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Hydrographic Patterns in McMurdo Sound, Antarctica and Their Relationship to Local Benthic Communities

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Summary. Measurements of hydrographic parameters (temperature, salinity, nitrate, nitrite, phosphate, chlorophyll *a*, phaeophytin, and oxygen) in McMurdo Sound, Antarctica during spring, 1984, before the regional phytoplankton bloom, and summer, 1984, after the peak of the bloom, indicate the several processes contribute to changes in the vertical and horizontal structure of the water column. Regional variation in the source of water masses within the Sound, ice cover patterns, and meltwater from the Ross Ice Shelf and nearby continental glaciers result in east-west and north-south gradients in the thermohaline, nutrient, and productivity characteristics of the Sound. These patterns are also related to the extremely variable structure and productivity of shallow water benthic macrofaunal communities in McMurdo Sound. Hydrographic patterns during Spring (November) were indicative of conditions at the end of winter prior to the spring phytoplankton bloom. The water column was nearly isothermal with temperatures near or below the surface freezing point of seawater with only a slight salinity increase with depth. Salinity was lower in the west Sound than in the east, probably in response to glacial meltwater input from the Ross Ice Shelf and/or terrestrial sources. Nutrient levels were high and nearly homogeneous throughout the Sound. Chlorophyll *a* was low ($<1.0\ \mu g/l$) throughout most of the Sound, but was lowest in the western sound, as expected from the circulation pattern (Barry and Dayton 1988). Oxygen was uniformly low during spring. The summer hydrographic distributions, estimated from samples collected during the decline of the regional plankton bloom, were dramatically different than in during spring. Both the salinity and temperature were vertically stratified at all sites, particularly in the west Sound. Temperatures near the surface were well above the freezing point and occasionally near or above 0 °C. Near surface salinity in the western Sound was nearly fresh (0.4 ppt) at some locations in the southwestern Sound. Chlorophyll *a* was high throughout the Sound relative to spring concentrations, and nutrient levels (NO_3, PO_4) were strongly depressed near the surface, due mainly to phytoplankton uptake rather than by dilution. Primary productivity estimates based on the summer nitrate and phosphate deficits over 90 days were 1.96–2.02 and $0.39-1.02\ gCm^{-2}d^{-1}$ for the east and west sound, respectively. Nutrient ratios indicated that glacial meltwater from the Ross Ice Shelf and/or nearby terrestrial sources may be an important component of the summer meltwater input to the western Sound. Enhanced water column stability due to this input may prolong the maintenance of high water column stability as this water mass flows northward and result in particularly high productivity in northern McMurdo Sound.

Introduction

Oceanographic processes in McMurdo Sound, Antarctica are the fundamental factors controlling regional biological productivity. Extreme environmental variability results in large seasonal fluctuations in primary productivity. The Sound is covered by sea-ice during most of the year and in winter and early spring, biological productivity is very low (Bunt 1964a). During December, the spring phytoplankton bloom is swept in from the north (Palmisano et al. 1986), intensifies, and finally declines through the austral summer (Bunt 1964a). The dominant bloom components vary; the prymenesiophyte *Phaeocystis* usually dominates, particularly during the onset of the bloom (Palmisano et al. 1986), but marginal ice zone blooms in the southwestern Ross Sea are also dominated by *Nitzschia curta* and other congenerics (Smith and Nelson 1985; Wilson et al. 1986). Oceanographic dynamics associated with the bloom are not completely understood. During the winter months, light limitation is obviously significant, but recent evidence north of McMurdo Sound indicates that during the spring and summer, water column stability is of primary importance.

Warming and dilution of surface waters along marginal ice zones increase water column stability (Smith and Nelson 1985; Wilson et al. 1986) and restrict the downward mixing of phytoplankton stocks below the critical depth (Sverdrup 1953). Consequently, primary productivity increases, and results in high production for several trophic levels (Smith and Nelson 1986; Fraser and Ainley 1986). Antarctic nutrient levels are usually high and may not be of critical importance to primary production (El-Sayed and Mandelli 1965; Holm-Hansen 1985).

Spatial gradients or patterns in the productivity of benthic and planktonic communities in McMurdo Sound are thought to be caused by the extreme regional differences in source waters and by more persistent ice cover in the western Sound (Dayton and Oliver 1977; DeLaca et al. 1980; Hodson et al. 1981; Dayton et al. 1986; Barry and Dayton 1988). Plankton-rich eastern Sound water is advected from the north and contributes to east sound benthic production (Dayton and Oliver 1977; Barry and Dayton 1988). In the west, plankton-poor sub-shelf waters, or a mixture of northern and southern shelf water bathe the benthos. Although the circulation patterns are at least partially responsible for the observed productivity patterns, ice and snow cover, higher in the western Sound, are also potentially important in regulating in situ primary production.

During the austral summer (January–February) of 1984, and the following spring (November–December), 1984, several hydrographic and current measurement stations were occupied to obtain a synoptic impression of the spatial distribution of various oceanographic parameters. The analysis of current patterns is presented in Barry and Dayton (1988).

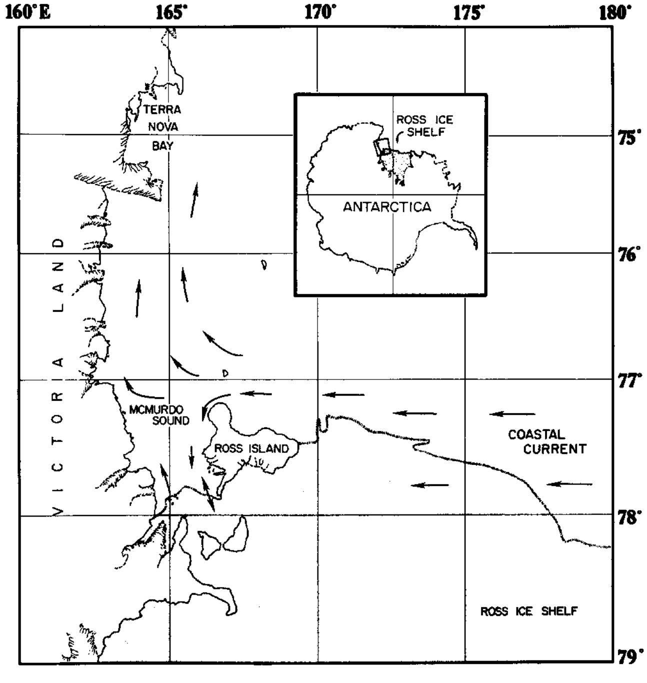


Fig. 1. Map of the southwestern Ross Sea showing McMurdo Sound. The coastal current flowing westward along the Ross Ice Shelf ede is indicated by *arrows*

This paper evaluates the spatial and temporal patterns in the hydrographic features of McMurdo Sound for several purposes. With regard to Dayton and Oliver's (1977) hypothesis explaining the divergent benthic productivity patterns within the Sound, one might ask whether there are any relevant hydrographic patterns (east-west, north-south gradients) which support or refute the hypothesis? Are their gradients in nutrient or chlorophyll *a* concentrations indicative of patterns in primary productivity across the Sound? Do the hydrographic features of the western Sound indicate a sub-Ross Ice Shelf source, and/or simply a return flow from the eastern Sound? In addition, how do the spring to summer changes in the density structure of the water column affect primary production (sensu Smith and Nelson 1985)?

Methods

Study Site

McMurdo Sound, Antarctica is located between Victoria Land on the antarctic continental coast, and the Ross Island coast (Fig. 1). The southwestern Ross Sea opens to the northeast and the Sound is bordered by the Ross Ice Shelf to the south. A deep (~600–700 m) basin is present in the eastern Sound, and slopes to ~200 m depth in the western Sound (Pyne et al. 1985). This basin continues through the pass between Ross Island and White Island. In the southwest, several islands and other complex topographical features are present. The Sound surfaces freezes annually and breaks out in the austral spring and summer, usually to the edge of the Ross Ice Shelf except along the Victoria Land coast where sea ice persists until late in the summer and often remains for two or more years.

Data Collection

Hydrographic surveys were conducted at 5 stations during late January and early February, 1984 (summer) and at 14 stations during November, 1984, (Spring; Fig. 2). Salinity, temperature, oxygen, nitrate, nitrite, phosphate, chlorophyll *a*, and phaeopigments were analyzed at most stations. Ammonia analyses were attempted but discontinued after unacceptable contamination levels of reagent blanks were discovered.

Water samples were collected through access holes created with a gasoline powered drill or through cracks in the sea ice. Niskin bottles with reversing thermometers were deployed and allowed to equilibrate for approximately 10 min. Upon collection oxygen samples were drawn into 300 ml BOD bottles and fixed. Salinity samples were then drawn in to 8 oz. medicinal bottles and sealed with waxed corks. Last, a nutrient sample was collected into a 1 l polyethylene jar and stored in dry ice where it usually froze within 1 h. Chlorophyll *a* samples were collected by a second hydrocast at the same station and were processed immediately by filtering through Millipore AA filters under dim light. Filters were frozen in dry ice and stored in light-proof freezer containers.

Samples were returned to the laboratory within 24 h and stored at −20 °C (nutrients, extracted chlorophyll *a* samples), or room temperature (oxygen, salinity samples) until they were analyzed. Salinity sample jar mouths were dipped in wax to prevent contamination and evaporation and analyzed by a high precision salinometer at the Scripps Institution of Oceanography analytical facility. Oxygen samples were analyzed within 24 h by a modified Winkler titration (Strickland and Parsons 1972). Nutrient samples were analyzed in batches whereby a group of samples were thawed and processed in as little time as possible. Due to the variable decay or utilization times of various nutrient samples (Strickland and Parsons 1972), nutrients were analyzed in the following order: reactive phosphate, nitrite, then nitrate. All nutrients where

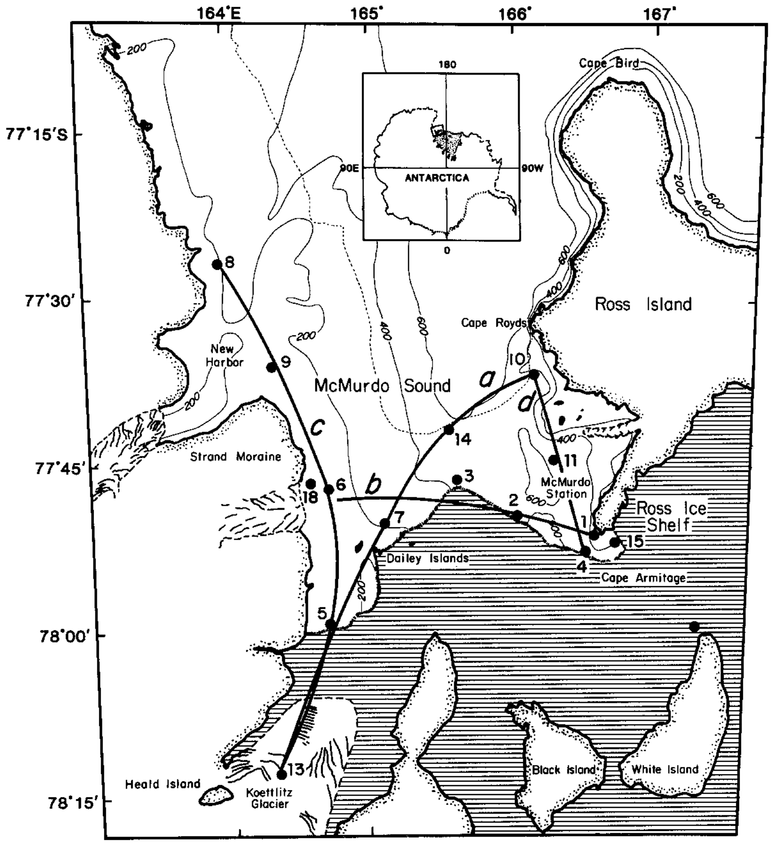


Fig. 2. McMurdo Sound Vicinity. *Dots* indicate hydrocast stations. *Thick solid lines* indicate transects used for hydrographic sections discussed in the text (*a* = long, *b* = cross, *c* = east, *d* = west Sound). *Thin lines* indicate bathymetry. *Dashed line* indicates the approximate location of the sea ice edge during November

analyzed by the methods described in Strickland and Parsons (1972) with a few minor modifications. All spectrophotometric measurements were made on a Perkin Elmer spectrophotometer. Extinction of phosphate samples were measured at 6900 nm rather than 8850 nm. Because of the modified technique and frozen rather than filtered or acidified samples, the phosphate data were compared to other data from the same region (Jacobs and Haines 1982; Nelson and Smith 1986) which indicated very similar results. Chlorophyll *a* concentrations were measured by the fluorometric technique of Strickland and Parsons (1972), with a Turner fluorometer calibrated with known standard chlorophyll *a* solutions. Sigma-t and the sea water freezing temperature were calculated according to Fofonoff and Millard (1983).

Results

Spring Conditions

Thermohaline Characteristics. During spring, water temperature was nearly homogeneous except for some significant variation near the surface and very cold water near the bottom in the central Sound and in the mid-water at Station 3 (Fig. 3a, b). One anomalous high surface temperture (+1.7 °C) was observed at Station 13 where a rift in the sea ice near the Koettlitz Glacier had melted open by late November and an early season surface plankton bloom had commenced.

Temperatures below the surface freezing point were observed at several sites, particularly where currents flow northward from under the Ross Ice Shelf, and are indicative of cooling by contact with the bottom of the Shelf. A few measurements near 50 m in the central western Sound, and near the surface adjacent to McMurdo Station were supercooled (temperature below the in sito freezing point; Fig. 4). Most east Sound stations were somewhat warmer and previous contact with the ice shelf was no evident. Nucleation leading to frazil or platelet ice formation can occur when deep water cooled below the surface freezing temperatures is upwelled and drops below the in situ freezing point. This process is apparently responsible for the extremely low temperatures and platelet ice distribution in McMurdo Sound. Frazil and platelet ice is closely associated with the Ross Ice Shelf edge and occurs most often in areas with northward flowing currents (Barry and Dayton 1988). Platelet ice indices compiled from observations of the amount of platelet ice present in hydrocast holes, current meter mooring lines, and diver observations indicate that sites nearest the shelf in the middle to western Sound contained the greatest platelet ice deposition (Fig. 5). At Station 3 in the mid-Sound near the Ross Ice Shelf edge, platelet ice on a mooring line exceeded 45 m depth, indicating a local source of very cold, upwelled water.

The highest salinities were in the northern and eastern Sound (34.86–34.89 ppt). Western Sound waters were slightly less saline (34.73–34.77) and were diluted by meltwater input from beneath the shelf and/or glacial meltwater from the Koettlitz Glacier region. Spring salinity sections show the stratification in the main Sound basin as well as a slight east-west salinity gradient (Fig. 6). The north-south transect from the western

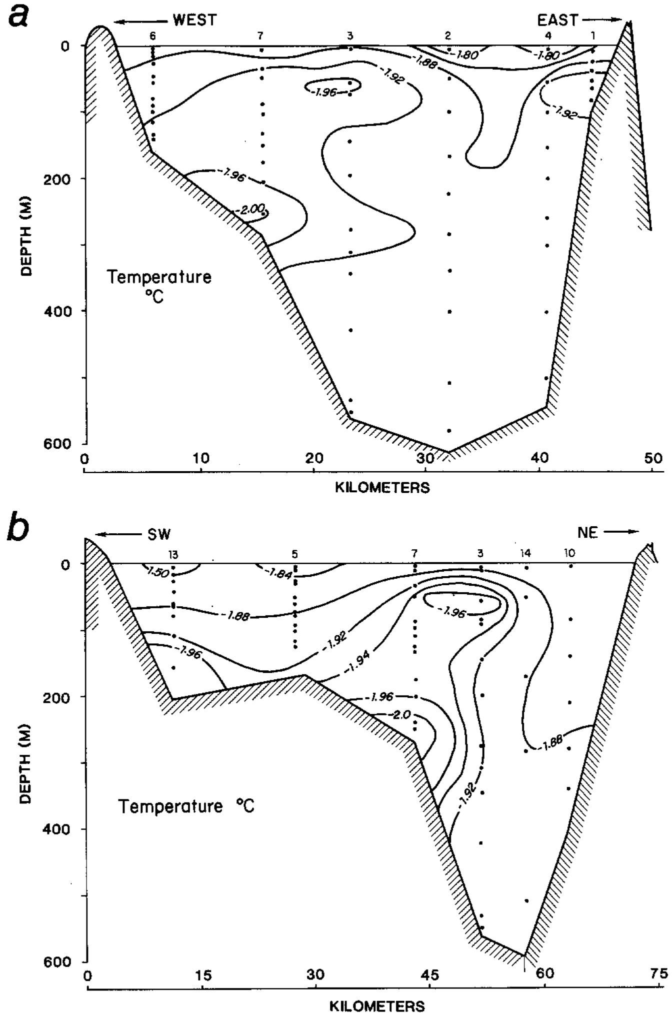


Fig. 3a, b. Temperature sections during November, 1984. **a** Cross Sound section (b) showing cold water predominantly over the west Sound slope. **b** Long Sound section (a)

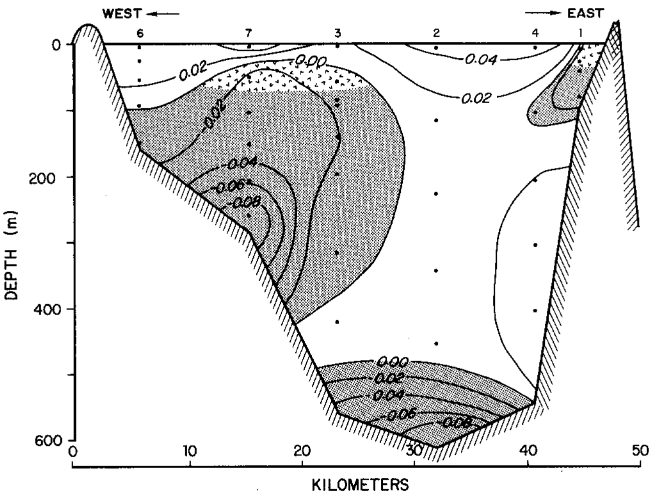


Fig. 4. Cross Sound section (b) of the difference between the surface freezing temperature and the in situ temperature. Contours are in °C above the surface freezing point. *Dark shaded areas* are below the surface freezing temperature. *Light shaded areas* are supercooled below the in situ freezing temperature

Sound (Fig. 6c) shows salinities from 34.73–34.75; similar depths from the east Sound were higher (34.76–34.80) (Fig. 6d; see Fig. 15b). In the eastern Sound a weak salinity front was present near the edge of the annual ice (Fig. 6d).

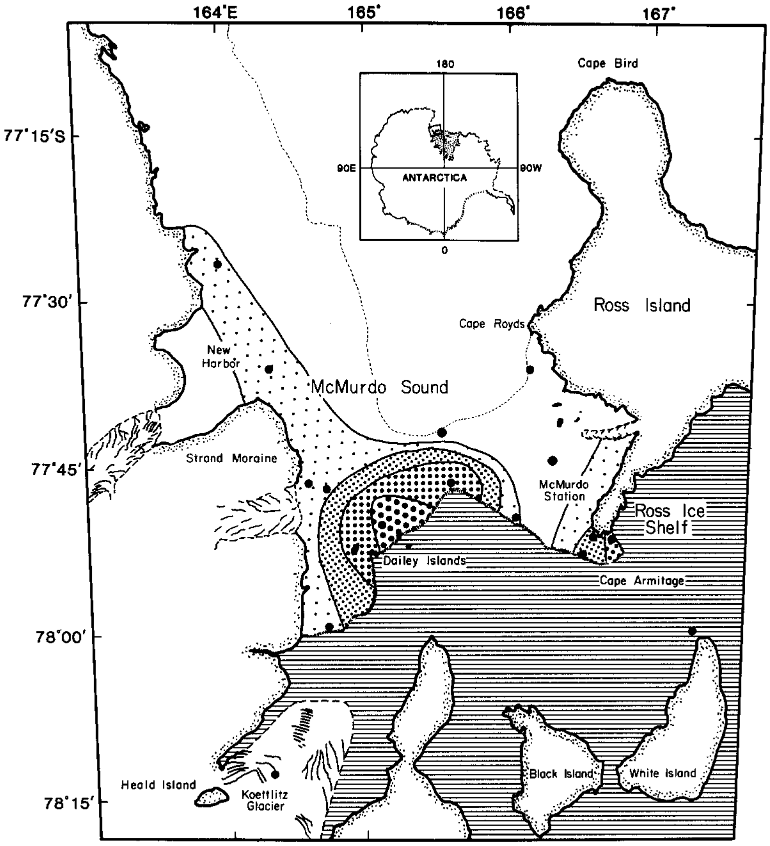
The density distribution in McMurdo Sound is controlled primarily by salinity patterns. Given the spring variation in salinity (0.2 ppt) and temperature (0.2 °C), the associated density changes are 0.15 kg/m^3 and 0.006 kg/m^3, respectively. Thus, densities in the south and west were lower than in the northeast. Density sections clearly show the lighter west Sound waters and denser eastern and northern waters (Fig. 7). Outflow areas from the sub-shelf cavity are characterized by relatively low salinity (34.75).

Because of the weak water column stratification during spring, water column stability was low and occasionally negative. Stability values (E) seldom ranged above 50×10^{-8} and Brunt-Vaisalla periods usually ranged from slightly less than 1 h near the surface to 1.5–3.0 h near the bottom. Such low stability results in a deeper mixed layer and can inhibit phytoplankton production by excessive downward mixing of phytoplankton stocks. In contrast, surface stability was much higher at Station 13 where meltwater had diluted the surface waters.

Nutrients. The spring, 1984 nutrient (NO_3, NO_2, PO_4) distributions in McMurdo Sound reflected the post-winter pattern before the onset of the seasonal phytoplankton bloom. During this period the relatively homogeneous and high nutrient levels throughout the Sound indicated low productivity and winter replenishment by regeneration and mixing. Nitrate concentrations were high (30 μM) with occasional slight surface or near-shore depressions (Fig. 8). Phosphate was also nearly homogeneous with high values near 2.3 μM (Fig. 9). Nitrite was usually low with the lowest values (<0.01 μM) in outflow areas from under the Ross Ice Shelf (Fig. 10). Nitrate: phosphate ratios were high during the spring (~14).

Biological Properties. Spring prebloom chlorophyll *a* levels were low throughout the Sound (0.01 to 0.06 mg/m^3), except for a few isolated high values. Nevertheless, the chlorophyll *a* distribution reflected the regional circulation pattern, with the highest concentrations in the north and east near the surface and lower values in deeper water, particularly in the middle to western Sound near outflow from under the Ross Ice Shelf (Fig. 11). Phaeopigment profiles were similar in shape to chlorophyll *a* profiles, with chlorophyll *a*: phaeopigment ratios generally highest (~1.0 to 2.5) in surface waters.

Oxygen levels were low throughout the Sound before the phytoplankton bloom; northeastern waters had slightly higher oxygen and chlorophyll *a* levels and slight-



◄ **Fig. 5.** Platelet ice abundance index distribution during November, 1984 (see text). Heavier dot pattern indicates greater platelet ice thickness, indicative of cold water outflow from under the Ross Ice Shelf

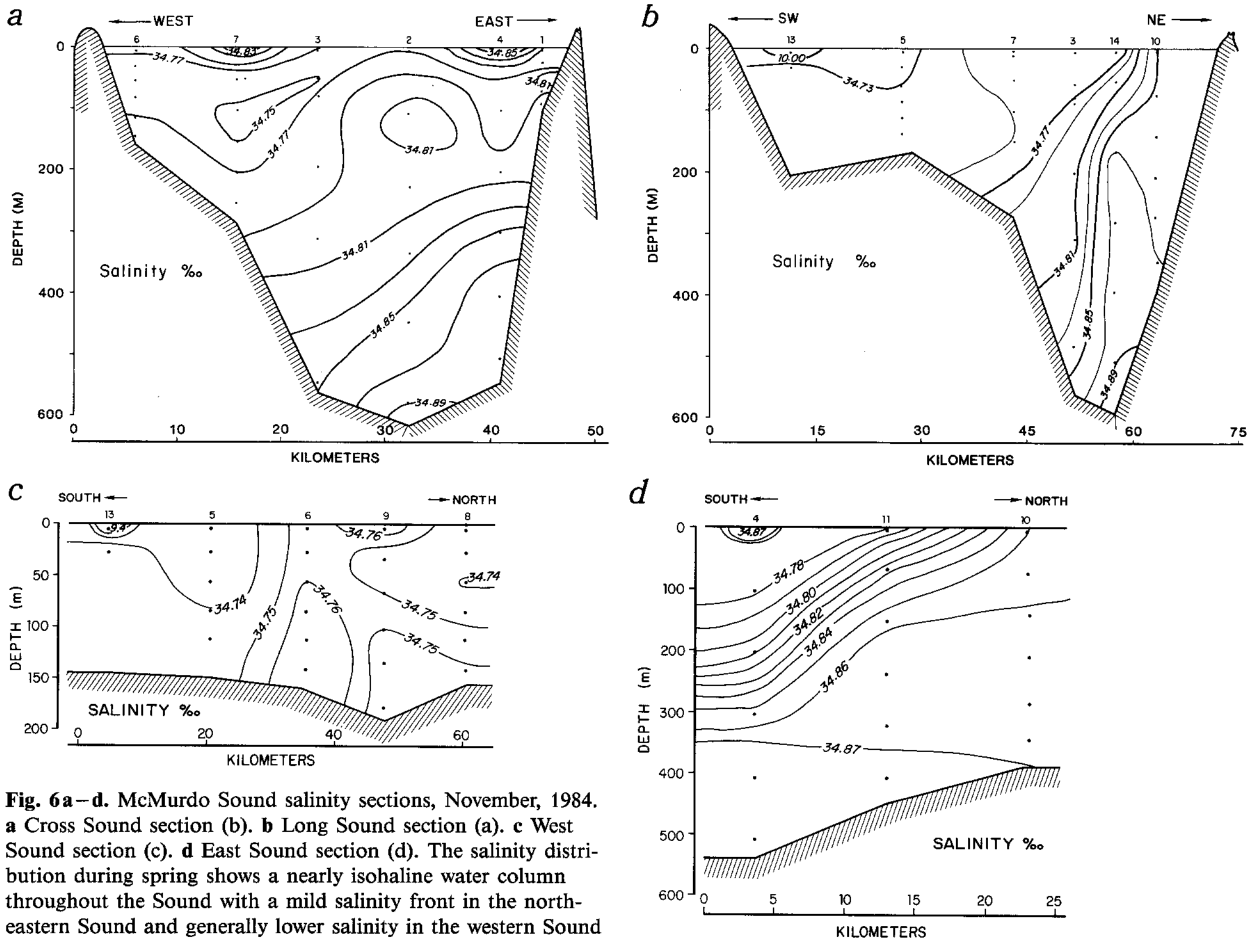


Fig. 6a–d. McMurdo Sound salinity sections, November, 1984. **a** Cross Sound section (b). **b** Long Sound section (a). **c** West Sound section (c). **d** East Sound section (d). The salinity distribution during spring shows a nearly isohaline water column throughout the Sound with a mild salinity front in the northeastern Sound and generally lower salinity in the western Sound

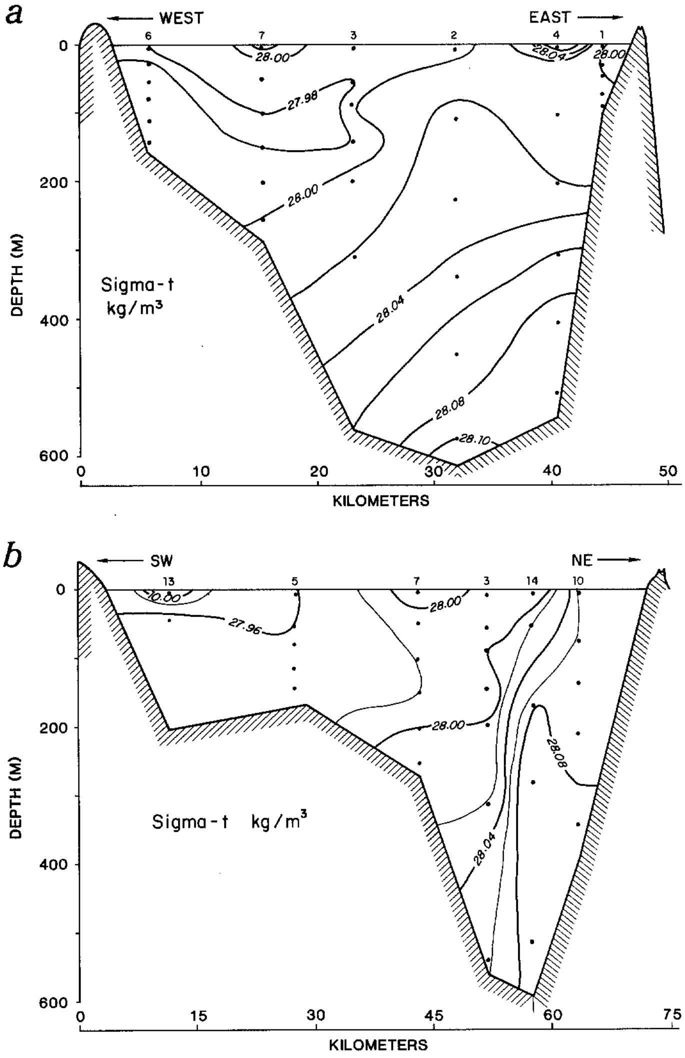


Fig. 7a, b. Density (sigma-t) distribution during November, 1984. **a** Cross Sound section (b). **b** Long Sound section (a). Note the similarity with the salinity distribution

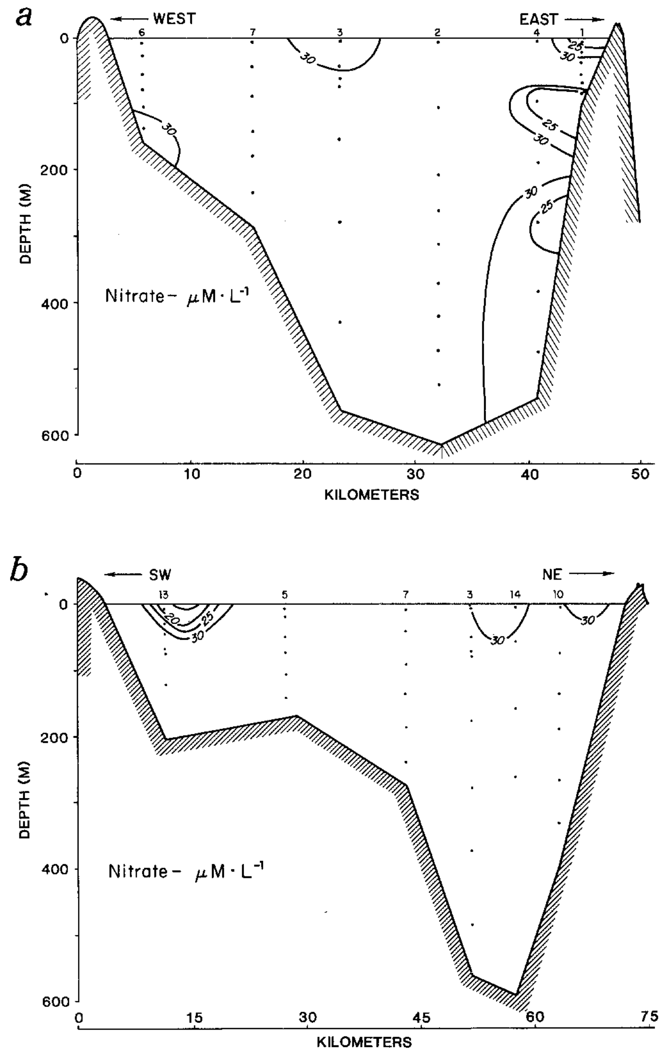


Fig. 8a, b. Nitrate distribution during November, 1984. **a** Cross Sound section (b). **b** Long Sound section (a). Note the nearly homogeneous nitrate levels

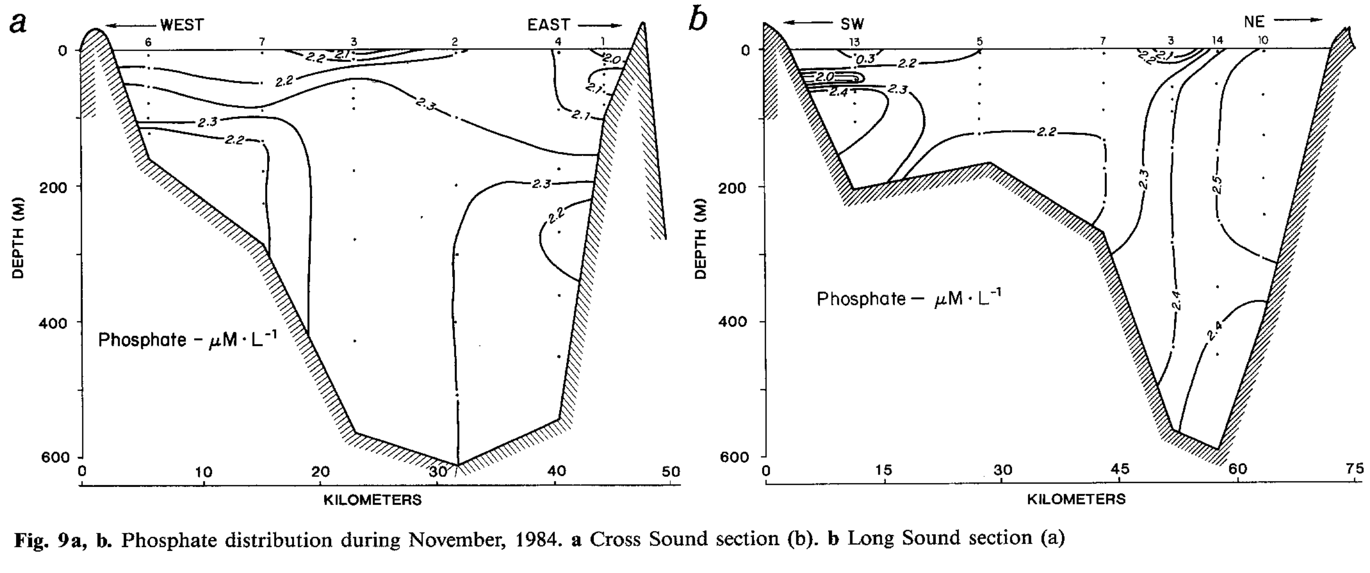


Fig. 9a, b. Phosphate distribution during November, 1984. **a** Cross Sound section (b). **b** Long Sound section (a)

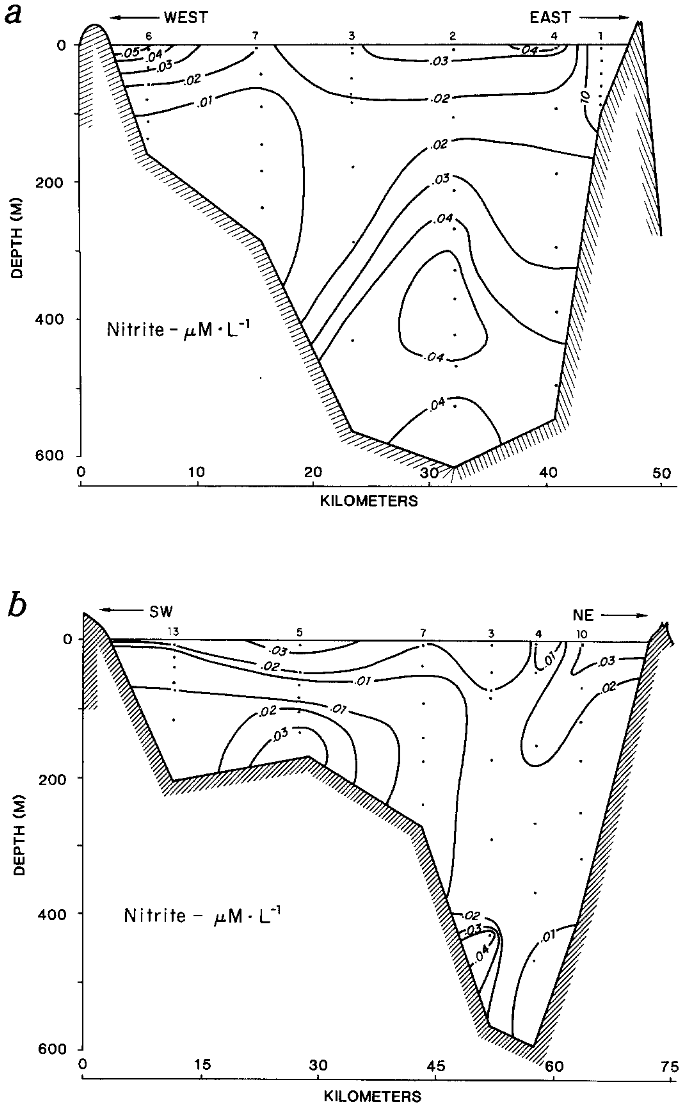


Fig. 10a, b. Nitrite distribution during November, 1984. **a** Cross Sound section (b). **b** Long Sound section (a)

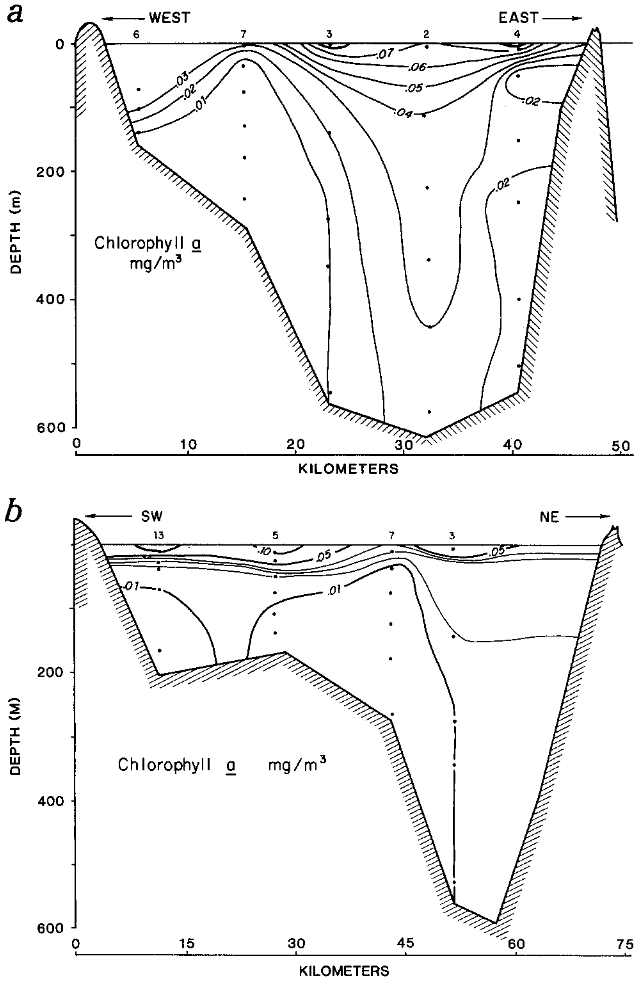


Fig. 11a, b. Chlorophyll *a* distribution during November, 1984. Note the low west Sound and relatively higher east Sound levels. **a** Cross Sound section (b). The values for the surface isopleths are not listed and were dramatically higher than in deeper water. At Station 3 the surface isopleth value is 0.41 mg/m^3, and at Station 4 the value is 0.42 mg/m^3. **b** Long Sound section (a). The surface isopleth value at Station 13 is 10.0 mg/m^3, much higher than in other areas

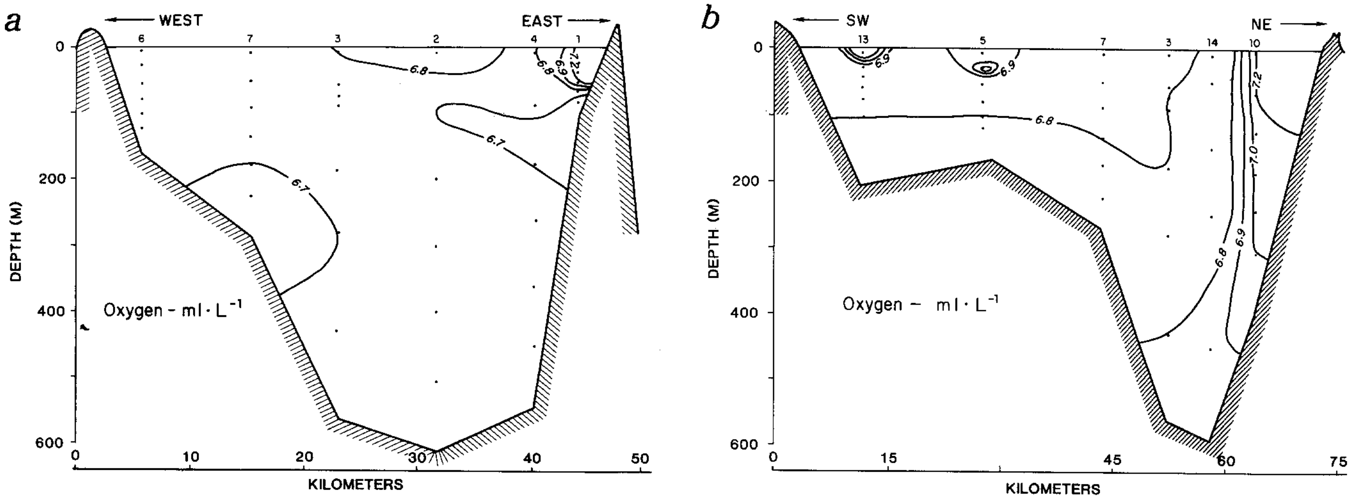


Fig. 12a, b. Dissolved oxygen distribution during November, 1984. **a** Cross Sound section (b). **b** Long Sound section (a). The surface values at Station 13 were high (14.6 ml/L). Pre-bloom oxygen levels were low with slightly higher levels visible in the north ly lower nutrient concentrations than stations in the western Sound (Fig. 12).

Summer Pattern

The summer sampling program was more restricted than during spring but it indicated that during the late spring and summer, oceanographic features in McMurdo Sound are modified by the decay of annual sea ice and by the regional phytoplankton bloom. Higher light levels and air temperatures result in higher surface water temperature and increased water column stability, thereby facilitating the increase in phytoplankton production (Smith and Nelson 1986).

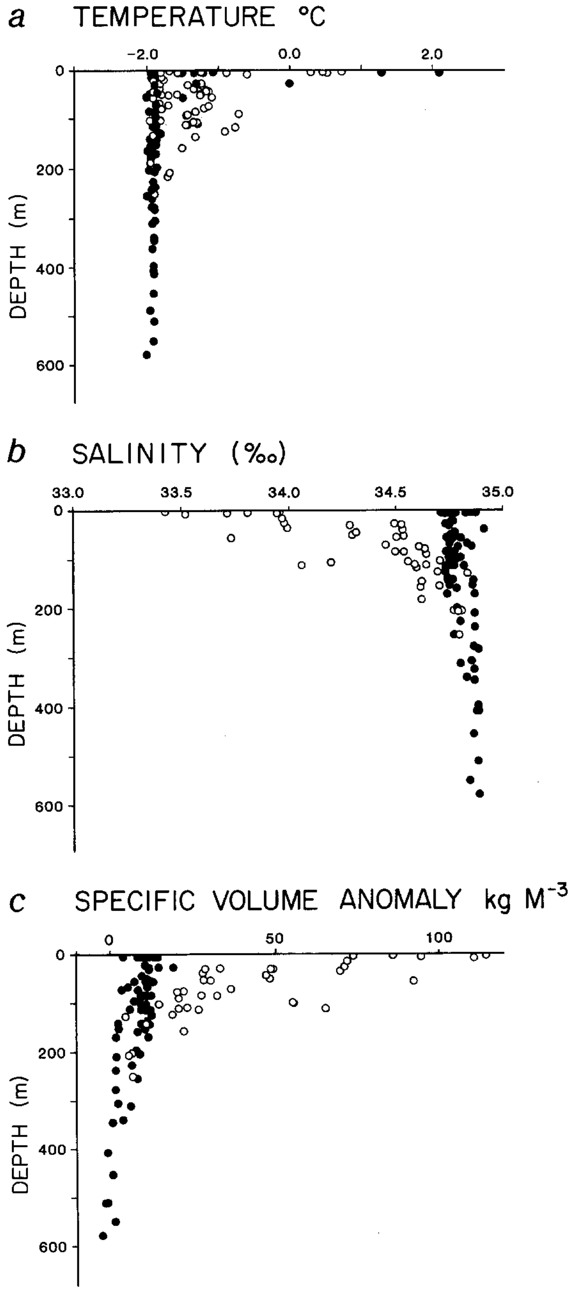


Fig. 13a–c. Spring/summer comparison of thermohaline properties of McMurdo Sound. **a** Temperature (°C). **b** Salinity (ppt). **c** Specific volume anomaly (kg/m^3). *Closed circles* indicate spring values. *Open circles* indicate summer values

Thermohaline Characteristics. Although summer temperatures near the bottom were near spring values (~ −1.9 °C), the upper 100 m became highly stratified with relatively warm near surface temperatures (−0.8 to −1.3 °C) and a few values above zero °C at isolated locations (Station 13, 17: Fig. 13a).

Salinity was strongly heterogeneous during summer with a substantial halocline near the surface (Fig. 13b). In addition to dilution from sea ice meltwater, terrestrial and Ross Ice Shelf meltwater must also have diluted surface waters, particularly in the western Sound (Fig. 14). During late January, 1984 a 6 m thick surface layer of fresh water (0.2–0.9 ppt) was present at Station 13, an isolated site in the western Sound under permanent ice. Divers have observed similar fresh water lenses at New Harbor, near the Daily Islands (P.K. Dayton, personal communication), and near tide cracks at White Island within 3 m of the surface (personal observation), which

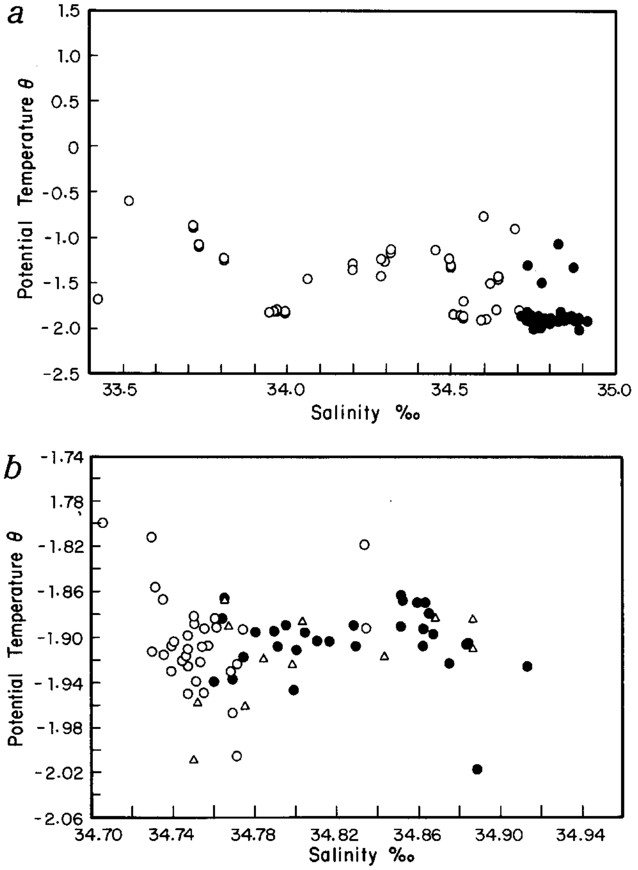


Fig. 14a, b. Potential temperature versus salinity plots for spring and summer data. **a** Wide range of salinity and temperature. Symbols as per Fig. 13. **b** Narrow range used to illustrate the distribution of temperature and salinity during spring. *Open circles* indicate west Sound samples. *Closed circles* indicate east Sound samples. *Triangles* indicate mid-Sound stations. Note the slightly more dilute water of the western Sound

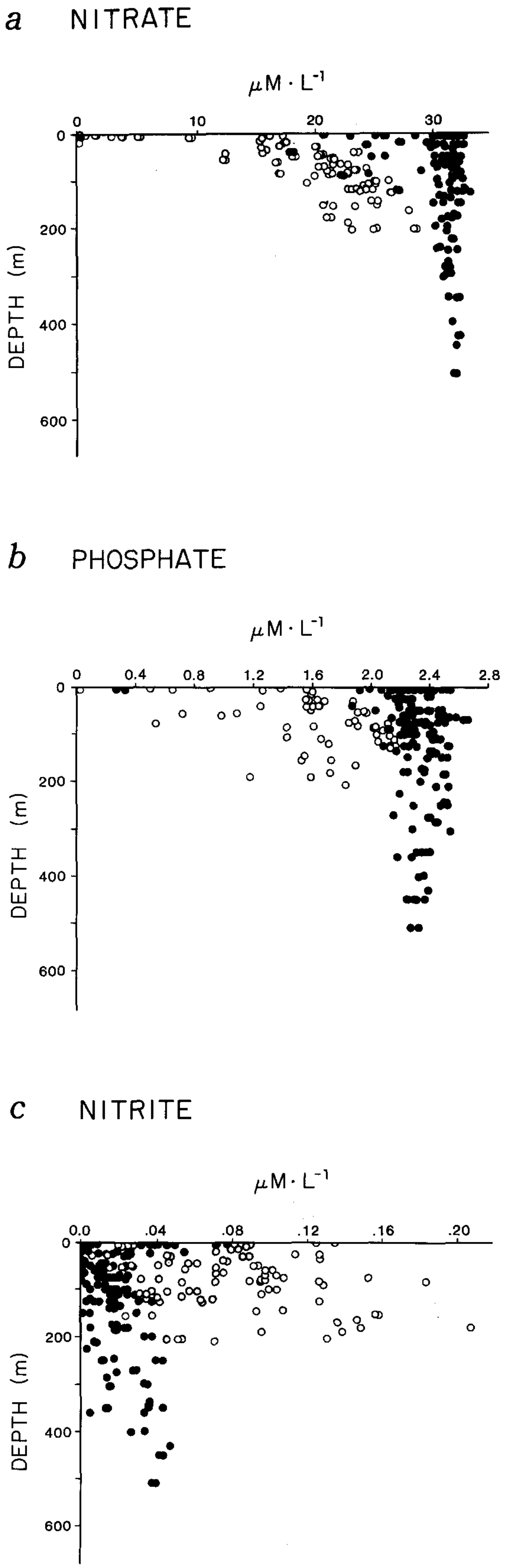


Fig. 15a–c. Spring/summer composite nutrient profiles. **a** Nitrate. **b** Phosphate. **c** Nitrite. Symbols as per Fig. 13. Note the summer depression of nitrates and phosphate in surface waters and the coincident increase in nitrite

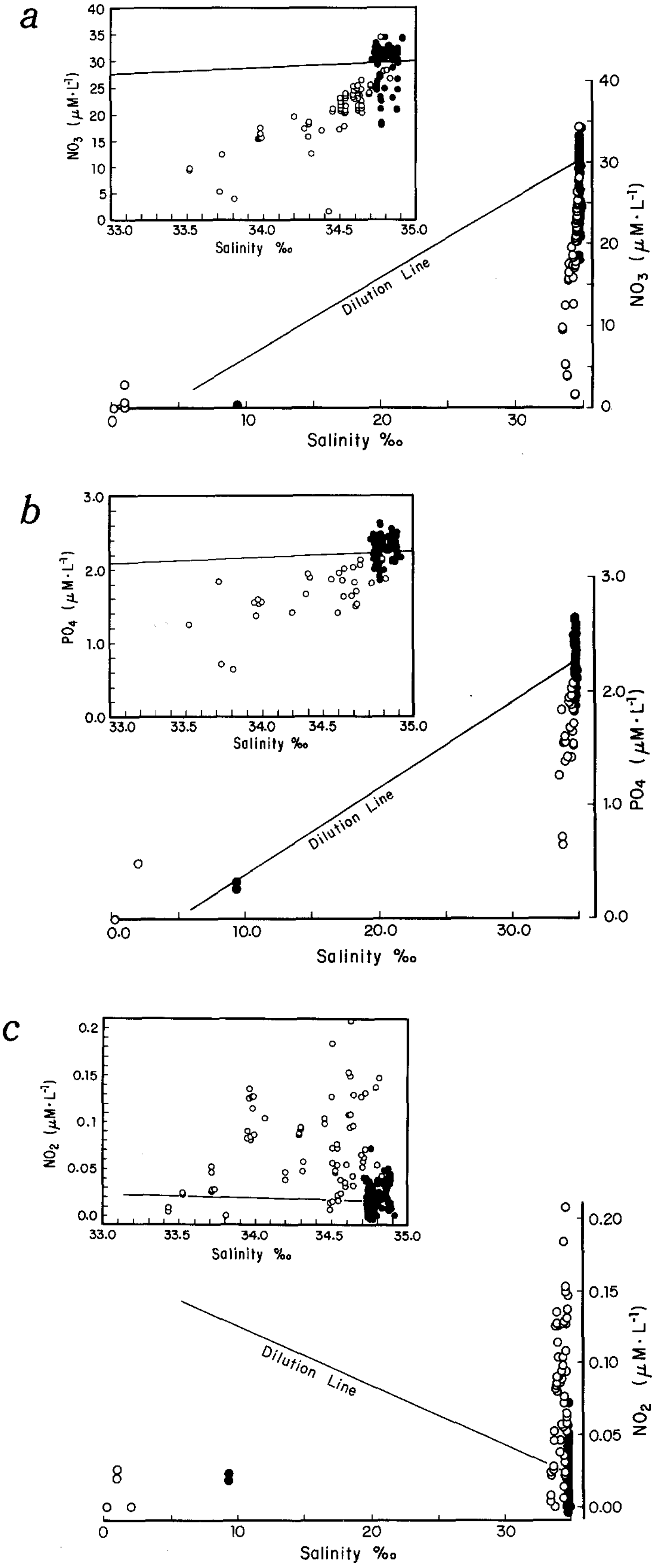


Fig. 16a–c. Nutrient dilution curves. **a** Nitrate. **b** Phosphate. **c** Nitrite. The dilution line is the predicted concentration for average spring nutrient levels diluted by sea ice meltwater with not phytoplankton uptake. Symbols as per Fig. 13. *Insets* show a narrower salinity range to illustrate detail

are visible by the highly refractile fresh water – sea water interface. The depth of these lenses was also identified by observations of secchi disk movement through the sharp interface.

Stratification was nearly always more intense during summer than spring and results in the maintenance of phytoplankton populations in the eutrophic zone by inhibiting vertical mixing. Summer salinities were highly variable and several surface values were near or below levels reported for sea ice (Fig. 13; Gow et al. 1982; Clarke and Ackley 1984). Brunt-Vaisalla periods ranged from 10–20 min at 100–150 m depth and near the surface periods near 1–5 min were common in the west Sound where surface salinity was very low.

Nutrient Distribution. Nutrients (NO_2, PO_4) were low following the seasonal phytoplankton bloom and were near zero at isolated locations. Depletion was greatest near the surface where water column stability was high (Fig. 15). Nitrate levels were near 15% of pre-bloom levels under sea ice near McMurdo Station (3.9–5.4 µM NO_3), and were lower (0.1–1.6 µM NO_3) in the west Sound. Near surface phosphate levels were also lowest during summer and at Station 15 phosphate was undetectable at 4 m depth.

Nutrient depression may be caused by phytoplankton utilization, low initial nitrate levels, or by dilution from low nitrate glacial or sea ice meltwater, and appears to have resulted from a combination of these sources. Figure 16 illustrates the relationship between nutrient concentrations and salinity. Excluding very low values, the summer nitrate and phosphate levels both generally fall well below the concentrations expected by dilution from glacial or sea ice meltwater.

In contrast, nitrite concentrations were highest during the summer (Fig. 15c), often with subsurface maxima, and were enriched relative to meltwater dilution. Elevated sea ice nitrite levels (~0.4 µM) have been attributed to nitrification of ammonia by sea ice bacteria (Clarke and Ackley 1984), and may account, in part, for increased water column nitrite levels during summer. Low surface nitrite levels may be caused by microalgal nitrite utilization stimulated by depressed nitrate concentrations.

Biological Properties. Summer chlorophyll *a* concentrations exceeded 8 µM; 2–4 orders of magnitude greater than prebloom values of the following spring (Fig. 17a). Samples were not collected during the peak of the summer bloom and chlorophyll *a* levels were perhaps much higher. Water clarity during late January and early February, 1984 was approximately 10 m. In early January, visibility was much less (< 3 m) and was probably indicative of much higher phytoplankton concentrations as observed in other studies (Bunt 1964a; Bunt and Lee 1970). The oxygen saturation levels paralleled the spring to summer increase in chlorophyll *a*. Summer oxygen samples were greater than 100% saturated, while spring levels were near 80% saturation. Similar findings were reported by Littlepage (1965).

Station 16, located 20–30 km south of the northern edge of the Ross Ice Shelf adjacent to White Island is of particular interest. At this site in situ primary productivity must be very near 0 because of the thick ice and heavy

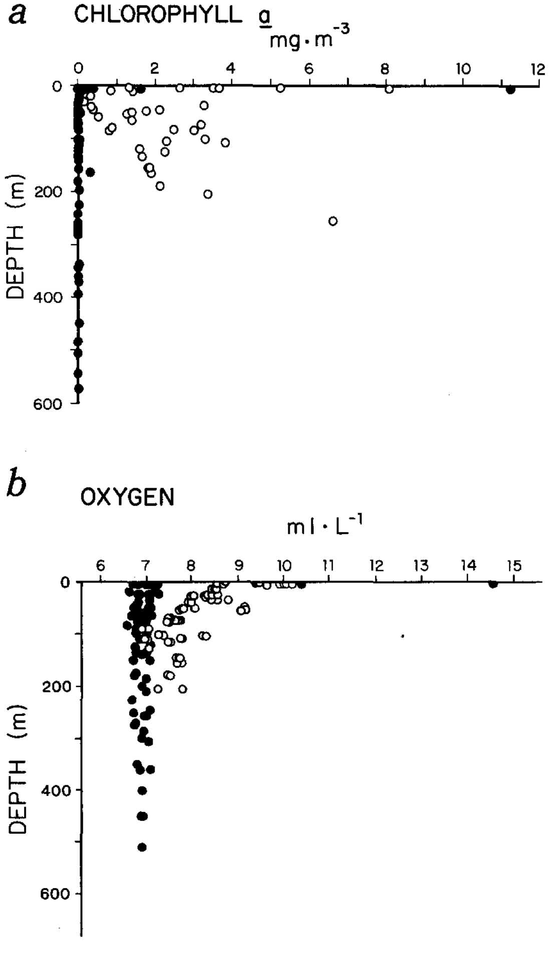


Fig. 17. **a** Spring/summer chlorophyll *a* profile. **b** Spring/summer dissolved oxygen profile. Symbols as per Fig. 14. Note the summer increase in both parameters

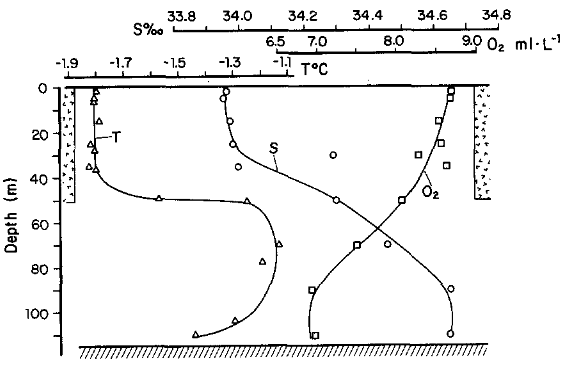


Fig. 18. White Island (Station 16) water column characteristics. *Triangles* indicate temperature (°C). *Circles* indicate salinity. *Squares* indicate dissolved oxygen. Curves were fitted by eye. The uniform upper 50 m is located in the rift crack, indicated by the shaded area

snow cover. Water samples were collected from a rift area at the northeastern tip of White Island where the Ross Ice Shelf (locally 50 m thick) flows northward around the island. The temperature profile (Fig. 18) has a sub-surface maximum, probably in response to cooling by contact with the Ross Ice Shelf. This profile was compiled from several hydrocasts and shows the homogeneous and low near surface salinity in the rift crack (Fig. 18), and increasing salinity with depth. Although temperature was lowest near the surface, the water column is stable due to the increase in salinity with depth. Midwater temperatures below the bottom of the ice shelf were very similar to that measured during summer near to Station 15, upstream of the White Island area (Barry and Dayton 1988). Near the bottom the temperature decreased slightly, for unknown reasons. Nutrient profiles were similar to other stations sampled during the summer, except for high surface concentrations. Like the profiles near Scott Base to the north, chlorophyll *a* was highest near the bottom, perhaps due to suspension of benthic micoralgae or the resuspension or settled planktonic and epontic algae (Berkman et al. 1986; Leventer and Dunbar 1986), and oxygen concentrations were higher than spring values from the main Sound. In contrast to Knox et al. (in press) who did not detect chlorophyll *a* in the summer waters near White Island during 1976–1977, these data are consistent with expectations associated with phytoplankton advection from the north during 1984. However, during 1976–1977, Knox et al. (in press) observed a slow northward flow near White Island.

Discussion

The thermohaline properties in McMurdo Sound result from the modification of source waters within the Sound and over larger spatial scales. Several water types are present in the vicinity of McMurdo Sound and each reflects physical processes which control changes in salinity and temperature (Jacobs et al. 1985). Circumpolar Deep Water (CDW) is the initial source from which all antarctic continental shelf waters are derived (Jacobs et al. 1970, 1985). This warm (1.17 °C), saline (34.7 ppt) water mass is altered by salinization, dilution, and cooling to produce Antarctic Surface Water (AASW), High Salinity Shelf Water (HSSW), and Ice Shelf Water (ISW), (Jacobs et al. 1979a; Jacobs et al. 1985), which are the most pertinent to McMurdo Sound thermohaline dynamics. Within McMurdo Sound, HSSW is by far the most abundant water type.

The regional circulation pattern relevant to the thermohaline dynamics of McMurdo Sound is presented in Heath (1977), Lewis and Perkin (1985), and Barry and Dayton (1988). Flow consists of a southerly component in the eastern Sound, apparently driven by geostrophic and wind forcing of the Cape Bird Current, (an extension of the westward coastal current along the Ross Ice Shelf), flowing south into McMurdo Sound (Barry and Dayton 1988; Heath 1977), and/or by tidal rectification (MacAyeal 1985). This southerly flow enters the sub-shelf cavity and continues south towards the deep basins of the sub-shelf area and/or mixes with northerly flowing sub-Ross Ice Shelf waters and turn west, finally exiting the Sound to the northwest (Tressler and Ommundsen 1962; Lewis and Perkin 1985; Barry and Dayton 1988).

The north/south salinity gradient in McMurdo Sound is the result of mixing between HSSW entering the Sound in the northeast, with the relatively low salinity water flowing northward from beneath the Ross Ice Shelf and any glacial meltwater input in the southwestern Sound. HSSW in northeastern McMurdo Sound is probably formed by salt rejection during ice formation in the southwestern Ross Sea (Jacobs et al. 1970; Jacobs et al. 1985). Annual sea ice freezing rates upstream of McMurdo Sound may be very high due to recurrent winter polynya formation typical near the margin of the western Ross Ice Shelf (Kurtz and Bromwhich 1985; Zwally et al. 1985).

Southward flow under the Ross Ice Shelf in eastern McMurdo Sound, indicated by Heath (1977), Tressler and Ommundsen (1962), Barry and Dayton (1988). MacAyeal (1985), and Lewis and Perkin (1985) may be modified to form Deep Ice Shelf Water (DISW), a very cold (−2.03 °C), relatively low salinity (34.68 ppt) water, or may turn west and north, mixing with sub-Ross Ice Shelf water and forming the western Sound water mass. Water entering the subshelf cavity can directly contact the shelf (Fig. 18), and contribute to the rapid bottom melting rates of the Shelf measured south of McMurdo Sound (Crary et al. 1962; Neal 1979), particularly during summer.

In contrast with the situation in the eastern Sound, northward flow of very cold, relatively low salinity (34.73 ppt) water in the southwestern Sound suggest recent contact with or convective cooling by the ice shelf (Lewis and Perkin 1985). Its source is unknown, but this northward flow must be derived from sub-Shelf water (ISW), and/or input from the eastern Sound. Glacial meltwater from the southwestern Sound during summer also contributes to the reduced salinity of western Sound water. Tritium and ^{14}C levels indicated a greater age for west Sound than east Sound water, presumably due to residence time (~6 years) under the shelf (Michel et al. 1979). However, a mixture of east Sound water with glacial meltwater could indicate a similar age. Considering the shallow depth (3 to 10 m) of the water samples from Michel et al. (1979), a mixture of 65% east sound water with 35% glacial meltwater (Ross Ice Shelf or nearby glaciers; Tritium = 0.0) could indicate a similar age. Freshwater lenses indicative of glacial rather than sea ice meltwater are present in the western Sound (Debenham 1965; Gow et al. 1965; this study) and may have been unwittingly sampled by Michel et al. (1979). Salinity values were not reported, but would clarify the status of the water samples from beneath the Shelf.

Summer nutrient and oxygen data indicate that west Sound waters are derived, in part, from the eastern

Sound. Nutrient levels were depressed and oxygen levels increased throughout the Sound during summer, associated with the spring bloom. Assuming a net northward velocity of 3.8 cm/s (Barry and Dayton 1988), the residence time of southwestern Sound waters is approximately 10 to 12 days. This short period is insufficient for the observed summer nutrient depletion by primary production (see below) in the western Sound and indicates that this water mass had a recent history in well lit areas, presumably in the eastern and northern Sound.

The dramatic differences in the thermohaline characteristics of AASW, HSSW, and ISW formed in the same regions illustrate the complementary processes active during the seasonal freeze/thaw cycle. Platelet and sea ice development both occur when terrestrial meltwater input to the Sound is minimal, leading to higher density during winter and spring. In contrast, summer density decreases are aided by high water column stratification, by the warming and dilution of surface water, rapid sea ice degradation, and maximal terrestrial meltwater input, leading to AASW formation.

Western Sound salinity is dramatically affected by meltwater from several ice sources, including platelet ice, glacial ice (Ross Ice Shelf melting and nearby terrestrial sources), snow, and sea ice. Meltwater sampled during summer at Station 13 was collected from a nearly fresh water lens (mean salinity = 1.04, n = 3) with nutrient concentrations near 0 μM (NO_3 = 0.83 μM, n = 2; PO_4 = 0.02 μM, n = 2). Because the salinity of antarctic sea ice is generally much higher (2–6 ppt, Clarke and Ackley 1984; 6 ppt, Gow et al. 1982), this highly dilute, low nutrient lens could only have been derived from glacial meltwater.

Dieckmann et al. (1986) content that platelet ice formed in deep water may entrap micro-organisms and lift them to the sea ice community. In addition, the accumulation of platelet ice under the sea ice increases the surface area and refuge space from predators, leading to higher standing stocks of platelet ice biota. Thus, the thick platelet layer near the outflow from the sub-Ross Ice Shelf cavity (Station 3), may enhance local microbial biomass. Nonetheless, it is perhaps more important to local productivity patterns by to its role in diluting the surface waters upon melting. Coupled with terrestrial glacial runoff and sea ice and snow meltwater, surface salinity drops considerably and leads to prolonged water column stratification and higher productivity as this water mass moves northward out of McMurdo Sound, where marginal ice zone plankton blooms are extremely intense (Smith and Nelson 1985; Wilson et al. 1986). Even though glacial meltwaters are low in nitrate, their high ammonia content (Biggs 1978; Jacobs et al. 1979b; Shulenberger 1983) can additionally enhance primary productivity.

Table 1. Primary productivity estimates from nutrient depletion calculations

	Spring	Summer deficit		%	Primary production gC/m^2/d
	μM/l	μM/l	μM/l		
East Sound					
NO_3	31.62	20.23	11.40	36.04	1.962
PO_4	2.33	1.44	0.89	38.10	2.015
Ratio	13.59	14.04	11.68		
West Sound					
No_3	32.00	20.56	11.44	35.75	1.024
PO_4	2.42	1.77	0.47	21.01	0.389
Ratio	14.27	11.61	31.57		

Spring Phytoplankton Bloom

Phytoplankton blooms in marginal ice zone seas contribute to the productivity of several trophic levels and are important components of polar ecosystems (Bunt 1964a, b; Bunt and Lee 1970; El Sayed and Taguchi 1981; Horner and Schrader 1982; Palmisano and Sullivan 1983; Palmisano et al. 1986; Smith and Nelson 1985, 1986; Fraser and Ainley 1986; Nelson and Smith 1986; Wilson et al. 1986). Primary production is not thought to be limited by nutrient availability (El-Sayed and Mandelli 1965), but instead by winter darkness and/or the downward mixing below the critical depth of phytoplankton stocks (Sverdrup 1953). These blooms typically have a rapid onset during spring which is thought to be initiated by increased water column stability from meltwater input (El-Sayed and Mandelli 1965; El-Sayed and Taguchi 1981), ice edge upwelling, and/or inoculation of surface waters with sea ice algae (Smith and Nelson 1985, 1986; Wilson et al. 1986).

The onset of the spring phytoplankton bloom in McMurdo Sound is apparent with the decrease in water clarity during late spring, falling from near 80 m or more to less than 3 m (underwater observations by SCUBA; P. K. Dayton, personal communication; personal observation). The bloom is advected from north to south in the eastern Sound (Palmisano et al. 1986). Assuming a southward drift of 3.0 cm/s (Barry and Dayton 1988), transit from Cape Bird to near McMurdo Station requires approximately 30 days. Consequently, the summer samples from the southern Sound were indicative of biological activity to the north as well as of in situ productivity, although in situ water column productivity under the sea ice is usually quite low, (Bunt 1964a, b).

Several sources indicate that western Sound waters are less productive than in the east due to the circulation pattern and/or differences in ice cover (Bunt 1964a; Dayton and Oliver 1977; DeLaca et al. 1980; Hodson et al. 1981). Although unmeasured, primary productivity was estimated from calculations of spring to summer nutrient (NO_3, PO_4) depletion rates in the east and west Sound using the methods of Jennings et al. 1984). Summer nutrient profiles from stations 15 and 18 in the east and west sound, respectively, were compared to the spring profiles from nearby stations (Table 1). Any difference between the integrated water column nutrient concentrations from spring to summer were assumed to reflect utilization by phytoplankton during the previous three months.

Primary productivity estimates were 1.97 – 2.02 g $Cm^{-2}d^{-1}$ in the eastern sound and 0.39 – 1.02 g $Cm^{-2}d^{-1}$ in the west (Table 1). These levels are quite high, but similar to data from Bunt (1964a), whose integrated east Sound productivity measurements were near 1.4 $gCm^{-2}d^{-1}$. McMurdo Sound productivity estimates based on nutrient profiles reported by Littlepage (1965) also indicated high eastern Sound bloom productivity (2.1 $gCm^{-2}d^{-1}$).

The injection of glacial meltwater to west Sound surface waters may alter the interpretation of these productivity estimates. Estimates based on separate nitrate and phosphate depletion calculations were similar in the east Sound. However, the same calculations for the west Sound differed (Table 1) from both nitrate and phosphate depletion calculations. Pre-bloom and post-bloom nitrate-phosphate ratios in the east Sound were near 14.0, and the ratio of nitrate depletion to phosphate depletion was 11.7, near the expected 12.0 for polar phytoplankton uptake (Jennings et al. 1984). In the western Sound, the pro-bloom and post-bloom nitrate-phosphate ratios were similar and near 14. However, the summer nitrate depletion:phosphate depletion ratio was 31.6, indicating that nitrate and/or phosphate concentrations in this area were modified independently from phytoplankton growth, or that phytoplankton were preferentially sequestering nitrate. The addition of low nutrient glacial meltwater with a NO_3/PO_4 ratio less than 13.0 can explain this discrepancy. Glacial ice nitrate levels are near 2,7 μM (Parker et al. 1978; Jacobs et al. 1979b), and phosphate levels have been reported at 2.04 μM (Amos 1978); a ratio of 1.32 (phosphate enriched). Figure 19 shows how phytoplankton utilization and dilution by sea glacial ice meltwaters may modify the nitrate to phosphate ratios from that expected simply by phytoplankton utilization. The spring nitrate-phosphate ratio fell from 13 to near 9 during the summer and was often much lower (3 – 6) near the surface, indicating a preferential uptake of nitrate (El-Sayed and Taguchi 1981), or the addition of low nutrient, but relatively high phosphate meltwater. Although this process could have contributed to the observed nutrient distributions, the seasonal salinity changes in the west Sound (1.0% dilution) were not sufficient to account for the predicted glacial meltwater dilution of 11 percent (Fig. 19).

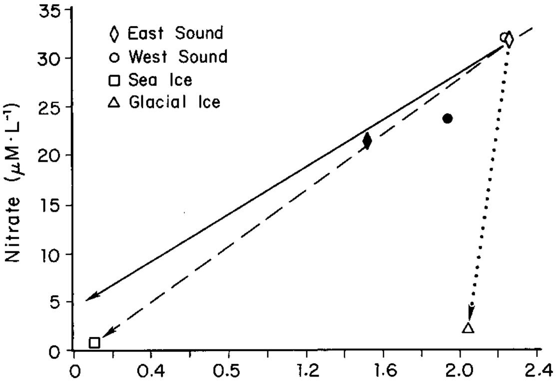


Fig. 19. Nitrate/phosphate rations for the east and west Sound during spring and summer. Spring samples are indicated by *open symbols*; summer samples by *filled symbols*. The *solid line* indicates the expected ratio after phytoplankton uptake only. The *dashed line* indicates dilution by sea ice meltwater addition and the *dotted line* indicates dilution by glacial meltwater dilution. Note the high phytoplankton utilization of eastern Sound waters with little dilution, and the relatively lower utilization and apparently greater dilution by glacial meltwater in the western Sound

Nutrient depletion or nutrient competition may also have restricted primary productivity in the surface waters of the western Sound. In the highly stratified surface layer below the sea ice, nitrate was well below 10 μM and near occasionally 0 μM (particularly in southwestern Sound stations), similar to concentrations in the Ross Sea near McMurdo Sound during a spring phytoplankton bloom (Nelson and Smith 1986).

In some cases, water column stability may actually depress primary productivity by limiting the input of inorganic nutrients by vertical mixing. In this study, the extremely low near surface nutrient levels at a few sites must nearly limit phytoplankton growth. This process, however, is unlikely to be of general importance except where low nutrient glacial meltwater is a significant component of surface waters and vertical mixing processes are severely restricted by high water column stability and low wind driven mixing (caused by the presence of ice cover). Moreover, glacial meltwater can be enriched in ammonia relative to seawater (Horrigan 1981; El-Sayed and Taguchi 1981), and thereby partially offsets any nutrient limitation due to low nitrate levels.

Hydrography and Benthic Production

Spatial patterns in the productivity of shallow water (< 60 m) benthic communities are closely related to hydrographic features and the circulation pattern in McMurdo Sound. For most trophic levels studies, productivity in the eastern Sound is higher than in the west (Barry and Dayton 1988). The hydrographic patterns presented here show that although there are differences in the standing stock of phytoplankton across the Sound (as measured by chlorophyll *a*), or in primary productivity (estimated from nutrient depletion), these differences arise from primarily from the circulation pattern in McMurdo Sound. Any regional differences in in situ primary production are probably caused either by differences in the standing stock of phytoplankton of source waters or by differences in the ambient light levels caused by ice and snow cover. Regional variation in source water phytoplankton concentrations and local differences in mean current speeds result in higher plankton concentrations and higher particle fluxes for benthic consumers in the east Sound than in the relatively oligotrophic western Sound (Barry and Dayton 1988). Hydrographic processes and their effect on productivity are perhaps most complex in the western Sound. Multiple source waters, ice cover, platelet ice effects, potential nutrient depletion related to extreme water column stratification, and very sluggish currents are factors which can dramatically modify the availability and flux of primary production for benthic species. Although together these factors are clearly responsible for the observed differences in production between the eastern and western Sound, their relative importance to the structure and productivity of McMurdo Sound communities is still unclear.

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