates and hence primary productivity. The sensor and satellite have outlasted their three-year design lifetimes, and a near-global data set is slowly being accumulated. However, the Southern Ocean surface is often obscured by clouds, and the sensor is not always on; so the potential of these satellite techniques for biogeochemical cycle studies in the polar regions has not been established. Judgment on this point requires a search through the NIMBUS-7 data set to identify cloud windows and other wavelengths that might be used to monitor biological processes in the ocean.

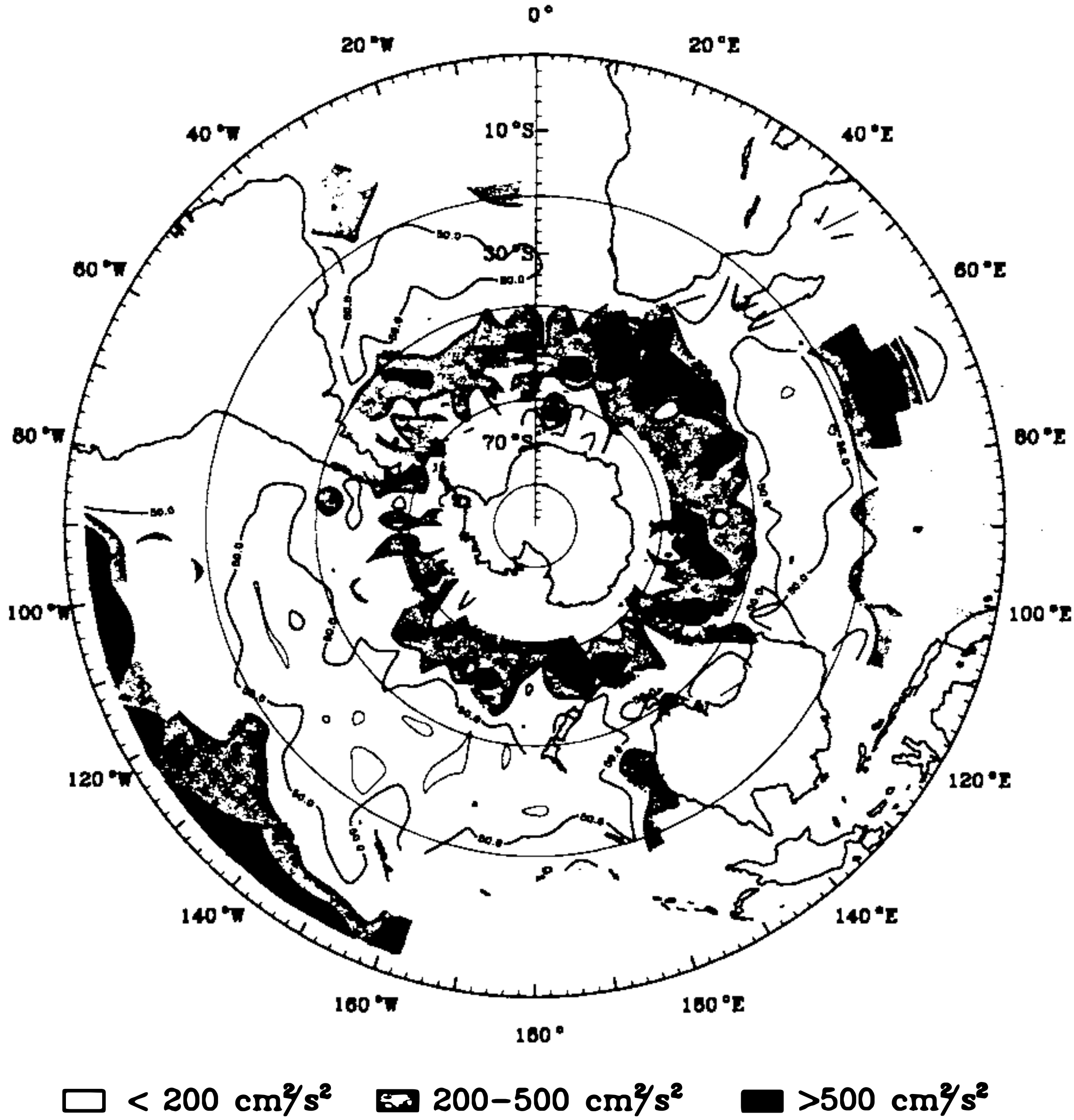

FIGURE 5 Surface mean kinetic energy derived from drifting FGGE buoys. Source: Patterson (1985).

Satellite programs scheduled during WOCE in the late 1980s and during the 1990s will provide new views of ocean processes and new opportunities for progress in understanding the global role of the Southern Ocean. Current meter and thermohaline probes (i.e., CTD) technology laid the basis for Southern Ocean studies recommended a decade ago. This technology will continue to be an essential element in the field observation plan, particularly within the ice-covered regions and winter period throughout the Southern Ocean. Further development of Southern Ocean

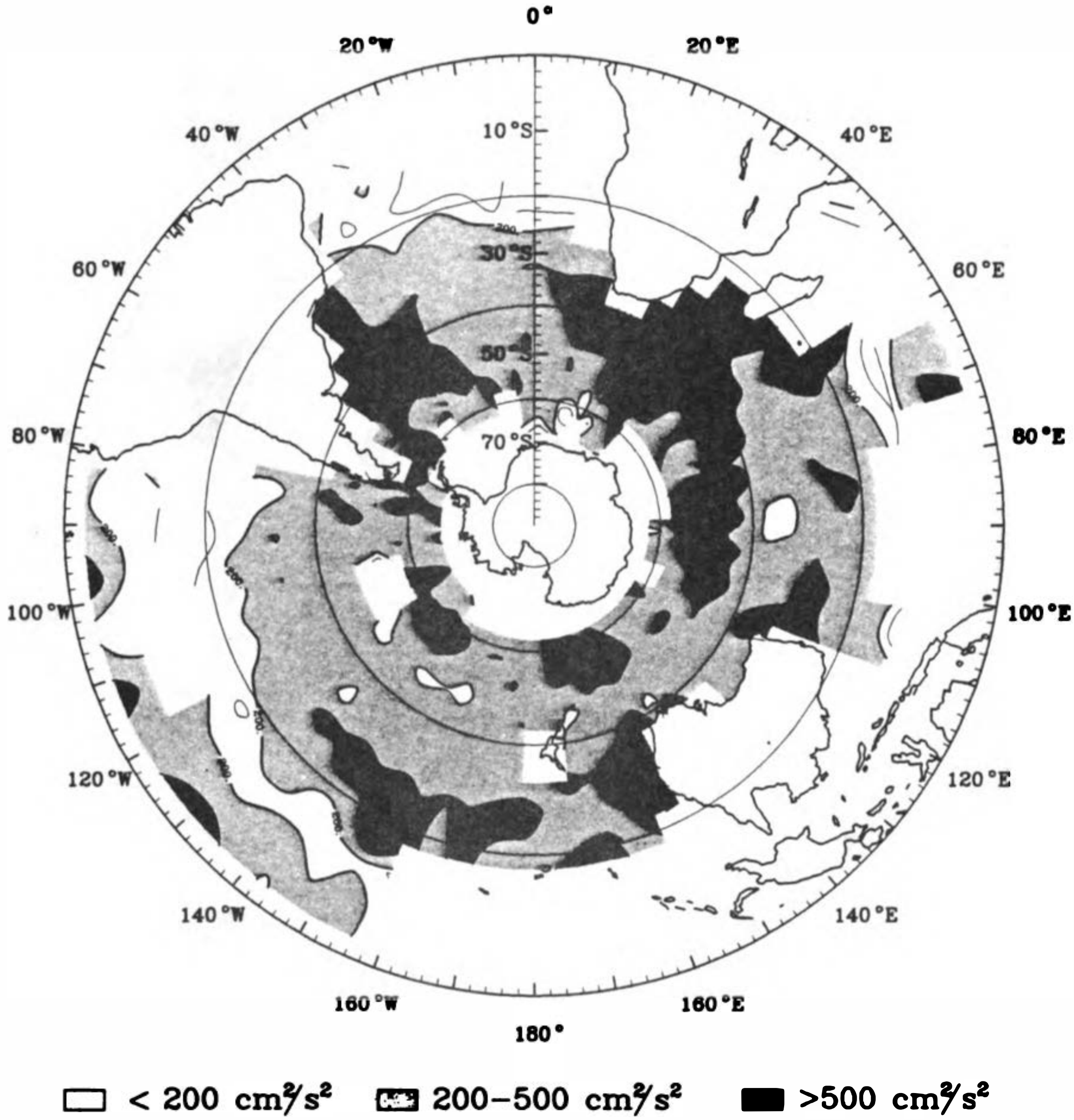

FIGURE 6 Surface eddy kinetic energy derived from drifting FGGE buoys. Source: Patterson (1985).

studies should also take advantage of evolving satellite and new surface-based technology, the next generation of high-speed computers, new analytical techniques, and the large data base assembled to date.

2
Recommendations

Study of the Southern Ocean began with general large-scale surveys and a wide range of observations from ships, and has been enhanced greatly by satellite monitoring of ocean surface characteristics. The survey phase is required for basic knowledge of the thermohaline and water mass distribution characteristics, so specific questions can be posed, process-oriented experiments and monitoring arrays designed, and theory and realistic models constructed. The circumpolar hydrographic data sets obtained by the *Discovery*, International Geophysical Year studies, and *Eltanin*, with the regional data sets of the International Weddell Sea Oceanographic Expedition and the Ross Sea studies, provide a view of the overall water mass structure of the Southern Ocean. Worthington (1981) pointed out that the Southern Ocean coverage is surprisingly good, relative to other areas of the world ocean. A total of 6,313 high-quality hydrographic stations were used in the *Southern Ocean Atlas* (Gordon and Molinelli, 1982; Gordon and Baker, 1982).

The hydrographic data set has good spatial coverage but, as Figure 7 shows, is highly biased toward the summer months, particularly south of 60° S. Thus, despite the overall good large-scale spatial statistics, the seasonal coverage is very poor. Much of our knowledge of the winter environment is based on inference from summers and occasional other ice-free periods. But the atmosphere-induced thermohaline alterations of the ocean are most extreme in winter. The winter end-members that contribute to various key water masses have not been identified fully. A series of questions concerns the ice cover's modification of the sea-air coupling, which in turn influences water mass conversion characteristics and other associated atmospheric and climatic processes. The sea ice is important as well in the biological cycles, particularly in the ice edge regime, not yet studied adequately. Collection of a full suite of oceanographic data within the ice-covered regions and during the winter remains a high priority for Southern Ocean studies.

As the fundamental structure of the ocean is resolved by the survey approach,

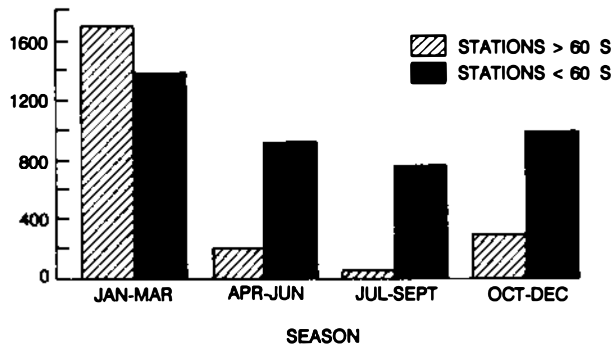

FIGURE 7 **Seasonal distribution of hydrographic stations. Source: Gordon and Molinelli (1982).**

attention turns to more directed field work that properly integrates theory and modeling efforts. Field work that addresses these issues may include more closely spaced hydrographic observations, tracer chemistry observations, and establishment of arrays of instrumented moorings and drifters to provide the necessary time-series data. Questions have been posed for various aspects of Southern Ocean phenomena, and appropriate field programs have been or can be designed to explore more quantitatively the dominant processes and dynamics of these features.

The following discussion first identifies the General Recommendations regarding the broad research questions for which significant advances are possible in the coming decade, then the more Specific Questions are presented. This is followed by a discussion of Methods (also covered in Chapter 1). The General Recommendations can be met by the formation of coordinated research projects. These projects would also address many of the Specific Recommendations.

GENERAL RECOMMENDATIONS

High priority in Southern Ocean research in the next 10 to 15 years should be given to research programs that address global issues, related to objectives of the WOCE Core Project 2. These programs require integrated surface and satellite observational, modeling, and theoretical work. Progress in physical and chemical oceanography of the Southern Ocean to address issues of global concern requires study of the four broad research topics: the Antarctic Circumpolar Current, sea-ice zone, cyclonic "subpolar" gyres, and continental margin.

Antarctic Circumpolar Current

Satellite altimeter and scatterometer data can provide a circumpolar view of variability of sea level and the wind field. Satellite data coupled with information from moored and drifting buoys will: allow extrapolation of International Southern

Ocean Studies results from the Drake Passage; permit further exploration of the Antarctic Circumpolar Current's relationship to wind fields; and provide Antarctic Circumpolar Current eddy statistics. To enhance these data, various surface-truth observations are needed from:

- Selective moorings of current meters to monitor vertical coherence of the variability observed by the altimeter, which resolves only horizontal scales. Instruments would be moored in a few regions that Seasat showed to be particularly variable, at a quiet site, and in the Drake Passage. Moored pressure sensors and tide gauges, to monitor Antarctic Circumpolar Current variability in transport, are recommended.

- Satellite-monitored drifters equipped with meteorological sensors and thermistor and conductivity chains. These will give further data on circulation and sea-air parameters for estimation of ocean-atmosphere exchange of heat, water, and momentum.

- Acoustical monitoring of ocean circulation; Doppler profiles, sound fixing and ranging floats, SOFAR/RAFOS tomography, and inverted echo sounders should be used as appropriate.

- Modern tracer techniques, especially dissolved atmospheric chlorofluoromethanes (Freons) and low-level radioisotopes, to study seasonal and regional ventilation and mixing processes in the Antarctic Circumpolar Current.

Experiments that test the form drag or mountain torque hypothesis may best be designed from results of specific numerical models. A geometry-specific model of the Antarctic Circumpolar Current should be developed to include both dynamics and thermodynamics.

Sea-Ice Zone

Information pertinent to ocean-atmosphere exchange rates is lacking within the area with a sea-ice cover, which in winter extends 20×10^6 km. The dynamics and thermodynamics of the ice cover must be known better if the ocean-atmosphere coupling is to be understood at the level required to incorporate into global circulation models for the atmosphere and ocean. Satellite infrared, microwave, SAR (both active and passive), and buoy tracking with telemetry capabilities, are key technologies in this research. Tracer chemistry is particularly vital. Tracers integrate the effects of sea-air-ice interaction, which are often in spatial and temporal scales too small to be resolved explicitly.

- The committee recommends that an array of satellite-tracked drifters with meteorological sensors and thermistor-conductivity chains be placed in selected sites within the sea-ice cover. They must be constructed to survive long enough to provide data on a full year's evolution of ocean stratification in response to atmospheric and sea-ice conditions. Drifters are important as well in resolving patterns of subpolar gyres circulation.

- A fully coupled ocean-atmosphere sea-ice model, including dynamic and thermodynamic terms, is needed.

- Study of the role of sea ice in the ocean-atmosphere heat, water, and gas exchange should be emphasized.

Cyclonic "Subpolar" Gyres

Circulation between the Antarctic Circumpolar Current and Antarctica is dominated by large cyclonic gyres. These features are driven by the wind field and can be considered to be the Southern Hemisphere counterparts of the subpolar gyres of the Northern Hemisphere. The Weddell Gyre is the largest and best formed of the Southern Hemisphere circulation gyres. It is believed responsible for the bulk of abyssal ocean ventilation. Because of deep-reaching, low-speed circulation and weak stratification characteristics, its role in vertical and horizontal exchanges of heat, water, mass, and gases is difficult to assess.

Further regional and process-oriented hydrographic research (particularly in the ice-covered areas and in winter), time series measurements, from a combination of instrumented moored and drifting buoy, and satellite data are needed within the cyclonic gyres. Measurements should be concentrated in the western margin of the gyres. This requires moorings and telemetering instrumentation to be set within the drifting multiyear ice cover. Telemetry to satellite or neighboring land stations is recommended. Gyre studies must include measurements of tracer chemicals to determine the source mechanisms, integrated production rates, and residence times of the principal water masses.

While all of the subcyclonic gyres of the Southern Ocean should be studied in general, the Weddell Gyre should receive special focus. Among subjects for research emphasis are the following:

- Study of the Weddell Gyre Western Boundary Current should have top priority. Data on its transport, variability, and thermohaline structure will provide a quantitative description of the integrated water mass modification accomplished within the Weddell Gyre. Included in this research should be the oceanographic characteristics of the Western Boundary Current's separation from the Antarctic Peninsula and its seaward extension in the Weddell-Scotia Confluence.

- Associated with monitoring of the western boundary current there should be at least one east-west CTD (with tracers) section across the Weddell Gyre. This section should extend from the Antarctic Peninsula to at least 40°E, nominally along 65°S.

- The process of formation of antarctic bottom water is concentrated along the southern and possibly western margin of the Weddell Gyre. The role of the strong flow of relatively warm, salty water over the continental slope into the Weddell Sea in the formation process should be determined. The dominant mechanisms of shelf-slope exchange along the gyre margins should be resolved.

- The eastern extent of the Weddell Gyre and its variation are not yet resolved. The Weddell Gyre probably is related to the vigor of the Antarctic Circumpolar Current and larger-scale wind forcing. An array of instrumented drifters within the Weddell Gyre may be a most effective research approach. Development of dynamic-thermodynamic coupled (air-ice-ocean) models is needed. Basic hydrographic work during winter and near Maud Rise would contribute to the design of experiments.

Continental Margin

Exchange of ocean properties across the shelf-slope front is tied to the glacial ice balance and formation of antarctic bottom water. The use of moored arrays, chemical tracers, modeling, and theoretical study of frontal dynamics to examine shelf-slope regimes in lower-latitude areas should guide the study of the shelf-slope process around Antarctica. Antarctic continental margin studies should focus on the unique Southern Ocean attributes of vast floating ice shelves; the sea-ice cover and frequent coastal polynyas; deep-reaching convective plumes over the slope; and on the generally low degree of stability. The objective is to determine the rates and variability of exchange of heat and salinity between the shelf and deep-ocean regimes:

- Shelf-slope time-series observations on a sufficiently small spatial scale are essential. Instrumentation that would be effective includes moored current meters, thermistor-conductivity chains, and moored acoustical doppler profilers. Data sets must be coordinated with satellite study of the varied sea-ice condition. Isotope studies are valuable in determining the glacial ice contribution and in distinguishing between freezing and evaporation mechanisms in increasing surface-water salinity.

- The ocean is most likely the dominant factor in melting glacial ice and in controlling the stability of the antarctic ice sheet. The glacial ice has an ocean effect, forming very cold water, well below the freezing point at the ocean surface. Isotopic evidence indicates that glacial meltwater plays a role in antarctic bottom water formation. A fully integrated physical and chemical oceanographic study directed at the ocean-glacial interaction is needed.

SPECIFIC RECOMMENDATIONS

The research recommended here is directed at more specific elements. The recommendations are presented in order of discussion of research composing Appendix A.

Air-Sea-Ice Interaction

Quantitative understanding of Southern Ocean processes requires reasonably accurate assessment of the exchanges of heat, water, gases, and momentum between the ocean and atmosphere for both open and ice-covered ocean, as noted in *Southern Ocean Dynamics—A Stratgegy* (National Research Council, 1974). This requirement for many aspects of Southern Ocean research cannot be overemphasized. Progress toward building the required data sets has been achieved but has been limited severely by the region's remoteness and relative inaccessibility in austral winter. We have witnessed the advent of year-round satellite passive microwave remote sensing (primarily of the sea-ice cover). Drifting data buoys were distributed during the Global Weather Experiment and since 1985 have again been developed over the Southern Ocean as part of the TOGA (Tropical Oceans Global Atmosphere) Program. Process-related experiments included the International Southern Ocean Studies work on the Antarctic Circumpolar Current and the late-winter US-USSR Weddell Polynya Expedition into pack ice and the 1986 Winter Weddell Sea Project aboard *Polarstern*.

These efforts have provided some limited modern-era measurements of the important physical processes in the Southern Ocean. More are needed, on a scale that can be achieved only through use of satellite remote-sensing methods and satellite telemetry of sensors placed on drifting and perhaps moored arrays of buoys:

- Specifically designed field programs are needed to provide the quantitative basis for calibration and utilization of data from satellites. The geographical and temporal (annual cycle and interannual variation) distributions of latent, sensible, short- and long-wavelength radiative fluxes from open water to the atmosphere, from various conditions of ice to the atmosphere, and from water to ice must be learned. The seasonal rates of growth, vertically and horizontally, and of ice and associated brine rejection must be discerned.

- Information is needed on momentum input (wind stress) to the ocean over open water, to the ice in various conditions (e.g., pack ice vs. loose ice), and from the ice to the water. To get this information requires improved specification of parameters for variables that are easier to measure—for example, determination of geostrophic drag coefficients to permit calculation of momentum flux to the water from atmospheric pressure distribution under various conditions of the atmospheric boundary layer, especially its stability and the condition of any ice beneath.

- Given adequate parameters, or the prospect of them, a program is needed to observe the distributions of air and sea temperature, atmospheric stability, sea level pressure, wind speed or surface pressure gradient, short- and long-wavelength radiation, and ice thickness and other conditions.

- Surface-truth experiments to check algorithms and parameter definitions will be necessary in conjunction with remote sensing from satellites. In-situ sensing and telemetry of most of these variables (and others, such as surface current and vertical temperature distribution) by relatively inexpensive, increasingly reliable, instrumented surface drifters in open water and in ice are becoming feasible.

- Improved air-sea flux information is needed. A figure of 3×10^{14} W has been computed for the annually averaged sea-to-air heat transfer of waters south of the Polar Front. This figure has been put to many uses, for example, by Bryden (1983) who compared it to eddy heat transport estimates in the Antarctic Circumpolar

Current, and it should be determined more accurately, with improved data input. Improvement of flux estimates would be accomplished if better atmosphere and sea-ice thickness and concentration data were available.

• To improve estimates of ocean-atmosphere exchanges of heat, water, gases, and momentum involves more quantitative use of satellite data, in turn requiring field programs specifically designed to calibrate satellite data. Use of drifters instrumented with meteorological sensors and thermistor and conductivity chains, with satellite telemetry, promises, together with satellite remote sensing, to do much to improve our estimates of sea-air exchange values.

• Altimeter data over ice may not prove useful in the study of ocean circulation, but processing of altimeter data to study sea-ice roughness may be useful. SAR would be particularly useful in the study of sea-ice roughness.

The committee endorses these antarctic sea-ice research recommendations of the Polar Research Board report *Snow and Ice Research—An Assessment* (National Research Council, 1983):

> Research on sea ice should be directed to measurements of ice growth, drift, and decay and to interactions of ice with the thermohaline structure on the marginal ice zone. These studies should include a winter lead experiment on freezing processes, convection, and haline-driven circulations and atmospheric fluxes and a summer field experiment to measure ice melting rate, radiation balances, and the structure of the pycnocline.
>
> The full potential of remote-sensing techniques for determining large-scale conditions (extent, concentration, thickness) should be implemented to achieve resolution and minimum turn-around time for data processing and distribution to users.
>
> An array of air-droppable buoys should also be deployed in the seasonal ice of the Southern Ocean to monitor pressure, temperature, and ice movement. Such data are needed to confirm and quantify the divergent nature of the antarctic pack ice and to estimate regional rates of ice production, salt rejection, and turbulent heat exchange with the atmosphere. Data from such studies could be applied to the development, modification, and verification of numerical air-sea-ice ocean models.
>
> A major emphasis in research on floating ice should be the formation, growth, and behavior of frazil ice, especially under field conditions, including:
>
> 1. The nucleation mechanisms of frazil ice formation;
> 2. The growth rates of individual frazil ice crystals in supercooled water;
> 3. The mechanical properties of frazil ice during the different stages of its growth and formation; and
> 4. Crystallographic studies of frazil ice cores to discern sediment entrapment, expulsion, and transport processes.
>
> The data needed for model development and verification in the very active and complex part of the sea-ice cover near its edge (the marginal ice zone) should be sought. These data should include measurements of ice drift, growth, and decay, ice pulverization by waves and transport by wind, and variations in atmospheric and oceanic fluxes near the ice edge. The role of frazil ice in the growth of sea and its effect on the exchange of heat between atmosphere and ocean should be evaluated, especially in the Southern Ocean. The oceanic and atmospheric processes leading to the generation and maintenance of polynyas should be resolved, and the role of polynyas in relation to climatic and ecological systems should be studied.
>
> Coupled sea-ice-ocean-atmosphere models that incorporate the essential physics of ice

and ocean processes, small-scale heat and mass transfer from leads, and low-level clouds should be developed. Especially needed is a simple sea-ice model that incorporates sufficient physics to present the essential interactive aspects of long-term climate simulations.

Antarctic Circumpolar Current

The following work is particularly important to understanding of the Antarctic Circumpolar Current:

- Moored arrays at other locations in and near the Antarctic Circumpolar Current could establish the extent to which site-specific kinematical dynamical quantities estimated at the International Southern Ocean Studies mooring locations are representative of the current along its path. Single moorings in conjunction with satellite altimetery can provide statistical information on the Antarctic Circumpolar Current.

- Synoptic time series of the surface elevation of the entire Antarctic Circumpolar Current can be obtained by satellite altimetry. The Ocean Topography Experiment mission will carry an altimeter with an accuracy of ±2 cm and can be tracked to determine the altitude of its orbit to within 5-10 cm. Coverage will extend to 63.4° S thus providing good coverage of the Antarctic Circumpolar Current. A subsequent geodetic satellite mission will provide accurate mapping of the geoid to 5-cm accuracy at wavelengths down to 100 km.

- For interbasin circulation studies and to provide data to examine dynamical forcing of the Antarctic Circumpolar Current, monitoring of the Antarctic Circumpolar Current transport could be accomplished with a pair of pressure gauges; expected accuracy would be within about 10 percent of the mean.

- Modeling efforts should be directed at learning the physical processes to be included in the model to reproduce an Antarctic Circumpolar Current with meridional zonation.

- Observations are needed to better describe the nature of the Subantarctic and Polar Fronts and their variability over space and time. Emphasis should be placed on satellite observations and on oceanographic and meteorological measurements from drifters and ships of opportunity.

- Numerical modeling efforts should seek to ascertain the mechanisms likely to be responsible for dissipation of energy provided to the Antarctic Circumpolar Current by the wind regime. Successful thermodynamic models must provide for observed zonation and must realistically reproduce transport and variability. To provide these models with adequate wind stress distribution, future satellite-derived, wind stress data should cover the Southern Ocean.

- Additional attempts should be made to relate Antarctic Circumpolar Current temporal variations of transport to the forcing functions.

Water Mass Formation

The Southern Ocean is responsible for intense modification of world ocean water masses. The mechanisms and rates for this modification are key issues in the global impact of Southern Ocean processes.

• Examination of requirements for a better quantitative scientific understanding of the deep-water ventilation and bottom-water formation in high-latitude Southern Ocean waters makes clear the following:

1. A better description is needed of the sidewall (at the antarctic continental shelf) boundary conditions, that is, of the vertical fluxes of heat, water vapor, momentum out of and into the water column, and the formation rates of ice; and
2. A better description is needed of the circulation and water masses in the high-latitude gyres, of the Weddell and Ross Seas, and of other areas, including the interaction of the gyres with the adjacent shelf circulation, the bottom topography, and Antarctic Circumpolar Current.

• Magnitude and variability of ocean-atmosphere exchange in the presence of a full or partial sea-ice cover must be better known in order to advance understanding of water mass conversion south of the Antarctic Circumpolar Current.

• Acquiring sufficient data on the ventilating power of the Southern Ocean as driven by winter conditions must be one of the top priorities for world ocean studies. The Southern Ocean's climatic relevance, its role in global budgets of heat, freshwater, and carbon dioxide, and the extent of the sea-ice cover make the need to develop further understanding of winter period oceanography based on direct observations even more timely. The need for high-quality summer data must also be stressed. The historical data set is not up to modern standards, although particularly for the nearly homogeneous ocean south of the circumpolar belt very high quality data are needed to resolve the ocean structure.

• To better resolve the role of the continental margins in ventilating the world ocean, the magnitude and primary processes of exchange between shelf and the slope across the shelf-slope front must be understood.

• To determine the magnitude and variability in formation rates of antarctic intermediate water and subantarctic mode water.

• Quantitative estimates of cross-frontal mixing by small-scale (smaller than rings) processes are needed.

• Improved estimates of air-sea-ice exchanges throughout the region are needed, particularly for the winters.

• Description of the water mass characteristics below the winter sea-ice cover, including the exchange processes and rates between deep-water and surface mixed layer, must be improved.

- Extent of water mass conversion within the Weddell Gyre and associated northward transfer within the western boundary current and Weddell-Scotia Confluence must be determined.

- Extent of water mass conversion over the continental shelf and interaction with glacial ice must be delineated.

- Rates and key site of shelf-slope exchange, including primary processes, must be determined.

- Knowledge of air-sea heat and moisture exchanges south of the Antarctic Circumpolar Current must be improved. Volumes, characteristics, and variability of water masses formed in the Southern Ocean and exported to the global ocean should receive high-priority attention.

- Although estimates of the relative importance of different processes responsible for meridional heat and salt exchange across the Antarctic Circumpolar Current have been made from observations at Drake Passage and southeast of New Zealand, the processes active at these locations may not be representative of the entire circumpolar current. Small arrays of moorings might be used to make estimates of eddy heat and momentum fluxes at circumcontinental sites expected to differ dynamically because of bathymetry and observed levels of fluctuation energy.

- Exchange of heat and water between the open ocean and the water cavity below the ice shelf must be understood quantitatively, and the role of the ocean in the glacial ice budget must be ascertained.

METHODS

Utilization of technology is key to furthering our understanding of the vast Southern Ocean. Methods of special use are discussed throughout this report. Summary remarks are contained herein.

Thermohaline and Tracer Distribution

High spatial resolution CTD stations are needed for the definition of fronts and water mass formation regions and the study of ocean dynamics. There is also a need to survey within the areas covered by sea ice and in the winter environment; gathering of winter data is critical to developing an understanding of the full annual cycle. Likewise, the introduction of integrated physical and chemical studies using modern tracer techniques in many regions of the Southern Ocean in all seasons is required. Large scale property distribution study is included within the WOCE Hydrographic Program (WHP) part of WOCE Core Project 2.

Tracer Chemistry

The interests and objectives of tracer chemical oceanographic research in the Southern Ocean are inextricably linked to physical oceanography, and integrated physical and chemical approaches are recommended accordingly. Certain problems and opportunities of chemical oceanography warrant special attention.

- Major emphasis should be placed on use of modern tracer techniques to study ventilation processes and integrated rates of subsurface circulation and mixing in the Antarctic Circumpolar Current, in mode water formation areas, and in the major gyres of the Southern Ocean, especially in the Weddell Sea. Among the most promising tracers for such studies are the dissolved atmospheric chlorofluoromethanes (Freons), which have simple boundary conditions and which can be measured from shipboard in mesoscale-resolving density. Other promising tracers, which vary according to independent boundary conditions, include: stable isotopes of water; helium-3; low-level tritium, measured by the helium-3 ingrowth technique; radiocarbon; krypton-85; and argon-39.

This research should be coupled closely with the physical oceanographic observations and with highest-quality measurements of temperature, salinity, nutrients, and oxygen. Broad geographical and seasonal coverage is needed, so the behavior of the entire Southern Ocean system can be studied in an integrated way.

- Studies of air-sea gas exchange and the dynamics of surface ocean biological activity and upwelling processes, especially as they relate to the role of the Southern Ocean in global climatic carbon dioxide problems, likewise are important. This work should include measurements that focus on seasonal and regional variabilities in the surface-water carbon system and in air-sea exchange coefficients. It should employ measurements of classical carbonate chemistry (carbon dioxide partial pressure, total carbon dioxide, and alkalinity) and related nutrients, oxygen, and hydrographic parameters, as well as isotopic studies of radiocarbon and carbon-13 distributions.

Regions that require special emphasis include the margins of the sea ice, areas of upwelling and water mass confluence in the Antarctic Circumpolar Current, locations of mode-water formation, and open water near the continental margins. Again, the need for seasonal observations, especially in the wintertime, cannot be stressed too strongly.

- Study of water-vapor and gas exchange processes in winter sea-ice conditions bears closely on questions of air-sea exchange and global climate and is critical to understanding the degree of ventilation of nascent deep and bottom waters. Evidence suggests that sea ice is an effective barrier to the exchange of oxygen, carbon dioxide, Freons, and helium-3, but exchange in areas of wintertime polynyas and leads may be intense and therefore may play a significant role in the exchange budgets, especially in years when these features are prominent.

- Chemical tracers are ideal for the study of exchange processes between major antarctic glacial ice shelves and the waters that circulate underneath. This subject merits emphasis, especially for the Filchner, Ronne, and Ross ice shelves. Because of the enormous contrast in stable isotopic composition between polar glacial ice and seawater, high-precision stable isotope measurements are remarkably sensitive to ice-shelf melting and also make it possible to carry out mass-balance calculations relating rates of bottom-water formation to rates of ice-shelf melting. In shelf waters the dissolution of air bubbles entrapped in glacial ice may also usefully trace the melting process. Time-dependent tracers such as Freons, oxygen, and nutrients should provide measures of the rates of circulation under the ice shelves and of the rates of metabolic processes in these inaccessible areas, through the study of shelf waters entering and emerging along the ice-shelf edges.

- Attention should be focused on nutrient budgets and recycling mechanisms and rates. Budgets and recycling rates of nitrogen, phosphorous, and carbon are important in the Southern Ocean's uptake of atmospheric carbon dioxide, hence in the global carbon cycle. The behavior of biogenic silica in the Southern Ocean is unusual and produces very distinctive silica properties of the waters and sediments in this region. In conjunction with process-oriented biological and physical studies, such as along the margins of sea ice, studies of silica production and dissolution as functions of depth and season are of interest.

Moorings and Drifters

Sensors placed on moorings on drifting platforms are essential observational technologies to establish time series data sets. Among these are:

- Satellite telemetry, tracking, and remote sensing.

- Instrument arrays moored to the seafloor or floating sea-ice cover; these can be instrumented with current meters, pressure sensors, inverted echo sounders, and/or thermistor and conductivity chains.

- Acoustical methods, including sound fixing and ranging floats, upward scanning sonar, Doppler profilers, and tomography arrays.

Emphasis should be directed at specific processes or phenomena, such as the Antarctic Circumpolar Current, meridional exchange of heat and salinity, and formation of antarctic bottom water.

The trends toward time-series data sets with arrays designed for specific objectives will continue both with familiar equipment and with equipment new to the antarctic environment as recently developed and tested within the Arctic. These include surface and subsurface Lagrangian methods.

The small temporal and spatial scales of many events in the Southern Ocean require special time-series data sets. Time series of this sort can only be done with arrays of instruments moored to the seafloor or to the sea ice or allowed to drift within the water column. Design of such arrays is developed from the knowledge obtained from the shipboard measurements, satellite data, and understanding of the general physics of the situation to be studied. Arrays consisting of current meters, thermistor and conductivity chains, and pressure gauges have been deployed successfully in the Southern Ocean. Further use of these instruments is essential.

Acoustical methods generally have not been applied to the Southern Ocean but might be quite effective in studying circulation characteristics not practically addressed with discrete mooring arrays. Acoustical doppler profiles operated from ships or moored to the sea floor are promising methods for direct current measurements within the boundary layers. Profiles may also be placed on top of mooring lines. Acoustical tomography could be effective in the study of mesoscale variability within large ocean volumes. Subsurface floats could provide the full circulation pattern over broad regions, without complication of sea-ice and mixed layer dynamics. Some modification of acoustical frequencies is required for the polar regions where the sound channel is at or near the sea surface. Acoustical technology is in use (testing phase) in the Arctic; its use in the Southern Ocean is recommended as well.

Satellite Methods

Satellite technology is essential for study of the Southern Ocean (Appendix B) but is insufficient without intercalibration of sensors and construction of realistic algorithms based on simultaneous surface observations. These observations must be made as part of a specially designed program, properly carried out in conjunction with the satellite schedule.

In order to record the SAR and other data from satellites, a need exists for a satellite recording ground station in Antarctica. It is noted that because of the very large volume of SAR data, the experiments using SAR must be carefully designed to maximize the science return.

Polar Research Vessel

Access to the Southern Ocean is always a problem, particularly in the ice-covered regions and winter period. Thus the following points are made:

An oceanographic research ship which can effectively work within the Southern Ocean is one that has long endurance and capability of working in rough seas and within sea ice. It must have an ability to deploy and recover large arrays of moorings and set-out drifters. It must be able to handle large CTD/Rosette and other over-the-side packages. Laboratory space must be adequate to allow all of the required science to be accommodated, including tracer chemistry, which requires "clean" laboratory conditions.

Need for an effective icebreaking or well ice-strengthened, research vessel is particularly obvious. Such a ship can be the base for detailed study of regimes within the sea-ice cover. The ship can allow for more precise deployment of arrays and for recovery of non-expendable systems. An icebreaker can obtain observations and place instruments in many otherwise inaccessible Southern Ocean environments.

The Polar Research Board's 1987 reports *Quality of Science on Existing U.S. Coast Guard Icebreakers: Report of a Survey*, and *Evaluation of the U.S. Coast Guard's 'Preliminary Design Document' for the Proposed Next Generation of Polar Class Icebreakers* are referred to.

The use of manned camps in the multiyear sea ice needs to be explored for cost-effectiveness. Unmanned, instrumented platforms may be effective, if the basic environment is known sufficiently to permit adequate design of the platform and instrument array.

Modeling

Verification of models is essential. The tracer chemistry data set provides a means to test the models. If a model correctly simulates the real ocean it should not only provide results that match the thermohaline field but also the transient tracer field, such as C-14 Tritium-Helium and Freon.

Measurement of ocean circulation (mean and eddy field) are also needed to validate Southern Ocean models. Requirements for Southern Ocean modeling that should be met first include:

- Quasi geostrophic studies (eddy-resolved) in channel and partially blocked channel geometry with and without bottom topography and with a variety of simple wind-forcing conditions (including transient winds).

- Beginning of the construction of a quasi geostrophic, eddy-resolving model of the complete Southern Ocean region, for eventual use with realistic wind-forcing patterns derived from satellite data and atmospheric models.

- Studies with simple-geometry, primitive-equation models to trace the intrusion of water masses from the surface into the ocean interior; models with reasonably high resolution would allow studies that were not dominated by the parameterized diffusion.

Longer-term needs include:

- Quasi geostrophic studies (eddy-resolved) with a complete Southern Ocean model.

- Primitive-equation studies with eddy resolution but with simple geometry to examine the influence of eddies on water mass formation and spreading.

APPENDIXES

Appendix A
Scientific Review

AIR-SEA-ICE INTERACTION

The Southern Ocean's air-sea processes and budgets of heat, momentum, salt, and trace constituents, including carbon dioxide, are fundamental to its roles in global oceanic and atmospheric dynamics. Estimates of ocean-atmosphere flux of heat, water and momentum are only roughly known. Proper definition of the annual cycle, interannual fluctuations, second moment statistics such as variances, and spatial and temporal scales need to be considerably refined.

Excellent discussions of Southern Ocean climatology are included in the 1984 volume edited by Van Loon, within the articles dealing with the three Southern Ocean basins: Hoflich (South Atlantic); Streten and Zillman (South Pacific), and Taljaard and Van Loon (South Indian).

The world's most vigorous large-scale atmospheric circulation occurs from 40°-70°S, that is, the circumpolar trough and its associated westerly wind belt (See Figure A-1). Most general circulation models represent these circulation features relatively poorly (Schlesinger, 1983). Present models tuned to represent the Southern Hemisphere more realistically are apt to cause the Northern Hemisphere circulation to become too vigorous. This suggests an excessive reliance on Northern Hemisphere analogies in most model validation. The implication is that we need to improve our understanding—by field, experimental, and theoretical analyses—of the unique exchange processes in the Southern Hemisphere. Incorporating these processes into improved models should increase our understanding and prediction of the global climate system and its interactive atmospheric cryospheric and oceanic components. Surface albedo and turbulent exchange between the ocean and the atmosphere is greatly influenced by ice cover. This affects the atmosphere, which in turn alters the sea-ice cover. Useful models need to account for all primary feedbacks and features like the Weddell Polynya that occur on time scales longer than 1 year.

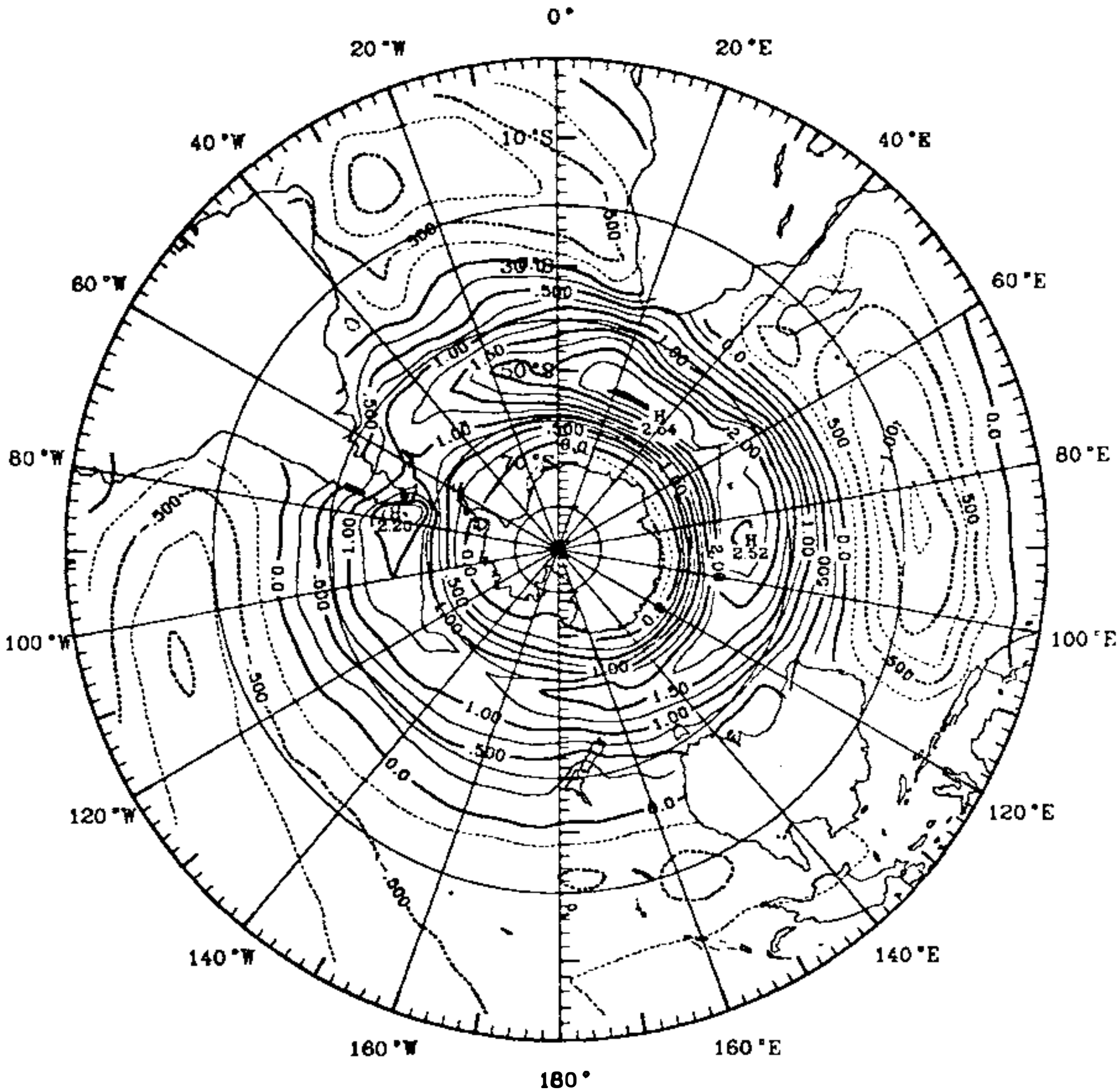

FIGURE A-1 Annual mean eastward wind stress (units: 0.1 N/m²). Source: Nowlin and Klinck (1986).

Air-Sea Heat Fluxes

The Southern Ocean sea-to-air heat flux changes sign near the Polar Front, from air to sea (positive values) south of the Polar Front and again near the northern extent of sea-ice cover (Figure A-2). The secondary maximum in heat loss near 50°S is associated with increased latent and sensible heat loss (Streten and Zillman, 1984) as the cold antarctic atmosphere crosses over warmer surface water north of the polar frontal system. The zonally averaged annual values given in Figure A-2 are rough estimates. Streten and Zillman's (1984) annual air-sea heat flux values for the South Pacific indicates larger heat loss, up to 100 W/m², south of 60°S.

The annual cycle of the heat balance for the South Pacific is discussed by Streten

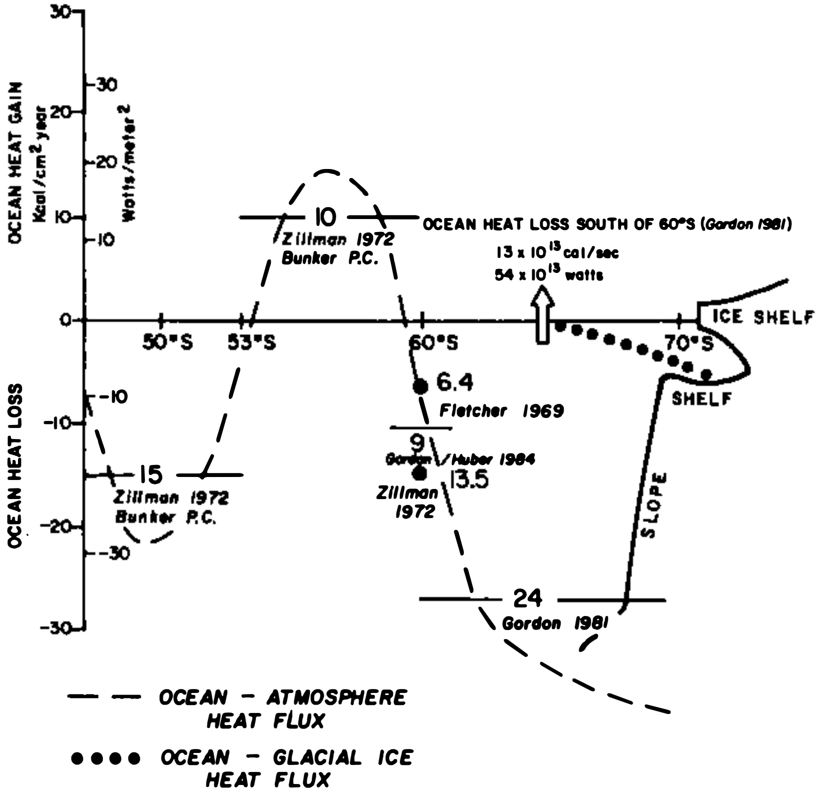

FIGURE A-2 Ocean atmosphere heat exchange for the circum-polar area south of 47°S. The values are drawn from numerous sources, as indicated. Source: Gordon and Owens (1987).

and Zillman (1984) (Figure A-3). The seasonal variability is very large. The complex coupling of the sea-ice cover is also very strongly seasonal, with the seasonal radiation budget and latent and sensible heat fluxes requiring careful consideration if we are to improve sea-air heat flux estimates.

The sea-ice region around Antarctica is the largest variable in the world's climate system on annual time scales (Weller, 1980). Properties of prime importance are the sea-ice albedo, which varies with the thickness, depth, and wetness of the snow cover, and the concentration of the ice cover. The variability of the extent of open water in the pack ice can vary the midwinter energy loss by a factor of ten (Weller, 1980). Weller also finds that using modern estimates of the ratio of thin ice to open water increases the winter air-sea flux estimate about sixfold from previous estimates. The interannual variability of the energy balance in the Southern Hemisphere is, to a large extent, controlled by the variations in the sea-ice cover, which undergoes seasonal variations of a tenfold change in area.

Because the variations in the ice cover are controlled by winds and air temperatures, the strong coupling of the atmosphere and the ice cover can significantly alter the amount of energy the atmosphere receives. The energy flow is complex, but is only roughly estimated; it is crucial to the explanation of the global climatic role of the polar heat sink, and must be better evaluated.

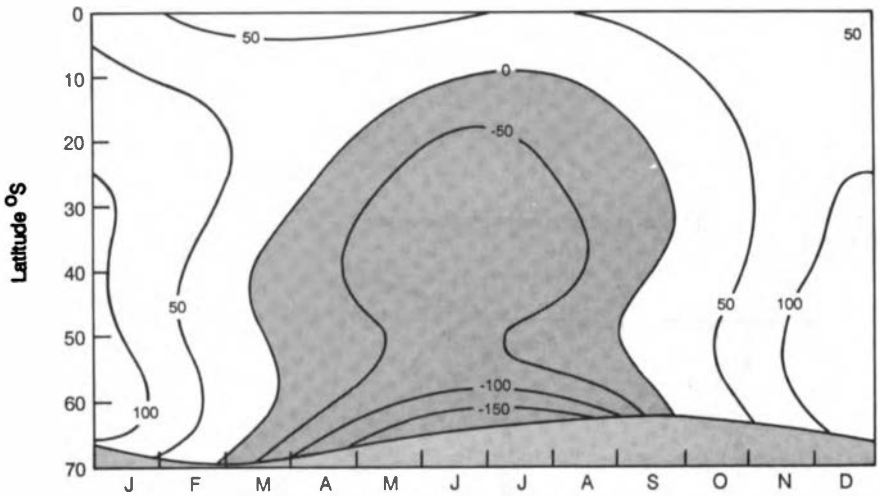

FIGURE A-3 Annual heat balance cycle for the South Pacific. The hatched area indicates the mean northward extent of the pack ice. Source: Streten and Zillman (1984).

Several studies (e.g., Schwerdtfeger and Kachelhoffer, 1973; Ackley, 1981; Carleton, 1981, 1983) indicate correspondence of cyclone activity with fluctuations in ice edge position and possibly with ice concentration. Fluctuations in high-latitude surface air temperature also have been correlated with sea-ice changes (Budd, 1975; Jacka, 1982). Apparent regional effects and feedbacks between ice anomalies and atmospheric anomalies make causality identification difficult.

Effects on Oceanic Processes

Sea-Ice Effects on the Ocean Hydrologic Cycle

The Southern Ocean is a major region of interaction between abyssal waters and the atmosphere. Sea ice uniquely modifies this interaction via the additional processes of freezing, melting, and ice transport.

Processes influenced by ice cover include the convection induced by brine rejection during freezing, and stratification of the upper ocean by melting ice. Because the ice usually is transported from one region to another, the upper ocean may be dominated in one area by freezing processes, resulting in convective instability (e.g., over the continental shelves of the Weddell and Ross Seas) and in another area by melting (near the ice edges), resulting in stability. A major influence is the drastic reduction of heat and moisture fluxes to the atmosphere when the ice cover is present. Ice transport alters the freshwater input to the ocean mixed layer. An ice-modeling study of the Weddell Sea suggests that this transport can remove 3 m of freshwater (as ice) from certain coastal locations and add over 1 m to the mixed layer over relatively localized regions of deep ocean (Hibler and Ackley, 1983). Climatic data indicate 0.5 m or less precipitation-evaporation difference over most of the Southern Ocean (Gordon, 1981).

A question of interest therefore is how sea-ice transport, in addition to the precipitation-evaporation process, can modify the regional upper-ocean salinity budget. The ice cover adds and subtracts freshwater intermittently; snow falling over an ice-covered region will not enter the ocean uniformly. These perturbations may influence calculations of the hydrologic cycle. Finally, sublimation from an ice-covered surface deposits salt in the ocean in quite a different manner than does evaporation from open ocean. Evaporation of an ice surface resulting in, for example, a 1 g ice loss results in an equivalent heat flux that would freeze 4-5 g of ice onto the bottom surface. Therefore the loss of 1 g of water vapor to the atmosphere over ice could result in salt flux to the ocean equivalent to what would result from evaporation of 4-5 g of water from open ocean.

These processes illustrate that open-water and ice-covered ocean processes and their effects lack direct comparability. The unique character of ocean behavior in the presence of ice cover requires unique measurements.Satellite imagery revealed the Weddell Polynya, a 500,000 km^2 open-water area surrounded by sea ice that persisted through the winters of 1974-1976 (Carsey, 1980). Substantial oceanic cooling over the deep-ocean may have taken place (Gordon, 1982). Occurrence of the polynya and the mechanisms of its initiation, maintenance, and eventual demise are the subjects of several studies. The polynya could be maintained by a process of sea-ice formation, brine rejection, convective overturning, and subsequent upwelling of deep-ocean heat, leading to melting of the ice cover (Martinson et al., 1981). The ice melt results in stabilization of the water column and shutdown of the convective overturning. The process may repeat itself, to induce intermittent polynyas (Comiso and Gordon, 1987).

Why the polynya disappeared is unknown. The polynya appeared to drift westward into the region of the western boundary current in the southern part of the Weddell Sea. The region is one of high production of sea ice, primarily because of wind transport of newly formed ice away from the antarctic coast, according to modeling studies (Hibler and Ackley, 1983). The polynya may have been eventually eradicated when the upwelled deep-ocean heat melted sufficient sea ice transported away from the coastline, stabilizing the water column and shutting down the convection.

The interaction of the winds with the upper ocean are important to upper-ocean mixing and in the driving of currents. The winds produce the turbulent exchanges via convection and evaporation and impart momentum to the ocean, generating waves and producing the major wind-driven circulations. These influences are particularly strong in the Southern Ocean because of the vigor of the westerly wind system at mid-high latitudes. How this interaction proceeds, the role of the atmosphere in heat and water vapor transport from one ocean region to another, the variability introduced into the upper ocean by atmospheric variability, and feedback processes whereby the upper ocean affects the atmosphere are still inadequately defined.

The air-sea momentum interaction in the Southern Ocean is unique, because of the extensive, seasonally varying sea-ice cover. The sea ice dissipates momentum by several processes that influence how sensitive the upper ocean is to the atmosphere. The rheological properties of the ice cover differ from those of ocean water. The ice can behave semirigidly, dissipating momentum by deformation and thereby reducing the energy available to the upper ocean for mixing. The ice cover can fracture, build ridges (converting kinetic energy to potential energy), and generate ocean mixing as the ice floes move through the water. By changes in its surface topography, the ice cover can also have a differential drag that changes both atmospheric and oceanic mixing. This characteristic is especially apparent in the marginal ice zones, where the drag coefficient of the surface is three or four times higher than over the winter open-ocean or interior pack-ice surfaces (Andreas et al., 1984). The increased drag can lift the atmospheric boundary layer under steady-flow conditions, markedly affect the downward mixing of air and, therefore, the turbulent exchanges at the surface.

High ocean wave attenuation especially of the higher-frequency components is readily apparent in an ice-covered region. Ice processes such as flow-interaction, flexure, rigid-raft scattering, and reflection provide the mechanisms for this behavior. How the upper ocean is affected is not well known, but the contrast between the sea surface behavior in ice-covered and open-ocean regions is obvious. Wind and wave fields apparently interact strongly at the ice margins. The highest drag coefficients observed (Andreas et al., 1984) are over ice fields with small flow sizes caused by wave-induced breakup of the pack-ice.

Effects on Sea-Ice Processes

Variability of the sea-ice cover can lead to significant seasonal, interannual, and feedback changes in the ocean and atmosphere budget quantities. The cause of the response or change in response of the sea ice is a complex interaction of oceanic and atmospheric forcing. Winds and air temperatures appear to provide the principal forces on the ice cover, with significant roles played also by ocean currents and the temporally and spatially varying oceanic heat flux in the Southern Ocean. Numerical modeling (Hibler and Ackley, 1983) has indicated that the seasonal variability in the Weddell Sea pack-ice is controlled primarily by wind-driven ice advection processes. The strong summer decay of the pack-ice area is related to the continuous transport of ice from the high-latitude embayment of the Weddell Sea. That transport prolongs the ice-covered seasons until overwhelmed by effects of high insolation at and shortly after the summer solstice. Retreat of the ice edge then proceeds rapidly by a combination of intense ocean heating in the open water in the vicinity of the ice edge and continuous transport of ice to be melted there.

Interannual variability of the winds that affect the ice transport significantly alters the advance-decay cycle of antarctic pack-ice. This variability, amounting to 1-2 $\times$ 10^6 km^2 of ice area, has been observed over the past few years. The regions of highest interannual sea-ice variability around Antarctica correspond to the dynamically controlled ice covers of the Weddell and Ross Seas (Lemke et al., 1980). Other climatic indicators, such as hemispheric air temperature, have not shown similar trends. During the 1970s, for example, periods of extended winter maximum sea-ice cover were sometimes followed by summer minima of ice area

(Figure 7 in this report; Zwally et al., 1983). This behavior suggests relatively strong coupling between ice area changes and winds. If the relationship of air temperature to ice area were the primary relationship, winter ice area maxima could be expected to be followed by summer ice area maxima. The seasonal cycle in antarctic sea ice evidently cannot be modeled adequately without the inclusion of appropriate ice dynamical effects (Hibler, 1984). These dynamical effects do not always relate simply to other climatic indices.

Strong influence of the ice cover is to be expected on oceanic heat flux by potential dynamical effects and instabilities induced by brine rejection and ocean overturning. Similarly, oceanic heat flux can affect the sea-ice cover directly as indicated in the extreme by the development of polynyas. How this interaction proceeds and how it can be coupled with secondary-layer models of the ocean, are problems for ice-ocean modeling over the next few years.

ANTARCTIC CIRCUMPOLAR CURRENT

The three major ocean basins are connected by the deep, circumantarctic belt of the Southern Ocean. Within this corridor, massive exchange of ocean water is accomplished by the strong Antarctic Circumpolar Current. The Polar Ocean reviews of the International Union of Geodesy and Geophysics (Gordon, 1983; Gordon and Owens, 1987) briefly describes progress in understanding the Antarctic Circumpolar Current in the Drake Passage. The review of Nowlin and Klinck (1986) goes into greater detail.

Since the mid-1970s, researchers have developed a much more quantitative understanding of the Antarctic Circumpolar Current, its mean and variable parts, and its relation to thermohaline field and meridional fluxes, within the Drake Passage. Researchers now need to assess how typical these results are for the rest of the Antarctic Circumpolar Current. The geometry of the boundaries and bottom topography varies greatly with longitude, and variation in the dominant terms within the dynamical balance may also occur. Because of the vastness of the Antarctic Circumpolar Current, the International Southern Ocean Studies approach is unrealistic as a general strategy. The use of a few moorings at properly selected sites and instrumented drifter arrays closely coupled to satellite-based sensing are needed.

Large Scale Characteristics

The best available station data selected for the *Southern Ocean Atlas* (Gordon and Molinelli, 1982; Gordon and Baker, 1982) have been used to describe the large-scale relative dynamic topography of the Southern Ocean (Gordon et al., 1978). The Antarctic Circumpolar Current is seen in their representation of the geostrophic surface current to 1,000 decibars (db) (Figure A-4). The flow position varies considerably in latitude, largely due to bottom topography. Even for this coarse representation, of 1° latitude by 2° longitude, multiple paths and differences in width are apparent.

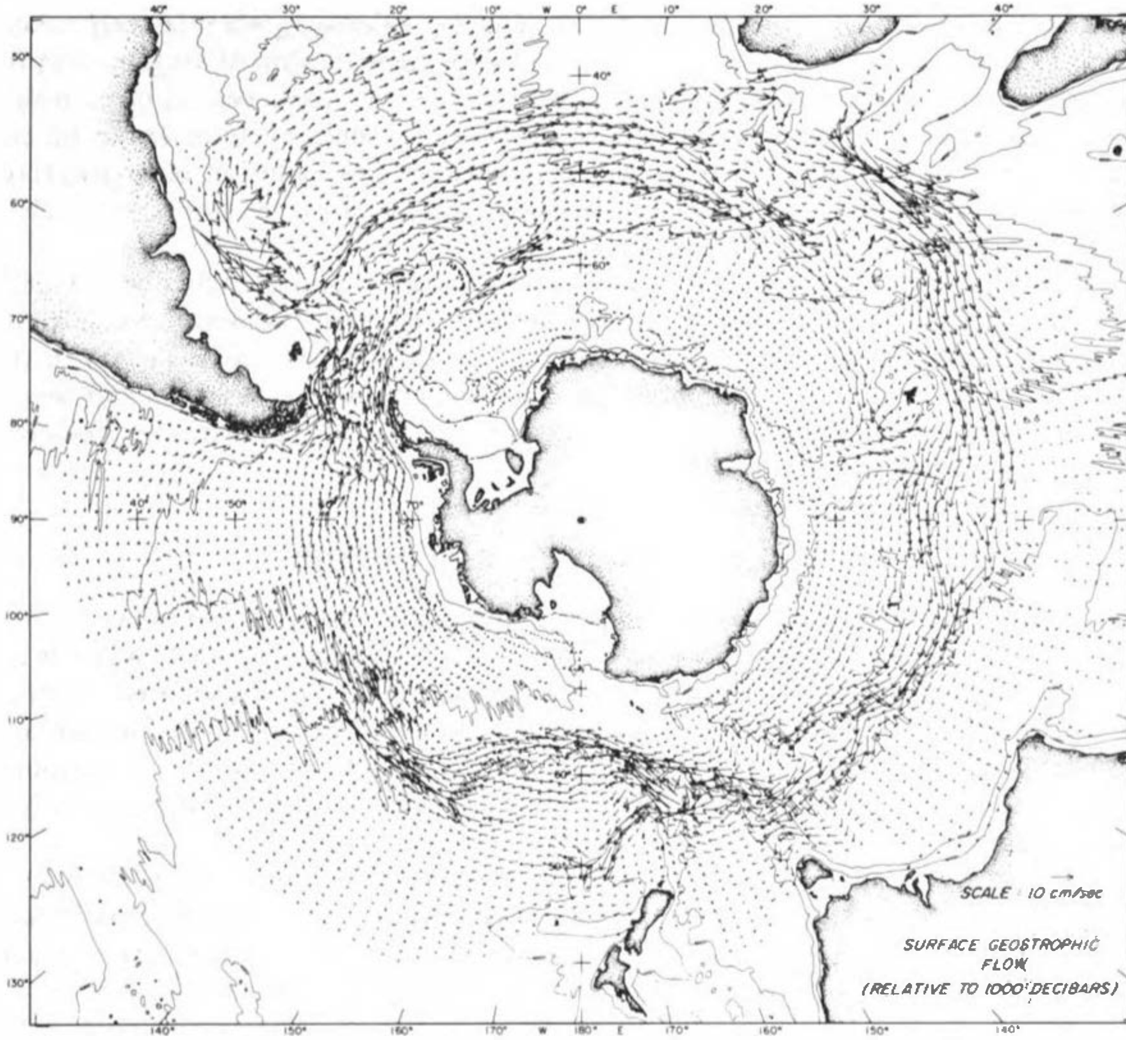

FIGURE A-4 Surface geostrophic current relative to 1,000 decibars. Source: Gordon, Molinelli, and Baker (1978).

The Antarctic Circumpolar Current is conceded generally to be driven principally by wind, although the coupling of wind and thermohaline driving has not been investigated adequately. Climatological surface winds data from Han and Lee (1981) show the annual mean eastward component of wind stress. As shown in many models, the wind stress is sufficient to drive the Antarctic Circumpolar Current. However, the mechanisms that dissipate the current's energy are unclear. Four major mechanisms have been suggested: thermodynamic effects (Fofonoff, 1955), water discharge from Antarctica (Barcilon, 1966, 1967), nonzonal dynamics (Stommel, 1957), and form drag of bottom topography (Munk and Palmen, 1951). The overall vorticity balance is still in doubt. The most likely dissipative mechanisms are form drag by bottom topography and lateral dissipation in western boundary currents.

Thermohaline Structure of the Antarctic Circumpolar Current

The Antarctic Circumpolar Current is composed of two current cores separated by a zone in which the near-surface characteristics are intermediate between those of the antarctic zone south of the current and the subantarctic zone to its north. These current cores are associated with fronts, with pronounced horizontal gradients of density, temperature, and salinity. Within the upper-water column, characteristics change abruptly across the fronts. A vertical section of density across Drake Passage shows three fronts separating four water mass zones, (Figure A-5). The Subantarctic Front and the Polar Front are probably circumpolar (Emery, 1977; Gordon et al., 1977a; McCartney, 1977, 1982; Hofmann, 1985). The fronts are narrow, if the few regions where sampling has been adequate are representative. Widths are 50 km or less at the Drake Passage (Nowlin and Clifford, 1982) and about 100 km in open ocean. This is twice the radius of local deformation.

Data on geostrophic shear, with reference to measured subsurface currents or to deep reference levels, indicate maximum geostrophic surface speeds at the Antarctic Circumpolar Current cores of 30-45 cm/s at Drake Passage (Figure A-6). With a very deep pressure surface as the reference, closely spaced stations along the Greenwich Meridian yield similar surface speeds. The geostrophic shear associated with these fronts extends deep into the water column—to the bottom in Drake Passage (Nowlin et al., 1977).

The structure of the transition from subantarctic to antarctic waters, with two fronts having deep-reaching baroclinicity separating a transition zone (Gordon et al., 1977a, 1977b), is not explained. The processes responsible for this horizontal zonation may occur for weakly stratified zonal flow through a meridionally confined region of reduced depth. The Antarctic Circumpolar Current must pass through such regions, including the Drake Passage, and this might influence zonation. Another influence may be the distribution of sea-air fluxes and ice distributions (Taylor et al., 1978; Toole, 1981). The processses responsible for the maintenance of the observed horizontal thermohaline zonation of the Antarctic Circumpolar Current remain unknown. Successful modeling of Southern Ocean circulation requires that they be understood.

Eddies and Rings

A large amount of mesoscale variability within the Antarctic Circumpolar Current is associated with its zonation. This eddy variability is due to a combination of factors. The current cores migrate laterally (Nowlin et al., 1977), by as much as 100 km in 10 days. Meanders, or waves, form and propagate along the Antarctic Circumpolar Current fronts. The first synoptic observations of their zonal propagation was from satellite and moored current meters (Legeckis, 1977; Sciremammano, 1979). Subsequent observations by larger arrays of moored instruments, satellites, and surface drifters have documented the commonplace existence of such meanders. These meanders sometimes develop into closed current rings. The first such observation of formation was reported by Joyce and Patterson (1977); many more observations

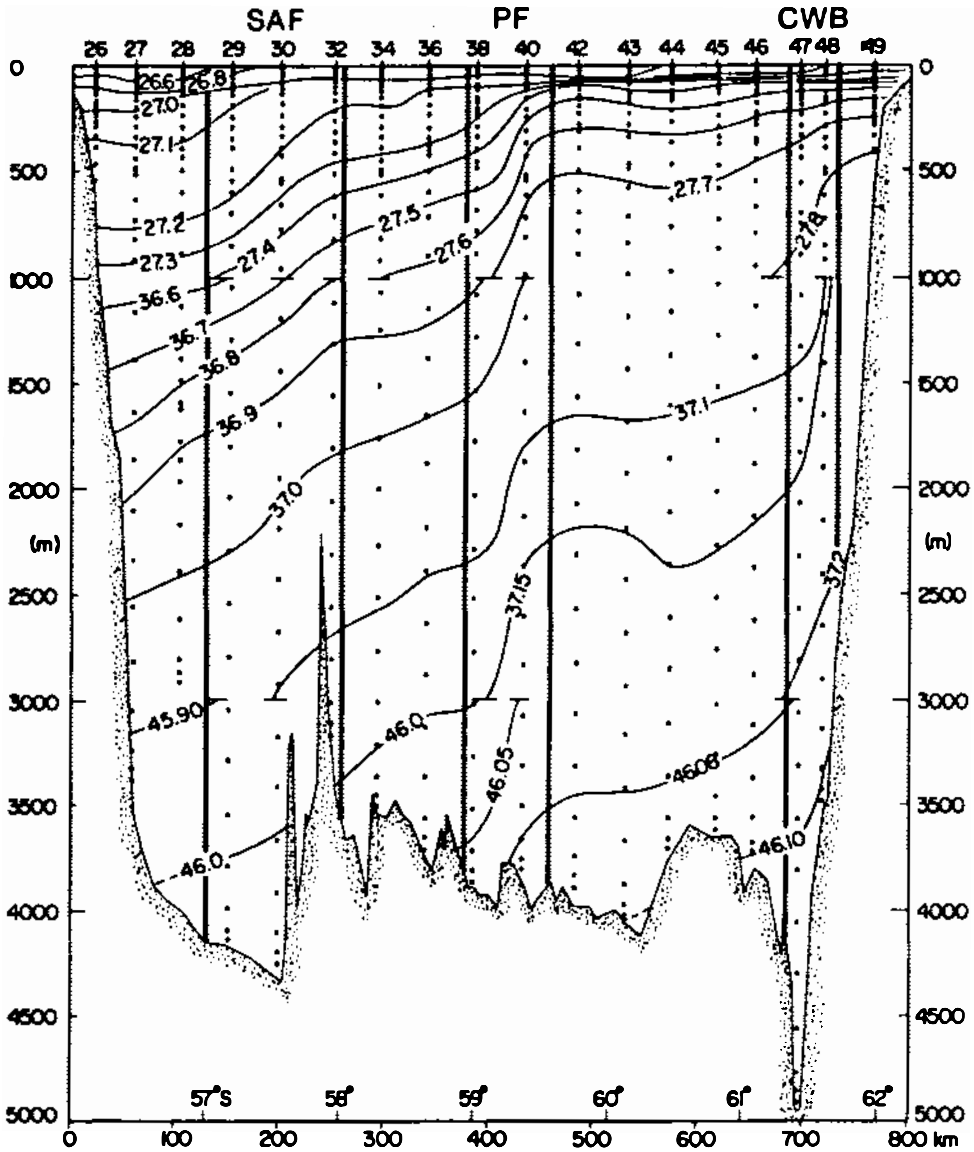

FIGURE A-5 Potential density anomaly. Source: Nowlin and Clifford (1982).

of rings have followed. Cold and warm core rings have both been observed. They appear to form from both the Subantarctic Front and the Polar Front.

Bryden (1983), summarizing the characteristics of eddy variability observed in the Southern Ocean, stated that such variability is found everywhere observations

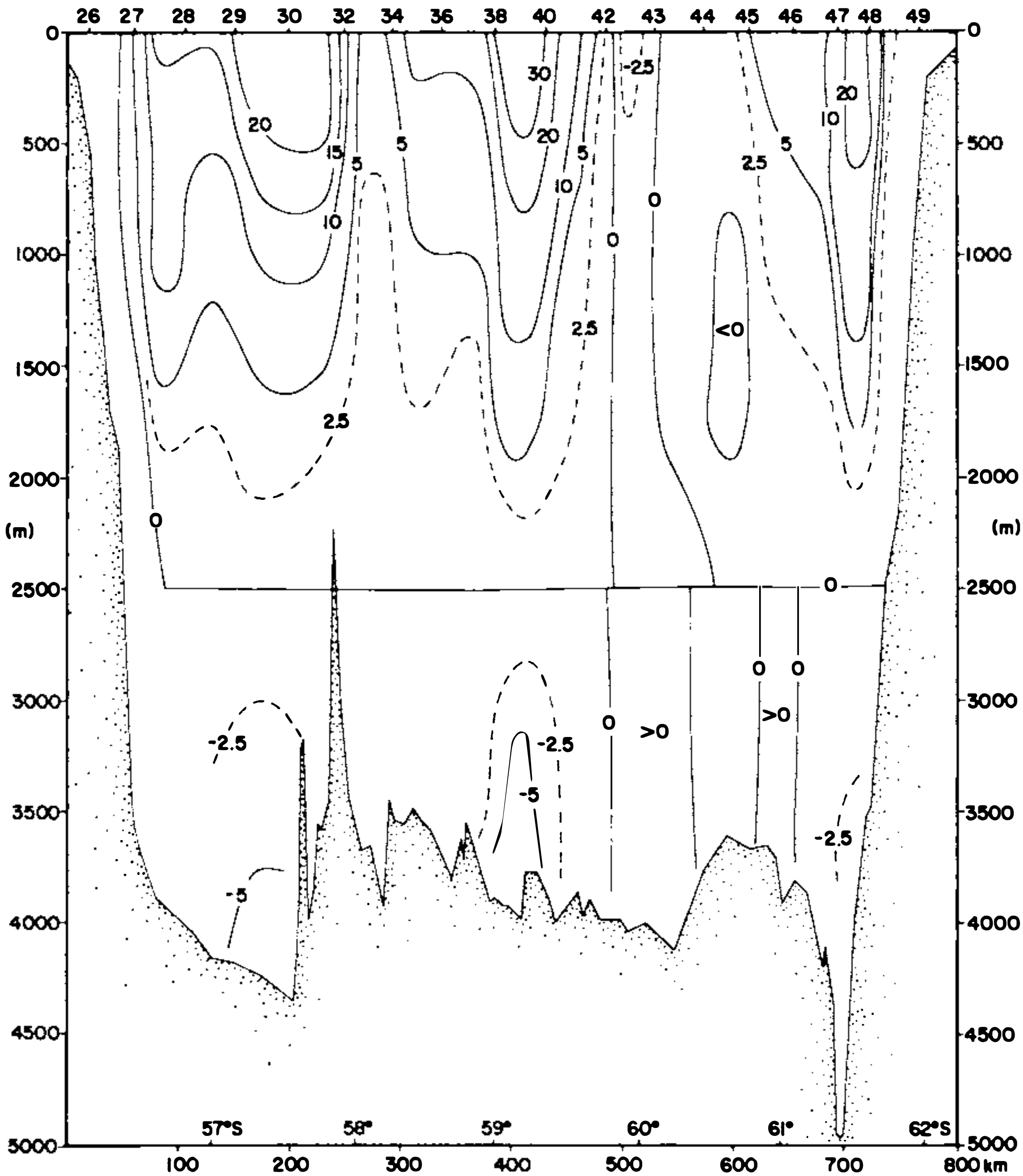

FIGURE A-6 Through-passage geostrophic speed (cm/s). Source: Nowlin, Whitworth, and Pillsbury (1977).

have been made, eddies are 30-100 km wide, their surface velocities are typically 30 or more cm/s, and eddies are vertically coherent from surface to bottom. Numerous current rings and meanders have been reported at Drake Passage. Heat, salt, and mechanical and potential energies of various rings have been estimated and reported (Joyce and Patterson, 1977; Peterson et al., 1982; Pillsbury and Bottero, 1984).

Cold core rings have been observed forming from the Polar Front on two occasions (Joyce and Patterson, 1977; Peterson et al., 1982). Counting such occurrences or the ratio of warm core to cold core rings is difficult. Cloud cover limits satellite images of surface color and temperature. From time series at moored arrays, Pillsbury and Bottero (1984) interpreted the records from a mid-passage location as showing that five cyclonic rings and one anticyclonic ring passed from June 1975 through January 1976. The cyclonic ring has the properties of the continental water and is likely derived from the continental water boundary; the anticyclonic (warm core) ring is believed to have separated from the Polar Front. The rings had diameters of 30-130 km and extended at least 2,500 m vertically. Weekly synoptic maps constructed for the central passage during 1979 by Hofmann and Whitworth (1985) tracked four rings, north of the Polar Front, and several large meanders. Although the Drake Passage may not be characteristic of the circumpolar situation, these data imply that the number of Antarctic Circumpolar Current rings may be large.

Bryden and Heath (1985) studied mesoscale fluctuations by using data from the measurement site southeast of New Zealand, just north of the Subantarctic Front. They reported energetic eddies, with typical amplitudes of 200 cm/s at 1,000 m depth, to be vertically coherent throughout the water column, to vary over 30 days and 60 km, and to propagate toward the southeast at about 12 cm/s. Maximum eddy kinetic energy (169 cm^2/s^2) was found at their shallowest record depth (1,000 m). Though the horizontal scales from the Pacific location are somewhat larger than those in Drake Passage, the other results are in remarkable agreement.

Transport of Antarctic Circumpolar Current

Estimates of the volume transport of the Antarctic Circumpolar Current have frequently been used as inputs to and observational checks on global circulation models. Realistic estimates of the transport and its variability provide a test for the ability of models to account for pertinent dynamics. A model that cannot produce reasonable transport estimates is deficient.

Early estimates of Antarctic Circumpolar Current transport that required the selection of a reference level varied greatly. Because the geostrophic shear in the current fronts extends practically to the bottom, mid-depth choices of reference levels indicated westward deep flow under eastward flow and led to poor transport estimates. Distinguishing between the Antarctic Circumpolar Current flow and the flow due to adjacent currents is difficult, particularly in estimating transport at locations other than Drake Passage. In the open ocean the southern limbs of the subtropical gyres and northern limbs of the subpolar gyres also flow eastward. South of Australia and Africa, other current systems, e.g., the Agulhas Current, add to the confusion.

Geostrophic transport through Drake Passage relative to 3,000 db for five crossings made during 1975 and 1976 showed the baroclinic field to be relatively constant, with an average of 95×10^6 m^3/s (Nowlin et al., 1977). This is consistent with estimates of relative geostrophic transports from earlier sections at Drake Passage (Reid and Nowlin, 1971). Nowlin and Clifford (1982) showed that the transports associated with the three fronts in Drake Passage account for approximately 75 percent of the total baroclinic transport, relative to 2,500 db, although the fronts occupy only 19 percent of the width of the passage.

The first estimates of Antarctic Circumpolar Current transport at Drake Passage by reference of geostrophic shear to direct current measurements were made at Drake Passage in 1969 (Reid and Nowlin, 1971) and 1970 (Foster, 1972). These were confusing and provocative; the two independent estimates gave widely disparate results (15×10^6 m^3/s westward and 237×10^6 m^3/s eastward).

A principal objective of the International Southern Ocean Studies was to obtain a year long record of Antarctic Circumpolar Current transport at Drake Passage. Initial effort went into the determination of velocity scale lengths. As a result of that work several preliminary transport estimates were produced by using data collected in 1975: $110 - 138 \times 10^6$ m^3/s (Nowlin et al., 1977); $139 \pm 36 \times 10^6$ m^3/s (Bryden and Pillsbury, 1977); and $127 \pm 14 \times 10^6$ m^3/s (Fandry and Pillsbury, 1979). All indicated eastward flow, and the agreement was good. Improved description of the Antarctic Circumpolar Current showed that the disparate results of 1969 and 1970 resulted from undersampling of the reference velocities in the presence of highly structured current consisting of meandering current cores.

The final International Southern Ocean Studies product was a time series of transport from January 1979 to January 1980. The data were from precision pressure transducers and heavily instrumented moorings simulating hydrographic stations on both sides of the passage, from a large array of current meters moored on a line across the passage, and from three shipboard density surveys. Results have been described by Whitworth (1983) and Whitworth and Peterson (1985). The final transport (Figure A-7) has a mean of 125×10^6 m^3/s with a standard deviation of 10×10^6 m^3/s. As can be seen by comparing the geostrophic transport of the upper 2,500 m relative to 500 m (also shown) with the net transport, higher frequency fluctuations occur in the barotropic mode.

Pressure records from both sides of the passage during the two years preceding the 1979 experiment have been used by Whitworth and Peterson (1985) to extend the transport time series to three years. Comparison of net transport and transport estimated from pressure differences above during 1979 shows a maximum difference of 24×10^6 m^3/s; more than 90 percent of the pressure-derived estimates are in error by less than 10×10^6 m^3/s. The three-year pressure-derived transport has a range of 61×10^6 m^3/s and a standard deviation of 10×10^6 m^3/s around a mean of 123×10^6 m^3/s, and suggests annual and semiannual fluctuations.

Kinematics of the Antarctic Circumpolar Current

The first estimates of circumpolar distributions of kinematic variability and surface kinetic energy have become available in the last 10 years. Based on geopotential anomalies, ship drift records, surface drifter trajectories, and satellite altimetry, these distributions reveal regional differences in kinetic energy and variability

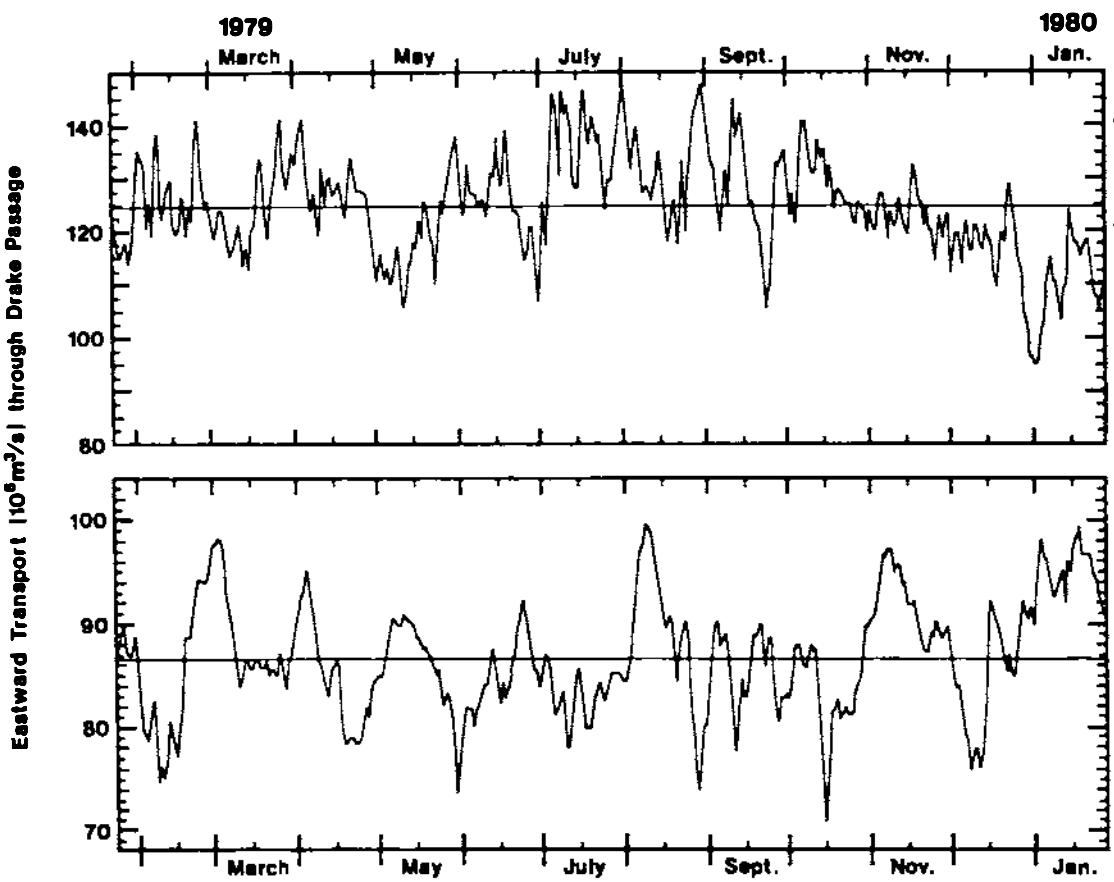

FIGURE A-7 Transport time series at Drake Passage. Source: Whitworth (1983).

over the path of the Antarctic Circumpolar Current inferred to be associated with current-topography interactions, interactions of the Antarctic Circumpolar Current with other current regimes, and boundary effects.

Wyrtki et al. (1976) used merchant vessel observations of surface drift current to calculate kinetic energy of the mean flow and of the fluctuations, interpreted as eddy kinetic energy, for the world ocean based on 5° squares. Though the sparsity of data from high southern latitudes precluded good coverage of the Antarctic Circumpolar Current, a general distribution of mean kinetic energy and some indications of regions with unusually high eddy kinetic energy (e.g., Drake Passage and south of Africa) were revealed.

Using all available hydrographic stations, Lutjeharms and Baker (1980) carried out a statistical analysis of the mesoscale variability of the Southern Ocean. They presented patterns in the circulation intensity as expressed by the variance and spatial structure function of the 0-1,000 db dynamic height interval. The intensity of the mesoscale field was shown to be inversely proportional to the distance from the mean Antarctic Circumpolar Current axis. The Polar Front may act as an eddy-generating region over its length. An upper limit of 150 to 250 km for the mesoscale turbulence was found for most of the Southern Ocean. Distinct patterns of high intensity of the variability correlated closely with prominent topographic features.

The satellite altimeter has proven to be an effective way to study the temporal variations of the Antarctic Circumpolar Current (Fu and Chelton, 1984, 1985). Colinear altimeter data from the last 25 days of SEASAT have been used in several studies of mesoscale variability, including the region of the Antarctic Circumpolar Current. Colton and Chase (1983) selected three regions for study of sea surface variability induced by interaction of the Antarctic Circumpolar Current with bottom topography: the Indian-Antarctic Ridge south of Australia, representing zonal flow over a zonal ridge; the Macquarie Ridge southwest of New Zealand, representing zonal flow over an isolated bump; and the Indian Mid-Ocean Ridge south of Africa, representing zonal flow over a meridional ridge. Residuals of colinear tracks from the mean profile were calculated to represent variations of sea surface height.

Cheney et al. (1983) presented a global distribution of mesoscale variability of the sea surface (Figure 3 in this report). The high variability of the Antarctic Circumpolar Current extended nearly continuously around Antarctica. Only in the extreme southeast Pacific and in the central South Atlantic were values of variability less than 5 cm based on 2° gridded values. Values in excess of 6 cm were found over much of the Antarctic Circumpolar Current path, with decreasing values both to the north and the south. The largest variability again seemed to be associated with areas of major topographic relief. Fu and Chelton (1985) used the three-month set of SEASAT crossover difference to study large-scale temporal variability of the Antarctic Circumpolar Current. They show eastward acceleration of the current (with some deviations from the trend), which appears to be associated with bottom topographic features.

Using data from the drifting buoys deployed for the Global Weather Experiment, Garrett (1981) computed the mean and eddy kinetic energy on a 10°-latitude by 10°-longitude grid for the Southern Ocean. The results showed a general increase in kinetic energy levels, particularly the mean, associated with the Antarctic Circumpolar Current. However, the grid size was too large to permit much definition.

Patterson (1985) generated hourly buoy positions from smoothed trajectories. The drifter trajectories showed highly zonal distribution of surface mean kinetic energy associated with the Antarctic Circumpolar Current (see Figures 5 and 6 in this report). Relatively high mean kinetic energies (500 cm^2/s^2) appear within the Antarctic Circumpolar Current near major bathymetric features. The two regions of relatively low kinetic energy are in the extreme southeast Pacific and south of Australia, upstream of major topographic obstructions. Most of the kinetic energy of the surface circulation is in the eddy field (Figure 6). Eddy kinetic energy was calculated as the difference between total and mean kinetic energies for each 5° × 5° box.

Unlike the mean kinetic energy distribution, which is zonal, the highest values of eddy kinetic energy are associated with western boundaries. Secondary maxima occur in patches within the zonal flow of the Antarctic Circumpolar Current shown in the mean kinetic energy pattern. This suggests that energy emanates from southern sources in the western boundary regimes, as well as from regions with major topographic features of variability.

The kinetic energy levels in the Antarctic Circumpolar Current at Drake Passage have been studied in considerable detail. Nowlin et al. (1981) examined 31 long records. They found no significant temporal variability, based on comparison over four years, but they found large spatial variability. The general trend is for mean kinetic energy values of 5-15 cm^2/s^2 at 2,500-3,000 m increasing upward to values near 300 cm^2/s^2 at 500 m. Eddy kinetic energy values seem rather uniform in the southern passage, increasing northward into the Antarctic Circumpolar Current. Maximum values were found at the northernmost moorings (total eddy kinetic energy in the deep-water increases by a factor of 5). Studies of the principal short-period tides (Nowlin et al., 1982) and of internal and near-inertial oscillations (Nowlin et al., 1986) have led to estimates of the fractions of eddy kinetic energy—for periods of two hours to two days—associated with these phenomena at Drake Passage.

WATER MASS CONVERSION

Antarctic Circumpolar Zone

Water mass conversion and Polar Front research probably benefited more than any other phase of antarctic physical oceanography from the availability of profiling instruments. Increased reliance on conductivity-temperature-depth (CTD) equipment for hydrographic measurements with expandable bathythermographs (XBT) revealed the complex nature of water mass stratification and made possible the mapping of coherent fine structures; and the details of the Polar Front zone (Gordon et al., 1977a, b; Joyce et al., 1978).

Numerous closely spaced hydrographic sections across the Drake Passage and in the Western Scotia Sea confirmed a series of large horizontal density gradients associated with high-velocity cores in the Antarctic Circumpolar Current. From small-scale heat and salt exchanges associated with interleaving at the boundary of water masses at the Polar Front in the Drake Passage, Joyce et al. (1978) estimated that intrusive heat flux across a 500-m-deep circumpolar Polar Front would be 36 $\times 10^{13}$ W (about ten percent of the required heat flux). The intrusive salt flux was estimated to be more significant in relation to the likely total salt flux across the Antarctic Circumpolar Current. Few studies of other processes responsible for transport of salt across the Antarctic Circumpolar Current have appeared.

During the past decade, traditional theories of antarctic intermediate water formation were refined. A new interpretation advanced (McCartney, 1977; Molinelli, 1981) that identified antarctic intermediate water solely as the end product of progressive circumpolar cooling of subantarctic waters by winter heat loss. Subantarctic waters (subantarctic mode water) are characterized by a low vertical stability (pycnostad) and are warmest in the western South Atlantic and coolest in the southeast Pacific. McCartney (1977, 1982) found that southeast Pacific subantarctic mode water undergoes additional cooling in the Drake Passage and Western Scotia Sea, and passes into the Atlantic where it can be identified as antarctic intermediate water. However, Piola and Georgi (1981) calculated that the sea-air heat exchanges are insufficient to convert southeast Pacific subantarctic mode water into South Atlantic antarctic intermediate water. Although a purely subantarctic origin appears unlikely to account for all types of antarctic intermediate water found in the world's oceans (Piola and Georgi, 1982), subantarctic mode water appears to contribute volumetrically significant quantities to the subantarctic and subtropical thermohalines (Georgi, 1979). The controversy has spurred the collection of modern winter hydrographic data in the Drake Passage and southeast of New Zealand, benefiting a variety of Southern Ocean studies.

Because most relevant hydrographic observations in the last 10 years have been made in the immediate vicinity of the Drake Passage, the magnitude of cross-frontal mixing in the full circumpolar Polar Front cannot yet be estimated. Are the calculated fine structure fluxes from the Drake Passage and south of New Zealand typical of those south of Africa or Australia? How do Polar Front fluxes compare to the fine-structure-derived lateral fluxes that appear to be dissipating the antarctic intermediate water in the Brazil-Falkland (Malvinas) confluence or where the Agulhas Current impinges on antarctic intermediate water moving eastward with the circumpolar current? What role do double-diffusive processes play in formation and destruction of antarctic intermediate water? Is fine structure ubiquitous and merely another signature of baroclinic instability?

These are questions that we have only recently been able to pose. Answers to some can be achieved in the next decade. One fundamental assumption in theories of formation of antarctic intermediate water and subantarctic mode water is that the oceans are in steady-state equilibrium. However, some water masses observed today may not be routinely generated in the same quantities or with the same characteristics.

On what scale do we need to monitor the renewal of antarctic intermediate water and subantarctic mode water formation? In order to address the role of cross-frontal mixing and to gain a better understanding of the physics of small-scale processes, both field experiments and theoretical studies should be pursued. New field experiments and observations should incorporate geochemical tracers (helium-3/hydrogen-3, Freon), and investigate the use of expendable velocity probes and shipboard acoustic Doppler instruments. Such equipment can provide detailed descriptions of high-frequency and high-vertical-wave-number internal wave motion and perhaps illustrate its role in mixing and stirring.

Neutrally buoyant floats proved useful as water-parcel tags in small experiments carried out in the Southern Ocean by Joyce et al. (1978). New technology that would permit the floats to alter ballast and follow all internal-wave-induced motions should make possible the monitoring of thermohaline evolution of individual water packets.

Full documentation of the role of deep-winter convection in the formation of subantarctic mode water and antarctic intermediate water requires improved methods to monitor air-sea heat and freshwater exchanges. The presence of a ship contaminates meteorological data, and monitoring for winter convection from oceanographic vessels may be impractical because of the vast expanse of the Southern Ocean. Development and deployment of instrumented drifting buoys with satellite data links are essential. Such platforms should carry meteorological sensors and thermistor chains. Humidity and wind indicators aboard the buoys would permit the use of bulk aerodynamic formulas to estimate air-sea heat exchanges.

XBTs have been used relatively inexpensively from ships of opportunity, but an exhaustive study of past data should precede additional data collection. Data from XBT probes can be used to monitor heat storage in the subantarctic; a long-term program should be established with XBT transects repeated regularly.

Divergence of flux associated with sea-air-ice interaction must be compensated by meridional exchange of ocean properties. In this way, water mass characteristics modified by exposure to the polar environment spread to the rest of the world ocean.

By very early in this century, warm deep water had been shown to upwell to shallow depths near Antarctica and relate to the formation of an abyssal layer of cold antarctic water. Warren (1981) reviews the development of this understanding. The surface modifications necessary to produce these dense waters require a large heat exchange from ocean to atmosphere (Figure A-2) and an equivalent poleward heat flux in the ocean.

The heat flux across the Antarctic Circumpolar Current is estimated as 10^{14} W (Gordon and Owen, 1987). It can be accomplished by large-scale mean geostrophic circulation, the eddy field, by Ekman transport, and by deep boundary currents (Nowlin and Klinck, 1986).

The advective geostrophic heat flux and Ekman flux across a circumpolar boundary were determined by deSzoeke and Levine (1981) from selected historical hydrographic and wind data, taken to represent the mean climatic state. They found that the mean circulation field is not a significant contributor to meridional heat flux. They estimated a total equatorward heat flux of 1.50×10^{14} W associated with an Ekman transport of 28×10^6 m^3/s.

Eddy processes and deep boundary currents are the prime candidates responsible for the poleward heat flux. As an extreme example deSzoeke and Levine (1981) calculated a poleward heat flux by deep boundary currents of 1.5×10^{14} W (deep outflow of 20×10^6 m^3/s with an average potential temperature of -0.5°C). Monitoring of conditions in the major deep outflows is one way to determine the heat transported by deep boundary currents.

Bryden (1979) estimated meridional eddy flux from six nearly yearlong measurements of temperature and velocity from depths near 2,700 m at locations spanning

Drake Passage. His average poleward heat flux estimate of 6.7 kW/m^2 across the Antarctic Circumpolar Current yields a circumpolar poleward flux of 5×10^{14} W. Sciremammano (1980) compared eddy heat flux estimates based on 1976 records with Bryden's results from 1975 records for the same locations and found little difference at the northern and southern positions. Using 1977 measurements from a cluster of five moorings in the central passage, Sciremammano extended Bryden's estimates to depths of 1,000-2,500 m. The variation in estimated eddy heat flux at this location during 3 years at all depths was large (9-28 kW/m^2, with a mean of 17 kW/m^2), considerably larger than Bryden's deep-water value of 6.7 kW/m^2.

All of the above estimates were based on records of at least five months in duration. The data used in those studies were not corrected for temperature variations due to vertical motions as in a later study (Nowlin et al., 1985) using a more extensive instrument array (Figure A-7).

Bryden and Heath (1985) examined mesoscale variability at the northern edge of the Antarctic Circumpolar Current in the southwest Pacific. They used current and temperature records from an array moored for 2 years near 49°30'S, 170°W, southeast of New Zealand. Their estimated values of meridional heat flux varied from 1 to 35 kW/m^2, within the range calculated at the Drake Passage. Bryden and Heath (1985) found that because of the long-time scales of energetic variability, the overall eddy heat flux was not statistically significant, although that portion in the 20- to 40-day band is significantly poleward.

Poleward of the Antarctic Circumpolar Current

The Southern Ocean waters poleward of the Antarctic Circumpolar Current lie in the primary source region for the deep and bottom waters of the world ocean.

The average temperature of the abyssal ocean that has isopycnal communication with the surface water south of the Antarctic Circumpolar Current is 1.76°C (derived from Worthington, 1981). Reduction of this water temperature to the sea surface freezing point, −1.9°C, would require a volume flux of 32×10^6 m^3/s to support the characteristic meridional heat flux discussed above. Because water that returns northward across the Antarctic Circumpolar Current is warmer than the freezing point, the actual volume flux would be larger (Gordon and Taylor, 1975).

Evidence of this large volume flux is clearly observed in the world ocean—84 percent of the 200 most voluminous T/S (temperature/salinity) modes in the world ocean, representing 57 percent of the world ocean volume, are colder than 2°C, determined from data presented by Worthington (1981). They cannot be associated with North Atlantic deep water and hence must be Antarctic in origin.

The ocean area south of the Antarctic Circumpolar Current (average position at 53°S) covers approximately 40 million km^2; 35 million km^2 is within the deep ocean, the rest is over the continental shelf(Carmack, 1977). The atmosphere removes heat and, depending on the magnitude of the freshwater flux, removes buoyancy. The wind stress curl induces regional Ekman upwelling (Gordon et al., 1977a), which removes surface water and replaces it with denser-deep water. Surface water residence time attributable only to the Ekman upwelling effect is approximately 2 to 3 years. Buoyancy removal in conjunction with Ekman upwelling is responsible for the intense and far-reaching influence of the water conversion south of the Antarctic Circumpolar Current.

Water mass conversion associated with ventilation south of the Antarctic Circumpolar Current is often discussed in terms of continental margin and open-ocean processes (Carmack, 1984). The former have received more attention, and both have been subjected to speculation because winter observations were lacking. Our understanding is largely based on integrated effects and extrapolations from the summer data. Recent progress has been reviewed by Warren (1981) and Killworth (1983).

The deep-ocean regime south of the Antarctic Circumpolar Current is influenced by the positive wind stress curl, which in combination with general upwelling induces poleward Sverdrup transport. Eversen and Veronis (1975) showed that south of the maximum westerlies, with the Antarctic Peninsula serving as both the eastern and western boundaries, the total Sverdrup transport amounts to 300×10^6 m^3/s. This requires a mean poleward baroclinic velocity of only 0.4 cm/s. Hydrographic data indicate very weak baroclinic flow south of the Antarctic Circumpolar Current; characteristic velocities are 1 cm/s. Values of 5-10 cm/s are associated with boundary currents over the continental slope and the western boundary currents of the three cyclonic flowing subpolar gyres. Much of the circulation is with large cyclonic flowing gyres. These can be considered to be subpolar gyres, southern hemisphere counterparts to the Greenland gyre and Bering Sea gyre. The largest and best defined of these is the Weddell Gyre, extending east of the Antarctic Peninsula to 20-30°E and from Antarctica near 70°S to 55-60°S (Deacon, 1979; Gordon et al., 1981). The others are the Ross Gyre, north and east of the Ross Sea (Deacon, 1937; Tchernia and Jeanen, 1983) and a poorly defined gyre east of the Kerguelen Plateau (Deacon, 1937; Rodman and Gordon, 1982; Tchernia and Jeanen, 1983).

The Weddell Gyre is a large, wind-driven subpolar Sverdrup gyre, with a transport of 70-90 $\times 10^6$ m^3/s (Carmack and Foster, 1975; Gordon et al., 1981). Antarctic bottom water is formed along the Weddell Sea continental boundary. Along its northern boundary the Weddell Gyre merges with circumpolar waters entering the Atlantic via the Drake Passage, creating a zone of low stability, the Weddell-Scotia Confluence (Gordon, 1967; Patterson and Sievers, 1980). This region and the Branfield Strait along the northern top of the Antarctic Peninsula are subject to convective processes (Deacon and Moorey, 1975; Gordon and Nowlen, 1978) and high biological activity.

The Weddell Gyre is likely to be the source of much of the abyssal ocean characteristics (Reid et al., 1977), and thus is of prime concern in regard to open-ocean water mass conversion. The thermohaline stratification of the open ocean south of the Antarctic Circumpolar Current occurs in three layers. A cold, 100m thick, low-salinity layer overlies a weak pycnocline of similar thickness, beneath which is the much larger, warmer, and saltier deep stratum. With increasing depth, the deep layer yields to slightly colder and fresher water derived from various sites along the continental margin.

Pycnocline stability is weak, with buoyancy input by freshwater, marginally compensating the Ekman-induced upwelling of salty deep water. Upwelled deep water apparently is converted to surface water and is removed laterally by Ekman drift. Within the subpolar gyres, however, the pycnocline shoals and weakens. This makes the gyres, particularly the Weddell Gyre, susceptible to deep convective processes (Martinson, et al., 1981; Killworth, 1983), as occurred during the Weddell Polynya episode in the austral winters of 1974, 1975, and 1976 (Carsey, 1980). Massive convective overturning cooled the deep water by up to 0.5°C to a depth of 2,500 m (Gordon, 1982). Shorter-lived but recurring polynyas within the subpolar zone have been observed by satellite near 65°S, 5°E, and near 67°S, 45°E (Zwally et al., 1979; 1983; Comiso and Gordon, 1987). Convective processes at several sites may be intermittent but frequent.

Factors that link deep-water upwelling and entrainment, deep- and bottom-water formation, the seasonal production of sea ice, and the variability of atmospheric forcing must be better understood to permit effective parameterization in modeling. The significant water mass conversion associated with these processes occur primarily during winter whereas our view of the thermohaline structure of the Weddell Gyre is based on summer data. Buoyancy within the gyres is removed by cooling and by salinization from ice formation only in winter. The mixed-layer density is increased as turbulent energy introduced by sea-ice movement stirs up salt from the halocline below (Gordon and Huber, 1984). Measurements from ships, from instrumented arrays below the ice cover, and from satellites are needed to obtain the necessary understanding of winter conditions below the sea ice. The 1986 Winter Weddell Sea Project aboard the German research vessel *Polarstern*, should provide basic information required to set out specific winter observational strategies.

The water over the continental shelf is exposed to the harshest form of the antarctic atmosphere, as very cold dry air flows off the continent. Strong winter winds often remove the insulating cover of sea ice adjacent to the coast (Zwally et al., 1985). These coastal polynyas become potential sea-ice factories, in which massive amounts of sea ice can form and be quickly transported northward. This in turn induces extreme thermohaline alterations of shelf water (Zwally et al., 1985) increasing salinity by as much as 0.3 ppt. The shelf water contacts the fronts and bases of the glacial ice shelves, further modifying the water masses (Jacobs et al., 1979, 1985; Weiss et al., 1979).

Shelf water is colder than the deep-ocean water column but displays a wide range of salinity, and hence density. At several sites the shelf-water density is high enough, even in summer, to allow deep-reaching convection, if it escapes from the shelf. Deep-reaching convection, not necessarily to the seafloor (Carmack and Killworth, 1978), is often suggested by hydrographic data from the vicinity of the continental margin.

Environmental conditions specifically responsible for the wide range of shelf-water characteristics, its mixing with deep water, and the formation of antarctic bottom water are not known. Killworth (1983) reviewed observations and argued that five ingredients appear to be involved in production of deep water near oceanic boundaries; a reservoir in which to form dense water, a source of dense water within the reservoir, a "reason" for the dense water to leave the reservoir, the involvement of more than one water mass in dense water formation, and a combination of densities, geography, and dynamics that do actually permit the dense water to sink. Regional influences in the process of recent interest include glacial ice and the atmospheric and coastal polynyas.

One of the strongest fronts of the Antarctic Ocean separates the shelf and deep water (Killworth, 1977; Jacobs et al., 1985; Figure A-8). Across this front must pass the supply of new shelf water, potential bottom water, and large volumes of sea ice and glacial ice. Recipes for mixing at the shelf-slope front have been proposed from summer observations of the integrated effects of water mass conversion, but the actual exchange processes the subject to speculation.

Formed at several sites, the coldest, freshest, and probably the largest volume antarctic bottom water is formed in the southwest corner of the Weddell Gyre in winter by the sinking along the continental slope of cold shelf water, the salinity of which has been raised by haline convection, and its subsequent mixing with Weddell deep water (Carmack, 1977).

Postulated processes and sources contributing to Weddell bottom-water formation have included cabbeling, haline convection by evaporation or freezing in open leads and polynyas, cooling under the Filchner Ice Shelf, Ekman-layer effects, sinking along frontal zones, derivation from deeper oceanic areas, overflow of dense water from the Bransfield Strait, and double-diffusive convection. Estimates of the formation rate of bottom water in the Weddell Sea range from 1-5 $\times 10^6$ m^3/s (Foster and Carmack, 1976). Estimates of circumpolar production rates of antarctic bottom water is in excess of 10×10^6 m^3/s (Jacobs et al., 1985). The importance of antarctic bottom water to the world ocean warrants more information on fluxes and production processes.

A core of relatively warm and saline deep water over the continental slope in the Weddell Sea is associated with strong baroclinic westward flow. This is likely to be the primary source of oceanic heat and salinity for the western portion of the Weddell Gyre. Surface flow is near 10 cm/s, relative to the seafloor, in general agreement with iceberg drift rates. This is the Weddell Gyre's most active circulation component, comparable with a western boundary current and with characteristic volume transport around 10×10^6 m^3/s. The pycnocline capping the deep water is strongly tilted down to the south, where the winter mixed layer can reach thicknesses of several hundred meters. It remains to be determined whether this is a baroclinic adjustment or the result of intense water mass conversion in response to frequent coastal polynyas.

The slope current enters the Weddell Sea west of Cape Norvegia, where it splits into continental slope and the coastline branches (Gill, 1973; Carmack and Foster, 1975; Tchernia and Jeannen, 1983). Because of the slope current's great depth, significant shear is likely to be associated with this branching. The relatively warm and originally deep water that comprises the slope current can, in the presence of intense cooling and in the absence of excessive dilution, produce dense water without

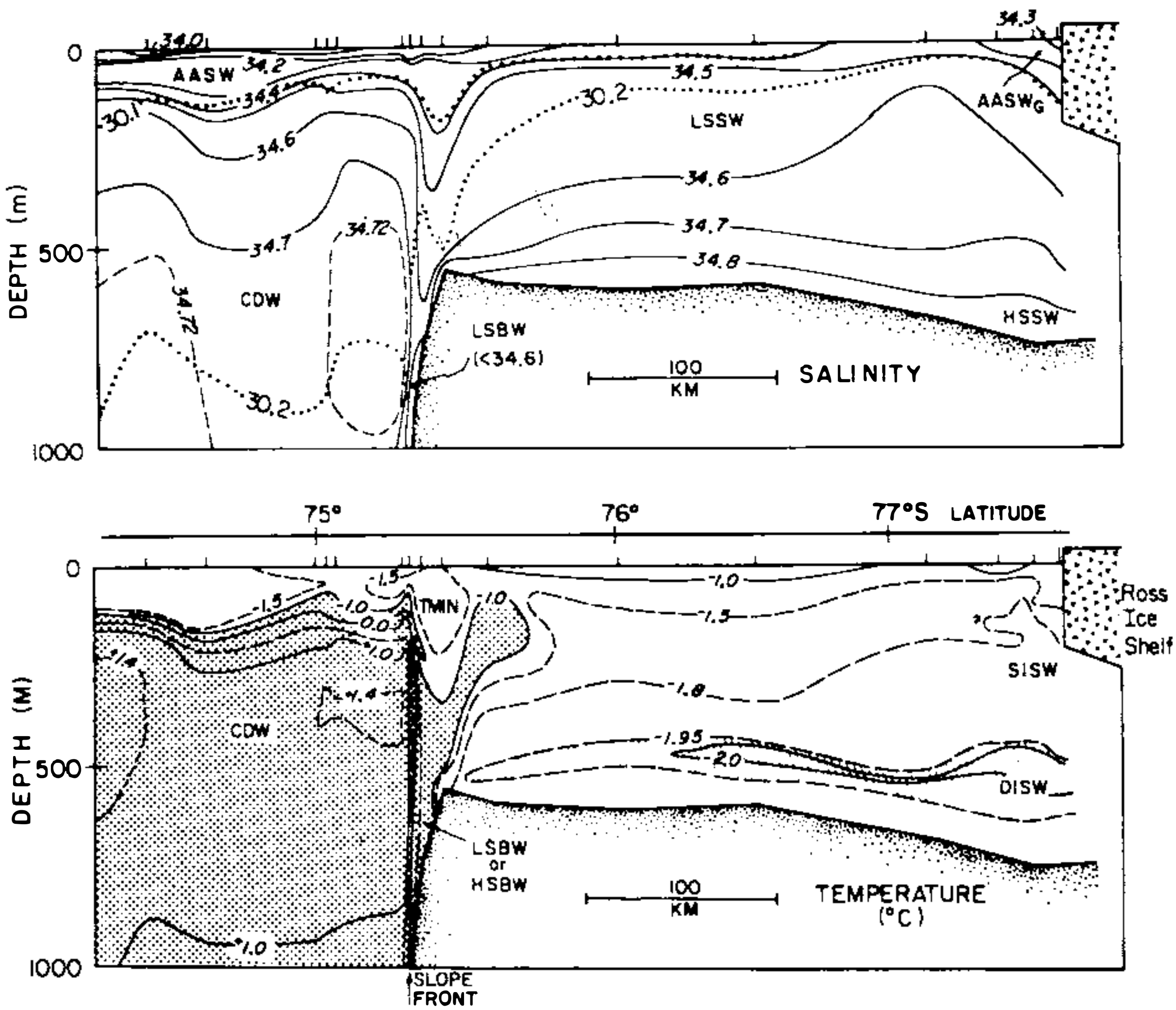

FIGURE A-8 Shelf-slope frontal zone in the Ross Sea. Salinity and temperature versus depth along transect, December 1976 STD stations. Vertical ticks indicate station locations. Dotted isopycnal surfaces in the salinity section are referenced to 500 db. At these continental shelf depths, potential temperatures would be about 0.03°C colder than the in situ temperatures shown. Source: Jacobs, et al (1985).

any shelf water contributions. The water column ejected into the open ocean at the Weddell-Scotia Confluence no longer contains the deep-water characteristics of the slope current. Apparently the "warm" water drawn into the southern Weddell Sea by the slope current is completely altered during its transit of the Weddell Gyre and boundary current, making it a primary input to formation of bottom water.

CHEMICAL OCEANOGRAPHY

Chemical oceanography of the Southern Ocean has become integrated closely with other scientific disciplines; the problems that it addresses are important regionally and globally. These include the chemical coupling between the Southern

Ocean and the atmosphere and its effect on climate, the effects of the abundant biota of the Southern Ocean on the chemistry of these waters, and the use of chemical tracers to determine mechanisms of water mass formation and rates of transport and mixing. Although the focus of each of these areas of research may be different, they are strongly interconnected. Progress requires integrated understanding of the chemistry, physics, and biology of these waters.

CO_2 in the Southern Ocean

In the vast area of the Southern Ocean, the deep waters of the major oceans outcrop and exchange heat, momentum, and chemical substances with the atmosphere. Chemical processes in the Southern Ocean are linked to global chemical cycles and to related global phenomena. Because of the importance of atmospheric carbon dioxide in moderating global climate, the role of the Southern Ocean in the global carbon cycle is of special interest.

The deep waters of the oceans contain 50 times more carbon dioxide than the atmosphere and are important in the control of atmospheric carbon dioxide level over long periods. Recent measurements of partial pressure of carbon dioxide in surface water lead to estimates that the cold waters located south of about 30°S take carbon dioxide from the atmosphere at a rate of about 1.8×10^9 metric tons of carbon per year, which is a flux comparable to about 30 percent of the assumed annual industrial carbon dioxide emission rate. The Southern Ocean thus constitutes a major sink and important pathway for the storage of natural and anthropogenic carbon dioxide

The Southern Ocean uptake of carbon dioxide probably played an important role in major climatic excursions of the recent geologic past. As demonstrated by the analysis of air trapped in polar ice-cores, the atmospheric carbon dioxide level increased from about 200 ppm during the last glacial period, 15,000 to 30,000 years ago, to about 280 ppm during the postglacial period about 13,000 years ago and thereafter. Although the causal relationship between climate change and atmospheric carbon dioxide is not understood, the ice-core carbon dioxide observations have been attributed to changes in oceanic carbon dioxide reservoirs resulting from changes in ocean circulation and/or changes in oceanic biological activity (Broecker and Takahashi, 1984). Whether an increase in the ocean circulation rate would result in an increase or decrease in the atmospheric carbon dioxide level is not clear; nevertheless, the deep-ocean ventilation through the Southern Ocean and its biological activity is an important air-ocean coupling mechanism affecting changes in atmospheric carbon dioxide levels, and hence changes in climate. How such coupling and feedback occur in the Southern Ocean must be understood in addressing the societally relevant industrial carbon dioxide problem as well as other scientifically challenging questions such as the origin of the Ice Age.

The air-sea carbon dioxide flux is governed by the difference in carbon dioxide partial pressure between the atmosphere and surface ocean water and by the carbon dioxide gas-exchange coefficient across the air-sea interface. The former represents the thermodynamic driving force for gas exchange, and its variation is due mainly to variations in the surface ocean carbon dioxide partial pressure, since variations in atmospheric carbon dioxide partial pressure are comparatively small.

The carbon dioxide partial pressure in ocean water is a function of temperature (approximately 4.3 percent carbon dioxide partial pressure per degree Celsius in an isochemical condition), the concentration of total carbon dioxide dissolved in seawater, and the alkalinity. A one percent increase in the total carbon dioxide concentration or a one percent decrease in the alkalinity causes an increase in carbon dioxide partial pressure of about 10 percent in warm waters and about 15 percent in cold waters. Thus, the surface water carbon dioxide partial pressure is regulated mainly by the biological utilization of carbon dioxide and deep-water upwelling, which supplies carbon dioxide, alkalinity, and nutrients to the surface.

The mean integrated carbon dioxide gas-exchange coefficient for the world ocean has been determined, mainly from the exchange of radiocarbon—carbon-14 (e.g., Craig, 1963; Rafter and O'Brien, 1970; Peng et al., 1979); the published values range between 12 and 25 moles carbon dioxide per square meter per year. However, its dependences on temperature, wind speed, and water turbulence and ice cover have not been clearly resolved. These dependences should be investigated thoroughly, in addition to the regional problems associated specifically with the Southern Ocean. The net carbon dioxide flux across the air-sea interface is generally smaller than that supplied to the surface by upwelling or consumed or produced there by biological activity.

The measurements of surface water carbon dioxide partial pressure in the Southern Ocean (e.g., Takahashi, 1960; Keeling and Waterman, 1968) show that the surface waters in this region generally are undersaturated with respect to the atmospheric carbon dioxide but vary locally from 10 percent supersaturation to about 30 percent undersaturation. This large variability may be attributed mainly to complex interactions between the effects of the upwelling of deep water, mixing of subtropical and antarctic waters, biological utilization of CO_2, and temperature change. Figure A-9 shows the surface water carbon dioxide partial pressure values observed in the November 1973-February 1984 austral summer by expeditions extending from the South Atlantic into the Weddell Sea (Takahashi and Chipman, 1982). Surface waters colder than about 24°C (or south of about 30°S) are undersaturated with respect to atmospheric carbon dioxide. Variability in carbon dioxide partial pressure is large in the waters colder than about 16°C and particularly large in those colder than about 2°C (south of the Polar Front). The carbon dioxide partial pressure change above 16°C is nearly consistent with the effect of temperature for an isochemical system. The high variability in carbon dioxide partial pressure at temperatures below 16°C cannot be attributed to temperature variability.

The nitrate concentration observed in the surface waters follows a similar trend with temperature. Nitrate is nearly absent in waters warmer than about 16°C and increases with decreasing temperature, reflecting its supply by upwelling of deep water at high latitudes and its biological utilization in warmer waters. Its variability increases in waters colder than 2°C, south of the Polar Front. To show the covariance of carbon dioxide partial pressure with nitrate in surface water, the

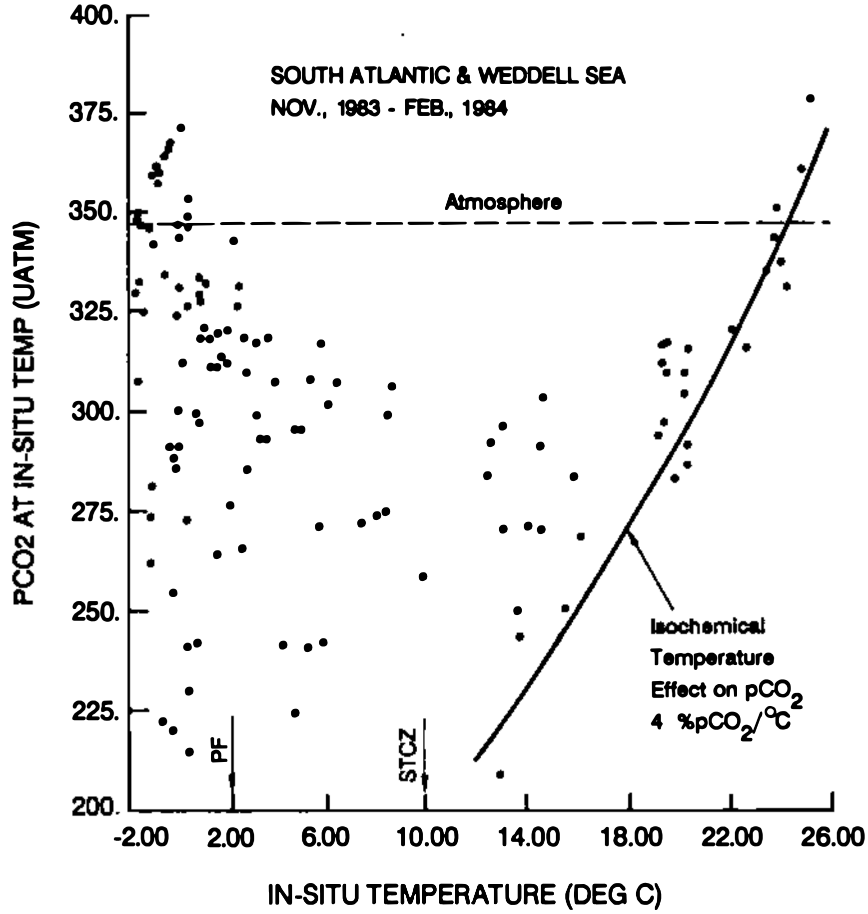

FIGURE A-9 Surface water carbon-dioxide pressure as a function of the temperature observed in the southwestern Atlantic and Weddell Sea during the austral summer, Nov., 1983-Feb., 1984, aboard the RRS "Bransfield." The warm and nutrient-depleted South Atlantic gyre water exhibits the pCO_2 value consistent with the effect of temperature in a temperature range of about 16°C to 26°C. This indicates that the surface water pCO_2 value in this temperature range is mainly regulated by the surface water temperature. On the other hand, that in the colder and nutrient-rich waters of temperatures less than 16°C is regulated mainly by the photosynthetic utilization and supply of CO_2 by upwelling deep waters. The approximate positions of the Sub-tropical Convergence Zone, STCZ, and Antarctic Polar Front Zone, PF, in the oceans are indicated. Source: Takahashi and Chapman (1982).

carbon dioxide partial pressure value normalized to a constant temperature is plotted in Figure A-10 against nitrate. This temperature normalization is made in order to remove the effect of temperature variation on carbon dioxide partial pressure. The normalized carbon dioxide partial pressure values thus are roughly proportional to the total carbon dioxide concentration. Figures A-9 and A-10 demonstrate that carbon dioxide partial pressure variation and its covariance with nitrate can be accounted for by the mixing of upwelled deep water with the nutrient-depleted subtropical gyre water and by the photosynthetic utilization of carbon dioxide.

In contrast, in the waters warmer than about 16°C, nitrate is almost completely depleted, and the biological productivity and upwelling rates are low, so that the

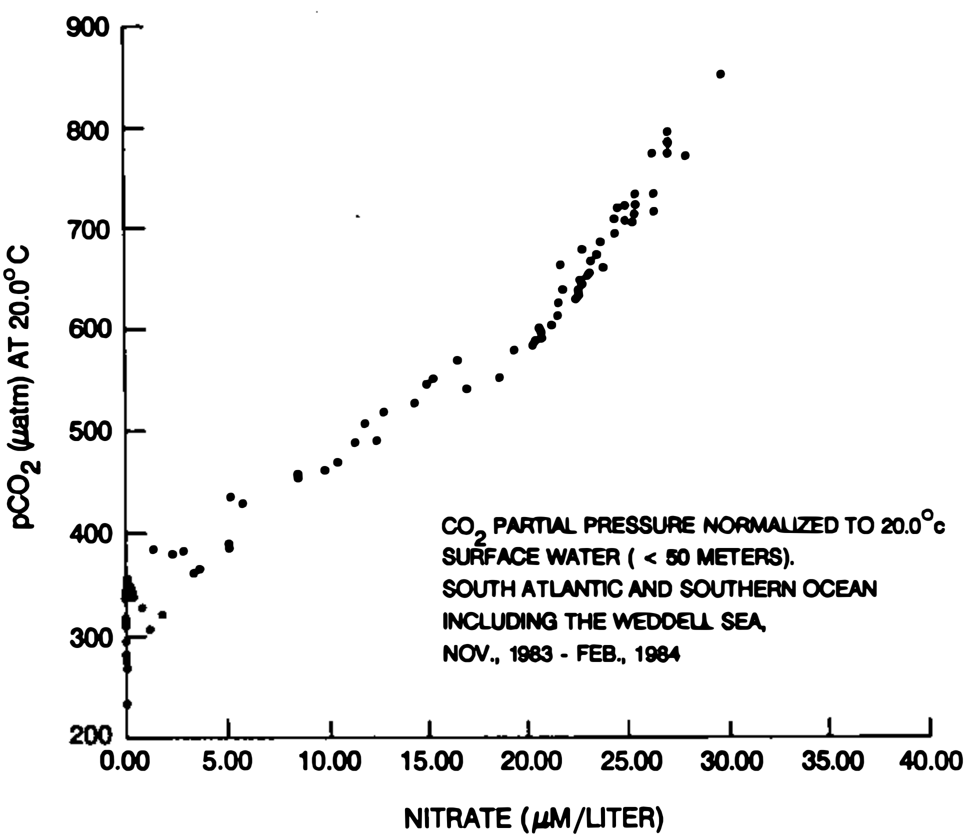

FIGURE A-10 A plot showing a covariance of the CO_2 partial pressure (normalized to 20.0°C) and nitrate concentration in the surface waters of the South Atlantic and Southern Ocean. The observed slope is consistent with the Redfield ratio of 16:106 for N:C. Source: Takahashi, personal communication (1986).

total carbon dioxide concentration is not significantly altered by biological utilization. Therefore, the surface water carbon dioxide partial pressure variations in these regions are mainly a function of temperature.

Carbon-14

An especially powerful technique for the study of the exchange of carbon dioxide between the Southern Ocean and the atmosphere involves the use of radiocarbon-bearing carbon dioxide (C-14) as a tracer of this process. The atmospheric testing of thermonuclear weapons in the mid-1960s increased atmospheric radiocarbon greatly over the background values produced by cosmic rays; therefore, the radiocarbon content of surface ocean water and that of the atmosphere differ sharply. The lowest surface water radiocarbon values in the world ocean are found in all sectors of the Southern Ocean south of the Polar Front (e.g., Weiss et al., 1979; Ostlund and Stuiver, 1980; Stuiver and Ostlund, 1980). The subsurface waters of these regions show even lower concentrations of radiocarbon and therefore reflect only limited exchange between the recent atmosphere and the nascent deep and bottom waters of the Southern Ocean.

For the Weddell Sea, probably the most important region of deep- and bottom-water formation in the Southern Ocean, the radiocarbon data have demonstrated (Weiss et al., 1979) that the carbon dioxide exchange rate in this region during ice-free periods is actually comparable to the global average. The observed low radiocarbon values are the result of three factors: the short residence time of surface waters, substantial dilution of deep and bottom waters by subsurface mixing with unventilated deep waters of North Atlantic origin; and effective inhibition of air-sea carbon dioxide exchange by sea ice, especially during winter. Sea ice has been shown to be an excellent inhibitor of the exchange of other gases.

Measurements of the carbonate chemistry and carbon isotopes of the Southern Ocean are essential to the study of the role of this area in the global carbon cycle and to the assessment of the local effects of biological activity. In the special case of radiocarbon, which until the perfection of new accelerator techniques will require 2001 samples of seawater, the present coverage in the Southern Ocean consists mainly of near-surface summertime samples and a few deep-profile measurements such as those made in the summertime in circumpolar regions by the GEOSECS program. A more detailed radiocarbon coverage, including wintertime end-members in the Weddell Sea and in other regions of deep bottom-water formation, will be useful in assessing the air-sea exchange flux and as an oceanographic tracer.

Measurements of total inorganic carbon, alkalinity, carbon-13, and surface water and atmospheric carbon dioxide partial pressure will characterize the behavior of the carbon system with respect to chemical, biological, and air-sea exchange processes. This research should lead to a better understanding of the behavior of the Southern Ocean in the global carbon dioxide climate system and to useful predictions of the response of the chemistry of this region to climate changes induced by carbon dioxide.

Southern Ocean Nutrient Cycles

Most vertical profiles of silicic acid, nitrate, and phosphate concentration in the ocean show strong depletion in the wind-mixed surface layer, a steady increase with depth from about 100 to 1,000 m (often reaching a maximum value), and high, relatively uniform concentrations in deep water (Sverdrup et al., 1942; Edmond, 1973; Edmond et al., 1979). These vertical distributions are a consequence of biological cycling. They result from uptake by phytoplankton in the surface layer, incorporation into new organic and structural plant matter, and the subsequent degradation of this surface-produced biogenic material at intermediate depths (Redfield et al., 1963).

The distributions of nitrate and phosphate in the Southern Ocean follow these principles, except that the short residence times of deep waters in some regions of the Southern Ocean regions limit the accumulation of nitrate and phosphate from degradation of surface-produced material. In the Weddell Sea, for example, alkalinity, nitrate, phosphate, and oxygen, which depend principally on these metabolic processes, show distributions consistent with conservative subsurface mixing (Weiss et al., 1979). Thus, the concentrations of these properties in Weddell Sea bottom water are explained as simple mixtures of waters found within the Weddell Gyre and on the antarctic continental shelf.

By contrast, distributions of silicic acid in the Southern Ocean differ markedly from those elsewhere. Most Southern Ocean silicic-acid concentration profiles increase nearly continuously with depth below 500 m, unaccompanied by similar increases in the nitrate or phosphate concentration.

Zonally, deep-water silicic-acid concentrations in the major ocean basins can be viewed as chemical signatures indicating how much a particular deep-water mass has been exposed to processes peculiar to the Southern Ocean. North Atlantic deep water, which flows southward toward the Antarctic Circumpolar Current, has silicic-acid concentrations of 40-50 μM/kg. The Indian Ocean's deep water, basically North Atlantic deep water modified by Southern Ocean processes as it moves eastward south of the Cape of Good Hope, is enriched to about 80 μM/kg. South Pacific deep water maximally exposed to Antarctic Circumpolar Current processes before flowing northward contains greater than 130 μM/kg silicic acid. Deep-water masses of the Indian and Pacific Oceans are somewhat enriched in nitrate and phosphate relative to North Atlantic deep water, but this enrichment is much less pronounced than that of silicic acid (e.g., Redfield, 1958; Broecker, 1974).

This selective vertical and zonal enrichment of water below 500 m with silicic acid is perhaps the most striking, single chemical feature of the Southern Ocean and one of the most pronounced anomalies in the global marine silicon cycle. The relative importance of the processes that produce and maintain this feature have remained obscure.

Further evidence that the cycling of silicon in the Southern Ocean differs substantially from that elsewhere in the ocean is provided by recent estimates of accumulation rates of siliceous sediments (De Master, 1979). By these estimates, approximately 75 percent of all biogenic silica accumulating in deep-sea sediments is accumulating in the Southern Ocean. The global silicon cycle will not be well understood until the relative rates of the processes resulting in the accumulation of silicon in both the deep-water and deep-sea sediments of the Southern Ocean are known.

Three sources of silicic acid to the deep water of the Antarctic Circumpolar Current region have been proposed. Dissolution of suspended silicate minerals of glacial origin had been considered the process most likely to be both peculiar to the Southern Ocean and capable of supplying silicic acid without simultaneously enriching the deep water substantially with nitrate or phosphate (Cooper, 1952; Schutz and Turekian, 1965; Burton and Liss, 1968).

However, Hurd (1973) found the amount of silicate minerals thus produced and their rates of dissolution much lower than previously estimated, while Edmond (1973) showed that the rate of biogenic silica dissolution in the Southern Ocean water column and sediments must greatly exceed that of mineral silicates. This indicates that quantitatively the production and dissolution of biogenic silica are the overwhelmingly important processes.

Whether the greatest inputs of silicic acid result from direct dissolution of biogenic silica within the water column (e.g., Berger, 1968; Nelson and Goering, 1977a) or from upward diffusion of silicic acid produced via dissolution of recently sedimented diatom silica (e.g., Fanning and Pilson, 1974; Schink et al., 1975; Edmond et al., 1979; Weiss et al., 1979) is not known and is difficult or impossible to determine on the basis of concentration data alone.

Perhaps more important, silicic acid concentration profiles cannot by themselves indicate what features of the near-surface cycling of biogenic silica in the Southern Ocean are responsible for the vertical and zonal accumulation of silicic acid at depth. The fraction of the biogenic silica produced in the surface layer and dissolved there and the fraction that remains available for transport to greater depths are not known.

Kozlova (1964) estimated from vertical distributions of diatom debris that more than 80 percent of the biogenic silica produced in the near-surface water in the Indian Ocean region of the Antarctic dissolved in the upper 100 m and that only about 2 percent penetrated to 1,000 m. Nelson and Goering (1977a) showed that almost none of the biogenic silica produced by diatoms in the upwelling region off northwest Africa (about 22°N) escaped dissolution in the upper 60 m. These studies suggest that the flux of biogenic silica to depth in the Southern Ocean may be very high when compared to downward biogenic silica fluxes elsewhere in the ocean although it seems low compared to near-surface silica production rates.

Thus, the very sparse data suggest that the efficiency of near-surface biogenic silica dissolution may vary considerably over the ocean and may be substantially lower than normal in the Southern Ocean. This implies that variations in this efficiency together with variations in near-surface production are important controls of Southern Ocean silica distributions and fluxes.

Several methods have been developed in the past 10 years to obtain direct measurements of biogenic silica production rates (Goering et al., 1973; Azam and Chisholm, 1976; Nelson and Goering, 1977b; Paasche and Ostergren, 1980) and particulate silica dissolution rates (Nelson and Goering, 1977a) in the ocean. These rate studies—of tropical and temperate systems, in which diatoms dominate the phytoplankton—do not show the deep silicic-acid accumulation observed in the Southern Ocean.

Nelson and Gordon (1982) used silicon-30 tracer techniques to measure production and dissolution rates of biogenic silica in the Antarctic Circumpolar Current system. This work showed denser concentrations of silicon near the surface and near the bottom, northward increases in near-surface silica production and particulate silica, 18-58 percent redissolution of surface-produced silica in the upper 90-98 m, and modeled silica dissolution rates below 100 m of 1.2-2.9 $\mu M/m^2$/day. These results are consistent with the hypothesis that biogenic silica penetrates to greater depths in the Southern Ocean than elsewhere in the ocean and that dissolution of this material at depth is responsible for the anomalous vertical profiles of silicic acid over the 500 to 4,000 m interval. Still to be determined are whether much of the biogenic silica leaving the upper 100 m penetrates below 500 m and whether the recycling of organic carbon, nitrogen, and phosphorus in these organisms is decoupled from silica by faster recycling in the upper-water column.

Tracer Chemistry of Subpolar and Continental Margin Zones

Geochemical measurements are useful in solving numerous important problems within the subpolar and continental margin zones including those of circulation, mixing, and water mass formation. In study of physical ocean processes, the geochemical tracers provide unique information on the mechanisms and rates of water mass formation and on subsurface circulation and mixing. The geochemical tracers complement the instantaneous physical oceanographic observations by providing integrated information. In global geochemistry, studies of Southern Ocean air-sea ice and sediment-water chemical exchange processes help to explain the role of antarctic margin seas in modulating the chemical composition of the atmosphere and the chemical properties of nascent antarctic bottom water. The geochemical tracers also provide information on the rates of biological processes in these waters.

Despite the importance of the Southern Ocean, especially the Weddell Sea, to global oceanography, extreme inaccessibility and the limited capability of most icebreaking vessels to carry out specialized geochemical sampling severely inhibit study of the geochemistry of ice-covered subpolar and continental margin zones. The most extensive geochemical study of this type (Weiss et al., 1979) was carried out as ancillary to a physical oceanographic expedition of the U.S. icebreaker *Glacier* in the Weddell Sea in austral summer 1973.

The deuterium and oxygen-18 stable isotope data from this study have shown that the high salinity of shelf water found on the western continental shelf in the Weddell Sea is due principally to freezing, rather than to evaporation. The isotopic composition of this water also requires that there be a significant net mixture of melt water from the base of the Filchner Ice Shelf, and mass balance calculations based on the stable isotope measurements show a reasonable consistency between the rate of ice-shelf melting and the rate of bottom-water formations. These same stable isotopic techniques have been used by Jacobs et al. (1985) to demonstrate that similar processes occur between the base of the Ross Ice Shelf and the waters of the Ross Sea.

Concentrations of the radioisotopes carbon-14 and tritium are exceptionally low in the Southern Ocean. The behavior of tritium in the average world ocean is dominated by molecular exchange, while the input of tritium to Weddell Sea surface waters is dominated by precipitation (Weiss et al., 1979). Based on the 1973 tritium data, the usefulness of which is severely limited by the difficulty of measuring concentrations near the detection limit by classical counting techniques, the rate of Weddell Sea bottom-water formation was found to be on the order of 4 $\times 10^6$ m^3/s. Measurements of tritium distributions in the northwestern Weddell Sea in 1975 and 1976 (Michel, 1978) showed still lower tritium concentrations, as the atmospheric reservoir of tritium produced by thermonuclear weapons testing in the 1960s continued to decrease.

The most serious limitation on sampling has been inability to collect wintertime samples in the regions of active water mass formation. Because geochemical tracers integrate these processes, sampling the end products of bottom-water formation as well as the extreme wintertime surface water, shelf water, and deep-water end-members, including the complete range of shelf water properties likely to be encountered, is especially important. Such studies are important not only in the Weddell Sea but in all the regions around the Antarctic Continent where significant wintertime water mass formation is believed to occur.

Of special interest among the time-dependent tracers are the dissolved atmospheric chlorofluoromethanes, CCl_3F (Freon-11) and CCl_2F_2 (Freon-12). These conservative tracers have different atmospheric source functions and thus independently constrain models of their oceanic distributions. Unlike the transient increases in tritium and radiocarbon from atmospheric nuclear weapons testing, the atmospheric distributions of Freon-11 and Freon-12 do not depend strongly on latitude and therefore are of special value as tracers in the Southern Ocean. Although the potential value of the Freons has been recognized for some years, routine measurement has been limited by analytical difficulties and only recently has become practical (Gammon et al., 1982; Bullister and Weiss, 1983; Weiss et al., 1985). Concentrations as low as 1/400 polar surface water equilibrium solubility can be detected.

Freon data from January and February 1984 within the Weddell Gyre confirm this optimism (Weiss et al., 1985; Figure A-11). Significant concentrations of Freon-11 and Freon-12 are found throughout the water column, with the lowest concentration in the warm, deep-water core and significantly higher values in the cold Weddell Sea bottom water. The Greenwich meridian section (Figure A-11) shows recently ventilated high-Freon bottom water flowing eastward at about 59°S and flowing westward at the base of the continental slope. Also, at about 59°S, a sharp front extends down to 4 km, separating the high-Freon, cold-water, mid-depth regime to the north from the low-Freon, warmer, mid-depth regime to the south. Further to the north, the sharp northward decrease in deep-Freon concentration marks the boundary of the circumpolar current. Nearer the surface, the high-Freon concentrations of South Atlantic intermediate waters are seen to outcrop in the polar frontal system. The measured Freon-11/Freon-12 ratios demonstrate that the mean flushing time of the Weddell Gyre is about a decade.

The Freon measurements thus promise to help show the rates of bottom-water and deep-water formation and mixing in the Weddell Sea, the Ross Sea, and throughout the circumpolar region. Measurement of winter Freon concentrations in the surface waters and shelf waters of these regions and obtaining detailed meridional Freon sections across the circumpolar current will be especially valuable.

Recent developments in tritium measurement techniques, based on mass-spectrometric measurement of the growth of the daughter product, helium-3, in stored samples, have significantly lowered the detection limit for tritium to 0.001 tritium units from 0.05 tritium units (Jenkins et al., 1983). This new capability should

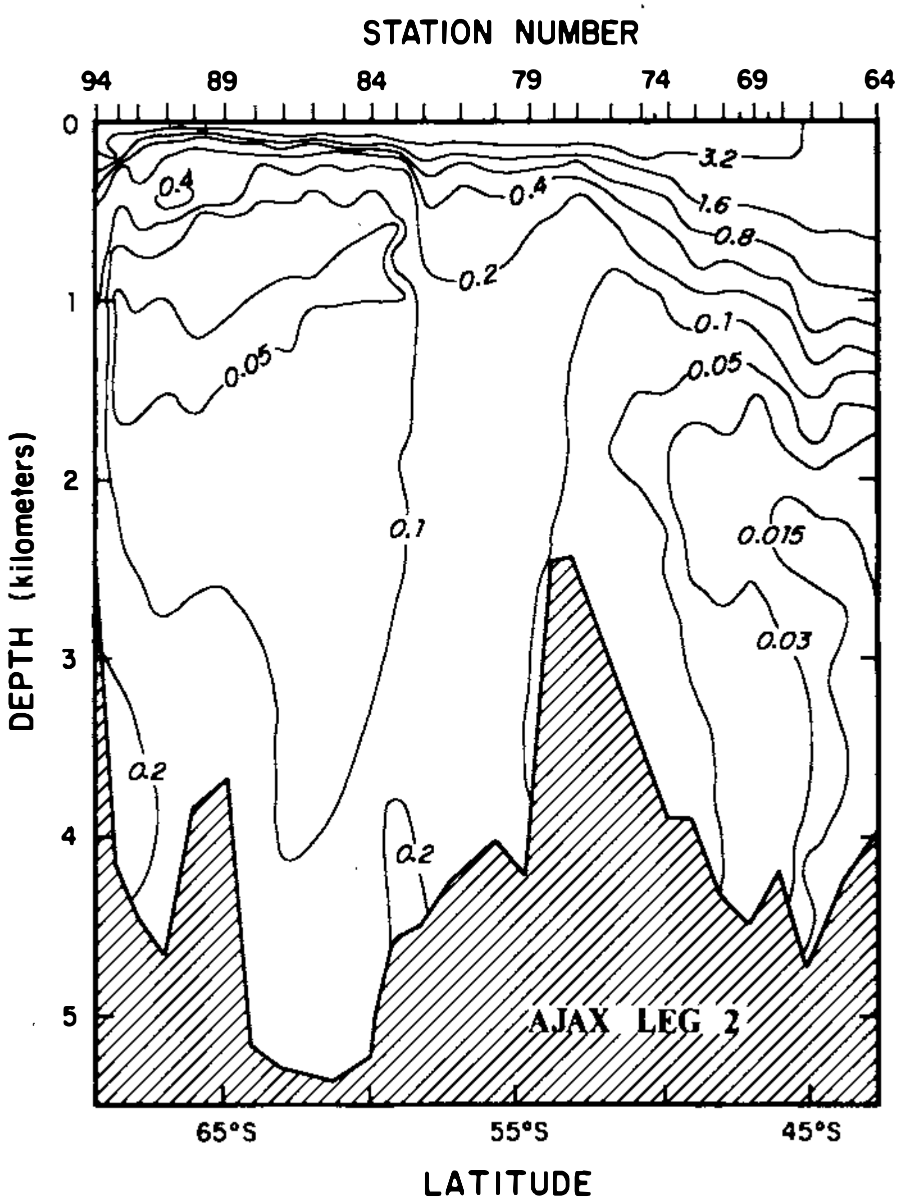

FIGURE A-11 Synoptic distribution map, Weddell Sea. Freon concentration along the Greenwich Meridian. Data obtained during the AJAX expedition. Source: Weiss and Bullister, personal communication (1985).

greatly extend the usefulness of tritium as a tracer in the Southern Ocean, where surface water tritium values are about 0.5 tritium units.

Measurements of helium-3 distributions simplify the interpretation of the tritium distributions by removing uncertainties in the atmosphere source function. The distributions of helium-3 and the Freons are also useful in the study of air-sea exchange processes and their inhibition by ice cover. The deep waters of circumpolar origin are supersaturated in primordial helium-3 and undersaturated in Freons, and their degree of re-equilibration with the atmosphere is a measure of air-sea gas exchange processes that take about a month (Broecker and Peng, 1974) and thus control the ventilation of upwelled surface waters. In winter, the sea ice blocks the exchange of these gases with the atmosphere, so their degree of re-equilibration instead becomes a measure of the amount of deep-water entrainment in the winter surface layer after the surface has been sealed with ice in the austral fall. This effect was observed first for oxygen (Weiss et al., 1979; Gordon et al., 1984), although the oxygen observations are subject to uncertainty concerning biological consumption, and very recently for Freons (Bullister and Weiss, 1983) and helium-3 (Jacobs, 1986; Schlosser, 1986), which are biologically inert.

Measurements of the stable isotope ratios deuterium/hydrogen and oxygen-18/oxygen-16 in polar waters help distinguish the effects of evaporation and precipitation, melting of shelf ice, and melting and freezing of sea ice in altering salinity. Sampling for these measurements is not difficult, but the highest analytical precision is required (less than or equal to 0.02 ppt in oxygen-18/oxygen-16 and less than or equal to 0.20 ppt in deuterium/hydrogen), and few laboratories have this capability. Samples of precipitation, sea ice, and shelf ice should also be collected around the Antarctic Continent.

Other tracers are of interest also in the study of physical oceanographic processes in the Southern Ocean and in assessing the chemical input of southern waters to the world oceans. These include radiocarbon and argon-39 for the study of rates of deep circulation and mixing on long-time scales. Krypton-85 is an inert, independently varying, short-time tracer to complement Freon and tritium studies. Recent developments in analytical techniques will greatly facilitate their routine use in antarctic oceanography. Radium-228, radon, and radium-226 are useful for studies of sediment-water exchange rates and near-bottom circulation and mixing studies. Trace element distributions are important to studies of nascent bottom-water composition and local scavenging processes.

Effective application of the geochemical tracers to the study of oceanographic problems requires the highest standards of accuracy and precision in routine hydrographic measurements and a close integration with physical oceanographic observations. No effort should be spared in assuring that the temperature, salinity, oxygen, and nutrient measurements in the Southern Ocean are of the highest quality.

SOUTHERN OCEAN MODELING

The research themes outlined above describe physical processes and dynamical problems to be studied. Ocean modeling, however, is a technique—used with observational programs to aid in rationalizing observations in a dynamic framework.

Revision of old models and development of new models in all categories of Southern Ocean research are timely. Certain kinds of critical observations to test the models and set them on a proper course have become available. A decade of model development has proven quite successful in illuminating dynamical issues in other oceans. Computer resources and expertise have become available on a scale needed to attack these large modeling problems.

Numerical models of large-scale ocean circulation help in understanding physical processes in the Southern Ocean, and models for other regions can be useful in the study of both the Southern Ocean and the distinctive problems that it may pose for modeling. Differentiation between models immediately available and those that need development over the next few years in order that further progress can be made later (in the 1990s) is important.

Highly idealized models, coarse-resolution primitive-equation numerical models, and eddy-resolving numerical models are all needed, and ultimately these models must be blended. Computational requirements needed to study different aspects of the Southern Ocean circulation are very large, and a hierarchy of models that treat a few processes in isolation is the only practical approach to understanding this very complex region of the world ocean.

Models of the Antarctic Circumpolar Current have concentrated on the gross features of the momentum and vorticity balances required to achieve an equilibrium. Munk and Palmen (1951) suggested that bottom pressure forces against submarine ridges would be needed to counterbalance zonal wind forcing if a realistic transport in a channel geometry is to be achieved without resource to quite large northward eddy momentum fluxes. Stommel (1957) pointed out that such simple zonal models may not be adequate; at no latitude does the 1,000 m ocean depth circle the globe (i.e., meridional barriers are inherent in the problem). Gill (1968) pointed out that northward momentum fluxes by turbulent processes could be responsible for an overall balance in the Antarctic Circumpolar Current if the variability in zonal current is as large as the mean.

Two quite different, much more elaborate models have shed some light on these questions. The first, by Gill and Bryan (1971), uses a coarse-resolution primitive-equation model driven by both wind stress and thermohaline forcing. Their results suggest that the bottom pressure against submarine ridges could act in consort with the wind to produce larger transports. This was related to the meridional overturning associated with thermohaline forcing. The second study, by McWilliams et al. (1978), using an eddy-resolved quasi geostrophic model developed by Holland (1978), showed that baroclinic instability would transmit the zonal surface wind stress to the deep ocean so that realistic transports could occur in a turbulent ocean with bottom friction. However, they also showed that bottom topography strongly affects overall vorticity and momentum balances in the presence of eddy-driven deep flow. Mesoscale eddies and bottom relief both are thus likely to be important in the Antarctic Circumpolar Current.

The study by Gill and Bryan and later studies of the world ocean by Bryan and collaborators (Bryan et al., 1975; Cox, 1975) suggest the importance of geometry of land barriers and bottom relief in determining the nature of meridional overturning and water mass formation. This work has not been followed by the thorough Southern Ocean study needed to understand deep-water formation processes and their relationship to topography and the time and space scales of atmospheric forcing.

Eddy-resolving numerical models of the instability-induced variability in midlatitude oceans have shown some success in explaining the nature and spatial structure of the variability and its associated mean flow there. Schmitz and Holland (1982) compared observations from the North Atlantic with model results to show that the structure and amplitudes of the mean and eddy fields could be substantially reproduced by the models. More important, the ways in which the model failed to relate to the data available have stimulated further development of the models and have led to better understanding of the critical dynamical issues involved. Similar comparisons in the antarctic circumpolar region should be possible when adequate eddy models have been developed.

Two broad areas of research go along with the categories of models mentioned. Primitive-equation models with high vertical resolution are needed to study problems of water mass formation and penetration into the interior. Other modeling is needed to address problems of variability and eddy behavior. The primitive-equation models with high vertical resolution would be suitable and are necessary for understanding meridional transports and the coupling of the Southern Ocean to the world ocean. Ideally, such models would have fine horizontal resolution as well, to include mesoscale eddies; but experience with such models is insufficient and computational expense is far too high at present.

Despite their limitations, the use of primitive-equation models with the best resolution we can achieve in the beginning of systematic study of water mass formation processes is timely. We want to understand how surface water with certain properties sinks, moves northward, and spreads. We want to examine how seasonal and other time scales of variability change the picture and how multiple sources (e.g., water masses) interact. Examination of the dependence of these results on mixing, on aspects of the model itself, on the parameterizations of mixing, and on the details of the surface boundary conditions is especially important. This is a very large program. Because the high-latitude oceans are the ultimate source of the major water masses, such ocean modeling studies are essential.

Quasi geostrophic and similar models with simpler physics must be used to address questions of variability. To show the eddy field, eddy mean flow interactions, and closely related phenomena explicitly, this type of modeling must forego study of water mass formation processes. However, it could be very effective in developing an understanding of the dynamics of the Antarctic Circumpolar Current, particularly responses of the current to transient winds, bottom relief, and the host of eddy mean flow interactors that lead to the equilibrium circulation.

Construction of a Southern Ocean quasi geostrophic model with realistic geometry, bottom topography, and wind forcing is well within our ability. It would allow a determination of the three-dimensional structure of the eddy field, including statistics such as eddy kinetic energy, which can be checked against the observations already available (e.g., from the Drake Passage). Such studies could identify certain critical localities by mapping the structure of the eddy kinetic energy around the globe.

An array of simpler model studies of circumpolar current variability would accompany development of the complete model. Modeling of channels and partially blocked channels with and without bottom relief and with and without transient forcing are needed to understand various dynamical effects in isolation.

Significant computational resources will be available to the research community during the next decade. Enough young scientists who can take on long-term model developments and application may not be available without constructive attention from and close coordination and cooperation between modelers and observational researchers. Joint training of postdoctoral students by observational researchers and modelers could be very productive.

Numerous comprehensive models are available and should be exploited. These include very-fine-resolution models to study eddy processes and coarser-resolution models to study long-term, thermohaline-structure problems. Because of the disparate time scales of these processes, these models can be used most efficiently only to study parts of the big picture. Ultimately, these models must be melded, which may begin to be possible in the next 10 years. True general circulation models must deal with all of the complexity mentioned—including eddies, active thermodynamic mixing, mixed layers, ice, and realistic atmospheric forcing—to begin to describe the complexity of the Southern Ocean. This work requires continued support to develop the trained people and the stable of ocean models needed.

Appendix B
Satellite Remote Sensing for Oceanography, 1986-1995
by *J. C. Comiso*

In recent years, a wide range of earth resource applications for satellite imagery has emerged utilizing the spatial and temporal detail which can be uniquely obtained from a space platform. There is now a widespread recognition of the complexity of the oceans and the limitations of the traditional techniques for the observation of large-scale phenomena.

Space sensors can provide useful data for studying some of the major oceanographic research areas including: (1) the circulation and heat content of the ocean and how they interact with the atmosphere; (2) the growth and decay as well as movements of sea ice and how they are coupled with the atmosphere and oceans; and (3) the primary productivity of the oceans and how it is influenced by the physical and chemical environment and higher elements in the marine food chain. Remote-sensing sensors take advantage of differences in emission characteristics as well as scattering cross sections of various materials in several regions of the electromagnetic spectrum. The accuracy in the determination of each parameter varies depending on the type of sensor and the characteristics of the instrument. Table B-1 summarizes the oceanographic and related parameters that can be derived from the visible, infrared, and microwave sensors. The satellite sensor needed to monitor each parameter is obviously not unique. In many cases, simultaneous or near-simultaneous data observed by different sensors from the same or different satellites provide more complete information about the geophysical parameter or oceanographic phenomena.

Among the most important oceanographic geophysical parameters that can be inferred from space platforms are: global ocean currents, ocean wave heights, sea surface winds, ocean color, sea surface temperatures, and sea-ice concentrations.

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TABLE B-1

TYPES OF SENSORS

VISIBLE (0.3 μm < λ < 0.7 μm)
- Strength: High Resolution
- Weaknesses: Darkness and Cloud Cover
- Field of view: 10 m for SPOT panchromatic, 35 m for LANDSAT TM, 1km for AVHRR and CZCS
- Applications:
  - Albedo/Reflectance
  - Chlorophyll Concentration
  - Ice/Ocean Boundary
  - Ice Thickness
  - Snow Mapping
  - Cloud Cover

INFRARED (0.7 μm < λ < 13 μm)
- Strengths: Night/Day, Good Resolution
- Weaknesses: Cloud Cover
- Field of View: 1 km for AVHRR, 6 km for THIR
- Applications:
  - Surface Temperature
  - Ocean Current Location
  - Snow Surface Albedo
  - Cloud Cover Characteristics
  - Water Vapor
  - Temperature and Humidity Profile
  - Hurricane and Storm Tracking

PASSIVE MICROWAVE (1mm < λ < 1m)
- Strengths: Night/day, Almost All Weather, Global Coverage
- Weaknesses: Low Resolution
- Field of View: 25 km
- Applications:
  - Composition and State of the Surface
  - Sea Surface Temperatures
  - Ice Concentration/Type
  - Ice/Ocean Boundary
  - Water Vapor
  - Rainfall

ACTIVE MICROWAVE (Altimeter, SAR)
- Strengths: Night/Day, Almost All Weather, Good Resolution
- Weaknesses: Limited Coverage
- Fields of View: 25 m for SAR, 1 km for Altimeter
- Applications:
  - Ocean Current
  - Significant Wave Heights
  - Wave Patterns
  - Sea Surface Wind Velocity
  - Surface Roughness

A brief discussion of the satellite sensors and the procedures used to derive these parameters follows.

A still ocean influenced solely by gravity and the earth's rotation would have a large-scale topography described by its geoid. The large-scale ocean movements (e.g., the geostrophic currents) cause bulges or depressions in the sea surface. The ocean currents can be inferred indirectly by taking the difference between actual surface topography and the geoid. The surface topography and its variations with time can be determined by a radar altimeter (AL), which measures the time for a transmitted pulse to travel to the surface and back to the satellite. The altimeter thus measures the relative positions of the sea surface that can be combined with a knowledge of the satellite orbit to construct a global map of the shape of the surface. Changes in the shape of the surface could then be monitored and global ocean currents could be derived provided the tidal effects are properly extracted.

The radar altimeter is also a valuable tool for measuring oceanic significant wave heights that are useful for swell forecast and studies of wind stress and wave characteristics. The significant wave heights are inferred from analysis of the shape of the return echo signal yielding accuracies comparable to this acquired using surface measurements. A good complementary tool is the synthetic aperture radar (SAR), which is an active microwave imager noted for high resolution (about 25 m). The good resolution is obtained by taking advantage of the movement of the spacecraft to synthesize coherently the echoes received from a target. Individual resolution cells within the field of view of large antenna are discriminated according to range and Doppler shift in frequency of the reflected radiation. Of crucial importance in the analysis is to find a relationship between waves on the sea surface and features in SAR images. An inversion technique has to be developed to deduce the structure of the sea surface from SAR data. Substantial progress to resolve these problems has been demonstrated.

It has been demonstrated that near-surface winds over the oceans can be measured with the use of scatterometers (SC). Scatterometers are active microwave instruments that directly measure backscattered radiation from an area of the sea surface, the size of which depends on the beam width of the antenna of the instrument. The intensity of the backscatter varies depending on the characteristics of the short surface waves (a few centimeters long) that are in equilibrium with the local winds. Two or more measurements of the surface made from different directions enable a determination of both speed and direction, using an empirically derived relationship between the radar cross section and the vector winds. While altimeters and microwave radiometers are capable of measuring the magnitude of the wind speed, only the scatterometers allow for measurements of vector winds.

Biological productivity can be inferred indirectly from chlorophyll concentrations estimated from visible and near-infrared radiances from the ocean. The Coastal Zone Color Scanner (CZCS) and the proposed Ocean Color Imager (OCI) are imaging radiometers that use a minimum of four spectral bands to estimate the near-surface concentration of phytoplankton pigments. This estimate is based on the intensity of backscattered solar radiation in the different bands. Phytoplankton pigments can be identified because waters low in phytoplankton pigments reflect more blue light and green radiances while those high in pigments reflect more green than blue.

Although the ocean color data have been used primarily to quantify distribution and abundance of phytoplankton, there are other applications as well. The ocean color data can be used to investigate rapidly changing oceanographic features since they provide flow visualization of water mass transport including those of fronts and eddies. Furthermore, the images can be used to guide research ships to locations where important oceanographic phenomenas are occurring and commercial vessels to where ocean productivity could be used to improve understanding of carbon and nitrogen fluxes and the ocean's role in climate.

Sea surface temperatures can be detected from space using a variety of sensors, including multispectral infrared devices (IR) to multichannel passive microwave radiometers (MR). These radiometers measure the intensity of radiation naturally emitted from the surface. To derive physical temperatures from the radiance data, effects of the atmosphere and spatial variations in the emissivity of the surface have to be taken into account. This is usually done with the aid of a radiative transfer model of the atmosphere and of the emitting surface in conjunction with available in situ data. Global low resolution (50 km) and regional high-resolution data (14 km) are now routinely provided using mainly data from the Advanced Very High Resolution Radiometer (AVHRR) on board the NOAA polar orbiting satellite. New techniques have also been developed using both the High Resolution Infrared Sounder (HIRS) and the Microwave Sounding Unit (MSU), also on the NOAA polar orbiters, to produce global sea surface temperatures at a resolution of 15 km. For day/night, almost all weather coverage, passive microwave radiometers, like the Scanning Multichannel Microwave Radiometer (SMMR), are known to be effective but are limited by poor resolution (about 70 × 150 km) and data contamination near land and sea ice.

The characteristics of the sea-ice cover in the polar regions can be monitored by a variety of sensors. For large-scale global cover at a moderate spatial resolution (approximately 30 km), but good temporal resolution (daily or better), the multispectral microwave radiometers (e.g., SMMR) are most effective. The main advantages of microwave radiometers are the day/night, almost all-weather capability, and global coverage in a relatively short time period. Several techniques have been developed to derive ice concentration, total ice extent, and total ice cover from SMMR. If high resolution is required, SAR has been shown to be capable of discriminating individual ice floes even in cloud-cover conditions. The data are effective for studying ice velocities, polynyas, ocean eddies, and other processes in the marginal sea-ice region. However, global SAR coverage with good temporal resolution is not currently feasible with existing technology. Also, some ambiquities in the determinations of ice concentrations and ice types from the SAR data have not been resolved.

Other techniques for obtaining ice-cover data include the use of visible and infrared sensors like LANDSAT, SPOT, and AVHRR, respectively. The visible channel data have very good resolution but could provide ice-cover information only during cloud-free and good lighting conditions. The infrared sensors are useful even in poor lighting conditions, but the data are affected by the presence of clouds. At present, no single sensor could provide all the information required to understand completely the oceanographic (and atmospheric) processes near the ice edge and also within the ice pack. Thus, studies requiring good resolution should use data provided by SAR AVHRR and/or LANDSAT or SPOT, whereas large-scale processes studies and investigations of temporal variability of the ice cover could be more effectively implemented using multispectral microwave radiometer data.

Table B-2 shows a listing of ocean-related spacecrafts that are currently in existence. They are further classified into research or operational spacecraft. The availability of data from the research satellite during the next decade depends on the lifetime of the sensor and availability of funds to collect and reduce the raw data to useful form. The operational spacecraft, on the other hand, are more dependable because they are routinely replaced whenever they start to malfunction. The various sensors in each satellite as well as launch data are also given in Table B-2. Table B-3 shows a listing similar to that of Table B-2 but for those sensors which are expected to be launched in the next decade. The number of research spacecraft that will be launched by the United States are apparently declining. However, data from European, Japanese, and Canadian spacecraft will be made available to U.S. users through government-sponsored programs. Tables B-2 and B-3 indicate that there will be an abundance of visible, infrared, and microwave satellite data from the oceans in the next decade.

At present, in the visible region, the main source of data is LANDSAT 5, which was recently commercialized and is now operated by a private corporation. Plans call for the construction and launch of LANDSAT 6 in the early 1990s. For biological productivity studies, data from the CZCS on board the NIMBUS-7 satellite have been and still are the sole source of satellite color data. However, because of power limitations, CZCS coverage is very limited and special studies in some areas are not possible unless a special request for coverage are made. Infrared data from the NOAA operational satellite are very comprehensive and reliable, and are expected to be available for many years to come. The SMMR on board the Nimbus-7 satellite is still producing good data, although it has already outlived its design lifetime of two years. The Special Scanning Multichannel Imager (SSM/I), which is similar to and would be a worthy replacement of SMMR, was launched in 1987. Unfortunately, the SSM/I does not have the low-frequency channels required for sea surface temperature retrievals. However, it has high-frequency channels that will provide higher-resolution data and more information about surface and atmospheric characteristics. The Naval Research Oceanographic Satellite (NROSS) scheduled to be launched in the 1990s will also have an SSM/I sensor on board. (NROSS status is uncertain at time of printing of this report.) In addition, European and Japanese passive microwave sensors are expected to be launched starting in the late 1980s, but these sensors have only two channels and have limited applications for ocean

TABLE B-2

EXISTING OCEAN RELATED SPACECRAFTS (1987)

SATELLITE	SPONSOR	OCEAN-RELATED SENSORS	YEAR	LAUNCH TYPE
LANDSAT-5	Private	MSS Visible/Infrared	1984	Operational
SPOT 1	Foreign	MSS Visible	1986	Operational
NOAA-X	NOAA	AVHRR Visible/infrared	1984	Operational
	NOAA	HIRS/a Infrared Sounder	1984	Operational
	NOSS	MSU Microwave Sounder	1984	Operational
GOES	NOAA	VISSR Visible/Infrared	1975	Operational
DMSP	USAF	MIR Infrared	1970	Operational
DMSP	USAF	MTS Microwave	1970	Operational
NIMBUS-7	NASA	SMMR Passive Microwave	1978	Research
		THIR Infrared	1978	Research
		CZCS Visible	1978	Research
GEOSAT	USN	RADAR ALTIMETER	1985	Research

research. As for active microwave sensors, a radar altimeter on board the Geodetic Satellite (GEOSAT), which is sponsored by the U.S. Navy, was launched in 1985 and has been working very well. Another radar altimeter is intended for launch on board the NROSS satellite in the 1990s and should provide complementary coverage especially because the inclination of the orbit is different. Since the launch of SEASAT in 1978, which survived only about three months, no satellite with a SAR or a scatterometer has been launched. Thus, no new scatterometer data will be available until the launch of NROSS or the Japanese ERS-1. Also, satellite SAR data will not be available until the launch of the European ERS-1 and the Japanese ERS-1. Some space shuttle flights carrying SAR sensors are scheduled in the late 1990s but would be useful only for special short-term studies. Overall, however, oceanographers should have ample satellite data to work with in the next decade.

TABLE B-3

PLANNED AND PROPOSED SATELLITES FOR NEXT DECADE

SATELLITE	SPONSOR	OCEAN-RELATED SENSORS	LAUNCH	STATUS
DMSP	USAF	SSM/I (Passive Microwave)	1986	APPROVED
	NASA	SSM/I PROCESSING FACILITY	1986	APPROVED
MOS-1	JAPAN	MESSR (Passive Microwave) VTIR (infrared) MSR	1986	APPROVED
ERS-1	ESA	AMI (SAR) ASTR(IR) PPRARE (LASER)	1990	APPROVED
	NASA	SAR DATA RECEIVING/ PROCESSING	PROPOSED	
SPOT-3	FRANCE	Radar Altimeter Microwave Sounder	1989	PHASE-B
NROSS	USN	Radar Altimeter Scatterometer SSM/I Low Frequency/ Microwave Radar	1990	UNCERTAIN
JERS-1	JAPAN	SAR VNIR (Visible/Infrared)	1992	APPROVED
	NASA	UTILIZE SAR DATA FACILITY		PROPOSED
TOPEX	NASA	DUAL FREQUENCY ALTIMETER	1991	PHASE-B
POSEIDON	FRANCE	SINGLE FREQ ALTIMETER	1991	PHASE-B
RADARSAT	CANADA	SAR Wind Scattterometer Optical Sensor	1994	APPROVED
LANDSAT 6	USA	MSS, TM	PROPOSED	PROPOSED

Appendix C
Relevant Reports
(1981-1987)

1. Oceanography from Space—A Research Strategy for the Decade 1985-1995. Prepared by the Satellite Planning Committee of the Joint Oceanographic Institutions Incorporated, (JOI), Washington, D.C.
2. Polar Research Board Reports:
   - An Evaluation of Antarctic Marine Ecosystem Research, 1981
   - Research Emphasis for the U.S. Antarctic Program, 1983
   - Snow and Ice Research-An Assessment, 1983
   - The Polar Regions and Climate Change, 1984
   - Glaciers, Ice Sheets, and Sea Level: Effects of a CO_2-Induced Climate Change, 1985
3. Antarctic Climate Research. Prepared by a Committee of the Scientific Committee on Antarctic Research (SCAR), 1983.
4. Ocean Science for the year 2000. A report by the Scientific Committee on Oceanic Research (SCOR).
5. Global Observations and Understanding of the General Circulation of the Oceans. A Report of the Oceans Climate Research Committee Board on Ocean Science and Policy, National Research Council, 1984.
6. An Ocean Climate Research Strategy by Ferris Webster for the National Research Council, 1984.
7. Ocean Research for Understanding Climate Variations, Priorities and Goals for the 1980s. U.S. National Research Council, 1983.
8. WOCE, World Ocean Circulation Experiment Reports: Ocean Sector Reports, U.S. WOCE Office, Texas A&M, 1985.
9. Scientific Plan for the World Ocean Research Program. WCRP Publication Series No. 2, 1984.
10. General Circulation of the Southern Ocean, SCOR Working Group 74. Publication of the ICSU, 1985.

11. WOCE Core Project 2 Planning Meeting. The Southern Ocean. World Climate Research Program. WCP #138, World Weather Organization. Report 181, 1987.
12. Earth Observing System, NASA Reports:
    - SAR Synthetic Aperture Radar, Volume IIf, 1987.
    - HMMR High-Resolution Multifrequency Microwave Radiometer, 1987.

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