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Physical controls on biogeochemical zonation in the Southern Ocean

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Abstract

The primary control on the N–S zonation of the Southern Ocean is the wind-induced transport of the Antarctic Circumpolar Current (ACC). The ACC divides the Southern Ocean into three major zones: the Subantarctic Zone (SAZ) north of the ACC; the ACC transport zone; and the zone south of the ACC (SACCZ). The zone of ACC transport is most often subdivided into two zones, the Polar Frontal Zone (PFZ) and the Antarctic Zone (AAZ), but it may be appropriate to define more subzones or indeed only one at some longitudes. To maintain geostrophic balance, isopycnals must slope upwards to the south across the ACC, thus raising nutrient-rich deep water closer to the surface as one goes polewards. In addition, silicate concentrations increase polewards along isopycnals because of diapycnic mixing with silicate-rich bottom water. Surface silicate concentrations therefore decrease northwards from high levels in the SACCZ to low levels in the SAZ. Within the SAZ and PFZ and even in the northern part of the AAZ, silicate levels may drop to limiting levels for siliceous phytoplankton production during summer. Nitrate concentrations also decrease northwards, but only become limiting in the Subtropical Zone north of the SAZ. The second circumpolar control is the changing balance of stratification, with temperature dominating near-surface stratification in the SAZ and salinity dominating further south because of fresh water input to the surface from melting ice. This results in circumpolar features such as the subsurface 2°C temperature minimum and the subduction of the salinity minimum of Antarctic Intermediate Water, which are often but not always associated with frontal jets and large transports. The transport of the ACC is dynamically constrained into narrow bands, the number and latitudinal location of which are controlled by the bathymetry and so vary with longitude. Thus it is not the fronts that are circumpolar, but the total ACC transport and scalar properties of the salinity and temperature fields. Evidence of summer silicate and nitrate uptake in all zones (SAZ, PFZ and AAZ) shows that there is productivity despite their high-nutrient low-chlorophyll status. Blooms covering large areas (say 400 km across) in the PFZ and AAZ are found in the vicinity of submarine plateaux, which suggest benthic iron fertilization.

Résumé

La zonation nord-sud de l'Océan Austral est contrainte par le transport, induit par le vent, du Courant Antarctique Circumpolaire (ACC). Ce Courant divise l'Antarctique en 3 zones majeures: la zone subantarctique (SAZ) au nord de l'ACC, la zone de l'ACC proprement dite, la zone située au sud de l'ACC (SACCZ). La zone de l'ACC comprend la zone du Front Polaire (PFZ) et la zone antarctique (AAZ) mais il peut être opportun de la diviser plus finement selon les régions considérées. Pour maintenir l'équilibre géostrophique les isopycnes présentent un mouvement ascensionnel du nord au sud, permettant à des eaux riches en sels nutritifs de parvenir en surface dans la zone sud de l'ACC. De plus les

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teneurs en silicates dans les eaux de surface s'accroissent vers le sud en raison du mélange diapycnal avec les eaux profondes riches en silicates. Un gradient de silicates est donc observé du sud (eaux riches de la SACCZ) au nord (eaux pauvres de la SAZ). Les silicates peuvent être limitants de la production des diatomées en été. Les nitrates présentent également un gradient décroissant vers le nord mais ne sont limitants qu'en zone subtropicale, au nord de la SAZ. Un élément important du contrôle de la biologie par la physique est la variablité de la stratification de la couche de surface, à origine thermique dominante dans la SAZ ou à origine haline dominante plus au sud par fusion de la glace de mer. Au niveau circumpolaire il en résulte la formation d'un minimum thermique subsuperficiel (typiquement 2°C) et une subduction des Eaux Antarctiques Intermédiaires caractérisées par un minimum de salinité, souvent associés à des transports importants et à des jets frontaux. Le transport dynamique latitudinal de l'ACC est contraint en bandes étroites dont le nombre et la position dépend de la topographie. A proprement parler c'est le transport total de l'ACC ainsi que les propriétés scalaires de salinité et de température qui sont circumpolaires et non les fronts. Bien qu'il s'agisse en principe de systèmes HNLC (high nutrient low chlorophyll) des consommations intenses de silicates et de nitrates ont eté reportées dans toutes les zones (SAZ, PFZ, AAZ). Des floraisons phytoplanctoniques intenses couvrant de large zones (échelle de 400 km) dans la PFZ et dans l'AAZ sont fréquentes à proximité des plateaux sous-marins, ce qui pourrait provenir d'une fertilisation locale en fer, à partir des sédiments.

1. Introduction

The dominant physical control on biogeochemical distributions in the Southern Ocean is the banded structure of the Antarctic Circumpolar Current (ACC), descriptions of which go back to Deacon (1933) and beyond. Deacon (1982) summarized his 50 years of experience of physical and biological zonation in a paper still often referenced, starting with the role of the winds in driving convergences and divergences in the surface layer. More recently, physicists (e.g., Whitworth and Nowlin, 1987; Orsi et al., 1995; Belkin and Gordon, 1996) have described the fronts of the Southern Ocean, seeking to define their salinity and temperature properties and asking whether they are circumpolar in extent. In this paper we shall review both the role of the winds and the question of what features are circumpolar in order to examine chemical and biological zonation in relation to the physics. We need to start by summarizing definitions of fronts and zones in common use before developing our own definitions, which differ subtly but significantly from those in the literature.

Whitworth and Nowlin (1987) describe three main fronts, from north to south, the Subtropical Front (STF), Subantarctic Front (SAF) and Polar Front (PF, sometimes referred to as the APF, for Antarctic Polar Front). Orsi et al. (1995) add a fourth circumpolar feature, the Southern Boundary of the ACC (herein abbreviated to SB). Already these terms differ from those used by Deacon (1982), who referred to Subtropical Convergence (now STF), Antarctic Convergence (now PF), and Antarctic Divergence (which bears some relation to the SB), which are terms still commonly found in biological literature. Deacon's terminology related to features in the global scale wind field and to convergences and divergences in the Ekman drifts in the upper ocean that would result from them. However, the wind-driven convergences and divergences cover much wider bands of latitude than the sharp fronts of the Southern Ocean, so it is preferable to use the newer terminology that does not mention nor assume convergence or divergence.

Indeed, Ekman drifts are a secondary effect of the wind forcing. The primary effect of the strong winds of the Roaring Forties is to drive the ACC itself, which, in the circumpolar Southern Ocean uniquely, results in transports of 130–140 Sv ($1\,Sv = 10^6\,m^3\,s^{-1}$) (Nowlin and Klinck, 1986). In turn, for these currents to be in geostrophic balance, isopycnals must slope up to the south, which tends to occur in narrow frontal bands (a natural consequence of the small scale, tens of kilometres, of the Rossby radius of deformation) whose meandering courses are strongly steered by bathymetry. At each front, the sloping isopycnals expose different water masses to the surface layer, or remove them from it, resulting in different

Table 1
Definitions of Fronts and Zones of the Southern Ocean

Subtropical Front	Subantarctic Front	Polar Front	Southern Boundary
• T_{200} = 10°C • T_{200} = 12°C	• Pronounced Smin north of the SAF. • Subantarctic Mode Water (SAMW) thermostad to north	• Northern terminus of Tmin layer • T_{200} = 2°C	Southern terminus of Upper Circumpolar Deep Water (UCDW)

STF	SAZ	SAF	PFZ	PF	AAZ	SB	SACCZ
	Subantarctic Zone		**Polar Frontal Zone**		**Antarctic Zone**		**Zone south of the ACC**
	• T dominates S in contribution to stratification • This allows pronounced subsurface Smin • Weakening of T stratification in winter results in deep SAMW pycnostads		• T and S contribute equally to stratification • Therefore marked Tmin (2°C) and Smin (AAIW) are both absent in the PFZ		• S dominates T in contribution to stratification • Thus T can increase downwards to Tmax of UCDW • Presence of UCDW defines the AAZ		• Absence of UCDW defines SACCZ
		Antarctic Circumpolar Current (SAF to SB)					

The upper half of the table shows some of the frontal definitions given by Belkin and Gordon (1996) and Orsi et al.'s (1995) definition of the Southern Boundary. The lower half of the table shows the definitions of the zones used in this study and the relationships between the zones, the fronts and the ACC.

stratification and surface zonation with its biological consequences.

We start by defining the STF, SAF, PF and SB (Table 1), seeking correspondence with two of our own data sets, which will highlight some shortcomings of these definitions. The data sets we shall repeatedly refer to are two, quasi-meridional sections (Fig. 1). The first (Figs. 2 and 3), along 40–42°E, was part of the SouthWest Indian ocean EXperiment (SWINDEX) hydrographic survey described by Pollard and Read (2001), a UK contribution to the World Ocean Circulation Experiment. The second (Fig. 4), between 2°W and 13°E, described by Read et al. (2002), was collected at the start of a German Southern Ocean JGOFS cruise. For brevity, we shall refer to these two sections as 40E and 5E (without the ° symbol).

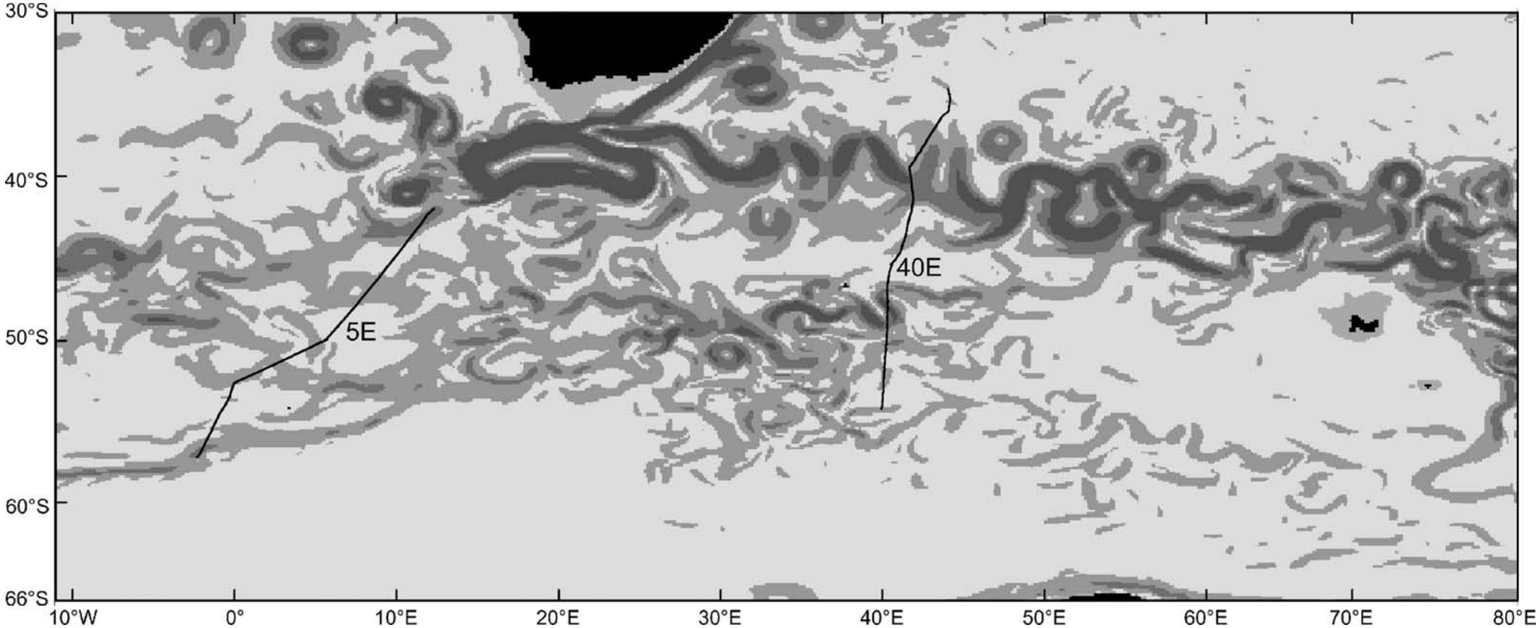

Fig. 1. Sections centred on 5°E and 40°E that are used in this paper are shown superimposed on output from a global eddy-permitting model OCCAM. Increasingly dark grey shades show areas of current speeds greater than 10, 30 and 50 cm s^{-1}, to make the point that continuous circumpolar fronts are not found in the model.

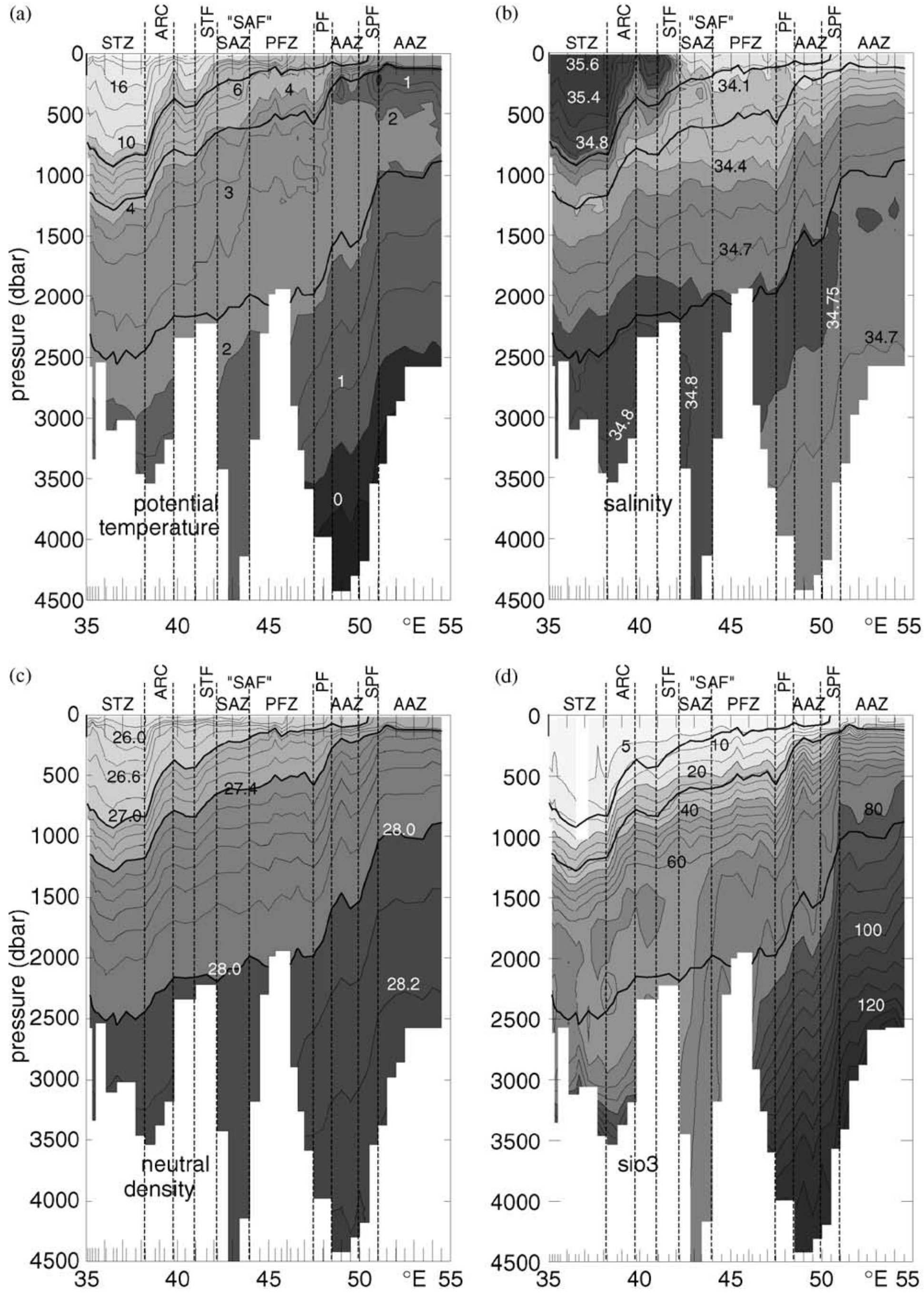

Fig. 2. Full depth CTDs along 42E (Fig. 1) from cruises in April 1993 (south of 44.5°S) and January 1995 (north of 44.5°S) (Pollard and Read, 2001) show the full depth distributions of: (a) potential temperature (°C), (b) salinity, (c) neutral density (kg m^{-3}), (d) silicate (SiO_3) (μmol l^{-1}), (e) nitrate ($NO_2 + NO_3$) (μmol l^{-1}), and (f) the ratio Si/N of silicate to nitrate .

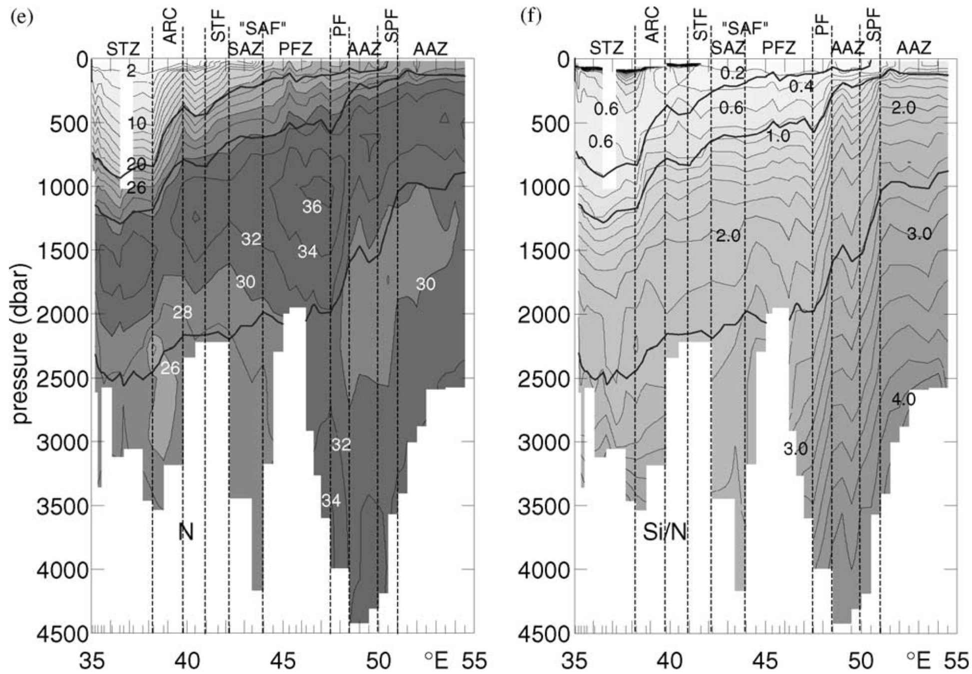

Fig. 2 (*continued*).

1.1. Subtropical front (STF)

The STF is the boundary between Subtropical Surface Water and cooler, fresher Subantarctic Surface Water. We need add little to the original description by Deacon (1937) and numerous authors since then, summarized by Belkin and Gordon (1996). Belkin and Gordon (1996) note that there may be several frontal jets (concentrated currents) in a Subtropical Frontal Zone, which they define as bounded by North and South STFs. The possibility of several jets in a frontal zone is an important concept, to which we shall return. In our examples, the Southern STF is clearly seen along 40E between 41° and 42°S in Figs. 2 and 3. Note that it is not a full-depth feature, as the isopycnals (Fig. 2c) become horizontal below 2000 m. On 5E (Fig. 4) the large, sharp (across barely 10 km) temperature and salinity changes mark the STF. Unfortunately the STF was crossed very shortly after SeaSoar deployment at the start of the cruise and collection of surface nutrients had not yet begun (Fig. 4f).

1.2. Subantarctic front (SAF)

North of the SAF there is a subsurface salinity minimum associated with subducting Antarctic Intermediate Water (AAIW). South of the SAF the lowest salinity water is in the surface layer. This change in vertical structure is the major identifier of the SAF (Whitworth and Nowlin, 1987). Put another way, north of the SAF salinity can decrease downwards because there is sufficient temperature stratification in the upper layers to compensate for a statically unstable salinity gradient. Thus temperature dominates the stratification north of the SAF, whereas to the south salinity and temperature contribute about equally.

The SAF is the northernmost frontal jet that passes through Drake Passage (Sievers and Nowlin, 1984) and is generally regarded as circumpolar in extent (Nowlin and Klinck, 1986). However, it may be merged with the PF (Read and Pollard, 1993) and may not be meaningfully defined in the vicinity of the Del Caño Rise (Pollard and Read, 2001). Thus, in Fig. 2, although the position at which a subsurface salinity minimum appears is easy to identify and label the SAF (Fig. 2b), the lack of sloping isopycnals (Fig. 2c) means that there is no current jet associated with it. Similarly, Read et al. (2002) defined the SAF at 48°S along 5E (Fig. 4) primarily by reference to the changes in stratification, as currents were relatively weak. Orsi et al. (1995) use the 0.9 dyn m dynamic height contour to define the northern boundary of the ACC, which lies not far to the north of the SAF at most longitudes, with the greatest discrepancies in the southwest Atlantic sector.

1.3. Polar Front (PF)

The PF is most frequently identified by the northernmost extent of the 2°C subsurface temperature minimum (Belkin and Gordon, 1996). If we ask how a temperature minimum with depth can exist, that is, of course, because the statically unstable temperature gradient is compensated for by the very fresh surface salinities; hence salinity dominates the stratification everywhere south of the PF. This change in the balance of stratification is the significant property change that is marked by the PF. If we ask further, why 2°C, we realize that the value of the temperature minimum is determined by the underlying Upper Circumpolar Deep Water (UCDW), which has a temperature maximum a little greater than 2°C.

The 2°C temperature minimum is not everywhere associated with a major current jet, for example south of Crozet (50°E), as discussed by Pollard and Read (2001). They showed that the ACC fragments as it crosses the Southwest Indian Ridge, resulting in two current jets crossing 40°E (Fig. 2), which we have labelled the PF and SPF (Southern PF) in order to distinguish them (see also Fig. 5). Rintoul and Bullister (1999) also reported two branches of the PF near 140°E. Following the 2°C definition, the jet at 48.5°S in Fig. 2 is the PF, but property changes across the southern jet (Southern Polar Front (SPF)) at 50.5°S are more pronounced. Note particularly the large horizontal changes in silicate (Fig. 2d) and the T/S and silicate changes on the 28.0 neutral density marked on each subplot of Fig. 2, showing a water mass boundary at 50.5°S. Similarly along 5E (Fig. 4), while the 2°C temperature minimum ends at 49°S (Fig. 4a), more significant changes, both physical and biological, were found at the front at 51.5°S (Pollard et al., 2002), which Read et al. (2002) called the "surface expression of the PF" following several previous authors. Thus, while 2°C marks the northernmost position of the PF, more significant frontal jets may be associated with colder subsurface temperature minima, 0.5–1.5°C along both 40E (Fig. 3a) and 5E (Fig. 4a). Because a significant branch of the ACC (i.e. current jet, so baroclinic front) south of the 2°C temperature minimum is found at many latitudes, we shall label it the SPF to distinguish it from the PF. We do not claim, however, that the SPF is circumpolar, as Read et al. (1995) did.

1.4. Southern Boundary of the ACC (SB)

South of the PF several fronts have been described and there has been some confusion in the literature about which are significant and which circumpolar. Deacon (1933) himself described surface and subsurface expressions of the PF, as did Sievers and Nowlin (1984) at Drake Passage, and Lutjeharms and Valentine (1984) found them up to 300 km apart. Note that the subsurface expression of the PF is the northernmost feature, and corresponds to the definition of the PF given above. Read et al. (1995) described the Southern Polar Front found in the Bellingshausen Sea but which they could identify at least as far as the Greenwich Meridian and Orsi et al. (1995) defined a "southern ACC front".

In our view, however, the most important feature identified by Orsi et al. (1995) is not the southern ACC front but the SB of the ACC, which Orsi et al. (1995) could clearly identify in numerous sections around the Southern Ocean as the southern terminus of UCDW. In some sectors the SB equates with the Continental Water Boundary, with continental waters to the south. In others it equates well with the northern boundaries of the Weddell and Ross gyres. It also lies close to the 0.35 dyn m dynamic height contour, which Orsi et al. (1995) used as the southernmost dynamic height contour to pass

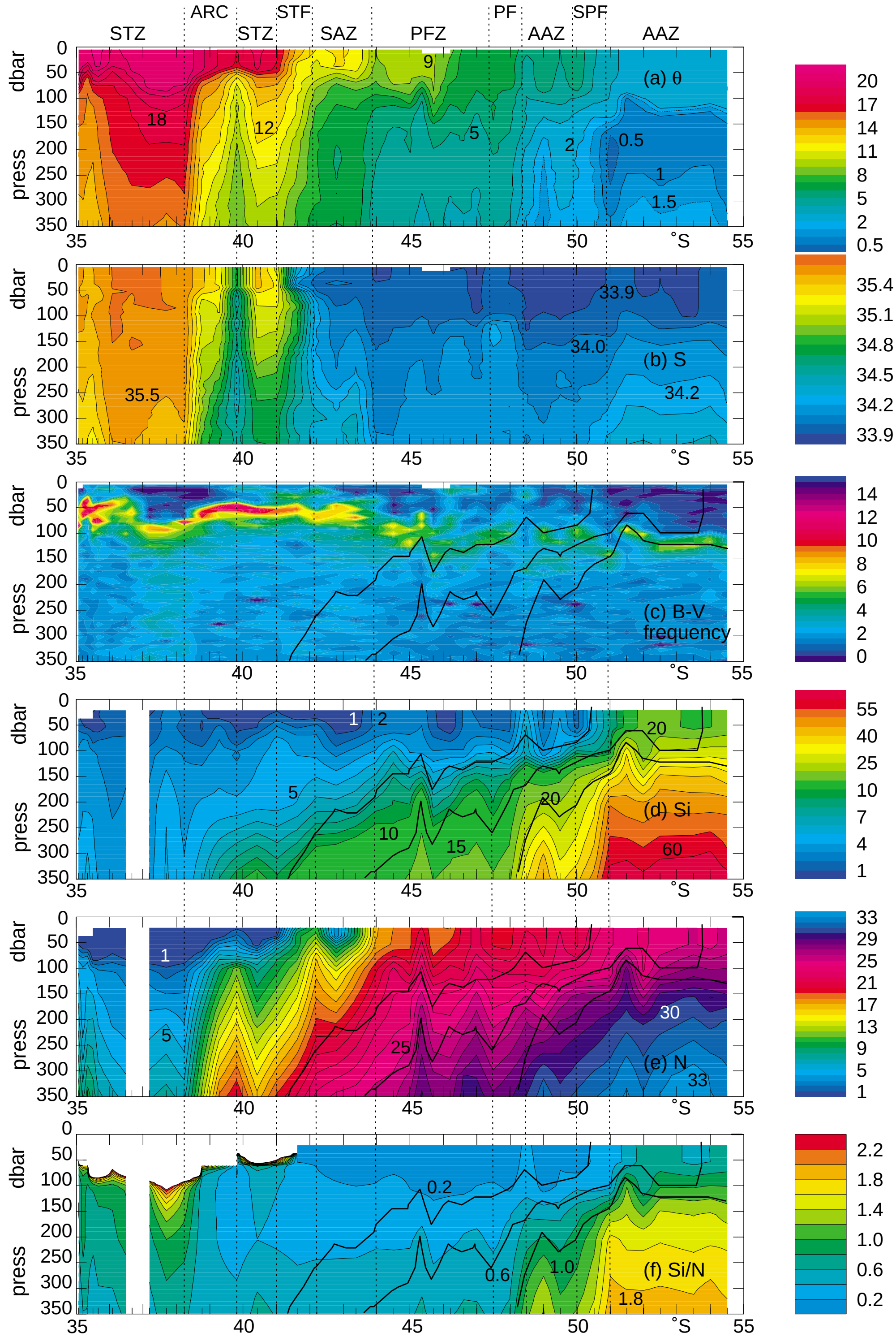

Fig. 3. Sections along 42E (Fig. 2) expanded to show the top 350 m of: (a) potential temperature (°C), (b) salinity, (c) Brunt Väisälä frequency (c.p.h.), (d) silicate (μmol l^{-1}), (e) nitrate (μmol l^{-1}), and (f) silicate/nitrate ratio. Neutral density surfaces 27.0, 27.2 and 27.4 are overlaid on (c)–(f) as bold lines.

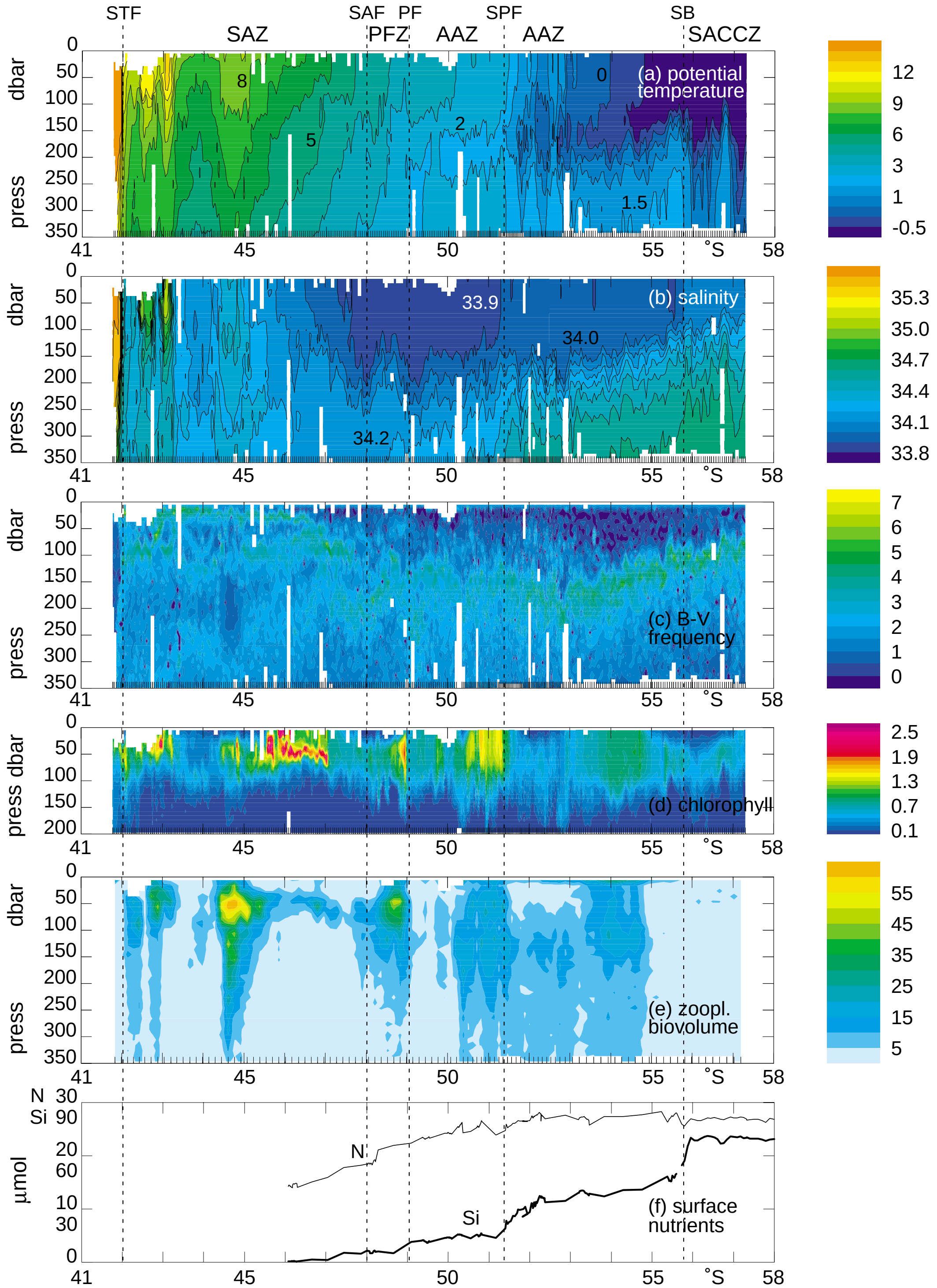

Fig. 4. The SeaSoar section from Read et al. (2002) along about 5E (Fig. 1) shows: (a) potential temperature (°C), (b) salinity, (c) Brunt Väisälä frequency (c.p.h.), (d) chlorophyll (mg m^{-3}), (e) zooplankton biovolume (p.p.m.), and (f) surface silicate and nitrate (μmol l^{-1}).

through Drake Passage. At Drake Passage Orsi et al. (1995) found that the SB lies a little to the south of the southern ACC frontal jet, and they concentrated on the latter, arguing that the southern ACC front is circumpolar. In our view it is the SB that is the well-defined circumpolar feature because, at all longitudes, there will be some latitude at which the UCDW outcrops and ends. Several frontal jets lie between the SB and the PF, none of which really merits naming individually, as they vary with longitude depending on the underlying bathymetry. However, we have made an exception for the SPF, because it can be more significant than the PF at the longitudes where it occurs.

Our section 40E did not go far enough south to reach the SB, but along 5E the position of the SB can be inferred to lie where the 1.5°C isotherm (Fig. 4a) suddenly plunges down past 350 m near 56°S. Surface silicate changes suddenly at that latitude (Fig. 4f) and isopycnals slope sharply up to the south (Read et al., 2002) inducing a strong surface current. Using the data of Whitworth and Nowlin (1987), Orsi et al. (1995) placed the SB at 56°S at the Greenwich Meridian, in nearly exact agreement with our section 5E, which crossed the Greenwich Meridian at 56°S.

1.5. Zonation—a new approach

The difficulty we have had in associating a frontal jet and only one frontal jet with each of the fronts STF, SAF, PF or SB indicates that we should consider a different approach to defining the circumpolar features of the Southern Ocean. Our fundamental conclusion is that it is not the strong current jets that are circumpolar, but latitudinal changes in structure that are induced by the changing contributions of temperature and salinity to the stratification with latitude. The winds generate 130–140 Sv of transport. How that transport is partitioned between fronts is determined by the bathymetry and will vary with longitude, as is apparent in Fig. 1 but was already well shown in current amplitudes from one of the first eddy-permitting Southern Ocean models (Webb et al., 1991). There is no physical reason why there should be, say, three circumpolar fronts (the SAF, PF and southern ACC front) carrying most of the ACC transport. Thus it is not the frontal jets that are circumpolar in extent. The ACC transport can be confined to a few jets or fragmented into many, depending on how the bathymetry channels the circulation.

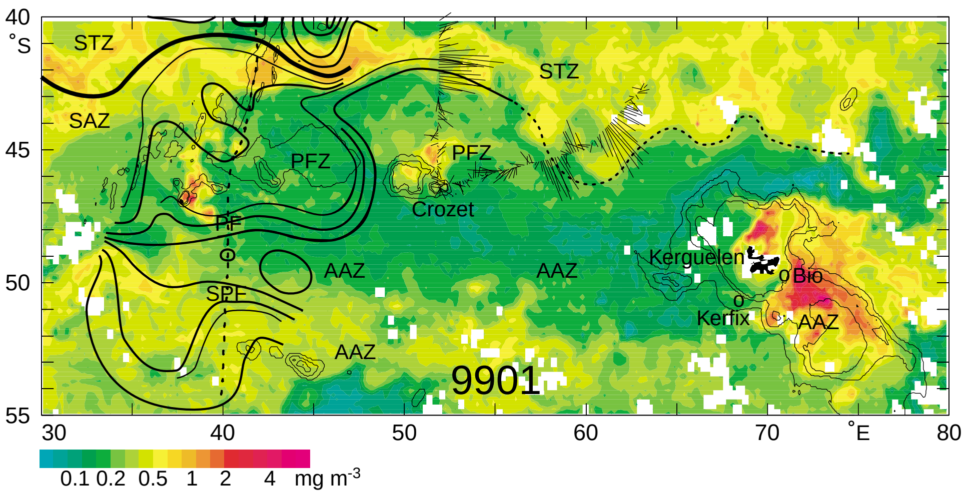

Fig. 5. SeaWIFS image of surface chlorophyll for January 1999. ADCP vectors at 100 m from the French JGOFS cruise Antares 4 in Jan/Feb 1999 are overlaid. Also overlaid is the SWINDEX circulation scheme taken from Pollard and Read (2001) and the 40E section (dashed) shown in Figs. 3 and 4. The heavy bold line marks the STF, along which chlorophyll values are elevated. The 500, 1000 and 2000 m depth contours are shown. Positions of the French Kerfix and Bio-stations in the vicinity of Kerguelen Island are marked.

What must be circumpolar, by simple mass balance, is the total transport of the ACC. For that transport to be in geostrophic balance, isopycnals must slope up to the south and it is easy to show that, for 140 Sv total transport, isopycnals must shallow by about 1000 m. This rise is the same whether the transport is spread across a wide or narrow band of latitudes. Thus, for example, the UCDW, found at a depth of 1000–1500 m north of the ACC, must rise by about 1000 m across the ACC, so that it outcrops at the southern edge of the ACC, thus forming the SB, which must therefore be circumpolar. In general, it is the outcropping of different isopycnals and the water masses associated with them that results in the physical zonation of the Southern Ocean. There is one more important point to be made. The fact that all isopycnals rise towards the pole does not tell us anything about convergence or divergence of the upper water masses. The zonation is not primarily a consequence of wind-driven convergence or divergence of the surface layer, but of the sloping isopycnals that must be present to ensure geostrophic balance of the ACC.

We therefore shall define four zones without reference to the frontal jets, but in line with the definitions of Nowlin and Klinck (1986), namely the Subantarctic Zone (SAZ), Polar Frontal Zone (PFZ), Antarctic Zone (AAZ) and the Zone south of the ACC (SACCZ). Table 1 summarizes our definitions and links them to the frontal definitions given above. A comprehensive summary of frontal definitions is given by Belkin and Gordon (1996). Only a few of these have been extracted into Table 1, chosen to show that fronts have often been defined by the properties of the adjacent zone rather than by the properties of the front itself. The definition of the SB is taken from Orsi et al. (1995).

1.6. Zone definitions

The *SAZ* is the northernmost zone of the Southern Ocean and is where surface temperatures are large enough that temperature stratification dominates over salinity stratification. Thus it is possible for salinity to decrease downwards, so the SAZ is defined by a marked subsurface salinity minimum associated with the relatively fresh AAIW. While the SAZ does not carry the ACC transport, it contains much fresh Subantarctic Surface Water that has been carried northwards from the PFZ in the surface layer by wind-driven Ekman transport.

In the *PFZ* salinity is as important as temperature in contributing to the stratification. Thus, while a weak subsurface salinity minimum or temperature maximum may sometimes be present, in general salinity increases downwards with Subantarctic Surface Water in the surface layer and temperature decreases downwards. Thus the absence of both a marked subsurface AAIW salinity minimum and of a marked shallow subsurface temperature minimum of 2°C or less defines the PFZ.

In the *AAZ* salinity is more important than temperature in controlling the stratification of the upper ocean. Thus temperature can increase downwards towards the temperature maximum of UCDW, and the induced near-surface temperature minimum ($\leqslant 2$°C) is the defining characteristic of the AAZ, coupled with indicators (such as a nitrate maximum) that the underlying warmer water is UCDW.

The most poleward zone of the Southern Ocean is the *SACCZ*, lying south of the outcrop or southern terminus of UCDW (the SB by Orsi et al's (1995) definition). The best way to distinguish the SACCZ from the AAZ is that the subsurface nitrate maximum of UCDW is absent. However, lacking nutrient data, an equivalent indicator is that the subsurface temperature maximum is <1.6°C.

Clearly these definitions are closely related to the previous definitions of the fronts, given by Whitworth and Nowlin (1987) as the location of the rapid descent of the salinity minimum for the SAF and the location of the rapid descent of the 2°C temperature minimum for the PF, quoting Gordon (1967). Our definitions of zones do not depend on the existence of the fronts, however, and can be used to determine the zone whether or not the positions of the fronts are known. However, strong frontal jets must be places where isopycnals slope most steeply. Thus it is highly likely that, say, the descent of the AAIW salinity minimum will be associated with a current jet that we can label the SAF. But, in the absence of a concentrated current (e.g. Fig. 2b), the AAIW salinity minimum will still descend, marking transition from the PFZ to the SAZ, even though the descent will not be "rapid".

2. Discussion

2.1. Physical zonation

While we have defined four zones to match previous terminology, it is important to recognize that it is no more valid to say that there are four biophysical zones than it is to say that there are three fronts. We could define zonation based on any number of features that are circumpolar, for example 2°C, 1.8°C and 1.6°C temperature minima. What is more useful is to note that, at any particular longitude, the bathymetry defines the major pathways of the ACC, i.e. the concentrated currents or fronts, and those in turn define the detailed zonation at that longitude.

We have chosen to define the zones based on the changing balance of the contributions of salinity and temperature to the stratification. We hope these are useful definitions, which can be related to chemical and biological consequences. But these are not exact definitions, and there will be many locations where it will not be obvious which zone you are in. In particular, this will be the case at the boundaries of the zones, which are usually fronts. As shown in Table 1, there are both fronts and zones, and it will often be most logical to consider the major fronts as lying between two zones, rather than being incorporated into a zone. Other fronts, such as the Southern ACC Front, the SPF and the surface expression of the PF, may be fully contained within a zone (for all these it is the AAZ as defined above), and may or may not have property changes across them that justify extra definitions of fronts or zones locally.

The primary difference between fronts and zones is that the majority of the transport of the ACC is carried by a few relatively concentrated fronts, or frontal jets. In Table 1 we have shown the ACC spanning the SAF, PF and SB, as well as the PFZ and AAZ. At most longitudes, much of the ACC transport is carried by the PF and SAF, but on any meridional section there will often be other fronts, named or unnamed, within the PFZ and AAZ that carry a significant fraction of the transport. In saying this, we are limiting our definition of a front to a baroclinic feature, i.e. a region where there are significant isopycnal slopes requiring a current for geostrophic balance. But there can also be regions where water mass properties change markedly, without isopycnal slopes. The SAF on 40E (Fig. 2) is one example.

Using the definitions just given, we have marked the SAZ, PFZ, AAZ and SACCZ in Figs. 2–4. But we have shown AAZ twice along 40E (Fig. 3) because there is a significant change in surface silicate at 51°S where there is a strong front (the SPF). Similarly, south of Australia, Parslow et al. (2001) call the northern part of the AAZ the "Inter-Polar front zone" and Trull et al. (2001) abbreviate the southern part of the AAZ to the "AZ-S". Again, this is because a branch of the ACC (the SPF) splits the AAZ into two zones with significantly different properties. However, in this paper we wish to avoid becoming bogged down in nomenclature and clarify the overall role of physics in creating the biological and chemical zonation of the Southern Ocean.

2.2. Macro-nutrient distributions in relation to physical zonation

So let us now address the question, how do the distributions of nitrate and silicate relate to the zonation? In brief, nutrients are raised from depth towards the surface both by isopycnic transport (advection and mixing along upward sloping isopycnals) and diapycnic mixing (near-vertical mixing across density surfaces). Once in the surface layer (i.e. shallower than the maximum depth of winter mixing), nutrient concentrations are controlled physically by entrainment from below by winter mixing and possibly by northward Ekman advection. During the summer months, phytoplankton growth in the euphotic zone will modify surface nutrient concentrations. Let us consider these processes in more detail.

Biological processes of export flux, dominated by diatom production, herbivory and re-mineralization on seasonal to decadal scales, are what set the differing distributions of nitrate (Fig. 2e) and biogenic silica (Fig. 2d) as functions of increasing density. Blooms of heavily silicified diatoms such as *Fragilariopsis kerguelensis* and *Corethron criophilum* may dominate. Empty frustules originating from senescent blooms, herbivory or cell division (Crawford, 1995; Quéguiner et al., 1997) result in the uncoupled export of Si and N, with the particulate Si sinking rapidly into cold UCDW where re-mineralization is slow (Tréguer and Jacques, 1992). Such export of biogenic silica leads to the extensive regions of Si accumulation within sediments reported by DeMaster et al. (1991) for the Atlantic sector. Conversely, particulate organic N is subject to bacterial decomposition and microzooplankton grazing activity, resulting firstly in ammonification and subsequent nitrification at mid-depths, corresponding with the nitrate maximum there and elevated Si/N ratios (Figs. 2e and 2f).

Simultaneously with these biological processes, the physical processes of isopycnic mixing and advection even out nutrient distributions on each density surface, and we can infer that this must happen on shorter time scales (up to years) because of the generally close correspondence between the slopes of the silicate (Figs. 2d and 3d) and nitrate (Figs. 2e and 3e) contours and neutral density surfaces (bold contours on each panel of Figs. 2 and 3). While we are using our data from 40°E for this discussion, similar correspondence between nutrient and density surfaces can be seen in the sections along the Greenwich Meridian presented by Whitworth and Nowlin (1987) and in the sections presented by Rintoul and Bullister (1999) from the WOCE SR3 line south of Australia (140°E). This correspondence also shows that the primary reason why nutrients increase southwards at a given depth is that the density surfaces slope upwards. Thus isopycnic mixing combined with the rise of isopycnals to the south results in nutrient-rich water being found closer to the surface the further south one goes.

Looking carefully at the deep 28.0 neutral density surface (Fig. 2d), which rises from 2000 to 1000 m across the ACC, we see that, in addition to the rise of the surface, silicate also increases towards the south on the 28.0 surface itself. Note in particular the pronounced increase from 75 to 85 μM across the AAZ. Because silicate increases downwards, the increase on a density surface can only result from vertical mixing, particularly in the AAZ, which mixes the silicate-rich bottom water upwards. Nitrate, with its different vertical distribution, does not show this trend.

Can we distinguish physical effects (Ekman advection, vertical mixing) from biological effects (summer utilization of Si and N) in the surface layer? It is clear from the salinity distributions (Figs. 3 and 4) that Ekman advection carries fresh surface water northwards into the SAZ. Sigman et al. (1999) have shown that it is possible to distinguish between nitrate supplied by the two processes by examining $\delta^{15}N$, and they concluded that, in their summer and autumn data set, Ekman flux of Antarctic surface water was the major factor. However, even the strong westerly winds over the ACC will only advect the surface layer northwards by perhaps 500 km per year. While nitrate is nowhere limiting in and south of the SAZ, Figs. 3 and 4 show that silicate may well be limiting in the SAZ and PFZ, as recently discussed by Smetacek (1998), Read et al. (2000), Franck et al. (2000), and Trull et al. (2001). Surface Si as a function of latitude shows a clear downward trend from south to north, with marked steps at each front. What is the explanation for these steps?

Consider the 27.4 neutral density surface, which rises from over 1000 m in the STZ (Fig. 2) into the shallow pycnocline at 120 m in the AAZ south of the SPF (Fig. 3). Comparing properties on this surface in the three zones PFZ, AAZ north of SPF, AAZ south of SPF (PFZ:nAAZ:sAAZ), we find the pressure (500:200:120 dbar), Si (25:22:30 μM), N (32:28:28 μM) and Si/N (0.8:0.8:1.1). Thus, at the base of the mixed layer in late summer (April 1993) in the southern AAZ, elevated Si (30 μM) on 27.4 indicates that physical effects (sloping isopycnals and diapycnic mixing) dominate. Similarly, in the northern AAZ, the isopycnically upwelled silicate supply at the base of the mixed layer (120 m) is 10–15 μM.

Now look at the net reduction in nutrients (i.e. the balance between uptake, export and remineralization) on the 27.2 neutral density surface (the middle of the three bold lines in Figs. 3d and 3e) from the base of the well mixed (Fig. 3c) layer (100 m) to the surface in the southern AAZ. The reduction of over 10 μM in Si (from 25 to under 15 μM, Fig. 3d) and over 2 μM in N (from 27 to under 25 μM, Fig. 3e) indicates phytoplankton production with high levels of silicate uptake. In the northern AAZ, similar reductions across the surface layer therefore reduce the Si to limiting values of 2 μM near the surface. The inference of high silicate uptake is consistent with Tréguer and van Bennekon (1991), who found high annual production of biogenic silica in the Permanently Open Ocean Zone, here identified with the AAZ. Given that silicate uptake is similar both north and south of the SPF along 40E (Fig. 3), our conclusion is that the north to south gradient in surface Si is primarily a consequence of isopycnals rising to the south, with Si well-mixed along isopycnals and increasing with density. A sharp "step" in Si across a front (here the SPF) in the surface layer is simply a consequence of steeply sloping isopycnals across a front, which of course extend into the surface layer and result in a density step across the front.

This conclusion must be refined to take into account the time of year. On our section, in late summer, Si in the stratified surface layer has been biologically reduced to <2 μM across the whole of the SAZ, PFZ and AAZ north of the SPF, so there will be no Si gradient across any fronts north of the SPF. Rintoul and Bullister (1999), in contrast, occupied a section along 140°E in late winter (October 1991), and found surface Si increasing from 5 μM at the SAF to 60 μM at the SB. Thus winter mixing resets the properties of the surface layer in both density and nutrients, re-establishing the close correspondence between neutral density contours and Si contours, as comparison of Rintoul and Bullister's (1999) density and nutrient sections shows.

Seasonal progression of Si gradients has been recently reported by Smith et al. (2000), who described surface variations of properties along 170°W in five occupations of the AESOPS section spanning a summer season from October 1997 to February 1998. In austral spring surface silicate increased southwards from about 5 μM at the SAF, with a strong latitudinal gradient across the PF at 61°S. By January, surface silicate was close to zero across the whole of the ACC to 65°S, approximately the SB. Franck et al. (2000) found evidence of Si limitation at 62°S once silicate levels had been reduced to below 5 μM. These changes are consistent with our assertion that nutrient levels are set at the end of winter on sloping isopycnals, but we cannot validate that conclusion against the AESOPS data in the absence of any vertical section plots.

In summary, remineralization sets the deep, vertical nutrient distributions, but isopycnic mixing is the dominant process which creates the strong correspondence between density and nutrient contours. Diapycnic mixing also plays a role, mixing Si upwards in the AAZ. Geostrophy requires the density contours to slope up to the south to balance the ACC. At the end of winter, the correspondence between density and nutrient contours extends right to the surface in the winter mixed layer. Where there is a strong current, there will be a step in density across it and consequently also a step in nutrients. These nutrient steps will persist through the summer, as long as nutrients are taken up by phytoplankton growth at the same rates on either side of the front. Once a nutrient is reduced to a limiting near-zero value, the step in the surface layer will disappear. Nitrate is nowhere limiting within the ACC, though it becomes the limiting nutrient north of the STF (e.g. Fig. 3). However, there is increasing evidence that Si can be the limiting nutrient across most of the ACC, certainly in the SAZ where end of winter concentrations are only about 5 μM, but extending south across the PFZ and AAZ as the summer progresses. Ekman advection has been mentioned as a factor in the SAZ, but does not appear to be important in the Si zonation. Nor have we found any need to invoke enhanced productivity at fronts to explain the Si steps.

2.3. Possible distribution of iron in relation to physical zonation

There has been much recent investigation of the possible role of iron as the limiting nutrient in the high nutrient low chlorophyll (HNLC) regime in the Southern Ocean, culminating in the SOIREE experiment summarized by Boyd et al. (2000). Interestingly, we have not had to invoke HNLC conditions in the discussion above. Along the SWINDEX 40E and AESOPS 170°E sections, silicate appeared to be the limiting nutrient, reducing to near-zero values except possibly at the very southern end of the sections, certainly not across most of the ACC. Or again, along our section 5E (Fig. 4), we have phytoplankton and zooplankton data (Figs. 4d and 4e) that show blooms and grazing limitation (Read et al., 2002) in the SAZ, PFZ and AAZ. It is noteworthy that, in the AAZ, near-surface chlorophyll levels were not large enough to constitute a bloom (defined as over $1.5\,\mathrm{mg\,m^{-3}}$), but significant chlorophyll values extended to depths of 100–150 m, so that the vertically integrated chlorophyll values were as large in the AAZ as in the PFZ (Read et al., 2002).

However, we can add a little to the debate about the role of iron in relation to Southern Ocean zonation. Fig. 5 shows SeaWiFS data for the Southwest Indian Ocean sector of the Southern Ocean in January 1999. Most striking are the blooms north and east of Kerguelen Island. Note the narrow north–south streak of low chlorophyll (running through station Bio) that separates these blooms. Bucciarelli et al. (2001) and Blain et al. (2001) have shown that both blooms are iron fertilized. The bloom north of Kerguelen is easily explained by the island itself as a source of iron. We infer that the bloom over the Kerguelen Plateau east of station Kerfix is sustained by a benthic source of iron, from the plateau itself, but this needs verification by in situ observations.

The circulation scheme determined by Pollard and Read (2001) is overlaid on the western half of Fig. 5, as is the track of 40E (compare Figs. 1–3). North of the Crozet Plateau, SeaWiFS images (not shown) show an annual bloom in October or November which appears to be exactly bounded to the west and north by the front shown in Pollard and Read's (2001) schematic. It is this that suggests to us a benthic source of natural iron fertilization, in this case from the Crozet Plateau. We cannot strongly establish this hypothesis here. Our intention, in the context of Southern Ocean zonation, is simply to point out that blooms covering substantial areas (say 400 km × 400 km for the bloom over the Kerguelen Plateau, a similar area north of Crozet) can be found in the Southern Ocean in both the AAZ (Kerguelen) and PFZ (Crozet). In both these regions, nitrate and silicate values are high enough not to be limiting, at least in austral spring. A benthic source of iron is a plausible explanation for why the blooms are spatially bounded.

Apart from the blooms, elongated west to east streaks of enhanced and diminished chlorophyll are apparent in Fig. 5, which are evidence for the importance of the Southern Ocean fronts and advection along them. The enhanced chlorophyll along 42°S runs along and north of the STF, so is strictly in the STZ, outside the zones being discussed here. Southeast of Africa, this is discussed by Weeks and Shillington (1996). A second band of enhanced chlorophyll extends eastward from 50°S at 30°E towards 53°S at 60°E. This band lies in the AAZ, and is centred on the SPF. From our discussion above, we know that silicate levels are not limiting in the southern AAZ, and we found evidence for phytoplankton production in the reduction of silicate and nitrate in the surface layer in late summer (Fig. 3).

3. Conclusions

In this paper we have sought to revise our paradigm for the physical structure of the Southern Ocean and its biological consequences. The main circumpolar feature is the wind-driven transport of the ACC. The ACC transport tends to be concentrated in frontal jets, the number, strength and latitudinal locations of which are determined by the bathymetry and so vary with longitude. Because the frontal jets can merge or fragment along their paths, it is misleading to think of any of them as being circumpolar. It is also misleading to define any front solely by scalar properties, for example to assume that the 2°C temperature minimum defines the Polar Front. While the 2°C temperature minimum is a circumpolar feature, it is not at every longitude associated with a major current jet.

A more robust definition of Southern Ocean zonation is achieved by considering the relative contributions of temperature and salinity to the stratification and how that balance changes with latitude. Towards the equator, temperature dominates. Towards the pole, salinity dominates. These features are circumpolar. Thus, in the northernmost zone of the Southern Ocean, the SAZ, salinity increases downwards to the AAIW salinity minimum and there is strong seasonality because of the temperature control, with very deep mixed layers possible in winter. The transport of the ACC is confined to the central zones, the PFZ and AAZ, being primarily concentrated at fronts within and bounding those zones. The distinction between these zones is that in the AAZ there is a summer subsurface temperature minimum of 2°C or less, as low surface salinities allow the surface temperature to be colder than the temperature maximum of the underlying UCDW. The southern boundary (SB) of the ACC is where the UCDW outcrops, south of which is defined as the SACCZ.

Geostrophic balance of the ACC transport requires isopycnals to slope upwards towards the south, so that the major nutrients, nitrate and silicate, which are broadly constant on isopycnals because of isopycnic mixing, are largest in the south at any given depth in the top 500 m. In addition, silicate increases to the south on each isopycnal, which is an evidence that silicate is also mixing up through the water column. At each current jet of the ACC there tends to be a steplike decrease in surface values, which is primarily a consequence of the strongly sloping isopycnals, with their associated nutrient values, penetrating the surface layer at the end of winter. In summer these steps may disappear if silicate is removed by primary productivity on both sides of a front. By the end of summer silicate may be limiting in the surface layer in all zones of the ACC including the AAZ as far south as the SPF. Nitrate is not limiting south of the STZ, however.

Blooms covering areas as large as 400 km across may be present in both the PFZ and the AAZ; thus these zones are not everywhere HNLC regions. Such blooms appear to be associated with submarine plateaux like the Kerguelen and Crozet Plateaux, leading us to hypothesize that a benthic souce of iron is the likely source of natural fertilization. Elongated streaks of chlorophyll are probably stretched by the currents associated with major fronts.

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