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POLAR OCEANS

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Abstract. We survey progress in studies of ocean circulation, water mass formation, and ocean-ice interaction in both the Southern Ocean and the Arctic region during the period 1983-86. This review places emphasis on U.S. publications, but other significant work is included. It is not meant to be a complete synthesis of polar oceanography of the last four years, but rather to provide an overview of progress. There are articles included in the reference list not cited in the text.

Southern Ocean

The polar oceanographic community lost a valued member when Sir George E. R. Deacon died on 16 November 1984 (Charnock, 1985). Sir George established the basis of understanding for the Southern Ocean, upon which much of the present research is built.

There were three main streams of research in Southern Ocean oceanography during the 1983-1986 period. These are: advances in our understanding of the Antarctic Circumpolar Current (ACC) dynamics stemming from the productive observational program of the 1970's, the International Southern Ocean Studies (ISOS); water mass structure and modification, primarily within the Weddell Gyre; and the oceanography of the continental margins of Antarctica.

Data derived from satellites are increasingly linked to progress within these areas. They provide a large scale synoptic view of the Southern Ocean, unattainable by any other method. The 3 month Seasat altimeter data set reveals low frequency, large scale variability of the ACC, with a general acceleration towards the east (Fu and Chelton, 1984, 1985). Sea ice trends during the mid-1970's were recorded by passive microwave radiometers (Zwally et al, 1983). This coverage along with visible and infra-red imagery, is establishing a most useful fully circumpolar time series of ice cover. Sturman and Anderson (1985) compare the estimates of sea ice cover based on satellite data since 1980, carried out by a number of authors; they conclude that the estimates are technique dependent, e.g. mean monthly sea ice area from the various estimates varies by approximately 2 million square kilometers.

During the 1979-1982 IUGG period there were a series of review articles and atlases pertaining to polar oceanography (see the IUGG polar oceans review of Gordon, 1983). This trend continues into the present period with a review of ACC research by Nowlin and Klinck (1986) and a study of the ACC characteristics by Sarukhanyan (1985). Joe Reid (1986) produced a comprehensive study on the South Pacific circulation, which includes a large segment of the Southern Ocean. Foster (1984) provides a general review of the Southern Ocean.

Antarctic Circumpolar Current

We now have reliable values for the ACC transport and variability through the Drake Passage during the ISOS observing period. Furthermore, eddy statistics are resolved to sufficient detail to allow meaningful estimates of eddy fluxes of heat and momentum as well as partitioning of energy within a broad spectral band (figure 1).

The ISOS current meter and pressure transducer 1979-1980 time series in the Drake Passage indicate a transport above 2500 meters of 125 Sv (Sverdrup (Sv) = 1 x 10^6 m^3/sec) with a standard deviation of 10 Sv (Whitworth, 1983; Whitworth and Peterson, 1985). The baroclinic mode accounts for 70% of the transport, with the barotropic mode accounting for the remainder mainly at the higher end of the frequency range. The pressure transducer data set (from sensors placed at 500 meters depth on both sides of the Drake Passage), which extend to March 1982 (Whitworth and Peterson, 1985) agrees with the current meter results to within 24 Sv.

Significant variability occurs within the ACC at a variety of spatial and temporal scales. It extends throughout the water column (Klinck and Hofmann, 1986). However, time lags of one to three days are observed in the deep levels relative to the 500 meter variability, which is attributed to the effects of local bottom topography rather than advection of disturbances through the Drake Passage (Klinck and Hofmann, 1986). Energetic and deep-reaching mesoscale rings, generated primarily by baroclinic instability along the various frontal zones associated with the ACC, are commonly observed moving through the Drake Passage (Table I, from Nowlin and Klinck, 1986). They are strongly influenced by topography (Pillsbury and Bottero, 1984; Hofmann and Whitworth, 1985); they, in turn would effect the transport through the deep passages (Klinck and Hofmann, 1986).

The eddy field associated with the ACC continues to attract interest, since it appears to be significant to the overall heat, fresh water and perhaps, momentum balance of the region. The source of these fluctuations appears to be barotropic and the first mode baroclinic instability (Inoue, 1985). The fastest growing waves are at 183 km wave length in the northern Drake Passage (subantarctic zone) and 91 km in the south continental margin zone, with growth rates of 3 to 5 days in the fronts and 15 to 40 days between fronts. Measurement of velocity fluctuations southeast of New Zealand, near 49° 30' S, 170° W over a two year period (Bryden and Heath , 1985) reveals energetic eddies with characteristic amplitudes of 20 cm/sec at 1000 meters and temporal scale of 20 days. These features are vertically coherent to 5000 meters, with only a slight tendency for the deeper flow to lead the shallower expression of the fluctuations. The eddy kinetic energy decreases with increasing depth from 169 cm^2/sec^2 at 1000 meters to 58 and 38 cm^2/sec^2 at 2000 and 4000 meters respectively. These values are similar to those found in the northern Drake Passage and relatively energetic in comparison to the Gulf Stream or Kuroshio.

A compilation from numerous sources indicates that the total oceanic heat loss south of 60° S is approximately 5.4 x 10^{14} Watts, with 3.1 x 10^{14} Watts of oceanic heat loss for the region south of the ACC (approximately 53° S for the circumpolar average; figure 2). Large oceanic heat loss to the atmosphere south of 60° S is supported by 1986 austral winter measurements obtained from the POLARSTERN along the Greenwich meridian, particularly in the vicinity of

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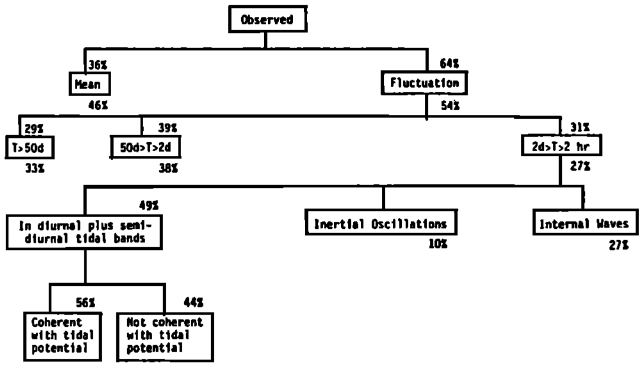

Fig. 1. Partitioning of kinetic energy of horizontal motions at Drake Passage. Fractions shown above boxes are averages for entire passage; those below the boxes are averages from the central passage locations. From Nowlin, Bottero and Pillsbury, 1986.

Maud Rise. Northward mass flux within the surface Ekman layer carries approximately 30 Sv across the ACC. Since this water is warmer than the average temperature of the water south of the ACC, the Ekman transport effectively exports heat from the ocean south of the ACC. When this amount is included in the net heat loss to the south, the total requirement for poleward heat flux across the ACC increases to 4 .6 x 10^{14} Watts (deSzoeke and Levine, 1981; Nowlin and Klinck, 1986).

There are a number of mechanisms which could account for this flux: mean flow, eddy field and deep boundary currents. The mean flow is ruled out as being significant in regard to meridional heat flux by deSzoeke and Levine (1981). The near bottom currents of cold Antarctic Bottom Water (AABW) balancing southward flowing warmer Circumpolar Deep Water (CDW), might account for 25%, but direct measurement of these features are needed to assess this means of heat transfer.

Estimates of the eddy heat flux indicate that at scales from the 4 to 90 days in the Drake Passage (Nowlin, Worley and Whitworth, 1985) and from 20 to 50 days southeast of New Zealand (Bryden and Heath, 1985), eddy activity provides for significant poleward heat flux. Nowlin, Worley and Whitworth (1985) determine an average eddy heat flux across the entire Drake Passage of 3.7 kW/m^2. However, 15.1 kW/m^2, is accomplished in the northern Drake Passage, with a value closer to 40 kW/m^2 for the upper 1000 meters. This is close to the value (30 kW/m^2) reported for the 1000 meter level along the northern edge of the ACC southeast of New Zealand (Bryden and Heath, 1985). While extrapolation of the average Drake Passage value for the full depth circumpolar belt yields net poleward heat flux roughly equivalent to the ocean heat loss south of the ACC, the value characteristic of the northern side of the Passage, which is most appropriate for comparison to the oceanic heat loss south of the ACC, would produce four times the required heat flux. However, in view of the large uncertainty in estimating oceanic heat loss south of the ACC and the questionable reliability of extrapolating Drake Passage values to the full circumpolar belt, the agreement, at least, indicates that eddy flux is the best candidate for maintenance of thermal balance of the Southern Ocean.

Analysis of FGGE drifter data set has produced useful results. Peterson (1985) compares drifter tracks to the extensive 1979 ISOS current meter array. The deep flow as measured by the current meters was well reflected in the drifter tracks. Deviations correspond to the wind action on the drifters and on the surface layer of the ocean. The drifters generally moved at 3.4% of the wind speed at an angle of 25° to the left of the wind. Hofmann (1985) and Patterson (1985) discuss large scale circulation patterns revealed by the drifters. Patterson provides maps of the mean and eddy kinetic energy distributions. These compare favorably with maps produced from hydrographic data and from Seasat altimeter (Cheney, Marsh and Beckley, 1983). A clear relationship between ACC characteristics and bottom topography is observed. Hofmann (1985) finds that the drifter tracks respond to the basic multi-filament nature of the ACC.

Water Masses (Weddell Gyre)

The southern extreme of the South Atlantic sector of the Southern Ocean is occupied by a large sluggish flowing but deep reaching cyclonic gyre, the Weddell Gyre. The water mass characteristics within the gyre suggest that it is the source of much of the bottom water for the world ocean. Interest in the water mass formation and deep ventilation in this area grew after observation of an isolated winter period

Table 1. Estimates of Property Anomalies for Select Southern Ocean Current Rings From Nowlin and Klinck, 1986

	Joyce et al. [1981]*	*Peterson et al.* [1982]† Relative to PFZ Characteristics	*Peterson et al.* [1982]† Relative to SAZ Characteristics	*Pillsbury and Bottero* [1985]‡ Anticyclonic	*Pillsbury and Bottero* [1985]‡ Cyclonic
Available potential energy, J	5.1×10^{14}	...	...	0.9×10^{14}	3.9×10^{14}
Kinetic energy, J	3.4×10^{14}	...	...	0.5×10^{14}	1.5×10^{14}
Heat anomaly, J	1.2×10^{19}	0.8×10^{19}	3×10^{19}	1.0×10^{18}	-1.9×10^{18}
Salt anomaly, kg	2.5×10^{11}	2.0×10^{11}	8×10^{11}	...	...

*Anomalies, relative to Polar Front Zone characteristics, were integrated between $\sigma_t = 27.0$ and 27.7 (approximately sea surface to 1500 m in PFZ) based on a section through a 1975 cyclonic ring in the Polar Frontal Zone. Kinetic energy is based on geostrophic speeds relative to 2800 dbar.

†Anomalies integrated from $\sigma_t = 27.0$ to 27.8 (approximately sea surface to 2500 m in the PFZ) based on a vertical section through a 1979 cyclonic ring in the Polar Frontal Zone.

‡Values of velocities and temperatures obtained from a symmetric ring model with parameters determined by time series observations of these parameters. Values shown on the left are for an anticyclonic ring of Polar Frontal Zone water and those on the right are the average for five cyclonic rings of continental water, all observed in the Antarctic Zone. Anomalies relative to Antarctic Zone characteristics were integrated down to 3500 m as a nominal bottom depth.

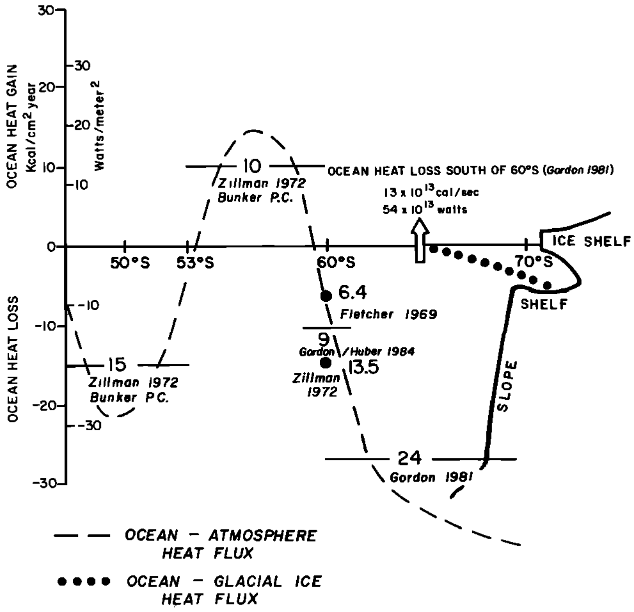

Fig. 2. Ocean-atmosphere heat exchange for the circumpolar area south of 47 ° S. The values are drawn from numerous sources, as indicated.

ice free region, now referred to as the Weddell Polynya (Carsey, 1980). Parkinson (1983) provides the most recent modelling attempt of the polynya. Comiso and Gordon (in press) present passive microwave data which indicates recurring polynyas in the vinicity of Maud Rise and near 65° S and 45° E (Cosmonaut Polynya). These polynyas are smaller and do not persist for the entire winter, but each is associated with shallowing of the pycnocline, considered to be an effective preconditioner for convection.

The Greenwich meridian region was investigated during October and November 1981 during the US-USSR Weddell Polynya Expedition, aboard the Soviet ship MIKHAIL SOMOV. The SOMOV, which attained a southern point of 62.5° S, about 550 km south of the ice edge, provided a significant data set pertinent to the study of sea ice, sea-air exchange, physical and chemical oceanography and biology (the collected reprints of the project are available, Ackley and Murphy, 1986). In the austral winter and spring of 1986 more extensive work was carried out from the German ship POLARSTERN over a six month period, reaching the continental margin and covering the region from the Greenwich meridian to the eastern side of the Filchner Depression in the Weddell Sea.

Using the SOMOV data Gordon and Huber (1984) and Gordon, Chen and Metcalf (1984) report that the mixed layer below the sea ice is slightly above freezing (average +0.035° C) and is undersaturated (86% of full saturation) in oxygen. This condition is attributed to entrainment of deep water into the surface mixed layer, brought about by buoyancy flux at the sea surface and perhaps more importantly, mechanical stirring due to relative ice movements. The incorporation of deep water heat and salt appears to be a significant factor in the heat and fresh water balance, and to have an important impact on the sea ice budget . The SOMOV data revealed a series of warm deep water cells, accompanied by shallowing of the pycnocline (Gordon and Huber, 1984). Their spin down dynamics is investigated by Ou and Gordon (1986), who find that the cells survive for long periods and may be effective preconditioners for deep convection.

Comiso, Ackley and Gordon (1984) relate the sea ice observations from SOMOV to the NIMBUS 7 satellite passive microwave (SMMR) data, in order to establish improved understanding of the satellite signal. Different sensitivities of the various SMMR channels to ice characteristics are found: the 18 GHz provides the best description of the spring ice edge.

Sievers and Nowlin (1984) discuss the water mass and frontal zone structure of the water entering the Scotia Sea from the Drake Passage. The frontal zone, often referred to as the Weddell-Scotia Confluence, between the Weddell Gyre and the Scotia Sea is discussed by Foster and Middleton (1984). This region has intense eddy activity, which increases downstream from the initial contact of the two circulation regimes. The sea ice along this front is investigated with the shuttle imaging radar-B (SIR-B) by Carsey et al (1986). Comiso and Sullivan (1986) compare passive microwave data from satellite with field observations along the ice edge of the region.

Continental Margins

The continental margins are the focus of a collection of articles in a Antarctic Research Series volume edited by S. Jacobs (1985). The following presents an overview of some of these articles.

The Weddell Sea region is discussed by Foldvik et al (1985a,b) using hydrographic and year-long current meter data. They provide a full hydrographic section along the barriers of the Filchner and Ronne Ice Shelves. Ice shelf water is observed leaving the Filchner Depression forming a slope plume with a transport of 1 Sv producing a total of 2 Sv of new Antarctic Bottom Water. The current meter array at the shelf break displays strong tidal currents, dominated by the solar diurnal component, though this component weakens during the winter, perhaps in response to reduced thermohaline stratification.

Currents and temperature along the Ross Ice Shelf Barrier are presented by Pillsbury and Jacobs (1985). These measurements were obtained January to August 1978 and from February 1983 through January 1984 as part of a study of the exchange of water between the open ocean and the water below the Ross Ice Shelf. These data show that the warm water feature apparent in summer hydrographic data between 170° and 175° W flows into the ocean volume below the floating ice shelf. Typical velocities are 5 to 9 cm/sec. A mooring within the colder water to the west reveals flow away from the ice shelf, in a pattern consistent with circulation schemes inferred from water mass considerations. Higher kinetic energy levels are evident during the winter, as are generally lower average temperatures; though warm events are common during the winter.

The overall water mass structure and budgets are discussed by Jacobs et al (1985), using hydrography and stable isotopes of oxygen and hydrogen. Warm slope water spreads onto the shelf where it is modified by the atmosphere and interaction with the glacial ice, to form various shelf water masses. The slope water provides the primary heat source for melting of glacial ice. A best estimate for shelf water residence time is 6 years with a total circumpolar bottom water production rate of 13 Sv, accompanying 0.4 meters/year of basal ice shelf melting and sea ice production of 1.9 meters/year.

Oceanography related to the glacial ice is the subject of 4 other papers in the volume. MacAyeal (1985a,b) reports on the results of a numerical model of tidal flow below the Ross Ice Shelf. Rectification of the periodic tidal currents induces a large scale mean circulation pattern that may be a factor in the heat and mass exchange between the ice shelf region and the open ocean. The rectification associated with Roosevelt Island may initiate the flow of warm shelf water into the sub-ice ocean volume near 170°-175° W. However, tidal rectification is not sufficient by itself to ventilate the entire water volume below the ice shelf at the rate suggested by the stable isotope data; thermohaline circulation is required. However, tidal rectification may also contribute by triggering thermohaline plumes of meltwater, at depths greater than 550 m. The Coriolis force attenuates this process, unless the plumes are channelled, as is the case under the George VI ice shelf.

Potter and Paren (1985) report ocean glacial ice interaction at the George VI ice shelf, which is located within a narrow channel between the west coast of the Antarctic Peninsula and Alexander Island. Strong melting is induced by relatively warm water (about 1° C) which flows from the circumpolar deep water mass to below the glacial ice by way of the northern barrier (Marguerite Bay). This circulation pattern melts between 1.1 to 3.6 meters/year of glacial ice, which may account for one-sixth of the total glacial ice loss (assuming equilibrium).

Injection of glacial ice melt water into the ocean is discussed by Schlosser (1986) and Jacobs (1986). Schlosser finds a supersaturated helium layer which he attributes to glacial melt water, derived from the air bubbles trapped in the ice and freed upon ice melting. Jacobs discusses the possible role of glacial melt water in formation of bottom water, at least as a tracer.

Passive microwave radiometer measurements from NIMBUS satellites have revealed numerous coastal polynyas with widths of a few hundred kilometers at various sites around Antarctica (Zwally et al, 1985). Coastal polynyas are primarily latent heat features, in that the large heat flux to the atmosphere is maintained by release of latent heat of fusion as ice forms and is then transported away by the wind. This process may be an important factor in increasing the shelf water salinity, enough to allow deep-reaching continental margin convection (Zwally et al 1985; Cavalieri and Martin, 1985). The amount of ice formed within these polynyas may be as large as tens of meters per winter, elevating shelf water salinity by approximately 0.3 ppt. A recurring polynya in Terra Nova Bay, just north of the Drygalski Ice Tongue, also appears to be a latent heat polynya (Kurtz and Bromwich, 1985). It may play a role in supplying salt to the high salinity shelf water of the Ross Sea.

Arctic Circulation

Since the last review, there have been significant developments in the description of the flow within both the halocline and deep layers of the Arctic "Mediterreanean" Sea, that is the Arctic Ocean and its surrounding seas that lie north of the Greenland-Scotland ridge. This work supports the earlier work of Aagaard and co-workers (Aagaard, 1981; Swift and Aagaard, 1981; Aagaard, Coachman, and Carmack, 1981).

Circulation and water masses

Within the central Arctic, water mass formation along continental margins of the Arctic, rather than inflow of Greenland Sea deep water, appears to be the source for water lying below the salinity maximum. The recent work is based on new high quality hydrographic and geochemical data, particularly from the Iceland, Greenland, and Norwegian Seas and from the Arctic Ocean in the vicinity of Fram Strait. This data was collected during the Transient Tracers in the Ocean (TTO) cruise as well as more recent hydrographic surveys of the region by Clarke, Swift, and Koltermann (Aagaard, Swift, and Carmack, 1985; Koltermann and Swift, in preparation; Smethie, Ostlund, and Loosli, 1986). Similar quality data has also been gathered near the Lomonosov Ridge (Moore, Lowings, and Tan, 1983).

In a excellent synthesis Aagaard, Swift and Carmack (1985) show that when an appropriate deep reference level is used to calculate potential density there is no possible path for deep water formed in the Greenland Sea or in the Eurasian Basin to enter the Canadian Basin. Similarly, they show that the only deep water that enters the Eurasian Basin through Fram Strait (Norwegian Sea Deep Water overlying fresher Greenland Sea Deep Water) cannot produce Eurasian Basin Deep Water without additional air-sea heat or mass exchange within the Arctic basin(Swift, Takahashi, and Livingston, 1983). Concentrations of radionuclides suggest that a significant fraction of this water is formed on the Barents Sea shelf by atmospheric cooling. However, this need not include brine production during ice formation, as is the case in the Canadian basin, but only atmospheric cooling. The inflow of Deep Greenland Sea water through the Fram Strait mixes with the water produced on the shelf to give the fresher Eurasian Basin Deep water compared to that in the Canadian basin. The shallow sills to the south exclude these deep waters from entering the Iceland Sea and, in turn, the North Atlantic. As a result the deep circulation must be internally recirculating with diabatic mixing balancing the shelf and mid-gyre deep water production.

It now appears that the mid-gyre bottom water formation within the Greenland Sea is also a more complicated process than previously depicted. As it nears Fram Strait, the inflowing Atlantic Water bifurcates, with some water circulating westward as in the northern part of a Greenland Sea gyre (Aagaard, Swift and Carmack, 1985) and some entering the Arctic Ocean. Within the Arctic this water is continuously mixed with colder, fresher water formed on the continental margins (Aagaard, Coachman, and Carmack, 1981). It then exits in a narrow current on the western side of Fram Strait and appears in the western Greenland Sea with local potential density equal to Greenland Sea Deep Water. Aagaard, Swift and Carmack (1985) argue that the vertical and horizontal confinement of this water is caused by compressibility and rotational effects, respectively. Mixing by double diffusion between these waters and the Atlantic water may be partial sources for Greenland Sea Deep water (McDougall, 1983).

Smethie, Ostlund, and Loosli (1986) have used a simple box model to estimate residence times of the Greenland Sea and Norwegian Sea deep water and the transports between the surface and deep layers of the Greenland Sea as well as between the deep waters of the Greenland Sea, the Norwegian Sea and the Arctic Eurasian basin. They found short residence times, approximately 10 years south of Fram Strait, and interbasin transports consistent with the above circulation scheme. Other recent measurements and analyses of radionuclides suggest that the residence times within the upper layers of the Arctic Mediterranean are quite short, with renewal occurring on time scales of 2-10 years (Aagaard, Swift and Carmack, 1985). Using only isotope and salinity data, Ostlund (1982) and Ostlund and Hut (1984) estimate that the average residence time in both the surface and pycnocline waters of the Arctic Ocean is approximately 10 years.

Eddy Variability

The decreased residence times within these layers compared to those based on mean circulation advection may, to a large degree, be due to strong mixing by a very vigorous eddy field. Manley and Hunkins (1985) have shown that the Arctic Ocean contains many small scale, intense eddies at depths between 50 and 300 meters depth. Within the Canadian Basin, these eddies may occupy up to one fourth of the area. Water property anomalies within the eddies suggests that they originate near the Chukchi Sea and Alaskan Shelf.

During the recent Arctic Internal Wave Experiment in the Beaufort Sea, D'Asaro (in preparation) was able to survey several of these eddies describing their dynamic structure from velocity and density data. These eddies often appear in pairs, although they appeared to separate quickly, possibly due to mean vertical shear. Their dynamic signatures were quite strong, with potential vorticities approaching the magnitude of the local Coriolis parameter.

Very strong eddy activity has also been observed in the marginal ice zones in both the Bering Sea (Muench, 1983) and in the Greenland Sea (Smith, Morrison, Johannessen, and Untersteiner, 1984; Wadhams and Squire, 1983). Further descriptions of these eddies and their role in determining the structure of the marginal ice zone should be published soon as the data obtained during the 1984 Marginal Ice Zone Experiment (Johannesen, et. al. 1983) are analyzed.

Sea Ice - Ocean Interactions

The interaction of the sea ice with the ocean has continued to be an active area of research. McPhee (1983) has investigated the transfer of momentum and heat through the oceanic boundary layer. Interactions between the internal wave field and the ice edge have been studied by Muench (1983) in the Bering Sea. Muench, Hendricks, and Stegen (1985) have estimated the heat budget in the vicinity of the ice edge in the Bering Sea. Further work can be expected as the MIZEX-84 data is analyzed. Hakkinen (1986a, b) investigates the ocean-ice coupling within the marginal ice zone. Wind generation of vertical circulation and eddies (induced from instability of an ice edge current) at the ice margin influences the nature of the ice edge and may precondition the ocean for convection.

Shelf Processes

As was described above, it is now clear that shelf processes are important both for their economic significance and for their role in producing, or modifying, water masses throughout the water column in the Arctic Ocean. As part of their synthesis Aagaard, Swift and Carmack (1985) also show some new data from the Alaskan shelf and slope indicating significant salinity increase by brine rejection induced by ice formation. Melling and Lewis (1982) describe plume drainage down the continental slope in the Canadian Beaufort and present a gravity driven model of the flow. The effects of a polynya on the production of cold water over the Bering shelf are discussed by Schumacher, Aagaard, Pease, and Tripp (1983). Using current meter data Aagaard, Roach, and Schumacher (1985) have studied variations in the flow from the shallow Bering Sea into the Arctic ocean through the Bering Strait.

Modeling

Semptner has carried out three separate modeling efforts focused on seasonal to climatic time scales in the Arctic Ocean. He studies the response to Soviet river diversions, using a primitive equation model integrated to steady state with a crude ice boundary condition. Two cases were run, one with climatological runoff and one with decreased river outflow. It appears that there is increased ice buildup due to decreased inflow of warm Atlantic water (Semptner, 1984a). A simple one dimensional ice-model has been used by Semptner (1984b) to investigate the effects of changes in atmospheric carbon dioxide. Semptner (submitted) has also developed a new numerical model, using a simplified version of Hibler's (1979) ice model appropriate to seasonal time scales. Simulations of the seasonal cycle appear quite robust in terms of ice extent, but fail to predict the observed rates of deep water formation. This deficiency is probably due to the coarse resolution of the model and lack of a new parameterization of such small scale processes as shelf brine rejection and mid-gyre convection, both of which occur on small scales. Hibler and Walsh (1982) also have investigated the seasonal and interannual variability of Arctic sea ice.

Ongoing and Future Work

Within the Southern Ocean there is a need to extend the results of the Drake Passage research to the full circumpolar belt. While the ACC does have many features which are invariant with longitude, there is significant spatial variability. These changes appear to be related to the nature of the bottom topography. The ACC is a well defined jet-like flow over high relief features but more diffuse over broad abyssal basins. The intensity of temporal variability also varies spatially in a pattern suggesting response to topographic features. The exact nature of this coupling needs to be defined.

The Drake Passage ISOS results must be reliably extended to the full circumpolar region. To do this measurement of mean flow and eddy variability like those already obtained in the Drake Passage during ISOS, should be extended to the full circumpolar region. With such data the zonally integrated balances of heat and momentum fluxes can be investigated. Simple extrapolation of the Drake Passage results is risky before the representativeness of the Drake Passage for the full circumpolar belt is determined. There is still the major question as to how the wind energy introduced into the ACC is dissipated. The eddy field seems inadequate as does the bottom stress; form drag is a likely candidate.

Poleward of the ACC there is major loss of oceanic heat to the atmosphere through a seasonal and often partial sea ice cover. Associated with this exchange is water mass modification which leads to ventilation of much of the world ocean. Exchange of water and gases such as CO_2 is also considered to be large. While progress has been made recently in gaining a quantitative understanding of these fluxes, much more remains to be done if the Southern Ocean is to be well represented in the global scale climate models. Included in this requirement is better understanding of the interaction of the ocean with the glacial ice.

The extensive Southern Ocean data set obtained from the POLARSTERN during the austral winter of 1986 in the Weddell gyre region, will be analyized during the coming years. This should do much to expand our understanding of winter and spring ocean atmosphere ice interaction.

Because of the difficulties of working in ice covered regions there are few direct measurements of the currents in the polar regions. Increased use of instrumented moored or drifting monitoring arrays; acoustical methods, such as SOFAR/RAFOS floats, tomographic methods and doppler profilers, would dramatically extend our knowledge of polar ocean dynamics. These studies should be closely coupled to observations from satellites. CTD hydrographic work coupled with tracer geochemistry, would be most effective in the investigation of water mass formation and of specific features within both the Arctic Seas and Southern Ocean are needed. These observational techniques should be planned and considered in conjunction with modelling efforts.

Since the Fram Strait is such an important chokepoint in the circulation of the Arctic Mediterranean, a monitoring program of current meters across the width of the strait was begun in 1984 by Aagaard. This work has continued under the direction of Meincke and Aagaard and will provide estimates of the flow through this passage for at least three years. We can expect important results from these moorings to appear in the near future. A major international experiment aimed at the circulation and deep water production processes in the Greenland Sea is in the final planning stages and is to begin in 1988.

As was mentioned above in the section on eddy variability, in May 1985 an experiment to examine the internal wave activity in the Beaufort Sea was carried out. Preliminary indications are that the internal wave field under the ice is 1-2 orders of magnitude less energetic than in the open ocean (D'Asaro, in preparation; C. Morrison and Paulson, personal communication). This result clearly has important implications for the role of various sources and sinks for internal waves.

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