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Biogeosciences
Discussions

# *Interactive comment on* "Sedimentary and atmospheric sources of iron around South Georgia, Southern Ocean: a modelling perspective" *by* I. Borrione et al.

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We thank the first referee of our manuscript for the constructive comments. Our Author Replies are labeled AR, and will follow each Reviewer's Comment (labeled RC). To clearly distinguish between Figures and Tables presented in the discussion paper (DP) from those accompanying our replies, we will add the prefix DP or AR to the Figure or Table numbers. For example, Figure DP-3b will correspond to Figure 3b of the discussion paper.

Specific comments RC1) Bathymetry: Looking at a map of South Georgia, it is clear that the near-coast bathymetry is very steep, and the bays have a deep, fjord-like



bathymetry. There are no extensive shallow areas and the 50m contour appears to be at most about 5km from the coastline. With a model resolution of around 11 km, I am very surprised that you have cells with the shallow depth ranges you quote in table 1. How realistic is your model bathymetry? If the model bathymetry is unrealistically shallow, the conclusions of your study may be invalid. Please comment on this.

AR1)Due to the way the ROMS-grid is constructed, horizontal and vertical resolution can be of different orders of magnitude (km and m, respectively). In the model, topography is constructed by combining a land mask, which indicates if grid cells are over land or in water, and a smoothed bathymetric dataset of the region (in our case ETOPO2). The model's horizontal resolution (11km) controls the degree of smoothing. Smoothing is fundamental to prevent model instability (model blow ups) due to horizontal pressure gradient errors. The surface connecting the coastline (i.e. the periphery of all land grid cells) and bottom topography (smoothed ETOPO2) is vertical and at least 50m deep (this depth is set with a parameter). Therefore, near-coast bathymetry is very steep (actually vertical). Depths increase gradually (following the smoothed bathymetry) below 50m. With a resolution of 11km, smoothing smears the details of the rugged coastline and near-coast features (bays and fjords) mentioned by the first reviewer. A much higher resolution, (i.e., 3km, as in Young et al., 2011) would certainly improve this aspect. However, such high resolution would compromise our ability to include the biogeochemical model PISCES.

The model's vertical layers (terrain following, i.e., sigma-layers) are constructed separately. They keep into account the smoothed bathymetry obtained as above, however the distance between adjacent sigma-layers depends on other parameters (which control surface and bottom stretching). As it is important to also assess the model's ability to reproduce primary productivity patterns in the region (directly linked to the distribution and sources of iron), we decided to have maximum vertical resolution at the surface (few meters). Due to the presence of a vertical shore (explained above), and the high vertical resolution close to the surface, the depth of the shallowest sediments releasing iron can be of the order of few meters, explaining the depth values reported in DP-Table 1. Clearly, the current represantation of bathymetry in the model is not (and cannot be) fully realistic, causing some of the discrepancies observed in the model (reduced vertical and horizontal mixing, smooth-looking circulation patterns over the shelf of the island). However, we should stress that simulations summarized in DP-Table 1 were used as sensitivity tests aimed at understanding better which depth layers (in the model) contribute most of the iron observed at the surface, where primary productivity occurs.

RC2) Lack of freshwater: The lack of coastal freshwater in the model is a concern. As you discuss on p. 10835-10836, glacial sources of iron could be significant, but you do not identify it as a 'main' source and do not attempt to quantify its possible impact. Coastal freshwater inputs will also have an important influence on seasonal stratification and water column stability, and hence vertical mixing. Please comment on this.

AR2) As stated in our reply to the second reviewer, to the best of our knowledge, we don't have information on how much dFe could be released from the glaciers melting around South Georgia, although satellite images show evident glacier-flour plumes (see also Whitehouse et al., 1996). Several studies have shown that aging of particles in ice favours the dissolution of iron (Gerringa et al., 2012; Raiswell et al., 2008; Lannuzel et al., 2007). Using the measurements of Gerringa et al., 2012 who found in the Admunsen Sea concentrations ranging between 0.4 – 1.31 nM we can make a rough estimate. As input of iron from glacier melt is independent from the other two sources considered here, its contribution would likely add up to our observations, mostly at the surface of the water column due to the positive buoyancy of melt water, and close to the island where most glacier-flour plumes are observed. In that case we could expect a slight improvement in our comparisons with underway dFe concentrations measured by Nielsdóttir et al., 2012 over the shelf of the island (Fig. DP-7B). However, due to the large variability in both types of measurements, in the future a dedicated modelling



configuration including fresh-water fluxes and iron release from melting ice (see Taylor et al., 2013) could test the relative importance of sedimentary and glacier-related iron inputs. In the current model configuration, the two types of inputs cannot be resolved. An input of a fresh-water source in the model (i.e., to represent run-off or melt water) will also require higher modelling resolution which would allow a better representation of all processes controlling vertical and horizontal mixing (i.e., cross-shelf exchanges or mesoscale circulation features).

RC3) Local dust source: You do not consider the potential contribution of local dust from South Georgia in your model. During strong wind events, a significant amount of red dust, rich in iron, is observed to blow off the island, and this could be a far more significant source than Patagonia.

AR3)In the model, dust deposition is taken from the climatology of Tegen and Fung., 1995. In this datasets, the only sources of dust deposited over the Southern Hemisphere are located in South America, South Africa and Australia.The same sources are accounted for in more recent modeling studies (Ginoux et al., 2001; Mahowald et al., 2005; Li et al., 2010). Therefore, with the model it is not possible to quantify the importance of local dust sources. Satellite observations would also be of limited use, due to extensive cloud cover and the fact that dust plumes close to South Georgia will likely travel at low altitudes (Gassó and Stein, 2007). Consequently, on site observations (i.e., applying the method of Heimburger et al., 2012) are fundamental to better describe and constrain this source. Locally, dust from South Georgia could prevail on South American dust and in some years could explain irregular patches of Chl a observed around the island. However, two aspects suggest that over the main bloom area local dust sources may still be nebligeable compared to sedimentary sources: 1) around South Georgia prevail westerly winds (Chelton et al., 2004) therefore most of local dust will be transported eastwards, while South Georgia blooms develop mostly to the north of the island. 2) the typical bloom area (Borrione and Schlitzer, 2013) agrees in shape and location with the iron plume simulated by the model and originating from the island, which hence has sedimentary origins. Moreover, the vicinity of the main bloom area to South Georgia suggest that dust falling to the ocean surface has undergone limited atmospheric aging, which is believed to be an important factor increasing the solubility of iron in dust (i.e., Baker and Croot, 2010; Johnson et al., 2010; Mahowald et al., 2005)

RC4) Physical oceanography: The description of the general oceanography of the region needs rewriting as at present it is not entirely accurate. In particular, the following need correcting: p.10813, lines 8-14: The SACCF flows around the southern South Georgia shelf, not along it. The meander in the SACCF is not the cause of downstream waters being transported to the north and northwest. The shelf waters at South Georgia are strongly influenced by local processes, and can be very different to the surrounding oceanic waters, with the latter dominated by the properties of the ACC.

AR4) The text of the revised manuscript will be modified accordingly.

RC5)p. 10821-10823, section 4.1: The ACC is characterised by strong fronts (e.g. as depicted in figure 1) and this section should include reference to the fronts, instead of 'branches' or 'currents' of the ACC.

AR5)The text of the revised manuscript will refer directly to the ACC fronts.

RC6)p. 10821, line 27: I would be wary of using the word 'join' in regard to the oceanic flows as it implies strong diapycnal mixing across fronts.

AR6)We will rephrase the text accordingly.

RC7)p. 10821, line 25: A significant portion of the flow appears to go north and then east. Please reflect this in your description.

AR7)In the current description we included it implicity by describing a "cyclonic flow along the borders of the Georgia Basin". A more expicit description of the charachteristic flow will be included in the revised version of the manuscript.



RC8)p. 10822, lines 13 and 28: please use 'through' instead of 'across' for flows through passages.

AR8) The text of the revised manuscript will be modified accordingly.

RC9) p. 10822, line 24: The strongest flows from altimetry are around the shelf edge and not along the shelf (which is expected from bathymetric steering of the SACCF). Please correct this. Note also that flows on the shelf from satellite altimetry should be treated with caution due to significant errors in such regions. This latter point is also of relevance for the discussion on p. 10825, lines 9-19 and should be considered.

AR9)The text will be rephrased accordingly. Moreover, we will refer to the potential limitations of satellite altimetry close to the coast. Nevertheless, using ADCP current measurements to the southwest of the island, Whitehouse et al., (2008) confirm our observations, showing decreasing current velocities towards the coast. Similar velocity gradients are shown using modeling results by Thorpe et al., 2002.

RC10) Representation of iron: Given the emphasis on sedimentary sources of iron in the paper, the model representation of iron fluxes from sediments needs to be more fully described. Specifically:

p. 10816, line 28: How did you adapt the denitrification model described by Middelburg et al. to dFe fluxes?

AR10) From Middleburg's model, one can compute the proportion of organic matter whose degradation occurs through denitrification. This gives an indication on how anoxic the sediment is. Subsequently, assuming that there is a linear relationship between denitrification relative contribution and iron release from the sediments, the iron flux is calculated as a linear dependancy with proportion of organic matter. Further details are found in the supplementary material published in Aumont and Bopp (2006).

RC11) p. 10818, line 1: Why did you choose the value of 1 mol dFe m-2day-1? Was this based on data? What is the relevance of the 2 mol dFe m-2day-1 from the Moore &

Braucher modeling study? It appears that your choice of this parameter value is based on previous modeling studies. RC12) How well does it relate to values from field data, and how sensitive are the model results to variations in the parameter (within observed ranges)?

AR11-12)The choice of the parameter is based on Aumont and Bopp (2006), who set this parameter to the value that minimized the RMS between the model and the data on the global scale. Without increasing the model's resolution, higher dFe fluxes (especially if at greater depths) might not significantly alter the current observations.

RC13) p. 10817, line 2: How realistic is it to use depth as a proxy for sediment oxygenation? Does the way this is approximated strongly influence the depth/iron relationship predicted by the model (and detailed in Table 1)? How sensitive is the model to this approximation?

AR13)The paper by Middleburg et al., 1995 explains this aspect in detail. It is difficult to quantify how much this approximation can influence our results. However, in the specific model configurations, it appears that the amount of iron released from the sediments alone does not control entirely the amount of iron observed in the region at the surface. In the manuscript in fact we find that only the very shallow layers determine the iron plumes observed downstream of the island. Increased vertical mixing, due to a finer model resolution and tidal forcing (not included in our simulations) will likely increase the influence of deeper layers.

Model configuration:

RC14)p. 10815, line 12: What do you mean by coastline-following curvilinear coordinates?

AR14) This was meant to be terrain-following curvilinear coordinates.

RC15) p. 10817, line 24: As you're interested in sediment fluxes of iron, why did you not increase the near-bed resolution as well?



AR15)In ROMS, it is not possible to increase the resolution both at the surface and the bottom. As it was important to also assess the model's ability to reproduce primary productivity patterns in the region (directly linked to the distribution and sources of iron), we decided to have maximum vertical resolution at the surface (few meters).

RC16)p. 10817, line 27: Please explain the nature of the 'r-parameter'. How sensitive is the model to the choice of this parameter?

AR16)The r-parameter controls the slope of the sigma layers. In an initial phase of our model experiments, we tested few different values, (ranging 0.2 – 0.25), but did not observe significant changes. Therefore, we kept the parameter to 0.25 which is given as default value for the preparation of the model's grid (Penven et al., 2006).

RC17)p. 10818: The description of the model forcing is confusing, in particular regarding the temporal resolutions of the datasets. Specifically: lines 2-7: Over what period did you obtain SODA data? Were these averaged to create a climatology? lines 7, 10 & 12: what is the resolution of the 'climatology'? Are they monthly means? line 10: '2000-2007' time-period. What is the relevance of this time period? How does it compare to the time periods used to construct the other climatological forcing data? line 17: What is the temporal resolution of the WOA climatology? line 19: What is the temporal resolution of the ORCA2 model output?

AR 17) All forcing fields are climatologies, i.e., averages of several years of data to produce a monthly mean. Unfortunately, not all datasets allowed the same temporal coverage for the preparation of the climatologies. Therefore, where possible, we used as many years as possible. The SODA dataset, in particular, was retrieved from the web (http://iridl.ldeo.columbia.edu ) with OpenDAP for the years 1998-2008. In some cases (i.e., for COADS) climatologies were available in the model pre-pocessing datasets. The clarity of this section will be improved also with the help of a native English speaker.

RC18)p. 10818, line 23: Why did you run for an additional 10 years if the model was already at quasi-equilibrium? Why not just use the following year?

AR18)Veryfying that the model had reached a quasi-equilibrium state was not trivial. In this case we could identify the point in time it reached quasi-equilibrium only after examining several years of simulations.

RC19)p. 10818, line 26: Why was the iron source only modified in the last 3 years and not throughout the model run? Similarly, why did you choose to modify it for 3 years? Did it make much difference if you modified it for longer?

AR19)The different experiments are sensitivity studies which should help evaluate the impact of the sediment source. The equilibration time of the boundary layer or of what is called the bowl (the seasonally ventilated part of the water column) is rather short : 1-3 years. So, there is no need to run the model for longer if one is interested in the upper ocean in such a small regional domain. Certainly a longer simulation would be justified in a larger scale configuration when studying non local effects and the long term balance of the Southern Scean. But, this regional configuration is certainly not appropriate for that and running the model would not provide additional information.

RC20)General question: What is the timestep of the coupled ROMS_AGRIF-PISCES model? Assuming it's much shorter than the climatological forcing, how did you deal with the difference in temporal resolution?

AR20)Forcing fields are linearly interpolated at the model time step.

Other general issues RC21 )p. 10813, line 16: The previous sentence only discusses Si, not other macronutrients. Why are ALL macronutrients at excess concentrations? AR21)Here, "ALL" referred to phosphate, nitrate, silicate. However, it will be stated more clearly in the revised version of the model.

RC22)p. 10814, line 8: You should mention other sources here, including upwelling at the shelf edge, freshwater sources at the coast and local dust from South Georgia itself. p. 10815, line 1: '...main sources...'. In my opinion, you are neglecting some potentially



very important local sources and can therefore not identify the main sources with your model, only which of shelf sediments or dust is the more important. Similarly, p. 10821, line 15, you cannot say that you're identifying the principal sources if you're neglecting important local sources. Similarly, p. 10830, line 27: you should not refer to 'two main iron sources' if you haven't considered all possible sources.

AR 22) The statement that this study focuses on the main sources of dissolved iron around the island will be modified accordingly, to reflect the fact that we specifically considered sedimentary and aeolian dust. Where appropriate, more detail will be added to describe the other potentially important sources, such as local dust depostion, glacial inputs and upwelling.

RC23)p. 10819, lines 3-5: Did you consider any deeper depth bands, which might reveal upwelling of iron from the shelf-edge, for example?

AR23)In the default simulation iron is released from all depths and we could not identify specific upwelling processes. Fig. AR-2 (in reply to the second reviewer) shows dFe concentrations at 100m. The plot shows higher dFe concentrations in the vicinity of the shelf-sediments.

RC24)p. 10819, line 17: Why did you choose the period 2006-2011 for construction of the climatology? I believe the data are available for a longer time period (from 2003 for January and February).

AR 24) we chose a time-period centred around 2008, when dFe observations are available. As phytoplankton blooms in the region are very regular (in space and time), for the purposes of introducing the region a longer time-series would not add further details. In fact, the 13-year long climatology shown by Borrione and Schlitzer, 2013 around South Georgia is very similar to the one depicted in Fig. DP1.

RC25)p. 10819, line 24; p. 10820, line 10, p. 10825, line 20: Why did you choose 2011 to compare with the model? As the model is a climatology and not appropriate to any specific year, would it not make more sense to compare with climatological data?

AR25)Our objective was to show that the model underestimates Chl a concentrations in the region. This was already evident by comparing model results with the climatology shown in Fig. DP-1. However, we wanted to verify that the same conclusion would have been reached comparing model results with monthly averages. We found that in the whole ocean colour dataset the 2011 austral summer (here Jan-Feb) was one of the less productive ones. Nevertheless, Chl a concentrations were still above those simulated by the model.

RC26)p. 10820, line 1: The ability of the model to predict the vertical water column structure is also important. For example, vertical stratification would suppress vertical mixing of iron from sediments. How well does the model simulate the observed vertical water column structure on the South Georgia shelf?

AR26)Calculating an average MLD for the whole shelf region (depth <200m), the model returns a value of approximately 20m. This value is below measurements shown by Young et al., 2011 who used a model with a 3-km resolution forced with a very extensive dataset of in situ temperature and salinity measurements. Out results however fall in the range of MLD measured during austral summer by Korb et al., 2012 to the north of South Georgia.

RC27)p. 10820, line 14: Over what temporal period are the data averaged? Can you include a measure of variance associated with the mean values on figure 5?

AR27)In Fig AR-1 we reproduced the plots shown in the manuscript together with the standard deviation. Averages and standard deviations are calculated using all modeled and observed concentrations included in the domain shown in Fig. DP-7a. Model results are from the last modeling year, while observations are from the CARS climatology. As the domain includes waters with very different water properties (i.e., to the south and north of the island, in-bloom and out-bloom waters) the standard deviation shows large variability.



RC28)p. 10821, lines 8-13: This section would be more appropriate in the model description.

AR28)The manuscript will be reorganized accordingly.

RC29)p. 10823, line 15: Minimum values are observed in late austral summer (not early).

AR29)The manuscript will be reorganized accordingly.

RC30)p. 10823-10824, section 4.2: How are the SD and SE calculated, in particular the model values? Why do you use '$\sim$' and not '='? Is it appropriate to quote errors to 2 decimal places?

AR30)SE and SD are calculated using all measurements and model results included in the domain shown in DP-Fig 7a. The SE is calculated by dividing the standard deviation by the square root of the number of measurements. Model results are from the last model year, while observations are from the CARS climatology. We used $\sim$ as a synonim of approximately, but it will be removed.

RC31)p. 10826, line 7: The model bloom to the N and NE of South Georgia is consistently further south than observed. Why is this?

AR31)Unfortunately there are no austral summer observations of dFe with which we could compare modeled dFe concentrations. Therefore, one possibility is that to the north of the Georgia Basin dFe concentrations are too low to stimulate phytoplankon, as it occurs, instead, further south. Future simulations, with increased ligand concentrations (which can increase the life time of iron in the water column, Hunter et al., 2007) could test this discrepancy.

RC32)Figure 6: The model predicts high chlorophyll a values on the northeast shelf, which are not seen in the MODIS images. What might cause this discrepancy?

AR32)One reason could be related to the very smooth model bathymetry which does not allow for a more complex representation of circulation around the island. As local circulation is strongly oriented by bottom topography, a higher model resolution and hence a more realistic (and rugged) bathymetry would likely lead to a differently-shaped bloom. Moreover, Chelton et al., 2004 indicates a persistend wind-shadow to the east of the island that could possibly modify the structure of the water column (i.e., MLD). Unfortunately, the combination of surface forcing and resolution used here does not allow for a representation of this feature, rather a uniform and smooth distribution of Chl a around the island.

RC33)p. 10827, line 24: Are you sure you mean 'relative variability'? You appear to be comparing absolute values.

AR33)In this comparison we aimed at veryfing if the model could capture regions of high and low dFe concentrations, and not necessarily single values, which would be largely affected by local circulation features.

RC34)p. 10828, line 2: Do you mean 'modeled', not 'measured'? AR34)Modeled is correct and will be replaced.

RC35)p. 10828, lines 25-29: Looking at the flows and iron distributions, it is hard to tell how much of the 'second' iron plume is actually iron that has exited the shelf to the northwest and then turned eastward. Are you able to discriminate between these two possible pathways?

AR35) Observing circulation patterns in the region from a sequence of daily model output snaphots one can see that both plumes originate close to the shelf region, but then separate to follow different routes.

RC36)p. 10831, line 13: What proportion of the shelf is represented by each depth band? For example, if the 25-30m band includes only 1 model grid cell, whilst the 5-10m band has 5 cells, it would not be surprising that the 5-10m band has a bigger influence on simulated iron. Can you include some information on the geographical



area represented by each depth band?

AR36)As the chosen depth bands are shallower than 50m (i.e., the maximum depth of the vertical shore, see AR1) each 5m thick layer will account for comparable sediment surfaces.

RC37)Figure 10: I don't think this figure is necessary.

AR37) Figure DP-10 aims at presenting the complexity of the iron cycle around South Georgia. It highlights that several mechanisms, acting jointly, are responsible for the island mass effect, likely explaining how particularly intense and prolonged phytoplankton blooms can be observed around the island. Therefore, we believe that this figure is an important part of the manuscript and should not be removed.

Technical corrections RC 38)I would suggest that this paper be edited by a native English speaker to correct the grammatical errors that appear throughout the paper. AR 38)The revised manuscript will be checked and edited accordingly

Literature cited in our replies, but not included in the discussion paper.

Chelton, D. B., Schlax, M. G., Freilich, M. H., and Milliff, R. F.: Satellite measurements reveal persistent small-scale features in ocean winds, Science, 303, 978-983, 10.1126/science.1091901, 2004. Heimburger, A., Losno, R., Triquet, S., Dulac, F., and Mahowald, N.: Direct measurements of atmospheric iron, cobalt, and aluminum-derived dust deposition at Kerguelen Islands, Global Biogeochem. Cy., 26, GB4016, 10.1029/2012gb004301, 2012. Li, F., Ginoux, P., and Ramaswamy, V.: Transport of patagonian dust to antarctica, J. Geophys. Res., 115, D18217, 10.1029/2009jd012356, 2010. Li, F., Ginoux, P., and Ramaswamy, V.: Distribution, transport, and deposition of mineral dust in the southern ocean and antarctica: Contribution of major sources, Journal of Geophysical Research, 113, 10.1029/2007JD009190, 2008. Cropp, R. A., Gabric, A. J., Levasseur, M., McTainsh, G. H., Bowie, A., Hassler, C. S., Law, C. S., McGowan, H., Tindale, N., and Viscarra Rossel, R.: The likelihood of observing duststimulated phytoplankton growth in waters proximal to the australian continent, Journal of Marine Systems, 10.1016/j.jmarsys.2013.02.013, 2013. Whitehouse, M. J., Priddle, J., and Symon, C.: Seasonal and annual change in seawater temperature, salinity, nutrient and chlorophyll a distributions around south georgia, south atlantic, Deep-Sea Res Pt I, 43, 425-443, 10.1016/0967-0637(96)00020-9, 1996.

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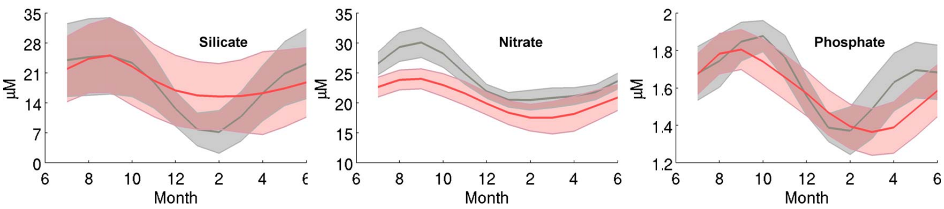


**Fig. 1.** Annual cycles of surface macronutrients. Solid curves indicate average cycle, the shaded are denotes the standard deviation interval.