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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, 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 leads to increases in productivity. We find that positive nutrient perturbations in subsurface waters in the southeast Pacific result in the largest boost of productivity over the shelf. These source waters are rich in nutrients and upwelled from the 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.

1. Introduction

The South Atlantic ocean to the east of Patagonia is one of the most biologically productive regions in the global ocean (Acha et al., 2004; Bisbal, 1995; 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 (Machado et al., 2013; Rivas et al., 2006; Romero et al., 2006).

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 macronutrient (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 are 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 groundwater from remote regions.

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

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

In this study, we seek to understand the sources of nutrients and the physical processes of delivery from a large-scale perspective. To explore the origin of the source water we conduct an adjoint model with a passive tracer. The adjoint tracer approach is a powerful tool to identify water sources for a chosen area (see Chhak and Di Lorenzo, 2007; Fukumori et al.,2004; Song et al., 2011). In addition, it underscores the processes responsible for the delivery since it integrates backward in time. Results from the adjoint model simulation are evaluated using 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.

Our paper is organized as follows. The description of the adjoint model using a passive tracer and the forward biogeochemical model with nutrient 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) (Adcroft et al., 1997; Adcroft and Marshall,1999; Marshall et al., 1997a,b, 1998). 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 $m^2\ s^{-1}$ 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 includes 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 (see Appendix A). This model was integrated for a long period of time (>300 years) along with the global ocean circulation model with the normal year CORE-II surface forcing to get a quasi-equilibrium biogeochemical state for an initial condition.

The adjoint model integrates the sensitivity of a cost function J to model parameters backward in time. 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 bottom pressure of the Arctic Ocean (Fukumori et al., 2015).

In our study, we define a cost function J 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:

$$J = \int_{T-\Delta t}^{T} \int_{A} C \Delta z dA dt, \tag{1}$$

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

We further verify the result from the adjoint experiment with a series of forward integrations of the biogeochemical model. This is prudent because the adjoint model experiment is carried out with passive tracers, and so results do not necessarily apply to biogeochemical variables which experience additional sources and sinks. We therefore perturb nutrient concentrations at the source guided by the adjoint and monitor subsequent changes over the Patagonian shelf.

We assume that the size of perturbation in x_i, the ith element of the state $x = [x_1, x_2, \cdots, x_N]$, is proportional to its contribution to J so that no perturbation is introduced in the regions which do not provide water to the area of interest. A perturbation δx_i is expressed as

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

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

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

3. Results of forward and backward calculations

3.1. Simulated biogeochemical ocean states

The biogeochemical simulation is first evaluated by comparing it with a climatology and with observations (Fig. 1). The zonal mean of simulated NO_3 generally agrees well with the World Ocean Atlas 2009 climatology in the Southern Ocean (Fig. 1 (a, b)), showing an increase toward Antarctica and with depth. The simulated Fe is compared with three meridional sections (Fig. 1 (c–e)). Two meridional sections upstream of Drake Passage show near-depletion at