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Circulation and seasonal evolution of polar waters south of Australia: Implications for iron fertilization of the Southern Ocean

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Abstract

The Southern Ocean Iron Release Experiment (SOIREE) was carried out in late summer (February 1999) south of Australia (61°S, 140°E). This region of the southern Antarctic Zone (AZ-S), between the southern branch of the Polar Front (PF) and the southern front of the Antarctic Circumpolar Current (SAACF), is characterized by weak currents and is remote from the influence of sea-ice or coastal waters. The SOIREE site exhibits high nutrient concentrations year-round (phosphate, nitrate and silicate remain above 10 μM), low chlorophyll accumulations (< 0.5 μg/l), and moderate summer mixed-layer depths (50–70 m). The SOIREE iron fertilization led to a large increase in algal biomass, particularly large diatoms, and persisted into March well after normal seasonal production is complete. No increase in carbon export occurred during the SOIREE 13-day observation period. The seasonal cycles of mixed-layer development and low biomass accumulation at the SOIREE site are representative of most of the region between the PF and the SACCF, i.e. between ~ 54 and ~ 62°S, and to a lesser extent the Polar Frontal Zone. However, north of ~ 59°S surface waters are depleted in silica by mid-summer (as occurs year-round north of the Subantarctic Front). A different response to iron fertilization is likely under these conditions, possibly the promotion of lightly silicified diatoms and non-siliceous organisms, whose ability to export carbon is uncertain. The SOIREE fertilized waters are likely to have remained at the surface in the AZ-S throughout the winter. In general, carbon sequestration by subduction of iron-enhanced biomass accumulations is unlikely south of the SAF, except in very limited regions. Moreover, intermediate water masses formed in the Southern Ocean sink with little pre-formed silicate, so that the "silica pump" is already working at close to maximal capacity. Therefore, in the absence of significant changes in community structure or algal physiology, which increase the ratio of carbon export to silicate export, increased iron supply is unlikely to increase the magnitude of carbon sequestration. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The Southern Ocean Iron Release Experiment (SOIREE) was carried out to examine the hypothesis that iron supply controls the rates of primary and export production in the "high nutrient, low chlorophyll" (HNLC) waters of the Southern Ocean, and that changes in iron supply can thereby affect atmospheric carbon dioxide concentrations (e.g. de Baar et al., 1995; Martin, 1990; Martin et al., 1990). Two mesoscale iron-fertilization experiments (IronEx I and II) in the equatorial Pacific ocean (Coale et al., 1996; Martin et al., 1994) demonstrated that iron addition accelerated phytoplankton growth, and that larger species, particularly diatoms, were able to escape grazing pressure and increase in both relative and absolute abundance (Cavender-Bares et al., 1999). Significant reduction of surface water nutrient concentrations (Coale et al., 1996) and carbon dioxide partial pressures (Cooper et al., 1996) were observed during IronEx II, and ^{234}Th observations suggested export also increased (Bidigare et al., 1999). The applicability of these results to the Southern Ocean is unclear, in light of its colder waters, lower mixed-layer light levels, and different plankton communities, all of which can influence the effects of iron supply on production and export (e.g. Boyd and Newton, 1999; Cullen, 1995; Frost, 1991; Laws et al., 2000; Morel et al., 1991). In addition, water masses formed in the Southern Ocean return excess macro-nutrients to the ocean interior, in contrast to equatorial Pacific where excess nutrients are advected into the sub-tropical gyres and consumed (Sarmiento and Orr, 1991). Thus, in comparison to the equatorial Pacific, iron-induced enhancement of carbon export from the Southern Ocean has a greater potential role in the regulation of atmospheric carbon dioxide concentrations.

During SOIREE, addition of iron to a 55 km^2 area of Antarctic Zone waters south of Australia in late summer (February 1999) enhanced both growth and accumulation of phytoplankton, providing the first in situ demonstration of the impact of iron fertilization in the Southern Ocean (Boyd et al., 2000). Four successive iron additions were carried out over 8 days, and the fertilized region was monitored for biological changes over a total of 13 days. After ~ 5 days, algal biomass began to increase noticeably, reaching $\sim 2\,\mu$g/l Chl *a*, (an ~ 5-fold increase over initial levels) by the time of the ship's departure. This "bloom" developed within the surface mixed layer and was dominated by large ($> 20\,\mu$m) diatoms (Boyd & Abraham, 2001a; Gall et al., 2001a). Dissolved nutrient concentrations and carbon dioxide partial pressure were considerably reduced by the iron-induced bloom (Bakker et al., 2001), and were accompanied by changes in phytoplankton physiology and community structure (Boyd et al., 2001a; Gall et al., 2001a,b), and bacterial and zooplankton heterotrophy (Hall and Safi, 2001; Zeldis, 2001). Most of the consumed nutrients remained within the mixed layer, in the form of suspended algae (Boyd et al., 2000). During the 13-day observation period there was no indication of increased export (Charette and Buesseler, 2000; Nodder and Waite, 2001; Trull and Armand, 2001), although changes in algal sinking rates and aggregate characteristics suggested export was likely to increase with time (Waite and Nodder, 2001).

In this paper, we first describe recent observations of the physical and chemical characteristics of surface waters south of Australia to provide a context for the SOIREE results. We then assess whether a similar response to iron fertilization can be expected across the full north to south extent of the Southern Ocean. Finally, we examine the mechanisms of carbon sequestration from iron-induced algal blooms, including controls on particulate carbon export and the possibility of bloom subduction during formation of deep and intermediate waters. We conclude that less than half of the Southern Ocean is likely to exhibit a response similar to that which occurred during SOIREE (because only waters well south of the Polar Front are silica-rich throughout the year), and that carbon export by bloom subduction is unlikely. Moreover, consideration of the composition of newly formed deep and intermediate waters in the Southern Ocean suggests that export of silica from the surface of the Southern Ocean is already operating at close to full capacity, and iron-enhanced carbon sequestration will require either additional silica supply or a decoupling of silica and carbon export.

2. Observations

2.1. Fronts and Zones of Southern Ocean waters south of Australia

The physical and chemical characteristics of Southern Ocean surface waters vary from north to south. These changes occur as a series of steps across each of the fronts of the Antarctic Circumpolar Current (ACC). Between the fronts lie zones of weak flow and relatively uniform water properties. From north to south, these fronts and zones are the Subtropical Front (STF), Subantarctic Zone (SAZ), Subantarctic Front (SAF), Polar Frontal Zone (PFZ), Polar Front (PF), and the Antarctic Zone (AZ) (Gordon et al., 1977; Whitworth, 1980). Further south, close to the Antarctic shelf, two additional circumpolar fronts have been identified: the southern ACC front (SACCF) and the "southern boundary" (SB) of the ACC (Orsi et al., 1995).

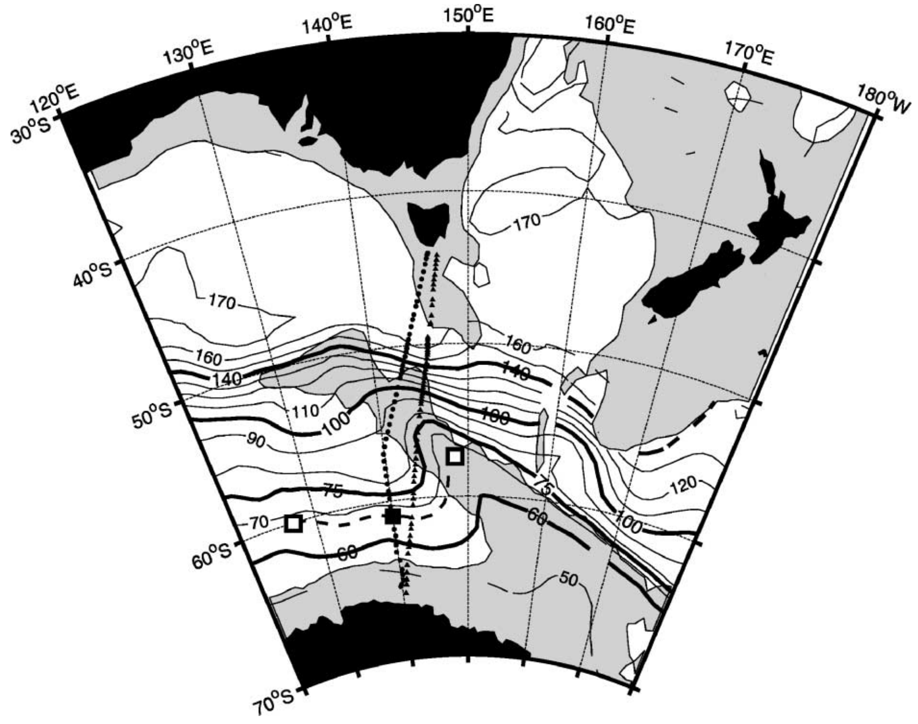
Two branches of the Polar Front have been found in each of the six CTD sections occupied south of Tasmania since 1991: the northern branch (PF-N) lies between 53 and 54°S, and the southern branch (PF-S) is found near 59°S (Rintoul and Bullister, 1999; Rintoul and Sokolov, 2001). Two branches of the PF also have been found at other longitudes (Sievers and Nowlin, 1984; Sparrow et al., 1996). As described below, the physical and chemical characteristics differ on either side of the PF-S. To assist in the discussion, we follow Parslow et al. (2001) and call the zone between the two branches of the Polar Front the Inter-Polar Front zone (IPFZ), and call the region between the PF-S and the SACCF the southern Antarctic Zone (AZ-S). In other words, the southern branch of the PF divides the AZ south of Australia into two zones: the IPFZ between the two branches of the PF, and the AZ-S between the southern branch and the SACCF. Table 1 summarizes the definitions used to identify the individual fronts and the nomenclature used in this study. The locations of the fronts in the Australian sector are indicated in Fig. 1, by highlighting of the dynamic height contours that most closely correspond to the front locations of Orsi et al. (1995), Rintoul and Bullister (1999) and Rintoul and Sokolov (2001).

The deep-reaching fronts define water-mass boundaries and account for most of the eastward transport of the ACC (Nowlin and Clifford, 1982; Rintoul and Sokolov (2001). The overturning circulation in the meridional plane (Fig. 2) is also relevant to our discussion, as it plays a role in the carbon and nutrient supply to and export from the surface mixed layer. Nutrient-rich Circumpolar Deep Water (CDW) upwells south of the SAF, where the Ekman transport is divergent. Part of the upwelled CDW loses buoyancy near Antarctica to form Antarctic Bottom Water (AABW). The remainder gains bouyancy due to warming and freshwater input as surface waters are driven north in the Ekman layer, ultimately sinking to form Antarctic Intermediate Water (AAIW) and

Table 1
Criteria used to identify fronts south of Australia and the zones of relatively uniform water properties between the fronts. Front locations are identified primarily on the basis of enhanced horizontal gradients of density (hence maxima in geostrophic flow). These bands of enhanced gradient generally coincide with the phenomenological indicators given in the table[a]

Front	Zone	Criteria used to define front location
STF		$T < 11°\mathrm{C}$ to the south, at 150 m depth
	SAZ	
SAF		Pronounced salinity minimum present to the north Salinity less than 34.2 to the south, above 300 m depth
	PFZ	
PF-N		Northernmost limit of T-min water cooler than 2°C at 200 m
	IPFZ	
PF-S		T-max layer with $T > 2.2°\mathrm{C}$ thins rapidly to the south Depth of T-min increases to the north
	AZ-S	
SACCF		T-max $> 2.0°\mathrm{C}$ near 300 m depth
	Southern	
SB		T-max $> 1.5°\mathrm{C}$

[a] Abbreviations used: STF, Subtropical Front; SAZ, Subantarctic Zone; SAF, Subantarctic Front; PFZ, Polar Frontal Zone; PF-N, northern branch of the Polar Front; IPFZ, inter-Polar Front Zone; PF-S, southern branch of the Polar Front; AZ-S, southern Antarctic Zone; SACCF, southern ACC front; SB, southern boundary of the ACC. Criteria used to define each front generally follow Orsi et al. (1995), but some of their circumpolar definitions need to be slightly modified in the region south of Australia.



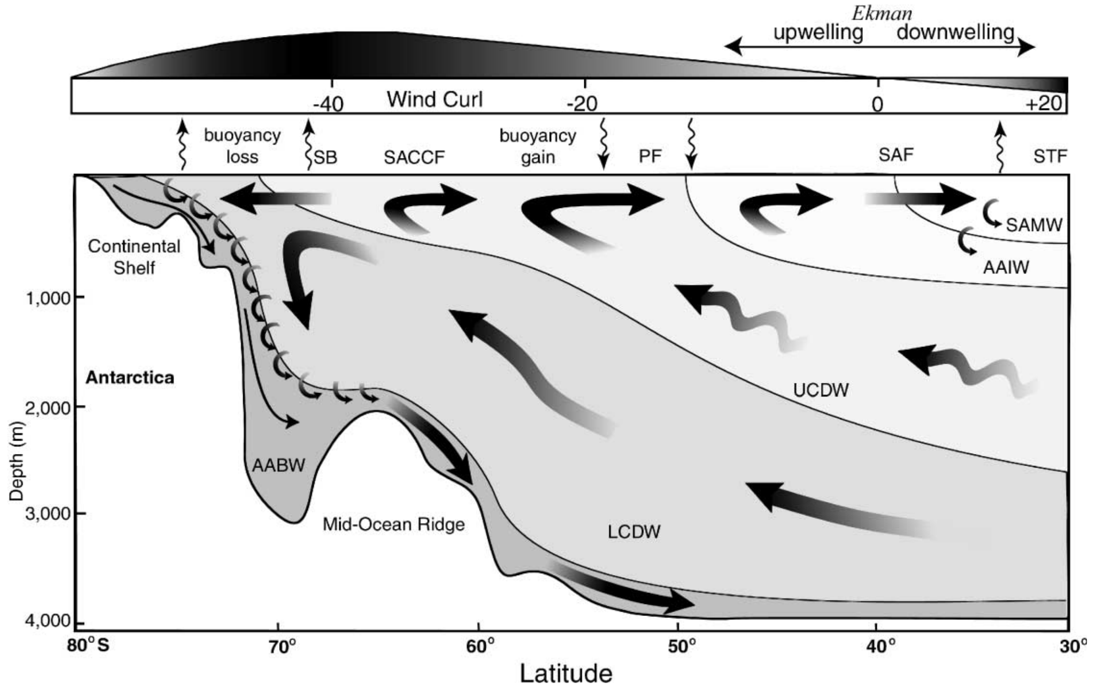
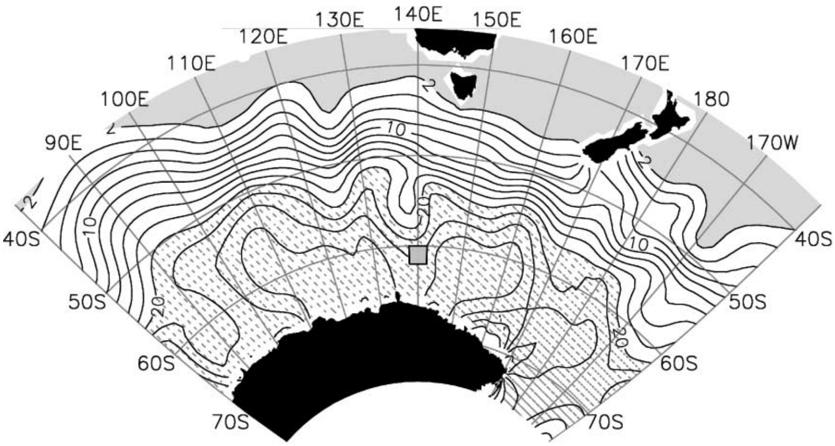


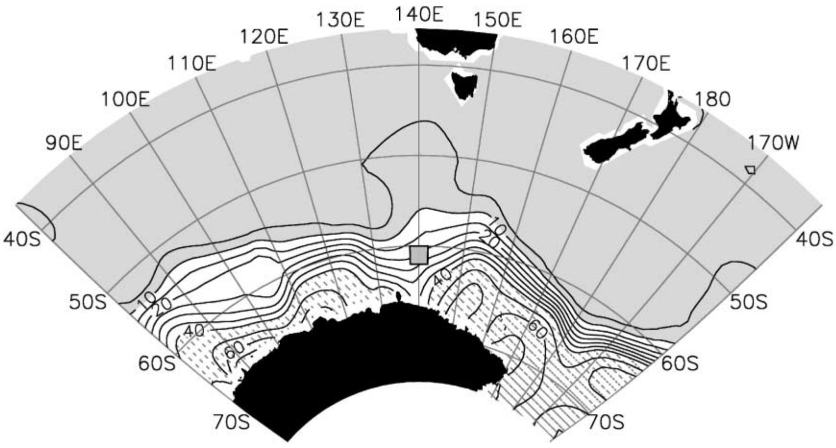
Fig. 2. A schematic view of the meridional overturning circulation, modified from (Speer et al., 2000) to show annual mean wind-stress curl (10^9 dyn cm^{-2}) from Trenberth et al. (1989). Negative values of wind stress curl correspond to Ekman divergence and upwelling. The transition from upwelling and buoyancy gain in the south to downwelling and buoyancy loss in the north roughly coincides with the Subantarctic Front (SAF). Formation of Subantarctic Mode Water (SAMW) and Antarctic Intermediate Water (AAIW) north of the SAF, and Antarctic Bottom Water (AABW) on the Antarctic Shelf occurs only in restricted locations. Nutrients are brought to the surface from Upper and Lower Circumpolar Deep Water (UCDW and LCDW) with increasing efficiency further south as a result of the increasingly negative wind-stress curl, as well as deep winter convection associated with sea-ice formation (Gordon and Huber, 1990).

Subantarctic Mode Water (SAMW, Speer et al., 2000; Sverdrup, 1933). While the circumpolar-average view in Fig. 2 is broadly accurate, the sinking of surface water into the ocean interior occurs in only a few locations. For example, Antarctic Bottom Water (AABW) forms primarily in the Weddel and Ross Seas, and along the Adelie Land coast (Orsi et al., 1999; Rintoul, 1998). SAMW is formed throughout the circumpolar extent of the SAZ (McCartney, 1977), but new

Fig. 1. Dynamic height at 200 m relative to 2000 m in the Australasian sector of the Southern Ocean (dyn cm, from Olbers et al., 1992). Locations of the WOCE SR3 repeat hydrographic section (small filled circles) and the WOCE IX-28 repeat XBT section (small triangles) are indicated. The bold dynamic height contours correspond with the following fronts: 140 dyn cm, the Subantarctic Front; 100 dyn cm, the northern branch of the Polar Front (PF-N); 75 dyn cm, the southern branch of the Polar Front (PF-S); and 60 dyn cm, the southern ACC front (SACCF). The filled square at 61°S, 140°E indicates the site of SOIREE; the open squares to the west and east of 140°E indicate the likely position of the SOIREE patch six months before and after the experiment (based on the mean geostrophic flow along dynamic height streamlines). Bathymetry shallower than 3500 m is shaded.



a) nitrate



b) silicate

Fig. 3. Map of dissolved (a) nitrate and (b) silicate summer average concentrations at 10 m from the NOAA online World Ocean Atlas (www.nodc.noaa.gov) (Levitus, 1998). Phosphate shows a similar distribution to nitrate.

oxygen-rich AAIW is formed only north of the SAF in the regions east and west of Drake Passage, where it coincides with the coldest and freshest varieties of SAMW (McCartney, 1977, 1982; Talley, 1996). AAIW found at other locations is derived from these sources, with properties that have been slowly modified by mixing and decomposition of organic matter (which decreases the oxygen and increases the nutrient concentrations). For example, the AAIW south of Australia is relatively old (pCFC-11 ventilation age > 20 years) and low in oxygen (65% of saturation), reflecting the effects of mixing and oxygen consumption along the long sub-surface trajectory from its source in the southwest Atlantic (Rintoul and Bullister, 1999).

Macro-nutrient concentrations (silicate, phosphate and nitrate) increase from north to south across each of the Southern Ocean fronts (Fig. 3). As discussed in further detail below, this pattern

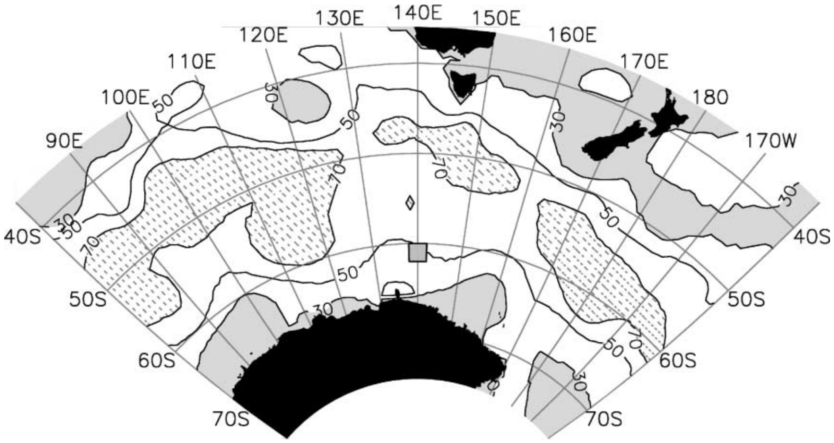


Fig. 4. Map of mid-summer mixed-layer depths estimated from the World Ocean Atlas 1994 temperature and salinity data (Levitus, 1998). The mixed-layer depth is defined to be the depth at which density increases by 0.1 kg m^{-3} from its surface value.

varies seasonally, and by mid-summer, phytoplankton production has depleted silicate concentrations over most of the northern half of the Southern Ocean, although nitrate and phosphate concentrations remain high (Fig. 3). Mixed-layer depth, hence the light environment experienced by phytoplankton, also varies systematically across the Southern Ocean, but in contrast to nutrient concentrations this variation is not monotonic with latitude (Fig. 4). Summer mixed-layer depths are deepest in the PFZ ($>$ 70 m), somewhat shallower to the north in the SAZ and to the south in the IPFZ (50–70 m), and become progressively shallower further south in the AZ-S (30–50 m) and south of the SACCF ($<$ 30 m).

SOIREE was carried out in the quiescent AZ-S (61°S, 140°E), between the stronger flows associated with the southern branch of the PF and the SACCF (Figs. 1 and 5). The mean eastward geostrophic surface velocity at the SOIREE site estimated from the WOCE SR3 transects is $0.03 \pm 0.02\,\mathrm{m\,s^{-1}}$. These weak currents also are confirmed by sea-surface height variations of $<$ 0.05 m (rms variation calculated from the MSLA data set of (Le Traon et al., 1998). The small displacement of the SOIREE iron-fertilised patch ($\sim$ 40 nm in 12 days), and subsequent long residence time in the region as revealed by SeaWiFS ocean colour images (Abraham et al., 2000), were consistent with expectations from the WOCE SR3 results. At these slow rates of advection, the patch of water fertilized during SOIREE is likely to have experienced its seasonal development within the Australian sector, and to remain there through the following winter (as indicated in Fig. 1).

The SOIREE site experiences high nutrient concentrations throughout the year (Fig. 3) and moderate mixed-layer depths (as illustrated in Fig. 4, and documented in detail in the next section). It is north of the Seasonal Sea-Ice Zone (Gloersen et al., 1993; Worby et al., 1998), and based on drift tracks of sea-ice (Heil and Allison, 1999) and ice-bergs (Young, 1998), is isolated from exchange with Antarctic coastal and shelf waters. The SOIREE site, and AZ waters in general in this region, exhibit very low levels of chlorophyll *a* ($<$ 0.5 μg/l) in surface waters (Parslow et al., 2001; Popp et al., 1999; Suzuki and Fukuchi, 1997; Wright et al., 1996). Ocean colour images from the CZCS

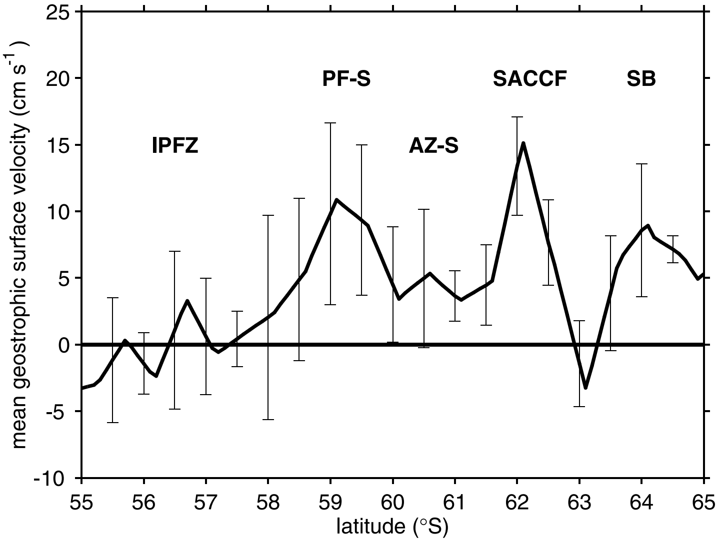


Fig. 5. Mean geostrophic surface velocity along 140°E, from five occupations of the WOCE SR3 section. Error bars represent ± one standard deviation, using all station pairs within each 1° bin. The three main fronts are labelled (PF-S = southern branch of the Polar Front; SACCF = southern ACC front; SB = southern boundary of the ACC).

and SeaWiFS satellite sensors (available on-line from the NASA SeaWiFS Project website: http://seawifs.gsfc.nasa.gov/seawifs_scripts/czcs_subreg.pl.) confirm these low levels and demonstrate that they extend throughout the Southern Ocean sector south of Australia. Iron levels have not been studied in detail in the AZ south of Australia, but measurements in both spring (Sohrin et al., 2000) and late summer at the start of the SOIREE experiment (Boyd et al., 2000) found very low concentrations of 0.1–0.2 nM. In summary, the SOIREE site is well described by the iron-poor HNLC paradigm for all three nutrients: silicate, phosphate, and nitrate.

2.2. Seasonal evolution of mixed-layer characteristics

The seasonal evolution of water-column properties in the Subantarctic and Polar Frontal zones south of Australia has recently been summarized by Rintoul and Trull (2001). Here we provide a similar summary for the IPFZ, AZ-S and waters south of the SACCF, and then briefly compare with the SAZ and PFZ results. The vertical sections shown in Fig. 6 illustrate the seasonal evolution of the upper water column between 55 and 65°S, i.e. across the Antarctic Zone

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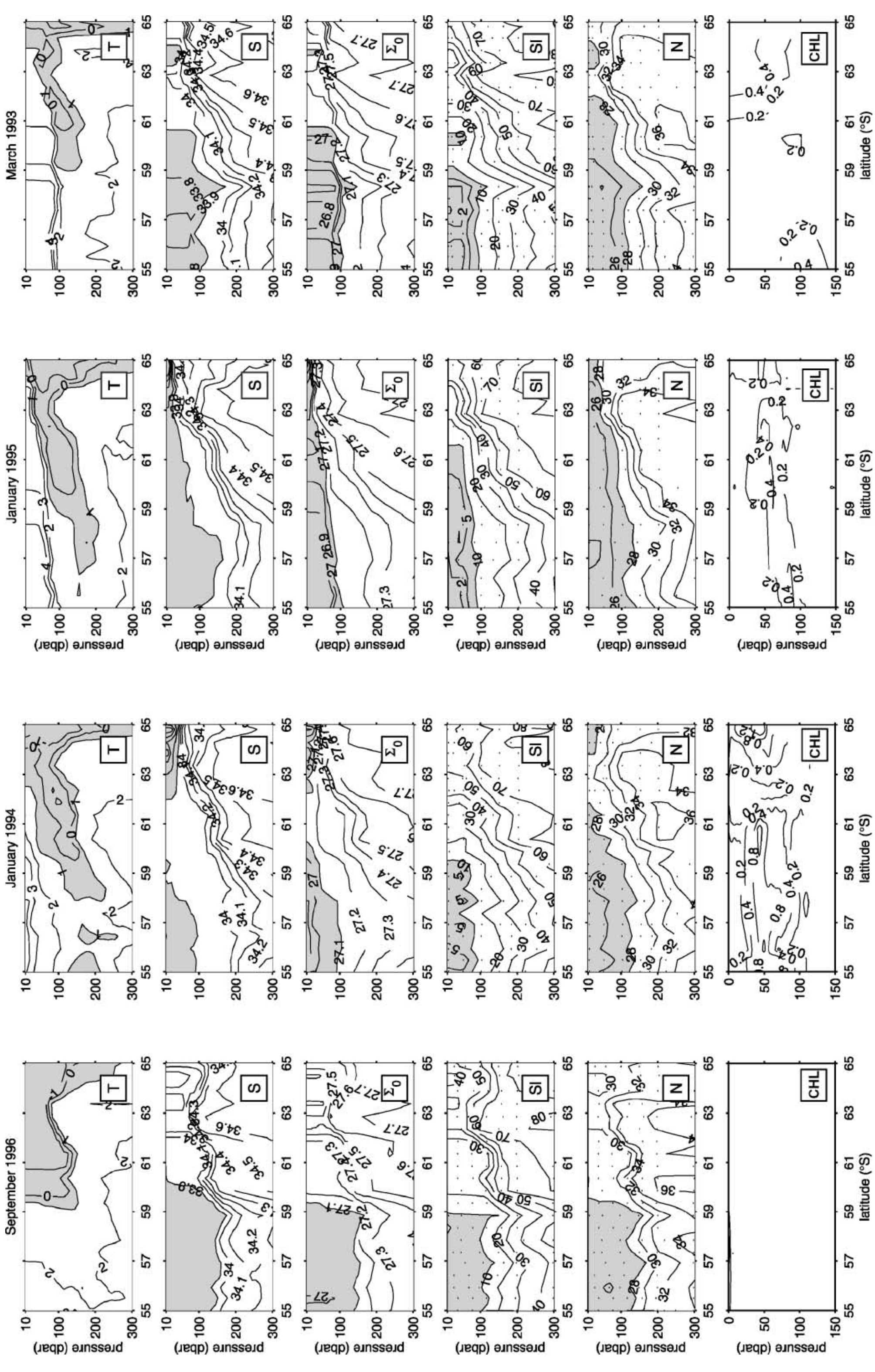
Fig. 6. Seasonal sequence of water column properties across the Antarctic Zone along the WOCE SR3 repeat section. Top to bottom: temperature (values less than 1°C are shaded in each of the plots), salinity (< 33.9 shaded), potential density anomaly ($< 27.1\,\mathrm{kg\,m^{-3}}$ shaded), silicate ($< 10\,\mu\mathrm{M}$ shaded), nitrate ($< 28\,\mu\mathrm{M}$ shaded), and chlorophyll *a* (μg/l; note change in depth axis in chlorophyll *a* plot).


September 1996
January 1994
January 1995
March 1993
T
S
Σ_0
SI
N
CHL
pressure (dbar)
latitude (°S)
55
57
59
61
63
65
10
100
200
300
0
50
150

from near the Polar Front to south of the SACCF. In winter, heat loss to the atmosphere drives convection and deep mixed layers form. By late winter (September, Fig. 6) surface waters are near 2°C in the IPFZ, below 1°C in the AZ-S, and approach the freezing point of seawater (~ -1.8°C) south of the SACCF. Mixed layers are deepest in the IPFZ (~ 150 m), shoal to ~ 120 m at the PF-S, and then to 100 m or less south of the SACCF. Surface salinity increases southward from relatively fresh IPFZ waters (< 33.9) to above 34.4 south of SACCF. The deep winter convection supplies the surface layer by entraining fluid from the underlying saline and nutrient-rich Circumpolar Deep Water (CDW), and so nutrients also increase to the south. The southward increase in silicate (from 5–10 in the IPFZ to > 50 μmol/l south of the SACCF) is much larger than for nitrate (from 26–28 in the IPFZ to > 30 south of the SACCF) or phosphate (which exhibits a winter distribution similar to that of nitrate with a near-Redfield ratio of 15–16; sections not shown). Algal biomass in September is negligible throughout the region (Fig. 6).

Summer warming produces a seasonal thermocline, which is deepest in the PFZ and shoals southwards in steps across the PF, PF-S and SACCF (Figs. 4 and 6). The seasonal pycnocline is generally controlled by this warming in the IPFZ and AZ-S, but sea-ice melt makes an important contribution south of the SACCF (the January 1994 section illustrates this well, Fig. 6). Beneath the surface mixed layer, remnant cold winter water forms a sub-surface temperature minimum layer that is characteristic of the Antarctic Zone. This layer thins northward and disappears altogether at the Polar Front (Fig. 6). The timing of warming and stratification in spring is not well constrained by the WOCE SR3 repeats (which have a gap between September and January), but nearby XBT sections (Fig. 1) show that little warming occurs before mid-November (Rintoul et al., 1997). By late summer (March section in Fig. 6) surface water temperatures are above 4°C in the IPFZ, between 2 and 3°C in the AZ-S, but still below 1°C south of the SAACF.

For the SOIREE site, the seasonal evolution in water-column properties is best illustrated with vertical profiles (Fig. 7). A strong seasonal pycnocline is evident in both the profiles and the short north-south section obtained prior to the SOIREE iron release (Fig. 8). Considerable nutrient depletion occurs within the mixed layer, and by the time of the SOIREE iron fertilization silicate concentrations had already been reduced to $\sim 30\%$ of their winter values, although nitrate remained at $\sim 85\%$ of its winter value. This depletion occurs in the absence of high chlorophyll accumulations (Fig. 7). The timing of the summer nutrient minimum is not well defined by the SR3 profiles, as there are no profiles in spring or early summer, and interannual variability is large. For example, the January 24, 1995 profile suggests significant nutrient draw-down by mid-summer, while the January 12, 1994 profile shows little nutrient depletion. By early March, the mixed layer starts to cool and deepen, and nutrient levels increase as the seasonal pycnocline is eroded by surface cooling and convection.

Nutrient depletions broadly similar to those at the SOIREE site occur throughout the AZ-S, IPFZ, and south of the SACCF (Fig. 6), but with some important differences as summarized in Fig. 9. The seasonal decrease in silicate and nitrate concentrations was largest south of the SACCF (shown for 63°S), followed by the AZ-S SOIREE site, and lowest in the IPFZ. But because of the lower initial winter concentrations, the IPFZ experiences very low silicate concentrations (2–3 μM) by mid to late summer. None of the zones experience potentially limiting nitrate (or phosphate) concentrations. (It should be emphasized that waters south of the SACCF, and particularly south of the SB, in this sector are not homogeneous and include a wide range of mixed-layer structures, nutrient depletions, and algal populations in relation to the presence of sea-ice and the influence of

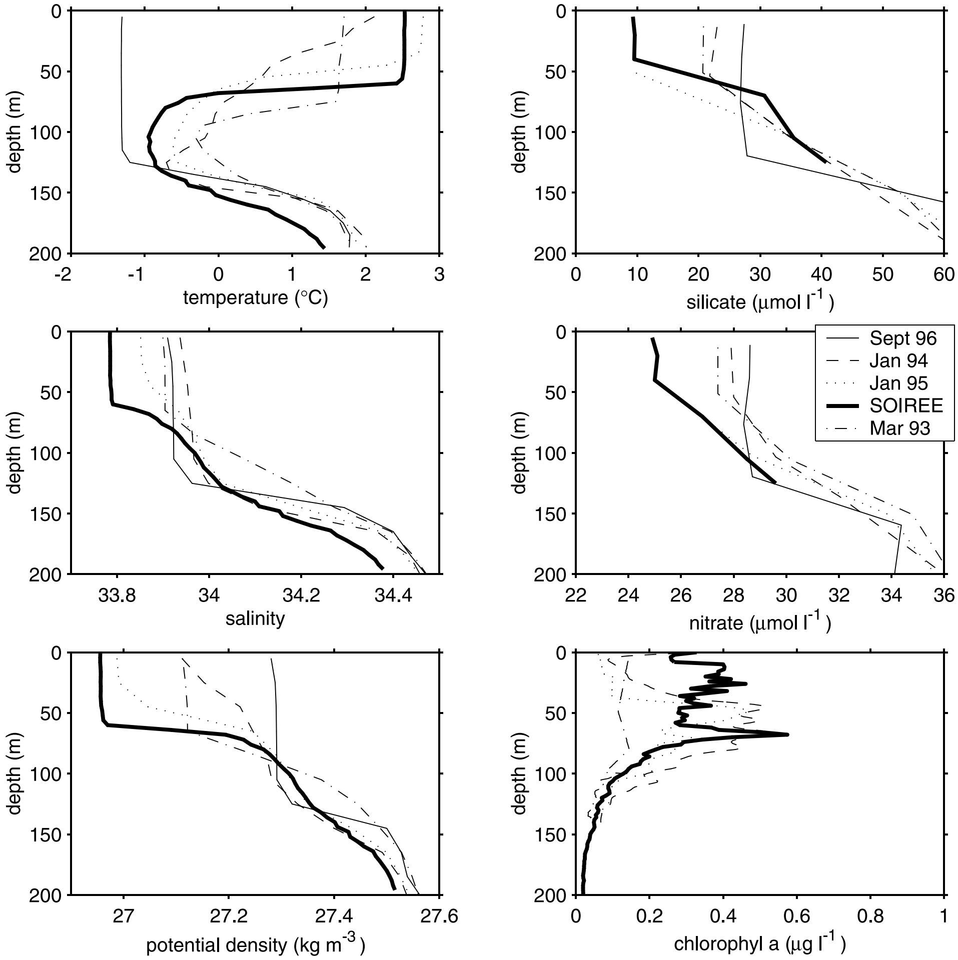


Fig. 7. Profiles of upper water column properties at the start of the SOIREE fertilization in comparison to a seasonal progression assembled from the WOCE SR3 sections.

shelf and coastal waters (e.g. Gibson et al., 1999; Gibson and Trull, 1999; Popp et al., 1999; Suzuki and Fukuchi, 1997; Wright et al., 1996; Wright and van den Enden, 2000).

SeaWiFS ocean colour estimates of chlorophyll *a* provide a more precise indication of the timing of biomass accumulation (Fig. 10), though not of export or nutrient depletion. Algal biomass starts to increase as early as late October in both the IPFZ and AZ-S, approximately a month before the development of any significant warming (Fig. 10b), or stratification (Rintoul et al., 1997). SeaWiFS chlorophyll *a* reaches a maximum between mid-December and early January. The levels are low (~ 0.4 µg/l or less throughout the year) and similar to water-column results from the SR3 transects. Interannual variability is considerable, but the AZ-S and IPFZ display similar seasonal cycles and amplitudes. The SeaWiFS observations do not capture an interesting aspect of biomass accumulations. The shipboard observations in January and March along the SR3 line (Fig. 6), as well as

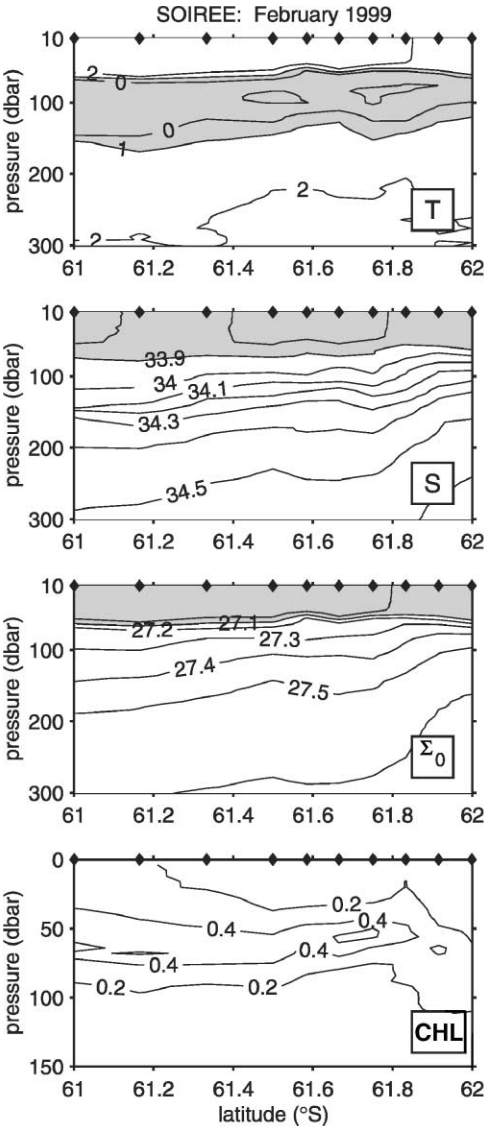


Fig. 8. North-south section of water column properties along 139°E acquired prior to the SOIREE fertilization in February 1999. Shading is as in Fig. 6.

those at the start of SOIREE (Figs. 7 and 8), reveal a sub-surface chlorophyll maxima (SCM) within the seasonal pycnocline below the mixed layer. This feature is particularly pronounced in the IPFZ, and also further north in the PFZ (Parslow et al., 2000), but its connection to nutrient depletion and export is not understood. The seasonal timing of export from the mixed layer in the AZ-S or south of the SACCF has not been studied, but particle fluxes to deep moored sediment traps at the border of the IPFZ and the PFZ near 54°S on the SR3 line peaked in the first week of February with little export after that time (Trull et al., 2001). The increasing ^{234}Th inventory observed

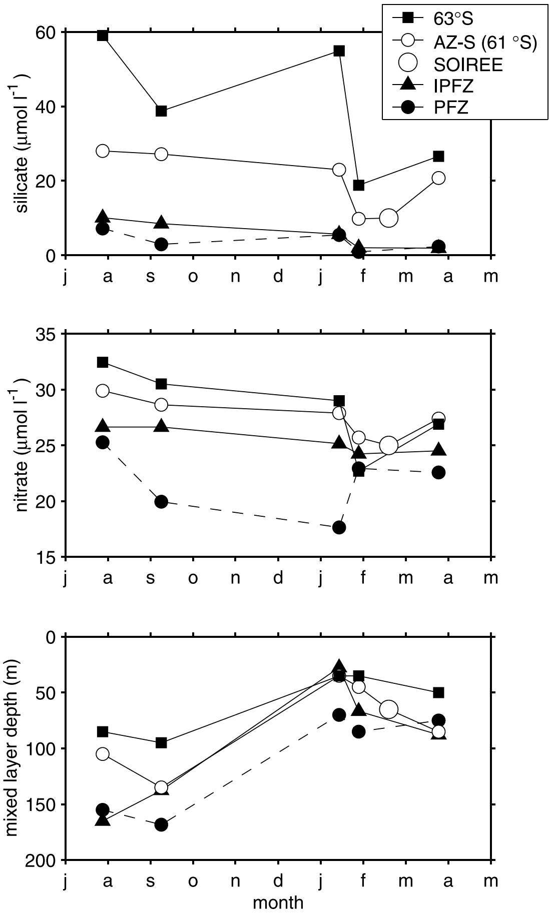


Fig. 9. Summary of seasonal evolution of mixed-layer properties (silicate, nitrate and mixed-layer depth) in the PFZ, IPFZ, AZ-S and south of the SACCF at 63°S. The conditions at the start of SOIREE in the AZ-S are also marked.

outside the iron-fertilized region during the SOIREE experiment (Charette and Buesseler, 2000) suggests that export was minimal after early February.

North of the AZ, in the PFZ and particularly in the SAZ, water-column properties and their seasonal evolution differ substantially from those at the SOIREE site (Rintoul and Trull, 2001). Mixed-layer depths are greater in the PFZ in both winter and summer than in the IPFZ, AZ, or SAACF (Fig. 9), and temperatures reach 4–6°C. The seasonal cycle of biomass accumulation in the PFZ is similar to that of the IPFZ and AZ-S although with slightly longer duration, and nutrient concentrations are generally lower, with silicate reaching potentially limiting levels of a few µM by mid-summer but nitrate still relatively high (above 20 µM; Fig. 9). The SAZ exhibits extremely deep winter mixed layers (up to 600 m) and summer mixed layers of 60–75 m, with temperatures of 9–12°C. Chlorophyll concentrations are somewhat higher, but display a temperate cycle of peaks in

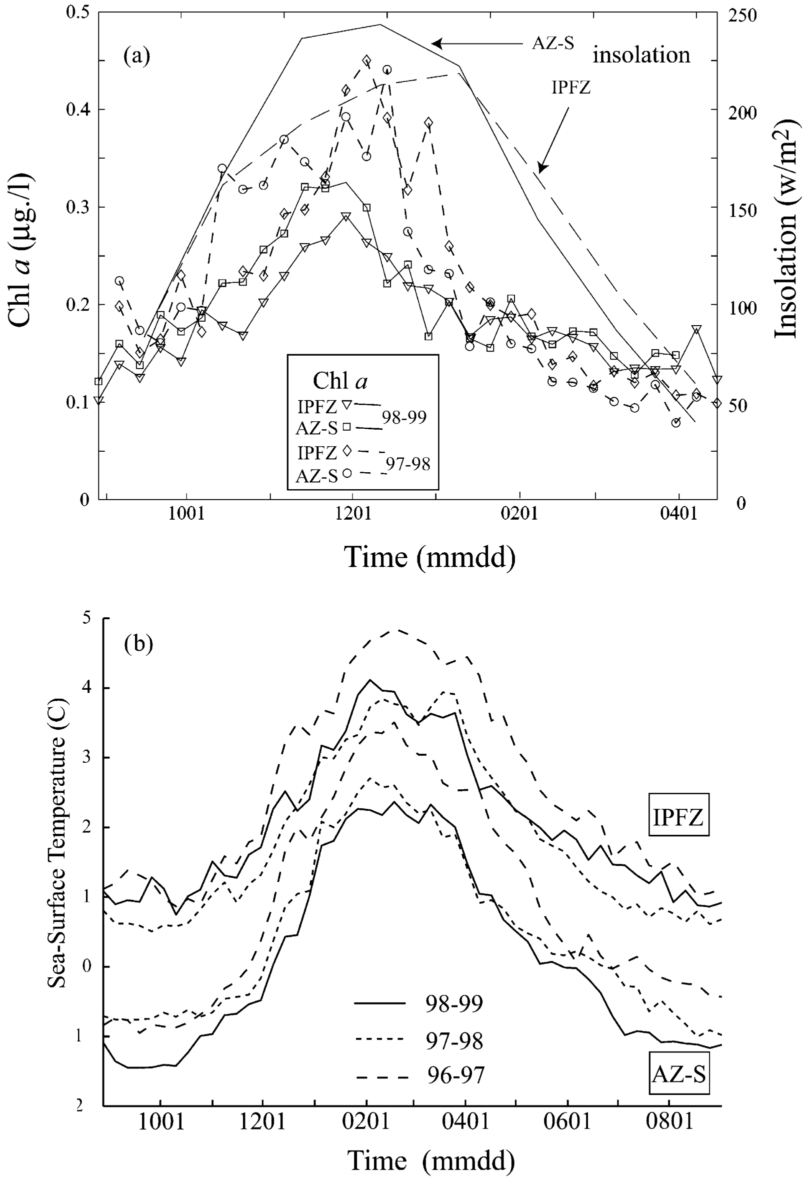


Fig. 10. (a) Seasonal progresssion of SeaWiFS phytoplankton chlorophyll *a* estimates. Values are averages from 8-day composite images for 130–150°E for the south Antarctic Zone (59.5–62.5°S) and the Inter Polar Frontal Zone (55.5–58.5°S), in the SOIREE 1998–1999 season and the previous 1997–1998 season. Also shown is the seasonal cycle of incident insolation at the sea-surface (Bishop and Rossow, 1991), including the effects of cloud cover, for the AZ-S and IPFZ. Values are averages from 130 to 150°E, and 52.5 to 57.5°S and 57.5 to 62.5°S, respectively, for the 1990–1991 season (no data is yet available in SeaWiFS operational years). (b) Seasonal cycle of sea-surface temperature in the AZ-S (60–62°S) and IPFZ (56–58°S). Values are averages of the NCEP 1° data (Kalnay et al., 1996) from 130 to 150°E. Results for the SOIREE 1998–1999 season and several previous seasons are shown. Note the longer time scale (*x*-axis) then in panel a.

early spring and late autumn, rather than the single summer maximum farther south. In the SAZ, silicate concentrations are low year round (1–4 μM), although nitrate is generally above 5 μM.

In summary, SOIREE took place in the southern Antarctic Zone, well after the normal seasonal peak in production and export, in a moderately deep mixed layer (~ 65 m) that had experienced considerable seasonal nutrient depletion, but still remained high in nitrate, silicate and phosphate. The physical characteristics and seasonal cycle at the SOIREE site are representative of most of the region between the PF and the SACCF, i.e. across the IPFZ and AZ-S between ~ 54 and ~ 62°S, and to a lesser extent the PFZ (although mixed layers are deeper and the sub-surface temperature minimum layer is absent in the PFZ). However, the IPFZ and PFZ differ strongly from the AZ-S in chemical properties, in that silicate becomes depleted by mid-summer. South of the SACCF, macro-nutrients are abundant year-round, but physical characteristics are very different from those at the SOIREE site — there is no sub-surface temperature minimum layer, the seasonal thermal cycle is much smaller, and the influence of sea-ice on stratification is much greater (particularly south of the SB). North of the SAF in the SAZ, temperatures are much higher, silicate is in low abundance year round, and winter mixed-layer depths are extreme.

3. Discussion

Applying the SOIREE results to estimate the probable response to iron fertilization in other seasons and oceanographic zones of the Southern Ocean is a multi-faceted task. We first focus on whether the physical and chemical characteristics of the different oceanographic zones south of Australia permit the level of iron-enhanced algal production and accumulation observed during SOIREE (see the Introduction for a brief summary of SOIREE results, Boyd et al. (2001a) for an overview, and other papers in this volume for details of the SOIREE response). We then consider whether this enhanced production is likely to lead to increased carbon transport to the deep sea, via either bloom subduction or particle export. Finally we outline the limitations of our assessment and identify specific areas for further reseach.

3.1. *Availability of iron, macro-nutrients, and light*

Although few measurements have been made, it appears that surface ocean iron concentrations are low in the SAZ, PFZ, IPFZ and AZ-S south of Australia (approximately 0.1–0.2 nM for "dissolved iron" determined in different ways Bowie et al., 2001; Croot et al., 2001; Sarthou et al., 1997; Sedwick et al., 1997, 1999; Sohrin et al., 2001). Deckboard incubations have shown strong responses to iron additions in all these zones (Boyd and Abraham, 2001a, Boyd et al., 2000, 2001b; Hutchins et al., 2001; Sedwick et al., 1999). South of the SB, iron concentrations are higher in Antarctic shelf and coastal waters (Sohrin et al., 2000) and elevated iron concentrations also have been measured near the Kergulen Islands (Blain et al., 2000; Bucciarelli et al., 2001). Similar patterns of low open-ocean iron concentrations and higher levels near land masses have been observed in other sectors of the Southern Ocean (e.g. de Baar et al., 1995, 1999; Loescher et al., 1997; Measures and Vink, 2001). Strong responses have been observed in deckboard iron-addition incubations of open-ocean waters (Buma et al., 1991; de Baar et al., 1995; Timmermans et al., 1998; van Leeuwe et al., 1997), with lower or no responses in the presence of iron supply from melting sea-ice (Sedwick and Ditullio, 1997; Sedwick et al., 2000) or coastal waters (e.g. Brandini, 1993; Buma et al., 1991). Overall it appears that low available iron and strong phytoplankton responses are likely across all of the open Southern Ocean, except in limited areas near or downstream of land or sea-ice sources of iron.

High nitrate, phosphate, and silicate concentrations are available year round in the AZ-S and further south (Figs. 3, 6 and 9). In contrast, the IPFZ is depleted to low levels of silicate by mid to late summer (2–3 μM), and so is the PFZ (1–3 μM), and silicate availability is low in the SAZ year-round (~ 4 μM in winter and < 1 μM by late summer, Rintoul and Trull, 2001). Thus, in the IPFZ and PFZ the response to iron fertilization is likely to vary seasonally. In spring, when silicate levels are high (close to the 9–10 μM encountered at the start of SOIREE) iron fertilization is likely to produce a similar response to SOIREE, i.e. enhanced growth of all phytoplankton classes, and preferential increases in the growth and abundance of large (> 20μm) diatoms. But after mid-January, iron-enhanced diatom production is likely to be affected by low silicate levels. Both reduced growth rates and a change in the type of diatoms stimulated by iron addition can be expected. Experiments in the PFZ along 170°W suggest that the growth rates of large heavily silicified diatoms (such as *Chaetoceros* spp. and *Fragilariopsis kerguelensis* which typically dominate silicate-rich Antarctic waters after iron enrichment; Gall et al., 2001a; Scharek et al., 1997; Takeda, 1998) are reduced at silicate levels below 5 μM and strongly curtailed below 2.5 μM, even when iron is added (Frank et al., 2000). Experiments in the SAZ and PFZ in the central Indian sector (Sedwick et al., 2001) and in the SAZ along 140°E south of Australia (Hutchins et al., 1999, 2001; Sedwick et al., 1999) have found that smaller, lightly silicified diatoms (e.g. *Pseudo-nitzschia* species) continue to respond to iron addition at silicate levels as low as 1.2 or even 0.7 μM. At lower silicate levels, iron additions have been observed to favor the growth of other organisms, particularly flagellates in the SAZ (Sedwick et al., 2000a).

From the perspective of silicate controls on algal communities, late summer fertilization in the IPFZ or PFZ is likely to drive a succession from early production of large heavily silicified diatoms to smaller lightly silicified species. After silicate exhaustion, continued iron fertilization might lead to the the development of a nano- and pico-plankton community similar to that present in the SAZ (Kopczynska et al., 2001; Odate and Fukuchi, 1995). This progression is more speculative, because while some components of the SAZ algal community are present south of the SAF (e.g., many of the prasinophytes, chrysophytes, and dinoflagellates; Gall et al., 2001a; Kopczynska et al., 2001; Odate and Fukuchi, 1995; Popp et al., 1999; Wright et al., 1996; Wright and van den Enden, 2000), others appear to be excluded by the lower temperatures. For example, coccolithophores are common in the SAZ and in the PFZ, but are in much lower abundance further south (Eynaud et al., 1999; Popp et al., 1999), and cyanobacteria abundances drop off exponentially with temperature (Marchant et al., 1987). Seasonal progression depends, of course, on not only iron stimulation of production, but the response of grazers, development of a microbial loop, particle aggregation and sinking, viral infections etc., (i.e. a full description of Southern Ocean ecosystems in a perturbed state), and probably cannot be predicted with the present state of understanding.

Low light availability in the deep mixed layers of the Australasian sector of the Southern Ocean reduces primary production to sub-optimal levels (Boyd et al., 2001b; Griffiths et al., 2001; Parslow et al., 2001; Sedwick et al., 1999), although it still permits net production and seasonal biomass accumulation in all zones. It is reasonable to expect that lower light in the deeper mixed layers in the PFZ and IPFZ in comparison to those at the SOIREE site might reduce the response to iron fertilization, and conversely higher light might increase the response in the shallower mixed layers south of the SACCF (Figs. 6 and 9). There is some evidence from the natural system to suggest that the effect of different light regimes is likely to be small, at least in terms of limiting the response in the IPFZ and PFZ. Mixed-layer growth rates estimated from productivity versus irradiance incubations during the January 1994 WOCE SR3 transect were similar in the PFZ, IPFZ and AZ-S (Popp et al., 1999), and phytoplankton in shallower mixed layers at the south of the transect have higher light requirements (higher half-saturation irradiances, I_k) than those in deeper mixed layers further north (J. Parslow personal communication). This may reflect adaptation to low light levels, as occurs in algae in the deep sub-surface chlorophyll maximum in the PFZ (Parslow et al., 2000). Seasonal biomass accumulation is also very similar in the IPFZ and AZ-S under natural conditions (Fig. 10).

The role of light availability of course will vary seasonally, and in this regard the strong response to the SOIREE fertilization in February and its persistence into March as light levels drop to less than half their peak values (Fig. 10) suggest that light limitation is unlikely to be a major control on the initial response to iron fertilization. This in part may reflect the fact that iron addition also acts to relieve light limitation through improved phytoplankton physiology (e.g. Sunda and Huntsman, 1997). This process has its limits, however, and an incubation experiment in the PFZ suggested that light availability restricts the response to iron at the very low light levels of a 100 m mixed layer in late March (Boyd et al., 2001b). The higher light levels available in the shallower mixed layers south of the SACCF may promote a greater response to iron fertilization than occurred during SOIREE, although this effect is likely to be offset by lower temperatures. For example, similar growth rates were found in the AZ-S and south of the SACCF during the January 1994 WOCE SR3 transect, and model calculations suggest that the expected increases from higher light and lower temperature are similar in magnitude (Popp et al., 1999). It is also possible that photo-inhibition will be important in shallower mixed layers. There were indications of its development in the upper water column during SOIREE, sugggesting that self-shading may eventually contribute to the maximum biomass levels achieved (Boyd et al., 2000). Estimating the response to iron additions south of the SACCF is further complicated by the complexity of the region (as discussed above), and because blooms of the prymnesiophyte *Phaeocystis antarctica* are important in the natural system (Arrigo et al., 1999), although little is known of its iron or light requirements. Despite these uncertainties, it appears that light availability will be secondary in the control of the response to iron fertilization in the Southern Ocean, particularly in terms of initial increases in phytoplankton growth rates.

3.2. Advective carbon transfer to the ocean interior

Vertical export via sinking particles has generally been considered the primary process responsible for carbon sequestration in response to iron fertilization. The formation of intermediate and deep waters in the Southern Ocean, and the shallow subduction of the IronEx I fertilized waters in the equatorial Pacific (Martin et al., 1994), have drawn attention to the possibility of sequestration of iron-induced algal blooms by ocean circulation. Processes that can subduct surface waters include Ekman pumping, lateral induction, and mixing along isopycnal surfaces. Across the entire Southern Ocean south of the SAF, the mean wind stress curl is of the wrong sign to cause subduction of surface waters (i.e. the Ekman transport is divergent, driving upwelling, not downwelling; Fig. 2). Lateral induction occurs when the mixed-layer depth decreases along the trajectory of a water column. For example, if a water column with a deep mixed layer is advected into a region where air–sea forcing forms a shallower, more buoyant mixed layer, the water beneath the base of the new mixed layer is then isolated from the sea surface, or subducted. The map of mixed-layer depths shown in Fig. 4, and the vertical sections in Fig. 6 suggest lateral induction is unlikely to cause subduction in this region. Water in the mixed layer is likely to be deflected to the north by the Ekman drift, but mixed-layer depths tend to increase, not decrease, to the north, so lateral induction is of the wrong sign to result in subduction south of the SAF. Vertical motions (both upwelling and downwelling) also occur in association with meandering fronts or eddies. Downwelling could transport an algal bloom along sloping isopycnals into the ocean interior, while upwelling will generally return more carbon-rich waters to the mixed layer. The net effect integrated over space and time is difficult to predict. Overall, it appears that these mesoscale processes are weak in the quiescent waters of the AZ, given the low oxygen and chlorofluorocarbon concentrations observed beneath the base of the winter mixed layer in this region (Rintoul and Bullister, 1999).

It should be emphasized that the Ekman velocity is relatively small at the SOIREE site. The mean zonal wind stress at 61°S, 140°E (the SOIREE site) is about $0.1\,\mathrm{N/m^2}$ (Kalnay et al., 1996). Assuming an Ekman layer depth of 50 m, this stress drives a northward Ekman drift of about 1.5 cm/s at this latitude. This is slow in comparison to even the weak horizontal currents of the AZ-S (Fig. 5). Over 6 months, the Ekman drift would carry surface waters about 2° of latitude (230 km) to the north, during which time advection at 5 cm/s parallel to the dynamic height streamlines would carry the patch to approximately the position shown in Fig. 1. Thus, despite the northward Ekman transport, the SOIREE patch probably would have remained in the AZ for several years.

Carbon fixed in the late-summer mixed layer during SOIREE might mix slowly to the north along the gradually deepening isopycnals, as shown in the short section obtained at the start of SOIREE (Fig. 8). However, even subduction via isopycnal mixing is unlikely to sequester carbon for very long, as the deeper mixing during winter will re-incorporate the waters of the seasonal pycnocline into the winter mixed layer. For example, the potential density of the summer mixed layer at the SOIREE site is less than $1027.0\,\mathrm{kg\,m^{-3}}$ (Fig. 8), while the winter mixed layer at least as far north as 55°S is more dense than $1027.0\,\mathrm{kg\,m^{-3}}$ (Fig. 6). It is possible that blooms induced further north, closer to the Polar and Subantarctic fronts where isopycnals turn steeply downwards into the interior, would be subducted by mixing along isopycnals (or sinking driven by mesoscale motions). However, the strong isopycnal gradients of oxygen that coincide with the SAF (Rintoul and Bullister, 1999) indicate that high oxygen surface waters south of the SAF are not subducted in this way. Indeed, the warm summer surface waters tend to be advected north across the Polar Front and the SAF, rather than subducted beneath them. This process is evident in summer sections across the SAF (Rintoul and Trull, 2001), and may be responsible for much of the nutrient supply to the SAZ (Sigman et al., 1999). North of the SAF, the Ekman flux is convergent and can drive subduction. However, winter convection is extremely deep (up to 600 m, Rintoul and Trull, 2001), and dissolved inorganic carbon contents in the remnant winter mixed layer (the Subantarctic Mode Water, between ~ 200 and 600 m depth) are in approximate equilibrium with the atmosphere (McNeil et al., 1999, 2001), so that long-term sequestration of carbon by bloom subduction in this region appears unlikely.

The possibility of bloom subduction in the vicinity of the Subantarctic and Polar Fronts is linked to the formation of Antarctic Intermediate Water (AAIW). Importantly, as discussed in the

Observations section above, this does not occur in all sectors of the Southern Ocean. Some subduction of iron-induced blooms might be achieved in the limited regions where AAIW forms. This carbon is likely to be sequestered for a few hundred years before returning to the surface (England, 1995). Formation of Antarctic Bottom Water (AABW) is limited to a few locations over the continental shelf of Antarctica (Orsi et al., 1999), and occurs in late winter. There is some evidence, from elevated DMS concentrations at depth in the Ross Sea, for subduction of algae (DiTullio et al., 2000), but given the restricted locations of AABW formation, a large transfer to the ocean interior is unlikely.

3.3. Iron-enhanced carbon export and its possible limitation by silica depletion

No increase in particulate carbon export was observed during the SOIREE experiment, largely because of the short 13-day observation period (Charette and Buesseler, 2000; Nodder and Waite, 2001; Trull and Armand, 2001). The potential for export later in the bloom's evolution has been considered by several authors in the context of iron and carbon budgets, phytoplankton physiology, grazer response, and bacterial respiration (Abraham et al., 2000; Bowie et al., 2001; Boyd et al., 2000; Hall and Safi, 2001; Waite and Nodder, 2001; Zeldis, 2001), with a general consensus that some export is certain. The fraction of primary production exported might be similar to that which occurs in natural large-diatom blooms in the Southern Ocean [i.e. as much as 20 to 50 %, (Buesseler, 1998; Buesseler et al., 1999), or might be considerably different. The unusual timing of the bloom in comparison to the normal seasonal cycle makes the assessment of its fate particularly difficult. The low grazing response during SOIREE could reflect the tuning of zooplankton feeding habits to normal phytoplankton availability. The low light levels of late February and March might have reduced the ability of the bloom to increase or to remain buoyant. In addition, the extremely high iron levels may have changed ecosystem functioning in unexpected ways after the observation period. These uncertainties only can be addressed by further experiments. For the moment, the magnitude and control of export production from iron-fertilized Southern Ocean waters remains unknown.

More generally, the probable response of Southern Ocean ecosystems to iron fertilization depends in part on the nature of the iron addition. Iron addition can be punctual and small scale, as in SOIREE, or large-scale and persistent, as may have occured via increased mineral dust inputs in the past (e.g., Martin, 1990; Watson et al., 2000). The response is likely to be different, both because the biogeochemical evolution of small iron-induced algal blooms depends on the extent of their exchange with surrounding waters, which is influenced by the local regime of advection and shear (Abraham et al., 2000), and because ecosystems may adapt to persistent fertilization. The form and rate of iron supply are also likely to affect the outcome, because the yield of dissolved iron from mineral dusts and industrially purified ferrous sulfate heptahydrate (as used in SOIREE) is different, and perhaps more importantly because the details of iron supply may affect the ability of the ecosystem to use, retain, and recycle iron. In this regard, the SOIREE experiment observed a surprising rebound in the presence of Fe(II) several days after the final iron addition, when expectations were that Fe (III) would dominate (Croot et al., 2001). The exact origin of this reappearance of Fe (II) is uncertain, but it may well have involved other components of the ecosystem than the primary producers, including grazers and bacteria (Bowie et al., 2001). This exemplifies the necessity to consider the response to iron fertilization at the ecosystem level, and not only in terms of phytoplankton growth. For this reason, a full assessment of iron-enhanced carbon sequestration will require further experiments and observations, and carefully structured and calibrated ecosystem models.

Despite the present inability to evaluate fully the possibility of iron-enhanced carbon export in the Southern Ocean, it is clear that one aspect of its HNLC characteristics is likely to play a major role. Approximately half the area of the Southern Ocean (the Subantarctic Zone) is silicate-poor year round, and other areas (the PFZ and IPFZ) are low in silicate by mid-summer. This situation is in direct opposition to the view expressed in extrapolating the results of the IronEx II experiment in the equatorial Pacific (Coale et al., 1996): "*There are few natural instances where nitrate is in abundance and silicate is not. With few exceptions therefore, silicate is not likely to limit carbon export... . It is likely that diatom growth will dominate the response to natural iron additions.*" The low silicate levels of some Southern Ocean surface waters (and other HNLC regions) have been noted before, including suggestions that this is likely to control phytoplankton community composition, and possibly carbon export (Dugdale and Wilkerson, 1998; Dugdale et al., 1995; Sommer, 1994; Treguer and Pondaven, 2000). Here we go further to point out that the total silica supply to Southern Ocean surface waters is already efficiently used, and therefore iron addition will not be able to stimulate further silica export.

In the regions of the Southern Ocean where SAMW and AAIW form, surface waters are extremely low in silicate (see Fig. 3 and the plates in Gordon and Molinelli, 1982; Levitus, 1998). This silicate depletion has important ramifications for the effectiveness of iron-enhanced carbon sequestration. Recent reviews have suggested that large diatoms dominate carbon export from both natural and iron-fertilised surface waters (Buesseler, 1998; Coale et al., 1996; Boyd and Newton, 1999; de Baar and Boyd, 1999). If this is true, then iron fertilization of the Southern Ocean may change the location, but not the magnitude, of particulate export, because surface waters are already depleted in silicate by the time they are subducted (several important caveats to this hypothesis are discussed below). In other words, carbon export by the silica pump is already operating at maximum efficiency. (AABW does form with high silicate concentrations, but the amount of surface water sinking in this way is small, < 5 Sv (Orsi et al., 1999), relative to the 30 Sv upwelling of nutrient-rich circumpolar deep water.)

The simple arguments presented above ignore a number of processes that may alter the conclusions in important ways. For example, iron addition (with no change in silicate supply) may drive enhanced carbon export from the Southern Ocean if one or more of the following occurs:

1. Iron fertilization drives physiological changes in diatom-dominated communites, which result in more carbon export per mole of silicate. There are some indications that this may occur. Two- to three-fold increases in the uptake of carbon or nitrate in comparison to silicate have been observed in iron-replete incubations dominated by diatoms (Frank et al., 2000; Hutchins and Bruland, 1998; Takeda, 1998) and during SOIREE (Watson et al., 2000). Whether this translates into increased export of carbon per unit silicate is, however, uncertain. Interestingly, the seasonal mixed-layer nutrient depletions (shown in Fig. 9) display similar silicate to nitrate depletion ratios to those associated with diatom uptake (Table 2), and increase from 2.7 in the PFZ to 3.4 in the IPFZ, 4.3 at the SOIREE site and and 4.1 south of the SACCF. If diatoms control export, this increase could reflect increasing iron stress with distance south. Alternatively it could reflect a greater contribution to export in the north from non-siliceous organisms, or preferential remineralization of nitrate in comparison to silicate, as proposed in earlier studies which found similar depletion ratios [e.g.

Table 2
Seasonal nutrient depletion estimates for different zones of the Southern Ocean south of Australia. ΔSi (ΔN) is the difference between the silicate (nitrate) concentration in the mixed layer in July and in late January (see Fig. 9), and mld ΔSi (mld ΔN) is silicate (nitrate) depletion integrated over the January mixed-layer depth

Zone	ΔSi (μmol l^{-1})	ΔN (μmol l^{-1})	ΔSi : ΔN ratio	mld ΔSi (mmol m^{-2})	mld ΔN (mmol m^{-2})
PFZ	6.3	2.3	2.7	55	20
IPFZ	8.1	2.4	3.4	54	16
AZ-S	18.3	4.2	4.3	82	19
Southern	40.3	9.8	4.1	140	34

(Dugdale et al., 1995; Minas and Minas, 1992). Given that seasonal nutrient depletions are incomplete indicators of seasonal export, particularly in the Southern Ocean (Wang et al., 2001), inferences from these ratios should of course be viewed with caution.

2. Iron fertilization increases the carbon export efficiency from diatom-dominated communites (i.e. the export f-ratio increases). This could occur in several ways. If the species that accumulate in response to iron-fertilization are those that best resist grazing (a tenet of the ecumenical iron hypothesis, Morel et al., 1991; Smetack, 1998), then more carbon may flow to the pathway of loss by sinking rather than to remineralization by grazing. It is also possible that high biomass accumulation may lead to increased particle sinking because of increased aggregation (Riebesell and Wolf-Gladrow, 1992). Countering these possibilites are the potential for greater grazing if higher biomass leads to greater grazing efficiency and the observation that iron fertilization reduced the sinking rates of large diatoms during SOIREE (Waite and Nodder, 2001).

3. Iron fertilization promotes phytoplankton community shifts to other organisms that do not require silicate, and which can exploit the added iron, continue to consume the excess nitrate and phosphate, and export carbon. Some iron-enriched incubation studies have observed increased growth rates of organisms that do not require silica (e.g. Hutchins et al., 1999; Sedwick et al., 1999, 2001; Zettler et al., 1996), as have open-ocean iron experiments (Cavender-Bares et al., 1999; Gall et al., 2001a, b). However, these studies often have found that these organisms do not increase significantly in abundance, perhaps because of tight control by grazing (Boyd and Newton, 1999; Frost, 1991; Morel et al., 1991), so that significant increases in biomass or export are perhaps unlikely. Countering the ecosystem function based inference of low export, there is some evidence that the small phytoplankton community in the silicate-depleted SAZ strongly depletes surface nitrate and phosphate (Lourey and Trull, 2001), and exports similar amounts of carbon to deep sediment traps to that from the diatom-dominated PFZ (Bray et al., 1999, 2000; Trull et al., 2001). Whether iron addition can increase this export, or cause it to occur south of the SAF after silicate depletion by diatoms, is unknown. It is also possible that prymnesiophytes such as *Phaeocystis antarctica* will respond strongly to iron fertilization, escape grazing pressures, and export carbon beyond that which can be achieved by diatoms because of silicate limitation. These are obvious targets for further iron-fertilization experiments.

Limitation of carbon export by silica supply in the Southern Ocean also has implications for Martin's (1990) hypothesis that increased aeolian iron flux during glacial periods increased biological productivity and export, resulting in lowered atmospheric CO_2. Simply adding iron to an ocean with silicate distributions similar to the modern Southern Ocean may not be sufficient to enhance carbon export (as has been recognized previously for the Pacific Equatorial Upwelling Zone; Dugdale and Wilkerson, 1998). Either additional silica supply also must have occured (increased silica inputs from aerosols, rivers, and ice-shelves have been proposed, Froelich et al., 1992; Harrison, 2000; Pollock, 1997; Pondaven et al., 2000) or carbon export must have become decoupled from silica export.

4. Conclusions

SOIREE was carried out in late summer, in quiescent Antarctic Zone waters between the southern branch of the Polar Front and the southern ACC front. The mixed layer was moderately deep (65 m), bounded below by a sharp pycnocline, and rich in all three macro-nutrients. The strong response to iron addition in moderately deep mixed layers late in the year suggests that substantial production can occur at relatively low light levels. Consideration of the seasonal cycle of physical and chemical characteristics in surface water suggests that a similar response to iron fertilization can be expected across much of the Southern Ocean in spring, but that silicate depletion in the IPFZ and PFZ by mid-summer and in the SAZ year-round is likely to lead to different responses.

The fate of carbon fixed as a result of the SOIREE iron fertilization remains unknown. Physical subduction of the fixed carbon is unlikely for any algal bloom south of the SAF and north of the Antarctic shelf, because both Ekman pumping and lateral induction are of the wrong sign to drive subduction. Moreover, Southern Ocean water masses, which sink from the sea surface to the ocean interior, either do so over a small area near the Antarctic margin in winter, or in parts of the ocean where silica is presently depleted, and thus iron fertilization can only change the location, but not the magnitude, of silica export. To the extent that diatoms control carbon export to the deep sea, this means that it may not be as easy as has often been assumed to exploit the reservoir of unutilized nitrate and phosphate in the Southern Ocean and thereby reduce atmospheric carbon dioxide levels. However, iron-induced changes in phytoplankton physiology, particle dynamics, ecosystem structure (grazing), or floristic shifts in the phytoplankton populations may act to increase the ratio of carbon export to silica export.

To state with more certainty the likely outcome of sustained iron fertilization, additional open-ocean iron-fertilization experiments are necessary. In particular, the community response to iron fertilization needs to be explored in regions with low silicate concentrations and different seasonal cycles. These experiments should be carried out for a sufficiently long period to observe whether the addition of iron drives a succession in phytoplankton and/or zooplankton community structures. Experiments in other seasons also would be informative (e.g., to test the idea that a bloom induced at the usual time of peak biomass would be more effectively grazed than the SOIREE bloom, which occurred when natural biomass levels are low). Substantial work is also required to improve our understanding of iron biogeochemistry and physiological changes induced by alleviation of iron stress. The breadth, quiescence, and extraordinarily low phytoplankton background of the Antarctic Zone in the Australian sector make it ideal for future experiments.

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