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Biogeosciences Discussions

Interactive comment on "Distribution and recurrence of phytoplankton blooms around South Georgia, Southern Ocean" *by* I. Borrione and R. Schlitzer

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We thank the second reviewer 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.

RC 1: This is a well-written and interesting paper about the occurrence and frequency of phytoplankton blooms in the South Georgia area of the Southern Ocean. Particu-

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larly to the north and northwest of the island, which is downstream of the ACC, large and persistent blooms occur. The authors determine the frequency of bloom occurrence (FBO) and with this tool identify a typical bloom area, where spring blooms and late summer blooms occur. The authors conclude that SG blooms have high regularity, which contrasts with work by Park et al. (2010). Park et al. (2010) only see low seasonality in the SG area and are being criticized by the present authors for having applied an unrealistic delimitation of the study area in the SG region. Park and co-workers based themselves on empirical orthogonal function analysis, to arrive at identifying eight different biological domains, which allegedly represented a good accordance with oceanographic and topographic features. Their focus was the larger southwestern Atlantic sector of the Southern Ocean, an area much larger than the SG area, but apparently they misjudged the situation around SG. They come however to similar conclusions regarding the transport of Fe. An important conclusion by Park et al. is the dependence of bloom occurrence on flow speed of the fronts bending their way around SG. Actually, what I think Park et al. try to say is that the higher the current speed, the more interaction with the topography, the more sediment resuspension from the island shelves, and the more Fe gets into the water column.

AR 1: The intentions of the present manuscript are not to criticize the work of Park et al., (2010). The statistical analysis adopted in their study returns biological domains that are in accordance with oceanographic and topographic features in the Scotia Sea. However, the biological domain they obtain for South Georgia (dashed grey polygon in Figure AR-3) does not follow the main topographic or oceanographic features of the region, i.e. the Georgia Basin, the Polar Front (PF) and the Southern ACC Front (SACCF). The accordance with these topographic and oceanographic features is more evident for the Typical Bloom Area obtained with the pixel count algorithm (solid grey polygon in Figure AR-3). Comparison with their work is necessary to stress the importance of the area chosen for analysis of Chl a time series. Their time series leads to important conclusions regarding the transport of iron from the island, but underestimates the Chl a concentration levels that characterize this exceptionally productive environment of the Southern Ocean. Again, the intentions of the present manuscript are not to criticize the work of Park et al., (2010); therefore, to make sure this will not be perceived in the future, where necessary the text will be rephrased in favour of a more objective comparison.

RC 2: Personally I don't think that Fe diffusion from the sediment is sufficient to sustain a lateral Fe flux from the island shelves, resuspension is the key. See also a recent paper by De Jong et al. 2012 (JGR Biogeosciences 117, G01029,doi:10.1029/2011JG001679), who not only describe long distance transport of Fe in the ACC, but also show the role of sediment resuspension in bringing loads of Fe in the water column of the western Weddell Sea and the SOI region. In the case of the SOI region (January 2005) a bloom with 9 g/L Chl a had developed.

AR 2: Among the physical processes mentioned as responsible for introducing iron to the waters found downstream of South Georgia (i.e. melt-water runoff and atmospheric depositions), we will highlight the importance of sediment resuspension. In the discussion paper, in fact, we do not specifically mention resuspension processes, despite their importance has been indicated elsewhere, including the Kerguelen Plateau region (Blain et al., 2008).

RC 3: This paper boils a bit down to a Park-is-wrong, we-are-right message, which is too simplistic. This probably is a matter of a discussion that stays a bit at the surface of things and doesn't go beyond what Park has already stated.

AR 3: As stated above, comparison with the analysis of Park et al., (2010) in the South Georgia area remarks the importance of the size and location of areas chosen for the examination of Chl a time series. Because the intentions of the present manuscript are not to criticize the work of Park et al., (2010), where this appears to be the case, the text will be rephrased accordingly.

RC 4: As the other reviewer observed, it would indeed be interesting to look with more detail into the role of wind forcing and radiation aspects on mixed layer depths development and the timing of bloom onset.

AR 4: The importance of wind forcing, radiation aspects and mixed layer depths (MLD) on the inter-annual variability of phytoplankton blooms has been discussed also in our replies to the first reviewer Dr. Jouandet. Wind speed from QuikSCAT and Photosynthetically Active Radiation (PAR) from SeaWiFS, have been extracted from the Typical Bloom Area and correlated to Chl a concentrations (Figure AR-1 and Table AR-1 in the supplement). Results reveal a positive correlation for the variable-pairs Chl a/SST (correlation coefficient = 0.48, in Figure AR-1a) and Chl a/PAR (correlation coefficient = 0.24, in Figure AR-1b), but no relationship between Chl a concentrations and wind speeds (correlation coefficient ∼0, in Figure AR-1c). One would expect that higher SST result in a shallower surface layer, and thus more favourable light conditions. As indicated by the positive correlation between Chl a concentrations and PAR, which increases from 0.24 to 0.54 if the values for the 1999/2000 and 2007/2008 seasons are removed from the calculations (dots indicated with a red line in Figure AR-1b), higher PAR levels positively affect phytoplankton growth (i.e., higher Chl a concentrations). The pronounced irregularity of wind speeds revealed by the time series extracted for the Typical Bloom Area (data not shown), which indicates similar occurrence of strong and weak winds during summer and winter, may explain results of this correlation.

Unfortunately, the number of MLD estimates obtained from Argo-floats for the Typical Bloom Area (but also for a larger domain around the bloom area) is too small to construct a full time series useful for our purposes. However, one would expect that a shallower MLD will provide more favourable light conditions to the growing phytoplankton, and will also reduce the dilution of the total phytoplankton biomass (Smetacek & Naqvi, 2008). Both effects will be reflected in higher surface Chl a concentrations.

In order to asses the importance of the same environmental variables in controlling the time of bloom onset, we calculated averages for the 15-day period prior to each year's date of bloom onset (i.e. first week in which Chl a were > 0.75 mg m-3). In the correlation calculations we used anomalies, therefore we subtracted from 15-day averages the climatological value of each variable during the same 15-day period; this was done because all three variables are likely to follow a seasonal cycle: PAR and SST will increase towards summer, while winds are likely to weaken in strength towards summer. Results are displayed in Figure AR-2 and reported in Table AR-2 (please refer to the supplement for Table AR-2). In all cases, correlation coefficients are negative: -0.37 for onset-date/PAR (Figure AR-2a); -0.19 for onset-date/SST (Figure AR-2b); -0.3 for onset-date/wind speed (Figure AR-2c). The relationship between PAR and SST with the onset of the bloom indicates that more favourable light conditions and higher SST have favoured an earlier onset of the bloom. Less clear are the reasons behind the negative correlation for onset-date/wind speed, which suggests an earlier onset of the bloom after a period of more intense winds. We thus repeated the correlation calculations excluding the 2006-2007 season (dots indicated with red lines in Figure AR-2), when the onset was particularly delayed in time. In this case, the onset-date/wind correlation changes from -0.3 to 0.12 (results from this second calculation are enclosed in parenthesis). Although one would expect more favourable bloom-onset conditions when winds are weaker (as suggested by the positive correlation obtained with the second calculation), from our results it is difficult to make a clear statement because they strongly depend on the number of observations. A longer time series is necessary to reach a more robust conclusion.

RC 5: An aspect that I find quite intriguing of this paper is the second bloom peak, or should we say the interruption of the blooming conditions due to the bloom running out of nutrients mid-summer, particularly silicate. I believe this is not the whole story. Judging from the very low Fe concentrations north of SG from Nielsdottir et al. (2011), I would say that the bloom runs into Si/Fe co-limitation. The authors claim that the bloom gets going again after renewed supply of Si. This should come from below or from advection of Si replete waters upstream ACC. The same is likely so for Fe, see Nishioka et al. (2011, JGR 116, C02021, doi:10.1029/2010JC006321) and De Jong et al. (2012) for mechanisms and fluxes. I could think up even a role for icebergs (see Raiswell et al. 2008, Geochemical Transactions, 9:7 doi:10.1186/1467-4866-9-7) in supplying bioavailable Fe, although that depends on the number of them present in the SG area. I really wonder if increased erosion of the upper mixed layer towards the end of summer (i.e. the onset of deep winter mixing) creates the right circumstances for increased upwelling of enriched waters from the UCDW. The authors believe this is not the case, as allegedly the UML remains relatively shallow until April, but is this true all the time? Couldn't it be that the first end-of-season storms increase the mixing after which the UML restores to its previous shallow state? This does happen in the PF, even in summer. I don't know if the data exist for the SG area to substantiate this hunch, the authors know probably better than me.

AR 5: Iron input and availability is one of the major factors influencing build-up of phytoplankton blooms in the HNLC waters of the Southern Ocean; however, during and after the phytoplankton growth season silicate concentrations may fall below the phytoplankton requirements, especially if the phytoplankton community is dominated by diatoms. The presence of large, intense and long-lived phytoplankton blooms downstream of South Georgia suggests that both nutrients (i.e. iron and silicates) are sufficient for growth. However, the processes leading to these conditions, including their magnitude and relative importance, are still not fully resolved. Because circulation in the South Georgia area is in large part controlled by bottom topography, and leads to a relatively fast transport of water from the island towards the bloom area (>40 cm sec-1), we hypothesized a continuous supply of shelf-derived iron. Furthermore, one would also include a contribution of iron from atmospheric deposition (mostly from Patagonian dust, although not yet clearly quantified); during summer, satellite imagery reveal the importance of glacier melt releasing large amounts of suspended glacial flour (see Figure 3 in Young et al., 2011). Indeed, as suggested by the present reviewer, the strong and intermittent winds would enhance mixing and likely lead to an increased source of iron from below; the transit of very large melting icebergs (see Trathan et al., 1997 for an example), but also excretion of iron by krill and whales (Nicol et al., 2010; Schmidt et al., 2011) would also need to be considered. Nielsdottir et al. (2011) measured rapidly decreasing dissolved-iron concentrations in the wake of South Georgia, but satellite ocean colour images of the same period indicated a widespread and very intense bloom (∼80000 km2, Jones et al., 2012) also much farther away from where the in-situ measurements of iron were taken, suggesting that measurements of dissolved iron alone, might not reveal the full story. Therefore, because several concomitant mechanisms can be proposed as supplying iron to the Typical Bloom Area, one could imagine iron-replete conditions; additionally, because in Figure DP-7 the annual cycle of surface silicate concentrations presents a trough when also the climatological Chl a cycle decreases in January, we considered this macronutrient as the principal driver of the double peak depicted in Figure DP-5 and DP-6. However, as suggested by the anonymous reviewer Si/Fe co-limitation must also be considered. Indeed, more iron measurements in the Georgia region, especially in the open-ocean waters of the Typical Bloom Area are fundamental to better discriminate between sources and processes; simulations with biogeochemical models, could also provide some answers to the long list of questions.

RC 6: Technical remarks Page 10091 line 16: distributed with capital D. Everywhere: chl-a, pleas write Chl a (a italic);

AR 6: These technical corrections will be applied to the revised manuscript.

RC 7: Page 10102 line 19: the very small yet positive slope: this is only going so far as the regression is significant. The authors should show its significance, otherwise this claim is mere hand waving and should better be deleted.

AR 7: The slope of the regression line obtained from the time series of Chl a concentrations averaged for the Typical Bloom Area (Figure DP-5a) is equal to 0.009 $\pm$ 0.01 mg m-3 yr-1. The slope is very small, and indicates the absence of a clear decadal trend in the Chl a time series. The positive value of the slope however indicates a slight increase of Chl a over time, which would integrate to an increase of 0.09 mg m-3 in ten years.

REFERENCES (cited in the present reply, but not included in the Discussion Paper)

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Please also note the supplement to this comment:
http://www.biogeosciences-discuss.net/9/C5953/2012/bgd-9-C5953-2012-supplement.zip

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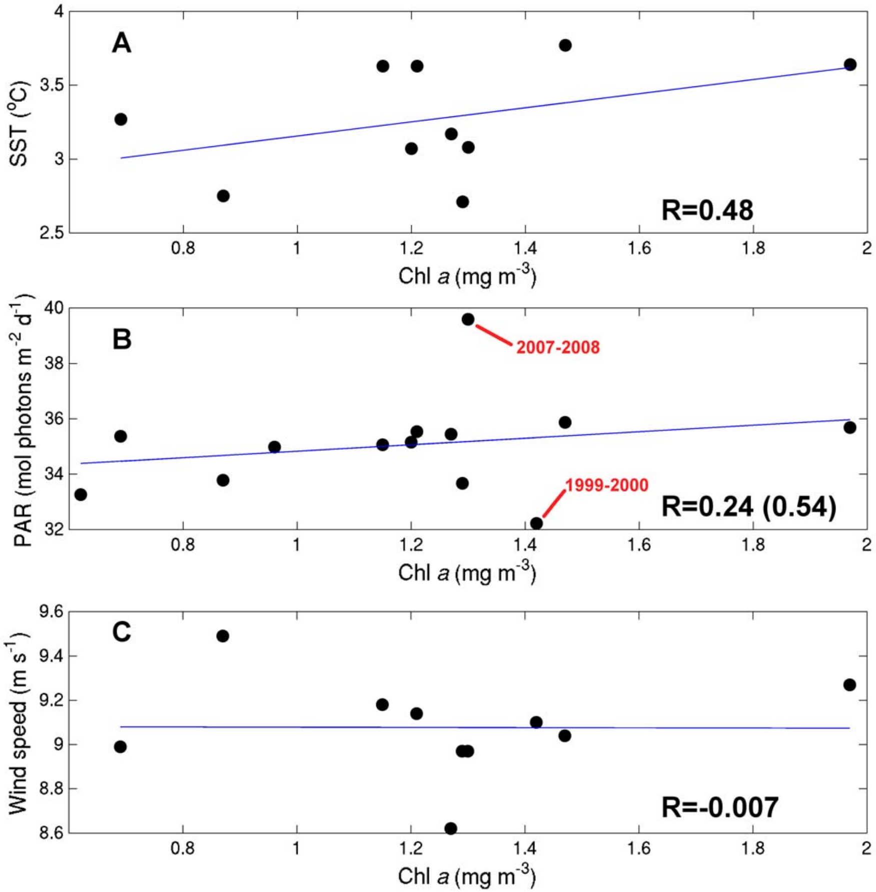

Fig. 1. Correlation plots and correlation coefficients (R) for growth-season averages of SST and Chl a (A), PAR and Chl a (B), Wind speed and Chl a (C). Values utilized in the calculations are in Table AR-1

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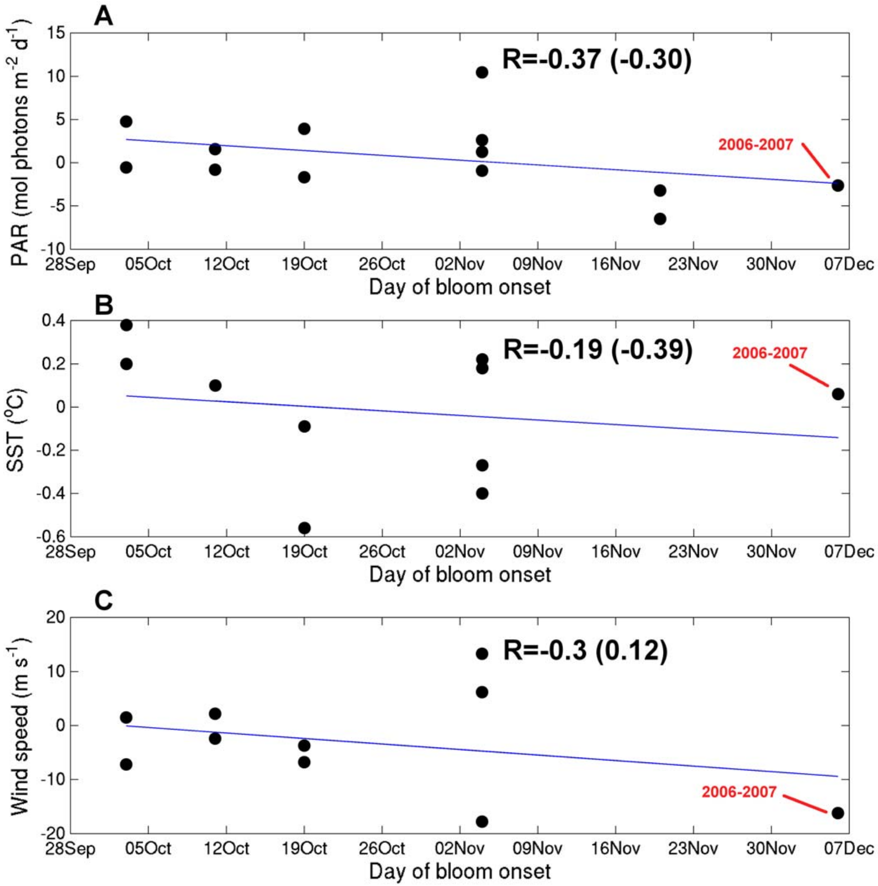

Fig. 2. Correlation plots and correlation coefficients (R), between the date of bloom onset and 15-day anomalies of PAR (A), SST (B), wind speed(C). Values utilized in the calculations are in Table AR-2

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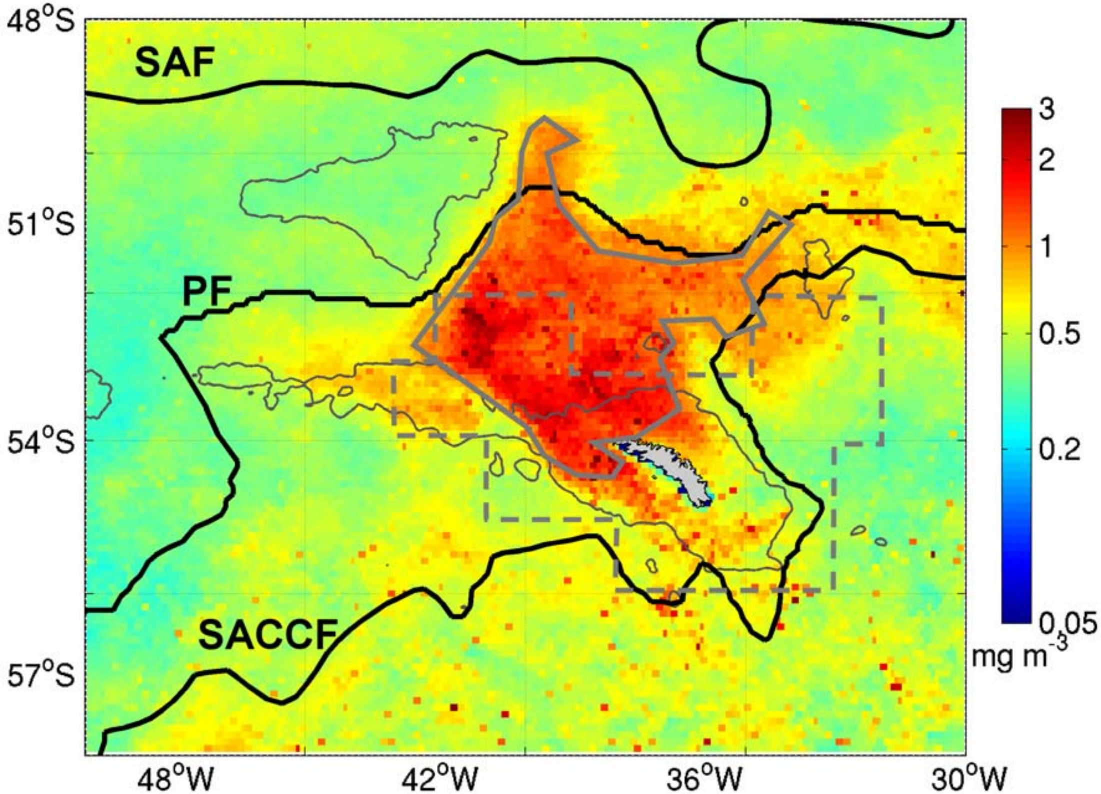

Fig. 3. Chl a climatology in the South Georgia region. The Typical Bloom Area is contoured with a bold grey line, the Park et al. (2010) Georgia bloom area is contoured with a dashed grey line

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