The Antarctic Circumpolar Productivity Belt

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Abstract

Interpretations of sediment trap data, remote ocean color data and inverse model analysis of ocean nutrient distributions in the Southern Oceans suggest the presence of a belt of enhanced primary productivity and export. We show that this “Antarctic Circumpolar Productivity Belt” also emerges in a global, three dimensional ocean circulation, ecosystem and biogeochemistry model and use the model to understand the underlying dynamics. Elevated export production occurs at the regime transition between the iron-limited Antarctic zone and the macro-nutrient limited Subantarctic zone, where both micro and macro-nutrients are available for the growth of phytoplankton. The position of the productivity belt is determined by the interplay of the upwelling of Fe-depleted and macro-nutrient rich deep waters by the residual circulation and the aeolian source of iron.
1 Introduction: The Circumpolar Productivity Belt.

Understanding of the biogeochemistry of the Southern Ocean has been considerably advanced in recent years due to intense observational studies. The meridional distribution of sinking particulate flux across the Antarctic Circumpolar Current (ACC) has been measured using sediment traps (Honjo et al., 2000) and inferred from thorium isotopes (Buesseler et al., 2002), revealing strong peaks of silica and organic export. Silica export appears to peak to the south of the Polar Front and is strongly associated with seasonal diatom blooms, while organic export is offset slightly to the north. While in situ field observations are limited in space and time, remote observations of ocean color provides a large-scale view of the surface chlorophyll. Moore and Abbott (2000; 2002) interpret remotely sensed ocean color data, and suggested that elevated chlorophyll concentrations are tightly coupled to the frontal structures of the ACC. Estimates of regional primary productivity and export production, based on the remotely observed chlorophyll structures, clearly indicate a strong zonal “belt” around 50S (Behrenfeld and Falkowski, 1997; Laws et al. 2000). In an alternative approach, Schlitzer (2002) used an inverse model to evaluate export production by fitting an ocean tracer transport model to observed tracer data, and found a belt of elevated export production around 55S, in the vicinity of the ACC. This feature is figuratively termed the “Antarctic Circumpolar Productivity Belt”. The position of the maximum organic export is close to the location of nitrate and phosphate fronts (where surface nutrient distribution has a large north-south gradient).

What physical mechanisms control the biological uptake and export in the Southern Ocean? What sets the position of the Antarctic Circumpolar Productivity Belt? Here we use a coupled physical-biogeochemical-ecological model to simulate the circulation and biogeochemistry of the Southern Ocean and develop a conceptual framework for understanding the physical and biogeochemical controls on the pattern of primary and export production. We use a diagnostic tracer, $Fe^*$, for evaluating the regimes of nutrient limitation and the interplay between large-scale transport and ecological dynamics in the model.
2 Coupled physical-biogeochemical model

The physical-biogeochemical model used in this study is described in detail in Dutkiewicz et al. (2005). We provide only a brief description as is relevant to this study. The model is based on the MITgcm (Marshall et al., 1997a; Marshall et al., 1997b) configured for the global ocean at coarse resolution (2.8 × 2.8 degrees, 15 vertical levels) where mesoscale eddy transfers are parameterized following Gent and McWilliams (1990).

The Southern Ocean circulation is dominated by the strong zonal flow of the ACC, facilitated by the lack of complete meridional blocking of the flow and westerly wind forcing. Ekman transport drives a northward surface flow across the current, opposed by eddy-induced transport. The residual mean flow, the net effect of Ekman and eddy-induced circulation, drives the transport of tracers, and is plotted in Fig.1. The simulated residual overturning is upwelling to the south of the Polar Front, and downwelling to the north. The meridional transport is somewhat weaker than estimates based on meteorological reanalysis data and those inferred from transient tracers (Ito et al., 2004). Vertical transport near the base of the surface mixed layer is particularly important for the supply of nutrients to the surface layer where biological uptake occurs, and is plotted in Fig 1b. Strong downwelling is found near the topographic features such as Drake Passage. In general, upwelling occurs in the latitude band of the ACC between 45S and 55S in the Atlantic sector and between 40S and 45S in the Indian sector.

[ Figure here : 1 ]

We use a NPZD ecosystem model (Dutkiewicz et al., 2005) including two phytoplankton functional groups, one zooplankton size-class, dissolved and particulate organic matters, and three nutrients: phosphate, silicic acid and iron. The growth rate of phytoplankton is limited by light and one of the nutrients, modeled as the minimum of Michaelis-Menten kinetics. The larger phytoplankton class, representing diatoms, utilizes silicic acid, phosphate and iron, whereas the smaller phytoplankton class, representing
nano-phytoplankton, utilizes only phosphate and iron. In addition to the consumption and regeneration process common to all nutrients in the model, iron has sources and sinks due to aeolian deposition, scavenging and complexation with an organic ligand (Parekh et al., 2004; Parekh et al., 2005).

Simulated distribution of small and large phytoplankton reveals the distinct spatial patterns of the functional groups coupled to the Southern Ocean fronts. Small phytoplankton are the dominant species to the north of the ACC, where silicic acid concentrations are low relative to phosphate. To the south of the ACC, where modelled silicic acid is abundant, large phytoplankton out compete small phytoplankton. This is consistent with previous observations (e.g. Mengelt et al. (2001)). Fig 2(a,b) illustrates the simulated, annual mean export production of biogenic silica and organic carbon. Here we calculate export production as the sum of the sinking particulate organic matter and the downward flux of dissolved organic material. The simulated export is able to qualitatively reproduce the zonal belt of high biological export in the Southern Ocean.

In Fig 2a, The spatial pattern of silica export is elevated in the southern flank of the ACC reflecting the distribution of large phytoplankton, and its maximum is close to the position of the silica front. The position of the maximum organic export is close to the phosphate front. Organic export is driven by both small and large phytoplankton, and the belt of organic carbon export is wider in latitude and located equatorward by several degrees relative to that of silica (Fig. 2b). The position of the silica and phosphate fronts are qualitatively consistent with the observed distributions (Honjo et al., 2000). The magnitude of the organic carbon export has significant zonal variability from 3 to 7 mol C m$^{-2}$ yr$^{-1}$. In this model, the largest export is found in the Indian sector of the ACC and the smallest in the Pacific, consistent with the finding of Schlitzer (2002). The large export in the Indian sector is associated with regional upwelling of the residual mean flow (see Fig 1).

[ Figure here : 2 ]
3 Mechanisms Underlying the Productivity Belt.

What circumstances lead to the existence of the productivity belt? What mechanisms control its position? We examine the modeled tracer distribution in the framework of a diagnostic tracer, $Fe^*$, which indicates the decoupling between Fe and macro-nutrients (Parekh et al., 2005). $Fe^*$ is defined as the difference in dissolved iron and macro-nutrient concentrations where the latter is scaled by the biological uptake ratio. Relative to phosphate, $Fe^*(PO_4)$ can be defined

$$Fe^*(PO_4) = Fe - <R_{F:P}>PO_4$$

where $R_{F:P}$ represents the biological uptake ratio between Fe and PO$_4$ which is set to $10^{-4}$ for small phytoplankton and $10^{-3}$ for diatoms within the range of observations (Sunda et al., 1991; Sunda and Huntsman, 1995). The net uptake rate therefore depends upon the composition of the ecosystem, and the net uptake ratio, $<R_{F:P}>$, is defined as the average of the uptake ratios of the two functional groups weighted by the relative abundances of small and large phytoplankton. Similarly, $Fe^*(Si)$ can be defined as

$$Fe^*(Si) = Fe - R_{F:Si}Si$$

where $R_{F:Si}$ is the biological uptake ratio between Fe and Si for large phytoplankton. Since silica is utilized by one functional group only, $R_{F:Si}$ is a uniform constant. In regions where $Fe^* < 0$, dissolved iron is depleted relative to the reference macro-nutrient and the growth of phytoplankton is limited by the availability of iron before that of the macro-nutrient. Conversely, where $Fe^* > 0$, phytoplankton growth is primarily limited by the availability of macro-nutrients. The surface distribution of modeled $Fe^*$ indicates the regional variations in nutrient limitation regimes.

The high latitude Southern Ocean, classified as a high nutrient, low chlorophyll (HNLC) region, is characterized by negative surface $Fe^*$ (Fig. 2) and the growth of organisms is likely to be limited by the availability of iron. In contrast, surface $Fe^*$ is positive in subtropical gyres and macro-nutrients are limiting the phytoplankton growth.
there. In Fig. 2(b), the pattern of organic export is closely associated with the transition between micro and macro-nutrient limited regions marked by $Fe^*(PO_4) = 0$.

In this model, the productivity belt and associated features, are controlled in the following way (depicted schematically in Fig.3): Circumpolar deep waters, relatively rich in silicic acid and phosphate, but depleted in iron, are brought to the surface in the southern flank of the ACC by the residual mean flow and isopycnic eddy stirring. In the spring and summer months, when light limitation is relieved, diatoms thrive in these upwelling regions (~55S) and dominate the modelled ecosystem, stripping out silicic acid and exporting them vertically to the deep ocean. Iron is the limiting nutrient at high latitudes (both $Fe^*(PO_4)$ and $Fe^*(Si)$ are negative), but organisms are also limited by light in weakly stratified surface waters. Unutilized surface phosphate (and nitrate) are transported northwards following the residual mean flow. The concentration of macro-nutrients decreases northward since only internal ocean sources are important for phosphate and silicic acid. On the northern flank of the ACC, silicic acid is strongly drawn down relative to phosphate, and the ecological community of the model shifts to favor small phytoplankton. A strong primary production and export continues as north as 45S, supported by the aeolian iron supply and relatively high concentration of macro-nutrients. Phosphate is drawn down north of 40S (See $Fe^*(PO_4) = 0$ contour, Fig. 2b), and the organisms are primarily limited by macro-nutrients there.

There is a sharp transition of limiting nutrients near the modeled polar front. The organic export is highest in the transition zone where neither macro-nutrients nor iron are high. However, organisms have access to both macro and micro-nutrients there, resulting in optimal conditions for phytoplankton growth. The aeolian source of iron increases northwards, and brings the ecological system toward macro-nutrient limitation. Northwards of 45S, primary and export production decreases sharply reflecting the reduced supply of macro-nutrients. At high latitudes, low iron concentrations and deep mixed layers ultimitaly limit the growth of phytoplankton. The slight rise in iron concentrations and the peaks in macro-nutrients around 65S in Fig.4(a) indicate the significance of light limitation there.

[ Figure 3 and 4 ]
4 Conclusion

We have illustrated the mechanisms controlling export production in the Southern Ocean using a coupled physical-biogeochemical model including an ecosystem of intermediate-complexity. The model reproduces a circumpolar belt of high export production figuratively termed as the “Antarctic Circumpolar Productivity Belt” which is qualitatively consistent with direct measurements of sinking particulate flux (Honjo et al., 2000), satellite-based estimates of Law et al. (2000), inverse modeling of Schlitzer (2002). The broad maximum of organic export spans the frontal region with contributions from diatoms and small phytoplankton. The simulated peak in organic carbon export is located near the regime transition between the iron-limited Antarctic zone and macro-nutrient limited Subantarctic zone where organisms have optimal access to both nutrients. In the model the diagnostic tracer, $Fe^*$, clearly defines the position of the productivity belt, relating the regime transition of the limiting nutrients and the growth of phytoplankton.

While the major emphasis in this paper has been on understanding the zonal “belt” structure of export production in the Southern Ocean, the conceptual understanding is based on the physical transport by the zonally averaged, meridional overturning circulation. However, there is significant zonal variability in the observed and modeled productivity at the latitudes of the ACC and a more detailed study is warranted in order to understand the zonal structures.

What might be the response of the Antarctic Circumpolar Productivity Belt to the changes in the physical circulation and atmospheric dust deposition of iron in the region? Sensitivity studies with numerical models have also been used to speculate about changes in productivity associated with climate variability (e.g. Bopp et al. 2003). We believe that the conceptual framework developed here, which intimately connects the productivity regimes of the Southern Ocean to its circulation and external iron supply, can provide a useful tool for interpreting such similar simulations and connecting the biogeochemical, paleorecords to our understanding of the circulation of the ocean and climate.
References


Figure 1: Simulated, annual mean circulation. (a) Global residual mean overturning (Sv). The residual mean flow represents the net effect of the Eulerian mean circulation and the parameterized eddy-induced circulation. (b) Vertical component of the residual mean circulation ($10^{-6}$ m s$^{-1}$) at 220 meters. Upwelling regions are shaded with gray scale.
Figure 2: Modeled Southern Ocean export of sinking particles evaluated at 220m: (a) Silica export (mol Si m\(^{-2}\) y\(^{-1}\)), dashed line indicates \(Fe^*(Si) = 0\); (b) Organic carbon export (mol C m\(^{-2}\) y\(^{-1}\)), dashed line indicates \(Fe^*(PO4) = 0\). In both figures \(Fe^*\) is negative to poleward of the dashed line, and positive to the north. However, in the Pacific sector, \(Fe^*\) changes sign again and is negative further north.
Figure 3: Schematic depiction of the mechanisms controlling the position of the regime transition for limiting nutrients and the position of the productivity belt. Arrows in the box depict the residual mean circulation.
Figure 4: Meridional distribution of: (a) modeled surface nutrients \(10^{-6} \text{ mol m}^{-3}\), and (b) organic carbon export \(\text{mol C m}^{-2} \text{ y}^{-1}\) in the Atlantic sector of the Southern Ocean. In (a) meridional distribution of surface nutrients including Fe(solid), PO\(_4\)(dash) and Si(dash-dot). Macro-nutrient concentrations are normalized by the uptake ratio with reference to iron.