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

Hajoon Song^{a,*}, John Marshall^a, Michael J. Follows^a, Stephanie Dutkiewicz^a, Gaël Forget^a

^a*Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge*

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, we identify three source waters: waters local to the Patagonian shelf, coastal waters near the Chilean coast and the subsurface waters in the southeast Pacific. We perform a series of forward simulations of a biogeochemical model to investigate the impact of nutrient perturbations in these source regions to productivity on the Patagonian shelf.

Positive nitrate perturbations from local waters have an immediate impact elevating productivity. Iron perturbations local to the shelf, however, do not change productivity because the shelf region is limited by nitrate. Additional nutrient supply from the other source regions lead to increases in productivity. We find that positive nutrient perturbations in subsurface waters in the southeast Pacific results in the largest boost of productivity over the shelf. These source waters are rich in nutrients and upwelled from

*Corresponding author, Tel. : +1 617 253 0098
Email address: hajsong@mit.edu (Hajoon Song)

depth where light levels are so low that they cannot be consumed. Finally we identify wintertime intense vertical mixing as the key process which draws nutrients from below 300-500 m to the surface before being delivered to the shelf.

Keywords: Patagonian Shelf, Nutrient sources, Adjoint sensitivity analysis, Vertical mixing, Southern Ocean

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). Padín 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 macronu-

trient (e.g. nitrate, nitrite, phosphate and silica) and micronutrient (e.g. iron). Hence, the distribution of the nutrients, their sources and delivery mechanisms are of great interest. Sabatini et al. (2004) explore the zooplankton hotspot in the Grande Bay on the southern Patagonian shelf, and suggest that elevated nutrient levels originate 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 high levels of chlorophyll biomass found near the shelf break area is associated with nutrient supply by the Malvinas Current. Nutrient-rich subantarctic water flows northward and provides nutrients to the shelf area through various physical processes including eddies and mixing. Romero et al. (2006) also identify the Malvinas Current as a nutrient source supporting high levels of chlorophyll near the shelf break. Additionally, 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 November 2004 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 of iron supply: frontal upwelling delivering subsurface iron in the Malvinas Current to the euphotic zone, tidal mixing that lifts iron in 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 the 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

44 identify the decreasing trend of nitrate moving toward the equator along the
45 shelf, which perhaps hints at the source of nitrate. Subantarctic waters with
46 high level of nitrate penetrate onto the shelf through the gap between Tierra
47 del Fuego and the Malvinas Islands and travel equatorward along the shelf.
48 One might then expect nitrate levels to naturally decrease as it is consumed
49 and mixed with surrounding water masses.

50 These studies reveal the importance of nitrate and iron sources contribut-
51 ing to high productivity over the Patagonian shelf and suggest controlling
52 physical mechanisms on a regional scale. However, it is still unclear how the
53 supply of nutrients is linked to the large scale ocean circulation, particularly
54 upstream of Drake Passage.

55 In this study, we seek to understand the sources of nutrients and the
56 physical processes of delivery from a large-scale perspective. To explore the
57 origin of the source water we conduct an adjoint model with a passive tracer.
58 The adjoint tracer approach is a powerful tool to identify water sources for a
59 chosen area (see Fukumori et al. (2004); Chhak and Di Lorenzo (2007); Song
60 et al. (2011)). In addition, it underscores the processes responsible for the
61 delivery since it integrates backward in time. Results from the adjoint model
62 simulation are evaluated using a series of forward biogeochemical model sim-
63 ulations with perturbations to the nutrients in the source water regions. The
64 results indicate that vertical mixing is the key process bringing nutrient-rich
65 water to the surface.

66 Our paper is organized as follows. The description of the adjoint model
67 using a passive tracer and the forward biogeochemical model with nutrient
68 perturbations is given in section 2. Results from these numerical experiments

are presented in section 3. Section 4 discusses nutrient supply to the region of interest, the spatial patterns of response 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., 1997a,b; 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), available at http://mit.ecco-group.org/opendap/ecco_for_las/version_4/release1/contents.html). The parameter values for the turbulent transport of geostrophic eddies (Gent and McWilliams, 1990) and isopycnal diffusion (Redi, 1982) are both $850 \text{ m}^2 \text{ s}^{-1}$ which is smaller than that in ECCO version 4. The vertical diffusivity for tracers is $1 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$. 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 include a representation of the biological uptake of inorganic nutrient (NO_3 , Fe) as a function of nutrient limitation and light availability. This biological uptake is termed here “community production” as it includes the impact of both primary producers and herbivores

93 (see Appendix A). This model was integrated for a long period of time (> 300
 94 years) along with the global ocean circulation model with the normal year
 95 CORE-II surface forcing to get a quasi-equilibrium biogeochemical states for
 96 an initial condition.

97 The adjoint model integrates the sensitivity of a cost function J to model
 98 parameters backward in time. It has proven to be a powerful tool in many
 99 studies such as heat transport sensitivity (Marotzke et al., 1999), carbon
 100 sequestration efficiency (Hill et al., 2004), sensitivity of biological production
 101 and air-sea CO_2 exchange (Dutkiewicz et al., 2006), ocean circulation and
 102 ecosystem in California Current System (Moore et al., 2009), Pacific sardine
 103 spawning habitat (Song et al., 2012) and bottom pressure of the Arctic Ocean
 104 (Fukumori et al., 2015).

105 In our study, we define a cost function J as the total amount of passive
 106 tracer at the surface over the Patagonian shelf during the last two weeks of
 107 the year when the shelf is biologically productive:

$$J = \int_{T-\Delta t}^T \int_A C \Delta z dA dt, \quad (1)$$

108 where T is December 31st, Δt is 2 weeks, A is the size of the area of interest,
 109 C is the surface passive tracer concentration which is set to 1, and Δz is
 110 the thickness of the model's surface layer. The adjoint model is integrated
 111 backward in time for one year to find the source waters of the Patagonian
 112 shelf.

113 We further verify the result from the adjoint experiment with a series of
 114 forward integrations of the biogeochemical model. This is prudent because
 115 the adjoint model experiment is carried out with passive tracers, and so
 116 results do not necessarily apply to biogeochemical variables which experience

117 additional sources and sinks. We therefore perturb nutrient concentrations
 118 at the source guided by the adjoint and monitor subsequent changes over the
 119 Patagonian shelf.

120 We assume that the size of perturbation in x_i , the i^{th} element of the
 121 state $\mathbf{x} = [x_1, x_2, \dots, x_N]$, is proportional to its contribution to J so that no
 122 perturbation is introduced in the regions which do not provide water to the
 123 area of interest. A perturbation δx_i is expressed as

$$\delta x_i = \frac{\partial J / \partial x_i}{\sum_{i=1}^N (\partial J / \partial x_i)^2} \delta J. \quad (2)$$

124 We perturb NO_3 or Fe by an amount that would lead to a 10% increase
 125 in J over the area of interest in December. If they are delivered without
 126 consumption, we expect the NO_3 or Fe levels to increase by 10% at the
 127 Patagonian shelf. A lesser increase would suggest net loss of nutrients along
 128 their path. We also monitor the changes in community productivity at the
 129 Patagonian shelf and offshore of the shelf break to explore the impact of
 130 nutrient perturbations in the water source regions.

131 After a series of forward experiments in which the initial time was var-
 132 ied, we chose June 1st as the starting date. We also performed additional
 133 experiments which started earlier than June, but the responses in the target
 134 area were not significantly different. These suggest that the 7-month forward
 135 integration begun on June 1st is long enough to capture most of the physical
 136 and biological processes associated with the nutrient delivery and the winter
 137 preconditioning of biological activity.

138 3. Results of forward and backward calculations

139 3.1. Simulated biogeochemical ocean states

140 The biogeochemical simulation is first evaluated by comparing it with a
141 climatology and with observations (Figure 1). The zonal mean of simulated
142 NO_3 generally agrees well with the World Ocean Atlas 2009 climatology in
143 the Southern Ocean (Figure 1(a,b)), showing an increase toward Antarctica
144 and with depth. The simulated Fe is compared with three meridional sections
145 (Figure 1(c-e)). Two meridional sections upstream of Drake Passage show
146 near-depletion at the surface in both observations and model simulations.
147 Fe concentrations increase with depth, and observations and model have
148 similar vertical profiles of Fe when averaged meridionally (Figure 1(c,d)). Fe
149 concentration across the Drake Passage is higher than the other two sections,
150 particularly at the surface of the southern Drake Passage. Along the Drake
151 Passage, the model underestimates Fe concentrations.

152 Although community productivity cannot be directly compared to chloro-
153 phyll concentration, the biological hot spot in the model coincides with areas
154 of high chlorophyll biomass in satellite data (Figure 2). Additionally, the
155 seasonal cycle of community productivity is similar to that of chlorophyll
156 biomass when averaged over the area shown in Figure 2. In this simulation,
157 the community productivity in the shelf regions in the southwestern Atlantic
158 are mostly limited by NO_3 (the areas with black dots in Figure 2(b)), whereas
159 community productivity is limited by Fe over most of the Southern Ocean.

160 *3.2. Adjoint determination of source waters*

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

174 Using adjoint sensitivity experiments, we can quantify the contribution
175 of source waters to the area of interest (see Appendix B). The contributions
176 of Regions I, II and III to the total passive tracer concentration at the Patag-
177 onian shelf, estimated following (B.1), are plotted in Figure 4(a). We also
178 compute the relative contribution of NO_3 and Fe in the source waters after
179 weighting by the adjoint sensitivity, and plot them in Figure 4(b,c), respec-
180 tively. Region III is the largest contributor (Figure 4(a)), providing nearly
181 half of the total passive tracer to the target area. Figure 4(b) shows that
182 Region III is the largest pool of NO_3 , contributing twice as much as Region I
183 and II. Region III contains the nutrient rich deep water source (Figure 1(b)),
184 and appears to be the largest supplier of NO_3 to the Patagonian shelf.

185 On the other hand, the largest Fe pool is Region I contributing almost
 186 half of the total Fe (Figure 4(c)). The geography of the Patagonian shelf
 187 enables Fe to be delivered to it rather readily from the sediment and atmo-
 188 sphere (both sources are simulated in the model; see Appendix A). Its wide
 189 shelf is an excellent source for Fe and there is substantial dust supply from
 190 Patagonia. The second largest Fe pool is Region III. In the Southern Ocean,
 191 Fe is depleted at the surface but increases with depth. Hence, the deep water
 192 source in Region III can also be a potent source of Fe.

193 *3.3. Forward perturbation experiments*

194 Perturbations in nutrients are introduced in one water source region at a
 195 time on June 1st, 7 months prior to the target date, at a concentration such
 196 that a 10% increase can be achieved at the Patagonian shelf if there is no
 197 consumption along the path, as described in section 2.

198 Perturbations in NO_3 (δNO_3) have positive impacts on the NO_3 level
 199 (ΔNO_3) and the community productivity (ΔBIO) but negative impact on
 200 the Fe level (ΔFe) over the Patagonian shelf (Figure 5(a-c)). The δNO_3 in
 201 Region I triggers the immediate increase of NO_3 by approximately 10% be-
 202 cause Region I encompasses the target area. The δNO_3 in Region I also has
 203 an immediate impact on the community productivity (Figure 5(c)). NO_3 is
 204 the limiting nutrient on the shelf, hence an additional NO_3 enhances the com-
 205 munity productivity without delay. ΔNO_3 gradually decreases toward the
 206 end of the year as newly introduced NO_3 is continuously consumed (Figure
 207 5(a)). As a result, ΔBIO also has a decreasing trend. The smallest ΔNO_3
 208 in December by δNO_3 in Region I is associated with the largest response
 209 in the community productivity (2% increase in ΔBIO). This suggests that

210 additional NO_3 in Region I is the most effective in promoting the community
211 productivity on the shelf. The enhanced community productivity consumes
212 Fe, resulting in a slight decrease in ΔFe in December.

213 δNO_3 in Regions II and III, in contrast, slowly increase the level of NO_3
214 and community productivity in the target area (Figure 5(a,c)). Region II
215 and III, upstream of Drake Passage, are distant from the Patagonian shelf
216 and δNO_3 in those regions initially does not impact the biogeochemistry in
217 the target area. As the water mass with additional NO_3 moves to the shelf,
218 ΔNO_3 begins to grow and exceeds the 10% increase in December, suggesting
219 that NO_3 is not heavily consumed before it is delivered to the Patagonian
220 shelf. In December, the community productivity experiences a decreasing
221 trend regardless of the perturbed region, suggesting that the consumption of
222 NO_3 is faster than the supply of additional NO_3 on the shelf.

223 Perturbations in Fe (δFe) influence the Fe level (ΔFe) and the ΔBIO
224 over the Patagonian shelf (Figure 5(d-f)). The ΔFe is increased by about
225 10% stemming from δFe in Region III, indicating that Fe is hardly consumed
226 along its path (Figure 5(e)). In contrast, δFe in Region I is almost all con-
227 sumed, resulting in only a slight increase (1.3%) after 7 months (Figure 5(e)).
228 The δFe in Region I has almost no impact on the community productivity
229 on the shelf even in June when additional Fe was introduced (Figure 5(f)).
230 The largest ΔBIO over the shelf associated with Fe supply is caused by δFe
231 in Region III, with Region II also contributing but to a lesser extent. Fe
232 perturbations in Region II and III elevate the community productivity in the
233 Fe-limited area at the southeast corner of the target area. Fe perturbations
234 in Region I remain on the northern shelf where Fe is not the limiting nutrient

235 and lead to very little impact on the community productivity (see Figure 7).

236 Combined perturbations in both NO_3 and Fe (δNO_3 and δFe) result in
237 changes in biogeochemistry on the shelf, and changes are similar to the sum
238 of responses to δNO_3 and δFe separately (Figure 5(g-i)). ΔBIO is the largest
239 with both δNO_3 and δFe (Figure 5(i)). This is to be expected because adding
240 both nutrients relieves the nutrient limitation regardless of the type. Among
241 water source regions, Region III has the most effect on the community pro-
242 ductivity. Perturbations in Region I lead to the smallest increase in the
243 community productivity 7 month later. This is because the additional Fe
244 in Region I does not contribute to productivity but perturbations of both
245 nutrients in Regions II and III can enhance productivity.

246 4. Discussion

247 4.1. How do source waters arrive at the Patagonian shelf?

248 The largest water source for the Patagonian shelf is Region III, the sub-
249 surface southeast Pacific ocean (Figure 4(a)). These waters arrive from a
250 depth of 500 m or so along 55°S , and are relatively rich in both NO_3 and
251 Fe compared to other sources. They are a prime candidate to power new
252 productivity on the Patagonian shelf. But how can water masses at depth
253 (> 300 m) be drawn to the surface within 7 months?

254 The Southern Ocean is characterized by persistent upwelling driven by
255 strong westerly winds (Marshall and Speer, 2012). This upwelling is driven
256 by a negative wind stress curl. However, given the value of this curl near the
257 ACC ($O(10^{-7})$ N m^{-2} , Chelton et al. (2004)), the upwelling rates are only
258 $O(10^{-1})$ m day^{-1} , too weak to bring the water at 300 m to the surface within

259 a few months. Furthermore, source waters in Region III are in fact generally
 260 located north of the ACC where typically downwelling occurs. The vertical
 261 velocity related to the meridional overturning circulation can be estimated
 262 as $w = \partial\Psi/\partial y$, where Ψ is the stream function for the residual circulation:
 263 the estimated w is even smaller than the wind-driven circulation due to eddy
 264 compensation (Karsten and Marshall, 2002; Marshall et al., 2006).

265 Instead, a time series of adjoint sensitivity clearly shows that wintertime
 266 convective mixing is the main mechanism bringing deep waters to the surface
 267 (Figure 6). On June 1st, source waters are below the mixed layer upstream
 268 of the Drake Passage. On August 1st, a sharp deepening of the mixed layer
 269 occurs resulting in the top 500 m of the water column becoming well mixed.
 270 The observed mixed-layer depth upstream of Drake Passage is found to be
 271 500 m in winter (Dong et al., 2008; Sallée et al., 2010; Holte et al., 2012;
 272 Forget et al., 2015b). It is during this period that source waters can be
 273 drawn up to the surface. The mixed layer is still deep on October 1st when
 274 Region III waters begin to mix with those of Region II. The majority of
 275 the source waters arrive on the Patagonian shelf in December. The mixed
 276 layer shallows to less than 100 m in depth as the upper ocean is stratified in
 277 summer.

278 Wintertime vertical mixing in the Southern Ocean has been highlighted as
 279 a key to processes in Subantarctic Mode Water formation (McCartney, 1977;
 280 Talley, 1996), subduction of anthropogenic CO₂ (Sallée et al., 2012) and
 281 light limitation for phytoplankton growth (Mitchell and Holm-Hansen, 1991;
 282 Sullivan et al., 1993; Cassar et al., 2011). Wintertime intense vertical mixing
 283 is also thought to be responsible for Fe supply to the surface (Tagliabue et al.,

284 2014). Our results show that community productivity on the shelf begins to
285 respond in October (i.e. in the spring) to the Fe perturbation in Region II
286 and III (Figure 5(b)). This suggests that Fe becomes available to the shelf
287 regions after wintertime intense vertical mixing upstream of Drake Passage.

288 4.2. *Spatial patterns in the response of community productivity*

289 The forward perturbation simulations guide us in understanding the bio-
290 geochemistry at work in the southwest Atlantic ocean. NO_3 perturbations re-
291 sult in an increase in community productivity on the Patagonian shelf where
292 NO_3 is the limiting nutrient (Figure 7(a-c)). In particular, NO_3 perturba-
293 tions in Region I lead to higher levels of community productivity over the
294 northern part of the shelf (Figure 7(a)). In contrast, NO_3 perturbations in
295 Regions II and III enhance community productivity on the southern margin
296 of the shelf. Additionally, enhanced NO_3 input in Regions II and III shrinks
297 the NO_3 -limited region over the southern part of shelf (Figure 7(b,c)).

298 The additional Fe introduced in Region I has almost no effect on com-
299 munity productivity over the Patagonian shelf where Fe is not the limiting
300 nutrient (Figure 7(d)). When more Fe is added in regions with nonzero
301 adjoint sensitivity on the shelf (colored area in Figure 3), the community
302 productivity offshore of the shelf break does not change, indicating that the
303 source waters over the shelf are trapped there. Fe perturbations in Regions
304 II and III also do not increase community productivity in the NO_3 -limited
305 shelf region. Instead, they promote community productivity offshore (Figure
306 7(e,f)). Although the increase of community productivity due to Fe is smaller
307 than that due to NO_3 over the shelf (Figure 5(c,f)), the Fe perturbations lead
308 to a larger increase of community productivity integrated over the southwest

309 Atlantic. The additional Fe from Region III boosts community productivity
310 by up to 30%. The size of the NO_3 -limited area extends over most of the
311 Patagonian shelf as more Fe is introduced there.

312 The combined increase of NO_3 and Fe in Region I increase community
313 productivity but only over the northern part of the shelf (Figure 7(g)), sim-
314 ilar to the NO_3 perturbation case. The extra NO_3 and Fe from Regions II
315 and III enhance productivity over both the shelf and offshore of the shelf
316 break. The enhanced community productivity upstream of Drake Passage
317 indicates where nutrient-rich water is upwelled. Addition of NO_3 and Fe in
318 Region III leads to the greatest enhancement of community productivity in
319 the southwest Atlantic ocean (Figure 7(i)).

320 *4.3. Increasing trend of chlorophyll biomass*

321 Rivas et al. (2006) report an increasing trend of the chlorophyll maximum
322 observed from SeaWiFS data during 1998 to 2003 over the Patagonian shelf.
323 They argue that higher nutrient supply together with a more stratified water
324 column is a main driver of the trend. Other studies consistently show an
325 increasing chlorophyll trend offshore of the Patagonian shelf (Gregg et al.,
326 2005; Henson et al., 2010; Vantrepotte and Mèlin, 2011; Siegel et al., 2013;
327 Gregg and Rousseaux, 2014). This increasing trend has been explained in
328 terms of temperature trends (Gregg et al., 2005; Siegel et al., 2013) and trends
329 in the Southern Annular Mode (SAM) (Vantrepotte and Mèlin, 2011).

330 Our study suggests that nutrient supply to the southwest Atlantic re-
331 lies on wintertime vertical mixing. If there is a long-term deeper wintertime
332 mixed layer, it is likely that the southwest Atlantic will be more replete with
333 nutrients. Sallée et al. (2010) show that mixed layer depths are largely mod-

334 ulated by SAM, and there has been a deepening mixed layer trend upstream
335 of Drake Passage. The deepening of the mixed layer potentially brings more
336 nutrient to the surface which can be subsequently transported to the Patag-
337 onian shelf by the ACC. Based upon our findings, community productivity
338 and chlorophyll biomass will also show an increasing trend.

339 5. Conclusion

340 We have explored how the ocean supplies nutrients to the Patagonian
341 shelf, one of the most productive areas in the global ocean with intense
342 CO₂ uptake. Three regions were identified as significant sources: (I) the
343 Patagonian shelf itself, (II) the southeast Pacific near the Chilean coast and
344 (III) the subsurface ocean upstream along the ACC in the Southeast Pacific.
345 Region III was found to be most responsible for providing tracers to the
346 Patagonian shelf.

347 The northern part of the shelf receives waters from regions local to the
348 shelf. This water mass is rich in Fe but remains on the shelf where macronu-
349 trient is limited. Hence, in our calculations, only additional NO₃ can enhance
350 the community productivity over the shelf. The source waters for the south-
351 ern shelf and offshore are found at depth in the southeast Pacific in Region
352 III. In our biogeochemical model, NO₃ perturbations applied in that source
353 region results in higher community productivity over the shelf where NO₃
354 is the limiting factor. Fe perturbations on the other hand lead to an in-
355 crease of community productivity offshore where Fe is the limiting factor.
356 Our study further shows that intense wintertime vertical mixing is the key
357 process drawing high nutrients from the subsurface of the southeast Pacific to

the surface and preconditioning nutrient fields to spur biological productivity
in the following spring in the southwest Atlantic.

6. Acknowledgement

We gratefully acknowledge NSF support of the MOBY project (grant
OCE-1048926). The authors would like to thank two anonymous review-
ers for valuable comments and suggestions, which significantly improved the
manuscript.

Acha, E. M., Mianzan, H. W., R. A. Guerrero, M. F., Bava, J., 2004. Marine
fronts at the continental shelves of austral South America: Physical and
ecological processes. *J. Mar. Syst.* 44 (1–2), 83 – 105.

Adcroft, A., C., H., Marshall, J., 1999. A new treatment of the Coriolis terms
in C-grid models at both high and low resolutions. *Mon. Wea. Rev.* 127,
1928–1936.

Adcroft, A., Hill, C., Marshall, J., 1997. Representation of topography by
shaved cells in a height coordinate ocean model. *Mon. Wea. Rev.* 125,
2293–2315.

Bianchi, A. A., Bianucci, L., Piola, A. R., Pino, D. R., I. Schloss, A. P.,
Balestrini, C. F., 2005. Vertical stratification and air-sea CO₂ fluxes in the
Patagonian shelf. *J. Geophys. Res.* 110, C07003.

Bianchi, A. A., Pino, D. R., Perlender, H. G. I., Osiroff, A. P., Segura, V.,
Lutz, V., Clara, M. L., Balestrini, C. F., Piola, A. R., 2009. Annual balance
and seasonal variability of sea-air CO₂ fluxes in the Patagonia Sea: Their

relationship with fronts and chlorophyll distribution. *J. Geophys. Res.* 114,
C03018.

Bisbal, G. A., 1995. The Southeast South American shelf large marine ecosystem: Evolution and components. *Mar. Policy* 19 (1), 21 – 38.

Cassar, N., Difiore, P., Barnett, B., Bender, M., Bowie, A., Tilbrook, B., Petrou, K., Westwood, K., Wright, S., Lefevre, D., 2011. The influence of iron and light on net community production in the Subantarctic and Polar Frontal Zones. *Biogeosciences* 8, 227–237.

Chelton, D. B., Schlax, M. G., Freilich, M. H., Milliff, R. F., 2004. Satellite measurements reveal persistent small-scale features in ocean winds. *Science* 303 (5660), 978–983.

Chhak, K., Di Lorenzo, E., 2007. Decadal variations in the California Current upwelling cells. *Geophys. Res. Lett.* 34 (14).

Dong, S., Sprintall, J., Gille, S. T., Talley, L., 2008. Southern Ocean mixed-layer depth from Argo float profiles. *J. Geophys. Res.* 113, C06013.

Dutkiewicz, S., Follows, M. J., Heimbach, P., Marshall, J., 2006. Controls on ocean productivity and air-sea carbon flux: An adjoint model sensitivity study. *Geophys. Res. Lett.* 33, L02603.

Dutkiewicz, S., Sokolov, A., Scott, J., Stone, P., 2005. A three-dimensional ocean-seaice-carbon cycle model and its coupling to a two-dimensional atmospheric model: uses in climate change studies. In: Joint Program on the Sci. Policy Global Change. MIT, Cambridge, Mass., Ch. Rep. 122.

402 Elrod, V. A., Berelson, W. M., Coale, K. H., Johnson, K. S., 2004. The
403 flux of iron from continental shelf sediments: A missing source for global
404 budgets. *Geophys. Res. Lett.* 31, L12307.

405 Forget, G., Campin, J.-M., Heimbach, P., Hill, C. N., Ponte, R. M., Wunsch,
406 C., 2015a. ECCO version 4: an integrated framework for non-linear inverse
407 modeling and global ocean state estimation. *Geosci. Model Dev.* 8 (5),
408 3653–3743.

409 Forget, G., Ferreira, D., Liang, X., 2015b. On the observability of turbulent
410 transport rates by Argo: supporting evidence from an inversion experi-
411 ment. *Ocean Sci.* 12 (3), 1107–1143.

412 Fukumori, I., Lee, T., Cheng, B., Menemenlis, D., 2004. The origin, pathway,
413 and destination of niño-3 water estimated by a simulated passive tracer and
414 its adjoint. *J. Phys. Oceanogr.* 34 (3), 582–604.

415 Fukumori, I., Wang, O., Llovel, W., Fenty, I., Forget, G., 2015. A near-
416 uniform fluctuation of ocean bottom pressure and sea level across the deep
417 ocean basins of the Arctic Ocean and the Nordic Seas. *Prog. Oceanogr.*
418 134, 152–172.

419 Garcia, V. M., Garcia, C. A., Mata, M. M., Pollery, R. C., Piola, A. R.,
420 Signorini, S. R., McClain, C. R., Iglesias-Rodriguez, M. D., 2008. Envi-
421 ronmental factors controlling the phytoplankton blooms at the patagonia
422 shelf-break in spring. *Deep-Sea Res. I* 55 (9), 1150–1166.

423 Gent, P. R., McWilliams, J. C., 1990. Isopycnal mixing in ocean circulation
424 models. *J. Phys. Oceanogr.* 20, 150–155.

425 Gregg, W. W., Casey, N. W., McClain, C. R., 2005. Recent trends in global
 426 ocean chlorophyll. *Geophys. Res. Lett.* 32, L03606.

427 Gregg, W. W., Rousseaux, C. S., 2014. Decadal trends in global pelagic ocean
 428 chlorophyll: A new assessment integrating multiple satellites, in situ data,
 429 and models. *J. Geophys. Res. Oceans* 119, 5921–5933.

430 Henson, S. A., Sarmiento, J. L., Dunne, J. P., Bopp, L., Lima, I., Doney,
 431 S. C., John, J., , Beaulieu, C., 2010. Detection of anthropogenic climate
 432 change in satellite records of ocean chlorophyll and productivity. *Biogeo-*
 433 *sciences* 7, 621–640.

434 Hill, C. N., Bugion, V., Follows, M. J., Marshall, J. C., 2004. Evaluating
 435 carbon sequestration efficiency in an ocean model using adjoint sensitivity
 436 analysis. *J. Geophys. Res.* 109, C11005.

437 Holte, J. W., Talley, L. D., Chereskin, T. K., Sloyan, B. M., 2012. The role
 438 of air-sea fluxes in Subantarctic Mode Water formation. *J. Geophys. Res.*
 439 117, C03040.

440 Ito, T., Parekh, P., Dutkiewicz, S., Follows, M., 2005. The Antarctic Cir-
 441 cumpolar Productivity Belt. *Geophys. Res. Lett.* 32, L13604.

442 Karsten, R. H., Marshall, J., 2002. Constructing the residual circulation of
 443 the ACC from observations. *J. Phys. Oceanogr.* 32, 3315–3327.

444 Luo, C., Mahowald, N., Bond, T., Chuang, P. Y., Artaxo, P., Siefert, R.,
 445 Chen, Y., Schauer, J., 2008. Combustion iron distribution and deposition.
 446 *Global Biogeochem. Cycles* 22, GB1012.

- 447 Machado, I., Barreiro, M., Calliari, D., 2013. Variability of chlorophyll-a in
448 the southwestern atlantic from satellite images: Seasonal cycle and enso
449 influences. *Continental Shelf Research* 53, 102–109.
- 450 Marotzke, J., Giering, R., Zhang, K. Q., Stammer, D., Hill, C., Lee, T.,
451 1999. Construction of the adjoint MIT ocean general circulation model
452 and application to Atlantic heat transport sensitivity. *J. Geophys. Res.*
453 104 (C12), 29529–29547.
- 454 Marshall, J., Adcroft, A., Hill, C., Perelman, L., Heisey, C., 1997a. A finite-
455 volume, incompressible Navier Stokes model for studies of the ocean on
456 parallel computers. *J. Geophysical Res.* 102 (C3), 5753–5766.
- 457 Marshall, J., Hill, C., Perelman, L., Adcroft, A., 1997b. Hydrostatic, quasi-
458 hydrostatic, and nonhydrostatic ocean modeling. *J. Geophysical Res.*
459 102 (C3), 5733–5752.
- 460 Marshall, J., Jones, H., Hill, C., 1998. Efficient ocean modeling using non-
461 hydrostatic algorithms. *J. Marine Syst.* 18, 115–134.
- 462 Marshall, J., Shuckburgh, E., Jones, H., Hill, C., 2006. Estimates and im-
463 plications of surface eddy diffusivity in the Southern Ocean derived from
464 tracer transport. *J. Phys. Oceanogr.* 36, 1806–1821.
- 465 Marshall, J., Speer, K., 2012. Closure of the meridional overturning circula-
466 tion through Southern Ocean upwelling. *Nat. Geosci.* 5, 171–180.
- 467 Martin, J. H., Knauer, G. A., Karl, D. M., Broenkow, W. W., 1987. VER-
468 TEX: Carbon cycling in the northeast Pacic. *Deep Sea Res. A* 34 (2A),
469 267–285.

- 470 McCartney, M. S., 1977. Subantarctic mode water. In: Angel, M. V. (Ed.), A
471 Voyage of Discovery: George Deacon 70th Anniversary Volume. Pergamon
472 Press, Oxford, pp. 103–119.
- 473 Mitchell, B. G., Holm-Hansen, O., 1991. Observations of modeling of the
474 Antarctic phytoplankton crop in relation to mixing depth. *Deep-Sea Res.*
475 *Pt. A* 38 (8), 981–1007.
- 476 Moore, A. M., Arango, H. G., Di Lorenzo, E., Miller, A. J., Cornuelle, B. D.,
477 2009. An adjoint sensitivity analysis of the Southern California Current
478 circulation and ecosystem. *J. Phys. Oceanogr.* 39 (3), 702–720.
- 479 Padín, X. A., Vázquez Rodríguez, M., Castano, M., Velo, A., Alonso Pérez,
480 F., Gago, J., Gilcoto, M., Álvarez, M., Pardo, P. C., de la Paz, M., Ríos,
481 A. F., Pérez, F. F., 2010. Air-sea CO₂ fluxes in the Atlantic as measured
482 during boreal spring and autumn. *Biogeosciences* 7 (5), 1587–1606.
- 483 Palma, E. D., Matano, R. P., Piola, A. R., 2008. A numerical study of the
484 Southwestern Atlantic Shelf circulation: Stratified ocean response to local
485 and offshore forcing. *J. Geophys. Res.* 113, C11010.
- 486 Paparazzo, F. E., Bianucci, L., Schloss, I. R., Almandoz, G. O., Solís, M.,
487 Esteves, J. L., 2010. Cross-frontal distribution of inorganic nutrients and
488 chlorophyll-a on the Patagonian Continental Shelf of Argentina during
489 summer and fall. *Revista de biología marina y oceanografía* 45 (1), 107–
490 119.
- 491 Parekh, P., Follows, M., Boyle, E., 2004. Modeling the global ocean iron
492 cycle. *Global Biogeochem. Cycles* 18, GB1002.

- 493 Parekh, P., Follows, M. J., Boyle, E. A., 2005. Decoupling of iron and phos-
494 phate in the global ocean. *Global Biogeochemical Cycles* 19, GB2020.
- 495 Parekh, P., Follows, M. J., Dutkiewicz, S., Ito, T., 2006. Physical and bi-
496 ological regulation of the soft tissue carbon pump. *Paleoceanography* 21,
497 PA3001.
- 498 Redi, M. H., 1982. Oceanic isopycnal mixing by coordinate rotation. *J. Phys.*
499 *Oceanogr.* 12, 1154–1158.
- 500 Rivas, A. L., Dogliotti, A. I., Gagliardini, D. A., 2006. Seasonal variability in
501 satellite-measured surface chlorophyll in the Patagonian Shelf. *Cont. Shelf*
502 *Res.* 26 (6), 703–720.
- 503 Romero, S. I., Piola, A. R., Charo, M., Garcia, C. A. E., 2006. Chlorophyll-a
504 variability off Patagonia based on SeaWiFS data. *J. Geophys. Res.* 111,
505 C05021.
- 506 Sabatini, M., Reta, R., Matano, R., 2004. Circulation and zooplankton
507 biomass distribution over the southern Patagonian shelf during late sum-
508 mer. *Cont. Shelf Res.* 24 (12), 1359 – 1373.
- 509 Sallée, J.-B., Matear, R. J., Rintoul, S. R., Lenton, A., 2012. Localized
510 subduction of anthropogenic carbon dioxide in the southern hemisphere
511 oceans. *Nat. Geosci.* 5 (8), 579–584.
- 512 Sallée, J. B., Speer, K., Rintoul, S., 2010. Zonally asymmetric response of the
513 Southern Ocean mixed-layer depth to the Southern Annular Mode. *Nat.*
514 *Geosci.* 3, 273–279.

515 Siegel, D., Behrenfeld, M., Maritorena, S., McClain, C., Antoine, D., Bailey,
516 S., Bontempi, P., Boss, E., Dierssen, H., Doney, S., Jr., R. E., Evans, R.,
517 Feldman, G., Fields, E., Franz, B., Kuring, N., Mengelt, C., Nelson, N.,
518 Patt, F., Robinson, W., Sarmiento, J., Swan, C., Werdell, P., Westberry,
519 T., Wilding, J., Yoder, J., 2013. Regional to global assessments of phy-
520 toplankton dynamics from the SeaWiFS mission. *Remote Sens. Environ.*
521 135 (0), 77–91.

522 Song, H., Miller, A. J., Cornuelle, B. D., Di Lorenzo, E., 2011. Changes in
523 upwelling and its water sources in the california current system driven by
524 different wind forcing. *Dyn. Atmos. Oceans* 52 (1), 170–191.

525 Song, H., Miller, A. J., McClatchie, S., Weber, E. D., Nieto, K. M., Checkley,
526 D. M., 2012. Application of a data-assimilation model to variability of Pa-
527 cific sardine spawning and survivor habitats with ENSO in the California
528 Current System. *J. Geophys. Res. Oceans* 117, C03009.

529 Sullivan, C., Arrigo, K., McClain, C., Comiso, J., Firestone, J., 1993.
530 Distributions of phytoplankton blooms in the Southern Ocean. *Science*
531 262 (5141), 1832–1837.

532 Tagliabue, A., Sallée, J.-B., Bowie, A. R., Lévy, M., Swart, S., Boyd, P. W.,
533 2014. Surface-water iron supplies in the Southern Ocean sustained by deep
534 winter mixing. *Nat. Geosci.* 7, 314–320.

535 Takahashi, T., Sutherland, S., Sweeney, C., Poisson, A., Metzl, N., Tillbrook,
536 B., Bates, N., Wanninkhof, R., Feely, R., Sabine, C., Olafsson, J., Nojiri,
537 Y., 2002. Global seaair CO₂ flux based on climatological surface ocean

- 538 $p\text{CO}_2$, and seasonal biological and temperature effects. Deep-Sea Res. II
539 49, 1601–1622.
- 540 Talley, L. D., 1996. Antarctic Intermediate Water in the South Atlantic. In:
541 et al., G. W. (Ed.), The South Atlantic: Present and Past Circulation.
542 Springer, Berlin, pp. 219–238.
- 543 Vantrepotte, V., Mèlin, F., 2011. Inter-annual variations in the SeaWiFS
544 global chlorophyll a concentration (1997–2007). Deep Sea Res., Part I 58,
545 429–441.
- 546 Verdy, A., Dutkiewicz, S., Follows, M. J., Marshall, J., Czaja, A., 2007.
547 Carbon dioxide and oxygen fluxes in the Southern Ocean: Mechanisms of
548 interannual variability. Global Biogeochem. Cycles 21, GB2020.

Table 1: Parameter names, values and units for the biogeochemical model

Parameter name	Value	Units
Light		
Light attenuation coefficient	0.014	m^{-1}
Self-shading coefficient	0.07	$\text{m}^2 \text{mg}^{-1}$
Photosynthetically active radiation	0.4	Nondimensional
Half saturation light constant (K_I)	30	W m^{-2}
Community productivity		
Maximum consumption rate (α)	0.33	$\mu\text{M month}^{-1}$
Half saturation NO_3 constant (K_{NO_3})	8	μM
Half saturation Fe constant (K_{Fe})	0.1	nM
Fraction of new production to DON pool	0.67	Nondimensional
Time scale for DON remineralization	6	month
N:Fe stoichiometry	0.016	Nondimensional
Iron		
Scavenging rate	0.2×10^{-7}	s^{-1}
Ratio of sediment Fe to NO_3 flux (β)	1.153	Nondimensional
Minimum Fe flux from sediment ($F_{\text{Fe},0}$)	0.001	pM s^{-1}

Figure 1: Zonally averaged NO_3 (mmol/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 lines represent the iron averaged over the sections in the model and the dots represent the iron observations from Tagliabue et al. (2014).

Figure 2: (a) December chlorophyll averaged over 1997-2010 SeaWiFS data and (b) the December-mean simulated community productivity. The area marked with the black line in (b) is the area where the passive tracer is measured in the adjoint calculation. Time series of spatially-averaged chlorophyll (red) and community productivity (blue) in that area are inserted in (b). 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 a black solid line) on the Patagonian shelf. The shading represents r_i , the relative contribution of each grid cell to the cost function change (See Equation (B.2)). Grid cells with contributions less than $10^{-3}\%$ are in white. Sums of all contributions from grid cells is 100%, although the maximum contribution is $O(10^{-1})$. Black dashed lines mark the boundaries between Regions I, II and III.

Figure 4: (a) The relative passive tracer (PTR) contributions of region I (salmon), II (blue) and III (green) to the Patagonian shelf one year prior to arrival. The percentage of (b) NO₃ 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: Time series of the changes (%) in NO_3 , Fe and community productivity (ΔNO_3 , ΔFe and ΔBIO , respectively) at the target area to the perturbations of NO_3 (δNO_3), Fe (δFe) and both nutrients introduced in Region I (salmon), II (blue) and III (green) on June 1st.

Figure 6: 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 (B.2)

Figure 7: Changes of the community productivity to the perturbations in (a-c) NO_3 , (d-f) Fe and (g-i) both nutrients (0.1 = 10%). Perturbations are introduced in Region (a,d,g) I, (b,e,h) II and (c,f,i) III on June 1st, or 7 months prior to the time when the responses are calculated. Black dots represent the region with NO_3 limitation.