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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

I. Borrione and R. Schlitzer

ines.borrione@awi.de

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The authors would like thank the first reviewer of our manuscript, Dr. Jouandet, for the helpful 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 Figures and Tables accompanying our replies, we will add the prefix DP or AR to the Figure or Table number. For example, Figure DP-3b will correspond to Figure 3b in the submitted discussion paper.

General comments

RC 1: The authors bring new lights on the interannual variability of the spatial bloom

distribution around Georgia Island and its intensity based on the analysis of the chla satellite data from SeaWIFS over the 1997 to 2010 period. Original result is the determination of an area of persistent bloom over the study period according to a new method based on 'Frequency Bloom Occurrence'(FBO), which is in agreement with the climatology. The authors show that the bloom delimitation is constrained by the topography. Interannual variability of the bloom dynamic and magnitude are also investigated in this study. The potential factors responsible of the patterns observed are reviewed in the discussion but with a lack of depth. Additional data would be helpful to rule out (or not) some hypothesis. It would be interesting to investigate the potential correlation of the IAV of the bloom with any solar flux, wind, SST variations over the study period. Wind intensity as well as solar flux radiation control the mixed layer depth and could explain change of the beginning of the bloom observed.

AR 1: Following the results of Park et al., (2010) who indicated that in the South Georgia region phytoplankton bloom events were rare and weak in intensity, we re-examined the available time-series of satellite ocean colour imagery with the main aim to identify and then describe recurrent patterns in the temporal and spatial occurrence of phytoplankton blooms. Utilizing the pixel count algorithm, which treats equally all Chl a values above 0.75 mg m-3 and hence does not discriminate between the magnitude of each recorded phytoplankton bloom, we could identify the Typical Bloom Area and its characteristic annual cycle. These two new results are the core of the present manuscript. Indeed, the time series of Chl a concentrations averaged from the Typical Bloom Area (Figure DP-5) indicates inter-annual variability in the magnitude of phytoplankton blooms. As suggested by Dr. Jouandet, but also by the second reviewer, a comparison between recorded Chl a concentrations and environmental properties (in particular mixed layer depth, wind speed, solar radiation and sea surface temperature) does provide a more quantitative way of understanding bloom variability than the review of influencing factors presented in the submitted version of the manuscript. For this purpose, the following environmental properties were added to our analysis:

1. Mixed Layer Depths (MLD) were estimated from all Argo-float profiles available from the 1997-2010 time-period. Argo profiles were downloaded for the Atlantic Ocean from ftp://www.usgodae.org/pub/outgoing/argo/geo/atlantic_ocean/. The MLD was estimated as the depth where the first along-depth derivative of the potential density anomaly relative to the surface (Ðś0) increased for the first time above 0.03 (kg m-2). Thresholds equal to 0.02 and 0.04 were also tested, but returned comparable MLD estimates.

2. Terra-MODIS (Moderate Resolution Imaging Spectroradiometer) Level-3 eight-day averages of daytime recordings of Sea Surface Temperatures (SST), were retrieved for the February 2002 to March 2010 time-period from http://oceancolor.gsfc.nasa.gov/

3. SeaWiFs Level-3 eight-day composites of Photosynthetically Active Radiation (PAR) measured from September 1997 to March 2010 were retrieved from http://oceancolor.gsfc.nasa.gov/

4. Daily QuikSCAT (Quik SCATterometer) wind speed measurements, available between 1999 and 2009 via OpeNDAP from the CERSAT facility, were retrieved from http://www.ifremer.fr/opendap/cerdap1/cersat/wind/l4/quikscat/daily/.

MLD estimates obtained from Argo vertical profiles in the Typical Bloom Area are too few to construct a full time series useful for our purposes. For almost all months in the time-period, the total number of available profiles is below 15 and often equal to zero. In particular, we find no data prior to 2003. We thus attempted increasing the size of the domain from which vertical profiles were extracted, but the number of observations remained very low.

To evaluate their influence on the inter-annual variability of phytoplankton blooms, PAR, SST and wind speed measurements for each year of observations, and pertaining to the Typical Bloom Area were averaged between 27 October and 02 April (i.e. the duration of the climatological growth-season), and then correlated with Chl a concentrations averaged in the same time-interval. Results of the calculations (averages and correlations) are reported in Table AR-1 and Figure AR-1 (refer to the supplement for Table AR-1), and will be added to Table 1 of the revised manuscript (from Table DP-1).

Correlation of SST and PAR with Chl a seasonal averages return, in both cases, a positive coefficient: R=0.48 for Chl a/SST (in Figure AR-1a) and R=0.24 for Chl a/PAR (in Figure AR-1b). One would expect a shallower surface stratification during summers when surface waters were overall warmer; in these years, phytoplankton growth would be enhanced by more favorable light conditions, but also the dilution of the total phytoplankton biomass in the (likely shallower) MLD would be reduced (Smetacek and Naqvi, 2008). The effects of shallow stratification due to warmer temperatures on improved light conditions and reduced dilution could explain the higher levels of primary productivity recorded during 2001-2002 and 2008-2009. More straight-forward is the significance of a positive correlation between PAR and Chl a concentrations, which indicates the occurrence of more productive years when cloud cover was reduced. The correlation coefficient for Chl a/PAR increases from 0.24 to 0.54 (the latter coefficient is indicated between parenthesis in Figure AR-1b) 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). Different, is the case for the Chl a/wind speed correlation (Figure AR-1c). Here the Chl a/wind speed correlation coefficient is very close to zero (R=-0.007). The pronounced irregularity of wind speeds revealed by the time series extracted for the Typical Bloom Area (not shown), which indicates similar occurrence of strong and weak winds during summer and winter, may explain results of this correlation.

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 (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 favorable light conditions and higher SST have favored 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 favorable bloom-onset conditions when winds are weaker (as suggested by the positive correlation obtained with the second calculation), it is difficult to make a clear statement from our results, because they strongly depend on the number of observations. A longer time series is necessary to reach a more robust conclusion.

Specific comments:

RC 2: The paper is well structured except for the sections 3.1 and 3.2. Results of satellite data analysis should be described first and secondly results derived from the FBO method.

AR 2: Following the suggestion of Dr. Jouandet, we have rearranged the two results sections, so that the description of satellite imagery precedes results from the calculations of the FBO.

RC 3: 3.2 section Why did you chose to show the spatial distribution of chl a at these specific dates? If there is no valuable reason, you should rather report the spatial distribution for one month for all the studied years.

AR 3: The four ocean colour monthly composites depicted in Figure DP-4 were chosen

because of reduced cloud cover within the Typical Bloom Area and because they provide examples of the major spatial Chl a patterns present in the time-series of analyzed SeaWiFs data.

Discussion section

RC 4: Could you briefly describe the methods used by Park et al. (2010)? Do they use also SeaWIFS data?

AR 4: Park et al., (2010) used ocean colour estimates from SeaWiFS for the period September 1997-December 2007 and from MODIS for the period January 2008-August 2008. An empirical orthogonal function analysis was then applied to the 11 yr-period of satellite observations and the k-means algorithm was used to delimit, among others, a polygonal area around South Georgia (outlined in dashed grey in Figure AR-3); across this area Park et al., (2010) studied temporal patterns of Chl a concentrations.

RC 5: The bimodal structure seen in the chla temporal evolution has also been pointed out in the Kerguelen area (Jouandet et al., 2011) and a comparison with this paper would improve the discussion (cf Table 1 of both papers).

AR 5: In the revised version of the manuscript bloom dynamics reported for the Kerguelen Plateau bloom (i.e. timing of first and second peaks) are included for a comparison with blooms in the Typical Bloom Area. However, it is not possible to make a comparison between bloom-season durations, because the criteria used to define the start and end of the blooms are different between the two studies. Here we defined bloom duration identifying the first and last week when Chl a concentrations were above 0.75 mg m-3, while in Jouandet et al., (2011) the bloom duration is defined using 0.3 mg m-3 as the threshold.

Conclusion

RC 6: Implication of the bloom IAV on the biological carbon pump needs also to be investigated

AR 6: The analysis of satellite ocean colour estimates from the South Georgia region has indicated that phytoplankton blooms, defined by Chl a values $\geq$ 0.75 mg m-3, occurred regularly every year between 1997 and 2010, and in most cases occupied the entire surface of the Typical Bloom Area ($\sim$145000 km2). The progressive increase of Chl a concentrations in spring followed by several months of sustained phytoplankton growth (Figure DP-6) is likely to reflect the rate of dissolved inorganic carbon (DIC) consumption, and the consequent enhancement of CO2 uptake from the atmosphere. Progressive reduction of CO2 fugacity and DIC with increasing surface Chl a concentrations has been reported for the Kerguelen Plateau region (Lourantou and Metzl, 2011; Jouandet et al., 2008) as well as downstream of South Georgia during the 2007-2008 season (Jones et al., 2012); Jones et al., (2012) estimated a summertime (February 2008) DIC deficit of 4.4 +- 0.8 Tg C when bloom-size estimates from satellite ocean colour measurements indicated an area of about 80000 km2, equivalent to $\sim$ 55% of the Typical Bloom Area. Although the time series of Chl a concentrations from the Typical Bloom Area (Figure DP-5) have indicated pronounced inter-annual and intra-annual variability in the magnitude of the bloom, in 9 out of the12 years the growth-season Chl a average was above 1.10 mg m-3 (Table DP-1) and in 8 out of the 12 years the bloom size was that of the Typical Bloom Area (which, by definition, is the region where blooms occurred at least in 8 years). Therefore, one would expect that the summertime deficit recorded for February 2008 by Jones et al., (2012), is likely to be a low estimate of the potential for atmospheric CO2 drawdown that would derive from the most productive months, when very high Chl a concentrations occupied the entire Typical Bloom Area, as in December 1998 (Figure DP-4a). Hence, unsurprising is the belief that the South Georgia bloom potentially creates the strongest seasonal carbon uptake of the Southern Ocean (Jones et al., (2012).

RC 7: Figure 3: add the bloom area from Park et al. (2010), it would facilitate the comparison with their study easier.

AR 7: The Georgia bloom area defined and utilized by Park et al., (2010) in their

analysis will be included in the revised manuscript, similarly to Figure AR-3.

RC 8: Figure 5: this figure is not very clear and the information provided by it are already shown in Table 1. Only the table should be kept.

AR 8: Table DP-1 is complementary to Figure DP-5; the table was included to provide quantitative information on each year's growth-season, i.e. bloom duration, Chl a seasonal averages. Table DP-1 alone cannot present the details of the temporal variability of Chl a concentrations in the Typical Bloom Area. In fact, only Figure DP-5 presents the progression of Chl a concentrations over the study period; it allows for identifying double (and at times triple) peaks, but also evaluating their intensity and evolution in time. Furthermore, in Figure DP-5 we express the level of data coverage during each 8-day ocean colour composite, and thus provide a way to evaluate the quality of the presented data. Furthermore, the time series of concentrations shown in the panels of Figure DP-5 allow a direct comparison with the time series presented by Park et al., (2010) and thus strengthens the statement that the area across which Chl a concentrations are extracted for time-series analysis is of critical importance.

REFERENCES (cited in the replies, but not included in the discussion paper)

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Lourantou, A., and Metzl, N.: Decadal evolution of carbon sink within a strong bloom area in the subantarctic zone, Geophys. Res. Lett., 38, L23608, doi: 10.1029/2011gl049614, 2011.

Jouandet, M. P., Blain, S., Metzl, N., Brunet, C., Trull, T. W., and Obernosterer, I.: A seasonal carbon budget for a naturally iron-fertilized bloom over the Kerguelen Plateau in the Southern Ocean, Deep Sea Research Part II: Topical Studies in Oceanography, 55, 856-867, 2008.

Jouandet, M. P., Blain, S., Metzl, N., and Mongin, M.: Interannual variability of net community production and air-sea CO2 flux in a naturally iron fertilized region of the Southern Ocean (Kerguelen Plateau), Antarctic Science, 23, 589-596, doi:10.1017/S0954102011000411, 2011.

Please also note the supplement to this comment:
http://www.biogeosciences-discuss.net/9/C5941/2012/bgd-9-C5941-2012-supplement.zip

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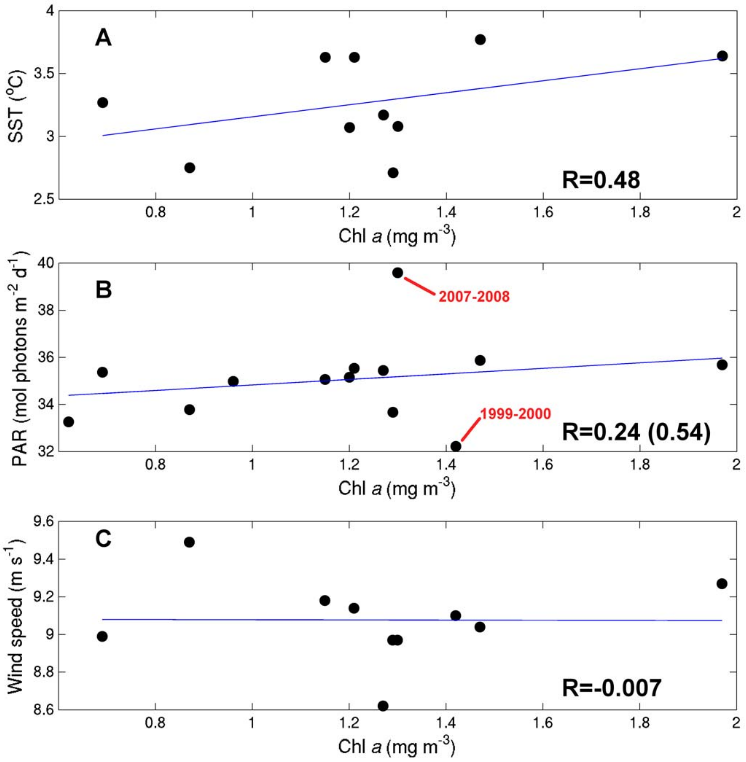

Fig. 1. Correlation plots and correlation coefficients (R) for growth-season averages of SST and Chl a (A), PAR and Chl a (B), Wind speed and Chl a (C). Values utilized in the calculations are in Table AR-1

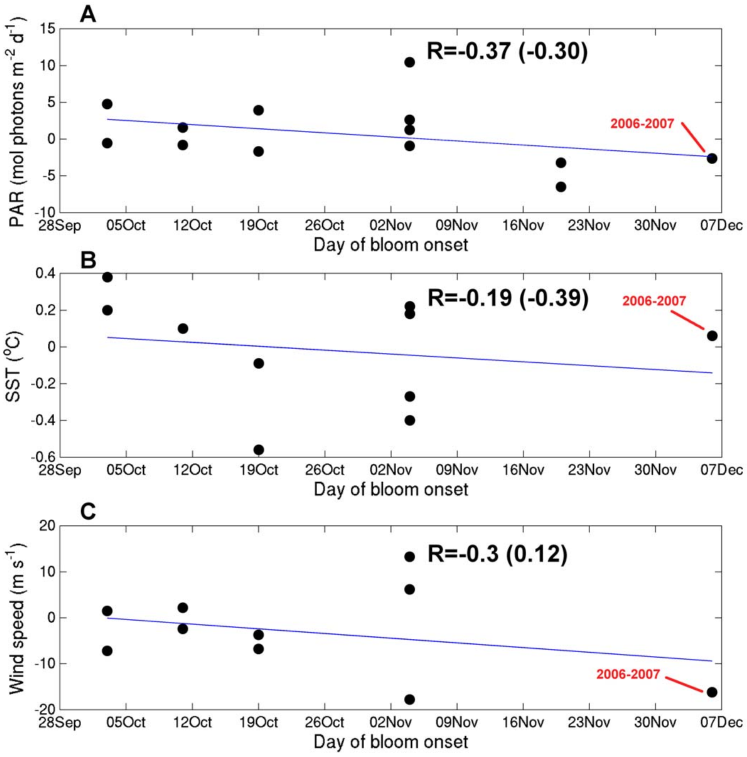

Fig. 2. Correlation plots and correlation coefficients (R), between the date of bloom onset and 15-day anomalies of PAR (A), SST (B), wind speed(C). Values utilized in the calculations are in Table AR-2

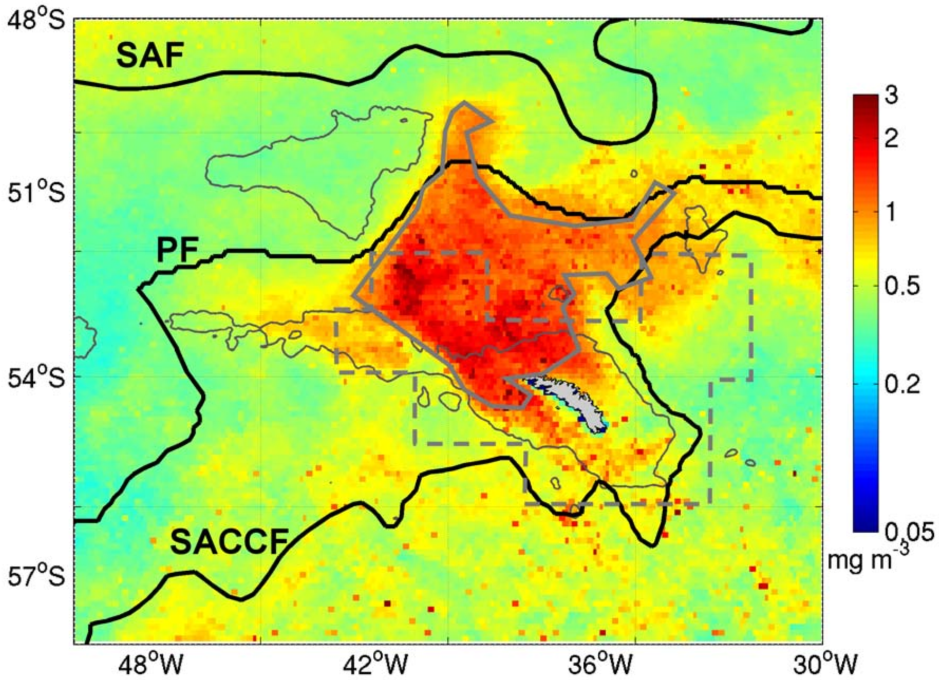

Fig. 3. Chl a climatology in the South Georgia region.The Typical Bloom Area is contoured with a bold grey line, the Park et al. (2010) Georgia bloom area is contoured with a dashed grey line.