

This discussion paper is/has been under review for the journal Biogeosciences (BG).  
Please refer to the corresponding final paper in BG if available.

# Regional scale characteristics of the seasonal cycle of chlorophyll in the Southern Ocean

**S. J. Thomalla<sup>1,2</sup>, N. Fauchereau<sup>1</sup>, S. Swart<sup>1,2</sup>, and P. M. S. Monteiro<sup>1</sup>**

<sup>1</sup>Ocean Systems and Climate Group, CSIR, P.O. Box 320 Stellenbosch, 7599, South Africa

<sup>2</sup>Department of Oceanography, UCT, Private Bag, Rondebosch, 7700, South Africa

Received: 2 February 2011 – Accepted: 28 April 2011 – Published: 13 May 2011

Correspondence to: S. J. Thomalla (sandy.thomalla@gmail.com)

Published by Copernicus Publications on behalf of the European Geosciences Union.

**BGD**

8, 4763–4804, 2011

## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Abstract

The seasonal cycle is the mode that couples climate forcing to ecosystem production. A better understanding of the regional characteristics of the seasonal cycle addresses an important gap in our understanding of the sensitivity of the biological pump to climate change. The regional characteristics of the seasonal cycle of phytoplankton biomass in the Southern Ocean were examined in terms of the timing of the bloom initiation, its amplitude, regional scale variability and the importance of the climatological seasonal cycle in explaining the overall variance. The study highlighted important differences between the spatial distribution of satellite observed phytoplankton biomass and the more dynamically linked characteristics of the seasonal cycle. The seasonal cycle was consequently defined into four broad zonal regions; the subtropical zone (STZ), the transition zone (TZ), the Antarctic circumpolar zone (ACZ) and the marginal ice zone (MIZ). Defining the Southern Ocean according to the characteristics of its seasonal cycle provides a more dynamic understanding of ocean productivity based on underlying physical drivers rather than climatological biomass. The response of the biology to the underlying physics of the different seasonal zones resulted in an additional classification of four regions based on the extent of interannual seasonal phase locking and the amplitude of the integrated seasonal biomass. This characterisation contributes to an improved understanding of regional sensitivity to climate forcing potentially allowing more robust predictions of long term climate trends.

## 1 Introduction

Biological production and carbon export to the deep ocean, “the biological pump” is considered a major contributor to the Southern Ocean CO<sub>2</sub> sink removing an estimated 3 PgC (1 PgC = 10<sup>15</sup> g of carbon) from surface waters south of 30° S each year (33 % of the global organic carbon flux) (Schlitzer et al., 2002). The Southern Oceans biological pump also plays an important role in regulating the supply of nutrients to

**BGD**

8, 4763–4804, 2011

### Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



thermocline waters (Subantarctic Mode Water and Intermediate Water) of the entire Southern Hemisphere and North Atlantic (Sarmiento et al., 2004), which in turn drives low latitude productivity (Sigman and Boyle, 2000). Climate models and decadal data sets suggest an increase in mixed layer stratification of the Southern Ocean through increased freshening and a shift towards a positive phase of the Southern Annular Mode (SAM) causing a poleward intensification of the westerly winds (Gille, 2008; Böning et al., 2008; Le Queré et al., 2009; Turner et al., 2009). Such trends will impact the Southern Ocean carbon sink and highlights gaps in our understanding about the regional character of the sensitivity of biological production in the Southern Ocean to changes in spatial and temporal atmospheric forcing scales (Sarmiento et al., 1998; Caldeira and Duffy, 2000; Russell et al., 2006; Arrigo et al., 2008).

A significant part of these gaps lies in the links between physical, physiological and ecological factors that influence the annual cycle of primary production growth and loss rates (Behrenfeld, 2010). The Southern Ocean is an unusual ocean in that it has the greatest inventory of unused macro-nutrients in the world ocean (Levitus et al., 1993) but low average phytoplankton standing stocks, with diverse spatial and temporal variations in phytoplankton biomass (Sullivan et al., 1993; Arrigo et al., 2008). Numerous studies in the literature have addressed the factors governing phytoplankton distribution, diversity, biomass and production. These include both bottom-up controls of the physiological response of phytoplankton assemblages to physical and biogeochemical forcing (e.g., Martin et al., 1990; Cullen, 1991; Nelson and Smith, 1991; de Baar et al., 1995; Boyd, 2002) as well as top-down controls of grazing (e.g., Cullen 1991; Price et al., 1994; Smetacek et al., 2004; Behrenfeld, 2010). Moreover, given the known influence of temperature on phytoplankton growth (e.g., Raven and Geider, 1988) and photosynthesis (e.g., review by Davidson, 1991) it is not surprising that the cold temperatures of the Southern Ocean also effect phytoplankton biomass and the seasonal cycle. However, despite the effects of cold temperatures on biological processes in the Southern Ocean, the key factors exerting bottom up control of phytoplankton production in this, the largest “high nitrate-low chlorophyll (HNLC)” region in the world

## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

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

ocean (Minas and Minas, 1992) are considered to be the availability of light, iron (Fe) and silicic acid (Boyd, 2002; Moore and Abbott, 2002; Arrigo et al., 2008). However, the complexity of the interaction between these various regulating factors in the diverse spatial domain of the Southern Ocean is still poorly understood. Part of the lack of understanding of the links between upper ocean physics and biological processes controlling production in the Southern Ocean is due to the operational limitations in resolving them at the required in situ spatial and temporal scales. This has necessitated the use of remotely sensed and modelling techniques to further our understanding of this complex environment. Although a current weakness in remotely sensed data is its inability to directly link ocean colour with carbon export, it has the added advantage of being able to address the temporal and spatial scale gaps in our knowledge of a hitherto under sampled ocean (e.g., Arrigo et al., 1998; Moore and Abbott, 2000; Korb and Whitehouse, 2004; Park et al., 2010).

The spatial distribution of surface chlorophyll blooms in the Southern Ocean in summer is thought to be consistent with an Fe limited regime, and this argument has been well documented (de Baar et al., 1995; Boyd et al., 2000; Gervais et al., 2002; Coale et al., 2004; Blain et al., 2007; Pollard et al., 2009). However, what has not been well understood are the physical control mechanisms responsible for supplying surface waters with Fe and modulating light that are ultimately responsible for controlling the phytoplankton seasonal cycle and spatial distribution. The intricate spatial and seasonal distribution of chlorophyll reflects the complex nature of the factors controlling production in the Southern Ocean, including sensitivity to mesoscale forcing as well as remarkable regional and basin scale differences. Understanding regional characteristics of variability in bloom dynamics and the associated physical drivers is necessary to understand the sensitivity of the response of ocean productivity to climate change.

One of the strongest modes of variability within the carbon cycle is the seasonal cycle. It is the mode through which the physical mechanisms of climate forcing are coupled to ecosystem responses such as productivity, diversity and ultimately carbon export (Rodgers et al., 2008). The regional characteristics of the seasonal cycle in

**BGD**

8, 4763–4804, 2011

## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



the Southern Ocean are however not well understood. In this study we aim to examine the regional scale characteristics of the seasonal cycle of phytoplankton biomass and propose a hypothesis that relates the observed variability in biological response to variability in the physical drivers. This study addresses an important gap in our understanding of the sensitivity of the biological pump to climate change in the Southern Ocean. Although this study is based exclusively on satellite data in a locale where ocean colour algorithms have well-known deficiencies, we anticipate that our results and hypotheses may guide future studies aimed at these gaps. The aim of this paper is not to investigate further the numerous controls of production in the Southern Ocean but rather to use remote sensing data at appropriate temporal and spatial scales to characterise regional differences in the Southern Oceans seasonal cycle.

## 2 Data and methods

### 2.1 Satellite-derived surface chlorophyll concentrations

Ocean colour data are used to examine seasonal, intra-seasonal and inter-annual dynamics of phytoplankton blooms in the Southern Ocean. SeaWiFS (Sea-viewing Wide Field of view Sensor, McClain et al., 1998) data used in this study cover the period from January 1998 to December 2007. 8 day mean level 3 standard mapped images of chlorophyll ( $\text{mg Chl m}^{-3}$ ) on a global 9 km equidistant cylindrical grid from SeaWiFS were obtained from the Goddard Space Flight Centre (GSFC) (<http://oceancolor.gsfc.nasa.gov>). The Southern Ocean domain south of  $30^\circ \text{S}$  was extracted and interpolated onto a regular  $1/4$  degree grid. Chlorophyll concentrations in the ocean tend to be log normally distributed (Campbell, 1995). When computing parametric statistical analyses on the original 8 day composite dataset, and in some cases for display purposes, the decimal logarithm of chlorophyll concentration has been used. Note that in most cases comparison with raw time-series do not lead to any substantial differences.

## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## 2.2 Mean Absolute Dynamic Topography (MADT)

We adapted the same technique described by Sokolov and Rintoul (2007b) to locate the main frontal branches of the Antarctic Circumpolar Current (ACC); the Subantarctic Front (SAF), the Polar Front (PF) and the Southern Antarctic Circumpolar Front (SACCF), as well as the Subtropical Front (STF) for the entire circumpolar extent. We did this using the CLS/AVISO MADT dataset from the Data Unification and Altimeter Combination System (DUACS) archive. The global, 1/4 of a degree, weekly averages are obtained through an improved space/time objective analysis method combining TOPEX/Poseidon, ERS-1/2, JASON-1, GFO and ENVISAT data (Le Traon et al., 1998). The MADT is the sum of the sea level anomaly data and a mean dynamic topography (Rio05-Combined Mean Dynamic Topography, from Rio and Hernandez, 2004). The original weekly maps have been linearly interpolated in time to match the 8 day composite calendar on which the SeaWiFS datasets are provided.

## 2.3 Bloom initiation date

We use “bloom” to refer to events of elevated chlorophyll concentration, without reference to a particular threshold. The initiation of the bloom (or the date of bloom onset) is understood here as the period of the year registering a relative increase in chlorophyll concentration, irrelevant of the actual value. The chlorophyll bloom is defined statistically, as in other studies (Henson and Thomas, 2007; Follows and Dutkiewicz, 2002; Siegel et al., 2002). Given the presence of missing values and the large degree of variability in some areas, extra care should be taken to allow the algorithm to accommodate for “aberrant” cases and avoid false detections of the bloom initiation date.

The mean bloom initiation dates were obtained for each pixel (on the 1/4 degree grid) as follows:

1. The time-series running from the 1st week of May 1998 to the last week of April 2007 is extracted.

**BGD**

8, 4763–4804, 2011

### Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



2. The aberrant values (isolated spikes over the 99th percentile) are masked and discarded in the subsequent calculations.
3. The mean seasonal cycle is computed over the 9 yr analysed.
4. A 1-D Gaussian filter (with  $\sigma = 1$ ) is applied, effectively reducing the degree of intra-seasonal variability.
5. The median is calculated.
6. The filtered mean seasonal cycle is repeated and wrapped around itself. The bloom initiation date is subsequently constrained to fall between the seasonal minima's.
7. The date of the bloom initiation is determined as the first week of the year where the chlorophyll concentration reaches +5% above the median and stays above this value for at least 2 consecutive weeks.

The bloom initiation dates for each year (from 1998/1999 to 2006/2007) have also been calculated. In this case steps 3 and 6 are not applied. It has been verified that the bloom initiation date obtained from the average of the 9 yr is generally comparable to the one obtained from the mean seasonal cycle, albeit presenting a more noisy field given the sensitivity of the mean to extreme values and the short period considered.

Inter-annual variability in the bloom initiation date was calculated as the standard deviation of the bloom initiation dates for each of the 9 yr. Given the short sample, one must be cautious in interpreting this figure, as the presence of some extremes can lead to high standard deviations.

### 2.4 Variance explained by the seasonal cycle

The part of the overall variance that is explained by the seasonal cycle was computed as the variance explained by the regression of  $\log(\text{chlorophyll})$  onto a repetition of the

climatological mean seasonal cycle (calculated over the 9 available years) smoothed by a Gaussian filter of  $\sigma = 1$ . A value of 1 (100%) indicates that the time-series is a perfect repetition of the climatological mean seasonal cycle (i.e. there is no intra-seasonal or inter-annual variability) while a value of 0 means that there is no yearly cyclic component in the overall variability or no annually reproducible mean seasonal cycle.

## 2.5 Mixed Layer Depth (MLD)

MLD's have been taken from the monthly climatology developed by De Boyer-Montegut (2004). This global gridded product at  $2^\circ$  resolution is based on 4 490 571 individual temperature profiles obtained from the National Oceanographic Data Centre and the WOCE sections datasets, over the period 1941–2002. As the spatial and seasonal distribution of temperature profiles in the Southern Ocean is better than salinity profiles (De Boyer-Montegut et al., 2004) the MLD's were defined according to the optimal temperature criterion as a difference of 0.2 degrees with the temperature at 10 m.

## 2.6 Photosynthetically Active Radiation (PAR)

PAR is defined as the quantum energy flux from the sun in the spectral range 400 to 700 nm. PAR is expressed in Einstein  $\text{m}^{-2} \text{day}^{-1}$  (where 1 Einstein is equivalent to the energy of 1 mole of photons of monochromatic light). We used here the PAR generated by SeaWiFS and obtained through the GSFC. This dataset is provided on the same 9 km resolution grid as the chlorophyll estimates, for 8 day composites. The same period January 1998–December 2007 has been extracted and the values interpolated onto a regular  $1/4$  degree grid. SeaWiFS PAR values do not take into account any reflectance incurred at the air-sea interface and may therefore overestimate the amount of radiation entering the water column. Maximum reflectance during winter, when solar radiation is low, ranges from 11% at  $40^\circ \text{N}$  to 23% at  $70^\circ \text{N}$ . During the summer months however, the zenith angle has little effect on the amount of surface reflectance which

**BGD**

8, 4763–4804, 2011

## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





is generally between 4 and 7% at all latitudes (40–70°) and under all atmospheric and wind conditions (Campbell and Aarup, 1989).

### 3 Results and discussion

#### 3.1 Zonal characterization of seasonal biomass variability

5 Remote sensing derived chlorophyll distributions in the Southern Ocean south of 30° S reflect a zonal (annular) character of variability such as observed between frontal and pelagic zones as well as remarkable regional contrasts between the Atlantic and Pacific Oceans (Fig. 1a). These spatial zones also display important seasonal contrasts and inter-annual variability (Fig. 1a–c). While technically an estimate of pigment concentrations, we use SeaWiFS surface chlorophyll as a proxy for phytoplankton biomass (Sullivan et al., 1993; Comiso et al., 1993; Moore et al., 1999; Moore and Abbott, 2000, 2002). Satellite surface chlorophyll concentrations do not however take into account deep chlorophyll maxima or changes in the carbon to chlorophyll ratio (C:Chl-*a*) with depth. Although typical deep chlorophyll maxima in the subtropics may result in under-estimated satellite derived chlorophyll, typical chlorophyll profiles in the Southern Ocean are uniform in the upper mixed layer and decreases exponentially at greater depths (Arrigo et al., 2008). The lack of depth integrated chlorophyll distribution is thus unlikely to significantly effect satellite derived chlorophyll concentrations in the Southern Ocean. Changes in C:Chl-*a* are associated with physiological responses to changing light, temperature and nutrient conditions and are lowest at high temperatures (25–30°C), low irradiances (< 20 μmol photons m<sup>-2</sup> S<sup>-1</sup>) and nutrient replete conditions and increase at high irradiances, low temperature and nutrient limiting conditions (Taylor et al., 1997). Although seasonal variability in C:Chl-*a* ratios is significant at lower latitudes, the variations are relatively minor at higher latitudes when compared with the much larger seasonal range in chlorophyll concentration (Taylor et al., 1997). Although changes in C:Chl-*a* ratios need to be considered when using satellite sur-

### Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



face chlorophyll measurements as a proxy for biomass, existing data suggest that these intra-cellular C : Chl-*a* ratios do not play a significant role in the seasonal cycle in the Southern Ocean (Taylor et al., 1997). In addition, standard ocean colour algorithms typically underestimate chlorophyll in the Southern Ocean by 2–3 times compared to in situ measurements (Kahru and Mitchell, 2010). Underestimated chlorophyll concentrations are however unlikely to impact the characterisation of the patterns of the seasonal cycle which forms the primary focus of this paper.

In the subtropics, surface chlorophyll concentrations are low year round, except for a band of increased chlorophyll between 30° and 40° S in winter when nutrients are replenished (Fig. 1b). Surface chlorophyll concentrations in the Southern Ocean are low during the austral winter when light levels are low (Fig. 1b) (Mitchell et al., 1991; Veth et al., 1997; Lancelot et al., 2000; Smith et al., 2000; Boyd et al., 2001). Given the importance of Fe for photo-adaptation, Fe-light co-limitation is also likely (Sunda and Huntsman, 1997; Smith et al., 2000; Boyd et al., 2001). With the onset of a higher irradiance-mixing regime in spring, chlorophyll concentrations increase rapidly forming blooms (Fig. 1a). Basin-scale differences are also evident with chlorophyll concentrations in the Pacific being noticeably lower than the Atlantic and Indian, in particular in the zonal band of 40–50° S which disrupts the almost symmetrical distribution around Antarctica. This band shows very little seasonal difference between summer and winter chlorophyll concentrations (Fig. 1a and b).

Lowest summer chlorophyll concentrations are associated with the pelagic waters north of the sea ice zone (Fig. 1a) where production rates are limited by deep mixing of the upper mixed layer and trace metal limitation (Mitchell and Holm-Hansen, 1991; Boyd et al., 2000; Sokolov and Rintoul, 2007a). An exception to these low production waters is found at oceanic frontal zones (Fig. 1a). Enhanced chlorophyll concentrations associated with the major fronts of the ACC have been well documented and attributed to a number of processes that include cross-frontal mixing of macronutrients, an improved light environment through enhanced stratification and increased Fe concentrations through upwelling and interaction of the fronts with shallow topography

## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



(e.g., Lutjerharms et al., 1985; Perissinotto et al., 1992; Pollard and Regier et al., 1992; Laubscher et al., 1993; De Baar et al., 1995; Moore et al., 1999; Moore and Abbott, 2002). Although traditionally, enhanced chlorophyll concentrations have been associated with mesoscale activities at the position of the fronts, Sokolov and Rintoul (2007b) more recently revealed that multiple frontal branches delimit regions with similar elevated chlorophyll concentrations and seasonality rather than the fronts themselves being associated with enhanced productivity, at least where fronts are distant from topography.

Another exception to low production Southern Ocean waters is found over regions of shallow bathymetry; around and downstream of subantarctic islands, over mid-ocean ridges and large plateaus (Fig. 1a). In these regions of shallow bathymetry, current flow through relative vorticity (Hogg and Blundell, 2006; Moore et al., 1999) and/or bottom pressure torque (Sokolov and Rintoul, 2007a) is thought to increase the flux of Fe into surface waters (Korb and Whitehouse, 2004; Park et al., 2010; Venables and Meredith, 2010; Venables and Moore, 2010) accounting for the generally inverse correlation between depth and chlorophyll in the Southern Ocean (Comiso et al., 1993). Highest chlorophyll concentrations are generally associated with the marginal ice zone (MIZ) and the continental shelf (Fig. 1a) (Smith and Gordon, 1997; Moore and Abbott, 2000; Arrigo and Van Dijken, 2004), through enhanced irradiance from increased vertical stratification when ice melts (Smith and Nelson, 1986), through Fe input from melting ice (Sedwick and DiTullio, 1997; Gao et al., 2003; Grotti et al., 2005) and mixing of Fe rich sediments along the continental shelf (Schoemann et al., 1998; Johnson et al., 1999).

### 3.2 The seasonal cycle of chlorophyll in the Southern Ocean

The characteristics of the seasonal cycle of phytoplankton biomass in the Southern Ocean are examined in terms of the timing of the bloom initiation, its amplitude, inter-annual and intra-seasonal variability and the importance of the climatological seasonal cycle in explaining the overall variance. The spatial distribution of the seasonal cycle

## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



is subsequently defined to four zonal regions. The subtropical zone (STZ), the transition zone (TZ), the Antarctic circumpolar zone (ACZ) and the marginal ice zone (MIZ). The following section will describe the foundation for these zonal definitions based on seasonal characteristics rather than the distribution of chlorophyll concentrations, which has generally been the case in previous Southern Ocean studies. Defining the Southern Ocean according to the characteristics of its seasonal cycle provides a more dynamic understanding of the characterisation of production based on underlying physical drivers rather than climatological biomass.

The chlorophyll bloom is considered a key phase in the seasonal cycle of phytoplankton biomass. The circumpolar mean bloom initiation dates are depicted in Fig. 2. Unlike in the Arctic, where significant trends towards earlier blooms were detected in 11% of the area of the Arctic Ocean (Kahru et al., 2010), no homogenous regions showing distinct trends in either earlier or later bloom initiation dates were detected in the Southern Ocean, thus justifying the use of a 9 yr mean. In this study, the bloom initiation date has been associated with high biomass standing stocks and classified statistically according to an increase in chlorophyll concentration relative to the annual median (Henson and Thomas, 2007; Follows and Dutkiewicz, 2002; Siegel et al., 2002). This classification of a phytoplankton bloom is different to that of a recent study by Behrenfeld (2010), which classifies the bloom initiation according to the time when phytoplankton population net growth rate becomes positive (see also Boss and Behrenfeld, 2010). Their results, based on chlorophyll concentrations in the North Atlantic, found that bloom initiation occurred in mid-winter when light levels are minimal and near-surface mixing is deepest. Behrenfeld's dilution-recoupling hypothesis challenges Sverdrup's Critical Depth Hypothesis (Sverdrup, 1953) by de-emphasizing the role of light and instead suggests a much greater role for the balance between phytoplankton growth and losses through grazing. Although net population growth may increase in mid-winter, which according to Behrenfeld (2010) marks the start of the seasonal bloom, chlorophyll concentrations and specific growth rates are at their seasonal minimum. Our definition of the chlorophyll bloom on the other hand coincides with peaks

## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

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

in phytoplankton productivity, CO<sub>2</sub> uptake and carbon export, all of which are products of phytoplankton biomass and specific growth rates (Boss and Behrenfeld, 2010). The annual cycles of phytoplankton biomass in our results emphasize the role of bottom-up controls (light and nutrients) on increases in phytoplankton specific growth rates for determining bloom initiation (Sverdrup, 1953). The lack of information on growth rates does not allow us to quantify the role of grazing. In this study, we do not assume that the role of grazing is negligible, but rather that statistically significant seasonal increases in biomass can only occur when specific growth rates exceed loss terms and net population growth remains positive, despite potential increases in grazing pressure associated with increased encounter rates when the seasonal mixed layer shallows.

According to Fig. 2, bloom initiation in the STZ (~30–40° S), is characterized by an onset taking place in autumn (April–June) when macro-nutrients are replenished with the deepening of the seasonal mixed layer. This STZ is well defined in its latitudinal extent. North of ~30° S, insufficient heat loss in winter limits the breakdown of stratification and deep winter overturning to below the nutricline preventing winter increases in chlorophyll biomass. South of ~40° S, low winter PAR limits net primary productivity, preventing concomitant increases in winter chlorophyll concentrations, forcing phytoplankton populations towards spring bloom initiations (September–November). The transition between autumn and spring bloom initiations is remarkably abrupt (with the exception of the central and eastern Pacific where the transition is extended in latitude). The abrupt transition is indicative of a rapid shift from one seasonal regime to another, rather than a monotonic progression in the timing of the bloom initiation with increasing latitude. Further south is the MIZ where bloom initiation dates are in summer (December to February), reflecting the delay in seasonal PAR availability as well as the time it takes for phytoplankton blooms to fully respond to the newly created ice-free waters associated with the region (Arrigo et al., 2008).

While the bloom onset in the STZ is spatially homogeneous, the Southern Ocean (south of 40° S) is characterized by large spatial variability with bloom initiation dates that can occur as early as May (e.g., Crozet, ~45° S, 50° E) or as late as January (south

**BGD**

8, 4763–4804, 2011

## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



of Tasmania,  $\sim 42^\circ$  S,  $147^\circ$  E). The transition between zonally comparable regions of early and late bloom onset can be relatively abrupt: for example the region of early (September,  $100\text{--}140^\circ$  E) and late (December,  $130\text{--}170^\circ$  E) bloom development found south of Australia ( $50\text{--}55^\circ$  S) and the region of early onset evident north east of Crozet where the spring bloom starts particularly early in the year (May).

Regions with high inter-annual variability (std. dev.  $10\text{--}16$ ) in bloom initiation date (Fig. 3) correspond to transition regions between different seasonal regimes. In particular the transition between autumn and spring bloom initiation around  $\sim 40^\circ$  S. The boundaries of this region of high variability in bloom initiation define what we term the TZ. The remaining region of spring bloom initiation between the TZ and MIZ is what we term the ACZ. Other regions of high variability in bloom initiation similarly coincide with transition regions between different seasonal regimes, e.g. the region of late bloom initiation south of Australia ( $130\text{--}170^\circ$  E) and the transition between spring and summer bloom initiation at the confluence of the ACZ and MIZ which is particularly extended in the Atlantic and the western Indian Ocean sector ( $20^\circ$  W– $60^\circ$  E). Although the shift in mean bloom initiation date appears abrupt (Fig. 2), the TZ of high variability in bloom initiation dates is extended in latitude highlighting the discrepancy between climatological (Fig. 2) and annual time series (Fig. 3).

The percentage of the variance explained by the mean seasonal cycle (Fig. 4) defines how well the mean climatological seasonal cycle (from 9 yr) represents the evolution of chlorophyll over each year. Immediately apparent from this figure are the sharp gradients between strongly contrasting regions where the seasonal cycle for each year is coherent with the 9 yr mean (i.e. high seasonality;  $> 70\%$ ) compared to regions where there is large variability from year to year in the timing and amplitude of the bloom and only a low percentage of the variance is explained by the mean seasonal cycle (i.e. low seasonality;  $< 30\%$ ) (Fig. 4).

Despite the amplitude of the seasonal cycle in the STZ being weak ( $\sim 0$  to  $0.5\text{ mg m}^{-3}$ ) between summer minima and winter maxima, (see Fig. 1a and b) the overall variance of the chlorophyll signal is strongly phase locked to the mean seasonal

**BGD**

8, 4763–4804, 2011

## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



cycle (> 70 % of variance explained) (Fig. 4). An example of the time series of chlorophyll compared to the climatological mean seasonal in the STZ is shown in Fig. 5a. In this nutrient limited region, phytoplankton blooms occur in a predictable manner (std. dev. < 4, Fig. 3;  $R^2 = 91$ , Fig. 5a) when seasonal net heat loss and overturning in late autumn/early winter deepens the mixed layer to below the nutricline, relieving nutrient stress in surface waters and allowing phytoplankton production and biomass to increase. This finding agrees well with Dandonneau et al. (2004), who found low ratios of inter-annual to total variance from monthly SeaWiFS chlorophyll concentrations in the subtropical band between 1998 and 2001.

In the ACZ and MIZ, large regions of relatively high seasonality are also found, e.g. in the Pacific south of 50° S (~ 50 %), east of Kerguelen (~ 49° S, 70° E) (60–80 %) and a finer scale banded structure associated with the SAF zone and PF zone in the eastern Atlantic (50–70° S, 0–10° E) (Fig. 4). In regions with a high degree of seasonality (e.g. Fig. 5b and c;  $R^2 = 66$  and 64, respectively) one would expect that intra-seasonal forcing does not play a significant role in the phytoplankton seasonal cycle and that the annual time series would be almost entirely explained by the seasonal forcing of light, heat flux and seasonal MLD (as in the subtropics, e.g. Fig. 5a). This does not mean that Fe or light is not limiting but merely that it does not vary sufficiently on an intra-seasonal time scale to influence the inter-annual variability of the phytoplankton seasonal expression. In such instances one would expect there to be sufficient winter preconditioning of the water column with limiting nutrients (notably Fe) to allow a bloom initiation when the seasonal PAR threshold for increased primary production and biomass accumulation is met in spring. The amplitude of the seasonal bloom would depend on the supply of Fe via physical forcing mechanisms that include a) the seasonal re-supply of Fe through winter overturning, b) the depth of the summer mixed layer relative to the ferricline (deeper MLD's having higher Fe reserves), c) the amount of lateral advection of Fe into surface waters (e.g. downstream advection from continents and subantarctic islands) and d) the amount of Fe supplied by upwelling at fronts (e.g. Fig. 5b and c for low (~ 0.25 mg m<sup>-3</sup>) versus high (~ 1 mg m<sup>-3</sup>) summer

**BGD**

8, 4763–4804, 2011

## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



blooms, respectively). In these instances, the intra-seasonal re-supply of Fe to surface waters through wind mixing or mesoscale variability plays a less significant role in promoting phytoplankton growth, hence the low degree of intra-seasonal and inter-annual variability ( $R^2 = 66$  and  $R^2 = 66$ , Fig. 5b and c, respectively).

Regions of low seasonality (Fig. 4) generally correspond to regions of high variability in the phasing of the bloom initiation (Fig. 3). The zone of low variance explained by the mean seasonal cycle (< 20%) marks the TZ ( $\sim 40^\circ$  S). This region is particularly extensive in the Pacific ( $\sim 40$ – $50^\circ$  S), where chlorophyll concentrations are so low that the seasonal cycle is indistinguishable from intra-seasonal noise (e.g. Fig. 5d;  $R^2 = 27$ ). The transition between spring and summer bloom initiation at the ACZ and MIZ confluence also marks a region of low seasonality. At a smaller scale, transitions between regions of contrasting bloom initiation dates within the ACZ are also characterized by weak seasonality e.g. the region of low variance explained by the seasonal cycle corresponding to the region of late bloom initiation south of Australia.

Low seasonality related to the transition between regions of different bloom initiation is potentially related to the diversity of conditions encountered at the confluence between contrasting seasonal regimes. Transition regions of low seasonality are thought to be driven by a combination of multiple limiting factors and forcing mechanisms from both seasonal regimes. If there are too many factors simultaneously limiting phytoplankton production (e.g. nutrients and light), phytoplankton are not able to optimise to their environment, restricting the ability of the system to build up biomass. The expression of this will manifest as low annual chlorophyll concentrations with high inter-annual and intra-seasonal variability in bloom characteristics such as are found at the TZ in the Pacific (Figs. 4 and 5d).

Low seasonality (Fig. 4) does not however necessarily coincide with low chlorophyll concentrations (Fig. 1a). The TZ of low seasonality in the Atlantic and Indian has relatively high summer chlorophyll concentrations (e.g. Fig. 5e;  $R^2 = 44$ ; chlorophyll max =  $\sim 1 \text{ mg m}^{-3}$ ). Likewise, low seasonality regions surrounding the continental margins of Antarctica, America and Africa (Fig. 4) reflect high summer chlorophyll

**BGD**

8, 4763–4804, 2011

## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





concentrations (Fig. 1a). If our hypothesis for the low chlorophyll concentrations in the Pacific TZ holds true then there has to be a reduction in the number of factors simultaneously limiting production in regions of low seasonality but high chlorophyll. We propose that in these regions intra-seasonal physical forcing mechanisms are sequentially relieving light and/or nutrients at a frequency that is long enough to allow phytoplankton blooms to fully develop. At the latitudes of the continental margins of Africa and America for example, nutrients rather than light are considered the dominant limiting factor in summer. The upwelling of nutrients, particularly on eastern boundaries, through periodic wind events relieves nutrient stress on a sub-seasonal time scale. The period of sub-seasonal forcing must optimise growth in biomass at rates that exceed losses to account for the high integrated summer chlorophyll concentrations found here. The sub-seasonal wind events responsible for the upwelling and mixing of nutrients are likely to be responsible for the high intra-seasonal and inter-annual variability expressed as low seasonality. Along the continental margins of Antarctica on the other hand, elevated Fe associated with the continental shelf and ice melt (Fitch and Moore, 2007) makes light the dominant limiting factor. Intra-seasonal forcing of the interaction between a deepening of the MLD through wind mixing and the re-establishment of stratification through fresh water buoyancy, at adequate time scales, similarly accounts for the high chlorophyll concentrations but low seasonality found in this region.

The Supplement accompanying Figs. S1–4 elaborates on intra-seasonal and inter-annual variability (that result in either high or low seasonality) and complements the zonal characterisation of the Southern Ocean's seasonal cycle. Inter-annual and intra-seasonal variability in the STZ is low and consistent with a high degree of seasonality (Fig. 4), whereas in the TZ, inter-annual and intra-seasonal variability is particularly high and seasonality consequently weak. A well defined but short lived bloom is found in the ACZ, and although there is low variability in bloom initiation dates, inter-annual variability in the amplitude of the bloom is high. In the MIZ, variability in bloom initiation dates is low but both inter-annual and intra-seasonal variability in the chlorophyll seasonal cycle is high, leading to low seasonality.

## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

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

## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Although the fronts of the STF and ACC clearly influence the regional characterisation of the seasonal cycle of chlorophyll in the Southern Ocean (Figs. 1a, 2, 4), the physical forcing mechanisms responsible for enhanced chlorophyll (large scale flow versus small scale instabilities) are still unclear and need to be investigated further.

5 Sokolov and Rintoul (2007) propose that mean chlorophyll distribution (and seasonal cycle) is best explained by upwelling where the ACC interacts with topography, followed by downstream advection where flow-topography interactions drive upwelling of nutrients, independent of mesoscale instabilities. Fronts however are known to provide a source of buoyancy through mesoscale and sub-mesoscale instabilities which influence phytoplankton production through nutrient supply (upwelling) and light availability (stratification) (Swart and Speich, 2010; Kahru et al., 2007) as well as being zones of seasonal convergence. High resolution satellite imagery and model simulations now show that incorrect representation of sub-mesoscale frontogenesis can result in errors of up to 50% in primary production estimates (Levy et al., 2001; Glover et al., 15 2008). Despite the significant contribution of fronts to characterising both the spatial and seasonal distribution of chlorophyll in the Southern Ocean, the contrasting view points in the literature highlights the indeterminate role of the fronts in controlling phytoplankton production. These differences seem to depend on the light/Fe co-limitation regime that they are superimposed upon which in effect determines the physical forcing mechanism that is ultimately responsible for the observed variability in the chlorophyll seasonal cycle.

### 3.3 Mixed layer depth, irradiance and the phytoplankton seasonal cycle

As expected, mean MLD's for winter (August) are deeper than in summer (February) and present large spatial variability (Fig. 6a and b). In the Atlantic ( $\sim 20^{\circ}\text{E}$ – $20^{\circ}\text{W}$ ) and eastern Indian Ocean ( $\sim 60$ – $180^{\circ}\text{E}$ ), MLD's of  $> 200$  and  $> 300$  m respectively are found between  $\sim 40$  and  $50^{\circ}\text{S}$  in winter (Fig. 6a). Whereas in the Pacific in winter, ( $\sim 150$ – $70^{\circ}\text{W}$ ) MLD's of  $> 400$  m are found further south between  $\sim 50$  and  $60^{\circ}\text{S}$ . In the  $40$ – $50^{\circ}\text{S}$  latitudinal band, MLD's are relatively shallow ( $\sim 80$ – $140$  m) in winter

compared to similar latitudes in the Atlantic and Indian (Fig. 6a). MLD's in summer present a more zonally coherent distribution, with MLD's shallower than  $\sim 50$  m observed north of  $40^\circ$  S and south of  $60^\circ$  S, with MLD's of 80–120 m in between (Fig. 6b).

The chlorophyll concentration at the sea surface generally responds to the seasonal cycle of solar radiation which strongly impacts vertical stability through net heat flux, influencing vertical nutrient supply and the timing and intensity of phytoplankton blooms (Dandonneau et al., 2004). A first order estimate of the large-scale relationship between the seasonal cycles of MLD and chlorophyll (Fig. 7) can therefore be used to improve our understanding of the transition between different seasonal regimes.

Consistent with our understanding of the subtropics as a nutrient-limited regime, the correlation in the STZ is uniformly positive ( $> 0.8$ ), with increased chlorophyll associated with of the deepest winter MLD's. High chlorophyll concentrations coinciding with deep MLD's in the subtropics are likely enhanced by photoadaptation of light limited cells in the deep winter mixed layer (Letelier et al., 1993).

The transition between a positive and negative correlation (Fig. 7) corresponds remarkably well to the transition between winter and summer centred seasonal cycles (Fig. 2) reflecting the sharp climatological change in physical control mechanisms. Negative correlations are evident in the ACZ and MIZ, consistent with a light limited regime where increased chlorophyll concentrations coincide with shallow MLD's. A shoaling of the MLD provides the required light environment for phytoplankton production favouring increases in specific growth rates that exceeds export and losses through grazing and results in biomass accumulation (Sverdrup, 1953; Mitchell et al., 1991a; Comiso et al., 1993). However, in these high latitudes, low light (PAR) environments, the relationship is more convoluted than in the subtropics, with areas of low and in some instances slightly positive correlations (e.g., Crozet) interspersed among the general trend of a negative correlation. This “patchy” appearance is indicative of maximum seasonal chlorophyll concentrations that are not uniformly phased with the timing of minimum MLD's. Unlike in the subtropics, where a simple overturning threshold initiates the seasonal cycle, the physical forcing mechanisms of the mixed layer

**BGD**

8, 4763–4804, 2011

## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



dynamics in the Southern Ocean are more varied and complex, as are the requirements to promote phytoplankton growth. Although the prevailing negative correlation between MLD and surface chlorophyll suggests that light is more important in limiting production in the subantarctic (relative to the subtropics), the Southern Ocean is also nutrient limited, in particular with regards to Fe and Si (Boyd et al., 2002). The prolonged persistence of a shallow mixed layer can in some cases lead to nutrient limitation of primary production such that a periodic intra-seasonal deepening of the mixed layer (allowing Fe re-supply), at time scales of the same order as the phytoplankton growth rate, is necessary to maintain production rates at high levels throughout the summer season (Pasquero et al., 2005). In such instances, phytoplankton population growth rates are able to exceed their losses resulting in a well defined seasonal phytoplankton bloom (the integrated effect of localised sub-seasonal blooms) that does not coincide with the shallowest MLD's.

Changes in the mixed layer result from the interaction of turbulent mixing, through wind stress, and buoyancy forcing, through air/sea heat fluxes, fresh water fluxes, entrainment and advection (geostrophic and Ekman). These two drivers (turbulent mixing and buoyancy forcing) compete to either strengthen stratification or destroy it. We propose that the complex nature of the controls on stratification and production in the Southern Ocean plays an instrumental role in the expression of seasonal, sub-seasonal and regional variability in chlorophyll concentrations and the seasonal cycle.

### 3.4 Basin scale meridional controls of the seasonal cycle

The zonally asymmetric nature of the seasonal cycle of chlorophyll in the Southern Ocean provides the impetus for basin scale comparisons in addition to zonal characterisation. This asymmetry was similarly noted in the response of the MLD to the SAM by Salle et al. (2009). From a heat budget of the mixed layer they conclude that meridional winds associated with the departure of the SAM from zonal symmetry causes anomalies in heat flux and MLD which has consequences for biological productivity. In the following section, particular emphasis is given to basin scale comparisons in order

## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



to more accurately characterise regional differences in the phasing of the chlorophyll bloom with respect to MLD's. The seasonal progression of chlorophyll anomalies with respect to the annual mean were plotted with mean MLD's for three transects, one in each of the ocean basins (Fig. 8a–c).

For each of the three transects a similar latitudinal progression in seasonal characteristics of the chlorophyll bloom is evident (Fig. 8a–c). In the STZ to the north maximum chlorophyll concentrations are in winter spanning August to October in the Atlantic (Fig. 8a), July to September in the Indian (Fig. 8b) and June to September in the Pacific (Fig. 8c), coincident with maximum winter MLD's (50–30 m). Minimum chlorophyll concentrations occur in late summer (January to March) when MLD's are shallow (20–50 m). There is a southward extension of the STZ in the Pacific ( $\sim 30\text{--}40^\circ\text{S}$ ) relative the Atlantic and Indian ( $\sim 30\text{--}35^\circ\text{S}$ ). Further south, in the ACZ, the phasing of the chlorophyll bloom switches to one in which maximum concentrations are centred around the summer months (November to January), following the shoaling of the winter mixed layer ( $< 70\text{ m}$ ). In the MIZ bloom initiation occurs one month later (Fig. 2) with maximum concentrations extend into autumn (March) coinciding with shallowest MLD's (30–40 m). The presence of the Weddell Gyre in the Atlantic transect (Fig. 8a) broadens the latitudinal extent of the MIZ ( $\sim 57\text{--}70^\circ\text{S}$ ) compared to the Indian ( $\sim 60\text{--}65^\circ\text{S}$ ) and Pacific ( $\sim 70\text{--}75^\circ\text{S}$ ) (Fig. 8b and c).

Besides the comparable characteristics in latitudinal progression of the seasonal cycle, inter-ocean basin differences are also evident. The Atlantic and Indian transects (Fig. 8a and b) are characterised by a relatively rapid TZ ( $\sim 35\text{--}40^\circ\text{S}$ ), the northern boundary of the summer bloom region of the ACZ occurring at  $\sim 37^\circ\text{S}$  and  $\sim 43^\circ\text{S}$ , respectively. In the Pacific transect (Fig. 8c); the TZ between winter and summer centred seasonal regimes is extended in latitude to  $\sim 10$  degrees ( $40\text{--}50^\circ\text{S}$ ), with distinct summer bloom characteristics only evident south of  $49^\circ\text{S}$ . The latitudinal transition to a summer bloom regime coincides with the northernmost expression of the deepest winter MLD's i.e. 130 m in the Atlantic ( $42^\circ\text{S}$ ), 300 m in the Indian ( $43^\circ\text{S}$ ) and 250 m in the Pacific ( $49^\circ\text{S}$ ). Although the mechanism responsible for the absence of a deep

**BGD**

8, 4763–4804, 2011

## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



winter mixed layer in the 40–50° S latitudinal band in the Pacific (90–100 m) is unclear (see also Fig. 6a), it is likely that an additional sustained input of buoyancy (e.g. additional heat source from southward penetrations of subtropical water) prevents the deepening of the mixed layer in winter to depths comparable to those of the Atlantic and Indian (130 and 250 m, respectively).

Intuitively, the Pacific, when compared to the Atlantic and Indian, has a potentially lower Fe supply to surface waters through the lack of continental or subantarctic island and sub-ocean land mass and lower mesoscale eddy activity from a lack of bathymetry to interact with the mean flow. Increased eddy kinetic energy associated with such features, enhances the sub-surface flux of Fe into surface waters, potentially enhancing phytoplankton growth (Hense et al., 2000; Moore et al., 1999; Sokolov and Rintoul, 2007a; Park et al., 2010). If the main source of Fe to the surface waters (73–99 %) of the Southern Ocean is through upwelling (Johnson et al., 1997; Lefevre and Watson, 1999; Archer and Johnson, 2000), one can deduce that in the Pacific, where Fe supply to surface waters through deep water entrainment is limited, shallow winter mixed layers are unlikely to be deep enough to entrain sufficient Fe into the surface waters for stimulating and maintaining high production rates through the summer. Hence, the extended (35–49° S) low chlorophyll TZ in the Pacific, with high variability and low seasonality likely results from Fe limitation.

## 4 Synthesis

Characterising the Southern Ocean according to the variability of the seasonal cycle provides a more dynamic understanding of the spatial heterogeneity of production based on underlying physical drivers rather than mean climatological biomass. Based on our analysis of the timing, variability and seasonality of seasonal chlorophyll distributions, we defined the spatial distribution of the seasonal cycle into four zonal regions: (1) the STZ (~ 30–35 or 40° S), characterised by an autumn bloom initiation (Fig. 2), low inter-annual and intra-seasonal variability and high seasonality (Fig. 4); (2) The TZ

**BGD**

8, 4763–4804, 2011

### Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



of high variability in bloom initiation dates (centred around  $\sim 40^\circ$  S) (Fig. 3), where inter-annual and intra-seasonal variability is also high and seasonality consequently weak (Fig. 4); (3) The ACZ (south of the TZ) where bloom initiations are generally in spring (Fig. 2), inter-annual variability in bloom initiation dates is low (Fig. 3) and large areas of both high and low seasonality are found (Fig. 4), and (4) The (MIZ) where bloom initiations are in summer (Fig. 2), variability in bloom initiation dates is low (Fig. 3) but inter-annual and intra-seasonal variability in the chlorophyll seasonal cycle is high, leading to low seasonality (Fig. 4).

This zonal classification effectively characterises the variability of the seasonal cycle in the Southern Ocean. However, when the response of the biology to the underlying physics of the different seasonal regimes was taken into consideration (i.e. low versus high seasonal chlorophyll maxima), an additional classification system was required. In order to summarise the varying responses of the phytoplankton community to the different seasonal regimes, we created a schematic that divides the Southern Ocean into a montage of four regions in addition to the four seasonal zones (Fig. 9). This schematic is created from a composite of the mean summer chlorophyll concentration from November to January (1998–2007) and the variance explained by the seasonal cycle (Fig. 4). The four regions result from a combination of high or low chlorophyll concentration and high or low seasonality. No allowance has been made for intermediate chlorophyll concentrations or seasonality, and as a consequence the boundaries between regions are not definitive. This needs to be taken into consideration when interpreting this figure which is intended as a support to a conceptual framework on the nature of the controls of variability in the phytoplankton seasonal cycle.

Region A is representative of a nutrient limited regime with low chlorophyll concentrations but high seasonality. In Region A, in the STZ ( $30\text{--}40^\circ$  S), nutrients (in particular  $\text{NO}_3$ ) are limited throughout the summer months and it is only when the mixed layer deepens in autumn that nutrient stress in surface waters is relieved, allowing phytoplankton production and biomass to increase. Similarly, Region A in the low chlorophyll pelagic waters of the Southern Ocean (north of the MIZ, away from fronts and shallow

**BGD**

8, 4763–4804, 2011

## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



---

## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



topographic features) is also nutrient limited. Winter overturning re-supplies limiting surface nutrients (in particular Fe) to support an increase in phytoplankton growth, but only in spring when light levels are sufficient. In these regions, the available nutrients are rapidly used up by the phytoplankton community and the bloom subsequently declines when community losses outweigh growth rates. Despite the amplitude of the seasonal cycle in these regions being weak, the overall variability of the chlorophyll signal is strongly phase-locked to the annual seasonal cycle. In these regions, no sub-seasonal forcing of the mixed layer to below the nutricline is replenishing surface nutrients on intra-seasonal time scales, which accounts for the low intra-seasonal and inter-annual variability and a predictable seasonal cycle (high seasonality).

The second region with low chlorophyll concentrations (Region B) is also characterised by low Fe concentrations but this region displays low seasonality. This region is particularly extensive in the Pacific where increased positive buoyancy forcing potentially prevents the deepening of the winter mixed layer to below the ferricline, thus failing to re-set the seasonal Fe supply. If the winter re-supply of Fe to surface waters is insufficient and/or the depth of the ferricline is below the deepest summer MLD's then phytoplankton lack the potential to significantly increase their biomass during the summer season through Fe limitation. These regions are characterised by chlorophyll concentrations that are so low and intra-seasonal variability so high that the seasonal cycle is indistinguishable from intra-seasonal noise.

The last two regions refer to areas of high chlorophyll but with either a low (Region C) or high (Region D) seasonality. Regions of high chlorophyll in the Southern Ocean result from integrated seasonal primary production that exceeds community losses and according to the literature results from the relief of Fe stress at ocean fronts, over shallow bathymetry, along continental margins and in the MIZ (e.g., Boyd et al., 2002). The different seasonal expressions of high and low seasonality, however implies distinct physical supply mechanisms of Fe and light to the surface waters.

In the high chlorophyll, high seasonality regions (Region C), intra-seasonal forcing of the nutrient and light regime is not the dominant mechanism responsible for enhanced



## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



summer chlorophyll. In these regions, the annual time series is almost entirely explained by the seasonal forcing of light, heat flux and seasonal MLD (as in the subtropics). This is not to say that Fe or light is not a limiting factor but merely that it does not vary sufficiently on an intra-seasonal time scale to influence the inter-annual variability of the phytoplankton seasonal expression. In such instances sufficient winter preconditioning of the water column with limiting nutrients is required in order to allow a spring bloom initiation. The integrated seasonal amplitude of the bloom would depend on the amount of Fe made available through winter overturning, the depth of the summer mixed layer relative to the nutricline, lateral advection of Fe into surface waters and upwelling at fronts.

In regions of high chlorophyll but low seasonality (Region D), the seasonal characteristics of high inter-annual and intra-seasonal variability are controlled by sub-seasonal forcing of the nutrient and light supply. In these regions, we hypothesize that high integrated summer chlorophyll concentrations are a direct consequence of high intra-seasonal physical forcing of the MLD at appropriate time scales (Pasquero et al., 2005). In these regions, shallow MLD's likely lead to short term depletions of surface nutrients such that a periodic deepening of the ML (to below the nutricline) is necessary for phytoplankton population growth to occur. This high intra-seasonal variability culminates from a combination of high wind stress variability at appropriate time scales and upper water column stabilisation through positive buoyancy forcing via mesoscale dynamics and fresh water (ice melt) fluxes.

Although the fronts of the STF and ACC clearly influence the regional characterisation of the seasonal cycle of chlorophyll in the Southern Ocean, the physical forcing mechanisms responsible for enhanced chlorophyll (large scale flow versus small scale instabilities) are still unclear and need to be investigated further.

The relevance of this more dynamic characterisation of Southern Ocean production is that it may contribute towards an improved understanding of the variability of regional sensitivity to climate forcing. The seasonal cycle is the most important mode of variability in climate change making it likely that long term trends will be reflected sensitively

through changes in the characteristics of the seasonal cycle. A better understanding of the regional sensitivities of the Southern Oceans biological pump to climate change will allow us to make more robust predictions of long term trends.

**Supplementary material related to this article is available online at:**

**[http://www.biogeosciences-discuss.net/8/4763/2011/  
bgd-8-4763-2011-supplement.pdf](http://www.biogeosciences-discuss.net/8/4763/2011/bgd-8-4763-2011-supplement.pdf)**

*Acknowledgements.* This work was undertaken and supported through the Southern Ocean Carbon – Climate Observatory (SOCCO) Programme. S. J. Thomalla and S. Swart were supported through SOCCO post doctoral fellowships funded by ACCESS and NRF/SANAP. P. M. S. Monteiro and N. Fauchereau were supported by CSIR's Parliamentary Grant.

## References

- Archer, D. E. and Johnson, K.: A model of the iron cycle in the ocean, *Global Biogeochem. Cy.*, 14, 269–279, 2000.
- Arrigo, K. R. and van Dijken, G. L.: Annual changes in sea-ice, chlorophyll a, and primary production in the Ross Sea, Antarctica, *Deep-Sea Res. Pt. II*, 51, 117–138, 2004.
- Arrigo, K. R., van Dijken, G. L., and Bushinsky, S.: Primary production in the Southern Ocean, 1997–2006, *J. Geophys. Res.*, 113, C08004, doi:10.1029/2007JC004551, 2008.
- Banse, K.: Low seasonality of low concentrations of surface chlorophyll in the Subantarctic water ring: underwater irradiance, iron or grazing?, *Prog. Oceanogr.*, 37, 241–91, 1996.
- Behrenfeld, M. J.: Abandoning Sverdrup's critical depth hypothesis, *Ecology*, 91, 977–989, doi:10.1890/09-1207.1, 2010.
- Blain, S., Queguiner, B., Armand, L., Belviso, S., Bombled, B., Bopp, L., Bowie, A., Brunet, C., Brussaard, C., Carlotti, F., Christaki, U., Corbiere, A., Durand, I., Ebersbach, F., Fuda, J., Garcia, N., Gerringa, L., Griffiths, B., Guigue, C., Guillerm, C., Jacquet, S., Jeandel, C., Laan, P., Lefevre, D., Lo Monaco, C., Malits, A., Mosseri, J., Obernosterer, I., Park, Y., Picheral, M., Pondaven, P., Remenyi, T., Sandroni, V., Sarthou, G., Savoye, N., Scouarnec, L., Souhaut, M., Thuiller, D., Timmermans, K., Trull, T., Uitz, J., van Beek, P., Veldhuis, M., Vin-

**BGD**

8, 4763–4804, 2011

## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- cent, D., Viollier, E., Vong, L., and Wagener, T.: Effect of natural iron fertilization on carbon sequestration in the Southern Ocean, *Nature*, 446, 1070–1074, 2007.
- Böning, C. W., Dispert, A., Visbeck, M., Rintoul, S. R., and Schwarzkopf, F.: The response of the Antarctic Circumpolar Current to recent climate change, *Nat. Geosci.*, 1, 864–869, 2008.
- 5 Boss, E. and Behernfeld, M.: In situ evaluation of the initiation of the North Atlantic phytoplankton bloom, *Geophys. Res. Lett.*, 37, L18603, doi:10.1029/2010GL044174, 2010.
- Boyd, P. W.: Environmental factors controlling phytoplankton processes in the Southern Ocean, *J. Phycol.*, 38, 844–861, 2002.
- Boyd, P. W., Watson, A., Law, C. S., Abraham, E., Trull, T., Murdoch, R., Bakker, D. C. E.,  
 10 Bowie, A. R., Charette, M., Croot, P., Downing, K., Frew, R., Gall, M., Hadfield, M., Hall, J., Harvey, M., Jameson, G., La Roche, J., Liddicoat, M., Ling, R., Maldonado, M., McKay, R. M., Nodder, S., Pickmere, S., Pridmore, R., Rintoul, S., Safi, K., Sutton, P., Strzepek, R., Tanneberger, K., Turner, S., Waite, A., and Zeldis, J.: A mesoscale phytoplankton bloom in the polar Southern Ocean stimulated by iron fertilization, *Nature*, 407, 695–702, 2000.
- 15 Boyd, P. W., Crossley, A. C., DiTullio, G. R., Griffiths, F. B., Hutchins, D. A., Queguiner, B., Sedwick, P. N., and Trull, T. W.: Effects of iron supply and irradiance on phytoplankton processes in subantarctic waters south of Australia, *J. Geophys. Res.*, 106, 31573–31584, 2001.
- de Boyer Montégut, C., Madec, G., Fischer, A. S., Lazar, A., and Iudicone, D.: Mixed layer depth over the global ocean: an examination of profile data and a profile-based climatology, *J. Geophys. Res.*, 109, C12003, doi:10.1029/2004JC002378, 2004.
- 20 Caldeira, K. and Duffy P. B.: The role of the Southern Ocean in uptake and storage of anthropogenic carbon dioxide, *Science*, 87, 620–622, doi:10.1126/Science. 287.5453.620, 2000.
- Campbell, J. W.: The lognormal distribution as a model for bio-optical variability in the sea, *J. Geophys. Res.*, 100, 13237–13254, 1995.
- 25 Campbell, J. W. and Aarup, T.: Photosynthetically available radiation at high latitudes, *Limnol. Oceanogr.*, 34, 1490–1499, 1989.
- Comiso, J. C., McClain, C. R., Sullivan, C. W., Ryan, J. P., and Leonard, C. L.: Coastal zone color scanner pigment concentrations in the Southern Ocean and relationships to geophysical surface features, *J. Geophys. Res.*, 98, 2419–2451, 1993.
- 30 Cullen, J. J.: Hypotheses to explain high-nutrient conditions in the open sea, *Limnol. Oceanogr.*, 36, 1578–1599, 1991.
- Davidson, I. R.: Environmental effects on algal photosynthesis: temperature, *J. Phycol.*, 27,

2–8, 1991.

De Baar, H. J. W., De Jong, J. T. M., Bakker, D. C. E., Loscher, B. M., Veth, C., Bathmann, U., and Smetacek, V.: Importance of iron for plankton blooms and carbon dioxide draw-down in the Southern Ocean, *Nature*, 373, 412–415, 1995.

5 Dandonneau, Y., Deschamps, P. Y., Nicolas, J. M., Loisel, H., Blanchot, J., Montel, Y., Thieuleux, F., and Becu, G.: Seasonal and interannual variability of ocean color and composition of phytoplankton communities in the North Atlantic, equatorial Pacific and South Pacific, *Deep-Sea Res. Pt. II*, 51, 303–318, 2004.

10 Fitch, D. T. and Moore, J. K.: Wind speed influence on phytoplankton bloom dynamics in the Southern Ocean Marginal Ice Zone, *J. Geophys. Res.*, 112(C8), C08006, doi:10.1029/2006JC004061, 2007.

Follows, M. and Dutkiewicz, S.: Meteorological modulation of the North Atlantic spring bloom, *Deep-Sea Res. Pt. II*, 49, 321–344, 2002.

15 Gao, Y., Fan, S., and Sarmiento, J. L.: Aeolian iron input to the ocean through precipitation scavenging: a modeling perspective and its implication for natural iron fertilization in the ocean, *J. Geophys. Res.*, 108, D7, 4221, doi:10.1029/2002JD002420, 2003.

Gervais, F., Riebesell, U., and Gorbunov, M. Y.: Changes in primary productivity and chlorophyll-*a* in response to iron fertilization in the Southern Polar Frontal Zone, *Limnol. Oceanogr.*, 47, 1324–1335, 2002.

20 Gille, S. T.: Decadal-scale temperature trends in the Southern Hemisphere ocean, *J. Climate*, 21, 4749–4765, 2008.

Glover, D. M., Doneym S. C., Nelsonm N. B., and Wallis, A.: Submesoscale anisotropy (fronts, eddies, and filaments) as observed near Bermuda with ocean color data, presented at Ocean Science Meet., Orlando, 25–27 March, 2008.

25 Grotti, M., Francesco, S., Carmela, I., and Roberto, F.: Trace metals distributions in coastal sea ice of Terra Nova Bay, Ross Sea, Antarctica, *Antarct. Sci.*, 17, 290–300, 2005.

Hense, I., Bathmann, U. V., and Timmermann, R.: Plankton dynamics in frontal systems of the Southern Ocean, *J. Marine Syst.*, 27(1–3), 235–252, doi:10.1016/S0924-7963(00)00070-1, 2000.

30 Henson, S. A. and Thomas, A. C.: Interannual variability in timing of bloom initiation in the California Current System, *J. Geophys. Res.*, 112, C08007, doi:10.1029/2006JC003960, 2007.

Hogg, A. M. and Blundell, J. R.: Interdecadal variability of the Southern Ocean, *J. Phys.*

**BGD**

8, 4763–4804, 2011

---

## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Oceanogr., 36, 1626–1645, 2006.

Johnson, K. S., Gordon, R. M., and Caole, K. H.: What controls dissolved iron concentrations in the world ocean?, *Mar. Chem.*, 57, 137–161, 1997.

Johnson, K. S., Chavez, F. P., and Friederich, G. E.: Continental-shelf sediment as a primary source of iron for coastal phytoplankton, *Nature*, 398, 697–700, 1999.

Kahru, M. and Mitchell, B. G.: Blending of ocean colour algorithms applied to the Southern Ocean, *Remote Sensing Letters*, 1, 119–124, 2010.

Kahru, M., Mitchell, B. G., Gille, S. T., Hewes, C. D., and Holm-Hansen, O.: Eddies enhance biological production in the Weddell-Scotia Confluence of the Southern Ocean, *Geophys. Res. Lett.*, 34(14), L14603, doi:10.1029/2007GL030430, 2007.

Kahru, M., Brota, V., Manzano-Sarabia, M., and Mitchell, B. G.: Are phytoplankton blooms occurring earlier in the Arctic? *Glob. Change Biol.*, 17, 4, 1733–1739 doi:10.1111/j.1365-2486.2010.02312.x, 2010.

Korb, R. E. and Whitehouse, M.: Contrasting primary production regimes around South Georgia, Southern Ocean: large blooms versus high nutrient, low chlorophyll waters, *Deep-Sea Res. Pt. I*, 51(5), 721–738, doi:10.1016/j.dsr.2004.02.006, 2004.

Lancelot, C., Hannon, E., Becquevort, S., Veth, C., and De Baar, H. J. W.: Modelling phytoplankton blooms and carbon export production in the Southern Ocean: dominant controls by light and iron in the Atlantic sector in Austral spring 1992, *Deep-Sea Res. Pt. I*, 47, 1621–1662, 2000.

Laubscher, R. K., Perisinotto, R., and Mcquaid, C. D.: Phytoplankton production and biomass at frontal zones in the Atlantic sector of the Southern Ocean, *Polar Biol.*, 13, 471–481, 1993.

Lefèvre, N. and Watson, A. J.: Modeling the geochemical cycle of iron in the oceans and its impact on atmospheric CO<sub>2</sub> concentrations, *Global Biogeochem. Cy.*, 13(3), 727–736, 1999.

Le Quere, C., Raupach, M. R., Canadell, J. G., Marland, G., Bopp, L., Ciais, P., Conway, T. J., Doney, S. C., Feely, R. A., Foster, P., Friedlingstein, P., Gurney, K., Houghton, R. A., House, J. I., Huntingford, C., Levy, P. E., Lomas, M. R., Majkut, J., Metzl, N., Ometto, J.P., Peters, G.P., Prentice, I.C., Randerson, J. T., Running, S. W., Sarmiento, J. L., Schuster, U., Sitch, S., Takahashi, T., Viovy, N., van der Werf, G. R., and Woodward, F. I.: Trends in the sources and sinks of carbon dioxide, *Nat. Geosci.*, 12, 831–836, 2009.

Letelier, R. M., Bidiare, R. R., Hebel, D. V., Ondrusek, M., Winn, C. D., and Karl, D. M.: Temporal variability of phytoplankton community structure based on pigment analysis, *Limnol. Oceanogr.*, 38, 1420–1437, 1993.

## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Le Traon, P. Y. and Ogor, F.: ERS-1/2 orbit improvement using TOPEX/POSEIDON: the 2 cm challenge, *J. Geophys. Res.*, 103(C4), 8045–8057, 1998.
- Levitus, S., Conkright, M. E., Reid, J. L., Najjar, R. G., and Mantyla, A.: Distribution of nitrate, phosphate and silicate in the world ocean, *Prog. Oceanogr.*, 31, 245–273, 1993.
- 5 Lévy, M, Klein, P., and Treguier, A. M.: Impacts of sub-mesoscale physics on phytoplankton production and subduction, *J. Mar. Res.*, 59, 535–565, doi:10.1357/002224001762842181, 2001.
- Lutjeharms, J. R. E., Walters, N. M., and Allanson, B. R.: Oceanic frontal systems and biological enhancement, in: *Antarctic Nutrient Cycles and Food Webs*, edited by: Siegfried, W. R.,  
10 Condy, P. R., and Laws, R. M., Springer-Verlag, Berlin, 11–21, 1985.
- Martin, J. H., Fitzwater, S., and Gordan, R. M.: Iron deficiency limits phytoplankton growth in Antarctic waters, *Global Biogeochem. Cy.*, 4, 5–13, 1990.
- McClain, C. R., Cleave, M. L., Feldman, G. C., Gregg, W. W., Hooker, S. B., and Kuring, N.: Science quality SeaWiFS data for global biosphere research, *Sea Technol.*, 39(9), 10–16,  
15 1998.
- Minas, H. J. and Minas, M.: Net community production in “high nutrient–low chlorophyll” waters of the tropical and Antarctic Oceans: grazing vs. iron hypothesis, *Oceanol. Acta*, 15, 145–162, 1992.
- Mitchell, B. G. and Holm-Hansen, O.: Bio-optical properties of Antarctic Peninsula waters: Differentiation from temperate ocean models, *Deep-Sea Res.*, 38, 1009–1028, 1991.
- 20 Mitchell, B. G., Brody, E. A., Holm-Hansen, O., McClain, C., and Bishop, J.: Light limitation of phytoplankton biomass and macronutrient utilization in the Southern Ocean, *Limnol. Oceanogr.*, 36, 1662–1677, 1991.
- Moore, J. K. and Abbott, M. R.: Phytoplankton chlorophyll distributions and primary production in the Southern Ocean, *J. Geophys. Res.*, 105(C12), 28709–28722, doi:10.1029/1999JC000043, 2000.
- 25 Moore, J. K. and Abbott, M. R.: Surface chlorophyll concentrations in relation to the Antarctic Polar Front: seasonal and spatial patterns from satellite observations, *J. Marine Syst.*, 37, 69–86, 2002.
- 30 Moore, J. K. and Doney, S. C.: Remote sensing observations of ocean physical and biological properties in the region of the Southern Ocean Iron Experiment (SOFeX), *J. Geophys. Res.*, 111, C06026, doi:10.1029/2005JC003289, 2006.
- Moore, J. K., Abbott, M. R., and Richman, J. G.: Location and dynamics of the Antarctic Polar

---

## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Front from satellite sea surface temperature data, *J. Geophys. Res.*, 104, 3059–3073, 1999.
- Nelson, D. M. and Smith, W. O.: Sverdrup re-visited: critical depths, maximum chlorophyll levels, and the control of Southern Ocean productivity by the irradiance-mixing regime, *Limnol. Oceanogr.*, 36, 1650–1661, 1991.
- 5 Park, J., Oh, I., Kim, H., and Yoo, S.: Variability of SeaWiFs chlorophyll-*a* in the Southwest Atlantic sector of the Southern Ocean: strong topographic effects and weak seasonality, *Deep-Sea Res. Pt. I*, 57, 604–620, 2010.
- Pasquero, C., Bracco, A., and Provenzale, A.: Impact of the spatiotemporal variability of the nutrient flux on primary productivity in the ocean, *J. Geophys. Res.*, 110, C07005, doi:10.1029/2004JC002738, 2005.
- 10 Perissinotto, R., Laubscher, R. K., and McQuaid, C. D.: Marine productivity enhancement around Bouvet and the South Sandwich Islands (Southern Ocean), *Mar. Ecol.-Prog. Ser.*, 88, 41–53, 1992.
- Pollard, R. T. and Regier, L. A.: Vorticity and vertical circulation at an ocean front, *J. Phys. Oceanogr.*, 22, 609–625, 1992.
- 15 Pollard, R., Sanders, R., Lucas, M., and Statham, P.: The Crozet natural iron bloom and export experiment (CROZEX), *Deep-Sea Res. Pt. II*, 54, 1905–1914, 2007.
- Price, N. M., Ahner, B. A., and Morel, F. M. M.: The equatorial Pacific Ocean: grazer-controlled phytoplankton populations in an iron-limited ecosystem, *Limnol. Oceanogr.*, 39, 520–534, 1994.
- 20 Raven, J. A. and Geider, R. J.: Temperature and algal growth, *New Phytol.*, 110, 441–461, 1988.
- Rio, M. and Hernandez, F.: A mean dynamic topography computed over the world ocean from altimetry, in situ measurements, and a geoid model, *J. Geophys. Res.*, 109, C12032, doi:10.1029/2003JC002226, 2004.
- 25 Russell, J. L., Dixon, K. W., Gnanadesikan, A., Stouffer, R. J., and Toggweiler, J. R.: The Southern Hemisphere westerlies in a warming world: propping open the door to the deep ocean, *J. Climate*, 19, 6382–6390, 2006.
- Sarmiento, J. L., Hughes, T. M. C., Stouffer, R. J., and Manabe, S.: Simulated response of the ocean carbon cycle to anthropogenic climate warming, *Nature*, 393, 245–249, 1998.
- 30 Sarmiento, J. L., Gruber, N., Brzezinski, M. A., and Dunne, J. P.: High-latitude controls of thermocline nutrients and low latitude biological productivity, *Nature*, 427, 56–60, doi:10.1038/nature02127, 2004.

---

## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Schlitzer, R.: Carbon export fluxes in the Southern Ocean: results from inverse modelling and comparison with satellite-based estimates, *Deep-Sea Res. Pt. II*, 49, 1623–1644, 2002.
- Sedwick, P. N. and DiTullio, G. R.: Regulation of algal blooms in Antarctic shelfwater by the release of iron from melting sea ice, *Geophys. Res. Lett.*, 24, 2515–2518, 1997.
- 5 Siegel, D. A., Doney, S. C., and Yoder, J. A.: The North Atlantic spring phytoplankton bloom and Sverdrup's critical depth hypothesis, *Science*, 296(5568), 730–733, 2002.
- Sigman, D. M. and Boyle, E. A.: Glacial/Interglacial variations in atmospheric carbon dioxide, *Nature*, 407, 859–869, 2000.
- Sokolov, S. and Rintoul, S. R.: Multiple jets of the Antarctic circumpolar current south of Australia, *J. Phys. Oceanogr.*, 37, 1394–1412, 2007a.
- 10 Sokolov, S. and Rintoul, S. R.: On the relationship between fronts of the Antarctic Circumpolar Current and surface chlorophyll concentrations in the Southern Ocean, *J. Geophys. Res.*, 112, C07030, doi:10.1029/2006JC004072, 2007b.
- Smetacek, V., Assmy, P., and Henjes, J.: The role of grazing in structuring Southern Ocean pelagic ecosystems and biogeochemical cycles, *Antarct. Science*, 16, 541–558, 2004.
- Smith, W. O. Jr. and Gordon, L. I.: Hyperproductivity of the Ross Sea (Antarctica) polynya during austral spring, *Geophys. Res. Lett.*, 24, 233–236, doi:10.1029/96GL03926, 1997.
- Smith, W. O. Jr. and Nelson, D. M.: Importance of ice edge phytoplankton production in the Southern Ocean, *Bioscience*, 36, 251–257, 1986.
- 20 Smith, W. O., Anderson, R. F., Moore, J. K., Codispoti, L. A. and Morrison, J. M.: The US Southern Ocean Joint Global Ocean Flux Study: an introduction to AESOPS, *Deep-Sea Res. Pt. II*, 47, 3073–3094, 2000.
- Sullivan, C. W., Arrigo, K. R., McClain, C. R., Comiso, J. C., and Firestone, J.: Distributions of phytoplankton blooms in the Southern Ocean, *Science*, 262, 1832–1837, doi:10.1126/Science.262.5141.1832, 1993.
- 25 Sunda, W. G. and Huntsman, S. A.: Interrelated influence of iron, light, and cell size on marine phytoplankton growth, *Nature*, 390, 389–392, 1997.
- Sverdrup, H. U.: On conditions for the vernal blooming of phytoplankton, *J. Conseil*, 18, 287–295, 1953.
- 30 Swart, S. and Speich, S.: An altimetry-based gravest empirical mode south of Africa: 2. Dynamic nature of the Antarctic Circumpolar Current fronts, *J. Geophys. Res.*, 115, C03003, 1–22, 2010.
- Taylor, A. H., Geider, R. J., and Gilbert, J. H.: Seasonal and latitudinal dependencies of phy-



toplankton carbon-to-chlorophyll-*a* ratios: results of a modelling study, Mar. Ecol.-Prog. Ser., 152, 51–66, 1997.

Tréguer, P. and Jacques, G.: Dynamics of nutrients and phytoplankton, and fluxes of carbon, nitrogen, and silicon in the Antarctic ocean, Polar Biol., 12, 149–162, 1992.

5 Turner, J., Bindschadler, R., Convey, P., di Prisco, G., Fahrbach, E., Gutt, J., Hodgson, D., Mayewsky, P., and Summeerhayes, C.: Antarctic Climate Change and the Environment. SCAR, Scott Polar Research Institute, Cambridge, 526 pp., 2009.

10 Venables, H. J. and Meredith, M. P.: Theory and observations of Ekman flux in the chlorophyll distribution downstream of South Georgia, Geophys. Res. Lett., 36, L23610, doi:10.1029/2009GL041371, 2010.

Venables, H. and Moore, C. M.: Phytoplankton and light limitation in the Southern Ocean: learning from high-nutrient, high-chlorophyll areas, J. Geophys. Res., 115, C02015, doi:10.1029/2009JC005361, 2010.

15 Veth, C., Peeken, I., and Scharek, R.: Physical anatomy of fronts and surface waters in the ACC near 6jW meridian during austral spring 1992, Deep-Sea Res. Pt. II, 44, 23–49, 1997.

**BGD**

8, 4763–4804, 2011

## Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

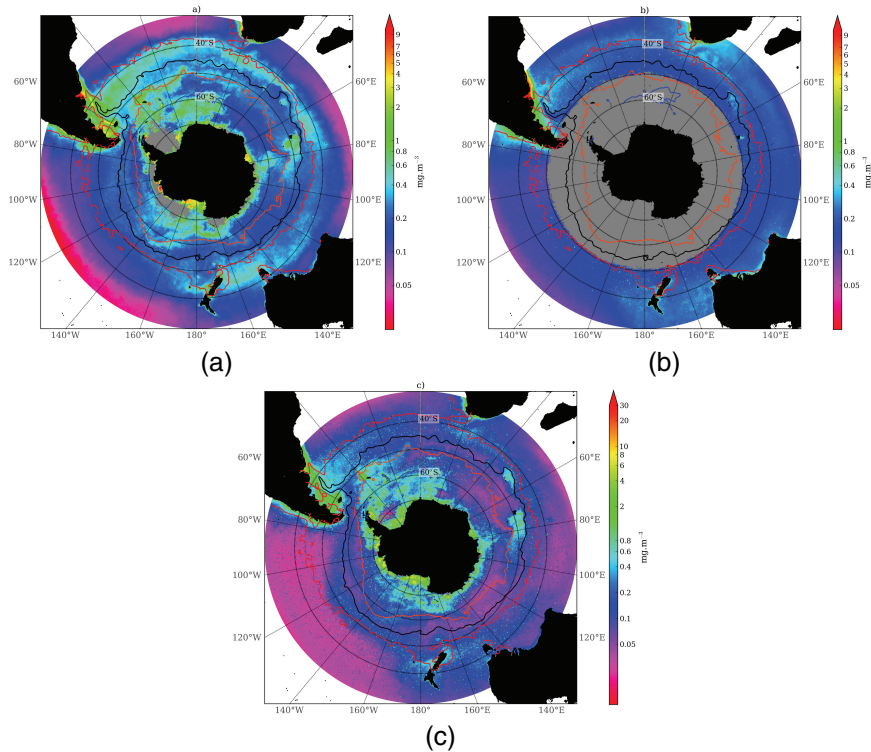
Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





**Fig. 1.** Spatial distribution of mean chlorophyll concentrations for the Southern Ocean south of 30°S for **(a)** peak summer – January, **(b)** peak winter – July and **(c)** the standard deviation of weekly chlorophyll concentrations over the period January 1998–December 2007. Mean July and mean January (1998–2007) frontal positions calculated from MADT contours are shown for the STF (red), SAF (black), PF (orange) and SACCF (blue).

**Seasonal characteristics of the Southern Ocean**

S. J. Thomalla et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

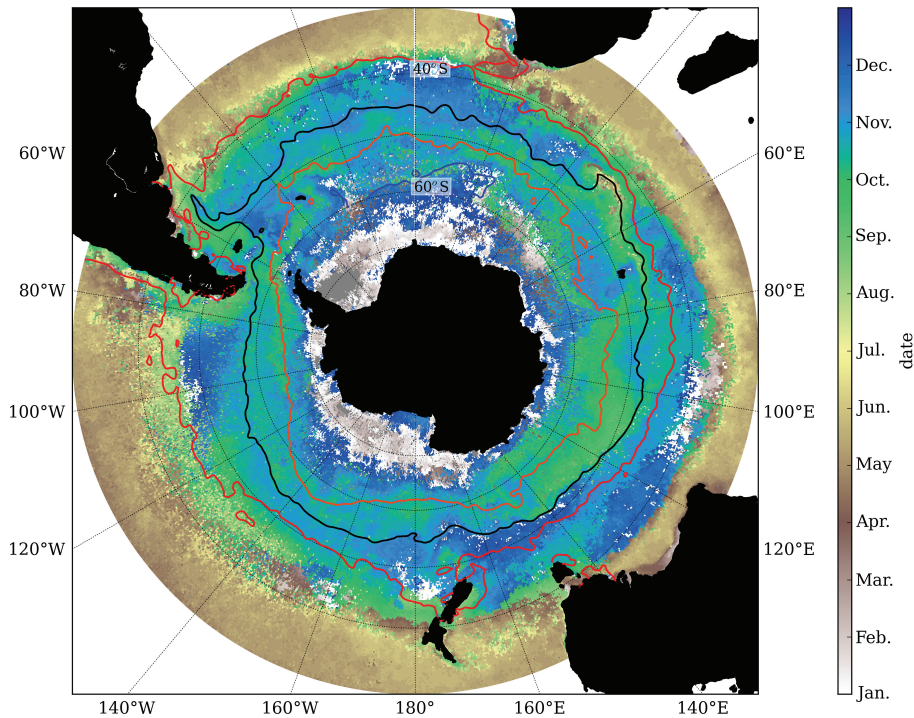
Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





**Fig. 2.** Date of the phytoplankton bloom initiation in the Southern Ocean south of 30° S. Mean (1998–2007) frontal positions calculated from MADT contours shown for the STF (red), the SAF (black), the PF (orange) and the SACCF (blue).

**Seasonal characteristics of the Southern Ocean**

S. J. Thomalla et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

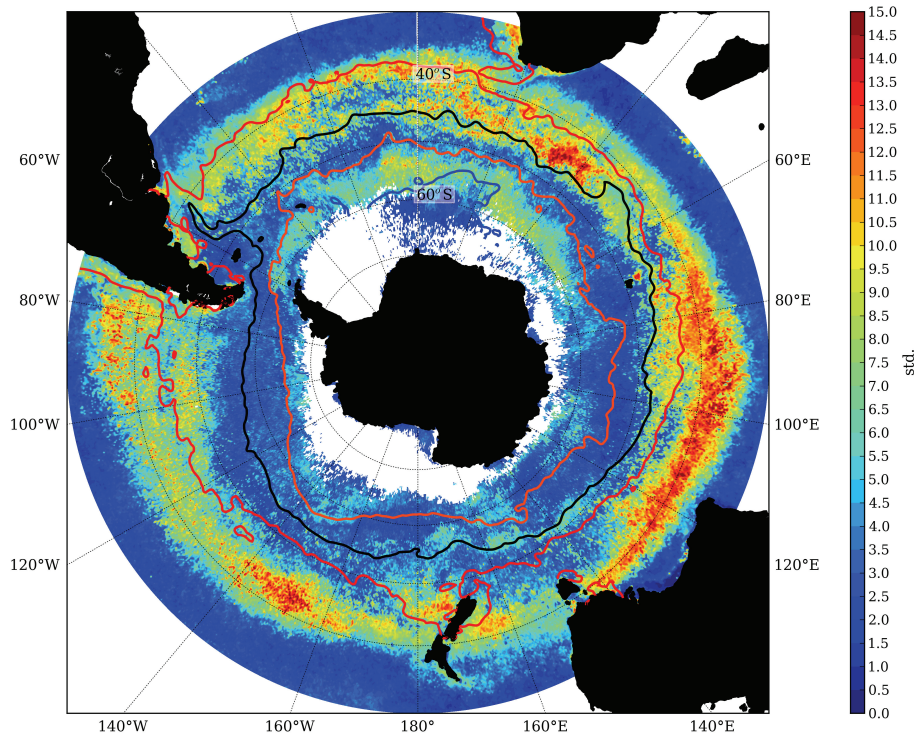
Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





**Fig. 3.** Inter-annual variability (standard deviation over the 9 yr) in phytoplankton bloom initiation dates in the Southern Ocean south of 30° S. Mean (1998–2007) frontal positions shown for the STF (red), the SAF (black), the PF (orange) and the SACCF (blue).

**Seasonal characteristics of the Southern Ocean**

S. J. Thomalla et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

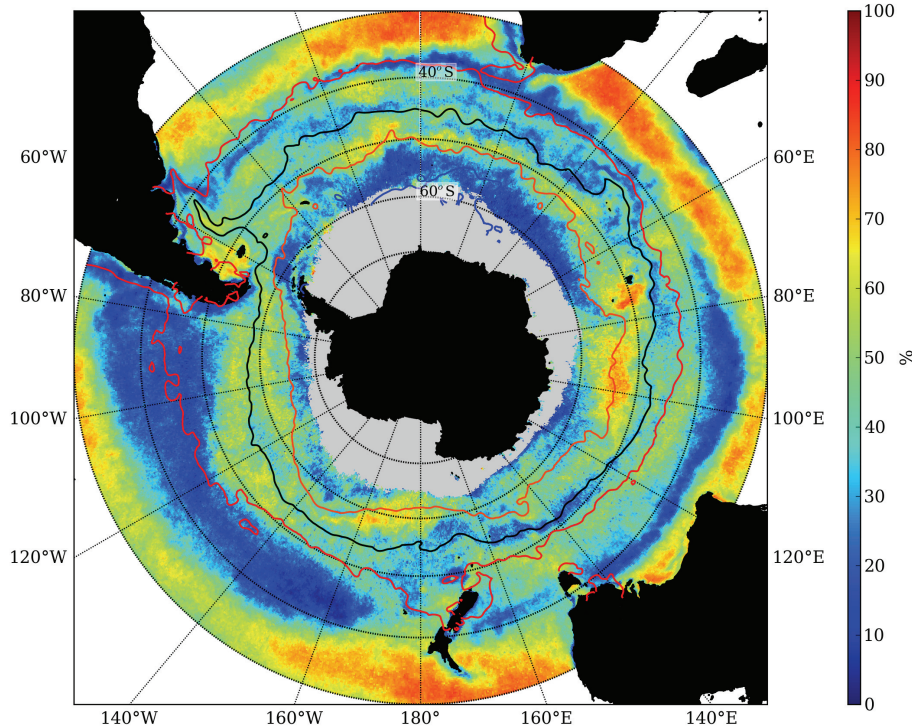
Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





**Fig. 4.** Percentage (from 0 to 1) of the overall variance explained by the mean seasonal cycle for the Southern Ocean south of 30° S. Masked grid-points in white correspond to areas where more than half of the weekly values are missing. Mean (1998–2007) frontal positions are shown for the STF (red), the SAF (black), the PF (orange) and the SACCF (blue).

**Seasonal characteristics of the Southern Ocean**

S. J. Thomalla et al.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

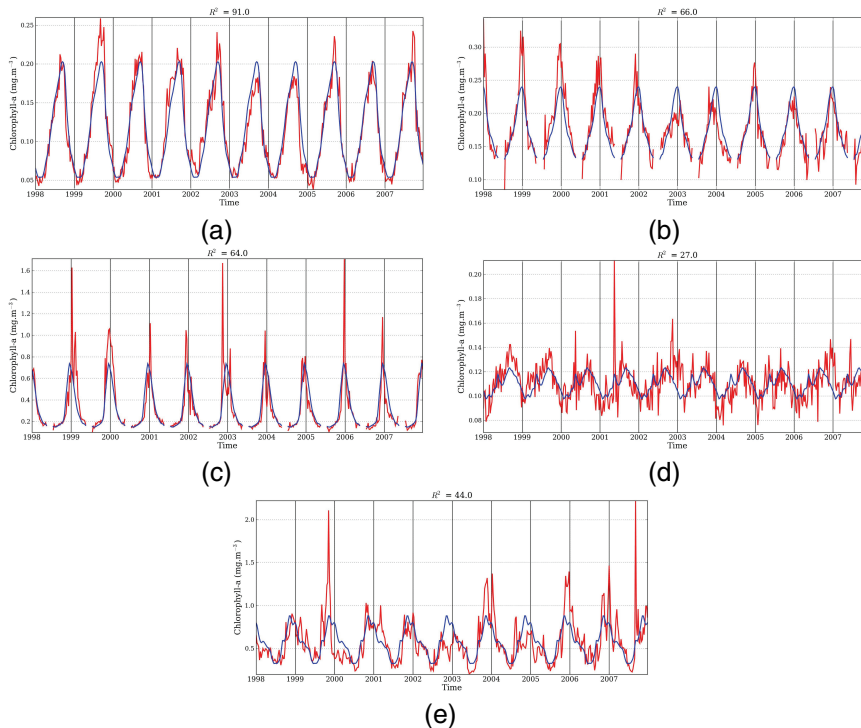
Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





(e)

**Fig. 5.** Time series of chlorophyll concentrations from 1998 to 2007 (in red) compared to the climatological mean seasonal cycle (calculated over the 9 yr) (in blue) for  $5 \times 5$  degree blocks in **(a)** a high seasonality region in the low chlorophyll STZ ( $30\text{--}35^\circ\text{S}$ ,  $0\text{--}5^\circ\text{W}$ ), **(b)** a high seasonality region in the low chlorophyll ACZ west of Kerguelen ( $50\text{--}55^\circ\text{S}$ ,  $55\text{--}60^\circ\text{E}$ ), **(c)** a high seasonality region of high chlorophyll in the ACZ, downstream of Kerguelen ( $50\text{--}55^\circ\text{S}$ ,  $70\text{--}75^\circ\text{E}$ ), **(d)** a low seasonality region in the low chlorophyll TZ in the Pacific ( $40\text{--}45^\circ\text{S}$ ,  $95\text{--}100^\circ\text{W}$ ) and **(e)** a low seasonality region of high chlorophyll in the TZ off the east coast of South America ( $40\text{--}45^\circ\text{S}$ ,  $50\text{--}55^\circ\text{W}$ ). The percentage of variance explained by the regression of the time-series (red) onto the mean seasonal cycle (blue) is shown on the figure ( $R^2$ ).

Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Seasonal characteristics of the Southern Ocean

S. J. Thomalla et al.

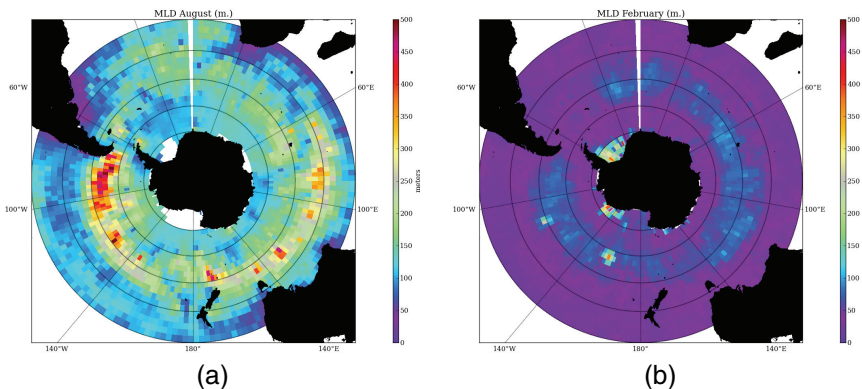


Fig. 6. Average MLD in (a) winter (August) and (b) summer (February) in the Southern Ocean from the De Boyer Montegut et al. (2004) dataset.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

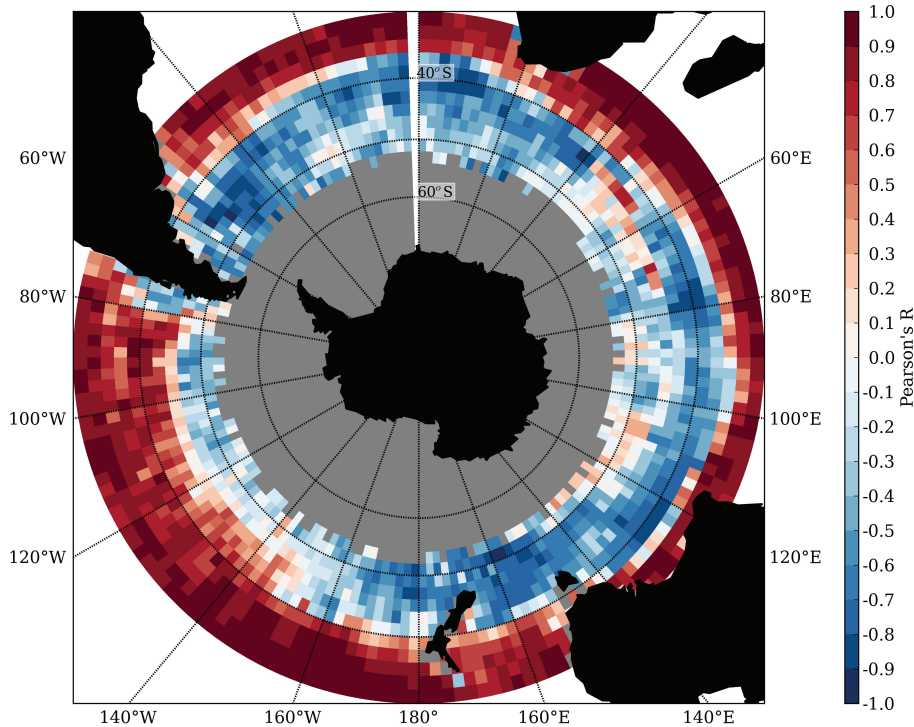
Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





**Fig. 7.** Pearson's correlation coefficient between seasonal cycles of monthly MLD from the De Boyer Montegut et al. (2004) dataset and chlorophyll. Masked grid-points in grey correspond to areas where more than half the monthly values were missing in the chlorophyll time series.

**Seasonal characteristics of the Southern Ocean**

S. J. Thomalla et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

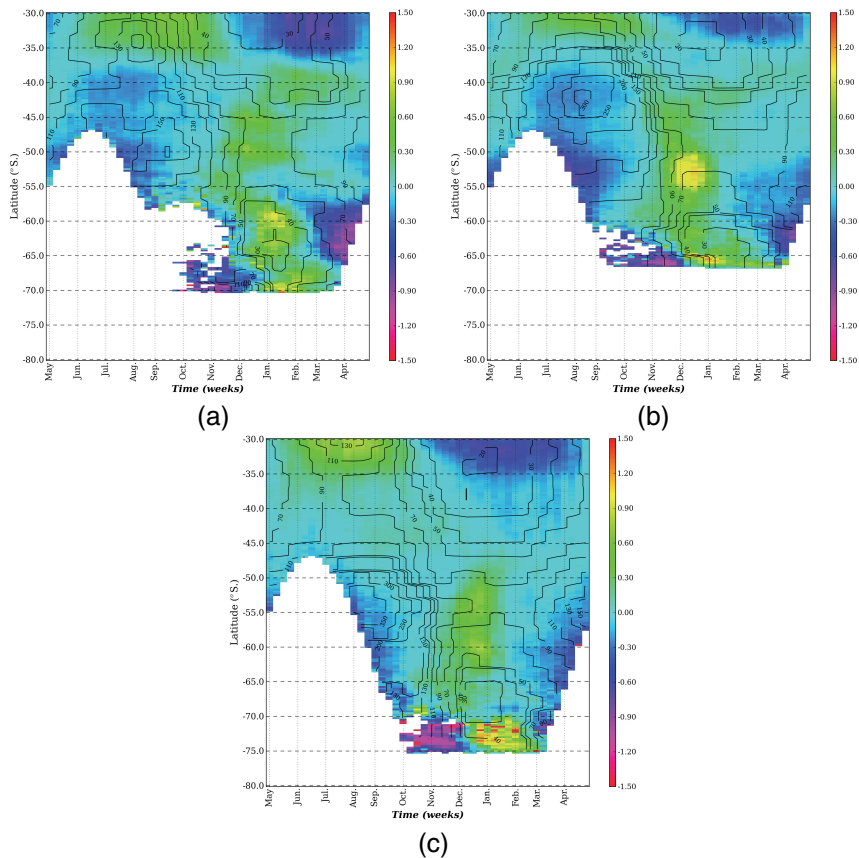
Full Screen / Esc

Printer-friendly Version

Interactive Discussion







**Fig. 8.** Mean seasonal cycles (May to April – x-axis) of chlorophyll (colour scale) and MLD (contours) as a function of latitude (30–80° S – y-axis) for a 10° longitudinal transect in **(a)** the Atlantic (0–10° E), **(b)** the Indian (85–95° E) and **(c)** the Pacific (110–100° W) Oceans. Chlorophyll concentrations are expressed as the anomalies in log(chlorophyll) with respect with the annual mean, MLD is in meters.

**Seasonal characteristics of the Southern Ocean**

S. J. Thomalla et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

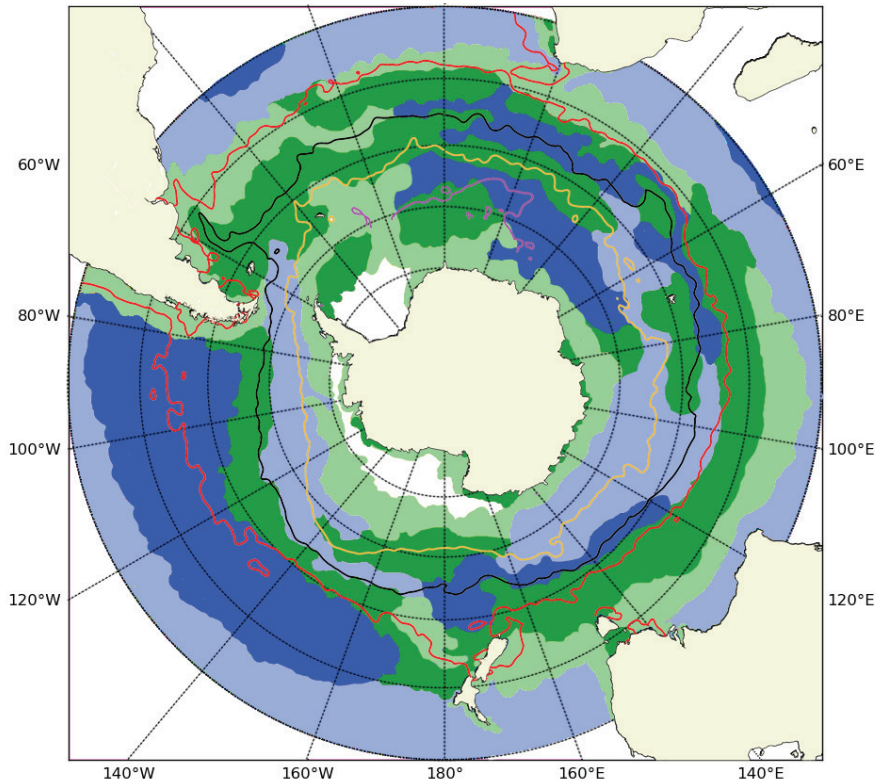
Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





**Fig. 9.** A schematic summarising the response of phytoplankton biomass to the underlying physics of the different seasonal regimes. Regions in blue represent regions of low chlorophyll concentration with either high seasonality (light blue) or low seasonality (dark blue). Regions in green represent regions of high chlorophyll concentration with either high seasonality (dark green) or low seasonality (light green). Mean (1998–2007) frontal positions are shown for the STF (red), the SAF (black), the PF (yellow) and the SACCF (pink).

**Seasonal characteristics of the Southern Ocean**

S. J. Thomalla et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

