Source waters for the highly productive Patagonian shelf in the southwestern Atlantic

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Abstract. Possible nutrient sources and delivery mechanisms for the highly productive Patagonian shelf in the southwest Atlantic are identified using a passive tracer adjoint sensitivity experiment and a series of forward simulations of a biogeochemical model. Three source waters contribute: waters local to the Patagonian shelf, coastal waters near the Chilean coast and the subsurface water along 55°S in the southeast Pacific. Although local waters have the highest iron concentration, it remains on the shelf where macronutrient limits productivity. Additional macronutrients enhance community productivity along the northern part of the shelf. Positive nutrient perturbations from the other source regions enhance community productivity not only on the southern part of the shelf but also offshore of the shelf break. In particular, the subsurface source water in the southeast Pacific boosts the community productivity over the larger part of the southwest Atlantic. We argue that this is because the subsurface source water is rich in nutrients, and upwelled from depth where light levels are so low that they are not consumed. We also find that wintertime intense vertical mixing is the key process which draws nutrients from below 300-500 m to the surface before being delivered to the southwest Atlantic.
1. Introduction

The South Atlantic ocean to the east of Patagonia is one of the most biologically productive regions in the global ocean [Bisbal, 1995; Acha et al., 2004; Palma et al., 2008] resulting in a very rich and diverse community [Romero et al., 2006]. The high productivity can be clearly seen in observations of chlorophyll-a from space with the maximum near the shelf-break [Rivas et al., 2006; Romero et al., 2006; Machado et al., 2013].

The Patagonian shelf region is a significant sink of atmospheric carbon dioxide (CO$_2$). Padén et al. [2010] suggested the Patagonian shelf as the strongest CO$_2$ uptake region in the Atlantic based on a survey between Spain and the Southern Ocean. It is likely one of the most intense sinks per unit area in the global ocean [Bianchi et al., 2005, 2009], with annual uptake rates rivaling those in the subpolar North Atlantic. In particular, the southwest Atlantic appears to be an area where the biological forcing of the CO$_2$ air-sea exchange exceeds that of solubility [Takahashi et al., 2002], implying that vigorous biological activity is largely responsible for net annual uptake of CO$_2$.

High community productivity requires sufficient supply of both macronutrient (e.g. nitrate, nitrite, phosphate and silica) and micronutrient (e.g. iron). Hence the distribution of the nutrients, their sources and the delivery mechanisms have been of great interest. Sabatini et al. [2004] explore the zooplankton hotspot in the Grande Bay, the southern Patagonian shelf, and suggest that the elevated nutrient level can be related to the input from land, river and runoff from the Magellan and Fuegian Channels, as well as frontal upwelling.
Acha et al. [2004], on the other hand, argue that the high level of chlorophyll biomass near the shelf break area is associated with the nutrient supply by the Malvinas Current. This nutrient-rich subantarctic water flows northward and provides nutrients to the shelf area through various physical processes (e.g. eddies and mixing). Romero et al. [2006] also identify the Malvinas Current as a nutrient source supporting the high level of chlorophyll near the shelf break. Additionally, the convergence in the bottom boundary layer and subsequent upwelling can supply nutrients to the Patagonian shelf break.

Garcia et al. [2008] analyze sampled nutrients from a cruise in 2004 November along and across the shelf break fronts and argue that macronutrient is supplied from the Malvinas Current through upwelling along the front. They also suggest four mechanisms for iron supply: frontal upwelling that delivers subsurface iron in the Malvinas Current to the euphotic zone, tidal mixing that lifts the iron from the sediment in the shallow shelf area, deposition of dust and influence of iron-rich ground water from remote regions.

Using the data collected from a series cruises along Patagonian shelf during 2001 and 2003, Paparazzo et al. [2010] show that nitrate is nearly depleted and negatively correlated with chlorophyll in summer, indicating that nitrate is the limiting nutrient on the Patagonian shelf. They further identify the decreasing trend of nitrate moving toward the equator along the shelf, which perhaps hints at the source of nitrate. The subantarctic waters with high level of nitrate penetrate into the shelf through the gap between Tierra del Fuego and the Malvinas Islands and travel equatorward along the shelf. One might then expect that nitrate level to naturally decreases as it is consumed and mixed with other water masses.
These studies reveal the importance of nutrient sources for the high productivity over the Patagonian shelf and hypothesis at the physical mechanisms that are responsible for its delivery on a regional scale. However, it is still unclear how the supply of the nutrients is linked to the large scale ocean circulation, particularly upstream of the Drake Passage.

In this study, we seek to understand the sources of nutrients and the physical processes of delivery from large-scale perspective. To explore the regions of the source water we conduct an adjoint model with passive tracer. The adjoint approach with injected passive tracer is powerful in identifying the water sources for the area of interest [Fukumori et al., 2004; Chhak and Di Lorenzo, 2007; Song et al., 2011]. In addition, it underscores the processes responsible for the delivery as it integrates backward in time. Results from the adjoint model simulation are evaluated with a series of forward biogeochemical model simulations with perturbations to the nutrients in the source water regions. The results indicate that vertical mixing is the key process bringing nutrient-rich water to the surface.

The paper is organized as follows. The description of the adjoint model with passive tracer and the forward biogeochemical model with nutrient perturbations is given in section 2. After the results from these numerical experiments are presented in section 3, section 4 discusses nutrient supply to the region of interest, spatial patterns of responses in productivity and the possible connection between the observed increasing trend of chlorophyll biomass and nutrient supply. We conclude in section 5.

2. Experimental design

The numerical experiments are carried out using the Massachusetts Institute of Technology General Circulation Model (MITgcm) [Marshall et al., 1997b, a; Adcroft et al., 1997; Marshall et al., 1998; Adcroft et al., 1999]. The global ocean model is configured following
Estimating the Circulation and Climate of the Ocean (ECCO version 4) [Forget et al., 2015a]. The parameter values for the turbulent transport of geostrophic eddies [Gent and McWilliams, 1990] and isopycnal diffusion [Redi, 1982] are both 850 m$^2$ s$^{-1}$ which is smaller than that in ECCO version 4. The vertical diffusivity for tracers is $1 \times 10^{-5}$ m$^2$ s$^{-1}$. The ECCO version 4 initial condition is integrated freely for one year with the normal year Common Ocean-ice Reference Experiments version 2 (CORE-II) surface forcing. A simple biogeochemical model is coupled to the physical system to simulate the transport of 6 biogeochemical tracers including both micro and macro nutrients [Dutkiewicz et al., 2005; Parekh et al., 2006; Verdy et al., 2007]. This biogeochemical model simulates the net community production with limitation by light availability and both nutrients, hence is a good tool to investigate the sources for micro and macro nutrients to the Patagonian shelf. Details of the biogeochemical model are presented in Appendix A.

The adjoint model integrates the sensitivity of a cost function $J$ to model parameters backward in time. If the sensitivity of a quantity $J(x_t)$ to $x_{t-1}$, where $t$ and $(t - 1)$ are time indices, is of interest, one can first rewrite $J(x_t)$ using a model $M$ such that

$$J(x_t) = J(M(x_{t-1}))$$

It follows that the sensitivity $\partial J(x_t)/\partial x_{t-1}$ can be obtained by calculating the difference in $J$ for a given perturbation $\delta x_{t-1}$. Alternatively, the sensitivity can be computed using the chain rule thus:

$$\frac{\partial J}{\partial x_{t-1}} = \frac{\partial x_t}{\partial x_{t-1}} \frac{\partial J}{\partial x_t} = (M_{t-1,t})^T \frac{\partial J}{\partial x_t},$$

(1)

where $M_{t-1,t}$ is a tangent linear model that integrates $x$ from $(t - 1)$ to $t$ in a linear sense, and $(M_{t-1,t})^T$ is the adjoint form of it. Since the adjoint model integrates the sensitivity itself, a single integration is enough to produce the sensitivities of $J$ to all
model parameters at various times. It has proven to be a powerful tool in many studies such as heat transport sensitivity [Marotzke et al., 1999], carbon sequestration efficiency [Hill et al., 2004], sensitivity of biological production and air-sea CO$_2$ exchange [Dutkiewicz et al., 2006], ocean circulation and ecosystem in California Current System [Moore et al., 2009], Pacific sardine spawning habitat [Song et al., 2012] and ocean bottom pressure of the Arctic Ocean [Fukumori et al., 2015].

In this study, $J$ is defined as the total amount of passive tracer at the surface over the Patagonian shelf during the last two weeks of the year when the shelf is biologically productive.

$$J = \int_{T-\Delta t}^{T} \int_{A} C \Delta z dA dt,$$

(2)

where $T$ is December 31$^{st}$, $\Delta t$ is 2 weeks, $A$ is the size of the area of interest, $C$ is the surface passive tracer concentration which is set to 1 in this study, and $\Delta z$ is the thickness of the model’s surface layer. The adjoint sensitivity thus tells us something about the source waters to that region. The adjoint model is integrated for one year backward in time to find the source waters of the Patagonian shelf.

Using adjoint sensitivity experiments, we can quantify the contribution of source waters to the area of interest. The changes in $J$, or $\delta J$, due to a perturbation $\delta x$ to the state $x = [x_1, x_1, \ldots, x_N]$ at an earlier time can be written as

$$\delta J = \frac{\partial J}{\partial x_1} \delta x_1 + \frac{\partial J}{\partial x_2} \delta x_2 + \cdots + \frac{\partial J}{\partial x_n} \delta x_N.$$

(3)

When $\delta x_1 = \delta x_2 = \cdots = \delta x_N = 1$ in (3), $\delta J$ is the sum of all the sensitivities, $\sum_{i=1}^{N} \partial J/\partial x_i$. Hence the relative contribution of $x_i$ to $\delta J$, $r_i$, is simply the ratio between $\partial J/\partial x_i$ and...
$\Sigma_{i=1}^{N} \frac{\partial J}{\partial x_i}$ in percentage, or

$$r_i = \frac{\partial J/\partial x_i}{\sum_{i=1}^{N} \partial J/\partial x_i} \times 100.$$  \hfill (4)

We further verify the result from the adjoint experiment with a series of forward integrations of the biogeochemical model. The adjoint model experiment is indeed done with passive tracers, so its result do not necessarily apply to the biogeochemical variables that experience additional sources and sinks. We perturb nutrient concentrations at the source as identified using the adjoint and monitor the resulting changes over the Patagonian shelf.

We choose the perturbation size of NO$_3$ or Fe that would lead to a 10% increase at the area of interest in December in the case of a passive tracer. If they are delivered without consumption, we expect the NO$_3$ or Fe level at the Patagonian shelf should increase by 10%. A lesser increase would indicate instead net loss of nutrients before reaching their destination. We also monitor the changes in the community productivity at the Patagonian shelf and offshore of the shelf break to explore the impact of nutrient perturbation at the water source regions.

After a series of forward experiments with different time for perturbation, we choose June 1$^{st}$ as the starting date. We also performed additional perturbation experiments started earlier than June, but the responses in the target area are not significantly different. These suggest that the 7-month forward integration started from June 1$^{st}$ is long enough to capture most of the physical and biological processes that are associated with the nutrient delivery and the winter preconditioning of biological activity.

3. Results
3.1. Simulated biogeochemical ocean states

The biogeochemical simulation is first evaluated by comparing it with the climatology and observations (Figure 1). The zonal mean of simulated NO$_3$ generally agrees well with the World Ocean Atlas 2009 climatology (Figure 1(a,b)), showing an increase toward Antarctic and with depth. The simulated Fe is compared with three meridional vertical sections (Figure 1(c-e)). Two meridional sections are occupied at the upstream of the Drake Passage and show near-depletion at the surface in both observations and model simulation. Fe concentrations increase with depth, and the observation and the model have similar vertical profiles of Fe when averaged meridionally (Figure 1(c,d)). Fe concentration across the Drake Passage is higher than the other two sections, particularly at the surface of the southern Drake passage. Along the Drake Passage, the model underestimates Fe concentration.

Although community productivity cannot directly be compared to chlorophyll concentration, the biological “hot spot” generally colocates with areas of high chlorophyll biomass (Figure 2). Additionally, the seasonal cycle of community productivity is similar to that of the chlorophyll biomass when averaged over the area shown in Figure 2. In this simulation, the community productivity in the shelf regions in the southwestern Atlantic are mostly limited by NO$_3$ (the areas with black dots in Figure 2(b)), whereas community productivity is limited by Fe over most of the Southern Ocean.

3.2. Source waters

Source waters that arrive over the Patagonian shelf after one year as determined by the adjoint are shown in Figure 3. Broadly three regions supply waters to the region: (I) waters local to the Patagonian shelf, (II) the southeast Pacific near the Chilean coast
south of 42°S and (III) the southeast Pacific subsurface ocean along 55°S. They are labeled
in Figure 2(a). In Region I, the depth of source waters is shallower than 200 m as they
are on the shelf. In Region II, the source waters are spread over the top 300 m, with the
peak near 250 m. Region III shows the deepest source, extending below 500 m. It is worth
noting that regions south of 60°S do not “source” to the Patagonian shelf, indicating that
nutrient-rich water masses south of the Antarctic Circumpolar Current (ACC) are not
involved in fueling productivity on the Patagonian shelf. Instead, nutrient-rich subsurface
water to the north of the ACC is implicated.

The contributions of Regions I, II and III to the total passive tracer concentration
at the Patagonian shelf, estimated following (3), are plotted in Figure 4(a). We also
computed the relative contribution of NO$_3$ and Fe of the source waters after weighting
by the adjoint sensitivity, and plot them in Figure 4(b,c), respectively. Region III is the
biggest contributor (Figure 4(a)), providing nearly half of the total passive tracer to the
target area. Figure 4(b) shows that the largest pool of NO$_3$ is Region III which makes
more than twice the contribution of Region I and II. Region III contains the nutrient rich
depth water source (Figure 1(b)), and appears to be the largest supplier of NO$_3$ to the
Patagonian shelf.

On the other hand, the biggest Fe pool is Region I with almost half of the total Fe
pool (Figure 4(c)). The geography of the Patagonian shelf enables Fe to be delivered to
it rather readily from the sediment and atmosphere (both sources are simulated in the
model; see Appendix A). Its wide shelf is an excellent source for Fe and there is substantial
dust supply from Patagonia. In the model, Region I is found to be the highest Fe pool.
The second biggest Fe pool is Region III. Iron at the surface in the Southern Ocean is
nearly depleted, but increases with depth. Hence, deep water source in Region III can be also be a potent source of Fe.

3.3. Perturbation experiments

Perturbations in nutrients are introduced in one water source region at a time on June 1st, 7 months prior to the target date, at a concentration such that a 10% increase can be achieved at the Patagonian shelf if there is no consumption along the path, as described in section 2. Perturbations in Fe have impacts on the Fe level and the community productivity over the Patagonian shelf (upper left corner in Figure 5(b,c)). The Fe level over the shelf is increased by about 10% stemming from Region III, indicating that Fe is barely consumed along its path. In contrast, Fe perturbations at Region I are almost all consumed, resulting in only a slight increase after 7 months (Figure 5(b)). This enhancement of productivity over the shelf associated with Fe supply is mainly controlled from Region III and from Region II to a lesser extent.

Perturbations in NO$_3$ change the NO$_3$ concentrations and the community productivity at the Patagonian shelf after 7 months (upper right corner in Figure 5). The NO$_3$ concentrations on the Patagonian shelf are increased slightly more than 10% with perturbation of NO$_3$ in Regions II and III. The NO$_3$ perturbation in Region I also results in the increase in NO$_3$ after 7 months, but less than 10%. The least increase in NO$_3$ at the target area by the NO$_3$ perturbation in Region I is associated with the largest response in the community productivity suggesting that additional NO$_3$ on the shelf is effectively used to promote the community productivity where NO$_3$ is the limiting nutrient (Figure 5(c)).

Perturbations in both NO$_3$ and Fe together lead to the biggest increase in the community productivity at the Patagonian shelf (bottom in Figure 5(c)). Among water source regions,
Region III has the most effect on the community productivity. Perturbations in Region I lead to the smallest increase in the community productivity 7 month later. This is because the additional Fe in Region I does not contribute the productivity enhancement but perturbation of both nutrients in Regions II and III will enhance productivity.

Figure 6, the time series of the community productivity change ($\delta$BIO in Figure 5(c)), clearly shows the different effects of nutrient perturbations in the water source regions. The NO$_3$ perturbation in Region I has an immediate impact on the community productivity because NO$_3$ is the limiting nutrient on the shelf (Figure 6(a)). The NO$_3$ perturbation is introduced once on June 1$^{st}$, and it is big enough to sustain the enhanced productivity for 7 months. In contrast, the NO$_3$ perturbations in Regions II and III slowly increase the community productivity until December 1$^{st}$. In December, the community productivity experiences the decreasing trend regardless of the perturbed region, suggesting that the consumption of NO$_3$ is faster than the supply of additional NO$_3$ on the shelf.

The Fe perturbations in Region I has almost no impact on the community productivity on the shelf even on June 1$^{st}$ when additional Fe was introduced (Figure 6(b)). On the shelf, the Fe is not the limiting nutrient, and the Fe perturbation has very little impact on the community productivity. The time series of $\delta$Fe at the target area suggests the additional Fe is gradually consumed through continued community productivity (not shown) that only shows a slight increased after 7 months (Figure 5(b)). The Fe perturbations in Regions II and III, on the other hand, trigger the community productivity enhancement after October, showing an exponential increase in time. The slower response of the community productivity to the Fe perturbations suggests that the Fe source is further from the target area than NO$_3$ source.
The perturbations in both nutrients together result in the biggest impact on the community productivity (Figure 6(c)). Since the additional Fe in Region I has no effect, the NO$_3$ perturbation and both nutrients’ perturbations in Region I produce almost the same time series of $\delta_{\text{BIO}}$. The increase in the community productivity is the greatest when additional NO$_3$ and Fe are introduced in Region III.

4. Discussion

4.1. How do source waters arrive at the Patagonian shelf?

The largest water source for the Patagonian shelf is Region III, the subsurface southeast Pacific ocean (Figure 4(a)). These source waters arrive from a depth of 500 m or so along 55°S, and are relatively rich in both NO$_3$ and Fe compared to other sources, being a good candidate to power new productivity on the Patagonian shelf. But how can water masses at depth (> 300 m) be drawn to the surface within 7 months?

The Southern Ocean is characterized by persistent upwelling driven by strong westerly winds. This upwelling is driven by a negative wind stress curl. However, given the value of this curl near the ACC ($O(10^{-7})$ N m$^{-2}$, Chelton et al. [2004]), the upwelling rates are only $O(10^{-1})$ m day$^{-1}$, too weak to bring the water at 300 m to the surface within a few months. Furthermore, source waters in Region III are in fact generally located north of the ACC where typically downwelling occurs. The vertical velocity related to the meridional overturning circulation can be estimated as $w = \partial \Psi / \partial y$, where $\Psi$ is the stream function for the residual circulation, and the estimated $w$ is even smaller than the wind-driven circulation due to eddy compensation [Karsten and Marshall, 2002; Marshall et al., 2006].
Instead, time series of adjoint sensitivity clearly shows that wintertime convective mixing is the main mechanism bringing deep waters to the surface (Figure 7). On June 1st, source waters are below the mixed layer upstream of the Drake Passage. On August 1st, a sharp deepening of the mixed layer occurs resulting in the top 500 m of the water column becoming well mixed. The observed mixed layer depth upstream of the Drake Passage is found to be 500 m in winter [Dong et al., 2008; Sallée et al., 2010; Holte et al., 2012; Forget et al., 2015b]. It is during this time period that source waters of depth can reach the surface. The mixed layer is still deep on October 1st when Region III waters begin to mix with those of Region II. The majority of the source waters arrive on the Patagonian shelf on December 1st. The mixed layer shallows to less than 100 m in depth as the upper ocean is stratified in summer.

The wintertime vertical mixing in the Southern Ocean has been highlighted as a key to processes such as Subantarctic Mode water formation [McCartney, 1977; Talley, 1996], subduction of anthropogenic CO$_2$ [Sallée et al., 2012] and light limitation for phytoplankton growth [Mitchell and Holm-Hansen, 1991; Sullivan et al., 1993; Cassar et al., 2011]. Wintertime intense vertical mixing is also thought to be responsible for Fe supply to the surface [Tagliabue et al., 2014]. Our results show that the community productivity on the shelf starts to respond in October to the Fe perturbation in Region II and III (Figure 6(b)). This suggests that Fe becomes available to the shelf regions after the wintertime intense vertical mixing at the upstream of the Drake Passage.

4.2. Spatial patterns in the response of community productivity

The forward perturbation simulations are helpful to better understand the biogeochemistry at work in the southwest Atlantic ocean. NO$_3$ perturbations result in an increase
in community productivity at the Patagonian shelf where NO$_3$ is the limiting nutrient (Figure 8(a-c)). In particular, NO$_3$ perturbations in Region I lead to higher levels of community productivity over the northern part of the shelf (Figure 8(a)). In contrast, NO$_3$ perturbations in Regions II and III enhance the community productivity on the southern margin of the shelf. Additionally, enhanced NO$_3$ input in Regions II and III shrinks the NO$_3$ limited region in the southern part of shelf (Figure 8(b,c)).

The additional Fe introduced in Region I has almost no effect on community productivity over the Patagonian shelf where Fe is not the limiting nutrient (Figure 8(d)). When more Fe is added at the area with nonzero adjoint sensitivity on the shelf (colored area in Figure 3), the community productivity offshore of the shelf break does not change, indicating that the source waters over the shelf are trapped there. Fe perturbations in Regions II and III also do not increase the community productivity in the NO$_3$ limited shelf region. Instead, they promote community productivity offshore (Figure 8(e,f)). Although the increase of community productivity due to Fe is smaller than due to NO$_3$ over the shelf (Figure 5(c)), the Fe perturbations lead to larger increase of community productivity integrated over the southwest Atlantic. The additional Fe from Region III boosts community productivity by up to 30%. The size of the NO$_3$-limited area extends over most of the Patagonian shelf as more Fe is introduced there.

The additional NO$_3$ and Fe together in Region I increase the community productivity only over the northern part of the shelf (Figure 8(g)), similar to the NO$_3$ perturbation case. The extra NO$_3$ and Fe from Regions II and III enhance productivity both over the shelf and offshore of the shelf break. The enhanced community productivity at the upstream of the Drake Passage indicates where the nutrient-rich water is upwelled. Addition of NO$_3$
and Fe in Region III lead to the greatest enhancement of community productivity in the southwest Atlantic ocean (Figure 8(i)).

4.3. Increasing trend of chlorophyll biomass

*Rivas et al.* [2006] report an increasing trend of the chlorophyll maximum observed from SeaWiFS data during 1998 to 2003 over the Patagonian shelf. They argue that higher nutrient supply together with a more stratified water column is a main driver of the trend. Other studies consistently show an increasing chlorophyll trend offshore of the Patagonian shelf [Gregg et al., 2005; Henson et al., 2010; Vantrepotte and Mélin, 2011; Siegel et al., 2013; Gregg and Rousseaux, 2014]. This increasing trend has been explained in terms of temperature trends [Gregg et al., 2005; Siegel et al., 2013] and trends in the Southern Annular Mode (SAM) [Vantrepotte and Mélin, 2011].

Our study suggests that nutrient supply to the southwest Atlantic relies on wintertime vertical mixing. If the long-term trend of the wintertime mixed layer deepening occurs, it is likely that the southwest Atlantic will be more replete with nutrients. *Sallée et al.* [2010] show that the mixed layer depths are largely modulated by the SAM, and there has been a deepening mixed layer trend upstream of the Drake Passage. The deepening of the mixed layer potentially brings more nutrient to the surface which can be subsequently transported to the Patagonian shelf by the ACC. Based upon our findings, community productivity and chlorophyll biomass will also show an increasing trend.

5. Conclusion

We have explored how the ocean supplies nutrients to the Patagonian shelf, one of the most productive area with intense CO₂ uptake in the global ocean. Three regions were
identified as significant source regions: (I) the Patagonian shelf itself, (II) the southeast Pacific near the Chilean coast and (III) the subsurface ocean upstream along the ACC in the Southeast Pacific.

The northern part of the shelf receives waters from regions local to the shelf. This water mass is rich in Fe but stays on the shelf where macronutrient is limited. Hence, in our calculations, only additional NO\textsubscript{3} can enhance the community productivity over the shelf. The water sources for the southern shelf and offshore are found in the southeast Pacific. In the biogeochemical model, NO\textsubscript{3} perturbations applied there result in higher community productivity over the shelf where NO\textsubscript{3} is the limiting factor. Fe perturbations rather lead to an increase of community productivity offshore where Fe is the limiting factor. Our study further shows that intense wintertime vertical mixing is the key process to draw high nutrients from the subsurface in the southeast Pacific to the surface and precondition nutrient fields to spur biological productivity in upcoming spring in the southwest Atlantic.

Appendix A: Biogeochemical model

The biogeochemical model coupled in the global circulation model has 6 components: dissolved inorganic carbon, alkalinity, nitrate (NO\textsubscript{3}), dissolved organic nitrogen (DON), oxygen and iron (Fe). In this simple model, the biological production is controlled by light \(I\), NO\textsubscript{3} and Fe whose contributions are parameterized by the Michaelis-Menten formulation.

\[
B = \frac{I}{I + K_I} \min \left( \frac{\text{NO}_3}{\text{NO}_3 + K_{\text{NO}_3}}, \frac{\text{Fe}}{\text{Fe} + K_{\text{Fe}}} \right), \tag{A1}
\]
where $\alpha$ is the maximum consumption rate and $K_I$, $K_{NO_3}$ and $K_{Fe}$ are the half saturation constants for the light, NO$_3$ and Fe, respectively. The parameters are tuned to have similar community productivity spatial and temporal variability as the observed chlorophyll biomass from the satellite, and key parameters are shown in Table 1.

This biogeochemical model has both aeolian and sediment Fe sources. The Fe dust data is extracted from the preindustrial value in Luo et al. [2008]. The sediment Fe source is added following Elrod et al. [2004] where the flux of Fe is expressed as a function of flux of organic matter to sediment based on the observations in California. We use NO$_3$ flux at the bottom of the ocean to represent the flux of organic matter, and convert it to organic carbon flux ($F_C$) using the N:C Redfield ratio of 16:106. Then the sediment Fe source is computed as

$$F_{Fe} = F_{Fe,0} + \beta \times (16/106) \times F_{NO_3},$$

where $F_{Fe,0}$ is the minimum value of the Fe flux from the sediment and $\beta$ is the ratio of sediment iron to sinking organic matter. These values are shown in Table 1.

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References


Figure 1. Zonally averaged NO$_3$ (µmol/l) in the Southern Ocean from the (a) climatology and (b) MITgcm. The simulated iron fields are compared with the observation along three meridional sections: near 170°W (blue dots), near 90°W (red dots) and the Drake Passage (green dots) as marked in the map. In (c-e), the solid and dots represent the iron averaged over the section in the model and the observation from Tagliabue et al. [2014], respectively.
Figure 2. (a) Chlorophyll from 1997-2010 SeaWiFS data, and (b) the simulated community productivity averaged in December. The time series of spatial averaged chlorophyll (red) and community productivity (blue) are inserted in (b). The area marked with the black line in (b) is the area where the passive tracer is measured for the adjoint simulation. Three possible source regions are also marked as I, II and III in (a). The areas with black dots in (b) are where NO$_3$ is the limiting nutrient.
Figure 3. The distribution of source waters one year prior to the arrival in the area of interest (marked with black solid line) on the Patagonian shelf. The shading represents $r_i$ or the relative contribution of each grid cell to the cost function change (See (4)). Grid cells with the contribution less than $10^{-3}\%$ are in white. It is worth noting that sum of all contributions from grid cells is 100% although the maximum contribution is $O(10^{-1})$. Black dashed lines are the boundary between Region I, II and III.
**Figure 4.** (a) The relative contributions of region I (salmon), II (dodge blue) and III (lime green) to the Patagonian shelf one year prior to the arrival. They are equal to the summation of all contributions over each region in Figure 3. The percentage of (b) NO$_3$ and (c) Fe at the source regions whose contribution is greater than $10^{-3}$% are also computed after weighting these variables by adjoint sensitivity.
Figure 5. The responses of (a) NO₃, (b) Fe and (c) community productivity at the Patagonian shelf to nutrient perturbations in source water regions. Each pie plot shows the response to perturbations in (upper left) Fe, (upper right) NO₃ and (bottom) both NO₃ and Fe. The color indicates the region where the perturbations are introduced. All perturbations are introduced 7 months prior to the arrival in the Patagonian shelf. The radius represent the size of responses (e.g. 1.1 means 10% increase with the perturbation).
Figure 6. Perturbations of (a) NO$_3$, (b) Fe and (c) both nutrients were introduced in Region I (salmon), II (dodge blue) and III (lime green) on June 1$^\text{st}$, and the time series of the area-averaged community productivity changes at the area of interest on the Patagonian shelf are plotted. These lines represent the time series of $\delta$BIO in Figure 5(c). For example, the line with salmon color in (a) is the time series of community productivity changes in the area of interest by NO$_3$ perturbation. The relative changes of $\delta$BIO at the final time are shown in Figure 5(c).
Figure 7. Source waters (shaded) and mixed layer depth (red line) on (a) 6/1 or 7 months before, (b) 8/1 or 5 months before, (c) 10/1 or 3 months before and (d) 12/1 or 1 month before. The shading is the relative contribution as defined in (4).
Figure 8. The relative responses of the community productivity to the perturbations in (a-c) NO$_3$, (d-f) Fe and (g-i) both nutrients. Perturbations are introduced in Region (a,d,g) I, (b,e,h) II and (c,f,i) III on June 1$^{st}$, or 7 months prior to the time when the responses are calculated. Black dots represent the region with NO$_3$ limitation.
Table 1. Parameter names, values and units for the biogeochemical model

<table>
<thead>
<tr>
<th>Parameter name</th>
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<th>Units</th>
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<td>Light</td>
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<tr>
<td>Light attenuation coefficient</td>
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<td>Self-shading coefficient</td>
<td>0.07</td>
<td>m(^2) mg(^{-1})</td>
</tr>
<tr>
<td>Photosynthetically active radiation</td>
<td>0.4</td>
<td>Nondimensional</td>
</tr>
<tr>
<td>Half saturation light constant ((K_l))</td>
<td>30</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>Community productivity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum consumption rate ((\alpha))</td>
<td>0.33</td>
<td>(\mu)M month(^{-1})</td>
</tr>
<tr>
<td>Half saturation NO(<em>3) constant ((K</em>{NO_3}))</td>
<td>8</td>
<td>(\mu)M</td>
</tr>
<tr>
<td>Half saturation Fe constant ((K_{Fe}))</td>
<td>0.1</td>
<td>nM</td>
</tr>
<tr>
<td>Fraction of new production to DON pool</td>
<td>0.67</td>
<td>Nondimensional</td>
</tr>
<tr>
<td>Time scale for DON remineralization</td>
<td>6</td>
<td>month</td>
</tr>
<tr>
<td>N:Fe stoichometry</td>
<td>0.016</td>
<td>Nondimensional</td>
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<tr>
<td>Iron</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scavenging rate</td>
<td>0.2\times10(^{-7})</td>
<td>s(^{-1})</td>
</tr>
<tr>
<td>Ratio of sediment Fe to NO(_3) flux ((\beta))</td>
<td>1.153</td>
<td>Nondimensional</td>
</tr>
<tr>
<td>Minimum Fe flux from sediment ((F_{Fe,0}))</td>
<td>0.001</td>
<td>pM s(^{-1})</td>
</tr>
</tbody>
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