Title
The US Southern Ocean Joint Global Ocean Flux Study: an introduction to AESOPS

Journal
Deep Sea Research Part II Topical Studies in Oceanography, 47(15-16)

ISSN
0967-0645

Authors
Smith, Walker O
Anderson, Robert F
Moore, J Keith
et al.

Publication Date
2000

DOI
10.1016/s0967-0645(00)00059-x

PERGAMON

Deep-Sea Research II 47 (2000) 3073–3093

DEEP-SEA RESEARCH
PART II

www.elsevier.com/locate/dsr2

The US Southern Ocean Joint Global Ocean Flux Study: an introduction to AESOPS

Walker O. Smith Jr.[a,*], Robert F. Anderson[b], J. Keith Moore[c], Louis A. Codispoti[d], John M. Morrison[e]

[a]*Virginia Institute of Marine Science, College of William and Mary, Gloucester Pt., VA 23062, USA*
[b]*Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10796, USA*
[c]*National Center for Atmospheric Research, Box 3000, Boulder, CO 80307, USA*
[d]*Horn Pt. Environmental Laboratory, University of Maryland, P.O. Box 775, Cambridge, MD 21613, USA*
[e]*Department of Marine, Earth and Atmospheric Sciences, North Carolina State University, Raleigh, NC 27695, USA*

Received 1 April 2000; received in revised form 15 May 2000; accepted 19 May 2000

Abstract

The United States Southern Ocean Joint Global Ocean Flux Study (JGOFS), also known as AESOPS (Antarctic Environment and Southern Ocean Process Study), focused on two distinct regions. The first was the Ross-Sea continental shelf, where a series of six cruises collected a variety of data from October 1996 through February 1998. The second area was the southwest Pacific sector of the Southern Ocean, spanning the Antarctic Circumpolar Current (ACC) at ~ 170°W. Data were collected within this region during five cruises from September 1996 through March 1998, as well as during selected transits between New Zealand and the Ross Sea. The first results of these cruses are described in this issue. The Ross-Sea investigation extensively sampled the area along 76°30′S to elucidate the temporal patterns and processes that contribute to making this one of the Antarctic's most productive seas. Hydrographic distributions confirm that stratification is initiated early in October within the polynya, generating an environment that is favorable for phytoplankton growth. Significant spatial variations in mixed-layer depths, the timing of the onset of stratification, and the strength of the stratification existed throughout the growing season. Nutrient concentrations reflected phytoplankton uptake, and reached their seasonal minimal in early February. Chlorophyll concentrations were maximal in early January, whereas productivity was maximal in late November, which reflects the temporal uncoupling between growth and biomass accumulation in the region. Independent estimates of biogenic export suggest that majority of the flux occurred in late summer and was strongly uncoupled from phytoplankton growth. The ACC region exhibited seasonal changes that in some cases were greater than those observed in the Ross Sea.

---

* Corresponding author.
E-mail address: wos@vims.edu (W.O. Smith Jr.).

PII: S0967-0645(00)00059-X

Sea ice covered much of the region south of the Polar Front in winter, and retreated rapidly in late spring and early summer. Mixed layers throughout the region shoaled in summer due to surface heating, while the addition of freshwater from melting sea ice enhanced stratification in the Seasonal Ice Zone, creating conditions favorable for phytoplankton growth. For example, silicic acid concentrations decreased from initial values as high as 65 to less than 2 μM within approximately 100 km (from 65.7 to 64.8°S). Fluorescence values, however, showed less than a two-fold variation over the same distance. The vertical flux of carbon in the Polar Front area is substantial, and marked variations in the composition of exported material exited over the region. The results provide a means whereby the controls of phytoplankton growth and organic matter flux and remineralization can be analyzed in great detail. Additional results of the AESOPS project are discussed.

1. Introduction

In the 1980s concern over rapidly increasing atmospheric carbon dioxide concentrations heightened. It was also realized that without a better understanding of the quantitative and mechanistic relationships among surface CO_2 concentrations, biological dynamics, and vertical flux of carbon, we would be unable to model and predict the role of the ocean in the global carbon cycle. In response, an international program (the Joint Global Ocean Flux Study, or JGOFS) was designed to evaluate the magnitude of the organic matter flux from the ocean's surface to depth, and the controls on the processes that regulate this flux. To address the uncertainty of the ocean's role in global biogeochemical budgets, a number of locations (e.g., the North Atlantic, the equatorial Pacific, the Arabian Sea, and the Southern Ocean) were chosen for intensive study, based on the perception of their importance to these budgets as well as the unique nature of physical–biological linkages within each. The first three studies were initiated in the late 1980s and 1990s (e.g., Ducklow and Harris, 1993; Murray et al., 1995; Smith et al., 1998), and many of the European efforts in the Southern Ocean began in the mid-1990s (Turner et al., 1995; Smetacek et al., 1997; Gaillard, 1997). The US field program in the Southern Ocean began in 1996.

Carbon fluxes in the Southern Ocean represents quantitatively significant components of the global carbon cycle. They are highly susceptible to perturbation, and are less understood these are fluxes in more readily accessible regions. Individual subsystems within the Southern Ocean act both as sources of CO_2 to the atmosphere and as sinks for atmospheric carbon dioxide that, independently, represent quantitatively significant terms in the global budget for air-sea exchange of CO_2. However, because our observations in the Southern Ocean are restricted, we remain uncertain as to whether the region as a whole acts as a net source or sink for atmospheric CO_2.

Biological productivity and the accompanying processes that transport fixed carbon and nutrients to the deep sea are spatially and temporally variable in Southern Ocean. Important processes (such as an understanding of the factors that limit productivity, the nature of the coupling between grazers and primary producers, and the efficiency of the microbial loop) and the magnitude of biogenic fluxes are poorly constrained. Furthermore, we cannot adequately address the changes that have occurred in recent geological times as they relate to present conditions in the Southern Ocean. To address these (and other) scientific questions, a multidisciplinary program was designed to study the seasonal changes at two sites in the Southern Ocean: the Polar Front and the Ross Sea.

The Southern Ocean presented unusual challenges for a JGOFS-type study. Waters of the Antarctic are heterogeneous, in that much of the region is influenced by the advance and retreat of the seasonal ice cover (Tréguer and Jacques, 1992). However, not all areas of the Southern Ocean are directly impacted by ice, as some are permanently ice-free. The Antarctic also has deep (up to 800 m) and productive continental shelf regions, and the entire realm is influenced by strong dynamic forcing (e.g., currents, convection, ice formation, etc.). Given the size of the Southern Ocean and its remoteness, it is not surprising that it is one of the most poorly sampled regions in the ocean. As study sites were considered for the US JGOFS effort, one (the Pacific Sector) had the advantage of being close to the extensive logistics bases in New Zealand and Antarctica (McMurdo Station), as well as part of it (the Ross Sea) having been well studied previously. However, the deeper waters near the Polar Front had been very poorly studied, despite that fact that it had been hypothesized as being a major oceanic site for the control in atmospheric CO_2 concentrations. After weighing the advantages and disadvantages of a number of study locations, it was decided that the Pacific Sector of the Southern Ocean would be the focus of the US JGOFS field effort. The overall study was named AESOPS: Antarctic Environment and Southern Ocean Process Study.

A series of cruises to the study areas were initiated in 1996 (Table 1). The first cruise, beginning in late August 1996, was a survey of the polar front region near 170°W. The bathymetry in this area was poorly known, and more information was needed prior to the deployment of time-series sediment traps and bio-optical moorings. The cruise was followed by three others designed to assess the biological processes and controls on carbon fluxes in the Ross Sea in early spring, summer and autumn. Time-series sediment traps were deployed in November 1996 in both areas and collected samples for 14 months. A fourth study in the Ross Sea was completed during austral spring of the following year at the time of the most rapid change in chemical and biological concentrations, and a benthic survey/sediment trap recovery cruise was conducted in February 1998. Four successive cruises to the polar front region were conducted from October 1997 through February 1998 to assess the distributions of surface layer properties and the processes responsible for generating those distributions. All sediment traps were recovered in February–March 1998.

2. Study area

All cruises to the Ross Sea used the R.V.I.B. *Nathaniel B. Palmer* (Fig. 1a), whereas cruises to the PF took place on the R.V. *Roger Revelle* (Fig. 1b). The area north of the Ross Ice Shelf and east of Ross Island has lower ice concentrations than the surrounding areas, and thus is known as a polynya (Fig. 2a). Studies of biological processes and

Table 1
Cruises conducted as the part of AESOPS

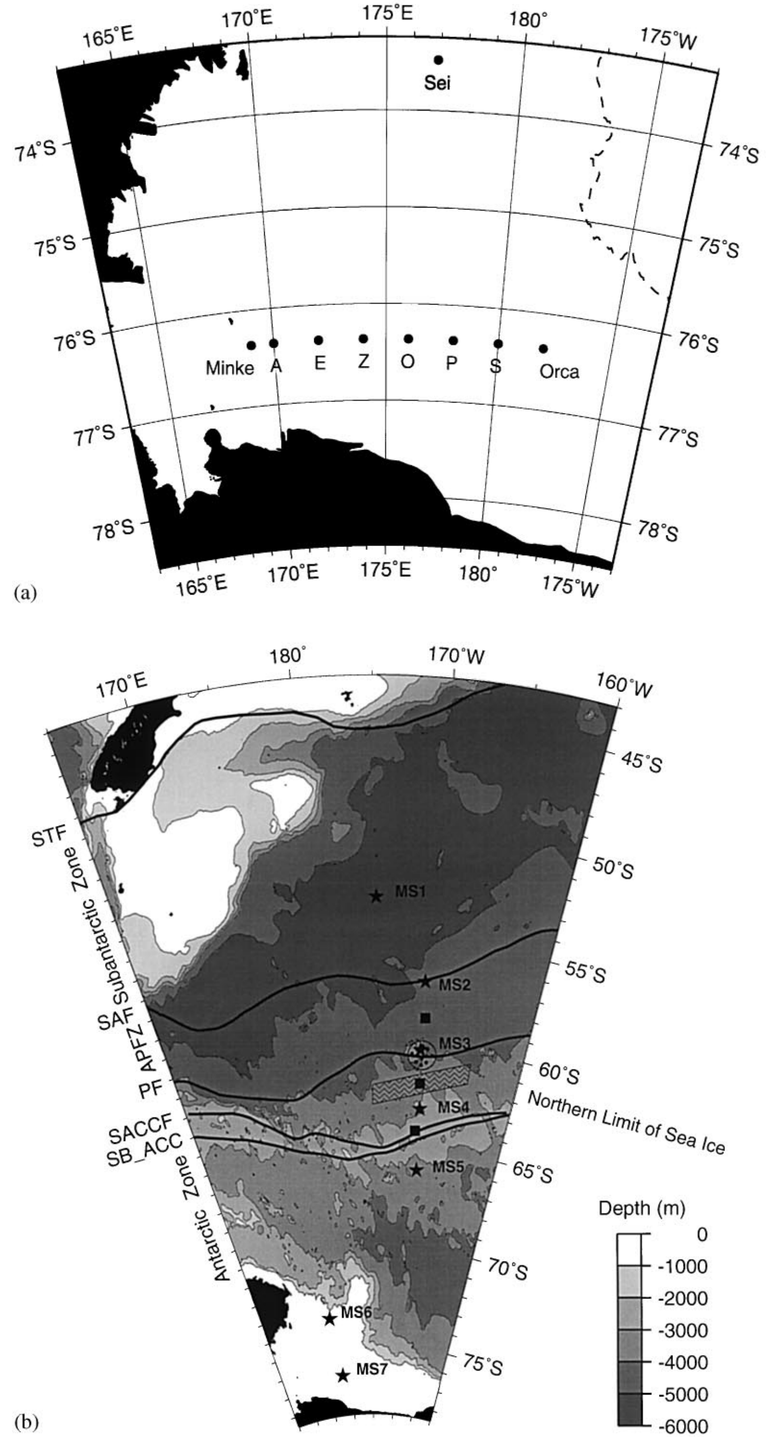
Dates	Ships/Cruise	Study Area	Objectives
8/30/96–9/24/96	R.V.I.B. *N.B. Palmer*	Polar Front, 170°W; NBP96-04	Provide accurate bathymetric data for sediment trap placement and winter underway nutrient data
10/2/96–11/8/96	R.V.I.B. *N.B. Palmer*	Ross Sea, 76°30′S; NBP96-04A	Provide rate process information during period of the initiation of phytoplankton growth
11/11/96–12/1/96	R.V.I.B. *N.B. Palmer*	Ross Sea; Polar Front; NBP96-05	Deploy time-series sediment traps
1/13/97–2/11/97	R.V.I.B. *N.B. Palmer*	Ross Sea; 76°30′S; NBP97-01	Provide rate process information on the controls of phytoplankton growth and losses during summer
4/4/97–5/12/97	R.V.I.B. *N.B. Palmer*	Ross Sea; 76°30′S; NBP97-03	Provide rate process information during a period of low and decreasing primary production
10/20/97–11/24/97	R.V. *Roger Revelle*	Polar Front, 170°W; RR06	Provide information on the mesoscale variations of the region's fronts; deploy bio-optical moorings;
11/5/97–12/13/97	R.V.I.B. *N.B. Palmer*	Ross Sea; 76°30′S; NBP97-08	Provide rate process information during the period of maximal phytoplanktongrowth and accumulation
12/2/97–1/3/98	R.V. *Roger Revelle*	Polar Front, 170°W; RR07	Provide rate process information during the period of increased production/biomass in the Polar Front
1/8/98–2/8/98	R.V. *Roger Revelle*	Polar Front, 170°W; RR08	Provide information on the summer mesoscale variations in the region of the Polar Front
2/13/98–3/19/98	R.V. *Roger Revelle*	Polar Front, 170°W; RR09	Provide rate process information during the summer in the Polar Front region
2/25/98–4/8/98	R.V.I.B. *N.B. Palmer*	Ross Sea; Polar Front; NBP98-02	Conduct benthic survey and recover sediment trap arrays

rates were concentrated along 76°30′S within a transect that was situated approximately normal to ice retreat and traversed the polynya (Fig. 1a). The area sampled also was known from historical studies to be largely ice-free for a substantial portion of the year. Sediment traps were placed at two locations in the Ross Sea, based on previous studies of flux and surface properties (DeMaster et al., 1992). Additional sites were selected for specific experiments within the framework of the entire AESOPS project. A mesoscale survey using a towed, pumping SeaSoar was conducted during the November–December 1997 cruise.

The location of the ACC study was selected based on the zonal orientation of the physical and chemical fronts found in that region (Daly et al., in press). There are a number of fronts in the area, including the Southern ACC Front (SACCF), the Polar Front (PF), the Subantarctic Front (SAF), and the Subtropical Front (STF) (Orsi et al., 1995; Fig. 1b). Each of these is delineated by a number of variables, including temperature, salinity, and oxygen concentration, that characterize the classical zonation of the Southern Ocean (Fig. 1b). Flow of the ACC is concentrated in narrow jets, coinciding with the principal fronts, which are interspersed with broader zones of reduced or even reversed flow, creating large shear within the water column (Daly et al., submitted). Sea ice covers most of the region south of the PF in winter, with the maximum extent of sea ice along 170°W reaching $\sim 62°$S in most years, including both AESOPS field seasons (Fig. 2b). The region covered by the seasonal advance and retreat of sea ice, while overlapping with the Antarctic Zone (compare Fig. 1b and 2b), is sometimes classified separately by biogeochemists as the Seasonal Ice Zone (SIZ; Tréguer and Jacques, 1992). This delineation is made because the stabilizing effect of freshwater added by melting sea ice often leads to phytoplankton blooms as well as to distinct species assemblages (Smith and Nelson, 1985; Mitchell et al., 1991; Tréguer and Jacques, 1992; Arrigo et al., 1999).

Four cruises to the ACC region included two that were designated as "survey cruises", in that a strong emphasis was placed on the assessment of mesoscale variations in temperature, salinity, nutrients and fluorescence within the region of the polar front using a SeaSoar (Table 1). The other two cruises were "process studies" in which a variety of rate processes were measured and the processes influencing carbon dynamics of the surface layer and vertical flux of particles investigated in detail. Sediment trap moorings and bio-optical moorings also were placed within the study region (Fig. 1b). Additional samples across the frontal regions also were collected as the R.V.I.B *Nathaniel B. Palmer* transited the region to and from the Ross Sea.

Both ships sampled using traditional CTD-Rosette systems as well as trace metal-clean rosettes (Hunter et al., 1997). Given the hypothesized importance of trace metals in waters of the Southern Ocean (e.g., Martin et al., 1990; de Baar et al., 1995), it was essential to the project that all samples in which biological rates were determined be sampled without contamination. Similarly, a strong emphasis was placed on obtaining trace metal distributions over the entire seasonal cycle at both locations. Finally, in October 1997 the NASA satellite SeaWiFS was launched. During the AESOPS cruises we attempted to use those initial passes over our study site to guide our sampling in as much as possible, as well as to collect data to test the validity of the bio-optical algorithms used in the processing of the remotely sensed data.


165°E
170°E
175°E
180°
175°W
Sei
74°S
75°S
76°S
77°S
78°S
Minke
A
E
Z
O
P
S
Orca
(a)
180°
170°W
170°E
160°W
45°S
50°S
55°S
60°S
65°S
70°S
75°S
STF
Subantarctic Zone
SAF
APFZ
PF
SACCF
SB_ACC
Antarctic Zone
MS1
MS2
MS3
MS4
MS5
MS6
MS7
Northern Limit of Sea Ice
Depth (m)
0
-1000
-2000
-3000
-4000
-5000
-6000
(b)

As in other JGOFS field experiments, a set of "core" measurements was completed at every station (Table 2) according to protocols which established for earlier field studies (JGOFS, 1996). These data have been checked for quality and consistency, and are publicly available on the internet (http://usjgofs.whoi.edu/jgofs.html). This site also lists additional experimental details and contacts for additional information.

3. Results

3.1. Ross Sea continental shelf

Ice concentrations had been suggested as being critical environmental determinants of phytoplankton growth in the Ross Sea. Ice (along with snow cover) not only attentuates irradiance, but freezing events effectively mix the water column beneath the ice. The seasonal changes in ice cover on the Ross Sea continental shelf were similar to those found in previous years (Fig. 2a; Comiso et al., 1993). The polynya formed close to the ice shelf in late winter, likely due to katabatic winds blowing off the continent, and expanded rapidly in size as the heat budget became positive in November. The region in the central polynya became ice-free due to the advective influence of winds, whereas to the east and west, ice disappeared largely due to in situ melting (as evidenced by salinity reductions at the surface; Gordon et al., 2000).

The strength of vertical stratification within the water column on the Ross Sea continental shelf in general increased with time (Fig. 3). Initially (in mid-October) mixed layer depths (determined by a $\Delta\sigma_T = 0.02$) were deep (up to 600 m in some locations; Fig. 3a), and the water column weakly stratified (Fig. 4a). Nutrient concentrations were uniform throughout the water column, and chlorophyll concentrations were extremely low ($< 0.1\,\mu g\,l^{-1}$). During summer the depth of the mixed layers decreased (Fig. 3b), and the strength of the stratification became substantial (Fig. 4b), particularly in areas where melting had imparted significant amounts of low-salinity melt water. Nitrate concentrations during summer were reduced (Gordon et al., 2000), with a minimum of 2 μM being observed on February 6, 1997 within the melting pack

◄

Fig. 1. Maps showing the two study locations in AESOPS: (a) Ross-Sea continental shelf (dashed line indicates the shelf break); and (b) Polar Front. Sediment trap positions are indicated by stars. Benthic stations were conducted during NBP9802 at the locations of the sediment trap moorings, as well as at stations indicated by large dots. Bio-optical moorings deployed in an array spanning the PF are indicated by small dots. The locations of the principal fronts (Orsi et al., 1995) are also displayed. The Southern Ocean is traditionally divided into concentric zones surrounding Antarctica. From north to south these are the Subantarctic Zone, lying between the Subtropical Front (STF) and the Subantarctic Front (SAF), the Polar Front Zone, located between the SAF and the Polar Front (PF), and the Antarctic Zone, encompassing all waters south of the PF (although some authors distinguish continental shelf waters as a separate zone; e.g., Nowlin and Klink, 1986; Patterson and Whitworth, 1990; Peterson and Strama, 1991; Orsi et al., 1995; Belkin and Gordon, 1996). The Seasonal Ice Zone (Tréguer and Jacques, 1992) overlaps the Antarctic Zone, and extends to ca. 62°S, while the Permanently Open-Ocean Zone, defined as the region between the PF and the northern limits of sea ice (Tréguer and Jacques, 1992) is virtually non-existent at 170°W. Cruise tracks and station locations for each AESOPS cruise can be accessed at: http://usjgofs.whoi.edu/aesops-cruises.html.

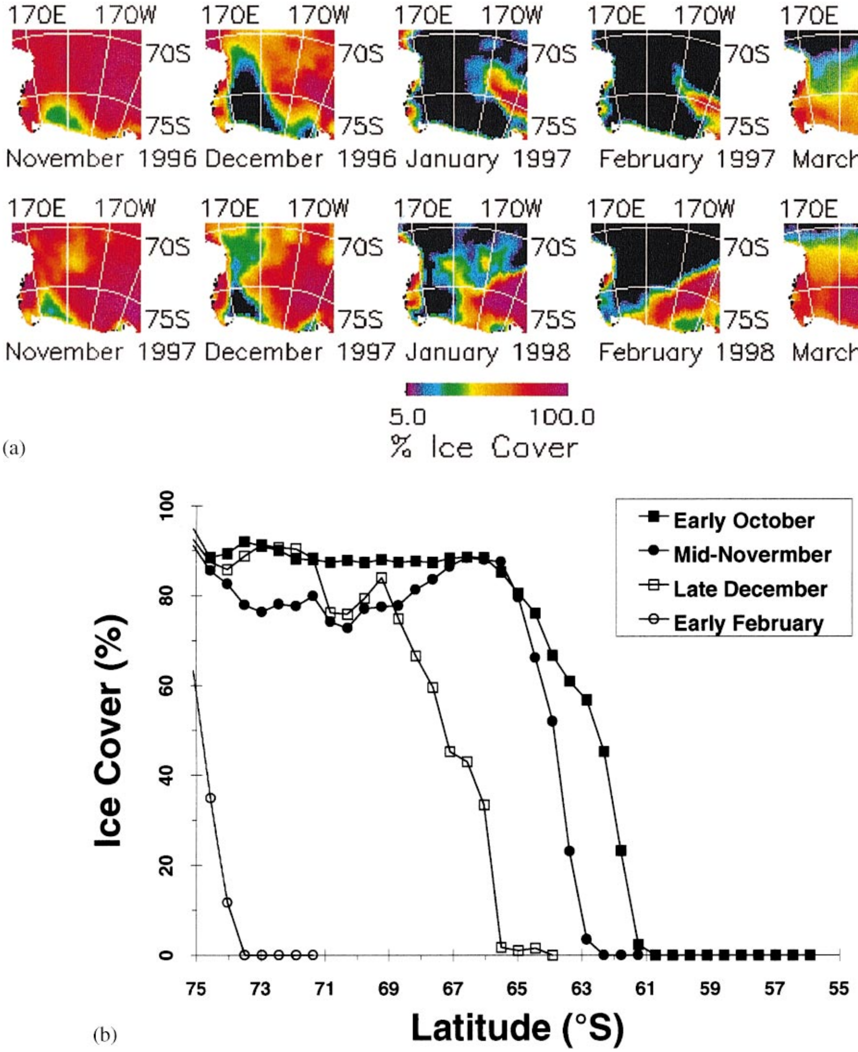


Fig. 2. (a) The distribution of ice and open water (black) during 1996–97 and 1997–98 on the Ross-Sea continental shelf. White signifies land. (b) The distribution of ice during selected weeks of 1997–98 along 170°W. The northern limit of sea ice in 1997, extracted from satellite records, is consistent with shipboard observations along 170°W in 1996 (NBP9604), indicating that the SIZ extended north of 62°S during both growing seasons from which particle fluxes were collected by sediment traps. Ice data from the National Snow and Ice Data Center (Passive Microwave Derived Monthly Polar Sea Ice Concentration Time Series; digital data available from nsidc@kryos.colorado.edu, Boulder, Colorado, NSIDC Distributed Active Center, University of Colorado at Boulder).

ice north of the AESOPS line. Dissolved inorganic carbon and other nutrients were similarly reduced. Chlorophyll concentrations were elevated as well, but maxima had been observed earlier in the austral spring (Smith et al., 2000), suggesting that substantial flux and/or heterotrophic removal of phytoplankton carbon had occurred.

Table 2
The "core" measurements that were generally made at each station. At some stations only a subset of these measurements were completed

	Parameter
1	Meteorology, PAR, ice concentrations and conditions, sea state, position
2	Continuous measurements of temperature, salinity, optical transmission, fluorescence, irradiance, and dissolved oxygen in vertical profiles
3	Dissolved oxygen
4	Dissolved carbon dioxide
5	Dissolved inorganic nutrients (nitrate, nitrite, ammonium, phosphate, silicic acid)
6	Fluorometric chlorophyll
7	Particulate organic carbon and nitrogen
8	Phytoplankton pigments by HPLC
9	Primary productivity by ^{14}C uptake
10	Bacterial abundance and productivity
11	Phytoplankton enumeration and taxonomy
12	Microzooplankton enumeration and taxonomy
13	Microzooplankton grazing rates
14	Mesozooplankton biomass, taxonomy and size structure
15	New production via ^{15}N uptake
16	Export of particles via ^{234}Th method
17	Deep, moored time-series sediment traps
18	Trace metal concentrations
19	Trace metal–phytoplankton interaactions
20	Silicon uptake and biogeochemistry

During autumn the mixed-layer depths increased, as did nutrient concentrations. Particulate organic matter levels were reduced to near background levels, and computations of export based on the POC deficit suggested that ca. 0.77 mol C m^{-2} had been exported by mid-February as particles, with ca. 3.12 mol C m^{-2} remaining in the water column (Sweeney et al., 2000). This export represents ca. 16% of the seasonal production, and a significant fraction of the remaining POC also is available for export at a later date.

The temporal variations in environmental conditions and phytoplankton biomass were evident in the changes in mixed-layer depth, nutrient concentrations, and chlorophyll levels in the surface layer (Fig. 5a and b). Because the Ross Sea appears to have two dominant phytoplankton assemblages (the first being dominated by diatoms, and the second by the colonial haptophyte *Phaeocystics antarctica*) that are often spatially distinct (Arrigo et al., 1999), we chose two sites where silicic acid temporal patterns were markedly distinct to illustrate the differences. At the first (76°30′S, 169°E) mixed layers were extremely deep in spring (>450 m), but decreased during summer to ca. 10 m due to local melting of ice and the release of low-density water at the surface. Nitrate concentrations were initially at winter levels (ca. 30.5 μM) and began to decrease by the end of November (Fig. 5b). Silicic acid concentrations (initially ca. 78 μM) also began to decrease at this time, although not as rapidly as

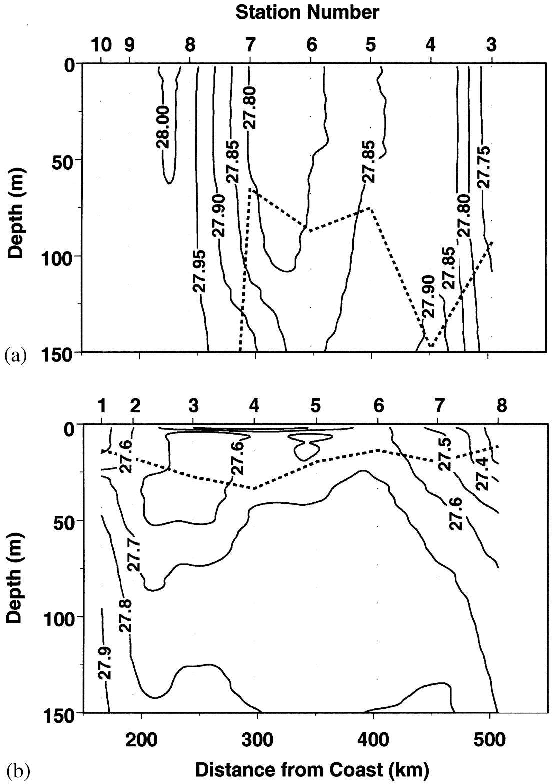


Fig. 3. The vertical distribution of density (expressed as σ_τ) along 76°30′S during (a) October 17–23, 1996, and (b) January 13–20, 1997. The dashed line represents the depth of the mixed layer. Station numbers correspond to locations along the AESOPS line.

nitrate. Minimum nitrate and silicic acid concentrations of 8.7 and 54.3 μM, respectively, were observed on January 13, and the concentrations of both increased thereafter. For this period the $\Delta Si/\Delta N$ removal ratio (adjusted to deep-water salinities; Sweeney et al., 2000) for this location was 1.29. Chlorophyll concentrations were extremely low in November ($< 0.05\,\mu g\,l^{-1}$), but increased to $12.8\,\mu g\,l^{-1}$ in mid-January (Fig. 5a). Increases in nitrate and silicic acid (and decreases in chlorophyll) during autumn primarily reflected the increased mixed layers at the time, and the observed nutrient "deficit" was a remnant signature of phytoplankton removal.

The temporal patterns at the second site (76°30′S, 172°E), which was dominated by *Phaeocystics antarctica*, were similar, although the magnitude of some of the changes was different. Mixed-layer depths decreased with time, although the greatest mixed-layer depth we observed was 148 m, and the minimum was 20 m (Fig. 5b). Hence minimal mixed-layer depths were greater in the areas dominated by *P. antarctica*; however, changes in mixed-layer depths between spring and summer were less than

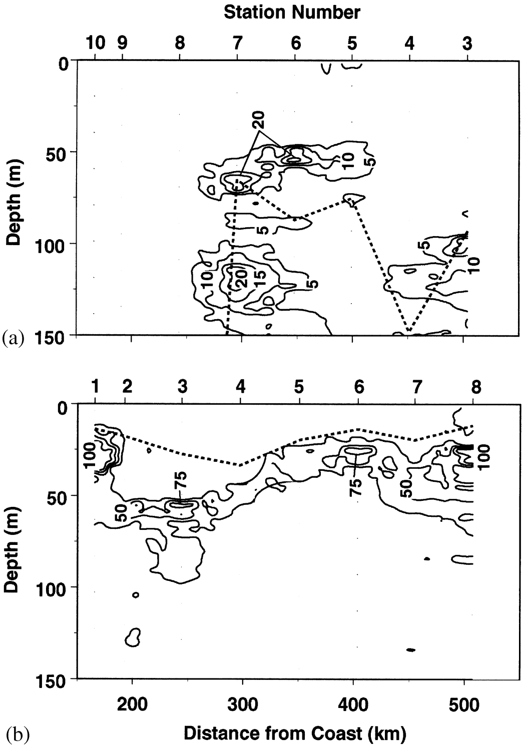


Fig. 4. The vertical distribution of the bouyancy frequency measure of the strength of stratification along 76°30′S during (a) October 17–23, 1996, and (b) January 13–20, 1997. The dashed line represents the depth of the mixed layer. Station numbers correspond to locations along the AESOPS line.

those experienced in diatom-dominated regions. Although the site where *P. antarctica* dominated was stratified earlier in the year, and this stratification lasted longer, the strength of the stratification at this site (based on its buoyancy frequency) was less than that observed at 76°30′S, 169°E. The minimum nitrate concentration observed was 9.2 μM, but silicic acid concentrations never decreased below 66 μM, (that any reduction occurred at all is reflective of the presence of some diatoms). Maximum chlorophyll concentrations reached 3.91 $\mu g\,l^{-1}$.

3.2. Antarctic circumpolar Current

Locations of the principal fronts during the AESOPS study coincided reasonably well with average positions reported by Orsi et al. (1995). Fronts in the ACC often extend to the bottom (> 3000 m). Locations of the fronts were confirmed by the high-velocity jets evident in shipboard ADCP measurements (Barth et al., submitted) as well as by increased meridional gradients in deep isopycnals (Anderson, unpublished). While the surface expression of the PF (sea-surface temperature and silicic acid

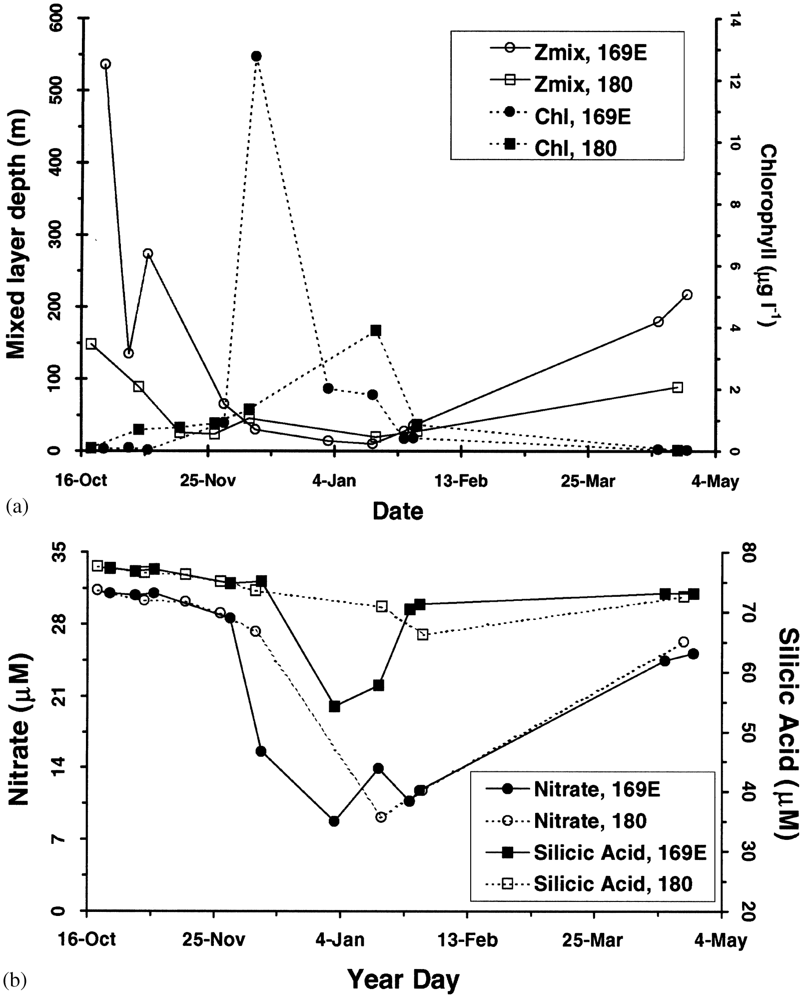


Fig. 5. The temporal changes in mixed layer depth, nitrate, silicic acid, and chlorophyll concentration at (a) 76°30′S, 169°E, and (b) 76°30′S, 172°E.

gradient; Fig. 6a and d) coincided with deeper, more permanent features in November, these surface features were obscured in summer by seasonal warming of the surface layer and by biological consumption of Si (Fig. 6d).

The PF separates the Antarctic Zone to the south, where high winter Si concentrations result from upwelling of Circumpolar Deep Water, from the Polar Front Zone (PFZ) to the north, where Si-depleted Antarctic Intermediate Water sinks and begins its northward transit. Stratification in both zones varied seasonally, and the biological response to summer stratification is evident in the reduction of nutrient concentrations.

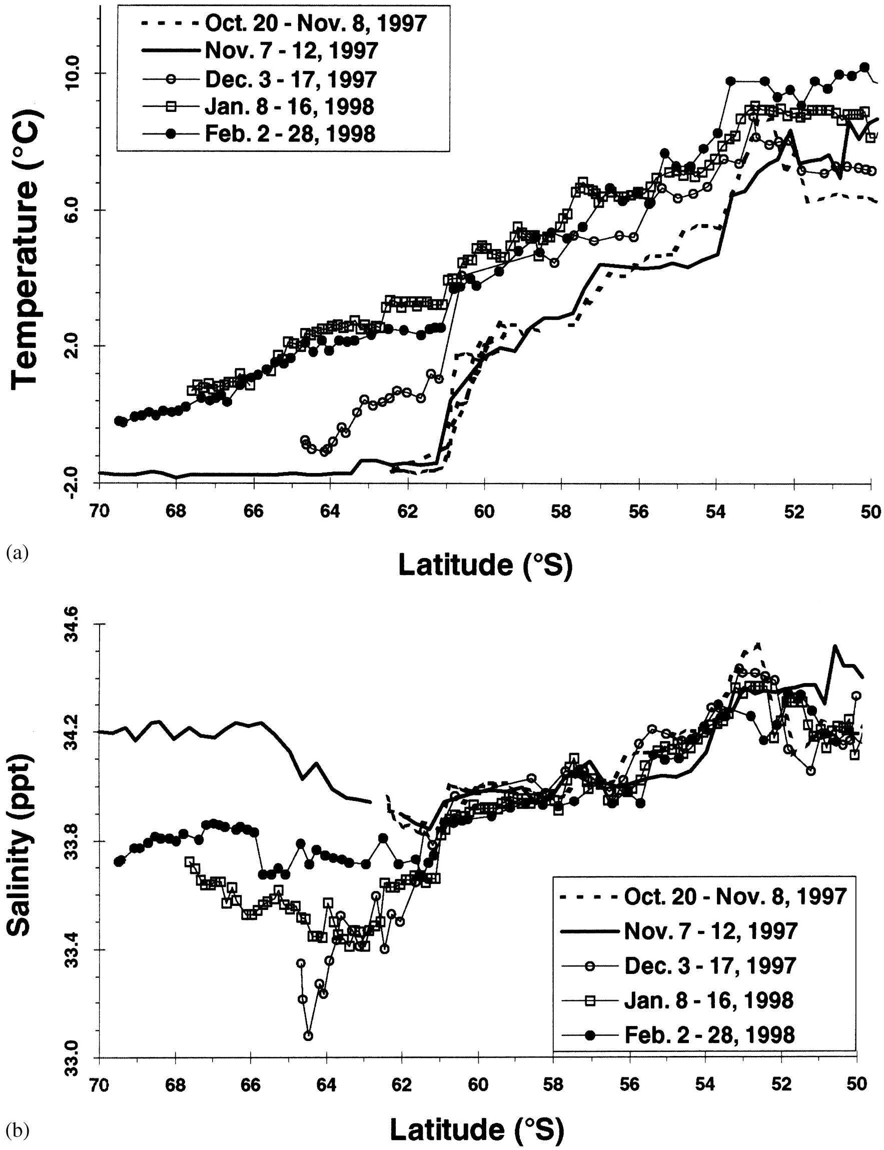


Fig. 6. The surface distribution along 170°W of: (a) temperature, (b) salinity, (c) dissolved inorganic nitrogen, and (d) silicic acid during five transits. Time periods sampled included late October, 1997, early November 1997, mid-December, 1997, mid-January, 1998 and mid-February, 1998. All samples collected from the ship's underway sampling system. The sequence of cruises captures the seasonal cycle of increase and decline of phytoplankton growth and the associated changes in nutrients.

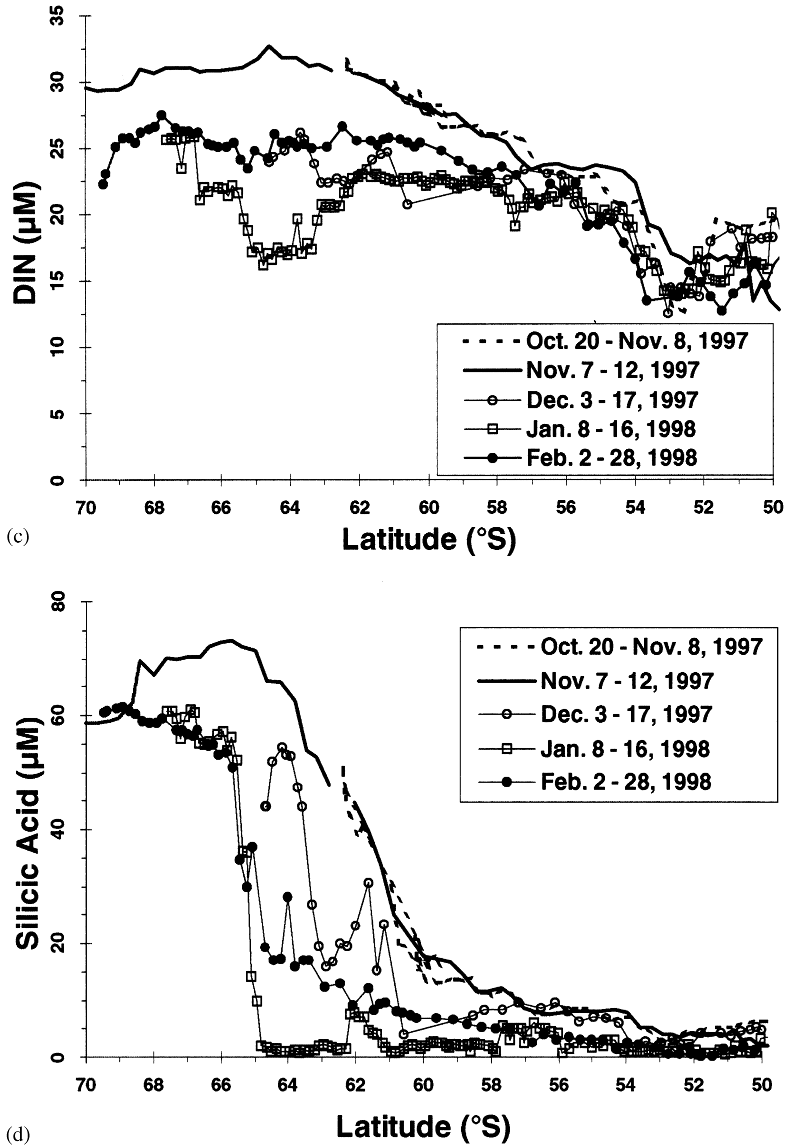


Fig. 6. (*continued*)

Seasonal variability in mixed-layer depths was observed throughout the region. Near the site of Sediment Trap Mooring 2 in the northern PFZ (Fig. 1b), winter mixed-layer depths ($\Delta\sigma_T = 0.02$) were in excess of 120 m. The location of Mooring 4 (63.1°S), in the Antarctic Zone, was not occupied in winter, but a station at 63.9°S (occupied in September 1996) had a mixed layer depth of 126 m, which is representative of the Antarctic zone. Surface heating contributed to summer stratification throughout the region (Fig. 6a), while the reduction of surface salinity (Fig. 6b) by melting sea ice in the SIZ further contributed to increased stratification south of the PF. Mixed-layer depths by January had shoaled to < 40 m, both in the Antarctic Zone and in the PFZ, and mixed layers < 20 m were encouraged during selected casts within the Antarctic Zone. By the time of the final cruises in February–March 1998, mixed-layer depths were increasing throughout the region.

Summer stratification, together with increasing solar angle, created favorable conditions for phytoplankton growth, as manifested by a decrease in surface-dissolved inorganic nitrogen (DIN) concentration of up to 15 μM at ~ 64°S (Fig. 6c), from a winter value of 32 to a summer minimum of 17 μM. At 57°S the contemporary (DIN) draw down was ~ 3 μM, from a winter values of ~ 24 μM to a summer minimum of 21 μM, although the summer depletion increased southward toward the PF (Fig. 6c). Late-winter surface Si concentrations were substantially lower north of the PF than to the south (Fig. 6d). During the course of the growing season, silicic acid was consumed by diatom growth to concentrations below 5 μM throughout the region, and to concentrations < 2 μM at many sites. The greater Si consumption south of the PF, together with the much smaller difference in nitrate consumption between the two zones, led to a substantially larger $\Delta Si/\Delta NO_3$ molar removal ratio in the Antarctic Zone (~ 4.6 at 63°S) compared to the PFZ (~ 2.3 at 57°S). Although winter silicic acid concentrations in the PFZ are modest compared to those in the Antarctic zone, diatoms contributed a large portion of the biogenic material exported from surface waters of the PFZ, as evidenced by the mean annual opal content (52%) of particles collected by a sediment trap at 57°S (Honjo et al., 2000).

The PF itself is a complex region, with the upper water column being characterized by interleaving water masses varying on scales of tens of kilometers. Stratification created by interleaving water masses, together with local upwelling induced by meanders in the PF, contributed to favorable growing conditions early in the season. Early signs of a developing bloom were first observed at the PF during November 1997 (Landry et al., submitted). Peak bloom conditions at the PF, in December, were subsequently recorded by an array of bio-optical moorings (Abbott et al., 2000), by remote sensing (Moore et al., 1999), and by ship-based observations.

The patterns of surface phytoplankton biomass co-varied with those of nutrient distributions (Fig. 7). During late winter fluorescence varied little throughout the entire region, whereas in December it not only increased to the seasonal maximum, but was correlated with the physical characteristics (fronts, stratification) found in the region. A secondary maximum was observed between 69 and 71°S, but few AESOPS observations were made in this region. Average concentrations of chlorophyll within the mixed layer north of the PF (St. 2, 56°50.4′S) were 0.19 $\mu g\,l^{-1}$ during December, whereas south of the PF they were an order of magnitude greater (mean of 2.90 $\mu g\,l^{-1}$ at St. 7, 64°9′S) during the same time period. By mid-January and late February chlorophyll levels at this same location had decreased to 2.33 and 0.44 $\mu g\,l^{-1}$. Hence the seasonal phytoplankton bloom in the region of the Polar Front is a short-lived event, and one that has likely been highly under-sampled by expeditions in the past.

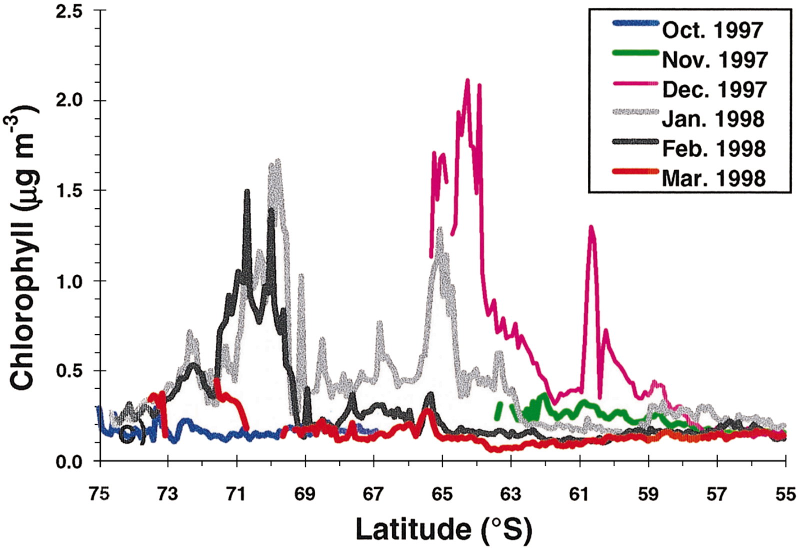


Fig. 7. The surface distribution of chlorophyll along 170°W during six satellite transits. The data are the average SeaWIFS-derived pigment concentration along 170°W (± 1°) for October through March (the mean of all pixels ± 1 week from the middle of the month).

Nitrate draw-down, integrated to a depth of 100 m and multiplied by a Redfield ratio of 6.6 (by atoms), yielded estimates of net carbon export over a 90-day growing season of 2.2 mol C m^{-2} in the PFZ and 3.2 mol C m^{-2} in the Antarctic Zone. Although the surface depletion of nitrate was larger in the Antarctic Zone, this was compensated, in part, when nitrate deficits were integrated through 100 m by greater mixed layer depths in the PFZ.

Maximum export fluxes along 170°W were collected by the sediment trap at 63°S (221 mg m^{-2} d^{-1} at 1031 m; Honjo et al., 2000). Fluxes were lower at 57°S (92 mg m^{-2} d^{-1} at 982 m), and intermediate fluxes were collected at the PF (Mooring 3, 60°S, 156 mg m^{-2} d^{-1} at 1003 m). To place these fluxes into a global context, the annual opal flux at 63°S is the largest ever measured (S. Honjo, personal communication), and greater than that measured in the highly productive Arabian Sea upwelling system (48 mg m^{-2} d^{-1} at 828 m; Honjo et al., 1999). Furthermore, the annual mass flux in the PFZ (57°S), despite being substantially less than the Antarctic Zone, is comparable to the largest annual flux (95 mg m^{-2} d^{-1}) measured during the US JGOGS study in the equatorial Pacific Ocean (Honjo et al., 1995). The maximum flux observed in all the sediment traps (220 mg m^{-2} d^{-1}) was only slightly less than the maximum observed in the Arabian Sea (252 mg m^{-2} d^{-1}; Honjo et al., 1999). Despite its reputation as a region of low annual productivity, the Southern Ocean clearly generates a substantial annual flux of biogenic material which is exported to the deep sea. Results from other national JGOFS programs working in the Southern Ocean show that the SW Pacific sector is not unique in this regard (Pondaven et al., 2000).

4. Discussion

The information we have provided is intended to be an introduction to the patterns and processes that were observed during AESOPS. Both the Ross Sea continental shelf and the Polar Front of the Pacific Sector show substantial seasonal variations in the broad hydrographic and nutrient distributions. Some, but not all, of the Ross Sea's changes are greater in magnitude than those of the Polar Front. The changes represent a large seasonal production signal, which is evidenced by nutrient and CO_2 utilization patterns, the vertical flux of organic particles, and the appearance of autotrophic and heterotrophic biomass within the water column (Sweeney et al., 2000; Collier et al., 2000; Smith et al., 2000). The seasonal production signal in the Polar Front is smaller, more spatially variable, and reflects the physically dynamic environment of the Antarctic Circumpolar Current.

Nutrient concentrations in the Ross Sea never reached levels that can be considered to limit phytoplankton growth (Smith and Harrison, 1991). However, north of the Polar Front, and across much of the Antarctic Zone, silicic acid concentrations reached extremely low levels. Because iron has been hypothesized to have a marked influence not only on phytoplankton (particularly diatom) growth but on their elemental ratios, it is likely that the region north of the polar front is silica limited, or co-limited by both silica and iron availability (Franck et al., 2000). Nutrient "disappearance ratios" in the vicinity of the polar Front ($\Delta Si/\Delta N$) were very high and suggest iron limitation (Takeda, 1998; Hutchins and Bruland, 1998), whereas in the Ross Sea they were close to 1, which implies little or no iron limitation. However, given that the assemblage composition of both locations included some non-diatomaceous forms, the "disappearance ratios" do not reflect just diatom growth but are confounded by nitrogen uptake of non-siliceous forms.

5. Other findings in AESOPS

AESOPS was a complex program, involving not only two ships and two major study areas, but also numerous principal investigators, post-doctoral associates, students and technicians. The results of the program are still being synthesized, and this volume represents a first effort to publish the program's results in the peer-reviewed literature. Many more publications are expected in the coming years as more results become available. The objectives of the entire project were to better constrain the fluxes of carbon in the Southern Ocean, identify the factors and processes that regulate the magnitude and variability of primary productivity (as well as the fate of biogenic material), and to gain a sufficient understanding of the Southern Ocean to model past and present carbon fluxes with sufficient accuracy to predict its response to future global changes. Some of the major findings addressing these objectives that are discussed in papers in the volume are as follows:

- The Ross-Sea continental shelf is among the most productive of all Antarctic systems, with growth being initiated in late October. Growth rates and biomass

accumulation are rapid in November, but growth rates decline markedly in mid-December, whereas biomass continues to increase until early January. Surface-layer particulate concentrations decrease to extremely low values in April (Smith et al., 2000; Gardner et al., 2000).
- A seasonal bloom occurs in the region of the Polar Front, although its magnitude is less than that observed in the Ross Sea (Moore et al., 1999). The spatial distribution of the enhanced pigment concentrations reflects the physical–biological coupling of the frontal regime, as well as the biological response to stratification following seasonal warming and release of freshwater by melting sea ice.
- The annual production of the Ross Sea can be quantified by measuring deficits of nutrients and dissolved carbon dioxide (Sweeney et al., 2000). This approach suggests that the net seasonal production in 1996/97 was $58\,\mathrm{g\,C\,m^{-2}}$. Furthermore, spatial differences in nutrient removal ratios can be distinguished between areas dominated by diatoms and those dominated by *Phaeocystics antarctica* by virtues of the silicic acid uptake characteristics. $\Delta N/\Delta P$ removal ratios are low in austral spring, but increase with time, and over a season are close to the classical Redfield ratio.
- The massive phytoplankton blooms in the Ross Sea have essentially no losses due to microzooplankton herbivory regardless of the season (Caron et al., 2000). Microzooplankton biomass, however, increases three orders of magnitude over the seasonal cycle.
- In low-Si waters north of the silica gradient, iron did not stimulate phytoplankton growth, indicating silica limitation. However, in waters south of the silica gradient, iron substantially stimulated diatom growth, which suggests that iron-limited phytoplankton growth in waters with sufficient Si (Franck et al., 2000). An interaction between Fe and Si complicates the use of Si as an indicator of new production in the Southern Ocean.
- Extreme mesoscale variability was noted in the vicinity of the Polar Front, which creates a strongly varying light and nutrient regime and variations in phytoplankton growth (Abbott et al., 2000). Bio-optical moorings clearly recorded the onset of phytoplankton growth, which preceded the pigment maximum by 15 days.
- Dissolved organic carbon concentrations increased seasonally by ca. $30\,\mu\mathrm{M}$, whereas particulate organic carbon levels increased by more than $100\,\mu\mathrm{M}$ (Carlson et al., 2000). DOC concentrations return to background levels by early winter.

These results, as well as others highlighted in this issue, will undoubtedly prove to be extremely useful in furthering our understanding of the structure and function of the Southern Ocean.

The Southern Ocean is recognized as a dominant region in the oceanic contribution to global carbon and silica flux, and it is also recognized that global change may have substantial impacts on its ability to contribute to atmospheric carbon removal (Sarmiento and LéQuére, 1996). Data collected in AESOPS and other Southern Ocean JGOFS programs will allow for a re-evaluation of global silica and carbon budgets, as well as a more detailed understanding of the controls of phytoplankton growth in this physically dynamic region. Given that the AESOPS program has provided an exceptionally complete data set on the chemical and biological processes responsible in controlling carbon production and flux, these data should also be immensely useful to modelers for years to come. We hope that by providing these data to all interested in the Southern Ocean and its impacts on the global biogeochemical cycles, that we can jointly provide insights and understanding of the importance of the Southern Ocean.

Acknowledgements

We thank the nutrient and hydrographic teams that participated in all of the AESOPS cruises, often under trying conditions, for the collection of the high-quality data set used herein, The Captains and crews of the R.V.I.B. *Nathaniel B. Palmer* and R.V. *Roger Revelle* also were tremendous help during course of many cruises. Finally, we thank members of the Division of Ocean Sciences and Office of Polar Programs for their support and understanding. Z. Chase and S. Polk generously assisted with graphics, and S.L. Smith provided numerous constructive comments. This work was supported by NSF grants OPP-9530382 and OPP-95303398. This is US JGOFS Contribution Number 571 and VIMS Contribution Number 2331.

References

Abbott, M.R., Richman, J.G., Lettelier, R.M., Bartlett, J.S., 2000. The spring bloom in the Antarctic Polar Frontal Zone as observed from a mesoscale array of bio-optical sensors. Deep Sea Research II 47, 3285–3314.

Arrigo, K.R., Robinson, D.H., Worthen, D.L., Dundar, R.B., DiTullio, G.R., van Woert, M., Lizotte, M.P., 1999. Phytoplankton community structure and the drawdown of nutrients and CO_2 in the Southern Ocean. Science 283, 265–267.

Barth, J.A., Cowles, T.J., Pierce, S.D. Mesoscale physical and bio-optical structure of the Antarctic Polar Front near 170°W during spring. Journal of Geophysical Research, submitted.

Belkin, I.M., Gordon, A.L., 1996. Southern Ocean fronts from the Greenwich meridian to Tasmania. Journal of Geophysical Research 101, 3675–3696.

Carlson, C.A., Hansell, D.A., Peltzer, E.T., Smith, Jr., W.O., 2000. Stocks and dynamics of dissolved and particulate organic mateter in the Southern Ross Sea, Antarctica. Deep-Sea Research II 47, 3201–3225.

Caron, D.A., Dennett, M.R., Lonsdale, D.J., Moran, D.M., Shalapyonok, L., 2000. Microzooplankton herbivory in the Ross Sea, Antarctica. Deep-Sea Research II 47, 3249–3272.

Collier, R., Dymond, J., Honjo, S., Manganini, S., Francois, R., 2000. The vertical flux of biogenic and lithogenic material in the Ross Sea: moored sediment trap observations during the US-JGOFS AESOPS study. Deep-Sea Research II 47, 3491–3520.

Comiso, J.C., McClain, C.R., Sillivan, C.W., Ryan, J.P., Leonard, C.L., 1993. Coastal Zone Color Scanner pigment concentrations in the Southern Ocean and relationships to geophysical surface features. Journal of Geophysical Research 98, 2419–2451.

Daly, K.D., Smith Jr., W.O., Johnson, G.C., Mordy, C.W., Feely, R.H., Hansell, D.A. Hydrographic properties and chemical distributions in the Pacific sector of the Southern Ocean. Journal of Geophysical Research, in press.

de Baar, H.J.W., de Jong, J.T.M., Bakker, D.C.E., Löscher, B.M., Veth, C., Bathmann, U.V., Smetacek, V., 1995. Importance of iron for phytoplankton blooms and CO_2 drawdown in the Southern Ocean. Nature 373, 412–415.

DeMaster, D.J., Dunbar, R.B., Gordon, L.I., Leventer, A.R., Morrison, J.M., Nelson, D.M., Nittrouer, C.A., Smith Jr., W.O., 1992. The cycling and accumulation of organic matter and biogenic silica in high-latitude environments: the Ross Sea. Oceanography 5, 146–153.

Ducklow, H.W., Harris, R.P., 1993. Introduction to the JGOFS North Atlantic Bloom Experiment. Deep-Sea Research II 40, 1–8.

Franck, V.M., Brzezinski, M.A., Coale, K.H., Nelson, D.M., 2000. Iron and silicic acid concentrations regulate Si uptake north and south of the Polar Frontal Zone in the Pacific Sector of the Southern Ocean, Deep-Sea Research II 47, 3315–3338.

Gaillard, J.-F., 1997. ANTARES-l: a biogeochemical study of the Indian Sector of the Southern Ocean. Deep-Sea Research II 44, 951–961.

Gardner, W.D., Richardson, M.J., Smith Jr., W.O., 2000. Seasonal patterns of water column particulate organic carbon and fluxes in the Ross Sea, Antarctica. Deep-Sea Research II 47, 3423–3449.

Gordon, L.I., Codispoti, L.A., Jennings Jr., J.C., Millero, F.J., Morrison, J.M., Sweeney, C., 2000. Seasonal evolution of hydrographic properties in the Ross Sea, Antarctica, 1996–1997. Deep-Sea Research II 47, 3095–3117.

Honjo, S., Dymond, J., Collier, R., Manganini, S., 1995. Export production of particles to the interior of the equatorial Pacific Ocean during the 1992 EqPac experiment. Deep-Sea Research II 42, 831–870.

Honjo, S., Dymond, J., Prell, W., Ittekkot, V., 1999. Monsoon-controlled export fluxes to the interior of the Arabian Sea. Deep-Sea Research II 46, 1859–1902.

Honjo, S., Manganini, S., Francois, R., Dymond, J., Collier, R., 2000. Export fluxes in the APFZ and the open Southern Ocean: a sediment trap array investigation along 170°W. Deep-Sea Research II, this issue.

Hunter, C.N., Gordon, R.M., Fitzwater, S.E., Coale, K.H., 1997. A rosette system for the collection of trace metal clean seawater. Limnology and Oceanography 41, 1367–1372.

Hutchins, D.A., Bruland, K.W., 1998. Iron-limited diatom growth and Si:N uptake ratios in a coastal upwelling regime. Nature 393, 561–564.

JGOFS, 1996. Protocols for the Joint Global Ocean Flux Study (JGOFS) core measurements. JGOFS Report Number 19. Intergovernmental Oceanographic Commission, Bergen, Norway, 170 pp.

Landry, M.R., Brown, S.L., Selph, K.E., Abbott, M.R., Letelier, R.M., Christensen, S., Bidigare, R.R., Casciotti, K. Initiation of the spring phytoplankton increase in the Antarctic Polar Front Zone at 170°W. Journal of Geophysical Research, submitted.

Martin, J.H., Fitzwater, S.E., Gordon, R.M., 1990. Iron deficiency limits phytoplankton growth in Antarctic waters. Global Biogeochemical Cycles 4, 5–12.

Mitchell, B.G., Brody, E.A., Holm-Hansen, O., McClain, C., Bishop, J., 1991. Light limitation of phytoplankton biomass and macronutrient utilization in the Southern Ocean. Limnology and Oceanography 36, 1662–1677.

Moore, J.K., Abbott, M.R., Richman, J.G., Smith, W.O., Cowles, T.J., Coale, K.H., Gardner, W.D., Barber, R.T., 1999. SeaWiFS satellite ocean color data at the U.S. Southern Ocean JGOFS line along 170°W. Geophysical Research Letters 26, 1465–1468.

Murray, J.W., Johnson, E., Garside, C., 1995. A.U.S. JGOFS Process Study in the equatorial Pacific (EqPac): introduction. Deep-Sea Research II 42, 275–294.

Nowlin Jr., W.D., Klink, J.M., 1986. The physics of the Antarctic Circumpolar Current. Reviews of Geophysics 24, 469–491.

Orsi, A.H., Whitworth, T., Nowlin, W.D., 1995. On the meridional extent and fronts of the Antarctic Circumpolar Current. Deep-Sea Research I 42, 641–673.

Patterson, S.L., Whitworth, T., 1990. Physical Oceanography. In: Glasby, G.P. (Ed.), Antarctic Sector of the Pacific. Elsevier Oceanography Series, Vol. 51. Elsevier, Amsterdam, pp. 55–93.

Peterson, R.G., Strama, L., 1991. Upper-level circulation in the South Atlantic Ocean. Progress in Oceanography 26, 1–73.

Pondaven, P., Ragueneau, O., Tréguer, P., Hauvespre, A., Dezileau, L., Reyss, J.-L., 2000. Resolving the "opal paradox" in the Southern Ocean. Nature 405, 168–172.

Sarmiento, J.L., LéQuére, C., 1996. Oceanic carbon dioxide uptake in a model of century-scale global warming. Science 274, 1346–1350.

Smetacek, V., de Baar, H.J.W., Bathmann, U.V., Lochte, K., Rutgers van der Loeff, M.M., 1997. Ecology and biogeochemistry of the Antarctic Circumpolar Current during austral spring: a summary of Southern Ocean JGOFS cruise *ANT X/6 of R.V. Polarstern*. Deep-Sea Research II 44, 1–22.

Smith, S.L., Codispoti, L.A., Morrison, J.M., Barber, R.T., 1998. The 1994–1996 Arabian Sea Expedition: an integrated, interdisciplinary investigation of the response of the northwestern Indian Ocean to monsoonal forcing. Deep-Sea Research II 45, 1905–1916.

Smith Jr., W.O., Barber, R.T., Marra, J., Hiscock, M.R., 2000. The seasonal cycle of phytoplankton biomass and primary productivity in the Ross Sea, Antarctica. Deep-Sea Research II 47, 3119–3140.

Smith Jr., W.O., Harrison, W.G., 1991. New production in polar regions: the role of environmental controls. Deep-Sea Research 38, 1463–1479.

Smith Jr., W.O., Nelson, D.M., 1985. Phytoplankton bloom produced by a receding ice edge in the Ross Sea: spatial coherence with the density field. Science 227, 163–167.

Sweeney, C., Hansell, D.A., Carlson, C.A., Codispoti, L.A., Gordon, L.I., Marra, J., Millero, F.D., Smith, W.O., Takahashi, L.I., 2000. Biogeochemical regimes, net community production and carbon export in the Ross Sea, Antarctica. Deep-sea Research II 47, 3369–3394.

Takeda, S., 1998. Influence of iron availability on nutrient consumption ratio of diatoms in oceanic waters. Nature 393, 774–777.

Tréguer, P., Jacques, G., 1992. Dynamics of nutrients and phytoplankton, and fluxes of carbon, nitrogen and silicon in the Antarctic Ocean. Polar Biology 12, 149–162.

Turner, D., Owens, N., Priddle, J., 1995. Southern Ocean JGOFS: the U.K. "STERNA" study in the Bellingshausen Sea. Deep-Sea Research II 42, 905–906.