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Seasonal changes of dissolved nutrients within and around Port Foster Deception Island, Antarctica

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Abstract

Temporal and spatial distribution of dissolved macronutrients (ammonia, nitrate, phosphate and silica) and productivity were investigated within and around Port Foster, the flooded 160-m-deep caldera of Deception Island, Antarctica. This study was part of the Erupt Project, which included five seasonal cruises over a complete annual cycle during 1999–2000. Seawater samples were collected and physical properties were monitored from seven stations within Port Foster and 12 stations in the adjacent Bransfield Strait. In addition, shallow-water and beach interstitial-water samples were collected along the shorelines of the peripheral coves. Port Foster macronutrient/depth profiles were typical for a normal shallow seawater column in a polar region. The water column in early austral spring was well mixed and changed to a stratified water column with a weak thermocline during the summer. By early winter, the thickness of the well-mixed surface layer increased until the entire water column returned to well-mixed conditions. This early winter transition from stratified conditions to well-mixed conditions occurred in June and appeared to be abrupt. During the seasons of light limitation and low-primary productivity, local currents were effective at redistributing dissolved biochemical components throughout the bay. During the summer season, the dissolved nutrient and oxygen distributions reflected consumption of nutrients by primary producers. The mid-depth maximum observed in the ammonia profiles implies the excretion of metabolites from resident animal populations. Residence time of dissolved ammonia must have been shorter than the circulation time within Port Foster because ammonia is not as uniformly distributed during the summer months as it was during the winter and spring. Dissolved nitrate concentrations in the Bransfield Strait during this study were similar to those measured in previous studies.

The mean concentrations of phosphate, nitrate, and silica in the beach interstitial samples were significantly higher (2.8–9.5 times) than in the shore, offshore and CTD samples. Possible sources for the high phosphate, nitrate, and ammonia concentrations in the beach interstitial and shore waters include decaying organic matter and bird and mammal excrement. Elevated silica concentrations appear to be associated with hydrothermal heating of beach and near-shore waters. However, the elevated macronutrient concentrations measured in the beach interstitial water were not traceable beyond 5 m of the shoreline.

Phytoplankton biomass in Port Foster exhibited temporal variability similar to other coastal and continental shelf zones (CCZ) of the Antarctic Peninsula. Blooms in February and November 2000 were dominated by the centric diatoms *Thalassiosira* spp. and *Rhizosolenia* spp. Chlorophyll *a* (chl *a*) values of 15 and 19 mg m^{-3} in Port Foster during

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these blooms were comparable to maximum-recorded levels in western Antarctic Peninsula CCZ (30–40 mg chl a m^{-3}), while chl *a* values from November 1999 and June 2000 (non-bloom conditions) corresponded to historical monthly chl *a* averages of western Antarctic Peninsula CCZ ($<5\,mg\,m^{-3}$). During blooms, phytoplankton standing stock could account for about 15 μM nitrate, which corresponds to the observed surface nitrate depletion.

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1. Introduction

The Erupt Project, a study of marine ecosystems, involved long time-series (February 1999 through November 2000) remotely sensed observations within Port Foster at Deception Island. Over this time period, five seasonal cruises were conducted during which discrete data and samples were collected (Smith et al., 2003a).

The Southern Ocean has been described as a region of low primary productivity despite relatively high nutrient concentrations (Smith and Nelson, 1986; Holm-Hansen and Mitchell, 1991). Yet, shallow regions around the Antarctic Peninsula, Bransfield Strait (Fig. 1) have relatively high primary productivity (Smith and Nelson, 1986; Arrigo et al., 1997; Holm-Hansen and Mitchell, 1991; Bode et al., 2002). Castro et al. (2002) found no evidence of nutrient limitation associated with relatively high nutrient consumption at frontal zones in the Bransfield and Gerlache Straits during the austral summer months of December 1995 and January 1996.

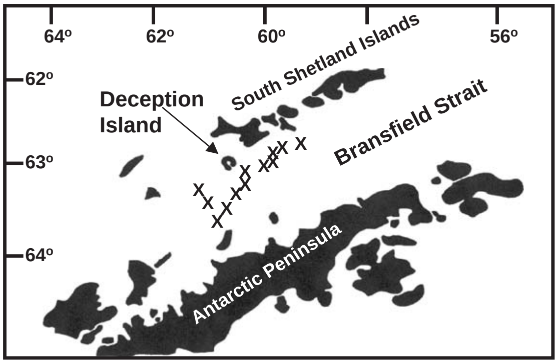

Fig. 1. Map of Bransfield Strait showing location of Deception Island. Bransfield Strait CTD stations (×) are located southwest, south and north of Deception Island.

The region near Deception Island experiences a maximum summertime day length of 19–20 h during which photosynthesis can proceed and a minimum wintertime day length of 5–6 h when photosynthesis is light-limited. Bode et al. (2002) suggest that, during the austral summer 1995–1996, high phytoplankton biomass was associated with zones of high nitrate ($>10\,mmol\,N\,m^{-3}$) and low ammonia (generally $<1\,mmol\,N\,m^{-3}$). These authors conclude that phytoplankton production in areas of high biomass was sustained by dissolved ammonia and that ammonia regeneration was sufficient to supply the daily phytoplankton demands during the austral summer. These results suggest that spatial and temporal changes in the distribution of dissolved ammonia may play an important role in overall biological processes in this region. In turn, redistribution of dissolved components, such as ammonia, by local currents exerts an important influence on the residence time of dissolved components and on dispersal of phytoplankton and zooplankton in and around the Bransfield Strait.

The surface circulation in the Bransfield Strait is difficult to determine because of the complex local topography. The Bransfield Strait is a tectonic extensional marginal basin formed between the South Shetland Islands volcanic arc and continental rocks of the Antarctic Peninsula (Rey et al., 1997; Keller and Fisk, 1992; Barker and Austin, 1998; Ibanez et al., 2000) (Fig. 1). The Strait has three deep (>2600 m) basins separated by sills less than 1500 m (Gordon and Nowlin, 1978). The South Shetland Islands, which are separated by shallow sills (<500 m), restrict deep and intermediate water flow into the Bransfield Strait from the north and west. Water enters the Bransfield Strait from the south through the Gerlache Strait and from the west through Boyd Strait. The Antarctic Peninsula blocks flow into the Bransfield

Strait from the south east (Gordon and Nowlin, 1978). Overflow from the Weddell Sea contributes to deep-water masses in the northeastern region of the Bransfield Strait (Gordon and Nowlin, 1978). Deception Island is located within the Bransfield Strait south of Livingston Island and northeast of the Gerlache Strait. Northeastward-flowing surface currents exit the Gerlache Strait and contribute to a large cyclonic gyre in the Bransfield Strait during the austral summer months (Zhou et al., 2002). This gyre is influenced by the presence of the volcanic edifice of Deception Island. General circulation exhibits temporal and spatial complexity, with jets and eddies forming over relatively short time scales. Some water parcels may exit the Strait in 10–20 days; but water parcels entrained into bays and shallow semi-enclosed regions may be retained for 50–100 days. Lopez et al. (1999) suggest that tidal flow is an important influence on horizontal advection in the Bransfield Strait. Lopez et al. (1999) observed geostrophic flow (relative to 400 m depth) with velocities around 0.2 m s^{-1} and tidal currents with velocities of 0.3–0.4 m s^{-1}. Prior to the Erupt Project, little was known about exchange of water and its dissolved and suspended components between Port Foster at Deception Island and the neighboring regions of the Bransfield Strait. Lenn et al. (2003) describe the local currents within Port Foster and exchange between Port Foster and the Bransfield Strait through Neptune's Bellows (Fig. 2). The objective of our study was to examine the distribution of dissolved chemical components as a consequence of the local and larger circulation patterns.

In order to evaluate the extent to which the physical and biological environment of Port Foster is representative of other shallow-water environments in the region, we considered two unique characteristics of Port Foster: (1) it is an enclosed bay surrounded by a 500-m above-sea-level volcanic edifice, and (2) it is the caldera of an active volcano with extensive hydrothermal activity (Ibanez et al., 2000). The composition of dissolved nutrients in the waters in Port Foster may be affected by aeolian and fluvial inputs, as well as by biogenic sources. High wind velocities have been recorded at Deception Island (Smith et al., 2003b). Particulate matter fluxes measured in Port Foster indicate that large volumes of lithogenous material from the island are being deposited into the middle of the bay (Baldwin and Smith, 2003, Gray et al., 2003). Here, we report results of shipboard-derived measurements and chemical analyses of water samples collected during Erupt cruises II through V: November 1999, February 2000, May–June 2000 and November 2000.

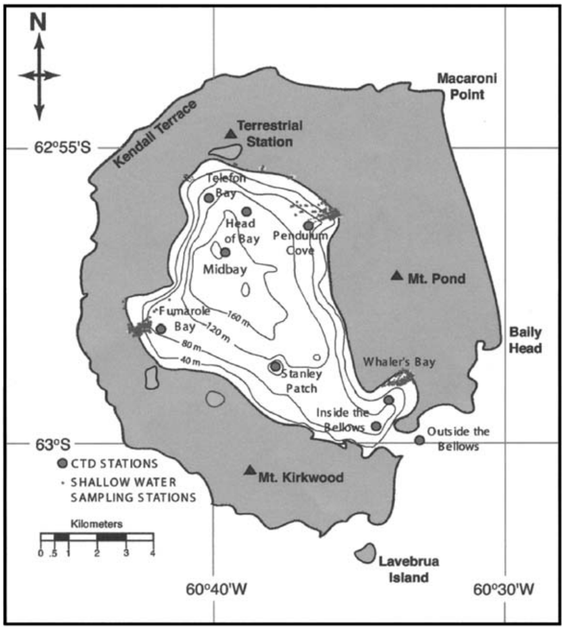

Fig. 2. Map of Deception Island. CTD are large gray circles; near-shore sampling stations at Mid Bay, Whalers Bay, Pendulum Cove, Telefon Bay and Fumarole Bay are small gray dots.

2. Methods

We monitored chemical and physical properties of water samples collected at locations in the central and near-shore regions within Port Foster and in the Bransfield Strait near Deception Island (Figs. 1 and 2). We occupied the Mid Bay Station in Port Foster a total of 76 times during Erupt II–V. CTD-rosette casts, with 12 GO-flow bottles triggered on the up-cast for water sampling, were conducted at noon and midnight on successive days over the duration of each cruise. In addition, we occupied stations at four of the peripheral coves (Whalers Bay, Pendulum Cove, Telefon Bay, and Fumarole Bay), and three other locations within Port Foster (Head of Bay, Inside the Bellows, Outside the Bellows) (Fig. 2). CTD casts were also taken at 12 stations in the Bransfield Strait (Fig. 1).

Concentrations of nitrate, ammonia, phosphate and silica were measured using natural pH samples aboard ship, usually within 3 h of sampling. Turbid samples were filtered through phosphate-free millipore filters prior to analyses. A segmented flow autoanalyzer system with multiple manifolds was used to measure dissolved nutrients using the following colorimetric methods: nitrate by cadmium reduction; ammonia by phenate; phosphate by molybdate/antimony; silica by molybdate/stannous chloride.

Over 268 shallow water and beach interstitial-water samples were collected in nalgene bottles during the austral winter (May–June 2000) and spring (November 2000) along transects in four coves of Port Foster: Whalers Bay, Pendulum Cove, Telefon Bay, and Fumarole Bay (Fig. 2). Areas where high water temperatures and steaming beaches suggested hydrothermal activity, hot-spots were targeted as sampling sites. No hydrothermal activity was observed at Telefon Bay in May-June 2000. In November-December of 2000 a hot spot was located at a site between Telefon Bay and Pendulum Cove. Sampling transects were conducted perpendicular to the shoreline from areas where beach interstitial-water temperatures were highest (Dykes, 2002). These sampling transects extended from less than 2 m landward of the shoreline out to the deeper area of the cove. Water temperatures were measured using digital and/or alcohol thermometers, and salinity was measured with a refractometer. Water samples from these transects were classified into four types: (1) beach interstitial, (2) shore, (3) offshore, and (4) deep. Beach interstitial water was collected by digging holes 20–50 cm deep and allowing them to fill with water. Because the beach sediment consisted of volcanic gravel of high porosity, with little sand or silt, these holes filled rapidly with water. Shore water samples were collected at the surface within 5 m of the shoreline, and offshore water samples were collected at the surface greater than 5 m of the shoreline along an approximate transect connecting the beach hydrothermal areas (hot spots) to the cove CTD stations. A Niskin bottle was used to collect water samples within a few meters of the seafloor at some locations along the transects. These samples were classified as "deep" water samples. In November-December of 2000, a few snow samples and water samples from small ephemeral melt-water streams running off into the coves were collected.

After chemical analyses, the mean and standard deviations of each sample type for each of the three sampling periods (February, May–June and November 2000) were calculated and compared using non-parametric ANOVA Kruskal Wallis and Mann–Whitney U tests.

For phytoplankton and chlorophyll measurements, sea water was collected using 10-l GO-Flo bottles attached to a CTD rosette at 1200 (local time) for chlorophyll *a* (chl *a*), as a proxy for phytoplankton biomass. Samples were taken from four discrete depths to characterize chl *a* maxima and minima. Sea water samples were filtered onto 0.7-μm Whatman GF/F filters by vacuum and frozen at −70°C for storage. In the laboratory, samples were extracted in darkness with 90% acetone for approximately 24 h, then analyzed on a Turner Designs fluorometer (Strickland and Parsons, 1972). The fluorometer was calibrated periodically using standard chlorophyll solutions checked with a spectrophotometer. For taxonomic purposes, phytoplankton were collected by vertically towing a 25-μm net from 15 m to the surface. Samples were stored in borax-buffered 10% v/v formalin and were analyzed in the lab using an inverted microscope. Phytoplankters in sub-samples were identified to genus and enumerated for relative abundance.

3. Results

3.1. Temperature and salinity profiles: Mid Bay and the peripheral cove

Temperature and salinity profiles for the Mid Bay, peripheral cove and Bransfield Strait stations

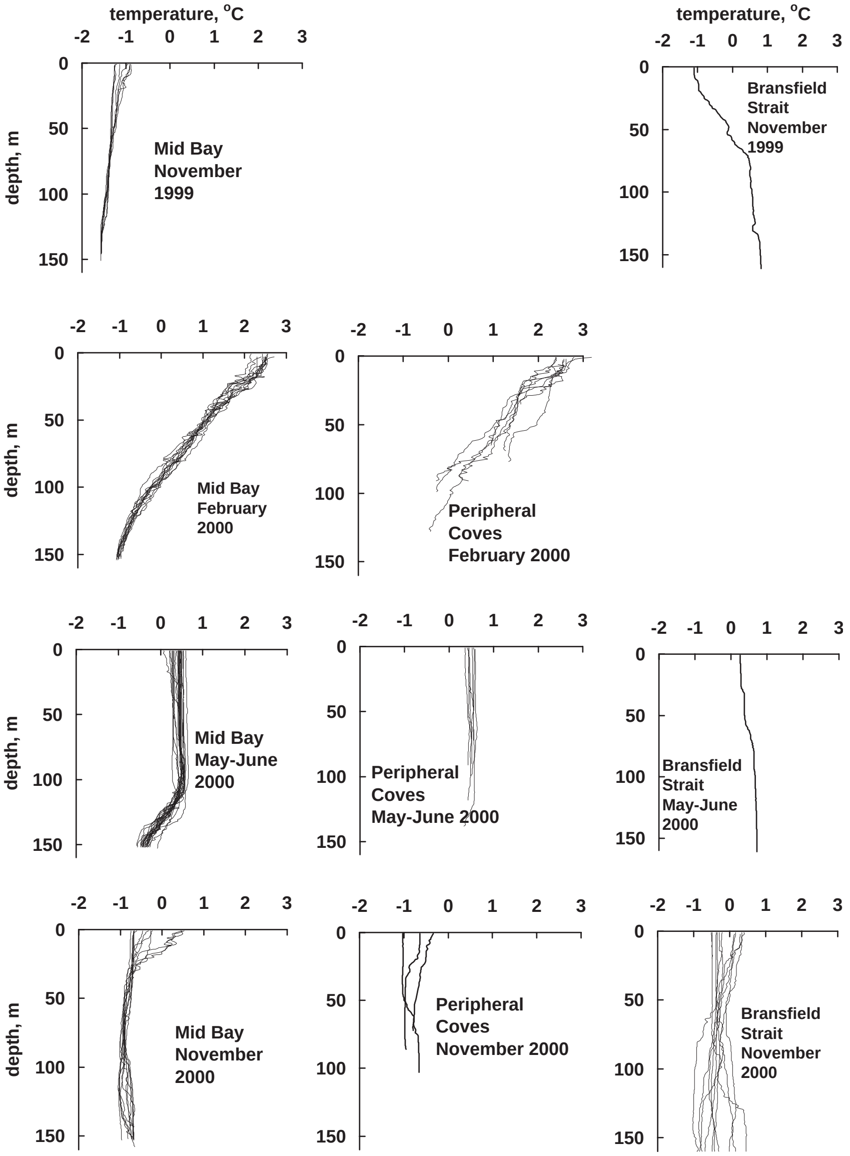

Fig. 3. Temperature/depth profiles at Mid Bay, the peripheral coves and Bransfield Strait during November 1999, February, May–June and November 2000. Temperature is in °C; depth is in meters.

for the four Erupt cruises (II–V) are given in Figs. 3 and 4. The results shown in Fig. 3 indicate that temperature/depth profiles had similar shape during a given season and that each season was distinctly different. For example, in November 1999 at the Mid Bay station, temperature was near −1°C (Fig. 3). The largest variation in temperature during November 1999 was seen in near-surface waters, above 50 m; however, the observed near-surface temperature variation was less than 0.5°C. Temperature varied little from 40 m to the bay floor at 160 m. In February 2000 at the Mid Bay station, surface waters were between 2°C and 3°C, substantially warmer than deeper in the water

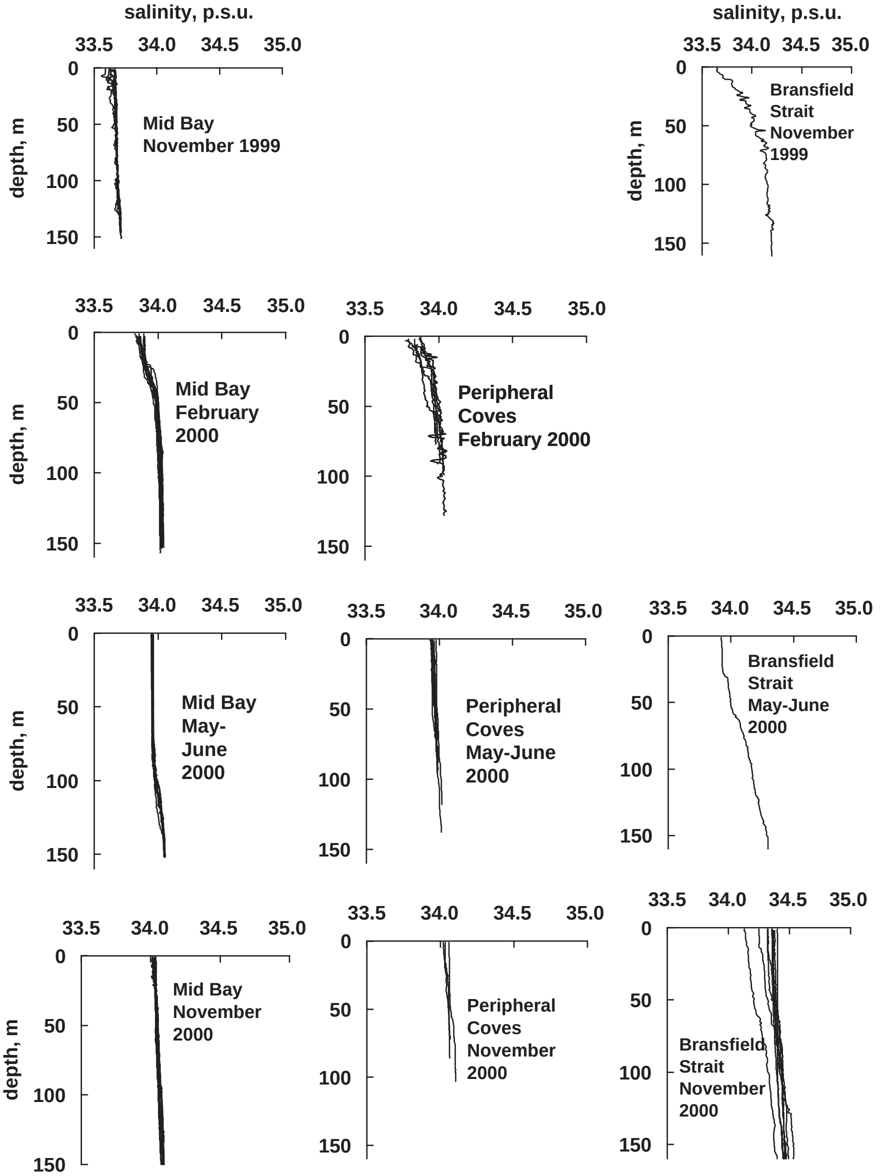

Fig. 4. Salinity/depth profiles at Mid Bay, the peripheral coves and Bransfield Strait during November 1999, February, May–June and November 2000. Salinity is in psu; depth is in meters.

column (below 120 m), which remained near −1°C. In May and June 2000 at the Mid Bay station, the profiles indicate that the upper 100 m of the water column was well mixed, with temperatures between 0°C and 1°C. A colder layer (−1°C to 0°C) between 100 m and the bay floor underlaid the well-mixed layer. By November 2000 at the Mid Bay station temperatures below about 40 m were near −1°C, slightly warmer than observed in November 1999, and near-surface water temperatures had a larger range (up to 0.5°C), suggesting that a transition toward the early summer condition of warmer surface water had begun to develop. Similar temperature/depth patterns were observed at the peripheral coves as those seen in the Mid Bay (Fig. 3). Temperature profiles from the peripheral coves were generally consistent within a given season, with temperature ranges near the ranges observed at Mid Bay. Similarly, the peripheral cove profiles had different patterns among the various seasons that were within the ranges observed at Mid Bay for that season. Bransfield Strait temperature profiles for the upper 100 m during the May–June and November 2000 cruises were similar to the Mid Bay and peripheral coves. Temperatures varied over a small range (<1°C) and were near 0°C. However, it is interesting to note that surface water (above about 30 m) temperatures in the Bransfield Strait near Deception Island were close to −1°C, near the values measured within Port Foster at that time.

Temperatures below about 50 m were between 0°C and 1°C, nearer temperatures observed during early winter and spring 2000.

Salinity values (Fig. 4) within Port Foster ranged from 33.5 to 34.0 psu over all sampling periods. The largest salinity values range occurred in February 2000 when salinity in near-surface water (<50 m) were about 0.2 psu less than those in deeper waters at Mid Bay. By May–June 2000, the water above 100 m was very slightly less saline than the water below 100 m at Mid Bay. In November 2000, the water column had returned to remarkably uniform salinity over the entire water column, though the salinity values measured in November 1999 were about 0.3–0.4 psu lower than those observed in November 2000. Salinity values in near-surface water of the Bransfield Strait (<25 m) were similar to those observed inside Port Foster in November 1999. Bransfield Strait water below about 50 m had higher salinities (near 34.3 psu) than observed inside Port Foster during any of the sampling periods. Salinity/depth profiles at the peripheral coves had the same range and profile shape as the Mid Bay.

3.2. *Oxygen and nutrient profiles: Mid Bay and the peripheral coves*

Oxygen concentration (Fig. 5) at the Mid Bay tracked temperature profiles during winter and early spring. Early in the November 2000 sampling period, oxygen values were nearly uniform with depth at Mid Bay. Later in the November 2000 sampling period, oxygen values in surface water was higher than values below 30 m. In February 2000, surface water had relatively high oxygen values and a slight mid-depth minimum near 50 m. In May–June 2000, oxygen values were nearly uniform to about 100 m depth, then decreased below 100 m. Oxygen values at the peripheral coves were similar to those at Mid Bay. Bransfield Strait oxygen showed little variation throughout the water column in November 1999. In May-June and November 2000, oxygen values were slightly lower, below 70 m.

Dissolved ammonia/depth profiles (Fig. 6) at the Mid Bay station also track the temperature profiles observed in early spring (November 1999 and the first few days of the November 2000 sampling period) and early winter (May–June 2000). Dissolved ammonia showed little variation over the entire water column at the Mid Bay in early November. In early winter, the ammonia profiles reflected the well-mixed water column from the surface down to about 100 m. There was an abrupt increase in concentration of dissolved ammonia in the colder layer below 100 m. However, the summertime (February 2000) ammonia profiles were different than the temperature profiles. Ammonia had a mid-depth maximum (>4 μM) at about 50 m, the same depth as the oxygen minimum. The peripheral cove ammonia profiles were similar to those observed at Mid Bay. Bransfield Strait ammonia profiles also in the upper 100 m were similar to those observed at Mid Bay and the peripheral coves.

Similar to dissolved ammonia, dissolved nitrate (Fig. 7) followed the temperature profiles in early spring and early winter. Nitrate was nearly uniformly distributed throughout the water column in November 1999. In May-June 2000, nitrate was well mixed in the water column and had increased concentrations below about 100 m. Surface depletions were observed at the Mid Bay station in February 2000. The peripheral cove nitrate profiles were similar to those observed at Mid Bay. The Bransfield Strait nitrate profiles had similar range and values in the upper 100 m as we

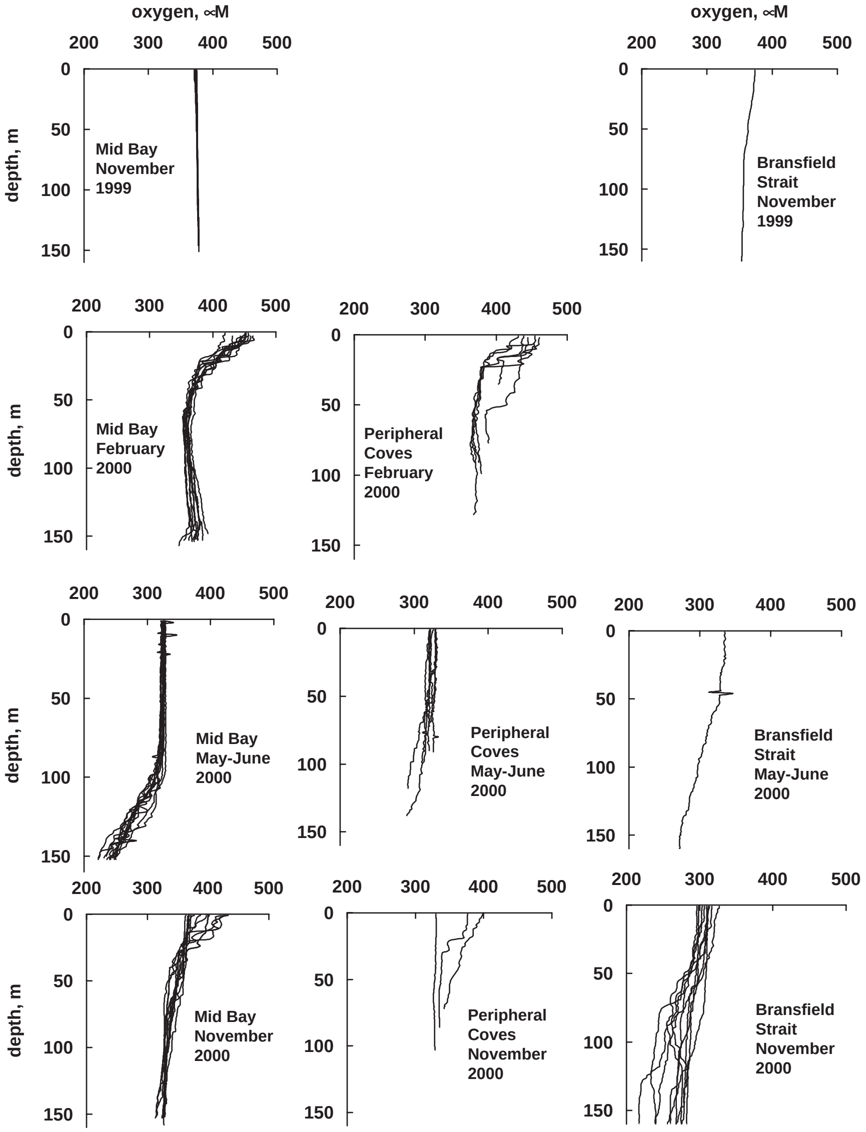

Fig. 5. Dissolved oxygen/depth profiles at Mid Bay, the peripheral coves and Bransfield Strait during November 1999, February, May–June and November 2000. Oxygen is in µM; depth is in meters.

observed at Mid Bay and peripheral coves within Port Foster.

Dissolved phosphate (Fig. 8) and silica profiles (Fig. 9) exhibited similar patterns to nitrate at the Mid Bay and peripheral coves. These profiles showed nearly uniform distribution over the entire water column in the early spring, nearly uniform concentration above 100 m and increased concentration below 100 m in early winter, and surface depletions during summertime.

The nutrient concentration for samples recovered during late November 2000 sampling period showed a transition consistent with the nearly uniform distribution of temperature throughout the water column to warming of surface waters late in the sampling period. Nitrate and phosphate

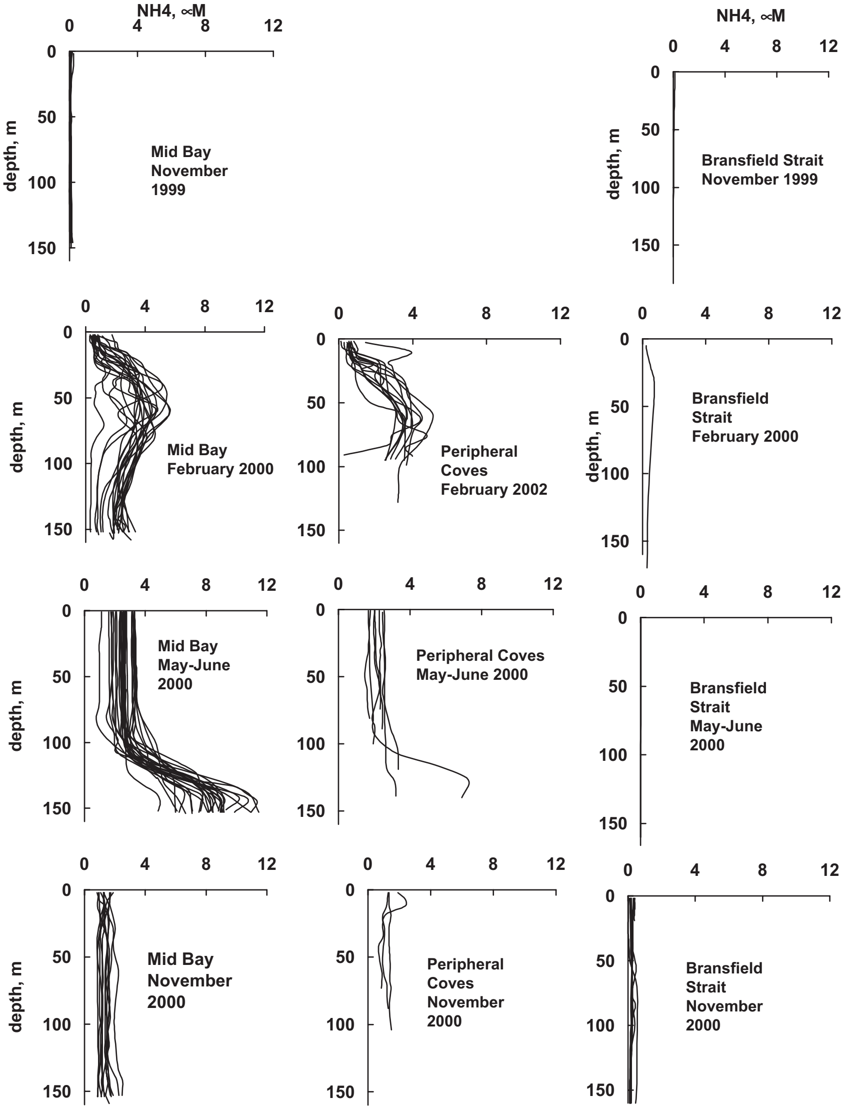

Fig. 6. Dissolved ammonia/depth profiles at Mid Bay, the peripheral coves and Bransfield Strait during November 1999, February, May–June and November 2000. Ammonia is in μM; depth is in meters.

profiles acquired early in the cruise indicate well-mixed, nearly uniform water column. Approximately 10 days later, these same parameters showed warmer surface water and surface water depletion of dissolved nitrate and phosphate (Figs. 3, 7 and 8, respectively). The change in dissolved parameters observed in November 2000 is particularly interesting because it captured the transition from the well-mixed winter–early spring condition to the more stratified summer condition. Such a rapid transition from well-mixed to well-stratified water column is supported by thermistor data from Port Foster from February to December 1999 (Lenn et al., 2003). Measured temperature plotted against time (Fig. 10) for thermistors at 11 m above bottom and 101 m above bottom further illustrates that surface waters were warmer (about 1.5°C to just below 0°C) between February

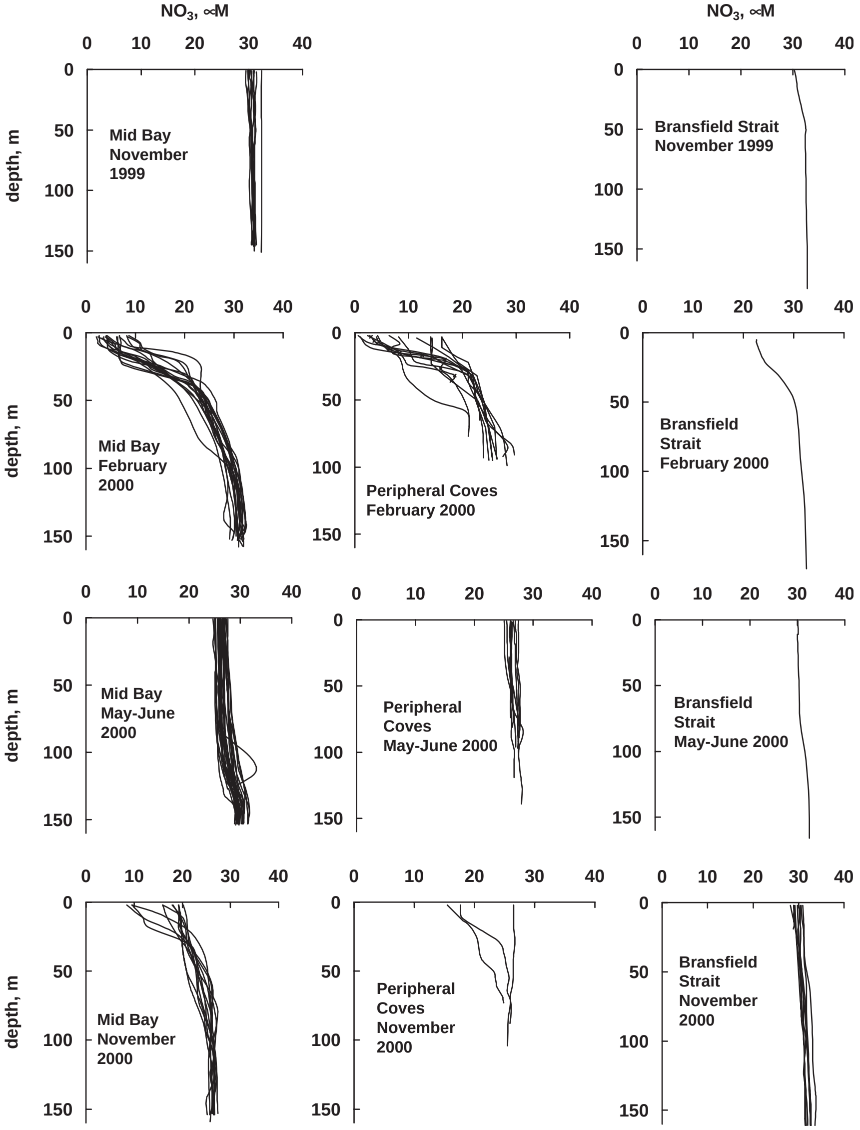

Fig. 7. Dissolved nitrate/depth profiles at Mid Bay, the peripheral coves and Bransfield Strait during November 1999, February, May–June and November 2000. Nitrate is in μM; depth is in meters.

and June 1999, indicating stratified water-column conditions. By mid-June 1999, water at 101 and 11 m above bottom had the same temperature, indicating well-mixed, non-stratified conditions. The transition from stratified conditions to well-mixed conditions occurred in June and was abrupt. The thermistor array data for November 1999 reflect the same well-mixed water column observed in the CTD data (Fig. 3).

3.3. Nutrients: shallow water and beach interstitial water

Mean nutrient concentrations for runoff, beach interstitial, and surface-water samples in shore, offshore, and the CTD stations collected during February, May–June and November 2000 are summarized in Fig. 11 and Table 1. The concentrations of dissolved nitrate, phosphate, ammonia,

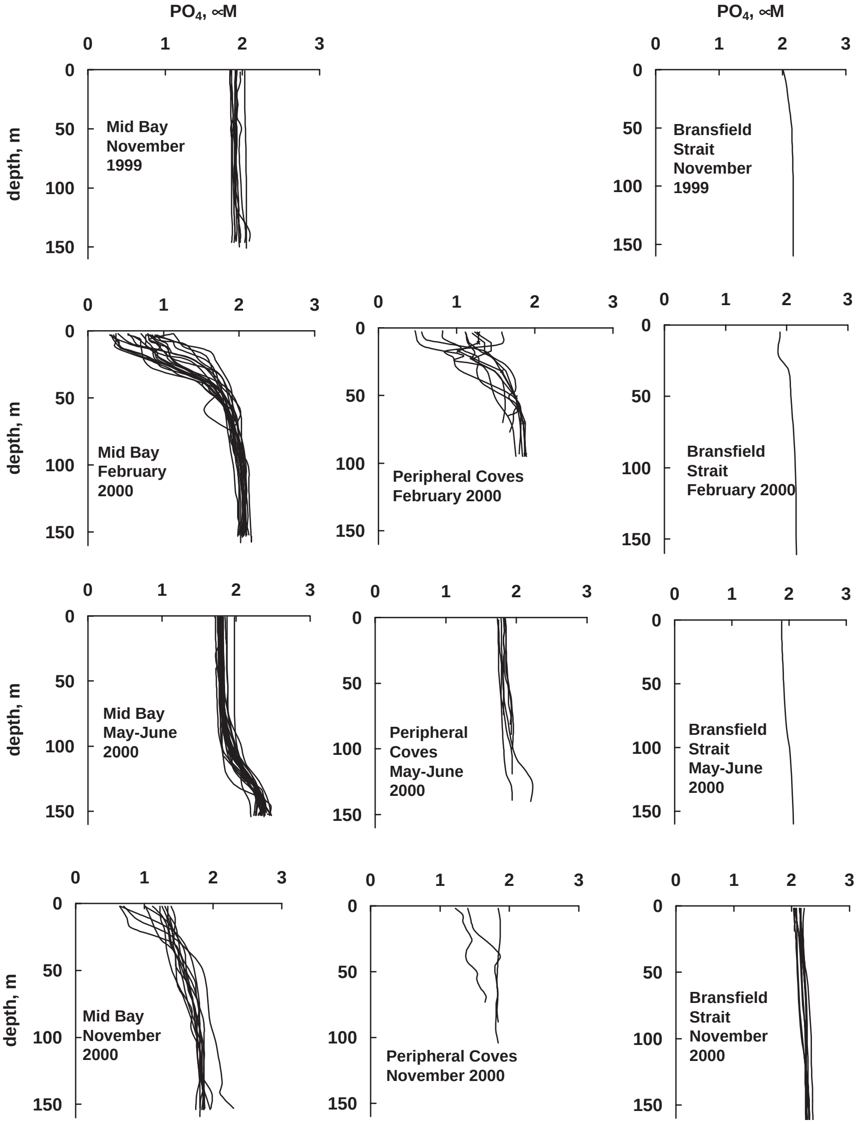

Fig. 8. Dissolved phosphate/depth profiles at Mid Bay, the peripheral coves and Bransfield Strait during November 1999, February, May–June and November 2000. Phosphate is in μM; depth is in meters.

and silica in the shore, offshore, and beach interstitial stations were much more variable than in the surface water samples collected at the CTD stations. In spite of their variability, the mean concentrations of phosphate, nitrate, and silica in the beach interstitial samples were significantly higher than in the shore, offshore and CTD samples ($p < 0.001$). Mean nutrient concentrations of the beach interstitial samples were 2.8–4.3, 3–5.7, and 6.3–9.5 times higher than CTD water samples, for phosphate, nitrate, and silica, respectively (Table 1). There was no significant difference in the concentrations of ammonia among the beach, shore, and offshore samples collected during November 2000. However, shore and offshore samples collected during May–June

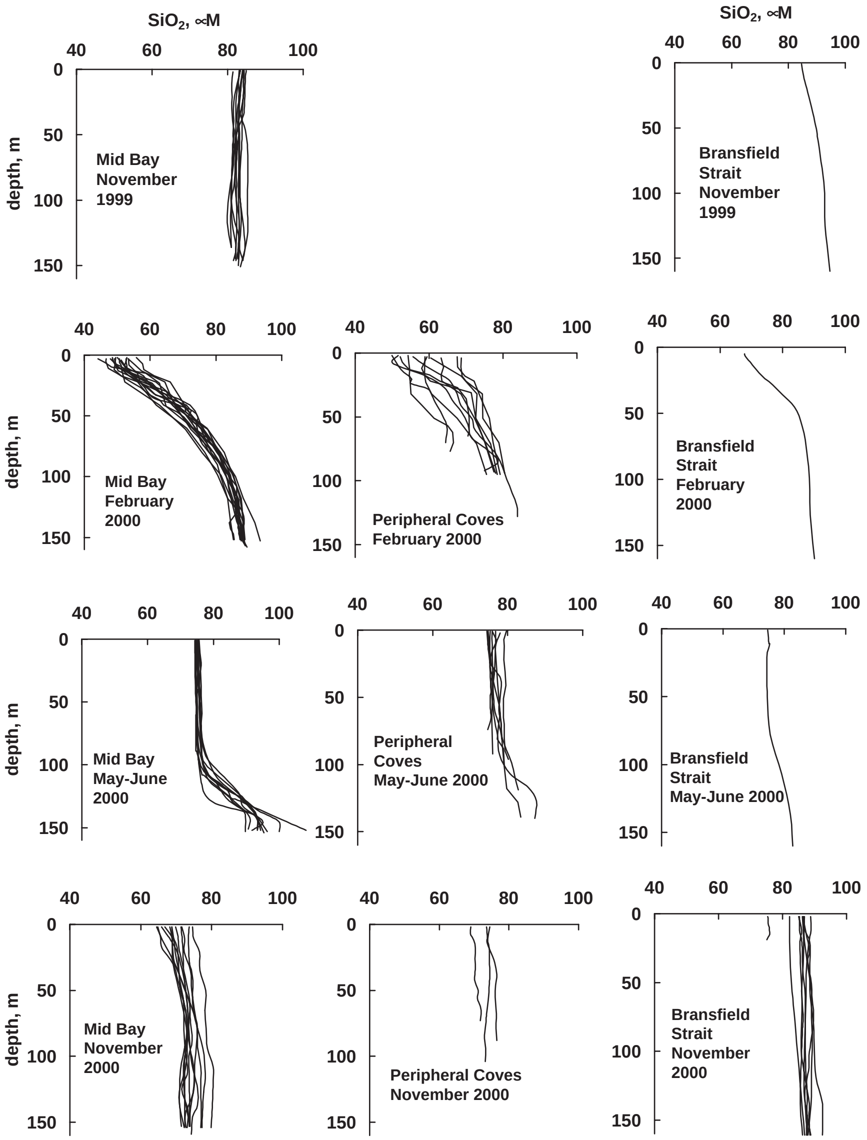

Fig. 9. Dissolved silica/depth profiles at Mid Bay, the peripheral coves and Bransfield Strait during November 1999, February, May–June and November 2000. Silica in is μM; depth is in meters.

2000 had significantly higher ammonia concentrations than did those collected on the beach ($p = 0.008$). Phosphate, nitrate and silica concentrations of the shore samples collected during November 2000 were significantly higher than the offshore samples ($p = 0.011$ for phosphate; $p < 0.001$ for nitrate; $p = 0.044$ for silica), but there were no significant differences in concentrations of these nutrients among the sample types collected during May–June 2000 (Table 1, Fig. 11).

For most sample types, mean nutrient concentrations for early winter and spring were not significantly different. However, mean ammonia concentrations of beach interstitial waters collected during November 2000 were significantly higher than those collected during May–June 2000

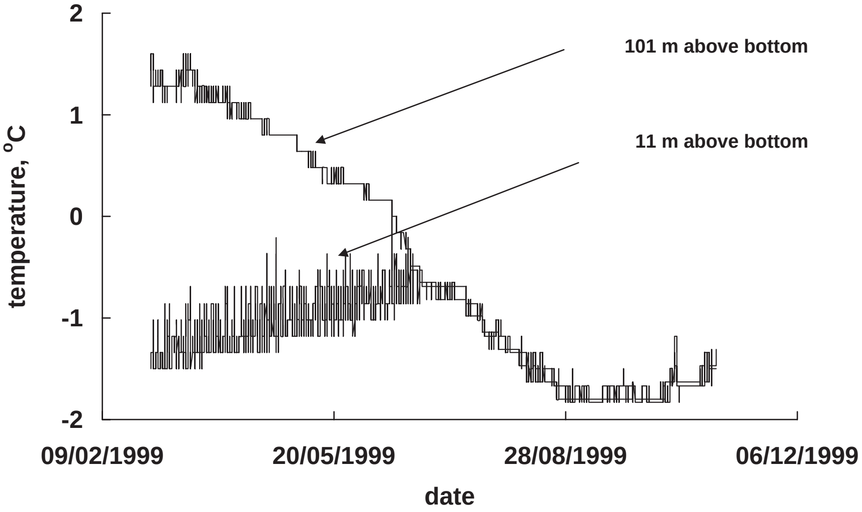

Fig. 10. Thermister array data. Temperature, in °C, variation from February to November, 1999 at 11 m above the sea floor and 101 m above the sea floor. Note the difference in temperature between the two depths from February to June. Note the abrupt transition to the same temperature at both depths in June and the maintenance of nearly the same temperature at both depths until November 1999.

($p = 0.003$). Also, mean phosphate and nitrate concentrations of offshore samples collected during May–June 2000 were significantly higher than those collected during November 2000 ($p < 0.001$) (Fig. 11).

Nutrient concentrations of snow and runoff samples collected during November 2000 were highly variable. The mean ammonia concentration of snow and runoff samples was 78 times higher than the mean ammonia concentration of Mid Bay samples (Table 1). The mean phosphate concentration of the snow and runoff was over five times higher than the mean Mid Bay phosphate concentration. Mean nitrate concentrations were similar to their concentrations at the Mid Bay and mean silica concentrations of the snow and runoff samples were less than 25% of their mean concentration at Mid Bay.

A positive linear correlation between phosphate and nitrate concentrations was evident in the offshore samples collected during February 2000 and May–June 2000 ($R^2 = 0.7$; $p < 0.001$) but not for the offshore samples collected during November 2000. Temperature was strongly correlated with silica concentrations for the shore and offshore samples ($R^2 = 0.93$ and 0.91, $p < 0.001$ and $p < 0.001$, respectively) and moderately correlated for the beach interstitial samples ($R^2 = 0.66$, $p < 0.001$) (Fig. 12). We did not find any relationship between nutrient concentrations and salinity.

3.4. Chlorophyll a and net phytoplankton: Mid Bay

Phytoplankton populations were observed in two conditions during the 1-year period: non-bloom and bloom (Table 2). During the non-bloom periods at Port Foster, in the top 40 m, chl *a* averaged 0.5 mg m^{-3} in November 1999 ($n = 5$), and 0.2 mg m^{-3} in June 2000 ($n = 9$). The austral spring and summer months were punctuated by averages of 19 mg m^{-3} in February 2000 ($n = 4$) and 15 mg m^{-3} in November 2000 ($n = 8$). During non-bloom periods, chl *a* was distributed fairly evenly throughout the top 40 m in November 1999 and very evenly distributed in June 2000. In November 1999, chl *a* was at a maximum at the surface or slightly below the surface (~10 m) followed by a decreasing gradient towards deeper water. In June 2000, chl *a* was evenly distributed showing very little vertical structure. Net phytoplankton collected during non-bloom periods were mainly composed of solitary disc-shaped diatoms

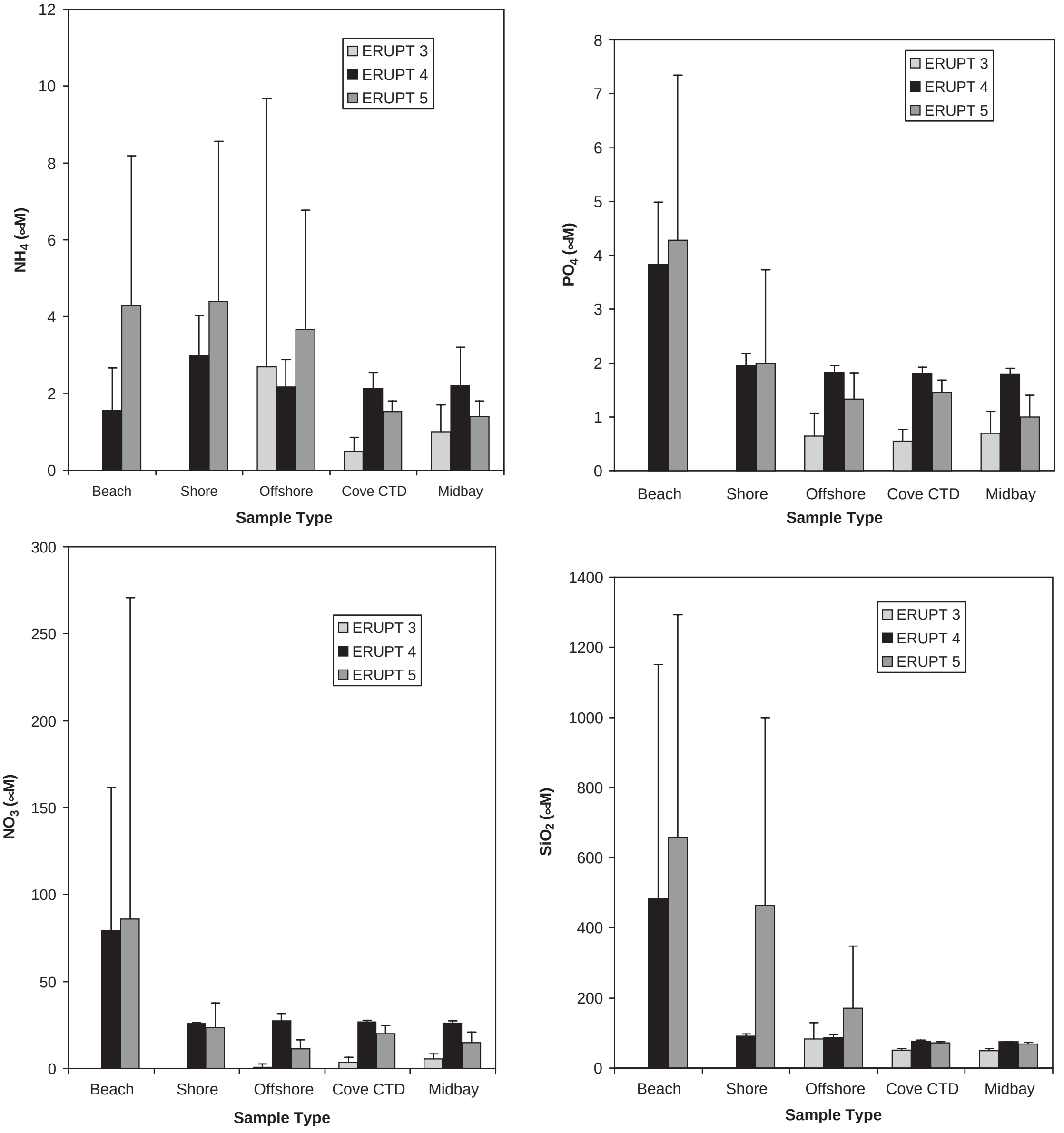

Fig. 11. Mean nutrient concentrations (+/−S.D.) for beach interstitial, shore, and offshore water samples. These samples were collected during Erupt III (February 2000), Erupt IV (May–June 2000) and Erupt V (November 2000).

such as *Conscinidiscus* spp., while other diatoms were present though less abundant (*Rhizosolenia* spp., *Thalassiosira* spp., *Eucampia* spp., *Chaetoceros* spp., and *Corethron* spp.). In contrast, during blooms in February 2000 and November 2000, the chl *a* vertical distribution was highly variable from the surface to 40 m (Table 2). The summer bloom in February 2000 was characterized by large chains of *Thalassiosira* spp. and *Rhizosolenia* spp., while the spring bloom in November 2000 was dominated solely by large chains of *Thalasiossira* spp.

Table 1
Mean nutrient concentrations (±S.D.) for beach interstitial, shore, offshore and surface CTD station water samples

Date	Sample type	Temp. (°C)	±	N	Salinity (psu)	±	N	Ammonia (µM) (*mg/kg)	±	N	Phosphate (µM) (*mg/kg)	±	N	Nitrate (µM) (*mg/kg)	±	N	Silica (µM) (*mg/kg)	±	N
Feb-00	Offshore							3 0.1*	7 0.1	21	0.7 0.06*	0.4 0.04	23	1 0.1*	2 0.1	23	83 5.0*	47 3	22
Feb-00	Cove CTD							0.5 0.009*	0.03 0.006	4	0.5 0.05*	0.2 0.02		3 0.2*	3 0.2	4	51 3.1*	5 0.3	4
Feb-00	Midbay CTD							1 0.02*	0.7 0.01	20	0.7 0.07*	0.4 0.04	20	6 0.4*	3 0.2	20	50 3.0*	6 0.4	20
May-00	Beach	9.5	14	12	26	8	13	2 0.03*	1 0.02	13	4 0.4*	1 0.1	13	79 4.9*	82 5	13	480 29*	670 41	13
May-00	Shore	−0.2	2	5	34	4	5	3 0.05*	1 0.02	5	1.9 0.18*	0.2 0.02	5	25.6 1.59*	0.7 0.04	5	91 5.5*	6.0 0.4	5
May-00	Offshore	1	1		37	1	54	2.2 0.040*	0.7 0.01	54	1.8 0.17*	0.1 0.009	54	27 1.7*	4 0.3	54	86 5.2*	10 0.6	54
May-00	Cove CTD							2.1 0.038*	0.4 0.007	12	1.8 0.17*	0.1 0.009	12	26.8 1.66*	0.9 0.1	12	77 4.6*	3 0.2	12
May-00	Midbay CTD							2 0.04*	1 0.01	27	1.8 0.17*	0.1 0.009	27	26 1.6*	1 0.08	27	75.0 4.51*	0.5 0.03	27
May-00	Deep	1.1	2.2	15	33	11	15	4 0.07*	6 0.07	15	2 0.2*	1 0.09	15	93 5.8*	180 11	15	103 6.21*	64 4	15
Nov-00	Beach	21.0	17.0	72	23	10	72	4 0.08*	4 0.07	52	4 0.4*	3 0.3	52	86 5.3*	180 11	54	660 39*	640 38	72
Nov-00	Shore	13.0	13.0	68	31	7	68	4 0.07*	4 0.07	42	2 0.2*	2 0.2	58	24 1.5*	14 0.9	59	460 28*	530 32	69
Nov-00	Offshore				35	4	114	4 0.07*	4 0.07	42	1.3 0.12*	0.5 0.05	57	11 0.71*	5 0.3	57	170 10*	180 10	110
Nov-00	Cove CTD							1.5 0.028*	0.3 0.005	4	1.5 0.14*	0.2 0.02	4	20.1 1.24*	4.8 0.29	4	72 4.3*	3 0.2	4
Nov-00	Midbay CTD							1.4 0.025*	0.4 0.007	12	1.0 0.095*	0.4 0.04	12	15 0.91*	6 0.4	12	69 4.2*	4 0.2	12
Nov-00	Snow & runoff							90 2*	130 2	3	7 0.6*	9 0.8	4	13 0.82*	16 0.9	4	15 0.90*	19 1.1	5
MEAN	Beach	19.6	16.8	84	23	9	85	4 0.07*	4 0.07	65	4 0.4*	3 0.3	65	85 5.2*	170 10	67	630 38*	640 38	85
MEAN	Shore	11.6	12.7	73	32	7	73	4 0.08*	4 0.07	47	2 0.2*	2 0.2	63	24 1.5*	14 0.9	64	440 26*	530 31	74
MEAN	Offshore	2.6	3.8	156	36	3	168	3 0.05*	3 0.05	117	1.4 0.13*	0.6 0.06	134	16 1.0*	11 0.7	134	130 8.2*	140 9	186
MEAN	Cove CTD							1.6 0.028*	0.7 0.012	20	1.4 0.13*	0.5 0.05	20	19 1.2*	9 0.6	20	70 4.2*	10 0.6	20
MEAN	Midbay CTD							1.2 0.021*	0.9 0.02	67	1.4 0.13*	0.6 0.06	67	19 1.2*	11 0.7	67	69 4.2*	14 0.8	67
MEAN	Deep	1.2	2.2	15	33	11	15	4 0.1*	6 0.1	15	2 0.19*	1 0.09	15	93 5.7*	180 11	15	103 6.21*	64 3.8	15
MEAN	Snow & runoff							90 1*	130 2	3	7 0.7*	9 0.8	4	13 0.82*	16 1	4	15 0.90*	19 1.1	5

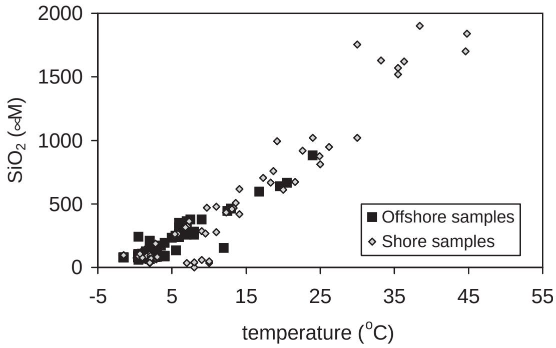

Fig. 12. Temperature versus silica, µM, concentrations for shore and offshore samples. Temperature is in °C; silica is in µM.

Table 2
Seasonal variation in mg chlorophyll $a\,\mathrm{m}^{-3}$ averaged over the upper 40 m (chl a)±standard deviation, and >25 µm phytoplankton species composition of a 1 year period

Cruise	Chl a	>25 µm species composition
November 1999	0.54±0.25	Solitary centric diatoms
February 2000	19±5	Chained centric diatoms
June 2000	0.23±0.05	Solitary centric diatoms
November 2000	15±2	Chained centric diatoms

4. Discussion

Within Port Foster temperature, dissolved nutrients and oxygen profiles exhibited typical distributions for a normal shallow seawater column in a polar region. We observed a well-mixed water column in the early austral spring, changing to a more stratified water column during the summer, and by early winter the water column was well mixed in a surface layer that increased with depth until the entire water column returned to well-mixed conditions. Long-term thermistor data supports the water chemical composition data by showing a weak but well-established thermocline during the late spring and summer followed by erosion of the thermocline over time progressing into the winter (also see Lenn et al., 2003). The peripheral cove profiles exhibit comparable shape and seasonal changes. Therefore, we are able to use the additional detail of data from Mid Bay to make some generalizations about the distribution of temperature, dissolved nutrients and oxygen in Port Foster as a whole.

Lenn et al. (2003) present data that define advection in two parts, within the mixed layer and below the mixed layer to the bay floor. Their data indicates current reversal across the base of the mixed layer. The depth of the layer of shear at the current reversal boundary follows the deepening of the mixed layer during the transition from summer stratification to the winter well-mixed water column condition. Dissolved nutrient profiles can be interpreted within the context of seasonal changes in the depth of the shear boundary.

As one would expect during the seasons of light limitation, when primary productivity was low, near-surface nutrient concentrations were not depleted (Libes, 1992). Decomposition of phytoplankton should lead to nitrogen and phosphorous compounds being released to the water column from soft tissue and dissolution of siliceous tests. Therefore, remineralization of biogenic material should contribute to the observed concentrations of dissolved nutrients in the mixed layer. During the winter, grazers may consume little to no phytoplankton. Though not all krill are grazers, krill collected during the May–June 2000 cruise had empty guts (Cullen et al., 2003). In addition, though they studied northern krill and worked at temperatures ranging from 4°C to 12°C, Saborowski et al. (2002) suggest that excretion of ammonia increases with rising temperature. Therefore, ammonia excretion by zooplankton was likely to be relatively low during the low-light season and higher during the austral summer. Dissolved oxygen was abundant, so dissolved ammonia would be rapidly oxidized to nitrate, leaving low concentrations of dissolved ammonia (Horrigan, 1990).

Effects of the resident animal populations would be seen as relatively high dissolved ammonia and low oxygen below the shear boundary (100 m) during May–June 2000. Relatively high ammonia could be attributed to either microbial decomposition of sinking organic detritus and/or excretion of metabolites by animals residing near the bay floor (Libes, 1992). The decrease in dissolved oxygen observed in the layer below 100 m supports the presence of animal respiration near the bay floor. Kaufmann et al. (2003) found a larger abundance of animals (macrozooplankton and micronekton) in the 100–150 m depth interval than at shallower depth during May–June 2000 in Port Foster.

It is important to remember that similar vertical distributions of dissolved nutrients were observed at the peripheral cove stations and at Mid Bay. This suggests that, during the seasons of low-primary productivity, local currents were effective at redistributing dissolved biochemical components throughout the bay. Dissolved biochemical components, such as nitrate, ammonia, phosphate and silica, accumulated during the winter and early spring had residence times that were longer than circulation time, leading to nutrient distributions that track the temperature profiles. Thus, evolution of the depth of the mixed layer from near-surface to the bay floor explains the profiles observed during winter and early spring. Vertical segregation is eliminated as the thermocline erodes. In other words, it is the physical redistribution processes that exerted the most important control on dissolved biogenic components distribution during seasons of low primary productivity.

During the summer season when light availability does not limit primary production in the upper part of the water column, the dissolved nutrient and oxygen distributions reflected consumption of nutrients by the primary producers (Libes, 1992; Dam et al., 1995; Steinberg et al., 2002). During the summer season, the thermocline, though weak, contributed to stratification of the water column. Vertical segregation of dissolved nutrients was maintained. Surface depletions were observed in the ammonia, nitrate, phosphate and silica profiles. Oxygen was higher in very near-surface water (down to about 20 m) and exhibited lower values below about 25 m, indicating oxygen production during photosynthesis, leading to super-saturation in the photic zone. Oxygen utilization by respiration at deeper levels, indicated by the mid-depth oxygen minimum at the same depth as the ammonia maximum implies the excretion of metabolites from resident animal populations in Port Foster (Dam et al., 1995; Steinberg et al., 2002).

The zooplankton and micronekton tend to reside at greater depth during the day and migrate upward at night (Kaufmann et al., 2003). Long-term acoustic backscatter data from an acoustic Doppler profiler moored in Port Foster also provide evidence supporting the diel vertical migration of zooplankton (Lenn et al., 2003). With diel migration of zooplankton in mind, we examined all of the daily noon/midnight Mid Bay station daily CTD cast pairs in order to look for coupled changes in the depth of the dissolved ammonia maximum. Some ammonia/depth profile pairs showed shallower maxima during dark hours than during light hours, as the zooplankton distributions would predict. However, we did not see such a pattern in all cases. We also tried to correlate the depth of ammonia maximum to time in the tidal/inertial current cycle in an attempt to link changes observed in the ammonia profiles to the advection patterns documented by Lenn et al. (2003). That effort also gave inconsistent results. Thus, we conclude that, during the summer season, distribution of dissolved ammonia reflects a complex pattern of both physical advection and biochemical processes. Dissolved ammonia must be influenced by more than simple placement of animal populations because the profiles observed during this study present a more complex pattern than direct correlation with animal population locations would predict. Certainly, microbes are likely to play an important role in ammonia distribution (Horrigan, 1990). However, microbial analyses were not part of the Erupt Project. In spite of our inability to resolve detailed daily patterns in the dissolved ammonia data, we can say that in general, we see a similar shape and magnitude of the dissolved ammonia at Mid Bay and the peripheral coves during the austral summer. We interpret the ammonia profiles to indicate that, on average, zooplankton populations, following the current, occupy most of the Port Foster area, including the peripheral coves. This is consistent with the persistent basin-wide circulation demonstrated by Lenn et al. (2003). Although we cannot confirm basin-wide zooplankton distribution because trawl collections were made only along the NW–SE axis of the main part of the bay (Kaufmann et al., 2003), it is reasonable to assume that the zooplankton populations do distribute basin-wide. This reinforces the interpretation that the same biochemical processes influence the peripheral coves as are observed at Mid Bay. If, as Bode et al. (2002) suggest, dissolved ammonia regeneration in high biomass frontal zones is sufficient to supply phytoplankton demands on a daily scale during the austral summer, advection within the semi-enclosed area of Port Foster must be sufficiently vigorous to maintain adequate supplies of nutrients to the photic zone throughout the bay.

Values of dissolved nitrate measured in the Bransfield Strait during this study are near those measured in the Bransfield Strait during the FRUELA cruises in summer 1995–6 (Bode et al., 2002; Castro et al., 2002). Bode et al. (2002) report dissolved nitrate values $>10\,\mu\mathrm{M\,N\,l^{-1}}$ seawater in near-surface waters, increasing to near $30\,\mu\mathrm{M\,N\,l^{-1}}$ seawater with depth. In their Zone 3, the region of Bransfield Strait nearest Deception Island, Bode et al. (2002) report dissolved ammonia values generally $<0.2\,\mu\mathrm{M\,N\,l^{-1}}$ seawater, with a subsurface maximum at one station at about 20–40 m near $20\,\mu\mathrm{M\,N\,l^{-1}}$ seawater. Dissolved ammonia values measured during this study in the Bransfield Strait (0.1–0.2 μM) are more in line with the average values observed by Bode et al. (2002) and lower than the maximum values observed at Mid Bay within Port Foster during summer (Fig. 6). The relatively high concentrations of dissolved ammonia found within Port Foster may reflect the confined nature of circulation within the semi-enclosed bay.

Port Foster's phytoplankton biomass exhibited temporal variability on seasonal scales, similar to other coastal and continental shelf zones (CCZ) of the Antarctic Peninsula (Holm-Hansen et al., 1989; Smith et al., 1996). Based on net phytoplankton analysis, blooms in February and November 2000 were dominated by centric diatoms *Thalassiosira* spp. and *Rhizosolenia* spp., and were presumably the summer and spring blooms, respectively. Chl *a* values of 15 and $19\,\mathrm{mg\,m^{-3}}$ in Port Foster during these blooms were comparable to maximum-recorded levels in western Antarctic Peninsula CCZ (30–40 mg chl $a\,\mathrm{m^{-3}}$), while chl *a* values from November 1999 and June 2000 (non-bloom conditions) corresponded to historical monthly chl *a* averages of western Antarctic Peninsula CCZ ($<5\,\mathrm{mg\,m^{-3}}$).

Observations of surface depletion of macronutrients nitrate and phosphate were concomitant with the observed spring and summer blooms. Silicate surface depletion was more evident in the summer bloom (February 2000) when compared to the spring bloom (November 2000). Using a carbon:chl *a* estimation of 60 and the Redfield ratio, 106 C:16 N:1 P, if Port Foster is was N-limited, complete N-utilization would yield about 40 mg chl $a\,\mathrm{m^{-3}}$. During blooms, phytoplankton standing stock could account for about 15 μM nitrate, which corresponds to the observed surface nitrate depletion (Fig. 7). Based on the above analysis of Port Foster, it can be concluded that macronutrients were only partially utilized by phytoplankton and that primary production was not limited by macronutrient availability. Antarctic waters have been observed to be far in excess of macronutrients with respect to the needs of phytoplankton growth (Bidigare et al., 1988). However, macronutrient depletion during blooms may be limiting with respect to phytoplankton growth rates (Holm-Hansen et al., 1989).

Elevated nutrients measured in the beach and interstitial and near shore cove however, appear to be influenced primarily by subaerial and shoreline processes. One approach to evaluate the contribution of these local processes to Port Foster is to examine nutrient concentrations in the waters of the shallow-water coves. Although eolian processes could transport material all over Port Foster, runoff, ice-rafting and hydrothermal processes are more pronounced in the coves. Fresh water from runoff, ice, and heated hydrothermal water would likely initially spread from the shoreline as a low-density surface plume before mixing with the ambient seawater.

For samples collected in the shallow waters between the beach and the cove CTD stations, the concentrations of phosphates and nitrates in the offshore surface samples are consistent with the surface samples from the CTD stations. Beyond a few meters of the shoreline, the temporal changes in surface nitrate and phosphate concentrations reflect Mid Bay values.

Throughout the year, eolian processes are depositing a high volume of sediment and dust derived from the volcano into the waters of Port Foster. More material is available for eolian transport when snow and ice cover are reduced. Settling particulate matter collected during this sampling program indicate that large volumes of lithogenous material from the island are being deposited into the middle of the bay (Baldwin and Smith, 2003; Gray et al., 2003). Given the temporal variability of windiness, runoff, and snow and ice cover, we might expect the relative contribution of subaerially derived dissolved nutrients to vary seasonally.

In addition to nutrient inputs from the surrounding volcano, hydrothermal processes, which are most active along the shorelines of the coves (Dykes, 2002), may affect dissolved nutrient concentrations. Not only does hydrothermal activity promote water–rock chemical exchange, but hydrothermal heating may affect the solubility of nutrients. Dissolved silica, in particular, is affected by hydrothermal processes.

Elevated nutrients measured in the beach and interstitial and near shore cove however, appear to be influenced primarily by subaerial and shoreline processes. Possible sources for the high phosphate, nitrate, and ammonia concentrations in the beach interstitial and shore waters include decaying organic matter such as krill carcasses that were occasionally seen washed up on the beaches and bird and mammal excrement. Observations during the Erupt Project indicate that mammals and birds tended to congregate in the coves where warm hydrothermal areas are located (Kendall et al., 2003). The high variability of the beach and shore nutrient concentrations as well as snow and runoff samples collected during November 2000 is consistent with the inherent temporal and spatial patchiness of these nutrient sources.

During the November-December field season, we observed the formation of melt water streams which flowed into the coves and spread low salinity water as a surface lens for tens of meters beyond the shoreline (Dykes, 2002). In contrast, the ground was frozen during May-June of 2000. The enhanced fluvial and groundwater flow during November 2000 may have delivered subaerially derived nutrients to the shore waters. In addition, higher animal populations were observed near the coves during the November field season (Kendall et al., 2003). Although ammonia concentrations of the beach interstitial waters were significantly higher during November than May-June of 2000, the data did not show a significant difference in the mean phosphate and nitrate concentrations of the beach interstitial or shore samples between the two sampling periods. However, even though there was no difference in the concentrations of nutrients between the shore and offshore samples during May-June, nutrient concentrations in the shore samples were significantly higher than the offshore samples during November 2000, suggesting that the increased runoff and groundwater flow from the shore could be delivering nutrients into the shore waters. The fact that our results did not show an inverse correlation between salinity and nutrient concentrations may be due to the temporal and spatial patchiness of the shoreline and near-shore nutrient sources. In summary, the elevated phosphate and nitrate concentrations measured in the beach interstitial water did not appear to persist beyond the shoreline during May-June 2000 or beyond 5 m of the shoreline during November-December.

Unlike phosphate, nitrate and ammonia, dissolved silica concentrations in the beach and shore samples were controlled primarily by hydrothermal, rather than biological processes. Dissolved silica in the near-shore areas is derived from chemical weathering of rocks and is more soluble at higher temperatures. Dissolution of diatom tests also may contribute to the dissolved silica in the water. The strong correlation between temperature and silica concentrations suggests that higher dissolved silica was found in waters that had been hydrothermally heated. There were very few diatom tests in the sediments collected in the near-shore or beach areas. Dissolved silica concentrations in beach interstitial waters were 6.3–9.5 times higher than at the CTD stations. Elevated dissolved silica concentrations were restricted to the beach interstitial waters during May-June 2000, when the ground was frozen and there was minimal groundwater flow. However, during November-December, elevated dissolved silica concentrations could be traced beyond the shore waters, 10's of meters beyond the shoreline.

Exchange across Neptune's Bellows has been modeled by Lenn et al. (2003) with current velocity of $25 \pm 5\,\mathrm{cm\,s^{-1}}$ and a volume transport of $1.5 \times 10^3\,\mathrm{m^3\,s^{-1}}$. Within Port Foster, persistent residual currents are on the order of 1–$3\,\mathrm{cm\,s^{-1}}$. Thus, documented circulation is also consistent with redistribution of dissolved and suspended components within Port Foster, and exchange across Neptune's Bellows. The higher values of dissolved ammonia within Port Foster compared to those in Bransfield Strait (Fig. 6) suggest that dissolved components produced within Port Foster are readily diluted as the mixing processes progress.

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References

Arrigo, K.R., Wothen, D.L., Lizotte, M.P., Dixon, P., Dieckmann, G., 1997. Primary production in Antarctic sea ice. Science 276, 394–397.

Baldwin, R.J., Smith Jr., K.L., 2003. Temporal dynamics of particulate matter fluxes and sediment community response in Port Foster, Deception Island, Antarctica. Deep Sea Research II, this issue (doi:10.1016/S0967-0645(03)00089-4).

Barker, D., Austin,, J., 1998. Rift propagation, detachment faulting and associated magmatism in the Bransfield Strait, Antarctica. Journal of Geophysical Reasearch 103, 24017–24034.

Bidigare, R.R., Ondrusek, M., El-Sayed, S., Stephens, C., 1988. Polar Programs Data Report: photosynthetic pigment investigations at Palmer Station, Antarctica, pp. 1–28.

Bode, A., Castro, G.C.G, Doval, M.D., Varela, M., 2002. New and regenerated production and ammonium regeneration in the western Bransfield Strait region (Antarctica) during phytoplankton bloom conditions in summer. Deep-Sea Research II 49, 787–804.

Castro, C.G., Rios, A.F., Doval, M.D., Perez, F.F., 2002. Nutrient utilization and chlorophyll distribution in the Atlantic sector of the Southern Ocean during austral summer 1995–96. Deep Sea Research II 49, 623–641.

Cullen, M., Kaufmann, R.S., Lowery, M.S., 2003. Seasonal variation in biological indicators of physiological status in *Euphausia superba* from Port Foster, Deception Island, Antarctica. Deep Sea Research II, this issue (doi:10.1016/S0967-0645(03)00088-2).

Dam, H.G., Roman, M.R., Youngbluth, M.J., 1995. Downward export of respiratory carbon and dissolved inorganic nitrogen by diel-migrant mesozooplankton at JGOFS Bermuda time-series station. Deep Sea Research I 42, 1187–1197.

Dykes, K., 2002. The influence of hydrothermal activity on seawater composition (Ca/Mg and Si) of Port Foster, Deception Island. Masters Thesis, University of San Diego.

Gordon, A.L., Nowlin Jr., W.D., 1978. The basin waters of the Bransfield Strait. Journal of Physical Oceanography 8, 258–264.

Gray, S.C., Sturz, A., Bruns, M., Marzan, R., Dougherty, D., Law, H., Brackett, J., Marcou, M., 2003. Composition and distribution of sediments and benthic foraminifera in a submerged caldera after 30 years of volcanic quiescence. Deep Sea Research II, this issue (doi:10.1016/S0967-0645(03)00090-0).

Holm-Hansen, O., Mitchell, B.G., 1991. Spatial and temporal distribution of phytoplankton and primary production in the western Bransfield Strait region. Deep-Sea Research II 39, 961–980.

Holm-Hansen, O., Mitchell, B.G., Hewes, C.D., Karl, D.M., 1989. Phytoplankton blooms in the vicinity of Palmer Station, Antarctica. Polar Biology 10, 49–57.

Horrigan, S.G., 1990. Oceanic and estuarine ammonia oxidation: effects of light. Limnology and Oceanography 35, 479–482.

Ibanez, J.M., Del Pezzo, E., Almendros, J., La Rocca, M., Alguacil, G., Ortiz, R., Garcia, A., 2000. Seismovolcanic signals at Deception Island volcano, Antarctica: wave field analysis and source modeling. Journal of Geophysical Research 105, 13905–13931.

Kaufmann, R.S., Fisher, E.C., Gill, W.H., King, A.L., Laubacher, M., Sullivan, B., 2003. Temporal patterns in the distribution, biomass and community structure of macrozooplankton and micronekton within Port Foster, Deception Island, Antarctica. Deep Sea Research II, this issue (doi:10.1016/S0967-0645(03)00092-4).

Keller, R.A., Fisk, M.R., 1992. Quaternary marginal basin volcanism in the Bransfield Strait as a modern analogue of the southern Chilean ophiolites. In: Parson, L.M., Murton, B.J., Browning, P. (Eds.), Ophiolites and Their Modern Oceanic Analogues. Geological Society Special Publication 60, The Geological Society of London, pp. 155–169.

Kendall, K.A., Ruhl, H.A., Wilson, R.C., 2003. Distribution and abundance of marine bird and pinniped populations within Port Foster, Deception Island, Antarctica. Deep Sea Research II, this issue (doi:10.1016/S0967-0645(03)00096-1).

Lenn, Y-D., Chereskin, T.K., Glatts, R.C., 2003. Seasonal to tidal variability in currents, stratification, and acoustic backscatter in an Antarctic ecosystem at Deception Island. Deep Sea Research II, this issue (doi:10.1016/S0967-0645(03)00085-7).

Libes, S.M., 1992. An Introduction to Marine Biogeochemistry. Wiley, New York, pp. 105–199.

Lopez, O., Garcia, M.A., Gomis, D., Rojas, P., Sospedra, J., Sanchez-Arcilla, A., 1999. Hydrographic and hydrodynamic characteristics of the eastern basin of the Bransfield Strait (Antarctica). Deep Sea Research I 46, 1755–1778.

Rey, J., Somoza, L., Martinez-Frias, J., Benito, R., Martin-Alfageme, S., 1997. Deception Island (Antarctica): a new target for exploration of Fe–Mn mineralization? In: Nicholson, K., Hein, J.R., Buhn, B., Dasgupta, S. (Eds.), Manganese Mineralization: Geochemistry and Mineralogy of Terrestrial and Marine Deposits. Geological Society Special Publication 119, pp. 239–251.

Saborowski, R., Brohl, S., Tarling, G., Bucholtz, F., 2002. Metabolic properties of Northern krill, *Meganyctiphanes norvegica*, from different climatic zones. Marine Biology 130, 547–556.

Smith Jr., K.L., Baldwin, R.J., Kaufmann, R.S., Sturz, A., 2003a. Ecosystems studies at Deception Island, Antarctica: an overview. Deep Sea Research II, this issue (doi:10.1016/S0967-0645(03)00081-X).

Smith Jr., K.L., Baldwin, R.J., Glatts, R.C., Chereskin, T.K., Ruhl, H.A., Lagun, V., 2003b. Weather, ice and snow conditions at Deception Island, Antarctica: long time-series photographic monitoring. Deep Sea Research II, this issue (doi:10.1016/S0967-0645(03)00084-5).

Smith Jr., W.O., Nelson, D.M., 1986. Importance of ice edge phytoplankton production in the Southern Ocean. Bioscience 36, 251–257.

Smith, R.C., Dierssen, H.M., Vernet, M., 1996. Phytoplankton biomass and productivity in the Western Antarctic Peninsula region. In: Ross, R.M., Hoffman, E., Quetin, L.B. (Eds.), Foundations for Ecological Research West of the Antarctic Peninsula. Antarctic Research Series 70, pp. 333–356.

Steinberg, D.K., Goldthwait, S.A., Hansell, D.A., 2002. Zooplankton vertical migration and the active transport of dissolved organic and inorganic nitrogen in the Sargasso Sea. Deep Sea Research I 49, 1445–1461.

Strickland, J.H.D., Parsons, T.R., 1972. A practical handbook of seawater analysis. Journal of the Fisheries Research Board of Canada 167, 1–311.

Zhou, M., Niiler, P.P., Hu, J.-H., 2002. Surface currents in the Bransfield and Gerlache Straits, Antarctica. Deep Sea Research I 49, 267–280.