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GENERAL CIRCULATION OF THE SOUTHERN OCEAN: STATUS AND RECOMMENDATIONS FOR RESEARCH

A Report by SCOR Working Group 74

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SCIENTIFIC COMMITTEE FOR OCEANIC RESEARCH

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The World Climate Data Programme (WCDP)
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General Circulation of the Southern Ocean;
Status and Recommendations for Research

A Report from SCOR Working Group 74

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PREFACE

The Scientific Committee on Oceanic Research (SCOR) established Working Group 74, "General Circulation of the Southern Ocean", following a proposal by the Scientific Committee on Antarctic Research (SCAR) that SCOR undertake the main responsibility for providing the focus within the International Council of Scientific Unions for physical and chemical oceanography of the Southern Ocean. Both SCOR and SCAR were aware that the Intergovernmental Oceanographic Commission (IOC) should have an important role in promoting international collaboration in physics and chemistry in the Southern Ocean, but that nevertheless there was a need for a scientific focus within the International Council of Scientific Unions which could best be provided by a SCOR Working Group.

During the August 1982 meeting of the Joint Oceanographic Assembly in Halifax, the SCOR Antarctic Review Group was disbanded and SCOR Working Group 74 was established with the following terms of reference:

(1) To identify major gaps in the knowledge of the general circulation of the Southern Ocean, bearing in mind its relevance to biology and climate.

(2) To specify physical and chemical programs to investigate these problems.

The members and SCOR Executive Reporter for Working Group 74 are listed in Appendix A to this report, together with their affiliations.

The initial meeting of Working Group 74 was held as soon as practicable after its establishment in order that preliminary considerations would be available for possible presentation at the fourth session of the Programme Group for the Southern Oceans (SOC) of the IOC, scheduled for 7-12 March 1983 in Paris. The WG met on 17 and 18 February 1983 at the Lamont-Doherty Geological Observatory in Palisades, New York. Based on that meeting, a preliminary report was presented to SCOR and in March 1983 to the fourth meeting of the SOC

During that SOC meeting several areas were identified in which advice from WG 74 might be useful in the planning or coordination of research programs in the Southern Ocean, including: consideration of requirements for a RNODC for Southern Ocean chemical and physical oceanographic data; advice regarding physical and chemical observational programs supportive of BIOMASS and the value of BIOMASS physical measurements to understanding the circulation; consideration of Southern Ocean studies using satellite-derived data, including surface drifters; and the value of ship-of-opportunity programs for the Southern Ocean. These matters were considered during the second meeting of WG 74.

The Institüt für Meereskunde an der Universität Kiel, hosted the second meeting of WG 74 on 15-17 May 1984. The principal items of business at that meeting were the discussion of draft sections of this report, identification of key scientific questions regarding the Southern Ocean circulation, and recommendations for some specific research programs. The group reached agreement on the key questions and recommended studies.

This report is a record of the discussions at the meetings of WG 74 supplemented by additional correspondence and personal contacts between members and the chairman. We consider that this report satisfies the original charge to the WG.

This report should be of particular interest to those planners of a World Ocean Circulation Experiment (WOCE), which is the principal activity of the World Climate Research Programme related to climate variability and prediction over periods of decades (WCRP, 1984). The inability to describe and model the circulation of the ocean is a major scientific problem limiting climate prediction over decades. Moreover, in the WOCE planning to date, the Southern Ocean has been prominent, because of its role in zonal exchanges between the other oceans, as a region through which poleward heat flux and loss to the atmosphere occurs and as the site of surface water mass modification, and thus formation of much of the subsurface water of the global ocean. This report reviews the status of these research topics and focuses on research necessary for their fuller understanding.

Worth D. Nowlin, Jr.
Chairman
SCOR Working Group 74

1 INTRODUCTION

The terms of reference given to Working Group 74, General Circulation of the Southern Ocean, are quite broad: "To identify major gaps in the knowledge of the general circulation of the Southern Ocean, bearing in mind its relevance to biology and climate; and to specify physical and chemical programs to investigate these problems." The approach of the Working Group to this charge was to review the present knowledge and understanding of Southern Ocean circulation bearing in mind the following questions: What are major oceanographic problems in the Southern Ocean which bear on the general circulation? Which are amenable to solution at this time and how should they be approached?

The Group also asked the questions: "Which studies would likely be advanced through intergovernmental projects?" and "Could the Southern Ocean Program Group (SOC) of the Intergovernmental Oceanographic Commission be of assistance in initiating or carrying out such projects?" Based on considerations of those issues, a preliminary report from WG 74 was prepared in February 1983 and presented to the fourth meeting of SOC in Paris on March 7, 1983.

In our review, and in framing questions and recommendations, we were aided particularly by the work of previous review groups. Included in the list of such studies which we considered are: the recommendations of the first three meetings of the IOC/SOC in 1970, 1974 and 1977; "Southern Ocean Dynamics: A strategy for scientific exploration, 1973-1983" (U.S. National Academy of Sciences, 1974); draft objectives and plans for a World Ocean Circulation Experiment; "Report of the WMO/CAS-JSC-CCCO Meeting of Experts on the Role of Sea Ice in Climate Variations" (WCP, 1983); various NASA documents describing planned and potential oceanographic scientific missions; recommendations from the "Summary Report of the Third CCCO Session" (CCCO, 1982); "Long-term sea level measurements; a global catalogue" (Lutjeharms and Alheit, 1982); the report "Antarctic Climate Research" (SCAR-ACR, 1983).

The general circulation of the Southern Ocean is a very large topic; to provide focus we discussed separately four different oceanographic regimes of the Southern Ocean: processes in the shelf-slope region, including especially deep water formation; the subpolar zone; the Antarctic Circumpolar Current; and the subantarctic zone, with attention on interactions between the Southern Ocean and the subtropics. Air-ice-sea interactions and sea level observations were treated as two additional topics.

Consequently, this report contains chapters dealing with each of these six topical areas. In each chapter is given a brief review of present status followed by suggested major scientific questions and recommendations for research. The reviews are not meant to be comprehensive assessments of the present state of knowledge; rather, they are meant to point out deficiencies in our descriptions and understanding within a framework of the present status.

We recognize that arranging the report by distinct oceanographic regimes may obfuscate the importance of the study and understanding of processes, many of which cut across these geographical boundaries. Here are offered examples of such chains of processes or phenomena.

The heat budget of the Southern Ocean and heat transports within that region are important elements for knowledge of the climate system. Improved description and understanding of these elements will require studies in all of the oceanographic regimes of the Southern Ocean. Surface water mass modifications near Antarctica lead to dense water production and renewal of much of the abyssal water of the world oceans. These modifications require large heat exchange from ocean to atmosphere, which requires in turn that an equivalent poleward heat flux must exist within the Southern Ocean.

The mechanisms responsible for the poleward heat flux across the subpolar zone from the Antarctic Circumpolar Current to the regions of major air-sea exchange have not yet been identified. It may prove very difficult to obtain quantitative estimates of heat transports associated with distinct processes within this area of annual ice cover.

Estimates have been made of the net heat exchange by the ocean across the Antarctic Polar Front and of the fluxes accounted for by different processes. Arnold Gordon (personal communication) estimated the ocean heat loss south of that front to be 3×10^{14}W based on climatological values of surface conditions, but the uncertainty may be large (as much as 50%). More definitive estimates will require improved estimates of atmosphere-ocean heat exchanges over the extent of the Southern Ocean, including likely large exchange rates associated with leads in the ice and polynyas.

Using historical hydrographic data, deSzoeke and Levine (1981) showed the advective geostrophic heat flux across a circumpolar path near the Polar Front to be small; and, using average wind fields, they estimated the equatorward heat flux due to Ekman transport to be 1.5×10^{14}W. Together with Gordon's estimate of air-sea exchange, this means that a poleward heat flux of approximately 4.5×10^{14}W must take place across the Polar Front within the ocean interior. Joyce, Zenk and Millard (1978) estimated intrusive heat flux associated with interleaving at the boundary of water masses across the Polar Front and found it to be only about 10% of the required flux. Candidate mechanisms responsible for this flux are eddy processes and deep boundary currents. Several workers (e.g., Bryden, 1979; Sciremammano, 1980; Nowlin, Worley and Whitworth, 1985) have estimated heat flux due to mesoscale eddy processes and found that such eddy heat flux could indeed account for the required poleward heat flux. However, these estimates all apply only to Drake Passage and may not be indicative of other areas around the continent. The answer to which processes are responsible in different areas for heat flux across the Polar Front and Antarctic Circumpolar Current awaits additional field observations.

It may prove more practicable to determine net ocean heat flux into the Southern Ocean and its variability by studies in the Subantarctic Zone or subtropical gyres than by estimating this flux at the Polar Front. This determination might be made by monitoring western boundary currents (at all depths) and using hydrography across the ocean to the eastern boundary of each basin.

An example of a phenomenon cutting across our oceanographic regimes is the Polar Slope Current of the Weddell and Scotia Seas. The principal circulation feature of the Weddell Sea is the clockwise flowing Weddell Gyre. The exact location and variability of the eastern extent of this gyre are not known. However, the southwestward flowing southern limb of this gyre interacts with the Maud Rise near 65°S, 4°E, resulting in the current turning first to the east and then to the west. This flow continues westward into the western boundary region of the Weddell Gyre. Along the outer shelf edge and continental slope of the Weddell Sea, as perhaps at other locations around Antarctica (Killworth, 1983), a narrow Polar Slope Current flows westward. The Polar Slope Current is likely part of the thermohaline circulation being driven by offshelf convection of dense water. The relation between the westward flows of the Weddell Gyre and the Polar Slope Current is unclear. However, it is thought that surface and lateral exchanges cause water mass modifications within the Polar Slope Current which may contribute to the production of dense subsurface waters. And, it is assumed that this current contributes to a western boundary current in the Weddell Sea, although observations have been hindered or precluded by the ice cover.

The downstream extension of that current along the continental slope has been inferred, from geological evidence (Hollister and Elder, 1969), to bifurcate after turning eastward along the South Scotia arc. One branch continues east, then northward around the eastern end of the arc, and then into the Georgia Basin; the second branch passes into the Scotia Sea through a channel west of South Orkney Islands and then flows westward along the continental margin into the Pacific Ocean. Recent *in situ* current measurements in the passage between the Weddell and Scotia Seas and at two locations in Drake Passage have confirmed the existence of a persistent westward current from the shelf edge to the base of the slope (Nowlin and Zenk, 1984).

This current system, if continuous, is involved in transporting Circumpolar Deep Water from the Antarctic Circumpolar Current system into the southern Weddell Gyre, in water mass modification and deep water formation in the shelf/slope regime, in contributing to the western boundary current of the Weddell Gyre, in transporting Antarctic water into the South Atlantic and in transporting water counter to the Circumpolar Current through Drake Passage into the subpolar zone of the Pacific Ocean. Many of these actions have important implications for the krill population and other elements of the Antarctic marine ecosystem.

The use of satellites as observational tools also tends to blur the lines between geographic regions. From satellite-born altimeters, we can obtain measures of the variability sea surface height (e.g., Cheney *et al.*, 1983) or descriptions of the spatial coherence of large-scale, longer-term changes in geostrophic surface current patterns (Fu and Chelton, 1984). Such perspectives allow us to view the relative variability in widely separated regions and consider the physical causes of similarities or differences with a data base unlimited by geography. We are also able to view interactions between the changes in one circulation regime, e.g., the Antarctic Circumpolar Current, and that in another, such as, the Weddell Gyre.

2 INTERACTIONS BETWEEN THE SOUTHERN OCEAN AND THE SUBTROPICS

The subantarctic zone, situated between the Antarctic Circumpolar Current (ACC) and the Subtropical Front (also referred to as the Subtropical Convergence), is the regime of the Southern Ocean nearest the equator. It extends around Antarctica in a band unbroken except by South America (Fig. 1). It is seen that the two fronts associated with the ACC--Subantarctic and Polar Fronts--are circumpolar in extent. The Subantarctic Front is the poleward limit of the subantarctic zone; the Subtropical Front is interrupted by the American continent. It is through the subantarctic zone that direct exchanges between the Southern Ocean and the subtropical portions of the Southern Hemisphere oceans must take place.

Discussion of the study of these interactions and recommendations for research may be arranged into four main categories: the Subtropical Front; formation and outflow of upper and intermediate waters; the subtropical gyres; and abyssal circulation.

<u>2.1 The Subtropical Front.</u> Based on available information, the nature of the Subtropical Front differs markedly from one geographical region to another--a pronounced feature in the western portions of the Southern Hemisphere oceans but a weak front in some mid-ocean positions. In addition, spatial and temporal variations are known to be quite large in some regions, e.g., southeast of South Africa, but in many areas the nature and variability of the STF are virtually unknown. This front may have important biological effects, e.g., south of Africa the STF exhibits enhanced primary productivity (Allanson *et al*., 1981).

We do not know which processes maintain the STF, either at sea surface or at depth, or whether these processes are different in degree only or in kind from one oceanographic area to another. It is assumed that significant meridional transfers of heat, mass and momentum take place across the front. The amounts and mechanisms of these transfers are important subjects of study. Intense mesoscale eddy transport has been observed at the STF in western boundary current areas, probably due in part to baroclinic instability and Rossby waves, as studied recently in the northeastern Atlantic (Kase, Zenk, Sanford and Hiller, 1985). Transfer in more quiescent areas such as in the mid South Atlantic Ocean might be considerably reduced, or of a different nature. Are areas recognized for their high dynamic variability the key areas of meridional interactions?

Work in the Drake Passage has shown that the largest part of the zonal flow is concentrated in narrow bands of high velocities that coincide with fronts. Work with historical data suggests that the same may be true for the Subtropical Front (Clifford, 1983). This should be studied further, keeping in mind the geographic variability in the frontal characteristics.

<u>2.2 Formation and Outflow of SAMW and AAIW.</u> The importance of

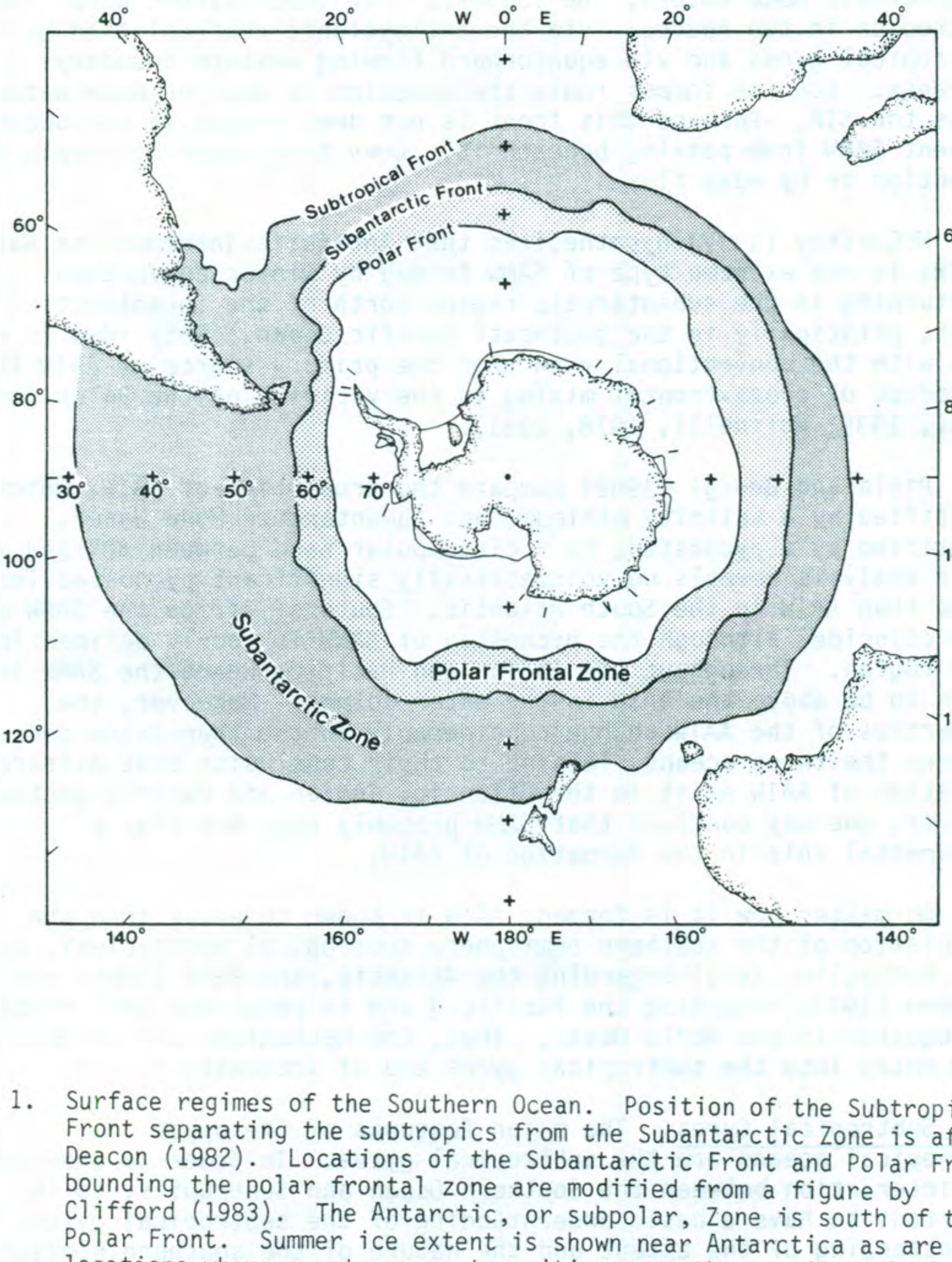

Fig. 1. Surface regimes of the Southern Ocean. Position of the Subtropical Front separating the subtropics from the Subantarctic Zone is after Deacon (1982). Locations of the Subantarctic Front and Polar Front bounding the polar frontal zone are modified from a figure by Clifford (1983). The Antarctic, or subpolar, Zone is south of the Polar Front. Summer ice extent is shown near Antarctica as are locations where a water mass transition near the continental slope has been observed (Clifford, 1983).

Subantarctic Mode Water (SAMW) to the ventilation of the thermocline of some ocean basins in the southern hemisphere has been demonstrated (McCartney, 1977). He hypothesizes that the principal formation of SAMW takes place immediately north of the circumpolar Subantarctic Front as a consequence of winter air-sea interaction, with the most dense classes being formed in the southeast Pacific near South America. It may well be that the maintenance of the Subantarctic Front is related to the formation of SAMW.

McCartney (1982) has discussed the subtropical recirculation of Subantarctic Mode Waters. He suggests that these waters enter the subtropics in two routes: via the anticyclonic recirculation of the subtropical gyres and via equatorward flowing western boundary currents. For the former route the question is how the mode waters cross the STF. Perhaps this front is not deep enough in mid-ocean to prevent SAMW from passing beneath it. Does this occur by simple mean advection or by eddy fluxes?

McCartney (1977) hypothesizes that Antarctic Intermediate Water (AAIW) is one extreme type of SAMW formed by winter convection overturning in the subantarctic region north of the Subantarctic Front, principally in the southeast Pacific Ocean. This idea is at odds with the conventional view that the primary source of AAIW is as a product of cross-frontal mixing in the vicinity of the Polar Front (Wüst, 1935; Molinelli, 1978, 1981).

Piola and Georgi (1982) compare the properties of AAIW, which is identified by a salinity minimum, and Subantarctic Mode Water, identified by a pycnostad, in a circumpolar band between 40° and 45°S. Their analysis reveals no volumetrically significant pycnostad less dense than AAIW in the South Atlantic. South of Africa the SAMW and AAIW coincide, although the pycnostad of SAMW is poorly defined in that region. Throughout the Indian and Pacific Oceans the SAMW is shown to be above the AAIW in the water column. Moreover, the properties of the AAIW change considerably in the transition areas between the three oceans, leading to their conclusion that different varieties of AAIW exist in the Atlantic, Indian and Pacific sectors. Further, one may conclude that SAMW probably does not play a fundamental role in the formation of AAIW.

No matter how it is formed, AAIW is known to enter into the circulation of the southern hemisphere subtropical anticyclonic gyres [See Buscaglia (1971) regarding the Atlantic, and Reid (1965) and Johnson (1973) regarding the Pacific.] and to penetrate well north of the equator in the World Ocean. Thus, the mechanisms and volumes of AAIW entry into the subtropical gyres are of interest.

<u>2.3 Subtropical Gyres.</u> The major features of the upper subtropical oceans are the subtropical gyres. In order to understand the interaction between the Southern Ocean and Subtropics, it is important to have a basic understanding of the subtropical gyres. Our understanding of the extent and the nature of the southern hemisphere subtropical gyres is fragmentary at best. We do not have good estimates of the transports and variability of the western boundary currents. We have only poor information on the amount of recirculation which occurs to the east of these boundary currents.

Transequatorial fluxes of mass, heat and other properties are poorly estimated as are the water layers in which these transports occur. The amount of temporal variation of configurations of the gyres or their transports is unknown. From work on historical data sets, Reid and Arthur (1975) have shown the gyres in the Pacific Ocean have different dimensions and shift poleward with increasing depth. The interaction between the deeper parts of the eastward flowing southern limbs of these gyres and the deep reaching ACC is another gap in our understanding.

2.4 Abyssal Circulation. It is generally held that a significant portion of the meridional transport of water characteristics takes place by the outflow of bottom water from the Southern Ocean and that this outflow is geographically limited by a combination of topography and dynamics to a few locations (Fig. 2). Abyssal boundary currents transport Antarctic Bottom Water northward: over the South Sandwich Trench and then into the Argentine Basin in the South Atlantic; around the Chatham Rise into the Southwest Pacific Basin; and at three longitudes as western boundary currents into the Indian Ocean.

The most accessible locations could be selected where the outflow in abyssal boundary currents could be monitored by moored arrays of current and temperature recorders. Since the outflows are narrow in certain places, and since the technology for such measurements is well-developed, valuable measurements of heat and mass flux over extended periods at certain locations might be achieved. Short and long-term variability in these currents could also be monitored.

2.5 Research Questions

* What is the nature of the Subtropical Front? How does it vary spatially and temporally? What processes are responsible for its maintenance?

* Can we estimate the exchange of heat, salt and other properties across the Subtropical Front due to mesoscale eddy fluxes and small scale structure?

* How large are the mass, heat or other property transports from the Southern Ocean due to deep boundary currents?

* Ventilation of the ocean by formation of Subantarctic Mode Water is of worldwide importance. What are the processes and rates of formation of Subantarctic Mode Water? How is SAMW incorporated into the subtropical gyres?

* Distinct mechanisms for Antarctic Intermediate Water (AAIW) formation have been proposed; can a definitive experiment to study its formation be designed?

* How much Antarctic Intermediate Water enters into the subtropical gyres and by what mechanisms and routes?

* Do the wind-driven subtropical gyres of the Southern Hemisphere extend deeper than those of the Northern Hemisphere because of the existence of the Antarctic Circumpolar Current?

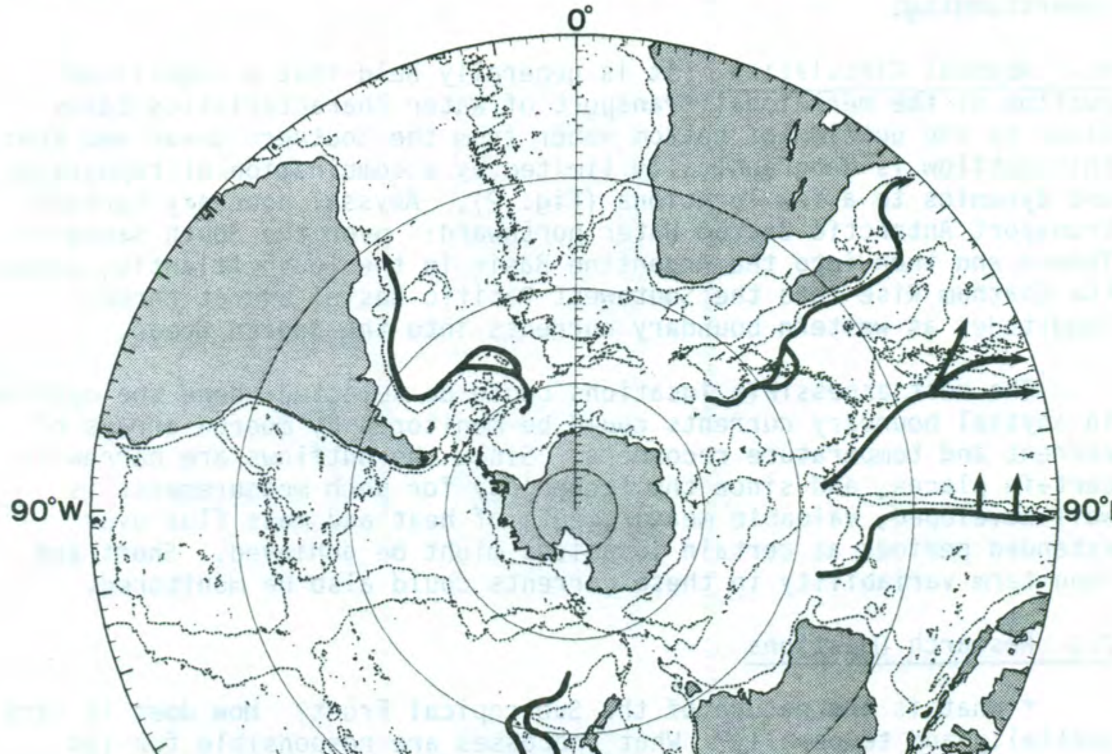

Fig. 2. Likely paths of major abyssal currents. Routes in Indian Ocean suggested by Warren (1984). Isobath shown is 3.5 km.

2.6 Recommendations

* Better description of the structure of the Subtropical Front and its space and time variability is needed. This may be obtained by:

  * Examination of existing data for information on the nature of the STF;

  * Encouraging ship-of-opportunity measurements across the Subtropical Front; and

  * A number of research cruises to characterize the STF in areas thought to be distinct in terms of forcing or topographic influence.

* Begin time series measurements of current, temperature, etc. in deep western boundary currents in an effort to characterize their variability and estimate their transport.

3 ANTARCTIC CIRCUMPOLAR CURRENT

3.1 Zonation. We now know the Antarctic Circumpolar Current (ACC) contains several current cores with large eastward speed relative to the water in which they are embedded. The current cores observed in Drake Passage are high velocity ($\sim$35 cm s^{-1} at the surface), narrow ($\sim$50 km) bands embedded in slower and wider zones (Nowlin, Whitworth and Pillsbury, 1977; Nowlin and Clifford, 1982). These current cores are fronts with pronounced horizontal gradients of density and of characteristics such as temperature, salinity, nutrients, etc.; and within the upper water column at least, characteristic relations (e.g., temperature-salinity) change rather abruptly across these fronts. There are three fronts at Drake Passage, but from the work of Emery (1977) and Clifford (1983), it seems likely that only the Subantarctic Front (SAF) and the Polar Front (PF) are circumpolar in extent (see Fig. 3). (A front analogous to the Continental Water Boundary of the southern Drake Passage is found at some other locations, but generally not where the ACC is far from land.) The PF forms the northern boundary of Antarctic surface waters; subantarctic surface waters extend poleward to the SAF. The Polar Frontal Zone between these fronts is a water mass transition zone.

The processes which cause and maintain this ACC zonation have not yet been identified. It has been shown that meridional zonation may occur for weakly stratified zonal flow through a meridionally confined region of reduced depth (Allen, McCartney and Yao, 1975). There are several such regions through which the ACC must pass, and this might influence zonation. In general, there is a close relationship between the ACC and the mid-ocean ridge system. However, zonation may also be influenced by the distributions of air-sea fluxes. A numerical modeling effort to reproduce this zonation might be an effective means of obtaining better understanding of this zonation.

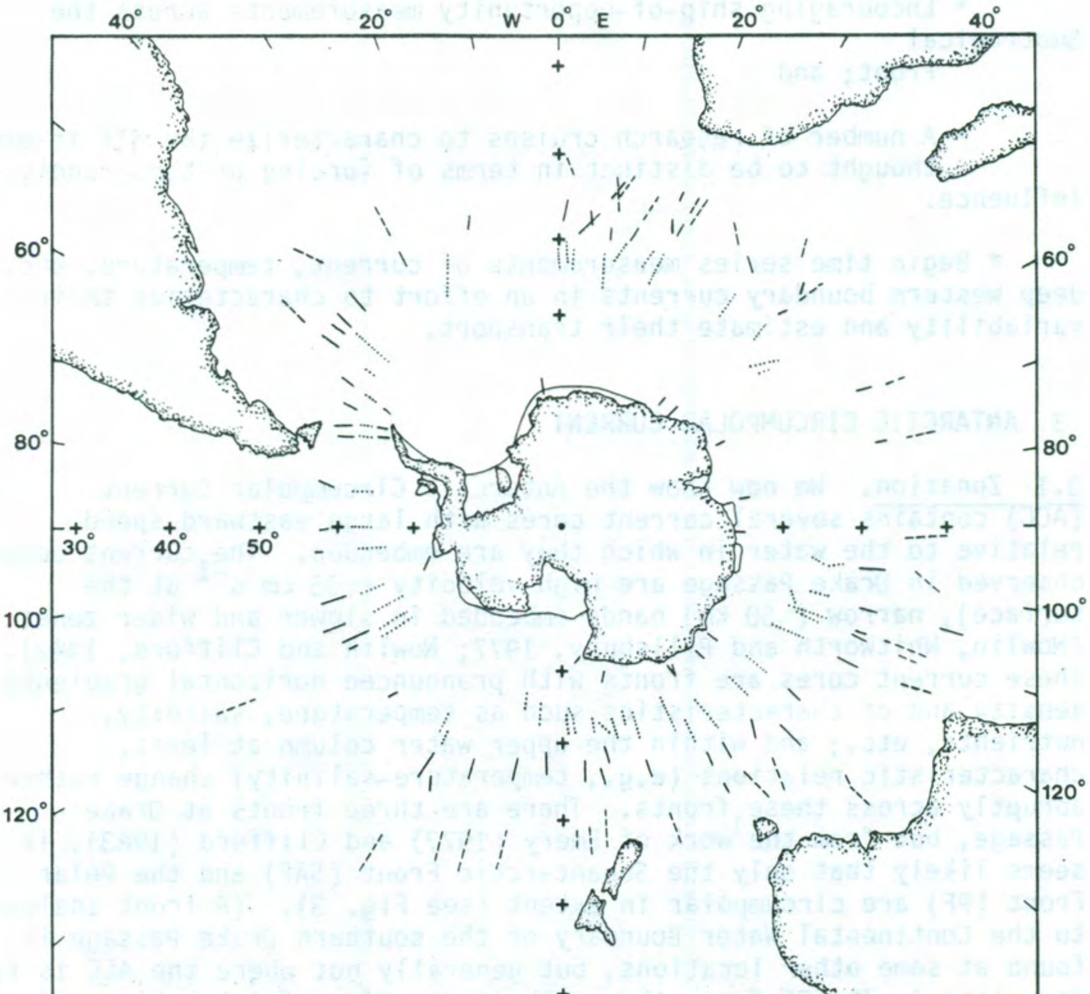

Fig. 3. Austral summer locations of the positions of the Subtropical Front (-----), Subantarctic Front (———) Polar Front (•••••) and the Continental Water Boundary (——) after Clifford (1983).

3.2 Mass and Property Transports. Much of the present knowledge about the ACC is derived from an intensive monitoring effort within the International Southern Ocean Studies (ISOS) that took place within the last decade in Drake Passage and southeast of New Zealand. The major goal of ISOS was to obtain a good estimate of the net volume transport (through Drake Passage). After four years of preliminary scale experiments, adequate resources were assembled and a time series of volume transport was obtained from February 1979 to March 1980 (Whitworth, 1983). The net transport above 2500 m had a mean of 123 x 10^6 m^3s^{-1}; the range was 87 to 148; and the standard error 10 (Whitworth and Peterson, 1985). See Fig. 4. Higher frequency fluctuations were found to occur in the barotropic mode, but approximately 70% of the net transport was associated with the shear flow, which was shown to be in approximate geostrophic balance for periods greater than 26 d. Geostrophic transport through Drake Passage relative to 3000 db for 5 crossings made during 1975 and 1976 showed the shear flow to be relatively uniform with an average 95 x 10^6 m^3s^{-1} (Nowlin et al., 1977), consistent with estimates by Reid and Nowlin (1971) from earlier sections. The eastward transport of the ACC must be slightly larger than this value because a westward flowing polar slope current along the southern margin of Drake Passage was included in net transport estimates.

This transport record has been examined in relation to several other time series of forcing mechanisms or possibly related events. Whitworth (personal communication) has compared the transport time series to Southern Hemisphere wind data analyzed various ways (sector averages, circumpolar averages of zonal wind stress, etc.) with inconclusive results. For fluctuations greater than several weeks duration changes in ACC transport seem related to variations in the rotation rate of Earth as determined from length-of-day measurements (Peterson, personal communication). Such studies are continuing. However, for many purposes a one-year time series is of insufficient length.

Pressure records from 500-m depths on both sides of Drake Passage were obtained for 4 years: mid-1976 through 1979 and 1981-82. Wearn and Baker (1980) reported on the 1976-78 results and claimed for periods greater than 30 d a significant coherence between the pressure difference and the zonal component of surface wind stress averaged between 40° and 60.5°S with the wind leading by approximately 9 days, but Chelton (1982) noted that this may be merely a result of both series containing strong seasonal signals. Whitworth (1983) identified only a narrow band, periods of 16 to 24 d, for which the circumpolar-averaged zonal wind stess was significantly coherent (at 95%) with the transport through Drake Passage during 1979. Comparisons by Whitworth and Peterson (1985) between net transport and transport estimated from the 1979 pressure difference shows a maximum difference of 24 x 10^6 m^3s^{-1} but that more than 90% of the pressure-derived transports are in error by less than 10 x 10^6 m^3s^{-1}. The three-year pressure-derived transport ranges from 98 to 154 with a standard deviation of 10 around a mean of 123 x 10^6 m^3s^{-1} and suggests near annual as well as semi-annual fluctuations (Fig. 5). The 1981-82 records show pressure-derived transport ranging from 95 to 158 x 10^6 m^3s^{-1} with a

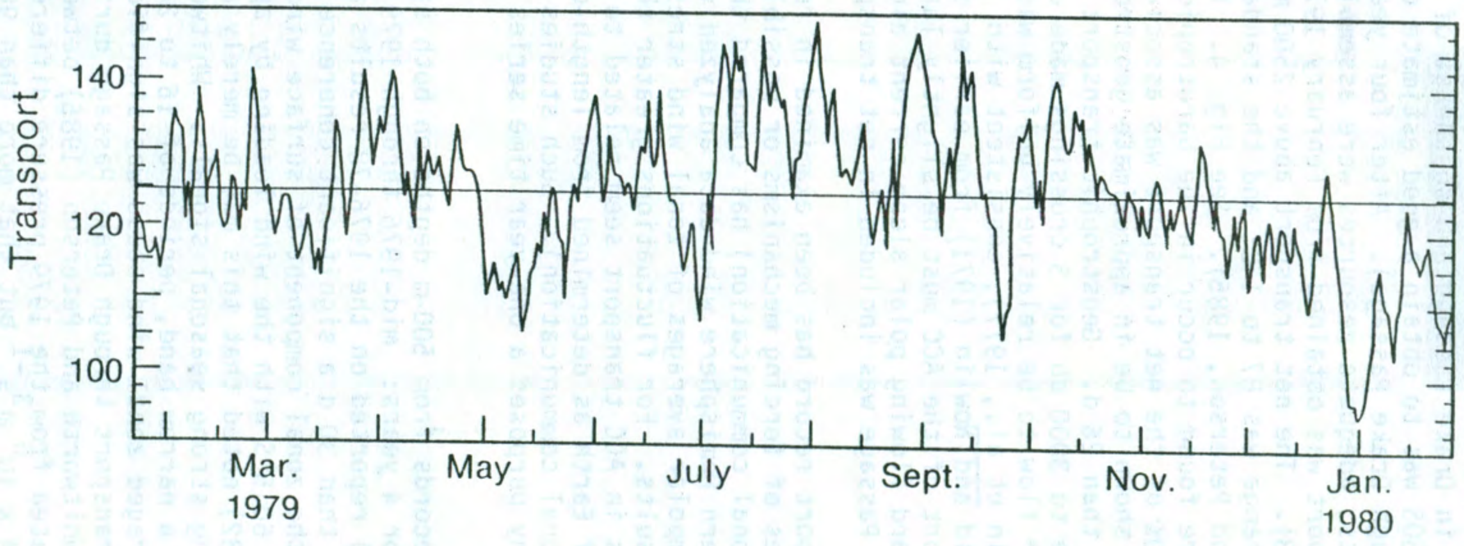

Fig. 4. Net transport (10^6 m^3 s^{-1}) through Drake Passage from January 1979 until February 1980 after Whitworth and Peterson (1985).

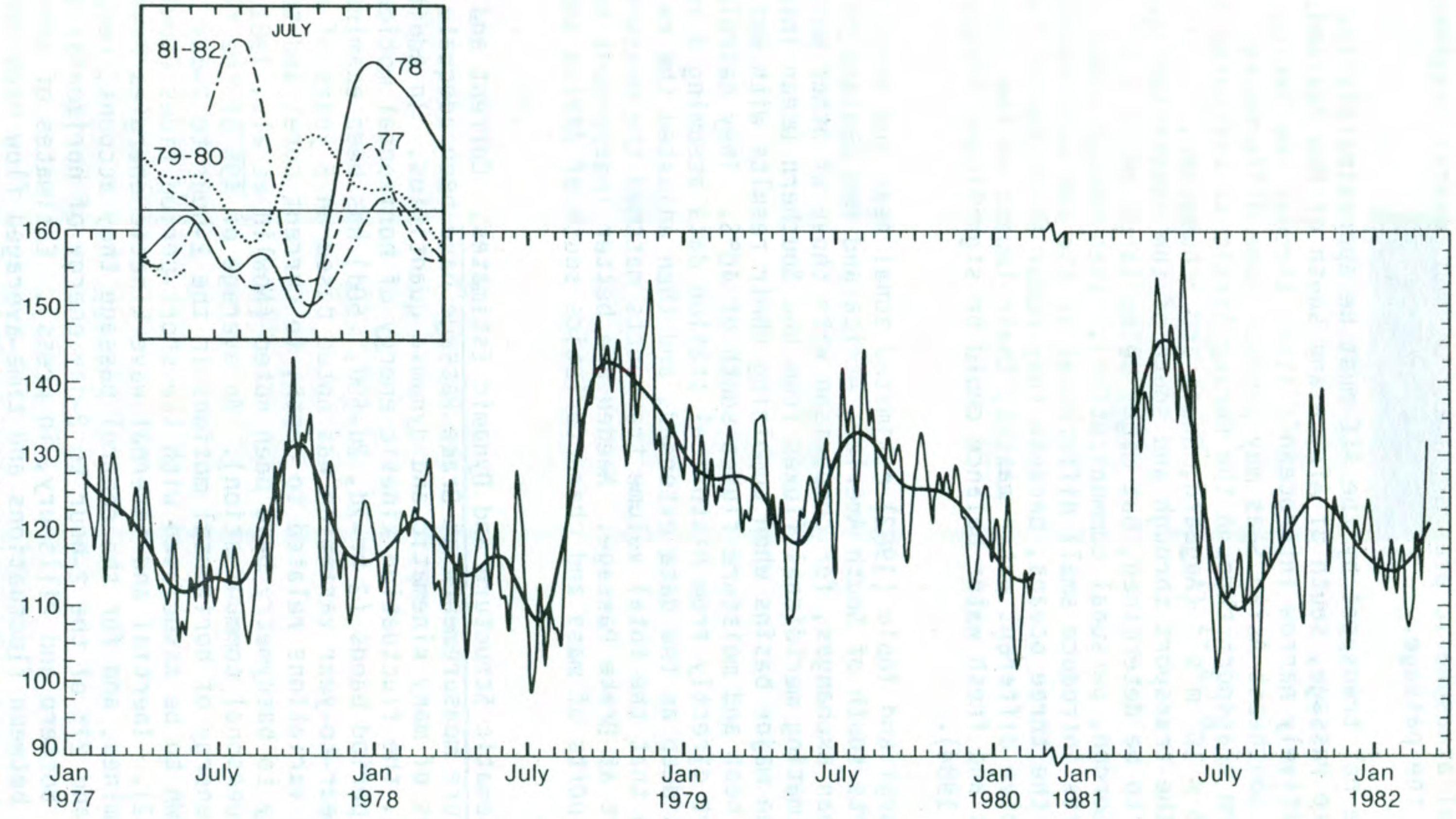

Fig. 5. Linear regression model of the net transport through Drake Passage from Jan. 1977-Feb. 1980 and from March 1981-March 1982. The light line shows 10-day daily transport which are smoothed with a 90-day low pass filter to illustrate the low-frequency variability. The inset shows yearlong segments of the 90-day low-passed series. (After Whitworth and Peterson, 1985).

standard deviation of 13. Attempts are now being made to extend this 4-year transport record over a much longer time using tide gauge and sea-level atmospheric pressure records from coastal stations on either side of the passage.

The net transport by the ACC must be approximately the same in the Drake Passage, south of Africa and south of New Zealand. However, the relatively narrow interoceanic links through the Bering Straits and the Southeast Asian Seas may produce some differences: the net long-term transport through the Bering Strait is estimated to be less than $0.6 \times 10^6\ m^3s^{-1}$ (Aagaard, Roach and Schumacher, 1985); the transport through and south of the Indonesian Archipelago remains to be determined, but might be as large as $15 \times 10^6\ m^3s^{-1}$ (Gordon, personal communication). Even though these transports introduce small differences in the net mass exchange between the three oceans, because they occur at different latitudes and involve different water masses, their impact on the interoceanic net heat and fresh water balance could be significant (Piola and Gordon, 1984).

Georgi and Toole (1982) estimated zonal heat and fresh water transports south of South America, Africa and New Zealand to obtain interocean exchanges, for comparison with those of other workers and for estimating meridional fluxes from the Southern Ocean into each of the three major basins when combining their results with estimates of air-sea heat and moisture fluxes south of 40°S. They calculated transport directly from historical station data assuming a reference level as deep as the data extended, and then adjusted the reference level so that the total volume transports matched the measured transport at Drake Passage. Needed are better independent estimates of transports of mass and characteristics south of Africa and of New Zealand.

3.3 Kinematic Structure and Dynamic Estimates. Current and temperature measurements at Drake Passage have been adequate for estimates of many kinematic and dynamic quantities. In addition to the mean, the fluctuation kinetic energy of horizontal motions for several period bands (2 hr-2d, 2d-50d, >50d) has been examined. Little year-to-year variation was noted based on 5 years of records, although variations related to depth, to current cores and to proximity to bathymetry have been noted (Nowlin et al., 1981; Nowlin, personal communication). An average of 49% of the fluctuation kinetic energy of horizontal motions in the 2-hour to 2-day band has been shown to be associated with the short-period tides (Nowlin et al., 1982). Inertial and internal wave kinetic energies have also been examined, and for the control passage they account, respectively, for 10% and 27% of the 2-hour to 2-day energy of horizontal variance (Nowlin, Bottero and Pillsbury, in press). Estimates of energy exchange between fluctuations and time-averaged flow have been examined by estimating terms in the energy equations by using time series of temperature, current and pressure made at a cluster of moorings in the central Drake Passage during 1977 (J. M. Morrison, personal communication). At that location, just south of the average position of the Polar Front, there was a net flux of energy from the fluctuations to the time-averaged flow.

Based on geostrophic shears referenced to measured subsurface currents the maximum surface speeds at the ACC cores are about 35 cm/sec. Surface drifter observations tend to confirm this (Peterson, 1985), although some surface drifter speeds near 1 m s^{-1} have been observed due to direct wind forcing. These currents are coherent throughout the water column at Drake Passage, (speeds are above 5-10 cm s^{-1} at 2500 m) but that area is relatively shallow (approximately 3600 m), and we know that in some other regions the ACC does not extend to the bottom (e.g., in the southern Argentine Basin north of Maurice Ewing Rise it extends down only to about 3000 m and crosses over the deep boundary current.) Whether the kinematic description of the mean ACC at Drake Passage will prove representative of the Southern Ocean must be determined by measurements in other regions.

Global distributions of the surface eddy variability is available from ship drift (Wyrtki et al., 1976) satellite altimetry (Cheney et al., 1983) and surface, satellite-tracked drifting buoys (Garrett, 1981; Patterson, 1985). As an example, we show in Fig. 6 the global mesoscale variability in sea height as measured by the SEASAT altimeter (Cheney et al., 1983). From these analyses it becomes evident that there is a strong increase in the surface eddy kinetic energy in regions of rough topography supporting previous estimates of current variability based on hydrographic data (Lutjeharms and Baker, 1980) and in regions of strong currents (e.g., ACC cores, Agulhas retroflection, Falkland-Brazil current confluence).

Estimates of typical time and space scales of the low frequency fluctuations (mesoscale) were also obtained from the Drake Passage data set (Sciremammano et al., 1980; Inoue, 1985). Using current and temperature time series in Drake Passage, Bryden (1979) and Nowlin et al. (1985) have shown that there is a significant poleward eddy heat flux across the ACC. This heat flux is believed to be a consequence of the conversion of mean potential energy in the mean flow to eddy potential and kinetic energy. In this regard, it has been possible to use ISOS data to test for baroclinic and barotropic instability in the ACC (Fandry, 1979; Bryden, 1979; Peterson et al., 1979; Wright, 1981; Inoue, 1985). The knowledge of how the ocean transfers heat poleward across the ACC is of significance to understand the Southern Ocean heat balance. So far it appears that neither the mean flow (deSzoeke and Levine, 1981) nor the cross-frontal isopycnal mixing across the Polar Front (Joyce et al., 1978) can account for the net meridional heat transport required to balance the estimated heat loss to the atmosphere south of the ACC. Therefore the eddy meridional heat transfer is a likely candidate. However, it must be kept in mind most of the data available to study this mechanism were collected in the special, constricted region of Drake Passage.

3.4 Dynamical Balance of the ACC. Finally we consider the general dynamical balance of the ACC. Hidaka and Tsuchiya (1953) applied the basic ideas regarding general ocean circulation, which were just developing in the early 1940's, to the Southern Ocean. It was treated as a wind-driven circulation in a zonal annulus. For realistic forcing the values of horizontal and vertical friction required to keep the transports small enough to be reasonable were

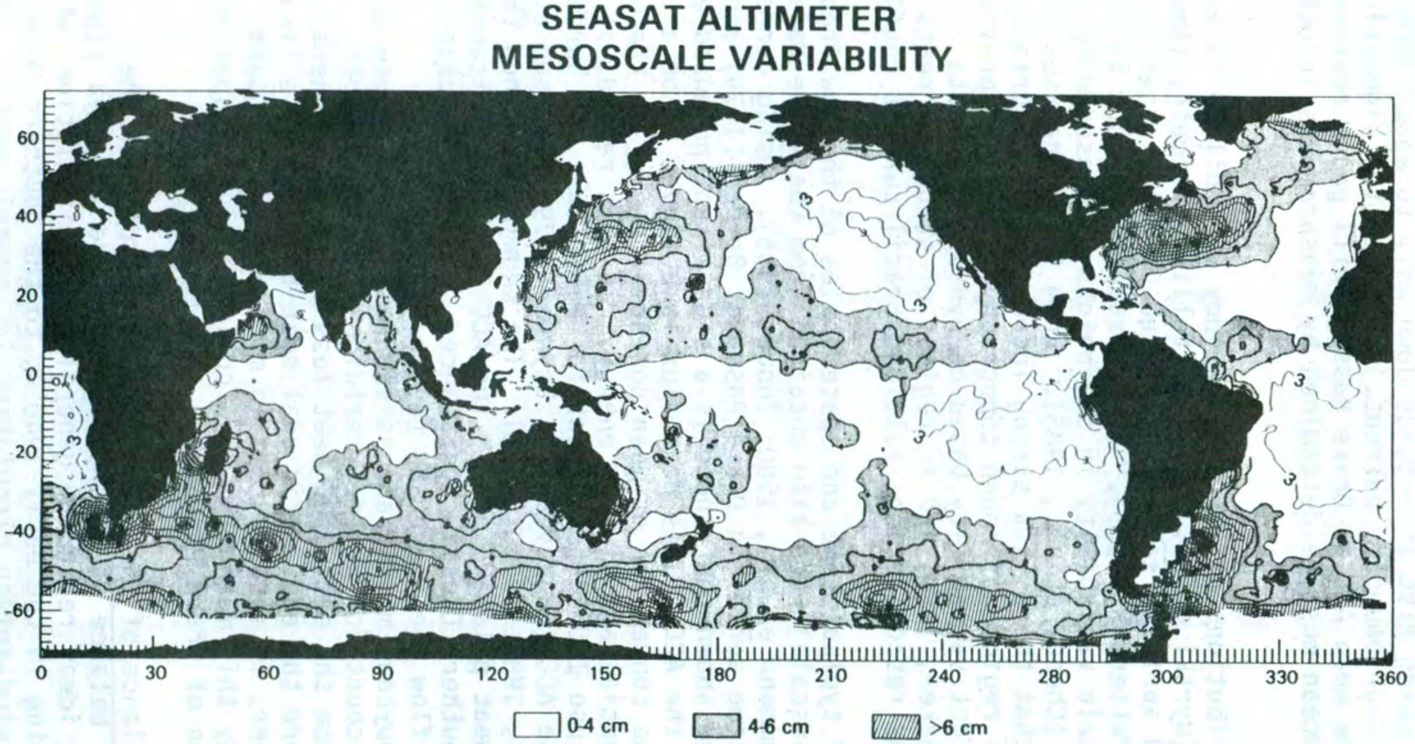

Fig. 6. Global mesoscale sea height variability measured by the SEASAT altimeter, September 15 to October 10, 1978. This map was constructed from 110,000 globally distributed variability values determined every 7 km along the tracks. A gridding routine was then used to obtain smoothed values at regular 2° intervals of latitude and longitude. These were contoured to reveal large-scale variability patterns due to current systems. In the southern hemisphere the Agulhas Current below Africa and the Falkland/Brazill Current confluence off South America are clearly apparent. High variability due to the Antarctic Circumpolar Current extends in a nearly continuous band around the polar oceans, with isolated maxima coinciding with major topographic ridges and plateaus (after Cheney et al., 1983).

unacceptably large. The basin problem reduces to finding acceptable dynamic mechanisms to balance the momentum input by wind while maintaining the ACC transport at a reasonable level. This was the basic justification for the considerable effort spent during the 1970's to determine the transport. Four dissipation mechanisms have been advanced and considered: thermodynamics effects (Fofonoff, 1955); water discharge from Antarctica (Barcilon, 1966, 1967); non-zonal dynamics (Stommel, 1957); and form drag by bottom topography (Munk and Palmén, 1951). Of these the most promising seem to be energy dissipation in non-zonal boundary regimes and form drag, but the question of a proper dynamic balance is still open.

Furthermore, better estimates of the space and time variability of surface forcing are needed. One of the major prerequisites of better dynamical understanding through modeling or analytical efforts is improved global synoptic estimates of surface wind stress. It is therefore necessary to rely on satellite measures, such as scatterometry in the Southern Ocean.

3.5 Research Questions

* The ACC seems to consist of two distinct horizontal fronts or current cores (the Polar and Subantarctic Fronts) separated by a transition region (Polar Frontal Zone) between waters of subantarctic and Antarctic characteristics. What is the nature of these fronts? They appear to be circumpolar in extent, but additional confirming observations would be desirable. How do they vary temporally and spatially? How are these fronts related to other fronts and currents of the Southern Ocean, e.g., the Continental Water Boundary at Drake Passage, the Falkland Current, the Weddell Scotia Confluence?

* What are the processes responsible for these fronts? Proposed candidates include interaction with topography and surface modification of water masses.

* How representative of other regions are the estimates of eddy heat flux and small scale heat exchange across the Antarctic Circumpolar Current (ACC) at Drake Passage and southeast of New Zealand?

* How representative of the ACC are the existing measurements of kinematic structure and estimates of dynamic quantities made at Drake Passage?

* What is the relation of ACC transport to wind stress, ice cover, the Southern Oscillation, variation in Earth's rotation rate, water discharge (or other driving mechanisms or indices)? Longer time series of ACC transport likely will be required.

* What are the correct interbasin exchanges of heat, salt and other properties? South of Africa? South of New Zealand?

* What are the critical processes (terms) in the ACC dynamical balance? How important are nonzonal flow regimes (western boundary regions)? How important is form drag?

3.6 Recommendations

* Observations to better describe the nature of the Subantarctic and Polar Fronts including their space and time variations is needed. Satellite observations of sea surface temperature by microwave radiometry and of surface topography, such as proposed by the European Space Agency's ERS-1 or NASA's Ocean topography the NASA/CNES Ocean Topography Experiment (TOPEX), are the key to synoptic data acquisition. Ocean and meteorological measurements from drifters and ships will be useful in calibrating the satellite data and providing in situ information on the structure beneath the surface.

* Encourage thermal structure and meteorological measurements from ships-of-opportunity crossing the Subantarctic and Polar Fronts. Special emphasis should be placed on using vessels involved in Antarctic marine ecosystem studies.

* Encourage modeling efforts to learn what physical processes must be included to produce an ACC with meridional zonation.

* Using moored instruments, make measurements at a series of locations around Antarctica chosen to represent regimes which might be expected to differ dynamically. The selection might be based on type of bathymetry and observed level of fluctuation energy, e.g., as indicated by variability in sea surface height measured by SEASAT altimetry during 1978 (Fig. 6). Estimate eddy heat and momentum fluxes, energy conversion by instability processes, and selected terms in the energy equations. (Such moorings could be available for geological and biological measures as well.)

* Make repeated hydrographic sections to Antarctica from South Africa and from New Zealand with complete suites of modern measurements including geochemical tracers and acoustic doppler current profilers.

* Modeling efforts should be begun to ascertain which mechanisms are likely responsible for dissipation of the energy provided to the ACC by the wind regime. These efforts should also help rationalize observed relationships between variations in ACC transport and other driving mechanisms or indices. In order to provide these models with adequate wind stress distributions it is emphasized that future satellite-derived wind stress data should cover the Southern Ocean.

4 SUBPOLAR ZONE

4.1 Introduction. The Antarctic Circumpolar Current (ACC) is associated with maximum westerlies of the wind field. The characteristic maximum surface velocity within its multi-axial features is about 30-35 cm/sec, and its volume transport is approximately $125 \times 10^6\ m^3 s^{-1}$ (Whitworth and Peterson, 1985). Estimates of poleward heat flux across the ACC due to the eddy field are of the same magnitude as the oceanic heat loss between the ACC and Antarctica (Bryden, 1983; Nowlin, Worley and Whitworth, 1985). The heat loss south of the ACC is coupled to deep reaching convective processes by water mass conversion; it involves complex interaction between the ocean, atmosphere, sea ice and glacial ice within the continental margin of Antarctica and over the open or deep ocean region. (In Section 5 of this report research on shelf-slope processes and deep water formation near the margins is discussed and recommendations for further research are made.) This section deals primarily with the deep ocean zone between the ACC and the Antarctic margins, here referred to as the subpolar zone.

The subpolar zone has an area of about 35 x 10^6 km^2 (Carmack, 1977). It is affected by positive wind stress curl (Gordon, Taylor and Georgi, 1976) and hence subject to Ekman-induced upwelling and poleward Sverdrup transport. Thus, the circulation should be cyclonic if the return flow within western boundary currents is considered. Three subpolar gyres can be identified: the Weddell Gyre (Deacon, 1976, 1979) is the largest and best defined; the Ross Gyre north and east of the Ross Sea (Deacon, 1937; Tchernia and Jeannin, 1983); and the poorly defined gyre east of the Kerguelan Plateau (Deacon, 1937; Rodman and Gordon, 1982; Tchernia and Jeannin, 1983).

The southern two thirds of the subpolar zone is covered by sea ice for a portion of the year (Zwally et al., 1983). During that time all, except possibly its northernmost extent, is subject to large heat loss to the atmosphere (Table I).

Table I
Oceanic heat loss within Subpolar Zone

Reference	Value ($W m^{-2}$)	Locations
Zillman (1972)	18	60°S, South of Australia
Bunker (1977, personal communication in Taylor et al., 1978)	9	60°S, 0-10°E
Gordon (1981)	31	60°-70°S, Circumpolar average
Gordon et al. (1984) Meridian	12	59°-62°S, Greenwich

The entire subpolar zone receives more fresh water by precipitation and glacial melt than loss by evaporation, although values are subject to great uncertainty. The precipitation minus evaporation for the 60°-70°S belt is estimated as 27 cm/year by Newton (1972) and 32 cm/year by Baumgartner and Reichel (1975). Continental runoff can be taken as 10 cm/year, if the antarctic ice cap is in steady state (Gordon, 1981). Thus, a total fresh water accumulation of 40 cm/year for the band 60°-70°S can be inferred. However, an important term in the local fresh water balance, neglected in the above values, is the net convergence or divergence of sea ice; sea ice need not melt where it is formed (Hibler and Ackley, 1983; Gordon et al., 1984). Thus, the effects of sea ice on the heat and fresh water budgets remain a major climate-related research problem for Southern Ocean study.

4.2 Circulation. Baroclinicity is very weak south of the ACC. Geostrophic surface speeds relative to 2500 db characteristically range from less than 1 cm/sec to 5 cm/sec (Fig. 7). However, the barotropic component may be significant, though variable. Using linear Sverdrup dynamics with the Kerguelan Plateau as an eastern boundary (Gordon, Martinson and Taylor, 1981) obtain a volume transport for the Weddell Gyre of 76 x 10^6 m^3/sec, a value not inconsistent with ship and iceberg drift, geostrophic calculations and the limited direct (current meter) and indirect (compass-oriented bottom photographs) data. Characteristic velocities are only 1 cm/sec in the interior and 5 cm/sec in the western boundary current adjacent to the east coast of the Antarctic Peninsula. Guretsky and Sarukhanyan (1980) estimate transports in the Weddell, Ross and Australian-Antarctic Gyres as 85, 15 and 100 x 10^6 m^3s^{-1}, respectively.

Direct measurements of current in the subpolar zone are mostly Lagrangian. In Fig. 8 are shown trajectories of FGGE surface drifting buoys and selected icebergs. The three main regions of northward flow are associated with what can be considered the western boundary currents of the three gyres.

Current meter measurements in the subpolar zone are few and mostly close to the sea floor rather than throughout the water column (Foster and Middleton, 1979; Rodman and Gordon, 1982; see Gordon's review for IUGG, 1983). Current magnitudes are all weak, less than 5 cm/sec, with directions nearly the same as depicted in the surface drift, indicating a significant barotropic component.

The baroclinic circulation based on hydrographic data with a deep reference level (e.g., Plate 232 of Gordon and Molinelli, 1982) do not show well defined gyres. Seen are waves in the circumpolar isopleths of relative dynamic height, with northward perturbations associated with each gyre.

Of the three gyres, the Weddell Gyre baroclinic field is best resolved in the hydrographic data (Fig. 7). The cyclonic gyre extends from the Antarctic Peninsula to 20°-30°E and is poleward of 57°-60°S (as defined by the 0.7-dynamic meter isopleth, the northernmost meander which does not extend into the Pacific Ocean). A large anticyclonic meander is found around and east of Maud Rise (65°S and the Greenwich Meridian), within which the deep water is much warmer than that of the cyclonic regime. Generally westward flowing water to the east and south of this meander can be traced by their characteristics as being derived in large measure from the Circumpolar Deep Water of the ACC regime.

The strongest east to west flow associated with the Weddell Gyre is found over the continental slope from 50°E into the Weddell Sea proper (Foster and Carmack, 1976; Tchernia and Jeannin, 1983). This current carries with it warm, salty deep water into the Weddell Sea (Plates 110-111 in Gordon and Molinelli, 1982). It is probable that

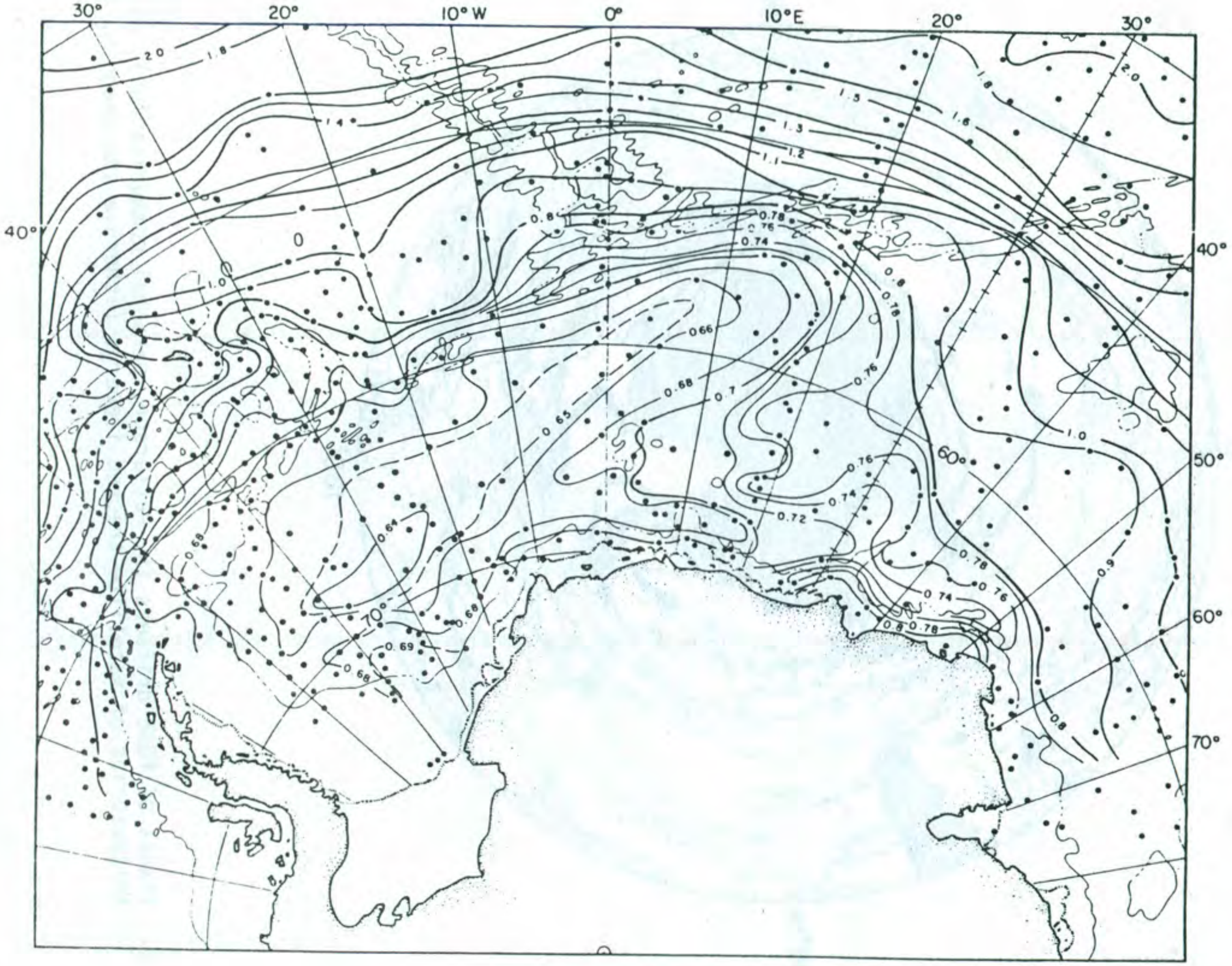

Fig. 7. 0/2500 db dynamic topography in dynamic meters based on pre-1976 hydrographic stations (A. Gordon, personal communication).

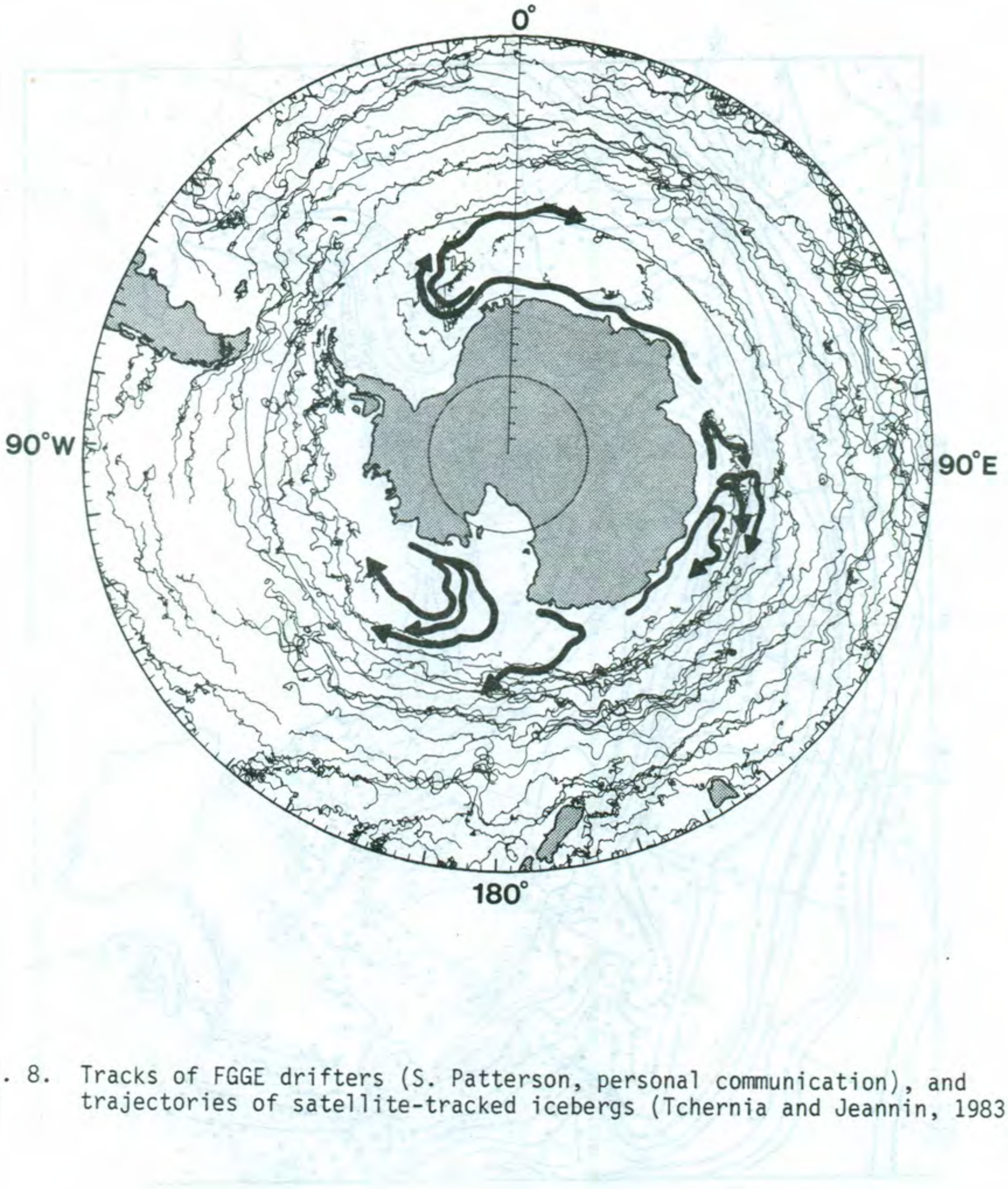

Fig. 8. Tracks of FGGE drifters (S. Patterson, personal communication), and trajectories of satellite-tracked icebergs (Tchernia and Jeannin, 1983).

this slope current is important in the bottom water formation process of the Weddell Sea.

Meridional heat and salt fluxes within the subpolar zone are important to the budget of glacial shelf ice and in driving convective processes near the continental margins. It is probable that this flux, unlike that crossing the ACC, is accomplished primarily by the mean circulation of the subpolar gyres. For example, a 76×10^6 m^3/sec Weddell Gyre in which the average temperature of the poleward flowing segment is 0.5°C colder than that within the western boundary current would carry 16.5×10^{13} W across 60°S. If the other gyres do likewise, the circumpolar heat flux would be 50×10^{13} W, about the same as determined to cross 60°S by Gordon (1981) or Hastenrath (1982).

Our knowledge of the circulation pattern and intensity is incomplete. The low degree of stratification and sluggish flow, coupled with the environmental difficulties of working in high latitudes, mean that special efforts will be required to improve our knowledge of this circulation. Satellite-tracked drifters which can float or be frozen into the sea ice are an attractive method for study of the surface circulation and its variability. These drifters should be equipped with atmospheric pressure sensors and submerged thermistor chains to acquire some information on winds and mixed-layer response to surface variability. Satellite tracking of icebergs by sight or by transmitter is also recommended.

Long-term moorings of current meters with accurate thermistors and conductivity sensors are needed to determine circulation and its variability as well as the heat and salty fluxes of the mean and eddy field. Pressure sensors might be useful in the study of variability, which could be quite large because of a significant barotropic component. Satellite altimetry should be particularly effective in the study of the circulation variability within the subpolar zone, although there are problems due to ice cover.

The Weddell Gyre is the best defined and probably strongest of the subpolar gyres. This, and its significance with regard to ocean ventilation, suggests that it receive emphasis, although current measurements everywhere in the subpolar zone are needed.

4.3 Water Masses. The thermohaline stratification of the subpolar zone can be approximated by three layers: a cold, low-salinity layer about 100 meters thick; a weak pycnocline of similar thickness; and a thick deep water stratum of relatively warm and salty water. In summer, the top layer is capped by a seasonally warmed and freshened layer. Within the deep layer are subtle, but significant, variations in stratification as the warm, salty deep water derived from the north is penetrated by colder bottom waters formed at various sites along the continental margin (as discussed in Section 5 of this report).

The pycnocline stability is quite weak, as buoyancy input by fresh water marginally compensates the Ekman-induced upwelling of salty deep water. Presumably, upwelled deep water is converted to surface water and is removed laterally by Ekman drift. Within the gyres the pycnocline becomes shallower and weaker. This makes the gyres, particularly the Weddell Gyre, susceptible to deep convective processes (Martinson, Killworth and Gordon, 1981; see Killworth, 1983 for a review). This occurred during the episode of Weddell Polynya in the austral winters of 1974, 1975 and 1976 (Carsey, 1980) when massive convective overturning cooled the deep water by as much as 0.5°C to depths of 2500 m (Gordon, 1982). Shorter-lived polynyas within the subpolar zone have been observed by satellite near 65°S, 5°E and 67°S, 45°E and on a number of occasions (Zwally et al., 1983; Joey Comiso, personal communication), raising the possibility of intermittent but frequent convective processes at a number of sites.

The northern boundary of the Weddell Gyre is also of interest in regard to water mass modification and convection. Here waters from the continental margins of the Antarctic Peninsula are injected into the open ocean by the boundary current regime. This zone of low stability, the Weddell-Scotia Confluence (Patterson and Sievers, 1980), is subject to convective processes (Deacon and Moorey, 1975), as is the Bransfield Strait at the northern tip of the Antarctic Peninsula (Gordon and Nowlin, 1978).

Only in winter is water mass conversion effected by removal of buoyancy due to cooling and salinization due to ice formation. Yet, it is in winter that we have a data gap. Although the integrated effects of winter are observed in the summer period data set, the winter processes are subjects of conjecture. There are many models for the formation of Antarctic Bottom Water in the Weddell Sea (e.g., Killworth, 1983) which involve interplay between an uncertain number of water mass end-members.

The winter period data gap coupled with the ventilating power of the Southern Ocean as driven by winter conditions makes filling the gap of priority for world ocean studies. The climate relevance of the Southern Ocean in regard to global heat, fresh water and CO_2 budgets and the extent of the sea ice cover makes the requirement to better understand winter processes even more timely.

However, the need for high quality summer data must also be stressed. The historical data set is not up to modern standards, yet it is in the nearly homogeneous subpolar zone that the data must be of high quality to be of scientific value.

More specific objectives are to resolve the vertical processes coupling the surface and deep water across the pycnocline. This involves the cold "hubs" of the gyres, the inflow regions of warmer circumpolar water, and water masses of the western boundary currents.

4.4 Research Questions

* What are the spatial and temporal scales of the circulation patterns and subpolar gyre characteristics in the subpolar zone, between the ACC and the continental margins of Antarctica?

* How does the ocean thermohaline stratification below the sea ice cover differ from its summer ice free state?

* How large are the horizontal and vertical fluxes of ocean properties within the subpolar zone and how do they respond to and influence atmospheric and sea ice conditions?

* What is the residence time of the various water masses within subpolar gyres?

The following questions pertain specifically to the Weddell Gyre, but could be asked of all the gyres:

* How does the eastern extent of the Weddell Gyre vary, spatially as well as temporally?

* What are the pathways by which the relatively warm and saline Circumpolar Deep Water spread within the Weddell Gyre?

* What are the frontal structures and exchange processes at the open ocean boundary of the Weddell Gyre, specifically within the Weddell-Scotia Confluence and its eastward extension?

* What are the exchange processes between the Weddell Gyre and continental margin water along the southern and western boundaries of the gyre?

* What are the properties (water mass characteristics, kinematic structure and transport) of the Polar Slope Current and western boundary current of the Weddell Gyre?

4.5 Recommendations

* The winter conditions of the atmosphere, sea ice and ocean stratification within the subpolar zone has not been observed directly, except in rare cases. It is recommended that winter observations be made within this Zone and specifically within the Weddell Gyre in order to observe the extent of thermohaline alteration. It is imperative that winter and summer observations in physical oceanography should be amplified with geochemical data to arrive at residence time estimates.

* The western boundary current of the Weddell Gyre carries northward the products of water mass conversion within the gyre and along its margins. A monitoring program to measure the stratification, velocity structure and variability of the western boundary using moorings and drifters is recommended. This monitoring program may extend into the Weddell-Scotia Confluence where the flow separates from the boundary and extends into the open ocean.

* The Polar Slope Current introduces relatively warm-saline water into the Weddell Sea, and represents the initial ingredient of Antarctic Bottom Water. A monitoring program to measure its stratification and velocity structure is recommended. This might be done in conjunction with the western boundary current monitoring program, as recommended in Section 5 of this report dealing with the study of shelf/slope processes.

5 SHELF-SLOPE PROCESSES AND DEEP WATER FORMATION

Bottom or deep water is formed around much of Antarctica when shelf water is made sufficiently cold and saline to flow down the continental slope, mix with the surrounding water masses and reach the bottom or some great depth. Reviews of present knowledge are given by Warren (1981), Carmack (1984) and Killworth (1983).

The primary source of deep water is the southwestern Weddell Sea, treated here as an archetype for the process. The cyclonic Weddell Gyre is intensified near the coast by a westward flow induced by katabatic winds off the continent. The resulting westward coastal current follows the bathymetry, hugging the shelf break, with suggestions of divergence at sites such as Halley Bay. Here one branch continues along the bathymetry (Gill, 1973), and another perhaps forms part of a complex on-shelf cyclonic circulation (Hempel et al., 1983; Carmack and Foster, 1975) which is also present in models (Killworth, 1974).

Summertime observations normal to the shelf break suggest a complex outflow of cold saline shelf water into the deep Weddell Basin (Foster and Carmack, 1976; Carmack and Foster, 1975), together with a layer up to 200 m thick of cold, fresher water ($\theta < -0.7°C$, S = 34.64-66°/₀₀) at the foot of the continental slope (Foster and Carmack, 1976). The minimal available data suggest that the layer extends along much of the east side of the Antarctic peninsula (Carmack, 1973). No sections currently exist which show a continuous layer of water extending from shelf break to bottom, however.

Another source is the Ross Sea, which possesses both low and high salinity bottom water (Jacobs, Amos and Bruckhausen, 1970), although the effect of Ross Sea bottom water on the surrounding deep water is less marked than the Weddell variety (Warren, 1981). Carmack (1977) estimates the Ross Sea to produce 10% to 20% as much bottom water as is produced in the Weddell Sea.

West of the Ross Sea, off the Adelie coast, a thin layer of bottom water forms intermittently (Gordon and Tchernia, 1972), and similar quantities are found off Enderby Land (Jacobs and Georgi, 1977). The evidence is that dense water of some variety is likely to be found along the foot of most of the Antarctic continental slope. In some regions the water formed is insufficiently dense to reach the bottom. Dense water formed off Wilkes Land, for example, is found near 2000 m underlain by more dense outflow from the Ross Sea (Carmack and Killworth, 1978).

The dynamics of dense water production need five main ingredients (Killworth, 1983). The first is a reservoir where the forerunner of bottom water may be stored. Both the Weddell and Ross Seas possess continental shelves several hundred km wide with depths of up to 500 m, giving room for a great volume of water to be stored. Other areas around Antarctica have narrower shelves, but possess geographical features which can aid in the storage of denser water. Sills occur, e.g., off the Adelie Coast and Wilkes Land, so that dense water may be temporarily trapped. Indeed, Gordon (1974) notes that the area or volume of the reservoir is positively correlated with the amount of deep water formed locally. The effects of sills on water mass formation were recently investigated by G. Wegner (personal communications) based on several short hydrographic sections, 15 km apart and normal to the coast, taken off Atka Bay near the German antarctic station Georg-von-Neumayer. There the continental shelf at 500 m is narrow and has an outer sill of approximately 100 m coinciding with the ice edge. All five sections showed a rising coherent plume of cold water ($\theta < -1.8°C$) over the sill. Characteristics on one example section are shown in Fig. 9.

Next, a source of dense water is required. Wintertime ice formation releases brine to the underlying water, which mixes to the depth of the reservoir. The result is cold saline water on the shelf at depth. Other sources include melting/freezing under ice shelves (Jacobs and Fairbanks, 1984) which can be affected by tidally-induced mixing (MacAyeal, 1984). Ice formation is a strongly seasonal phenomenon. Were it not for export of ice away from the coastline (Gill, 1973; Warren, 1981), the salinity gained in winter would be lost by summer melting. A net salinity increase is also aided by penetrative convection in winter.

A third ingredient is a pre-existing circulation to force the dense water out of the reservoir and down the slope. Early ideas (Mosby, 1934) suggested that buoyancy forces alone would pull dense water downslope; later dynamical considerations (Killworth, 1977) show that the lateral movement of dense water would be about a deformation radius (10 to 20 km) before a Coriolis-buoyancy balance was established, with almost no descent involved. Gill (1973) and Killworth (1974) note the strong salinity-controlled, east-west density gradients on both the Weddell and Ross shelves, and estimate around 10^6 m^3 s^{-1} of water is moved off-shelf by the geostrophic circulation.

A fourth ingredient is a complex interaction between several water masses. Proposed mixing diagrams for bottom water can be quite complicated; Foster and Carmack, (1976) suggest six water masses are involved in Weddell Sea Bottom Water formation. The details of the mixing are not understood in any of the cases, but usually are deduced post hoc. There is even evidence that slope water, by entraining deep water from beneath it as it flows west, may be sufficiently modified to create vertical convection with little interaction necessary with the shelf water. Because of the frequent interleaving observed, more closely-spaced sections across and along the continental slope are required to resolve the phenomena. Strong geographical variability will require several sets of observations.

The fifth ingredient is that the dynamics and the geography must permit dense water to reach the bottom (off Wilkes Land being an example where this does not occur). A component of velocity across depth contours implies that friction enters the triangle of forces begun by buoyancy and Coriolis forces; yet too much friction or entrainment will nullify the descent. Models of this process, including an internal energy source induced by the equation of state to low temperatures, suggest that the descent of water masses on the open slope depends on fine-tuned mixing parameters (Killworth, 1977). With more complex topography, other processes can enter. For example,

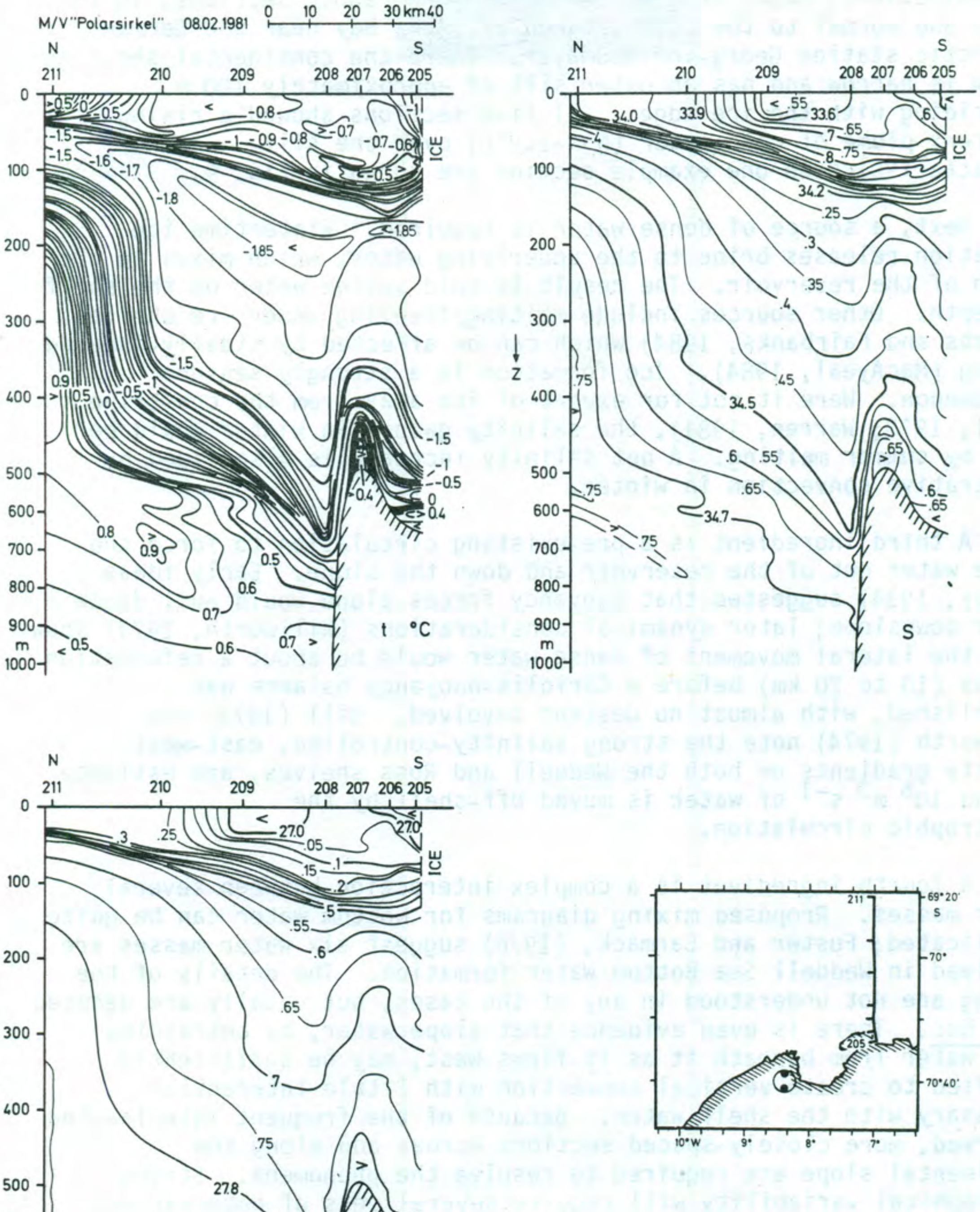

Fig. 9. Vertical distributions of temperature, salinity and sigma-t on the meridional section (7°W) off Georg-von-Neumayer, Atka Bay (courtesy G. Wegner, Deutsches Hydrographisches Institüt Hamburg). Note the rising plume of cold (<1.8°C) water originating from the shelf edge sill. The tilt of isopycnals suggests a strong baroclinic component of the westward coastal current, called Polar Current by Dietrich et al. (1980).

at the Filchner Ice Shelf the shelf is of extended width with a topographic depression having a sill at its northern boundary; these appear to give rise to a closed deep circulation involving the subglacial Berkner Island (Gammelsrod and Slotsvik, 1981) with occasional outflow events of supercooled water down the canyon and pronounced concentration increase in chemical parameters of the resolution with possible biological implications (Foldvik, Koltermann, personal communications). It is unfortunate that our knowledge of fundamental effects such as mixing is still in its infancy: tidal stirring (Foster and Middleton, 1980); cabelling (Foster, 1972), double diffusion (Schmitt, 1979; McDougall, 1983); and frontal instabilities and eddying (Griffiths and Linden, 1981; Killworth and Stern, 1982; Käse et al., 1985) may all be involved in the mixing.

Bottom water production rates now appear to be lower than estimated in the past. Previous estimates were based on analyses of the Atlantic and Pacific proportions of bottom water, which clearly had included a large amount of mixing between source and measurement. In-situ measurements, especially with current meters (e.g., Foster and Middleton, 1980) yield values of 2 to 5 x 10^6 m^3 s^{-1} for the Weddell Gyre (Carmack and Foster, 1975) and much smaller values for the other sources. How much of this bottom water leaves the Weddell Gyre without significant modification and what its residence time in the Gyre is are open questions. There is physical and biological evidence that much of the bottom water is topographically constrained to remain near Antarctica, whereas the less dense results of open-ocean convection are free to "ride over" the densest water and propagate north (Martinson, personal communication).

5.1 Research Questions

* What is the distribution of dense water on the shelves?

* What processes are responsible for the formation of dense shelf water? Is it formed only in winter?

* Can we identify likely areas for deep convection by examining the geographical constraints (canyons, sills, shelf width, etc. which can provide escape routes)?

* Is there any way to monitor the rate of deep and bottom water formation? What is the transport of the Polar Current and how does it interact with this formation?

* How could we measure the contribution of slope water to deep convection?

* Can we estimate the relative contributions of shelf-slope convection and open-ocean convection to the deep water budget?

* On the global climatic scale, what controls the rate of dense water formation? The net meridional circulation or local atmosphere-ice-ocean interaction?

* Can we transfer what we have learned from studies of fronts in

other oceans to the shelf-slope fronts in the Antarctic?

5.2 Recommendations

The flow of water off the shelf should be studied by a closely-spaced network of stations, coupled with long-term current meter moorings and onboard current profilers. Three possible test areas, chosen for their differing physics and geography are:

(a) off Georg-von Neumayer. This area is convenient logistically (close to German base) and has long-term meteorological data available from U.K. and German shore bases nearby. This area is selected for its narrow shelf.

(b) on the Filchner Shelf. This area is convenient because of the accumulated data in the area, although the complex topography and wide shelf including the under-ice-shelf circulation around Berkner Island make interpretation more difficult.

(c) The western boundary current under the multi-year sea ice at the northern tip of the Antarctic Peninsula. This area will allow some attempt at monitoring dense waterflow, and aid understanding of the shelf edge circulation pattern.

Interannual variability, and the connection (or lack thereof) between local atmosphere-ice forcing and the rate of production of dense water should be studied by the above methods, together with the use of ice-mounted drifters providing continuous meteorological and ice-drift data.

6 SEA LEVEL OBSERVATIONS

Sea level is one of the few oceanographic variables that has been measured continuously since before the turn of the century. Apart from their practical value, tidal measurements have also been made for their intrinsic scientific value. Scientific publications on tides are thus available from as early as 1665 (Association d' Oceanographie Physique, 1955). Sea level observations have applications for study of oceanographic variability on time scales ranging from hours to decades, including particularly tides, current variability and climatic variations.

Sea level observations in the Southern Ocean are sparce with poor geographic coverage (Fig. 10). Densities of sea level stations comparable to the densities of stations available in other parts of the world ocean (Lutjeharms and Alheit, 1983) are found only on the South American coastline, New Zealand, Tasmania and, to a lesser degree, along the coast of the Antarctic Peninsula. A fair number of stations are also located in the general vicinity of the Ross Sea. Apart from 6 stations in Tasmania, 7 in New Zealand and 6 stations along the coast of South America, only two tidal stations are at present in continuous operation south of 40°S (Intergovernmental Oceanographic Commission, 1983). These latter two are situated on the Antarctic Peninsula. To the best of our information no other continuously operating sea-level stations on the Antarctic continent

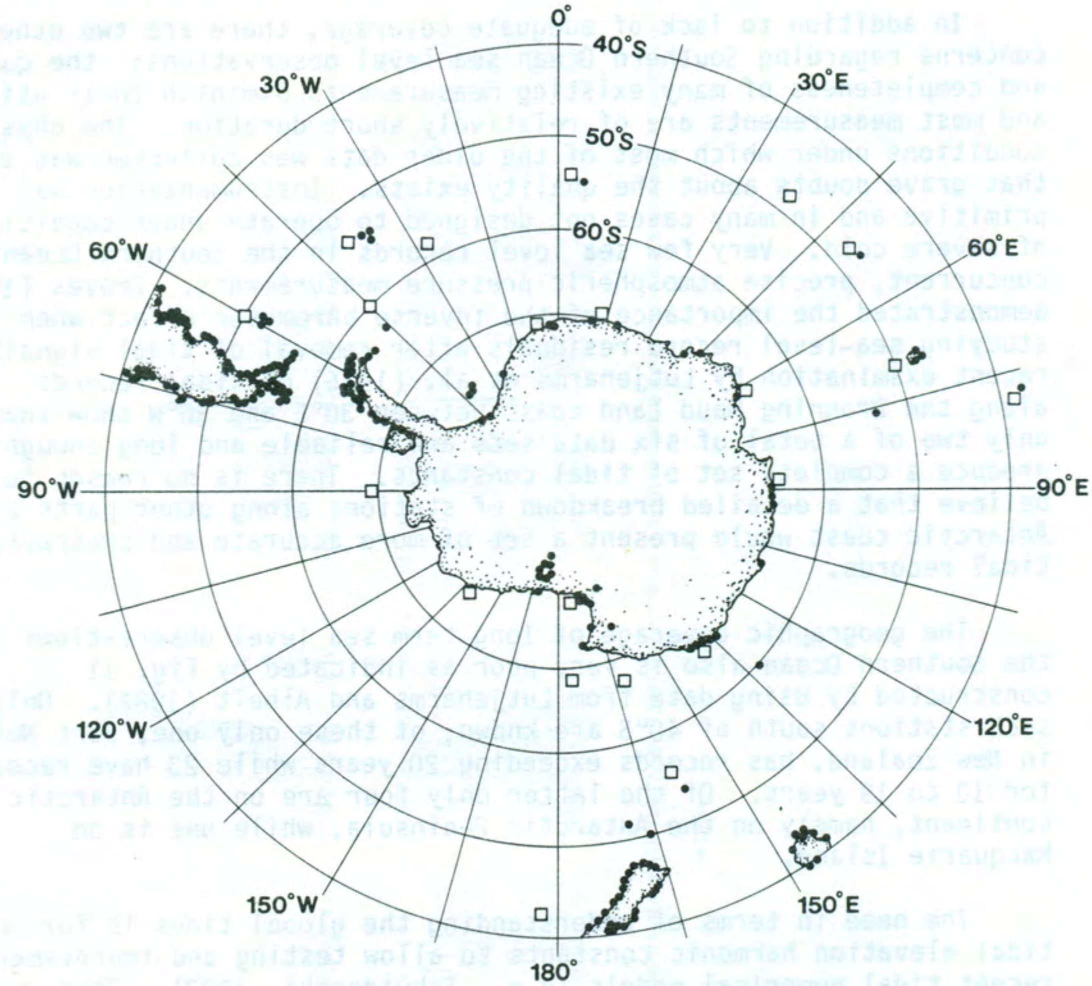

Fig. 10. Sea level records exist from positions indicated by solid circles (Lutjeharms, 1980). Proposed sea-level stations according to Wyrtki and Pugh (1984) are indicated by open squares.

or on the subantarctic islands exists. Only three deep-sea, or pelagic, tidal readings have been taken in the Southern Ocean (Cartwright et al., 1979) and these all between Australia and Antarctica (Irish et al., 1972). There are plans to improve the geographic coverage, as seen by proposed station locations in Fig. 10, in part to provide a global data base required for verification and calibration of planned and proposed satellite altimetry programs. Sun-synchronous satellites carrying altimeters require good tidal models to remove tidal alias.

In addition to lack of adequate coverage, there are two other concerns regarding Southern Ocean sea level observations: the quality and completeness of many existing measurements diminish their utility; and most measurements are of relatively short duration. The physical conditions under which most of the older data was collected was such that grave doubts about the quality exists. Instrumentation was primitive and in many cases not designed to operate under conditions of severe cold. Very few sea level records in the Southern Ocean have concurrent, precise atmospheric pressure measurements. Groves (1957) demonstrated the importance of the inverse barometer effect when studying sea-level record residuals after removal of tidal signals. A recent examination by Lutjeharms et al. (1985) of tidal records along the Dronning Maud Land coast between 30°E and 30°W show that only two of a total of six data sets are reliable and long enough to produce a complete set of tidal constants. There is no reason to believe that a detailed breakdown of stations along other parts of the Antarctic coast would present a set of more accurate and protracted tidal records.

The geographic coverage of long-term sea level observations in the Southern Ocean also is very poor as indicated by Fig. 11 constructed by using data from Lutjeharms and Alheit (1982). Only 40 such stations south of 40°S are known; of these only one, Port Nelson in New Zealand, has records exceeding 20 years while 23 have records for 10 to 19 years. Of the latter only four are on the Antarctic continent, namely on the Antarctic Peninsula, while one is on Macquarie Island.

The need in terms of understanding the global tides is for ocean tidal elevation harmonic constants to allow testing and improvement of recent tidal numerical models (e.g., Schwiderski, 1983). This would allow for more accurate estimation of tidal energy dissipation on the Antarctic continental shelf and slope. Current observations from the shelf and slope in association with the elevation harmonic constants would enhance the dissipation calculations which are required for refined estimation of the role of tidal energy loss in changes of the earth's speed of rotation. These latter observations also would allow for estimation of longer period tidal phenomena and tidal residual flow. For example the intensive current observations from the Drake Passage exhibit an enhanced fortnightly tidal response which if baroclinic may be of biological significance. Also, with the dominant current signal on the large Antarctic continental shelves (e.g., Ross Sea) being tidal, non-linear rectification of the tidal flows to produce a tidal residual should be assessed.

The scientific value of mean sea level, after the tidal signals

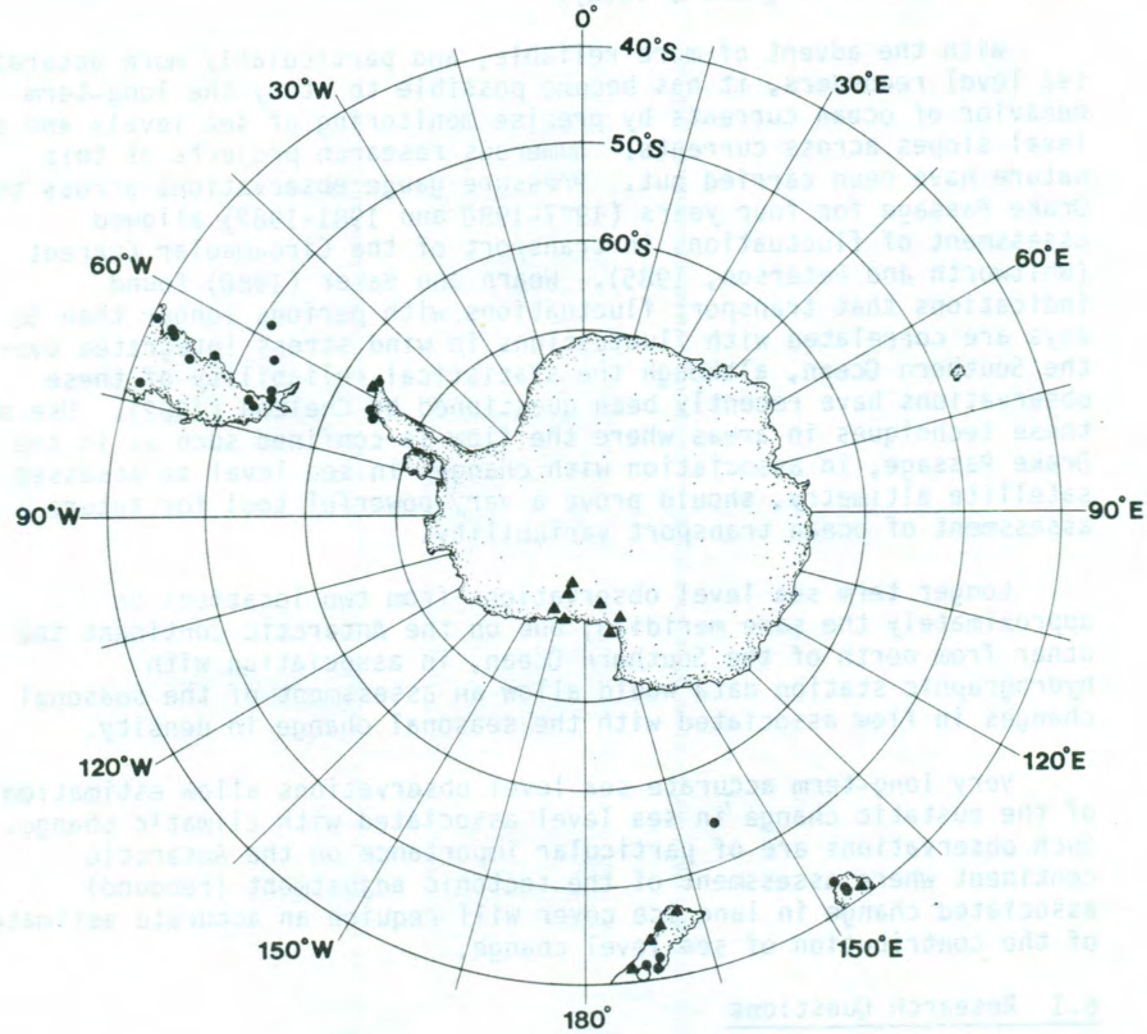

Fig. 11. Locations of all known sea level measurements in the Southern Ocean (Lutjeharms and Alheit, 1982) exceeding 5 years in duration (▲ 5-9 year records; ● 10-19 year records; o > 20 year sea level records).

have been removed, is recognized (Lisitzin, 1963). It has been shown that secular changes in mean sea level may be indicative of climatic change (Etkins and Epstein, 1982). Valuable work on long-term and interannual variability in sea level has been carried out for various parts of the world ocean. Roden (1966) has studied low-frequency sea level oscillations along the Pacific Coast of North America while an analysis of annual sea-level variations for European waters has been carried out by Rossiter (1967). Similar work has been done on the South China Sea (Tvi, 1970), the Bering and Chukchi Seas (Borisov, 1976), all United States waters (Hicks, 1981) as well as the east coast of Australia (Hamon, 1962).

With the advent of more reliable, and particularly more accurate, sea level recorders, it has become possible to study the long-term behavior of ocean currents by precise monitoring of sea levels and sea level slopes across currents. Numerous research projects of this nature have been carried out. Pressure gauge observations across the Drake Passage for four years (1977-1980 and 1981-1982) allowed assessment of fluctuations in transport of the Circumpolar Current (Whitworth and Peterson, 1985). Wearn and Baker (1980) found indications that transport fluctuations with periods longer than 30 days are correlated with fluctuations in wind stress integrated over the Southern Ocean, although the statistical reliability of these observations have recently been questioned by Chelton (1982). Use of these techniques in areas where the flow is confined such as in the Drake Passage, in association with changes in sea level as assessed by satellite altimetry, should prove a very powerful tool for future assessment of ocean transport variability.

Longer term sea level observations from two locations on approximately the same meridian, one on the Antarctic continent the other from north of the Southern Ocean, in association with hydrographic station data would allow an assessment of the seasonal changes in flow associated with the seasonal change in density.

Very long-term accurate sea level observations allow estimation of the eustatic change in sea level associated with climatic change. Such observations are of particular importance on the Antarctic continent where assessment of the tectonic adjustment (rebound) associated change in land ice cover will require an accurate estimate of the contribution of sea level change.

6.1 Research Questions

* How accurate are the present numerical models?

* What is the tidal energy dissipation on the Antarctic continental shelves?

* What is the spatial variation in mean sea level on the time scale of days to months associated with current variability? To what extent can the variations in strength of the ACC and subpolar gyres be deduced from such measurements?

* What are the longer-term overall trends in sea level associated with climatic changes?

6.2 Recommendations

* Additional determinations of tidal constants are required over the Southern Ocean. Such measurements should be spread along the coastline of Antarctica, on the Antarctic and subantarctic islands, and should include open ocean pressure observations. They should be of adequate duration so that a full suite of tidal constituents can be calculated. Such observations would allow testing and improvement of available numerical tidal models. At a later stage continental shelf and slope current observations should be included to allow direct estimates of tidal energy dissipation.

* A larger number of continuously recording tidal stations should be installed throughout the Southern Ocean to monitor components of the ocean circulation. The success in the use of Seasat altimetry by Fu and Chelton (1984) to assess the spatial coherence of the temporal variability of the Antarctic Circumpolar Current emphasizes the need for satellite altimetric observations. Used together with tide gauge and sea level atmospheric pressure measurements at locations across major currents, these observations would provide a very powerful tool in the study of Southern Ocean circulation patterns. Operating agencies should be encouraged to include full coverage of the Southern Ocean by future satellite possessing altimeters.

* Very long-term accurate tidal observations are needed from the Antarctic continent to allow the eustatic change in mean sea level to be assessed (the exact locations of such observations would be determined by the relative tectonic movement at the sites).

* Sea level recording should be managed so that the greatest accuracy and utility can be achieved. From the work of MacDonald and Burrows (1959), Thiel et al. (1960) and Bishop and Walton (1977) it is clear that difficulties arise in installing and operating mechanical tide gauges in Antarctic conditions, even for short periods. Precision pressure recorders may be deployed successfully at various depths and for short periods (Foldvik et al., 1981; Lutjeharms et al., 1985) or even for years (Wearn and Baker, 1980). To facilitate adequate analysis, recording stations should as a rule have concurrent sea-level atmospheric pressure recording (Groves, 1957).

7 AIR-SEA-ICE INTERACTION

7.1 Introduction. Exchange of momentum, heat, water and gases between the ocean and atmosphere is the basis of the ocean's influence on regional and global scale climate. Quantitative determination of the exchange rates is a difficult procedure anywhere in the ocean, but it is particularly so in the remote Southern Ocean environment, complicated still further in places by the sea ice cover, which not only makes measurements more difficult but also significantly modifies sea-air coupling. Another factor which complicates the ocean's reaction to the atmosphere is the glacial ice. The ocean interacts with the glacial ice (which in turn is coupled to the atmosphere) where the ice cap contacts the ocean along its seaward edge and at the base of the large areas of floating glacial ice called ice shelves. Additional interaction is accomplished after glacial ice breaks away from the ice cap, drifting to sea as icebergs.

In the Southern Ocean the magnitude, even the direction, of the exchange between the ocean-atmosphere and cryosphere is poorly known, though we do know from ocean observations that major water mass formation and conversion takes place within the Southern Ocean. Studies of the formation rates of water masses and the full extent of water mass conversion are hindered by uncertain estimates of ocean-atmosphere-cryosphere exchange rates. The heat exchange estimates for various latitudes for the Southern Ocean (Table I, Section 4 of this report) illustrate the wide range of values.

7.2 Open Ocean. North of approximately 60°S, and for most of the Southern Ocean during the austral summer, the ocean-atmosphere coupling is not modified by sea ice. In these open ocean areas standard shipboard meteorological observational data are used to determine exchange rates between the ocean and atmosphere using the bulk formulae, or profile method. However, the Southern Ocean is not well traveled, so the data set is sparse and heavily weighted with summer observations and because of logistical constraints.

Estimates of heat exchange over the open ocean (Bunker, 1976; Taylor, Gordon and Molinelli, 1978; Georgi, 1979) suggest very strong oceanic heat loss north of the Polar Frontal Zone, reduced values or even ocean heat gain immediately south of the Polar Front, large oceanic heat loss further south. Studies of the seasonal cycle of the mixed layer provide a view of the integrated effect of sea-ice exchange. Very deep mixed layers are achieved in the regime of large heat loss. These layers play an important role in ventilating the ocean. Large longitudinal variations are expected because the frontal zones move north and south with the ACC as a function of longitude in response to bottom topography and forcing, making extrapolation of results uncertain.

Improved heat exchange estimates require enhancing the meteorological and mixed-layer data sets to include information for all months. Satellite observations and measurements from drifting buoys offer the only reasonable approach to this goal.

The wind introduces momentum to the ocean, producing energy for waves, circulation and mixing within the ocean. Also, wind speed is a measurement needed in the usual estimation of heat and fresh water fluxes. The wind field over the circumpolar belt is very vigorous, offering the most extensive region of the world ocean with a stress of near 2 dynes/cm^2; however, it is not well determined. Recently use has been made of the SEASAT data to obtain synoptic wind and wave data (Mognard, Campbell, Cheney, and Marsh, 1982). Satellite scatterometry appears to be the most promising future technique for obtaining wind data in remote ice-free regions of the world ocean.

7.3 Sea Ice Covered Ocean. Each year sea ice forms over an area of some 16 to 18 x 10^6 km^2 and then melts; only 2.5 x 10^6 km^2 is covered year round. The ice does not form and then melt in place, but rather is advected by atmosphere and ocean forcing (Hibler and Ackley, 1982). This results in significant lateral transport of heat and water, with some regions (generally the southernmost) being net producers of sea ice and exporting it to other areas which experience net melting.

7.3.1 Momentum. The momentum balance of the sea ice needs to be better understood in order to understand the movement of the sea ice and to advance thermodynamic models of sea ice. Estimates of drag coefficients between ice and air and between ice and ocean have been made in the Arctic. The Southern Ocean sea ice cover is thinner and not as concentrated as the arctic pack and probably has smaller numbers of pressure ridges. It is possible that drag coefficients differ somewhat from the arctic situation and thus must be determined separately for the Antarctic.

The marginal ice zone is of particular concern, because its advance and retreat determines the area of ice coverage and because of its biological importance. Within the marginal zone, warm and moist air derived from over the open ocean alternates with colder and drier polar air masses. In addition, waves penetrate the ice, providing mechanical degradation and flooding the ice with sea water which are factors in its disintegration. Possibly the drag coefficients are larger within the marginal ice cover (Andreas, Tucker and Ackley, 1984) which further complicates modeling. Better understanding of marginal ice zone dynamics is important to atmospheric as well as oceanic modeling, because of the apparent impact of this zone on the atmosphere circulation and cyclonic activity (Streten and Pike, 1980; Carleton, 1983).

7.3.2 Fresh Water Budget. The total sea ice budget is needed to understand water mass conversion. Critical to this understanding is the fresh water balance; present values for precipitation (P) and evaporation (E) are hardly more than a guess. In the ice covered regime the major components of the fresh water balance are the local freezing-melting cycle and ice movement. Estimates of P-E on the 60°-70°S belt are about 30 cm yr^{-1} (Baumgartner and Reichel, 1975); with an average seasonal sea ice thickness of about 1 meter (Ackley , Clarke and Smith, 1983), however the seasonal and regional impacts of sea ice on the fresh water budget can overshadow P-E.

Evaporation is greatly increased within leads and polynyas, as is ocean-atmosphere heat exchange. Estimates of these exchanges should be made using the profile methods or direct methods. Flux values for "typical" leads and polynyas must be known, as must the distribution of leads and polynyas (from satellite data) in order to assess the full impact of these features.

7.3.3 Heat. Once sea ice is formed, heat exchange is attenuated, essentially insulating the ocean. Most of the oceanic heat loss to the atmosphere is then within the open water segments represented by leads and polynyas. The meager winter solar radiation which could add heat to the ocean is instead returned to the atmosphere by the high albedo of the ice. In summer when the radiation is strong the ice melts. However, estimates of the available atmosphere heat fall short of explaining the rapid melting of the ice cover each spring, and it has been suggested that ocean heat transferred across the pycnocline into the surface layer plays a significant role in the sea ice budget (Gordon, 1981; Gordon, Chen and Metcalf, 1984).

The direct contact between ocean and atmosphere offered within leads and polynyas leads to very large exchanges of heat and water. The leads open and close with the synoptic weather systems, whereas polynyas are more persistent features. Estimates of heat loss within these features are from 10 to 100 times that of the ice covered region, but direct flux measurements have been made only in a few situations in the Arctic.

Estimates of ocean-atmosphere heat exchange are hindered by lack of atmospheric data (temperature, humidity, wind) and by lack of information on the percentages of open water and thin ice.

There are two types of polynya regimes: in "latent heat" polynyas ice is formed but removed by wind; in "sensible heat" polynyas ice is inhibited from forming by oceanic heat. Coastal polynyas are examples of the latent heat type, because the katabatic winds maintain open ocean conditions. The accumulative amount of ice that can form in latent heat polynyas may be tens of meters.

The sensible heat polynya derives its heat from the relatively warm deep water, which can rapidly enter the mixed layer by convection. During the Weddell polynya of the 1974-1976 period (Carsey, 1980) significant ocean cooling to nearly 3000 m occurred (Gordon, 1982), representing a major deep ocean ventilation process. The processes responsible for initiation, maintenance and termination of the Weddell polynya is not known, though various schemes have been proposed.

7.4 Ocean-Glacial Ice. Early naturalists commonly assumed that glaciers and icebergs exerted the major influences on the characteristics of antarctic surface water masses. And, it was hypothesized by some that the relatively warm deep water might contribute to melting the glacial ice. Subsequently, it was realized that air-sea interactions exerted the dominant role in cooling antarctic surface waters, freshening them with precipitation and ice melt and increasing salt during evaporation and sea ice formation. Thus for some time, exchange processes between glacial ice and seawater largely were ignored by oceanographers and cryologists.

Interest in interactions between glacial ice and seawater have been revived by new observations, by theory and modeling, and even by considerations of the resource potential of icebergs. Near the antarctic ice shelves water has been found at intermediate depths which is near the in situ freezing temperature, and thus well below the sea surface freezing temperature, extending as a continuous layer hundreds of km northward to the continental shelf break. This ice shelf water, and smaller-scale thermohaline signatures in the water column have been taken as indicators of glacial melting. Mass balance calculations indicate relatively high melt rates beneath the northern margins of the fixed ice and numerical models show that melting induced by tidal mixing could be significant even near grounding lines. Data from ice cores and geophysical soundings reveal large areas where sea ice freezes onto the base of ice shelves.

Tongues of water warm enough to melt a considerable volume of glacial ice have been traced from the deep water to the northern edges of the ice shelves and glacier tongues. It has been postulated that the temperature of this water, which differs near the shelf break around the continent, may be related to the variable thicknesses of the ice shelves and to intermittent cooling in ice free regions of the deep ocean. Further, it is conceivable that the flux of warm water to the potentially vulnerable undersides of the ice shelves may be controlled in part by the volume of high salinity shelf water. Resulting primarily from sea ice formation, this water is denser than the warm water that intrudes onto the continental shelf and so may reduce that intrusion or allow more of it, in proportion to its volume. If ice shelves help to regulate the volume of the West Antarctic ice cap as some glaciologists believe, then there is an obvious link here to sea level.

Measurements of the oxygen-18 content of shelf and bottom water have not only confirmed the presence of glacial meltwater, but suggest quite large rates of glacial melting and/or long shelf water residence times (Weiss, Ostlund and Craig, 1979; Jacobs, Fairbanks and Horibe, 1985). In the latter case, there are interesting implications for bottom water formation, in that it may rely less than generally believed upon the flux of shelf water and more upon air/sea/ice interactions near the continental shelf break. Understanding the shelf break region, and the spatial and temporal variability of its shelf-slope front (Fig. 9) is critical not only to questions of bottom water formation, but to problems of vertical heat flux and the transport of mass, salt, heat, ice and bio-geological material on and off the shelf. Further, the shelf/slope fronts may well be a primary locus of high biological activity in the Antarctic.

7.5 Research Questions

* What are the spatial and temporal variations in the sea ice extent, thickness and concentration?

* What are the physical and chemical characteristics and biological and geological effects of activities affecting the properties of sea ice?

* What are the ocean-ice-atmosphere exchange rates of momentum, heat, water and gases within the open and ice-covered ocean?

* What are the atmospheric and oceanic processes that influence sea ice extent, especially the influence of atmospheric cyclones?

* What is responsible for the generation, maintenance and termination of leads, and of the coastal and open ocean polynyas?

* What are the ocean-atmosphere exchange rates within leads and polynyas and what is their relative importance to water mass formation?

* What role do icebergs play in water mass conversion?

* How representative are iceberg trajectories of ocean currents? What might we learn of general circulation from an improved iceberg monitoring program?

* What role does the ocean play in the mass balance of the glacial ice?

* What are the physical and chemical characteristics of the ice edge having special effects on the marine ecosystem?

7.6 Recommendations

We generally endorse the recommendations presented by the SCAR Group of Specialists on Antarctic Climate Research (1983) in the document "Antarctic Climate Research", particularly those studies and programs on sea ice processes (sections 4.3 and 4.4) and on remote sensing (sections 5.5 and 5.6).

* A year-round monitoring of the mixed layer characteristics at selected locations in the ice-free and ice-covered segments of the Southern Ocean is recommended. The annual cycle of the mixed layer depth, temperature and salinity is a measure of the integrated effects of air-sea exchange. (Monitoring can be made from ships using CTD or XBT equipment, but more complete time series observations can be made from satellite tracked drifters with thermistor and conductivity chains in the open ocean and within the sea ice. Additionally, drifters provide Lagrangian measurements of ocean and sea ice movements. The drifters should also measure meteorological parameters, such as pressure, air temperature and humidity).

* The use of satellites for the remote sensing of sea surface temperature, wind, waves, and ice extent and concentration is the only way practical to obtain an extensive synoptic data set over the Southern Ocean. It is recommended that these methods be refined, with special emphasis on the improvement of algorithms, which require ocean data. The satellite data set then should be used to determine better estimates of ocean-atmospheric exchange rates.

* Whenever possible winter period observations within the open ocean and sea ice covered ocean should be made. Direct measurement of fluxes, sea ice thickness and physical and chemical characteristics, and ocean stratification features below the sea ice cover and in leads and polynyas is recommended.

* Monitoring the fluxes of ocean properties into the water layer below the ice shelf and the glacial melt water distribution using physical and geochemical measurements, are needed to assess the ocean's role in the glacial ice budget.

* Efforts to model the development and movement of sea ice in relation to exchanges with ocean and atmosphere should be encouraged.

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APPENDIX B: List of Acronyms

AAIW	Antarctic Intermediate Water
ACC	Antarctic Circumpolar Current
ACR	Antarctic Climate Research
CCCO	Committee on Climatic Changes and the Ocean
CNES	Centre National d'Etudes Spatiales
CTD	Conductivity-temperature-depth recorder
ERS-1	European Space Agency Remote Sensing Satellite
FGGE	First GARP Global Experiment
GARP	Global Atmospheric Research Programme
IOC	Intergovernmental Oceanographic Commission
ISOS	International Southern Ocean Studies
IUGG	International Union of Geodesy and Geophysics
JSC	Joint Scientific Committee
NASA	National Aeronautics and Space Administration
PF	Polar Front
SAF	Subantarctic Front
SAMW	Subantarctic Mode Water
SCAR	Scientific Committee on Antarctic Research
SCOR	Scientific Committee on Oceanic Research
SOC	Programme Group for the Southern Oceans
SEASAT	Sea Satellite
STF	Subtropical Front
TOPEX	The Ocean Topography Experiment
WCP	World Climate Programme
WCRP	World Climate Research Programme
WMO/CAS	World Meteorological Organization, Commission for Atmospheric Sciences
WOCE	World Ocean Circulation Experiment
XBT	Expendable bathythermograph

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[Please note that the Report of the First Session of the CCl Working Group on Energy, which had earlier been assigned this number, will not now appear in this series].

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