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Distribution and recurrence of phytoplankton blooms around South Georgia, Southern Ocean

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BGD

9, 10087–10120, 2012

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Abstract

South Georgia phytoplankton blooms are amongst the largest of the Southern Ocean and are associated with a rich ecosystem and strong atmospheric carbon drawdown. Both aspects depend on the intensity of blooms, but also on their regularity. Here we use data from 12 yr of SeaWiFS ocean colour imagery and calculate the frequency of bloom occurrence (FBO) to re-examine spatial and temporal bloom distributions. We find that upstream of the island and outside the borders of the Georgia Basin, blooms occurred in less than 4 out of the 12 yr ($FBO < 4$). In contrast, FBO was mostly greater than 8 downstream of the island, i.e. to the north and northwest, and in places equal to 12, indicating that blooms occurred every year. The typical bloom area, defined as the region where blooms occurred in at least 8 out of the 12 yr, covers the entire Georgia Basin and the northern shelf of the island. The time series of surface chlorophyll-*a* (chl-*a*) concentrations averaged over the typical bloom area shows that phytoplankton blooms occurred in every year between September 1997 and September 2010, and that chl-*a* values followed a clear seasonal cycle, with concentration peaks around December followed in many years by a second peak during late austral summer or early autumn, suggesting a bi-modal bloom pattern. The bloom regularity we describe here is in contrast with results of Park et al. (2010) who used a significantly different study area including regions that almost never exhibit bloom conditions.

1 Introduction

Phytoplankton blooms play a key role in pelagic and benthic food webs, on the transfer of organic matter to the sea floor as well as on ocean biogeochemistry (Falkowski et al., 1998). In the presence of sufficient nutrient supply and light levels, phytoplankton can grow and accumulate to bloom levels where loss rates due to mortality (i.e. grazing) and sinking are exceeded. Across most of the Southern Ocean, despite the high macro-nutrient content of surface waters transported by the easterly flowing Antarctic

BGD

9, 10087–10120, 2012

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Circumpolar Current (ACC), chlorophyll-*a* (chl-*a*) concentrations generally remain low and do not exceed 0.5 mg m^{-3} (Comiso et al., 1993; Moore and Abbott, 2000). According to the iron hypothesis (Martin et al., 1990), these High Nutrient Low Chlorophyll (HNLC) conditions are due to iron limitation. In fact, when iron-stress was reduced by an exogenous source of iron, as for example during artificial iron fertilization studies (Boyd et al., 2007), phytoplankton blooms were observed. In natural conditions, regular blooms develop close to coastal regions and downstream of islands, where land masses constitute reliable sources of iron; examples are the western Antarctic Peninsula (e.g. Smith et al., 2008) or the sub-Antarctic Kerguelen and Crozet islands (Blain et al., 2008; Pollard et al., 2009; Planquette et al., 2007).

In the Southwestern Atlantic sector of the Southern Ocean (Fig. 1), strict HNLC conditions are mostly found in the Southern Drake Passage region, especially to the west of the Shackleton Transverse Ridge (STR in Fig. 1), where the absence of iron sources west of Drake Passage are believed to limit phytoplankton growth (Dulaiova et al., 2009; Hopkinson et al., 2007). East of the Drake Passage, phytoplankton blooms occur in response to diverse iron fertilization processes, including shelf-sediment interactions, i.e. along the shelf and continental regions of the Antarctic Peninsula or over the Southern Patagonian shelf (Ardelan et al., 2010; Hewes et al., 2008; Lutz et al., 2010), atmospheric dust depositions downwind of South America whether directly or following sea-ice melting (Lannuzel et al., 2007; Gassó and Stein, 2007; Smith et al., 2008), mesoscale features such eddies (Kahru et al., 2007) or iceberg melt (Lin et al., 2011). Whereas phytoplankton blooms in the open ocean waters of the Scotia Sea are short-lived and often unpredictable (Whitehouse et al., 2012), east of South America (north of the Sub-Antarctic Front) and downstream of islands they are recorded frequently. Among all island systems of the Scotia Sea (i.e. South Orkney or the South Sandwich Islands, indicated as SOI and SSI in Fig. 1), phytoplankton blooms of South Georgia are the largest and most intense, with chl-*a* concentrations often exceeding 10 mg m^{-3} (e.g. Korb et al., 2004).

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

The island of South Georgia, located at the north-eastern limit of the Scotia Sea, generates the largest meander in the eastward flowing ACC. As seen in Fig. 1, just before approaching South Georgia, the Polar Front (PF) veers north, and then resumes its eastward flow north of the island (Moore et al., 1999); to the south of the island, the Southern ACC Front (SACCF), which approaches South Georgia from the southwest, kinks westwards towards the Georgia Basin, before resuming its eastwards course (Orsi et al., 1995; Thorpe et al., 2002; Boehme et al., 2008). In response to this particular hydrography of the region, South Georgia phytoplankton blooms develop to the northwest of the island over the deep waters of the Georgia Basin (3500–4000 m, see Fig. 2 for a map of bathymetry around South Georgia).

The highly productive environment of South Georgia is known to sustain a rich ecosystem, characterized by large stocks of krill, numerous colonies of marine and land based predators (Atkinson et al., 2001), as well as a shelf region reported to have the highest recorded biodiversity in the Southern Ocean (Hogg et al., 2011). Consequently, much attention has been dedicated to the understanding of primary productivity regimes associated to South Georgia, by means of shipboard measurements (e.g. Whitehouse et al., 2008a; Korb and Whitehouse, 2004), as well as from satellite imagery (Korb et al., 2004, 2012; Park et al., 2010). These studies mostly focussed on the region located south of 50° S, in particular on the southern portion of the Georgia Basin and the island's shelf. Results have indicated phytoplankton growing seasons ranging between 3 and 6 months, as well as significant spatial and temporal variability in surface chl-*a* concentrations. In particular, a recent multi-year study indicated that around South Georgia phytoplankton blooms showed low predictability and no regular seasonality (Park et al., 2010). Considering that the shelf of South Georgia is likely providing a reliable supply of shelf-derived iron, similar to the other major sub-Antarctic islands of the Southern Ocean (i.e. those of the Crozet and Kerguelen plateaus, Blain et al., 2008; Pollard et al., 2009; Chever et al., 2010) one would expect the presence of regular seasonal blooms; hence, the results of Park et al. (2010) are rather unexpected.

Holm-Hansen et al, 2004; Korb et al., 2004) albeit concentrations above $\sim 0.5 \text{ mg m}^{-3}$ are underestimated (Garcia et al., 2005; Szeto et al., 2011).

2.2 Pixel count algorithm and frequency of bloom occurrences

The focus of this study is to investigate the spatial and temporal dynamics of chl-*a* concentrations that pertain to phytoplankton bloom conditions. Southern Ocean blooms were distinguished by Comiso et al. (1993) as having chl-*a* values $> 1 \text{ mg m}^{-3}$. However, because of the tendency of SeaWiFS to underestimate mid to higher chl-*a*, we chose 0.75 mg m^{-3} as a threshold value to define phytoplankton blooms, which has been also used by Korb et al. (2008) and is very close to the 0.8 mg m^{-3} value adopted by Fitch and Moore (2007). Consequently, only chl-*a* concentrations higher than 0.75 mg m^{-3} were accounted for and grouped in a single bloom category, independent from the bloom magnitude.

For every SeaWiFS data pixel in the South Georgia region (domain indicated in Fig. 1) we calculate the December–February austral summer average for each of the 12 yr between 1997 and 2010; missing values (i.e. due to cloud cover) were excluded in the calculations. In each of the 12 December–February austral summer averages, nearly all pixels from the main South Georgia bloom region contain chl-*a* concentration data. Then we calculate for every pixel the number of years (i.e. the number of austral summer averages) during which chl-*a* concentrations exceeded the bloom threshold value 0.75 mg m^{-3} .

Results are displayed as frequency of bloom occurrence (FBO) plots, where the colour scale indicates the number of summer seasons when chl-*a* concentrations corresponded to bloom conditions. For each pixel in the frequency plot ($\sim 60 \text{ km}^2$), the obtained FBO give an indication of the recurrence, and hence the predictability level of phytoplankton blooms. Phytoplankton blooms can be considered very recurrent (hence very predictable) in regions where FBO are closest to 12, which is the total number of austral summer seasons included in the analysis. Intermediate FBO (~ 6)

BGD

9, 10087–10120, 2012

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

indicate that chl-*a* concentrations fell recurrently both above and below the threshold (i.e. pronounced variability) in the 12-yr period while reduced FBO (FBO < 4) indicate less frequent or rare bloom events.

To assess the sensitivity of the results to the chosen threshold, we repeated the calculations with slightly different values (i.e. 0.7 mg m⁻³ or 0.8 mg m⁻³), but found nearly identical patterns in all cases. Further, we checked that the results obtained from the FBO calculated from seasonal averages (i.e. trimesters) is comparable to the FBO calculated by considering each summer month independently (i.e. not combined to form seasonal averages).

2.3 Surface water circulation

Surface circulation patterns in the South Georgia region were obtained from AVISO satellite altimetry (<http://www.aviso.oceanobs.com/duacs/>). Weekly delayed-time mapped absolute dynamic topography data, re-sampled on a regular 0.25° grid, were extracted for the months of December through February and for the period between 1997 and 2010. The AVISO altimeter product is based on multiple altimeter missions (*Jason-1&2*, *T/P*, *Envisat*, *GFO*, *ERS-1&2* and *Geosat*) and provides a consistent and homogeneous dataset. The altimeter data were averaged to form an austral summer climatology for the 1997 to 2010 period (Fig. 2). In addition, averages for individual months were used for instantaneous comparisons with monthly ocean colour composites (Fig. 4).

Surface dynamic topography contours represent geostrophic streamlines, and indicate pathways and strength of surface circulation; the former are parallel to isopleths, while the latter are stronger when isopleths run closer.

2.4 Macronutrients

In order to characterize the seasonal cycle of macronutrient concentrations in the South Georgia region, we retrieved surface (0–50 m) water concentrations of nitrate,

BGD

9, 10087–10120, 2012

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



phosphate and silicate from the World Ocean Database 2009 (WOD09, Boyer et al., 2009). Data from WOD09 are distributed by the NOAA National Oceanographic Data Center (http://www.nodc.noaa.gov/OC5/WOD09/pr_wod09.html).

3 Results

3.1 Austral summer climatology

Results obtained with the pixel count algorithm (Fig. 3a) provide information on the frequency of occurrence of summer phytoplankton blooms recorded in the South Georgia region. The colour of each image-pixel ($\sim 60 \text{ km}^2$) represents the total number of years when chl-*a* concentrations exceeded 0.75 mg m^{-3} (i.e. bloom conditions).

In the South Georgia region, the area where blooms occurred in at least 8 out of the 12 yr (coloured with shades of red) is largely confined to the Georgia Basin and the northern shelf of the island with highest values close to the western and northern periphery of the basin (FBO equal or greater than 10). Worth noting are the presence of high FBO also at the northernmost tip of the Georgia Basin (39° W , 50° S) which has often been excluded from ocean colour and in-situ investigations. Bloom conditions were more variable over Shag Rocks and the southern shelf of South Georgia, where FBO values mostly range between 4 and 7. Furthermore, FBO ranging between 1 and 4 indicate that summer blooms have occurred also south of the island, although only on few occasions (pixels coloured in shades of green and blue). Just outside the periphery of the Georgia Basin, especially to the west and north of the basin, as well as along the eastern shelf of the island, frequency values remain very low ($\text{FBO} < 2$), indicating that in almost all years blooms were absent.

Utilization of the pixel count algorithm with the objective to locate and enumerate the occurrence of chl-*a* concentrations greater than 0.75 mg m^{-3} in 12 summer seasons, has allowed for identifying a sector of the South Georgia region in which phytoplankton blooms have been most recurrent (FBO equal or greater than 8), and where, therefore,

BGD

9, 10087–10120, 2012

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



blooms can be considered predictable in time. This region, which we consider to be representative of South Georgia phytoplankton blooms, and which we hereafter refer to as the Typical Bloom Area, has been outlined in Fig. 3a by a dotted black line. The results on temporal variability of surface chl-a concentrations and phytoplankton blooms shown below are restricted to this area (Figs. 5 and 6).

In addition to the pixel count analysis described above, we also constructed a chl-a concentration climatology by averaging austral summer data (December to February) over the entire study period between 1997 and 2010. The climatological average, depicted in Fig. 3b, indicates the presence of chl-a values greater than 0.75 mg m^{-3} over the Georgia Basin and in the area west of the North East Georgia Rise, along the northern and southern shelf of the island as well as in the area surrounding Shag Rocks. Chl-a concentrations greater than 3 mg m^{-3} (shades of dark red) are indicated mostly in the south-western portion of the basin including the north-western shelf of the island. Overall, averaged chl-a values decrease in a north-easterly direction and reach values close to 0.75 mg m^{-3} in the area adjacent to the North East Georgia Rise.

The Typical Bloom Area defined by applying the pixel count algorithm (Fig. 3a) agrees in shape with the area of enhanced chl-a concentrations indicated in the summer climatology (Fig. 3b). Similarly in both the frequency plot and in the chl-a climatology, the core of the South Georgia bloom is found to the northwest of the island and is centred over the deep waters of the Georgia Basin (depths greater than 3000 m, Fig. 2); moreover, in both cases there is a clear indication of the narrow bloom protrusion extending north of the 50° S parallel (39° W , 50° S).

However, as only regions characterized by FBO greater or equal to 8 were considered in the successive steps of our analysis, most of the southern and eastern shelf of the island, as well as the area surrounding Shag Rocks and the area adjacent to the North East Georgia Rise were not included in the Typical Bloom Area. Although in these latter regions the chl-a climatology averages are above 0.75 mg m^{-3} , frequency calculations indicate that phytoplankton blooms have occurred less regularly or only on few occasions; this is especially valid for the area over Shag Rocks, where FBO are

BGD

9, 10087–10120, 2012

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

mostly close to or below 6. Portions of the South Georgia region where climatological chl-*a* averages indicate values below 0.75 mg m⁻³ (areas shaded in green and blue), are never part of the Typical Bloom Area.

The Typical Bloom Area contains the bloom region shown by Korb et al. (2008), but includes the area lying north of 50° S, where FBO indicate recurrent summer phytoplankton blooms. It is important to note that the Typical Bloom Area differs considerably from the South Georgia area illustrated by Park et al. (2010), which was obtained from an empirical orthogonal function analysis and k-means classification. Compared to the bloom area shown in Fig. 3a, their area was centred on South Georgia hence excluded the northern portion of the Georgia Basin, and included the low chlorophyll waters found to the southwest and east of the island. The sensitivity of the chl-*a* concentration time series on the specific area under consideration is discussed in Sect. 4.

3.2 Spatial and temporal variability

In Fig. 4 we show SeaWiFS chl-*a* data (colours) as well as satellite altimetry values (black contour lines) for four individual months to provide an indication of the magnitude of the spatio-temporal variability of austral summer pigment biomass patterns in the South Georgia region, and to examine how bloom distributions relate to local circulation. Unsurprisingly, all images reveal greater patchiness with respect to the previously described chl-*a* climatology (Fig. 3, see also Fig. 2 for a climatology of circulation around South Georgia).

In all chosen examples, a close match between chl-*a* distributions and surface flow fields (direction and intensity) is observed, also at the smaller scales. In December 1998 (Fig. 4a), for example, the phytoplankton bloom is clearly confined to the area comprising the shelf of the island and it extends over the southern and northern sectors of the Georgia Basin up to the southern limit of the Polar Front (bold line), here defined following Venables et al. (2012). All sides of the bloom are tightly contoured by closely spaced isopleths, which indicate strong currents. Similar phytoplankton blooms and circulation patterns are also observed in December 2001, January 2005 and January

BGD

9, 10087–10120, 2012

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



2006 (not shown). Over the North West Georgia Rise (37° W, 52.5° S), amidst chl-*a* concentrations greater than 2 mg m⁻³, a patch with lower chl-*a* values (~0.70 mg m⁻³) can be observed delineated by closed lines that indicate the presence of the anticyclonic eddy previously identified by Meredith et al. (2003). This eddy is present in most of the summer months considered for this study and is clearly captured by the circulation climatology of Fig. 2.

Compared to December 1998 (Fig. 4a), the periphery of the bloom observed in December 2009 (Fig. 4b) is less clearly defined and extends further to the west, following the pronounced meander kinking westwards. Most of the bloom is confined to the northern sector of the Georgia Basin and is missing around the island. Other examples of similar chl-*a* distributions are found in December 1999, January 2003 and December 2007 (not shown). Worth noting, is the anticyclonic eddy present north of the bloom area, with lower chl-*a* concentrations. This eddy, which is a recurrent feature of the region and is also present in the monthly images of December 2001 and December 2005 (not shown), is likely stabilized by bottom topography, which here is closely followed by the lines of flow (see also Fig. 2). In January 2004 (Fig. 4c) the phytoplankton bloom is much weaker and smaller and is confined to the area closer to the island; highest chl-*a* concentrations are found surrounding the North West Georgia Rise and over the northern shelf of the island up to the northern limits of the MEB-GB margin. In January 2007 (Fig. 4d), bloom conditions are mostly limited to a narrow band of very closely spaced dynamic topography isopleths to the north of South Georgia, following the approximate position of the Polar Front (bold contour line). In this monthly composite, as in December 2000 (not shown), intense blooms (chl-*a* > 2 mg m⁻³) are present far from the island shelf and at distances calculated along the direction of main flow that can be greater than 800 km. To the northwest of the island, and over the southern portion of the Georgia Basin chl-*a* concentrations are mostly below 1 mg m⁻³ and in the proximity of the North West Georgia Rise chl-*a* values are close to 0.2 mg m⁻³. The chl-*a* rich cyclonic eddy detaching from the northern tip of the South Georgia bloom is another

BGD

9, 10087–10120, 2012

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

recurrent feature of the region, and has been observed also in December 2000 and December 2004 (not shown).

Overall, we observe that protrusions and bends in regions of enhanced chl-*a* values generally coincide with meanders in the flow, while patches of higher or lower concentrations coincide with eddies. In most cases, largest concentration gradients are located along bands of rapid currents, which define the limits of the bloom area. This can be particularly seen along the -71 dyn cm contour (i.e. the southern limit of the Polar Front, Venables et al., 2012), which in all cases closely delimits the western extent of South Georgia blooms to the MEB-GB margin and determines the formation of the clock-wise flowing meander located at the northern tip of the Georgia Basin (39° W, 50° S). In these locations, the close correspondence between circulation and primary productivity patterns is well captured also by the climatologies depicted in Fig. 3. Furthermore, particularly recurrent appears to be the flow found along the northern flank of Shag Rocks and travelling from the north-western shelf of the island towards the MEB-GB margin. In most cases, this particular flow delimits the south-western extension of phytoplankton blooms occurring over the Georgia Basin.

Summarizing, phytoplankton blooms (i.e. chl-*a* concentrations greater than 0.75 mg m^{-3}) are observed on all occasions and they recur especially over the northern shelf of the island, and in the south-western portion of the Georgia Basin extending to its northern periphery along MEB-GB margin. Outside these regions phytoplankton blooms show larger variability. In particular, to the west and to the north of the line delimiting the southern extent of the Polar Front and due east of the island, summer chl-*a* concentrations never rise above 0.5 mg m^{-3} .

Occasional small-scale pattern differences between surface flows and chl-*a* distributions shown in Fig. 4 can be affected by the different spatial resolution of the two datasets ($1/4^\circ$ for AVISO and circa $1/12^\circ$ for SeaWiFS), or by the temporal average (here we show monthly composites). Such large averaging time period is dictated by the need for enough ocean colour measurements; the latter in fact are highly compromised by persistent cloud cover (white regions in the panels of Fig. 4).

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



3.3 Temporal variability across the typical bloom area

All SeaWiFS eight-day chl-*a* values between September 1997 and September 2010 were averaged over the Typical Bloom Area in Fig. 3a to construct the time series shown in Fig. 5a. For comparison with previous work, we also constructed a time series based on the median of the above chl-*a* values (Fig. 5b). Pixels with no data were excluded from the calculations. Chl-*a* average and median values that were obtained from less than 30 % of all pixels included in the Typical Bloom Area are marked with red dots in Fig. 5. Cloud cover, especially between late March and the first weeks of September, and low light levels between June and July are the main causes of reduced data coverage. The time series of average and median values are very similar, hence in the following we considered only average values. In order to investigate at greater detail the seasonal and intra-seasonal variability of phytoplankton blooms, in the second step of our analysis the time series obtained from chl-*a* averages (Fig. 5a) was split into separate seasons (coloured lines in Fig. 6a). The time series of chl-*a* concentrations was also used to derive the regression line depicted in blue in Fig. 5a.

Despite the pronounced inter-annual variability in the time series shown in Fig. 5a, phytoplankton blooms (i.e. chl-*a* > 0.75 mg m⁻³) occurred every year. Concentrations above 2 mg m⁻³ were reached in 7 yr, with values exceeding 3 mg m⁻³ in November 1999, December 2001 and February 2002, as well as in April 2006. Least productive growth seasons were in 1997/1998, 2000/2001 and 2006/2007 (see also Table 1). The very small slope of the regression line (blue line in Fig. 5a) indicates that in the time period analyzed here, chl-*a* concentrations did not follow an evident long term temporal trend.

The annual cycle of average chl-*a* concentrations over the Typical Bloom Area and the timing of the phytoplankton blooms is given for each year in Fig. 6a, together with the climatological seasonal cycle (solid bold black line) and the one standard error interval (dashed bold black lines). The one standard error interval is depicted also in Fig. 6b to allow for greater detail. Additionally, Table 1 provides for each year as well as

BGD

9, 10087–10120, 2012

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

for the climatological seasonal curve the phytoplankton bloom duration (expressed as the first and last week in which calculated chl-*a* averages were equal or greater than 0.75 mg m⁻³) and the total number of days in which chl-*a* concentrations averaged over the Typical Bloom Area were greater than 0.75 mg m⁻³. In addition, for each year are also indicated the chl-*a* value and the date of the week when the season's maximum value was recorded, as well as the growth-season chl-*a* average.

As described above and depicted in Fig. 5, chl-*a* concentrations reach phytoplankton bloom levels in all years. Typically, until late winter or early spring (i.e. mid-September) averaged chl-*a* values remain low (≤ 0.2 mg m⁻³); after September chl-*a* concentrations increase progressively and in most cases peak between mid-November and the end of December, although austral spring peaks are observed also earlier in the season, as in October 2008, October 2003 or November 2002 (1.4, 2.8 and 2.04 mg m⁻³, respectively). After the spring peaks terminate, as is occurring in most cases by the beginning of January, chl-*a* values gradually decrease and by the beginning of April (exceptions are April 2006 and April 2000) fall below ~ 0.75 mg m⁻³. During the first weeks of May chl-*a* concentrations are very low, except in May 2000 and May 2005 when concentrations were still close to 0.4 mg m⁻³. In contrast with this progressive decrease in chl-*a* concentrations, during several years, and especially between late summer and early autumn, a second or even a third intense peak in chl-*a* values (chl-*a* > 2 mg m⁻³) was observed (i.e. in the seasons of 2001/2002, 2008/2009, 1999/2000 or 2004/2005). At times, the second peak appears to be more intense than the preceding spring peak. In particular, a total of three chl-*a* concentration peaks were observed in the 1999/2000 season (red curve in Fig. 6a), at the end of November 1999, during late January/early February 2000 and in April 2000, respectively. Between mid May and mid July, the very low light levels preclude satellite estimates of winter chl-*a* concentrations.

Comparison between each seasonal curve and the chosen threshold (black horizontal line in Fig. 6a) indicates that in 9 out of 12 yr, phytoplankton blooms lasted more than four months (see also Table 1). The shortest phytoplankton bloom seasons

were recorded during the 1997/1998 and the 2006/2007 seasons, when phytoplankton bloom conditions were maintained for less than three months (Table 1).

The climatological growth season, obtained after averaging all years considered in this study, is characterized by two distinct productivity peaks. The first chl-*a* peak ($\sim 1.52 \text{ mg m}^{-3} \pm 0.21 \text{ mg m}^{-3}$) is recurrent and occurred regularly between late November and the first weeks of December. The second peak ($\sim 1.8 \text{ mg m}^{-3} \pm 0.31 \text{ mg m}^{-3}$) instead, is a less regular feature (both in timing and magnitude) and occurred between late January and early April. A transition phase, included between the last week of December and mid-January, can be observed between the peaks. Just before this trough, which appears as a regular feature of the seasonal cycle (standard error interval $\sim 0.1 \text{ mg m}^{-3}$, Fig. 6b), spring chl-*a* concentrations declined by about 30%, from 1.52 mg m^{-3} to 1.08 mg m^{-3} .

4 Discussion

The trajectories of the Polar Front and the Southern ACC Front in the South Georgia region (Venables et al., 2012; Park et al., 2010) together with the patterns of local circulation (Figs. 2 and 4) play a major role in controlling the location and extension of the blooms which develop to the north and northwest of the island and tend to reflect the geometry of the Georgia Basin. In particular, the southern limit of the Polar Front, identified following Venables et al. (2012), and the flow that travels westward from the northern shelf of the island along the northern flank of Shag Rocks generally separated bloom from impoverished waters outside the Georgia Basin. Hence, the boundaries of the Typical Bloom Area are clearly demarcated and vary little over time because the flow field is constrained by bottom topography.

The veritable absence of blooms along the eastern shelf of the island and their recurrence to the west and far north of the Typical Bloom Area can be explained by rapid transport of island and shelf-derived iron by intense currents ($20\text{--}40 \text{ cm s}^{-1}$, Ward et al., 2005) that flow to the northwest of the island and subsequently turn east. This

BGD

9, 10087–10120, 2012

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

circulation regime explains, e.g. the distribution of enhanced chl-*a* concentrations in Fig. 4c, where highest concentrations are found along the western periphery of the basin up to the northern limits of the MEB-GB margin. The importance of hydrography in controlling the extent of South Georgia phytoplankton blooms has been reported at the climatological level (i.e. Park et al., 2010) or for averages of a few years (Venables et al., 2012), but not at the high temporal and spatial resolution over 13yr that we present here.

Blooms always occurred within the Typical Bloom Area but their intensities and locations exhibited pronounced inter-annual variability. This is not surprising given the various independent factors that can influence surface chl-*a* concentrations. Among these: dust input (e.g. Gassó et al., 2010), variability in flow field (Thorpe et al., 2002; Boehme et al., 2008), mixed layer depth and its effects on bloom dilution (Smetacek and Naqvi, 2008), composition of the bloom (diatoms versus flagellates) and grazing (Whitehouse et al., 2009) are likely to be the most important. The intrinsic variability of top-down and bottom-up controls, as well as the fact that these may have additive or contrasting effects on pigment biomass accumulation, as would be the case for the controls mentioned above, may explain the absence of a prominent decadal trend in the chl-*a* time series. Similar conclusions were reached by Arrigo et al. (2008) who analyzed annual primary production in the Southern Ocean. However, the very small yet positive slope of the regression line, which suggests a slow increase in chl-*a* concentrations, appears to be in line with Whitehouse et al. (2008b) who expected an increase in productivity as a response to the gradual warming documented around South Georgia.

Pronounced variability in chl-*a* concentrations was also reported by Park et al. (2010), who utilized 11 yr of satellite ocean colour observations to study the temporal patterns of chl-*a* concentrations around South Georgia. They showed that in only six of the 11 yr, chl-*a* concentrations exceeded 0.75 mg m^{-3} and that in all cases they remained below 2 mg m^{-3} . Our time series, based on average or median values (Fig.5a and b) provide a different picture, indicating bloom levels in all years and chl-*a* concentrations exceeding 2 mg m^{-3} in at least five years.

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Large differences between the Typical Bloom Area and the South Georgia area used by Park et al. (2010) (outlined in their Fig. 5a) are most likely causing these very contrasting results. While the Typical Bloom Area is located to the north and northwest of the island only, where phytoplankton blooms are pronounced and most recurrent (i.e. over the Georgia Basin), the area defined by Park et al. (2010) occupies the southwestern portion of the Georgia Basin and includes waters to the southwest and east of the island, where chl-*a* values are generally below 0.5 mg m⁻³ and in some months even as low as 0.2 mg m⁻³ (i.e. in January 2007). Therefore, their analysis excluded the phytoplankton blooms occurring over the northern and eastern portion of the Georgia Basin, such as those observed in December 1998, December 2009 or January 2007 (Fig. 4), and introduced a systematic negative bias by including the impoverished waters to the southwest and east of the island. Consequently, differences between their time series and the one presented here are particularly pronounced when maximum chl-*a* concentrations were recorded only over the northern sector of the Georgia Basin, as in 2005/2006 and 2006/2007. Hence, the area across which chl-*a* concentrations are extracted is of critical importance and averaging areas that differ significantly from the Typical Bloom Area will yield different conclusions on the recurrence of phytoplankton blooms but also on their annual cycle.

Phytoplankton dynamics in the Southern Ocean are characterized by a pronounced annual cycle with a growth and non-growth season constrained by the combined effects of the solar cycle, shallowing and deepening of mixed layer depth and timing of sea-ice retreat and advance (Smith et al., 2008; Venables and Moore, 2010). Chl-*a* concentrations peaks have been observed in the first half of the growth season, while in the second half concentrations were progressively lower, resulting in an unimodal pattern mostly centred between late spring and early summer (Mongin et al., 2008; Moore and Abbott, 2000; Thomalla et al., 2011). Conversely, over the Typical Bloom Area chl-*a* concentrations remained high throughout the entire growing seasons, and in many years followed a bimodal pattern, which to our knowledge has been reported only on few occasions from the open Southern Ocean (Trull et al., 2001), but is a

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

(Fig. 7a and b). However, silicate concentrations decrease rapidly after October and reach limiting values between December and January (Fig. 7c). Because the spring bloom is dominated by diatoms (Korb et al., 2008, 2010, 2012) silicate exhaustion is the most likely cause of bloom termination reflected in the January minimum.

5 Groups other than diatoms, e.g. *Phaeocystis* or coccolithophorids, that could thrive under silicate limiting conditions and potentially form the second bloom also contribute to Southern Ocean blooms. e.g. in the Ross Sea (Arrigo et al., 1999) and in the Crozet region (Poulton et al., 2007) but were rare or have not been reported from the South Georgia region (Korb et al., 2008, 2012). These groups seem more susceptible to
10 virus infection and grazing by zooplankton and krill than diatoms (Smetacek et al., 2004), however, inter-annual variation in grazing pressure could result in build-up of their biomass and account for the chl-*a* increase observed in the second half of the growth season during some years. This needs to be verified by future ship-based investigations.

15 It is also possible that the moderate to high chl-*a* concentrations in the second phase of the growth season is due to diatoms responding to the progressive increase in silicate concentrations recorded after January (Fig. 7c). The sources of silicate at this time of the growth season could be due to deeper intrusions of SACCF water into the Georgia Basin (Korb et al., 2008; Boehme et al., 2008). Reduced uptake of silicate up-
20 stream of the island, where phytoplankton blooms are short lived and terminate earlier in the season depending on iron availability (Whitehouse et al., 2012), could also have an effect on the amount of silicate advected in the Typical Bloom Area. Because data coverage in ocean colour and nutrient measurements in the Typical Bloom Area are not concomitant nor at equal resolution, the responsible processes remain uncertain
25 and need more direct investigations.

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



5 Conclusions

The time series of chl-*a* concentrations averaged across the Typical Bloom Area shows that the South Georgia phytoplankton bloom, defined by chl-*a* values $\geq 0.75 \text{ mg m}^{-3}$, occurred regularly every year between 1997 and 2010. This result is in line with other sub-Antarctic islands, i.e. those of the Kerguelen or Crozet plateaus, where shelf-sediment interactions and local circulation provide a reliable annual supply of iron to the bloom region. Chl-*a* concentrations invariably peaked around December, and in many years peaked a second time between late January and April. Given the predominance of diatoms in the spring bloom and a most likely continuous advection of iron from the island, we attribute the second peak to a renewed supply of silicate which in January are reaching limiting concentrations and hence terminate the first (i.e. spring) bloom. To date only very few regional studies have reported bimodal bloom patterns in the open Southern Ocean and more studies, including biogeochemical modelling, are needed to help investigate the environmental controls behind it.

The recurrence and regularity of blooms described here is in marked contrast with Park et al. (2010) who showed a time series of weak and unpredictable South Georgia phytoplankton blooms. We point out that these significant differences arise from differences in location and extent of the study areas chosen. In fact, because the local flow is strongly constrained by topography and hence the bloom boundaries vary little in time, averaging areas substantially different from the Typical Bloom Area used here will necessarily exclude bloom waters or include others where blooms are rare or missing, hence introducing a systematic bias in the chl-*a* concentration analysis.

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BGD

9, 10087–10120, 2012

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

References

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- 30

BGD

9, 10087–10120, 2012

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

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Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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BGD

9, 10087–10120, 2012

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

Table 1. Column 2 and 3: phytoplankton bloom duration; Column 4: growth-season's maximum chl-*a* value and its timing (date of week); Column 5: year's specific seasonal chl-*a* average (based on the growth-season durations indicated column 2); Column 6: chl-*a* seasonal average based on the average growth-season length (i.e. from 27 October to 2 April). All concentrations values are expressed in mg m^{-3} .

Year	Date of first and last week when chl- <i>a</i> > 0.75 mg m^{-3}	Days with chl- <i>a</i> > 0.75 mg m^{-3}	Value and date of maximum chl- <i>a</i>	Growth-season chl- <i>a</i> average (year specific)	Growth-season chl- <i>a</i> average (27 Oct–2 Apr)
1997/1998	20 Nov 1997–04 Jan 1998	32	1.15 / 30 Dec 1997	0.78	0.62
1998/1999	20 Nov 1998–21 Feb 1999	96	2.51 / 22 Dec 1998	1.22	0.96
1999/2000	11 Oct 1999–3 May 2000	208	3.14 / 20 Nov 1999	1.34	1.42
2000/2001	18 Oct 2000–1 Mar 2001	96	1.4 / 28 Jan 2001	0.91	0.87
2001/2002	4 Nov 2001–17 Mar 2002	136	4.73 / 5 Feb 2002	2.19	1.97
2002/2003	19 Oct 2002–1 Mar 2003	144	2.04 / 4 Nov 2002	1.45	1.29
2003/2004	11 Oct 2003–16 Mar 2004	120	2.79 / 27 Oct 2003	1.18	1.15
2004/2005	3 Nov 2004–9 Mar 2005	128	2.67 / 27 Nov 2004	1.34	1.21
2005/2006	4 Nov 2005–10 Apr 2006	136	3.31 / 2 Apr 2006	1.31	1.27
2006/2007	6 Dec 2006–5 Feb 2007	56	1.45 / 20 Jan 2007	1.03	0.69
2007/2008	3 Oct 2007–NA	> 72	1.76 / 30 Dec 2007	1.2	1.3
2008/2009	2 Oct 2008–2 Apr 2009	176	2.43 / 1 Mar 2009	1.37	1.47
2009/2010	4 Nov 2009–17 Mar 2010	136	1.82 / 22 Dec 2009	1.29	1.2
Average	27 Oct–2 Apr	160	1.53 / 14 Dec	1.19	1.19

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

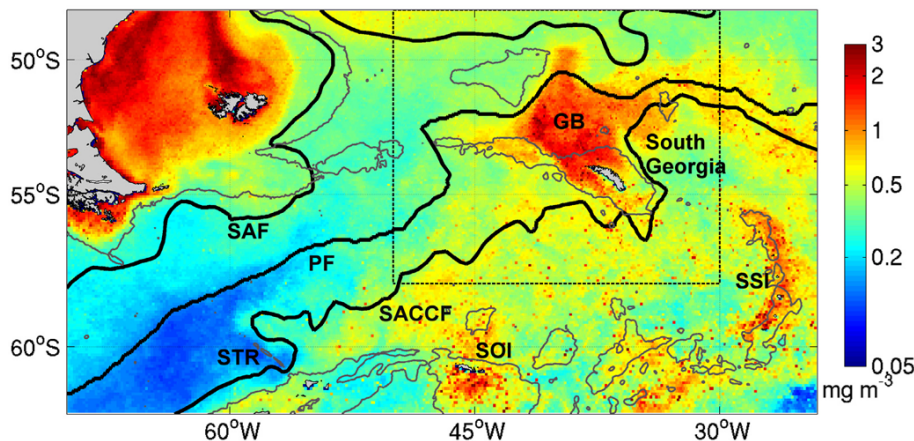


Fig. 1. chlorophyll-*a* climatology derived from SeaWiFS Austral summer (December–February, from 1997–2010) in the south-western sector of the Atlantic Southern Ocean. Bold lines indicate the Sub-Antarctic Front (SAF, Orsi et al., 1995), the Polar Front (PF, Moore et al., 1999) and the Southern ACC Front (SACCF, Thorpe et al., 2002). Bathymetric contours for the 2000m are indicated with thin lines. The position of the Shackleton Transverse Ridge (STR), that of the South Orkney Islands (SOI), the Georgia Basin (GB) and the South Sandwich Islands (SSI) are also indicated.

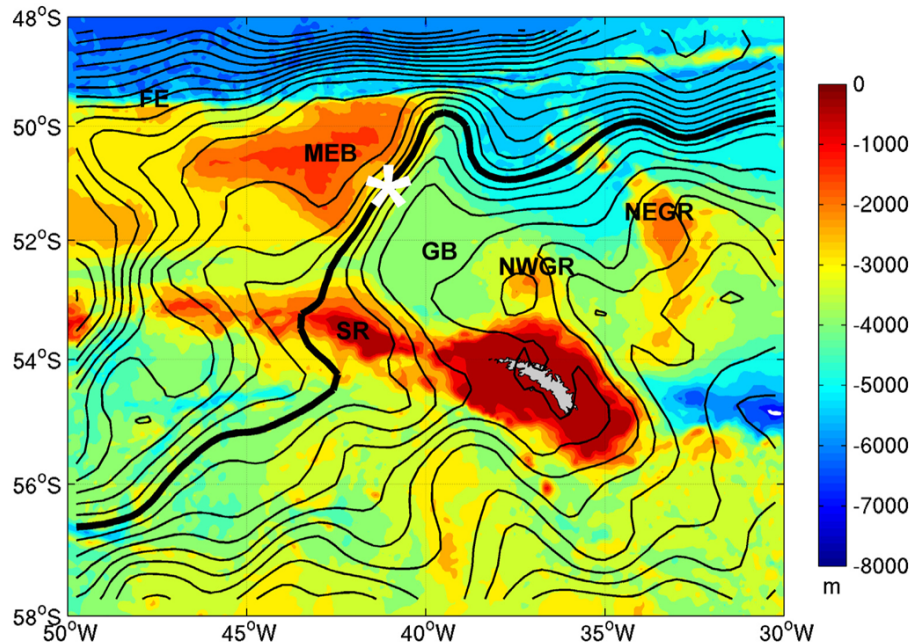


Fig. 2. Bathymetry (in colour) and climatological circulation (black lines) in the South Georgia region. Black lines correspond to AVISO dynamic topography isopleths for the summer climatology (December–February, from 1997–2010). Isopleths are equally spaced every 5 dyn cm, and dynamic topography values decrease from north to south; for reference, the -71 dyn cm contour line used by Venables et al. (2012) to locate the southern extent of the Antarctic Polar Front is shown in bold. FE: Falkland Escarpment, MEB: Maurice Ewing Bank, GB: Georgia Basin, SR: Shag Rocks, NWGR: North West Georgia Rise and NEGR: North East Georgia Rise. The position of the MEB-GB margin, referred to in the text, is indicated with a white star.

Phytoplankton blooms around South Georgia

I. Borrione and R. Schlitzer

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



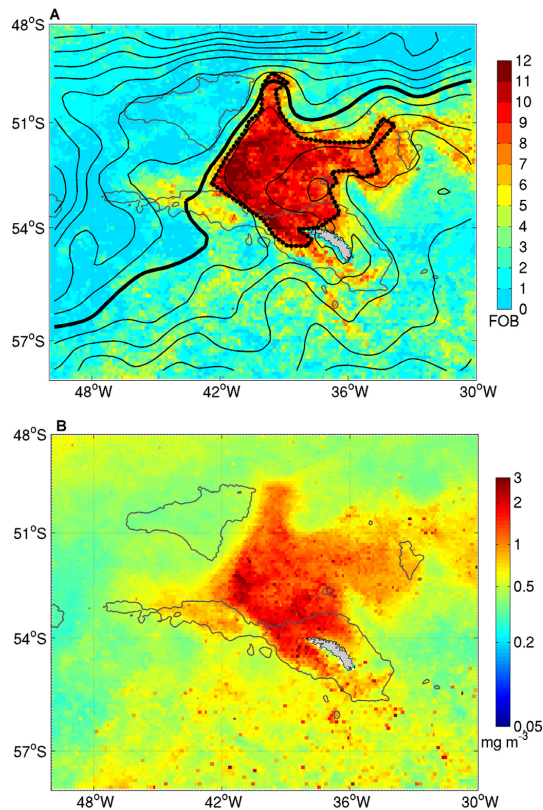


Fig. 3. Phytoplankton bloom occurrences and surface chl-*a* climatology in the South Georgia region obtained from SeaWiFS estimates and calculated for austral summer (December–February, from 1997–2010). **(A)** Colour indicates the frequency of occurrence of bloom conditions ($\text{chl-}a \geq 0.75 \text{ mg m}^{-3}$). Regions coloured in shades of red correspond to pixels where summer blooms have been recorded at least 8 times out of the 12 sampled seasons while regions in shades of blue indicate more rare bloom events. Black lines correspond to AVISO dynamic topography isopleths for the summer climatology (December–February, from 1997–2010); isopleths are drawn every 10 dyn cm. For reference, the bold black line corresponds to -71 dyn cm , and is indicated by Venables et al. (2012) as the southern limit of the Polar Front. The polygon drawn with a dotted black line indicates the extension of the Typical Bloom Area. **(B)** Surface chl-*a* climatology around South Georgia (detail from Fig. 1). In both panels the 2000m bathymetry contour is also indicated.

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

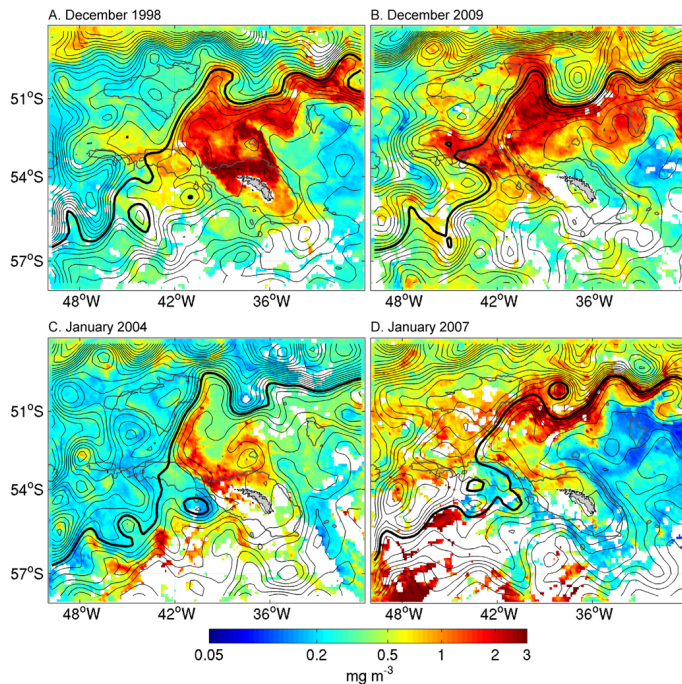


Fig. 4. Monthly composites of chl-*a* concentrations (colour) and concomitant dynamic topography isopleths (black lines) for **(A)** December 1998, **(B)** December 2009, **(C)** January 2004 and **(D)** January 2007, respectively. Isopleths are equally spaced every 5 dyn cm to highlight the smaller scale features; values decrease from north to south. As reference, the -71 dyn cm contour is depicted with a bold line, to indicate, according to Venables et al. (2012), the southern limit of the Polar Front. Colour scale units are mg m^{-3} . Yellow to red colours depict bloom conditions ($\text{chl-}a \geq 0.75 \text{ mg m}^{-3}$). Regions in white correspond to data gaps due to the presence of persistent cloud cover. For reference, the 2000 m bathymetry contour is also indicated with thin grey lines.

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

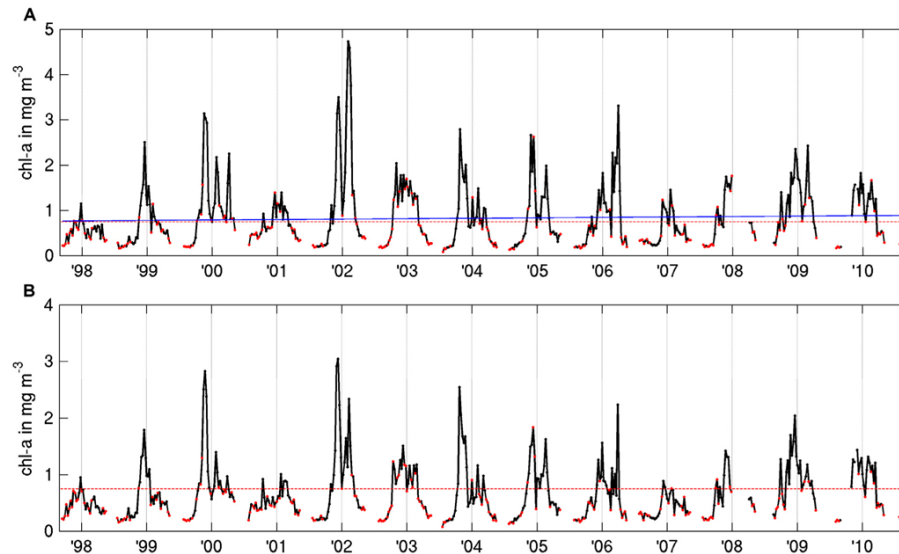


Fig. 5. Chl-*a* time series obtained from the mean **(A)** and the median **(B)** of all chl-*a* values available from eight-day composites of the Typical Bloom Area between September 1997 and September 2010. In **(A)** the regression line calculated along time is illustrated in blue. In both cases, as pixels with no data were excluded, we distinguish values that were obtained from more (black) or less (red) than 30 % of all pixels contained in the Typical Bloom Area. Between 9 January and 28 March 2008 no SeaWiFS data were available. Chl-*a* concentrations are expressed in mg m^{-3} . Vertical grid-lines indicate the first week of each year. The dashed red horizontal lines denote 0.75 mg m^{-3} .

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

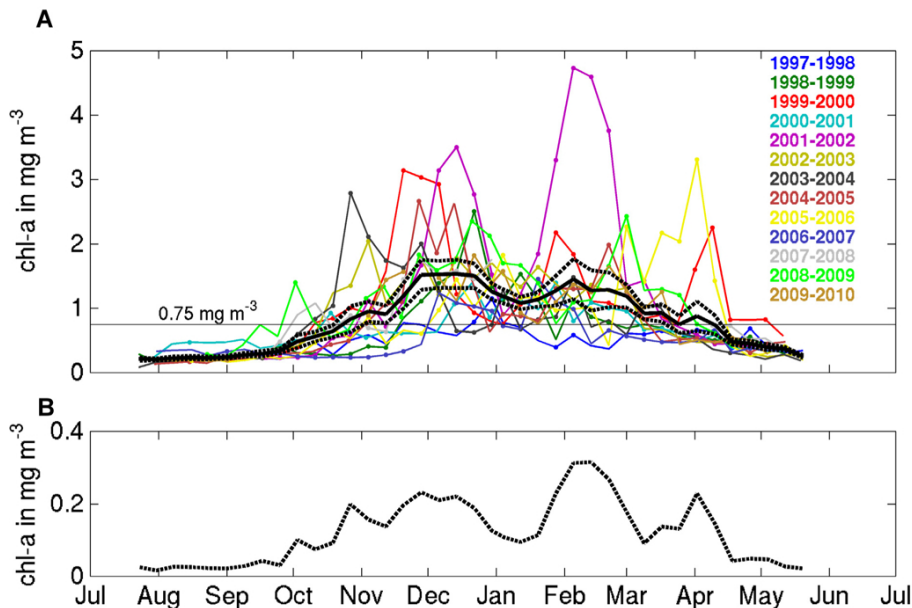


Fig. 6. Seasonal variability of chl-*a* concentrations and bloom occurrences in the Typical Bloom Area **(A)**. Every year included between September 1997 and June 2010 is colour-coded differently (see also Table 1). The solid bold black line represents the seasonal climatological average and the bold dashed lines indicate the one standard error interval. The horizontal black line marks 0.75 mg m^{-3} . Dots along each curve indicate when chl-*a* averages were obtained from more than 30% of all pixels contained in the Typical Bloom Area. **(B)** The black dashed line indicates the one standard error interval (as in panel **A**).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Phytoplankton blooms around South Georgia

I. Borrione and
R. Schlitzer

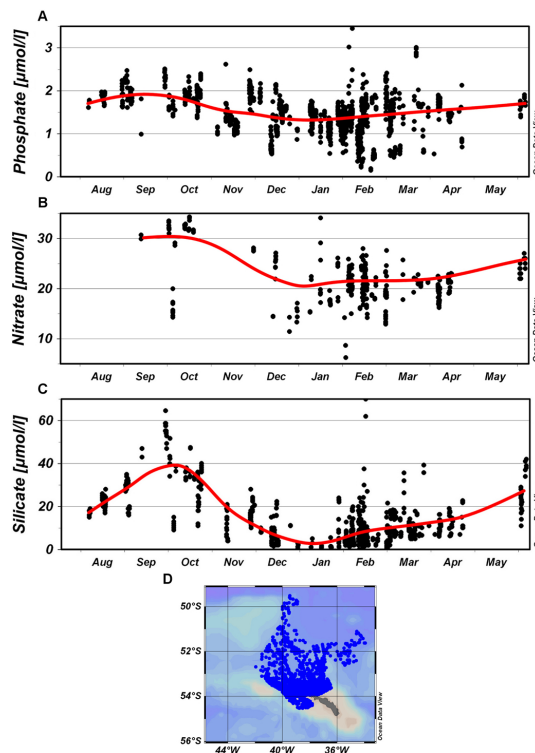


Fig. 7. Seasonal cycle of phosphate (A), nitrate (B) and silicate (C) in the Typical Bloom Area (D). All values are from the surface layer (0–50 m) and were extracted from the World Ocean Database 2009 (Boyer et al., 2009). In all panels black dots indicate individual original measurements, while red lines represent running averages.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)