Primary productivity and circulation patterns downstream of South Georgia: a Southern Ocean example of the „Island mass effect“

Ines Borrione[a,*], Olivier Aumont[b], Reiner Schlitzer[a]

[a]Alfred Wegener Institute for Polar and Marine Research, Am Alten Hafen 26, 27568 Bremerhaven, Germany
[b]Laboratoire de Physique des Océans, Centre IRD de Bretagne, 29280 Plouzané, France

Abstract:

Growth of phytoplankton in the Southern Ocean (SO) is largely limited by insufficient concentrations of the micronutrient iron, so that despite the large macronutrient reservoir, the SO is considered a High Nutrient Low Chlorophyll region. Therefore, phytoplankton growth is enhanced where exogenous iron is introduced to the system, for example downstream from islands. These confined regions sustain very rich ecosystems and are hot spots for atmospheric carbon dioxide drawdown. In this study, a combination of satellite derived measurements and model simulations are used to investigate the biological and physical environmental disturbances of the island of South Georgia (37°W, 54°S), which is located in the southwestern part of the Atlantic sector of the SO. We show not only that the island shelf is an important source of dissolved iron to the system, but also that the characteristic surface circulation patterns found downstream of the island play an important role in maintaining the shape and distribution of the developing phytoplankton bloom.

Keywords: Southern Ocean South Georgia Island mass effect Satellite observations Primary productivity High nutrient low chlorophyll regions Biogeochemical modeling Iron ROMS PISCES.

1. Introduction

The Southern Ocean (SO, latitudes south of 40° S) covers 20% of the global ocean, and surrounds the Antarctic Continent. The main hydrographic component is the Antarctic Circumpolar Current (ACC), an intense eastward flowing current encircling uninterrupted the continent.

The SO is a fundamental component of the Earth system and of its response to climate change (Marinov et al. 2006). Along portions of the Antarctic coast, the seasonal sea-ice formation generates intermediate and bottom waters which provide a major forcing to the global thermohaline overturning circulation, hence promoting heat, nutrient and gas fluxes with the other oceans.

Along the path of the ACC, upwelling of deeper waters replenishes surface waters with high concentrations of macronutrients (e.g., phosphates and nitrates)

In “Bridging the Gaps between Disciplines: Perspectives from a Multi-disciplinary Helmholtz Graduate Research School", Series: SpringerBriefs in Earth System Sciences. Lohmann, G.; Grosfeld, K.; Wolf-Gladrow, D.; Unnithan, V.; Notholt, J.; Wegner, A. (Eds.) 2013, 38-41, 138 p. ISBN 978-3-642-32234-1; Springer, Heidelberg. 2013.

necessary for the growth of phytoplankton. However, due to insufficient concentrations of the trace metal iron, which is necessary for photosynthesis, algal growth in the SO is reduced, a reason why it is defined as a High Nutrient Low Chlorophyll (HNLC) region (Sarmiento and Gruber 2006).

Higher algal biomass is found where exogenous iron is introduced to the surface layers; among others, noteworthy sources are continental margins and atmospheric dust depositions (Tagliabue et al. 2009), as well as sea-ice melting (Lannuzel et al. 2007).

In situ investigations of the remote SO are generally limited to Austral summer, when most oceanographic cruises can be conducted. Consequently, satellite observations and modeling experiments are necessary tools to integrate with available in situ measurements. The former provide a quasi-synoptic view of regions as large as the SO, while the latter, albeit the necessary simplifications, allow for a virtual laboratory where to test hypothesis and better understand processes. Both tools were combined in the current study to investigate how and to what extent the sub-Antarctic Island of South Georgia generates an “Island Mass Effect”, in other words, influences the surrounding physical and biogeochemical environment.

South Georgia (SG) is a relatively small island of the southwest Atlantic sector of the SO, lying between two of the major ACC fronts: the Polar Front (PF) to the north, and the Southern ACC Front (SACCF) to the south. Amidst HNLC waters, downstream from the island develops an intense phytoplankton bloom, which is clearly detectable from satellite ocean color imagery (Figure 1, refer also to (Park et al. 2010)) and in situ measurements (Korb and Whitehouse 2004). This highly productive system sustains a rich ecosystem and one of the largest commercial krill fisheries (Atkinson 2001); furthermore, due to the enhanced phytoplankton growth, which promotes the biological carbon pump, it is identified as one of the most important Antarctic regions of atmospheric carbon drawdown (Schlitzer 2002).

2. Data and Methods

Chlorophyll-a concentration (chl-a) estimates were derived from the satellite Sea-viewing Wide Field-of-View Sensor (SeaWiFS) at 9km resolution. Due to the large number of data gaps caused by frequent cloud cover, only monthly composites were used. Ocean color images were retrieved between November and February (austral summer) and between 1997 and 2010.

Surface circulation patterns were estimated from the AVISO Satellite Absolute Dynamic Topography (ADT) measurements. Weekly products were retrieved, and

In “Bridging the Gaps between Disciplines: Perspectives from a Multi-disciplinary Helmholtz Graduate Research School", Series: SpringerBriefs in Earth System Sciences. Lohmann, G.; Grosfeld, K.; Wolf-Gladrow, D.; Unnithan, V.; Notholt, J.; Wegner, A. (Eds.) 2013, 38-41, 138 p. ISBN 978-3-642-32234-1; Springer, Heidelberg. 2013.

averaged to form a monthly climatology corresponding to the same time period of the SeaWiFS observations.

Model simulations were carried out with a coupled configuration of ROMS, a free surface, topography following, primitive equation regional model (Shchepetkin and McWilliams 2005) and PISCES, a 24-compartment

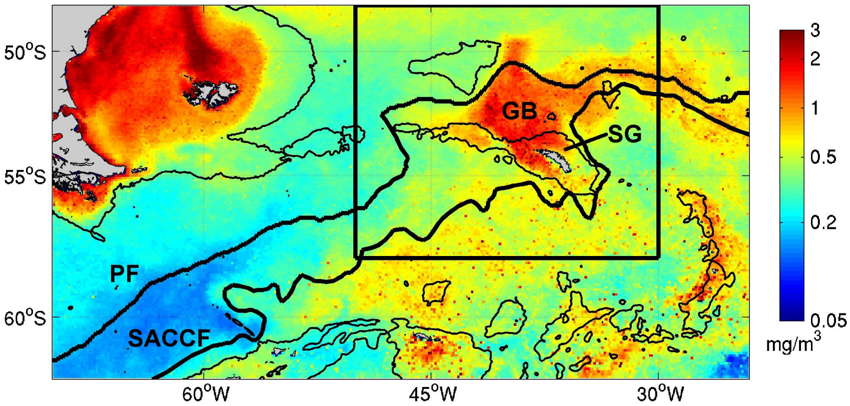

Figure 1: November-February chlorophyll-a climatology from 1997 until 2010 in the southwest Atlantic sector of the SO from satellite ocean color estimates. *Bold lines* indicate the Polar Front (PF) and the Southern ACC Front (SACCF), *SG* indicates the island of South Georgia, and GB stands for Georgia Basin, the *rectangle* depicts the South Georgia region; *thin black lines* indicate the 2000m isobaths.

biogeochemical model, where the cycles of carbon and the main nutrients (including iron) are resolved (Aumont and Bopp 2006). Simulations were run at 1/6° resolution (~12 km).

3. Results and Discussion

According to the climatology shown in Figure 1, a large phytoplankton bloom develops in the South Georgia region; the position of the bloom appears to be confined over the Georgia Basin while outside the basin borders, chl-a remains mostly below 0.5 mg/m^3 hence indicating typical HNLC conditions.

Measurements of ADT in the SG region, allow for estimating the main pathways and intensities of surface circulation; the former are parallel to ADT contour lines, while the latter are more intense when contour lines are closer. As indicated by ADT contours (black lines in Figure 2a), the flow encounters the

In "Bridging the Gaps between Disciplines: Perspectives from a Multi-disciplinary Helmholtz Graduate Research School", Series: SpringerBriefs in Earth System Sciences. Lohmann, G.; Grosfeld, K.; Wolf-Gladrow, D.; Unnithan, V.; Notholt, J.; Wegner, A. (Eds.) 2013, 38-41, 138 p. ISBN 978-3-642-32234-1; Springer, Heidelberg. 2013.

island from the southwest and then continues northeast embracing the Georgia Basin at all sides. Furthermore, it is possible to infer intense currents along the borders of the basin (especially along the northern periphery, where contour lines are closely spaced) and a weaker circulation regime in the region found directly above the basin.

The similarity between surface circulation patterns depicted in Figure 2a and the bloom distribution shown in Figure 1 suggests that the surface circulation in the SG region plays an important role in maintaining the shape and position of the phytoplankton bloom developing downstream from SG. Therefore, circulation patterns are such that phytoplankton cells remain entrained in a favorable region where the flow is weaker and nutrient reservoirs may be continuously replenished.

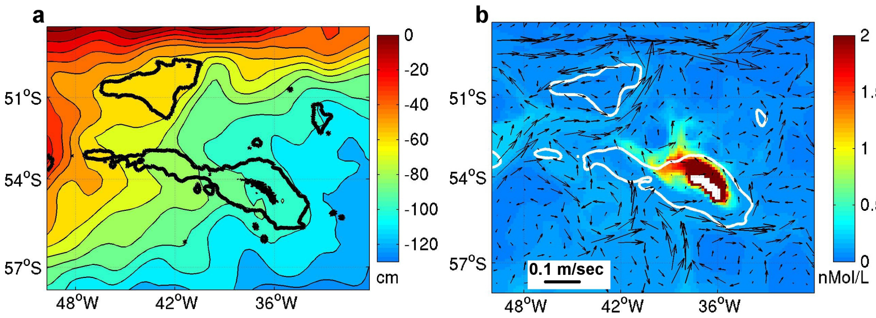

Figure 2: a Absolute dynamic topography in the South Georgia region between November and February according to the 1997-2010 climatology. *Contour lines* indicate direction of main flow and distance between isolines provides an estimate of flow intensity. **b** Simulated distribution of surface dissolved iron (*color code*) and circulation (*arrows*) during December of model year 3. In both panels, 2000m isobaths are indicated with *bold contour lines.*

The importance of SG as a source of dissolved iron is suggested by model simulations (Figure 2b), which show the presence of a plume originating from the island that follows the direction of the main flow (arrows). However, the characteristic circulation patterns depicted in Figure 2a remain difficult to resolve, possibly due to the sensitivity of the system to the adopted boundary conditions or the chosen model resolution which does not allow for a full representation of the physical environment (i.e., eddies, which at the chosen resolution are not resolved).

In “Bridging the Gaps between Disciplines: Perspectives from a Multi-disciplinary Helmholtz Graduate Research School", Series: SpringerBriefs in Earth System Sciences. Lohmann, G.; Grosfeld, K.; Wolf-Gladrow, D.; Unnithan, V.; Notholt, J.; Wegner, A. (Eds.) 2013, 38-41, 138 p. ISBN 978-3-642-32234-1; Springer, Heidelberg. 2013.

4. Conclusions

Although our results indicate that downstream from SG the observed phytoplankton bloom results from a characteristic physical environment, being SG a source of dissolved iron, a comprehensive understanding of the system, where a patchwork of top-down (i.e., grazing) or bottom-up (light or nutrient co-limitation) controls come into play, requires further in situ investigations and model experiments. The former would provide additional biogeochemical measurements which to date remain scarce, while the latter would help assess the relative importance of physical processes other than surface circulation (for example performing simulations where tidal effects and/or eddies are included) or additional nutrient sources in determining the observed biological response to the South Georgia "Island Mass Effect".

References

Atkinson, A., Whitehouse, M.J., Priddle, J., Cripps, G.C., Ward, P., Brandon, M.A.: South Georgia, Antarctica: a productive, cold water, pelagic ecosystem, Mar. Ecol. Prog. Ser. 216 (2001). doi: 10.3354/meps216279

Aumont, O., Bopp, L.: Globalizing results from ocean in situ iron fertilization studies. Glob. Biogeochem. Cycles. 20 (2006). doi:10.1029/2005GB002591

Korb, R.E., Whitehouse, M.J.: Contrasting primary production regimes around South Georgia, Southern Ocean: large blooms versus high nutrient, low chlorophyll waters, Deep-Sea Res. I. 51(5) (2004). doi: 10.1016/j.dsr.2004.02.006

Lannuzel, D., Shoemann, V., de Jong, J., Tison, J.L., Chou, L.: Distribution and biogeochemical behaviour of iron in the East Antarctic sea ice. Mar. Chem. 106 (2007). doi: 10.1016/j.marchem.2006.06.010

Marinov, I., Gnanadesikan, A., Toggweiler, J.R., Sarmiento, J.L.: The Southern Ocean Biogeochemical Divide. Nature. 441 (2006). doi: 10.1038/nature04883

Park, J., Oh, I.-S., Kim, H.-C., Yoo, S.: Variability of SeaWiFS chlorophyll-a in the southwest Atlantic sector of the Southern Ocean: Strong topographic effects and weak seasonality. Deep-Sea Res. I. 57 (2010). doi: 10.1016/j.dsr.2010.01.004

Sarmiento, J.L. Gruber, N.: Ocean Biogeochemical Dynamics. Princeton University Press, (2006)

Shchepetkin, A.F., McWilliams, J.C.: The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic model. Ocean Model. 9 (2005). doi:10.1016/j.ocemod.2004.08.002

Schlitzer, R.: Carbon export fluxes in the Southern Ocean: results from inverse modeling and comparison with satellite-based estimates, Deep-Sea Res. II. 49 (2002). doi:10.1016/S0967-0645(02)00004-8

Tagliabue, A., Bopp, L., Aumont, O.: Evaluating the importance of atmospheric and sedimentary iron sources to Southern Ocean biogeochemistry. Geophys. Res. Lett. 36 (2009). doi:10.1029/2009GL038914

In "Bridging the Gaps between Disciplines: Perspectives from a Multi-disciplinary Helmholtz Graduate Research School", Series: SpringerBriefs in Earth System Sciences. Lohmann, G.; Grosfeld, K.; Wolf-Gladrow, D.; Unnithan, V.; Notholt, J.; Wegner, A. (Eds.) 2013, 38-41, 138 p. ISBN 978-3-642-32234-1; Springer, Heidelberg. 2013.