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Substantial advective iron loss diminishes phytoplankton production in the Antarctic Zone

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[1] After 1 decade of research it is a well-established fact that iron limits photosynthetic CO_2 fixation and phytoplankton growth in the Southern Ocean; intense blooms are scarce. However, the input of iron to the Southern Ocean is considerable. An important factor for diminished phytoplankton production refers to the meridional circulation of the Southern Ocean. Intense, spatially relatively homogeneous upwelling of Upper Circumpolar Deep Water (UCDW) causes a large iron flux into the surface layer. However, the main entrainment of upwelled UCDW into the surface layer occurs in autumn and winter, which strongly restricts the usefullness of iron supply for phytoplankton due to unfavorable light conditions. Moreover, the meridional transport within the Ekman layer is intense enough to export at least 25% of the iron input away from the Antarctic Zone before it can be used by phytoplankton. This also depresses the potential phytoplankton primary production by at least 25%. Most iron that crosses the Polar Front unused probably leaves the surface ocean north of the Polar Front because the surface water participates in Antarctic Intermediate Water/Mode Water formation. *INDEX TERMS:* 4207 Oceanography: General: Arctic and Antarctic oceanography; 4279 Oceanography: General: Upwelling and convergences; 4805 Oceanography: Biological and Chemical: Biogeochemical cycles (1615); 4875 Oceanography: Biological and Chemical: Trace elements; *KEYWORDS:* Southern Ocean, iron, surface layer, upwelling, Upper Circumpolar Deep Water

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1. Introduction

[2] It has been suspected since the first part of the twentieth century that the trace metal iron (Fe) is potentially limiting for phytoplankton productivity. Yet, only toward the end of that century the introduction of ultraclean sampling techniques has allowed exploring this hypothesis in the field [*Martin and Fitzwater*, 1988; *De Baar*, 1994]. From the beginning, the Southern Ocean has been a prime candidate for iron limitation [*Gran*, 1931], because of the year-round occurrence of high nutrient levels in the surface layer in combination with low productivity. Also, a limitation caused by a lack of light energy was well recognized [*Tranter*, 1982], notably during austral autumn and winter due to the combination of low incident sunlight, extensive sea-ice cover and deep mixing by intense storms.

1.1. Iron and Light Limitation

[3] A major research effort during the last decade has brought compelling evidence that iron is the key limiting nutrient for phytoplankton primary productivity in the Southern Ocean [*De Baar et al.*, 1990; *Martin et al.*, 1990; *Boyd et al.*, 2000]. We now realize that both light and iron are the major limitations for plankton growth in the Southern Ocean. As a matter of fact, this is a colimitation as Fe plays a major role in the light harvesting within the plant cell [*Timmermans et al.*, 2001a]. First, Fe is essential for the synthesis of light-collector chlorophyll *a* [*De Baar et al.*, 1990], and second, Fe is pivotal in the electron transport chain; that is, upon Fe enrichment the efficiency of the overall photosynthesis increases markedly [*Boyd and Abraham*, 2001]. *De Baar and Boyd* [2000] noticed a uniform worldwide effect of stimulation of the class of large diatoms.

1.2. Iron Supply

[4] Iron sources to and within the surface layer include rivers, aeolian dust, vertical transport (upwelling of iron-rich deep water), release and advection from continental shelf sediments, icebergs and recycling of iron within the biological system of the surface layer [*Chester*, 1990; *Duce and Tindale*, 1991; *Lefèvre and Watson*, 1999; *Walter et al.*, 2000; *De Baar and Boyd*, 2000; *Banse*, 1996]. There has been comparatively little interest in iron loss processes.

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However, for the eventual availability of iron, these are as important as iron sources. Here, we want to draw attention to the influence of the large-scale circulation of the Southern Ocean on the availability of iron. We discuss a mechanism highlighting advection losses of iron which tends to lower total phytoplankton production.

[5] For large parts of the ocean surface the major source of iron is hinted to be aeolian dust [*Duce and Tindale*, 1991; *Fung et al.*, 2000; *Jickells and Spokes*, 2001]. However, little continental dust reaches the remote Southern Ocean and instead vertical transport of iron-rich deep water is likely to be the main source [*De Baar et al.*, 1995; *Löscher et al.*, 1997; *Lefèvre and Watson*, 1999; *Watson et al.*, 2000]. Neither the Fe supply by atmospheric dust, nor the upwelling Fe flux are well-constrained figures [*Fung et al.*, 2000; *De Baar and De Jong*, 2001; *Moore et al.*, 2002]. It is worthwhile mentioning that in contrast to the above studies favouring the atmosphere as the main iron source, *Archer and Johnson* [2000] in a modeling study found that 70–80% of the total oceanic new production can be sustained by iron from deep-water sources, which was indeed largely confirmed by *Moore et al.* [2002]. In any case, almost all studies appear to agree that for the Southern Ocean the upwelling iron flux strongly dominates the aeolian one.

1.3. Upwelling Supply

[6] In the Southern Ocean the upwelling of Upper Circumpolar Deep Water (UCDW) brings Fe into the surface layer. A typical dissolved Fe concentration in the UCDW is about 0.4–0.5 nmol kg^{-1} [see *Löscher et al.*, 1997; *Sedwick et al.*, 2000; *De Baar and De Jong*, 2001]. An annual mean estimate for UCDW upwelling gives 34 Sv (10^6 m^3 s^{-1}) [*Rintoul et al.*, 2001], which is supported by other independent modeling results [e.g., *Nycander et al.*, 2002]. The total annual Fe flux by UCDW is thus about 0.5 10^9 mol Fe yr^{-1}. UCDW upwelling occurs in the Antarctic Ocean south of the Polar Front, the total surface area of which is between 29×10^{12} m^2 and 39×10^{12} m^2. The range of surface area stems from the choice of the southern extent, the 500-m and the 200-m isobath, respectively. We take 35×10^{12} m^2 resulting in a mean iron flux of 14 μmol m^{-2} yr^{-1}. *Watson et al.* [2000] estimate the upwelling iron flux in the Southern Ocean to be 8–16 μmol m^{-2} yr^{-1}, which is in close agreement with our large-scale estimate. *De Baar et al.* [1995] using older upwelling velocity estimates and a twice as high deep-water Fe concentration, come to about 50 μmol m^{-2} yr^{-1} for supply of dissolved iron into the Atlantic sector near the Polar Front. Although not well constrained, a large flux of Fe into the surface layer of the Southern Ocean occurs, but the total phytoplankton production by the Southern Ocean is only moderate. In the following, we argue that the specific large-scale dynamics of the Antarctic Circumpolar Current (ACC) are a major reason for a suboptimal utilization of iron and decreased phytoplankton production in Antarctic waters.

2. Lateral Iron Export Mechanism

[7] We first focus on the role of the UCDW and the meridional circulation in the Southern Ocean. The ACC has always been viewed as an extraordinarily strong zonal feature, which transports water eastward around the Antarctic continent. However, a considerable component of meridional circulation exists as well. Recently, the issue has been explored by, for example, *Döös and Webb* [1994]. The total eastward transport of the ACC is currently thought to be about 130–140 Sv (= 10^6 m^3 s^{-1}) [*Whitworth et al.*, 1982]. The northward transport of UCDW is estimated to be 34 Sv [*Rintoul et al.*, 2001; *Sloyan and Rintoul*, 2001]. This compares well with the estimated northward Ekman transport of 28–30 Sv across the Polar Front [*de Szoeke and Levine*, 1981; *Döös and Webb*, 1994]. Since this transport is almost entirely fed by upwelled water, we conclude that most UCDW, a subsurface water mass in the southern ACC, is entrained in the surface layer and transported northward.

[8] The amount of upwelled UCDW is poorly constrained. Qualitatively, large upwelling activity of deep water can be deduced from the outflux of mantle ^3He [*Farley et al.*, 1995], which must derive from deep water because it has its sources only at the seafloor of the oceans. For the southern ACC, upwelling velocities in the range 60–100 m yr^{-1} have been reported [*Gordon et al.*, 1977; *Hoppema et al.*, 2000]. Further to the south in the Weddell Sea, lower values are found [*Gordon and Huber*, 1990; *Hoppema et al.*, 1999]. Although we cannot further constrain the 34 Sv of UCDW transport, we believe that the figure is reasonable.

[9] In the following, we address the role of the meridional transport of the ACC in the iron issue. Data found in the literature are used to calculate the meridional transport. In the surface layer south of the Polar Front, typical zonal current velocities of the ACC amount to 10–20 cm s^{-1} [e.g., *Reid and Nowlin*, 1971; *Whitworth and Nowlin*, 1987]. The meridional velocity can be estimated from the Ekman transport. The circumpolar path length of the Polar Front is about 25,000 km, and the Ekman layer is taken to be 50 m, which should be reasonable at a mean wind speed of about 10 m s^{-1} [*Boutin and Etcheto*, 1996]. Thus the Ekman transport of about 30 Sv takes place over a surface area of 2.3×10^9 m^2, which yields a mean equatorward velocity of 2.4 cm s^{-1}. This mean velocity is near the lower end of the range 2–5 cm s^{-1} as calculated for the northern ACC, Indian sector by *Park et al.* [1993]. The latter investigation shows that the variability of the meridional velocity can be large indeed.

[10] The full consequences of the mean equatorward velocity of 2.4 cm s^{-1} become obvious if referred to the width of the southern ACC. In 1 year the meridional path covered is at least 760 km. For illustration purposes, we estimate the mean meridional distance between the southern boundary of the ACC and the PF at about 800 km (with a large range) using the circumpolar front tracks determined by *Orsi et al.* [1995]. Hence, the equatorward conveyance of upwelled UCDW is large and its residence time in the ACC south of the PF is accordingly short, i.e., about 1 year. In certain regions, where the southern boundary and PF are closer than average, this may be less, for example north of the Ross Sea, near the Antarctic Peninsula and north of the Enderby basin. In other regions, like the western Indian sector, the residence time may be more than 1 year. Note

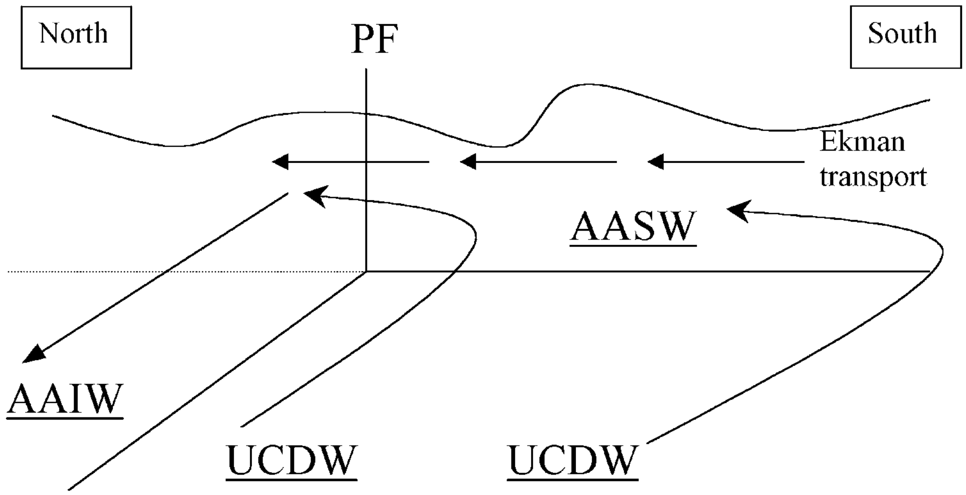

Figure 1. Simplified scheme of the meridional circulation cell in the Antarctic Circumpolar Current. Shown are the surface and subsurface layers. South of the Polar Front (PF), upwelling of Upper Circumpolar Deep Water (UCDW) contributes to Antarctic Surface Water (AASW). North of the PF, formation of Antarctic Intermediate Water (AAIW) occurs.

that the above estimated residence time inherently assumes that upwelling occurs homogeneously over the entire surface area south of the Polar Front. In section 2.2 this assumption is discussed and justified.

[11] Overall, the mechanism as applied to dissolved Fe is summarized as follows. Upwelling of Fe-rich UCDW south of the PF causes a large Fe flux into the surface area of the Antarctic Ocean. A very important point here is that upwelling of Fe-rich deep water occurs almost everywhere south of the PF (see section 2.2). Such abundant iron supply (see section 1) could support considerable phytoplankton primary production. However, a substantial part of this Fe-rich water is exported away from the Antarctic Zone by the marked meridional water transport. Thus, the supplied iron has vanished before it can be used by phytoplankton; that is, the net Fe flux to the Antarctic Zone is strongly decreased. In the following, we discuss details of the proposed mechanism, which is schematically shown in Figure 1.

2.1. Seasonal Mismatch

[12] A pivotal point within the mechanism of Fe loss for utilization by phytoplankton is that a substantial part of the upwelled iron enters the surface layer in a time of year when it is sub-optimally usable for phytoplankton. The reason for this is that, although upwelling of UCDW occurs all through the year, the process that actually transports Fe-enriched deep water into the surface layer is entrainment during the seasonal deepening of the surface mixed-layer [*Gordon and Huber*, 1990]. The latter process occurs predominantly in autumn and winter when the wind speeds are high, and turbulent mixing and convection are prevalent. However, autumn and winter are unfavorable seasons for phytoplankton growth because of severe light limitation with low incident light, sea-ice cover and deep mixed-layers of remaining open waters acting in concert. A substantial part of the new surface water, which is generated all over the Antarctic Ocean, is rapidly transferred equatorward from the southern ACC. If we presume a 6-month winter period, the meridional equatorward path covered during this period is about 400 km. With a mean southern-ACC width of 800 km, about half of this region is meridionally exchanged. This calculation holds for the Ekman layer, which is about 50 m thick. The winter mixed-layer, in which upwelled iron is collected, is at least twice as large. This in turn implies that about one fourth of the imported iron leaves the region before it can be used by phytoplankton.

[13] The changes of the Fe concentration in the surface layer are schematically depicted in Figure 2. In this Figure the Fe concentration is derived from a simple model with the following terms:

$$S - P - E = 0 \quad (1)$$

where S is the upwelling supply of Fe, with $S = c^* W$, where W is the upwelling rate ($m^3\ s^{-1}$). c is the Fe concentration

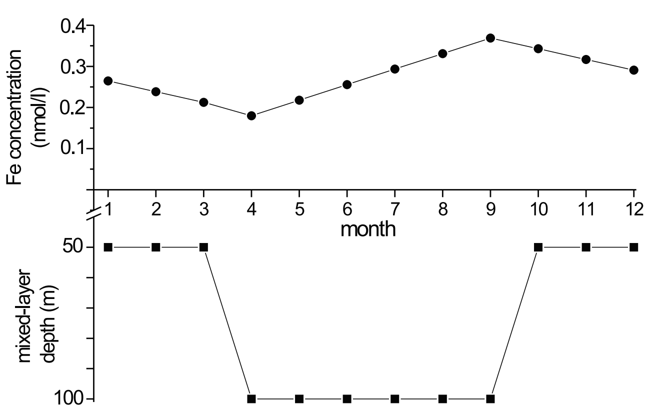

Figure 2. Schematic representation of the seasonal cycle of the Fe concentration in the surface mixed-layer of the Antarctic Circumpolar Current. Also shown are the assumed changes in the mixed-layer depth.

which varies seasonally as in winter entrainment reaches the deep water, whereas in summer entrainment is lower due to weaker winds and stronger stratification. P is the Fe consumption due to phytoplankton new production, $P = c^* F_1$, where F_1 is the rate of production ($m^3\ s^{-1}$). E is the northward Fe export by lateral advection, where $E = c^* V$, with V as the northward transport in the surface Ekman layer. V and W were derived from the coupled ice-ocean model BRIOS2.2 [*Assmann et al.*, 2003] for the region south of 55°S.

[14] Referring to Figure 2, we assume a mean mixed-layer depth of 50 m during the summer months and 100 m during winter. During summer the concentration decreases through consumption with the lowest values at the end of this season. The Fe concentration is highest at the end of winter due to major entrainment. Because of mixing with the Fe-depleted surface layer, the value is slightly lower than the deep-water concentration. This is in agreement with observational data by *Löscher et al.* [1997], who noticed that Fe concentrations in Antarctic surface waters in early austral spring are only slightly lower than those in the underlying deep water. *Measures and Vink* [2001] also found similar surface and subsurface Fe concentrations in early spring south of the PF in the Pacific sector of the Southern Ocean.

[15] With respect to the above assessment of 25% iron loss, it should be mentioned that the winter mixed-layer is on average deeper than 100 m, which decreases the percentual iron loss for an Ekman-layer depth of 50 m. On the other hand, the winter Ekman layer should be larger than the assumed mean of 50 m because of higher wind speeds. These opposite effects at least partly compensate each other. Additionally, surface water flows equatorward all year round. However, the water transport in summer is less and the Fe concentration is lower than in winter because of Fe uptake by phytoplankton. Therefore, the equatorward Fe transport is substantially smaller during summer than during winter. In sum, the above estimated 25% of iron loss from the original upwelled amount should probably be considered as a lower limit.

[16] In concert with the northward Ekman transport, the seasonal pycnocline formed by atmospheric heating and sea ice melting during spring and summer prevents depletion of all the iron originally present in the winter mixed-layer. It forms an effective isolating cap on the lower part of the winter mixed layer with phytoplankton growth largely restricted to the upper layer. The seasonal pycnocline leads to a substantial reduction of the winter mixed-layer depth, which in turn supports a rapid depletion of the iron, while little new iron is supplied from below.

2.2. Antarctic Divergence

[17] In the above, we emphasized that upwelling occurs all over the surface area south of the Polar Front. In the Southern Ocean, however, upwelling has often been brought in relation to the Antarctic Divergence (AD). The classical view is that almost all upwelling occurs near the AD, which usually lies south of the ACC. Data and modeling results show that upwelling is more widespread. Referring to the distribution of upwelling rate shown by *Comiso et al.* [1993, Plate 4] and the wind stress distributions by *Trenberth et al.* [1990], it can be seen that upwelling activity occurs relatively homogeneously around the continent. This is also confirmed by the results of the coupled ice-ocean model BRIOS2.2 (Figure 3), which simulates hydrographic features of the Southern Ocean quite well [*Assmann et al.*, 2003]. Homogeneous upwelling is a crucial condition for our concept of export of upwelled water from the ACC to the north. If upwelling would only occur near the AD, the export of upwelled iron-rich water would have only minor influence on the iron budget of the Southern Ocean.

2.3. Northward Iron Export

[18] The proposed mechanism effectively causes the loss of a substantial part of iron supply from the Antarctic Zone. Part of the Fe will be utilized at the convergent Polar Front (see below). Another part of the Fe-containing surface water will be involved in Antarctic Intermediate Water (AAIW) and Mode Water formation, whereas still another part will be dispersed in the surface water of the vast Subantarctic Zone. If involved in AAIW formation, Fe is lost for uptake in the surface layer. If dispersed in the Subantarctic Zone, the iron will certainly be fixed by phytoplankton, but the resulting Fe concentration will be too low to initiate blooms. *Sloyan and Rintoul* [2001] ascertain that almost all upwelled UCDW will become Intermediate Water. Despite a larger aeolian supply [*Duce and Tindale*, 1991; *Tegen and Fung*, 1995], the iron supply for the Subantarctic Zone is relatively poor as no upwelling of Fe-rich deep water occurs. Reportedly, there are no blooms in the Subantarctic Zone [*Banse*, 1996], which is not in contradiction with the dominance of the transformation of upwelled UCDW into intermediate water as proposed by *Sloyan and Rintoul* [2001]. Within the AAIW, the Fe concentration is comparable to that in the surface layer to the south, as can be recognized in the distributions shown by *Löscher et al.* [1997].

2.4. Regional Differences

[19] Equatorward transfer is an outstanding process to remove available surface-layer iron and in turn this strongly diminishes phytoplankton production. However, phytoplankton blooms do occur, while there are regional differences in their occurrence. Of interest here is the region around and dowstream of the Antarctic Peninsula, which is characterized by extensive phytoplankton blooms (Figure 4) [*Moore and Abbott*, 2000; *Comiso et al.*, 1993]. The exceptional situation near the Antarctic Peninsula has been explained by diagenetic Fe input from the shelf sediments [*Martin et al.*, 1990; *Nolting et al.*, 1991; *Westerlund and Öhman*, 1991]. It is very likely that such a process plays a role, because in the surface water downstream of the Antarctic Peninsula, Fe concentrations much higher than those in the upwelled UCDW have been observed [*Löscher et al.*, 1997]. Another explanation is based on the elevated atmospheric iron deposition from the South American continent [e.g., *Moore et al.*, 2002].

[20] Also downstream of the Antarctic Peninsula, a region exists where blooms occur frequently. We note that high chlorophyll values are mainly found south of the ACC boundary [*Orsi et al.*, 1995] within the subpolar

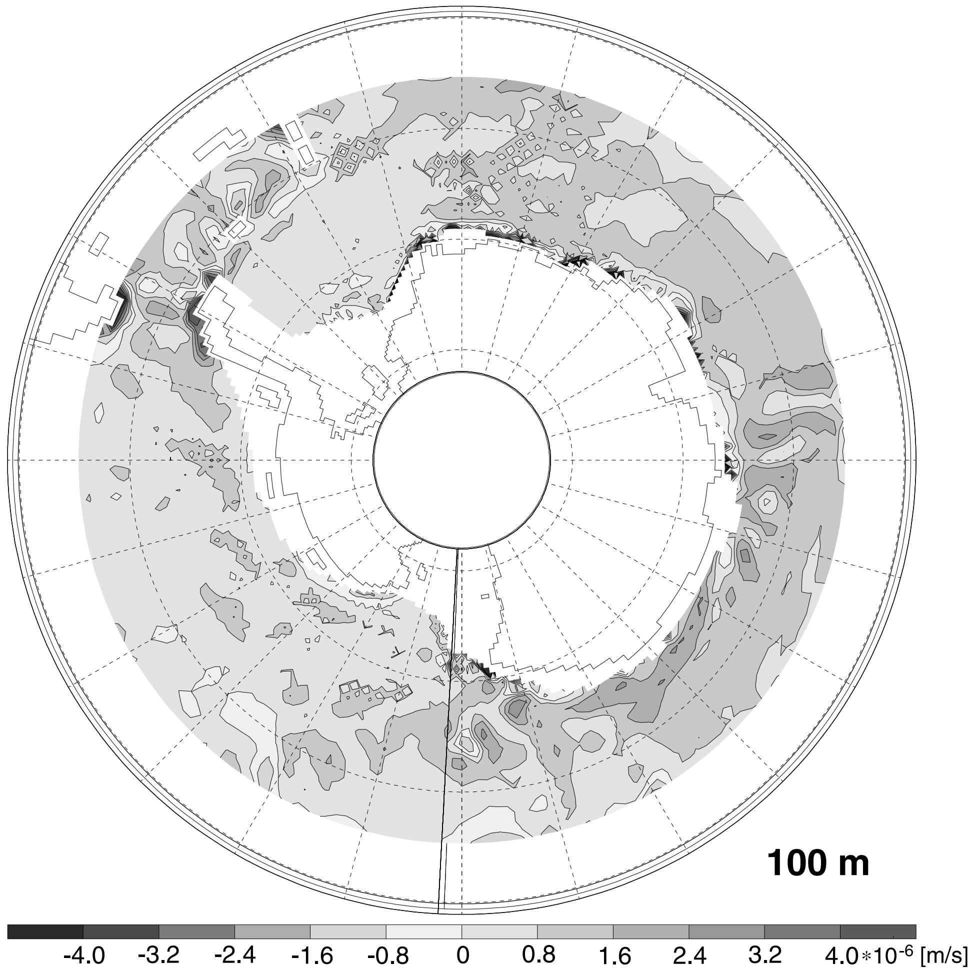

Figure 3. Annual mean vertical velocity at 100 m depth for the Southern Ocean south of 55°S and for water depths >1000 m derived from the numerical model BRIOS2.2 [*Assmann et al.*, 2003]. The 5° zonal band to the north is masked because of unrealistic values due to the proximity of the model's northern boundary at 50°S. See color version of this figure at back of this issue.

zone (Figure 4). Another high-chlorophyll patch occurs between the southern ACC boundary and the Polar Front. The high-chlorophyll region in the subpolar zone is largely part of the Weddell-Scotia Confluence (WSC). This is a zone where deep waters from the Weddell Sea and the ACC are mixed with shelf waters from the northwestern Weddell Sea [*Whitworth et al.*, 1994]. In this convergence zone, the northward transport of surface waters is restricted, causing a prolonged residence time of Fe-rich surface water and promoting phytoplankton blooms. Note that the shelf waters of the Weddell Sea additionally contribute high Fe concentrations [*Westerlund and Öhman*, 1991] to WSC waters, the latter of which indeed are rich in Fe [*Nolting et al.*, 1991]. A patch of high-chlorophyll water outside the WSC between 30 and 40°W (Figure 4) exists close to a northward excursion of the southern boundary of the ACC [*Orsi et al.*, 1995]. For this area, *Bagriantsev et al.* [1989] suggest outflow of subsurface water from the Weddell gyre and WSC. We surmise that together with this subsurface water an outflow of surface water occurs. This surface water carries a high iron load, which promotes blooms in this part of the Antarctic Zone downstream of the outflow in the Antarctic zone.

3. Discussion

3.1. New Production

[21] Above we estimated the total upward Fe flux in the Antarctic Ocean to be 0.5×10^9 mol Fe yr^{-1}. Combined with an assumed Fe requirement by phytoplankton, expressed as the Fe:C ratio, this would yield the potential carbon production. Note that this figure represents the so-called new production because the upward iron flux is new iron. The actual primary productivity then depends on the recycling efficiency of Fe (f-ratio) within the surface layer, relative to the f-ratio for C fixation. *Sunda* [1997] estimated the Fe:C ratio for Antarctic phytoplankton from the Ross Sea and Drake Passage to be about 2×10^{-6} mol/mol. *Moore et al.* [2002] simulated values of $2–3.5 \times 10^{-6}$ for the circumpolar ocean. Recently, experimental work has shown a fairly high Fe requirement for very large Antarctic diatoms [*Timmermans et al.*, 2001b]. An overall Fe:C ratio

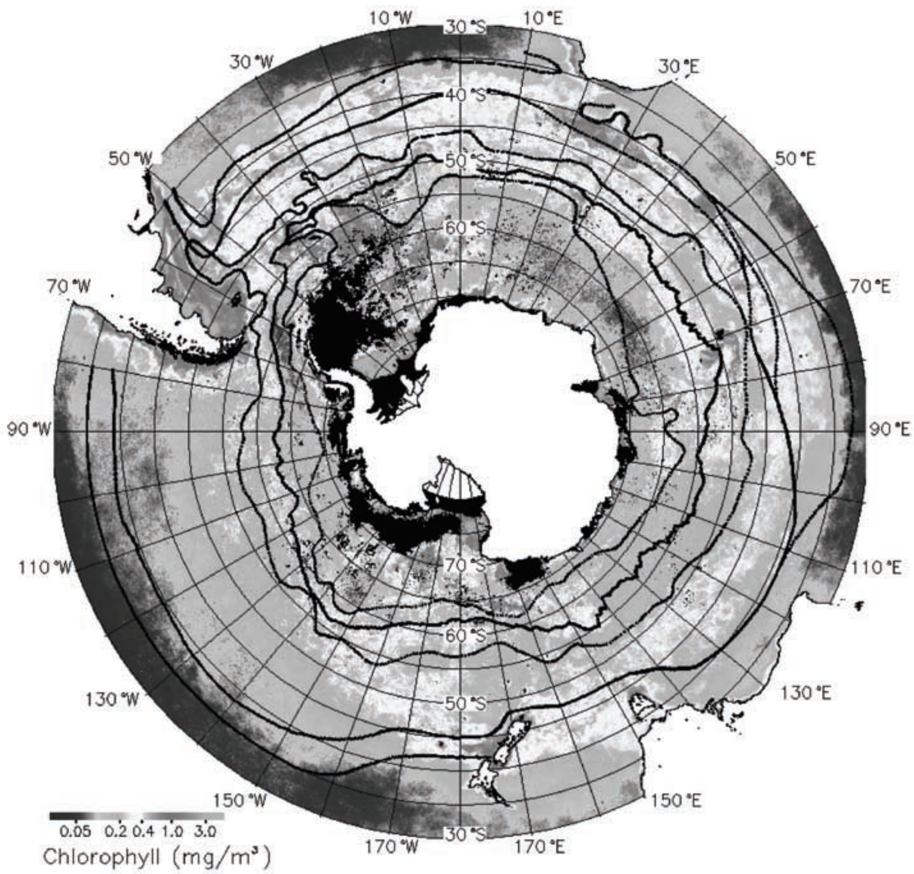

Figure 4. Mean SeaWifs chlorophyll for the summer months December 1997 through February 1998 and the mean location of the major Southern Ocean fronts. From south to north these are Southern ACC Front (SACCF), the Polar Front (PF) and the Subantarctic Front (SAF). SACCF and SAF are from *Orsi et al.* [1995], PF are from *Moore et al.* [1999]. More northern fronts are from *Belkin and Gordon* [1996]. Figure, with permission, is taken from *Moore and Abbott* [2000]. See color version of this figure at back of this issue.

in the order of $20 \pm 10 \times 10^{-6}$ mol/mol is deemed typical for these bloom-forming large diatoms. Ecosystem simulations of natural [*De Baar et al.*, 1995] or artificial [*Boyd et al.*, 2000] in situ Fe stimulation of the large Antarctic diatom *Fragilariopsis kerguelensis* also hinge on Fe:C ratios of $\geq 20 \times 10^{-6}$ mol/mol [*Lancelot et al.*, 2000].

[22] When we take the favorable Fe:C ratio of 3 10^{-6} mol/mol this converts into a total Antarctic Ocean new production of 1.7×10^{14} mol C yr^{-1}. Accounting for the surface area (35×10^{12} m^2) this becomes 4.9 mol C m^{-2} yr^{-1}. This is the potential new production, if there were no iron loss mechanism. This value (4.9 mol C m^{-2} yr^{-1} equals 58 g C m^{-2} yr^{-1}) is an order of magnitude higher than that given by *Smith* [1991] with 2.4 g C m^{-2} yr^{-1} for the open ocean (but 23 g C m^{-2} yr^{-1} for ice edge systems). The value is also substantially higher than the estimates by *Jacques* [1991], 27 g C m^{-2} yr^{-1} based on large-scale property distributions, and *Schlitzer* [2002] in an inverse modeling study with 1.4 Pg C yr^{-1} for dissolved and particulate carbon south of 50°S, which equals 35 g C m^{-2} yr^{-1}. We estimated above that at least 25% of the imported Fe flux is transferred unused equatorward, which would reduce our new-production estimate to about 3.6 mol C m^{-2} yr^{-1} (43 g C m^{-2} yr^{-1}) as a maximum value. This brings the iron-based estimate much closer to the high literature estimates. For the inner Weddell Sea, which probably receives less upwelled iron than the ACC to the north (see discussion above), the new production was found to be 21 g C m^{-2} yr^{-1} [*Hoppema et al.*, 2002]. This literature comparison strongly supports our arguments for a substantial advective loss of iron from the Southern Ocean.

[23] On the other hand, when taking the higher Fe:C ratio of 20–30 $\times 10^{-6}$ deemed typical for Fe-stimulated large diatoms, our new-production estimate would be ten-fold smaller at about 5 g C m^{-2} yr^{-1} which compares well with the above-mentioned 2.4 g C m^{-2} yr^{-1} for the open ocean [*Smith*, 1991]. However, since blooms are not the rule in Antarctic waters, this implies that, in general, smaller phytoplankton species with lower Fe requirement are prev-

alent. This would justify the above used relatively low Fe:C ratio. Finally, we should be aware that more sources of iron to Antarctic surface waters exist, which include dust from Patagonia [*Tegen and Fung*, 1995; *Moore et al.*, 2002], lateral sedimentary iron supply [*Martin et al.*, 1990; *Nolting et al.*, 1991], and iron from iceberg melting [*Löscher et al.*, 1997], but we do not know their source strengths.

3.2. Blooms at Frontal Systems

[24] Southern Ocean fronts have been found to support enhanced biological growth [*Laubscher et al.*, 1993; *Veth et al.*, 1997]. At the Polar Front, elevated concentrations of iron were measured, which were invoked to cause an observed phytoplankton bloom [*De Baar et al.*, 1995]. The latter authors explained the elevated concentrations of Fe by the jet flow of the Polar Front, which they suggested picked up Fe from sediment sources upstream around the Antarctic Peninsula. More recent investigations indicate that such Fe supply may not be continuous (M.M. Rutgers van der Loeff, AWI, personal communication, 2001) and thus blooms may be episodic or ephemeral. On the other hand, *Moore and Abbott* [2000] report satellite-derived elevated chlorophyll levels associated with the Polar Front (see also Figure 4) on an annual basis. We propose that a high base-level of iron could be maintained at the PF through the convergence of Fe-enriched surface waters, which originate from the upwelled deep water to the south. The lateral sedimentary Fe supply would merely be superimposed on this background level. Horizontal Ekman transport (via its iron supply) thus feeds the phytoplankton productivity at the Polar Front. For the North Atlantic, *Williams and Follows* [1998] proposed a similar mechanism involving horizontal Ekman transport of nutrients, which they found to be a significant contributor to the new production in the subtropical gyre.

[25] The southern boundary of the ACC has been proposed to be a band of water of elevated biological activity [*Dafner and Mordasova*, 1994; *Tynan*, 1998]. *Tynan* [1998] ascribed this to the upwelling of UCDW, with iron as a possible cause. As can be seen in a satellite-derived image of the annual mean pigment concentration (Figure 4) [*Moore and Abbott*, 2000], biological enhancement is not evenly distributed around the southern skirts of the ACC. *Nicol et al.* [2000] even noted the absence of biological activity in the southern ACC. This is possible because, as mentioned above, UCDW upwelling is not restricted to the southern boundary of the ACC. *Prézelin et al.* [2000] related UCDW upwelling onto the shelf south of the ACC with phytoplankton activity. We conclude that elevated biological activity at certain locations near the southern boundary of the ACC must be caused by specific local factors.

3.3. Winter Primary Production?

[26] Most iron is imported in the surface layer during autumn and winter. We suggested that this is a sub-optimal condition, because phytoplankton growth may be less efficient during this time of the year. However, we could provocatively also turn the argument around and hypothesize that because of the abundant Fe availability, phytoplankton blooms (or at least elevated production) may be occurring in winter. Of course, iron is not the only factor that influences phytoplankton production. In autumn and winter, low solar irradiance and a deep mixed-layer severely hamper the development of blooms. Additionally, intense grazing by zooplankton or salps may curb phytoplankton production [*Dubischar and Bathmann*, 1997; *Banse*, 1996]. However, blooms have been observed despite a deep mixed-layer [*Smetacek et al.*, 1997] and the low irradiance in October is well able to support dense blooms even at latitudes >70°S [*Scharek et al.*, 1994]. Further, note that in autumn and winter, phytoplankton grazers may migrate to depth [*Bathmann et al.*, 1993; *Banse*, 1996], which ameliorates the conditions for bloom development. Few available Antarctic autumn and winter observations from the ACC [*Heywood et al.*, 1985; *Dieckmann*, 1987] support our ideas on winter blooms. Autumn and winter production may be more common than generally thought. Salient additional indications can be extracted from satellite observations [*Comiso et al.*, 1993] which show the highest mean pigment concentrations for the Southern Ocean south of 50°S for the winter months! According to *Banse and English* [1994], these high winter pigment values may be overestimations, but these authors also report other elevated winter pigment values supported by ground truth data. Until now, the occurence and significance of winter blooms eludes unequivocal evidence. It will be a major challenge for investigators working in the field to adequately describe the primary production to the full seasonal extent as the winter accessibility of the Southern Ocean is notoriously unpleasant.

4. Summary

[27] Of the total iron import into the surface layer of the southern ACC from deep water upwelling, at least 25% is exported equatorward within the Ekman layer to beyond the Polar Front without being used by phytoplankton. This reduces the potential primary production in the Antarctic Ocean by at least the same amount. The advective export and the wintertime entrainment of upwelled Fe-rich water act in concert to diminish the availability of Fe to phytoplankton. Thus, the large-scale water circulation has a great impact on the cycling of iron. Under changed circumstances, for example during glacial conditions, the large-scale circulation may be significantly different, which could have an impact on iron supply and loss and, thus, on primary production as well.

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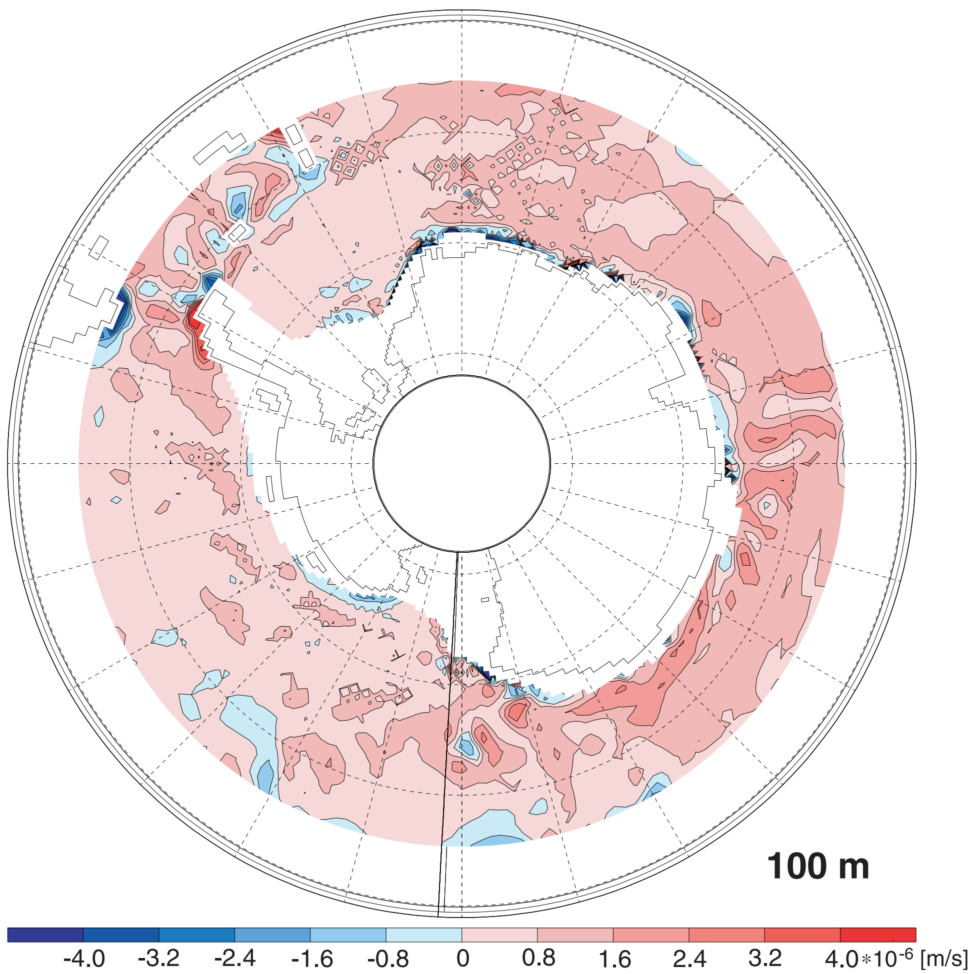

Figure 3. Annual mean vertical velocity at 100 m depth for the Southern Ocean south of 55°S and for water depths >1000 m derived from the numerical model BRIOS2.2 [*Assmann et al.*, 2003]. The 5° zonal band to the north is masked because of unrealistic values due to the proximity of the model's northern boundary at 50°S.

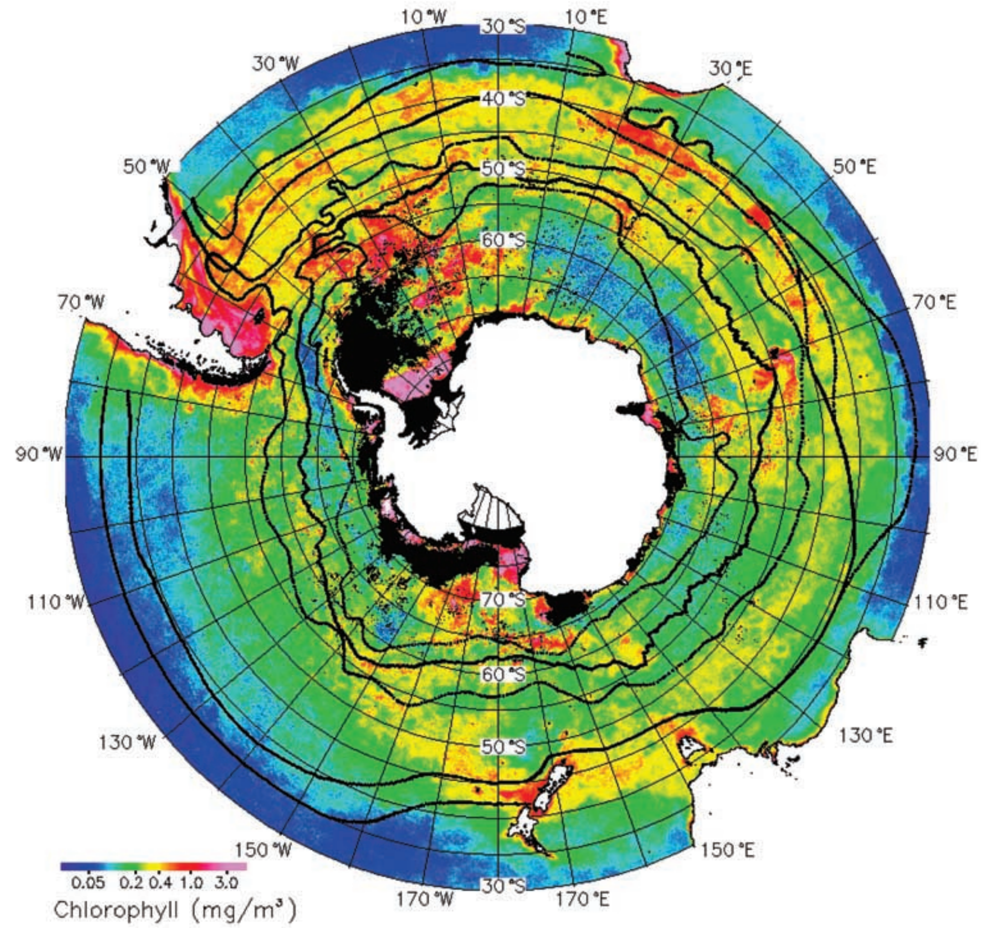

Figure 4. Mean SeaWifs chlorophyll for the summer months December 1997 through February 1998 and the mean location of the major Southern Ocean fronts. From south to north these are Southern ACC Front (SACCF), the Polar Front (PF) and the Subantarctic Front (SAF). SACCF and SAF are from *Orsi et al.* [1995], PF are from *Moore et al.* [1999]. More northern fronts are from *Belkin and Gordon* [1996]. Figure, with permission, is taken from *Moore and Abbott* [2000].