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# Eddies enhance biological production in the Weddell-Scotia Confluence of the Southern Ocean

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[1] Satellite data show that oceanic eddies generated in the Southern Antarctic Circumpolar Current Front (SACCF) are associated with increased phytoplankton biomass. Cyclonic eddies with high chlorophyll *a* concentration (Chl-a) retain phytoplankton within the eddy cores and increase the light available for photosynthesis in the upper mixed layer by limiting vertical mixing and lifting of the isopycnal surfaces. Anticyclonic eddies have low Chl-a in the core but increased Chl-a in the periphery. Cross-frontal mixing mediated by eddies transports nutrients (e.g., Fe and Si) to the north and contributes to the increased Chl-a in the frontal zone. Interannual variations in the cyclonic eddy activity are positively correlated with variations in Chl-a during the spring bloom in regions of the Antarctic Circumpolar Current around South Georgia. **Citation:** Kahru, M., B. G. Mitchell, S. T. Gille, C. D. Hewes, and O. Holm-Hansen (2007), Eddies enhance biological production in the Weddell-Scotia Confluence of the Southern Ocean, *Geophys. Res. Lett.*, *34*, L14603, doi:10.1029/2007GL030430.

## 1. Introduction

[2] Phytoplankton production in the Southern Ocean is relatively low, compared to the high surface nutrient (N, P and Si) concentrations [*Chisholm and Morel*, 1991], and has the potential to affect global atmospheric $CO_2$ levels [*Sarmiento and Orr*, 1991; *de Baar et al.*, 1995]. Some regions, however, support phytoplankton blooms and very productive higher trophic levels [*Sullivan et al.*, 1993; *Hewitt et al.*, 2004; *Holm-Hansen et al.*, 2004a]. Phytoplankton production in the Southern Ocean is known to be limited by iron [*Martin et al.*, 1991; *Helbling et al.*, 1991] and light [*Nelson and Smith*, 1991; *Mitchell et al.*, 1991]. Light limitation in the summer occurs due to insufficient stratification in the euphotic zone of the water column.

[3] The dominant hydrographic feature of the Southern Ocean is the eastward flowing Antarctic Circumpolar Current (ACC) that has most of its transport concentrated in frontal jets, the number, strength and latitudinal locations of which are influenced by the bathymetry [*Pollard et al.*, 2002]. From north to south, the main frontal systems in the Southern Ocean are identified as the Subantarctic Front (SAF), the Polar Front (PF), the Southern ACC Front (SACCF) and the southern boundary of the ACC [*Orsi et al.*, 1995]. Although the ACC frontal features are circumpolar in structure, the conditions required for phytoplankton blooming vary around Antarctica. Here we use satellite data to explain some of the mechanisms responsible for the variability in phytoplankton biomass in the Weddell-Scotia Confluence zone of the Southern Ocean. We show that the cross-frontal eddy activity in the SACCF zone provides enhanced conditions for phytoplankton growth during the spring bloom.

## 2. Data and Methods

[4] Satellite-derived Level-2 data sets of chlorophyll-a concentration (Chl-a) were obtained from the NASA Ocean Color website (http://oceancolor.gsfc.nasa.gov/). Monthly concentrations of Chl-a were calculated from OCTS and SeaWiFS monthly normalized water-leaving radiances using the maximum band-ratio algorithm [*O'Reilly et al.*, 1998] but with coefficients fitted to our Southern Ocean data (SPGANT algorithm). These monthly Chl-a composites were used to create monthly anomalies as the ratio of a current month to the long-term mean of the month and expressed as percentage anomaly. Since we are using anomalies to detect interannual variability, the exact Chl-a values are not critical and similar results are obtained by using alternative Chl-a algorithms.

[5] The SACCF zone is defined as a region with a north-south extent of about 280 km (150 nautical miles) centered at the mean position of the SACCF [*Orsi et al.*, 1995]. Time series of Chl-a anomalies were constructed for 4-degree meridional sections along the SACCF zone. At some locations (e.g., around South Georgia, Figure 1b) the SACCF makes a loop that resulted in two separate sections per 4-degree longitude range.

[6] Weekly maps of the Sea Level Anomaly (SLA) merged from TOPEX/POSEIDON, Jason and ERS-1/2 data from AVISO were used to evaluate eddy variability. As a measure of cyclonic eddy activity we calculated monthly root mean square (RMS) of negative SLA in $7 \times 7$ pixel windows of the updated SLA dataset (ftp://ftp.cls.fr/pub/oceano/AVISO/SSH/duacs/global/dt/upd/msla/merged/h/). Monthly time series of the negative SLA variance in 4-degree meridional sections along the SACCF zone were correlated with monthly Chl-a anomalies.

## 3. Results and Discussion

[7] Figure 1 shows the mean Chl-a for October when the austral spring bloom typically occurs and the contrasts are highest. The southern Scotia Sea and the neighboring South Atlantic Ocean around South Georgia comprise the largest and most persistent high-Chl-a area in the Southern Ocean south of the SAF. The distribution becomes more uniform later in the season but relatively high phytoplankton biomass persists throughout much of the Scotia Sea for the

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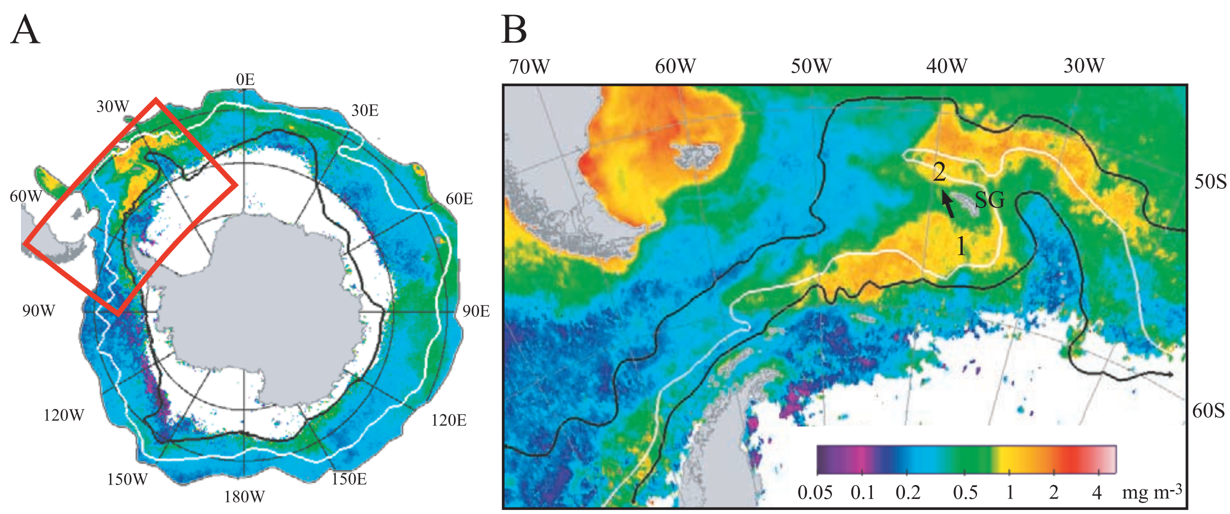


**Figure 1.** Mean Chl-a in October for 1998–2006. (a) The Southern Ocean south of the Subantarctic Front with the mean location of the Polar Front (PF, white curve) and the southern boundary of the ACC (black curve). (b) The Scotia Sea with the mean locations of PF and southern boundary of the ACC (black curves) and the SACCF (white curve). Areas 1 and 2 located around South Georgia (SG) with an arrow between them show the highest correlation between cyclonic eddy activity (in area 1) and increased Chl-a (in area 2).

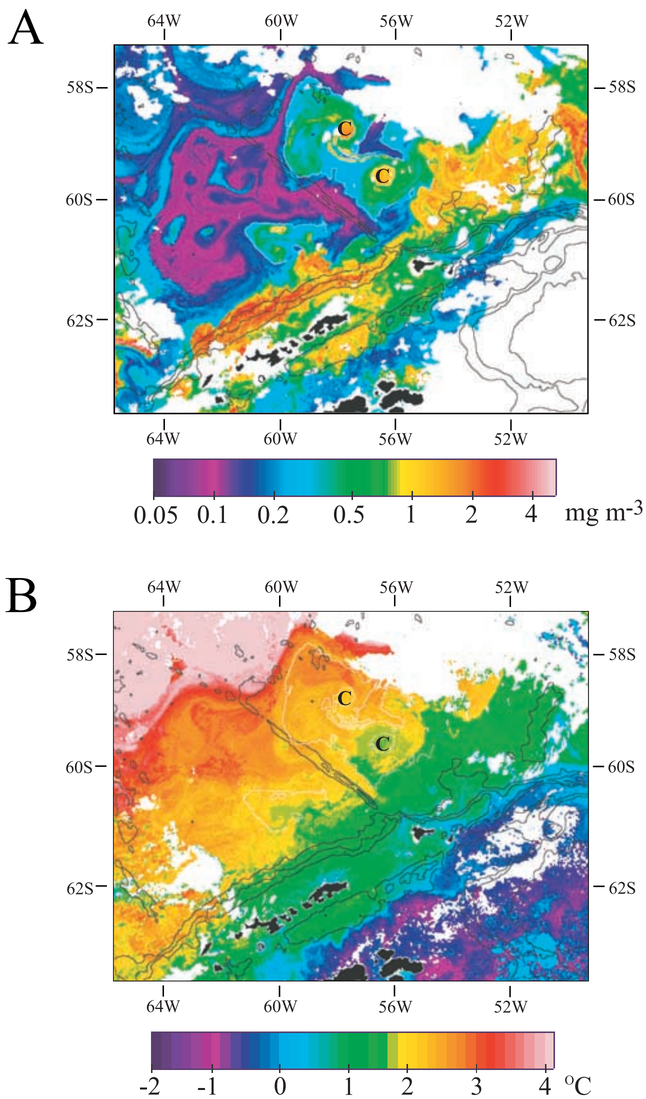


**Figure 2.** A pair of cyclonic eddies (C) in the SACCF zone on Jan 1, 2006: (a) Chl-a and (b) sea-surface temperature. Depth isolines of 1000, 2000 and 3000 m are shown as black contours. Ocean areas covered by clouds and/or ice are shown in white.

austral summer season [*Holm-Hansen et al.*, 2004b]. Closer examination of the Scotia Sea/South Georgia high-Chl-a area reveals that it is centered on the SACCF between the PF to the north and the southern boundary of the ACC to the south (Figure 1b).

[8] Iron input in the Southern Ocean is known to originate from bottom sediments or melting ice in the shelf areas around shallow banks and islands [*Blain et al.*, 2001], and iron concentrations are highest in these areas. In contrast, Figure 1b shows that the high Chl-a areas are offshore and not in the shallow shelf areas around South Georgia and other islands. This suggests that while the large-scale Chl-a distribution is consistent with iron limitation [e.g., *de Baar et al.*, 1995]; at smaller spatial scales around the islands it is the lack of vertical stratification and not iron limitation that limits phytoplankton growth.

[9] The high-Chl-a area centered at the SACCF appears compact due to averaging over a considerable time period. Individual satellite images are mostly cloudy but the rare clear scenes show a series of eddies in the frontal zones. The exchange mediated by mesoscale eddies in the SACCF appears to be an important mechanism increasing production and creating areas of increased Chl-a. Figure 2 shows two cyclonic eddies in the SACCF zone that effectively exchange heat between the warm northern side and the cold southern side and are both rich in Chl-a. While the eddy cores have temperatures that are intermediate between the cold southern side and the warm northern side, the Chl-a reaches local maxima in the eddies. This suggests that the eddies in the SACCF create favorable conditions for phytoplankton growth by establishing stratification and limiting vertical mixing due to interleaving layers. They also mediate cross-front transport of iron from the south to the north and heat from the north to the south. The high-Chl-a area centered at the SACCF is likely to be the result of this cross-front exchange.

[10] We find that cyclonic eddies (spinning clockwise in the Southern Hemisphere) contain elevated Chl-a (Figure 2) while anticyclonic eddies (spinning counterclockwise) have low Chl-a in the core but often elevated Chl-a in their periphery (Figure 3). The anticyclonic eddy in Figure 3 has a banded structure with the Chl-a approximately 0.15 in the core, 0.09 in the low Chl-a-band just outside the core and up to 1.0 mg $m^{-3}$ in the periphery.

[11] Figure 4 shows a string of eddies in the SACCF zone with the cyclonic eddies having high Chl-a in the cores and anticyclonic eddies high Chl-a in their periphery. Cyclonic eddies are associated with upwelling and anticyclonic eddies with downwelling [*McGillicuddy et al.*, 1998]. The periphery of anticyclonic eddies has been observed to be the site of secondary frontal upwelling [*Strass et al.*, 2002]. Our results are consistent with the idea that the upwelling in cyclonic eddies and along eddy boundaries provides benefits for the phytoplankton by lifting nutrient-rich waters closer to the surface and and/or providing vertical stability in the euphotic zone. Frontal eddies are also common further north along the Polar Front [*Moore and Abbott*, 2002; *Strass et al.*, 2002] but their positive effect on phytoplankton production is diminished as the southern side of that front has lower concentrations of Si and Fe. A major source of iron in the Weddell-Scotia Confluence zone is known to be the Weddell Sea water [*Nolting et al.*, 1991; *Sañudo-Wilhelmy et al.*, 2002; *Hoppema et al.*, 2003] and its influence in the Polar Front region is diminished. However, even in the Polar Front the mesoscale dynamics of fronts and eddies has been shown to enhance phytoplankton productivity [*Abbott et al.*, 2001; *Strass et al.*, 2002].

[12] Large interannual variability in the extent and intensity of phytoplankton blooms in the Southern Ocean has been observed earlier [*Korb et al.*, 2004; *Arai et al.*, 2005] but not explained. If eddy exchange in the SACCF zone significantly enhances phytoplankton production then we should be able link the strong interannual variability in the extent and intensity of the blooms to changes in the eddy activity. Visual inspection shows that the eddy field is dominated by large, warm-core eddies shed from meanders of the Polar Front. These anticyclonic eddies, similar to the

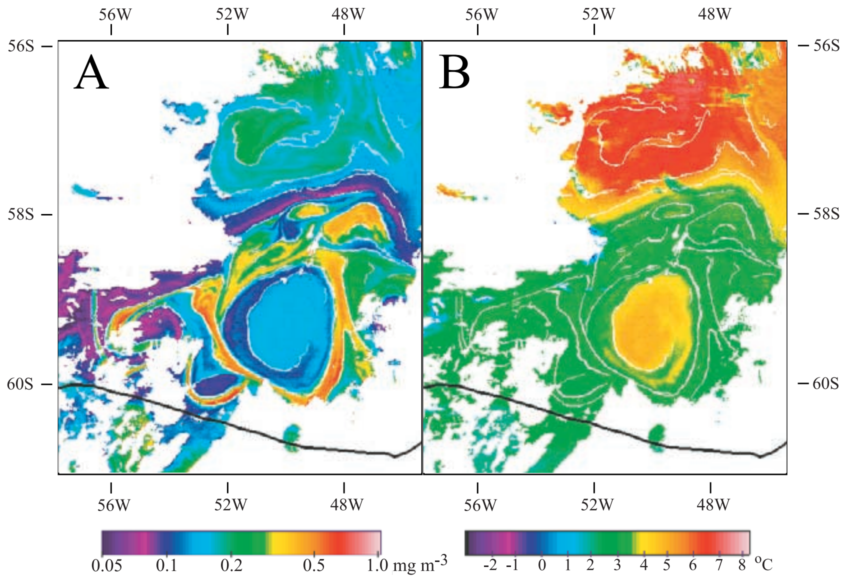


**Figure 3.** A large anticyclonic eddy north of the mean position of the Southern ACC Front (black curve) on Jan 28, 2004: (a) Chl-a and (b) sea-surface temperature. Ocean areas covered by clouds are shown in white. The white curves are edges determined on the Chl image but overlaid on both images.

eddy in Figure 3, may have increased Chl-a in their periphery but have generally low Chl-a in their cores and do not produce a significant net increase in surface Chl-a.

[13] Anticyclonic eddy motions (relative to the background mean flow) have positive (upward) sea level anomalies, and cyclonic eddies correspond to downward dips in sea level anomaly. Since only cyclonic eddies are associated with increased Chl-a in the core, we used the root mean squared (RMS) negative sea-level anomaly (SLA) as an indicator of cyclonic eddy activity. As a measure of the phytoplankton interannual variability we used monthly Chl-a anomalies. If calculated over large areas, such as the Scotia Sea/South Georgia region, we do not find significant correlation between the interannual variations in eddy activity and Chl-a anomalies. At these scales the eddy variability signal is dominated by the strong eddies shed from the Polar Front that have relatively weak influence on monthly Chl-a anomalies. However, away from the Polar Front, especially around South Georgia, we find significant positive correlation between cyclonic eddy activity and Chl-a anomalies during the spring bloom. The correlation is strongest in October–November and weak or even negative later in the season (not shown). Due to spatial and temporal displacements between the anomaly fields of cyclonic eddies and Chl-a the highest positive correlation with the Chl-a anomalies are found downstream of the eddy anomalies and lagged by one month. Figure 5 shows a significant influence of the cyclonic eddy activity in the SACCF zone between 36–40° W (area 1 in Figure 1b) on Chl-a anomaly further north (40–44° W, area 2 in Figure 1b), downstream

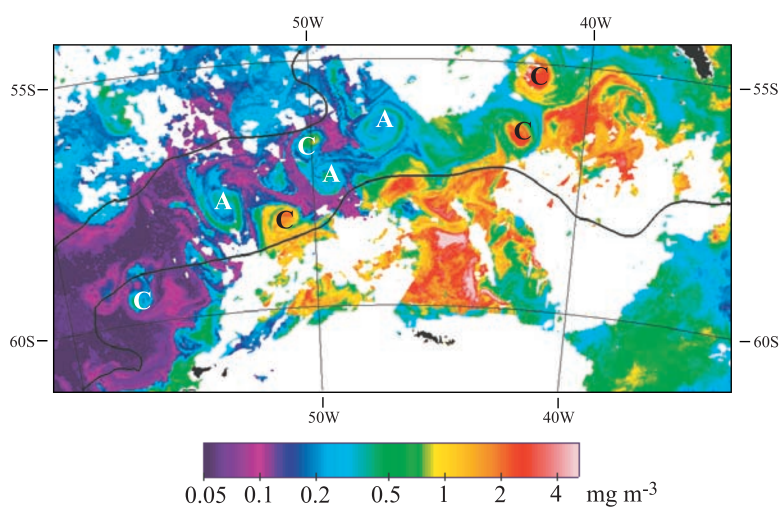


**Figure 4.** Chl-a distribution showing a string of cyclonic (C) and anticyclonic (A) eddies in the SACCF zone on Jan 26–30, 2005. The mean positions of the PF (northern black curve) and SACCF (southern black curve) are shown.

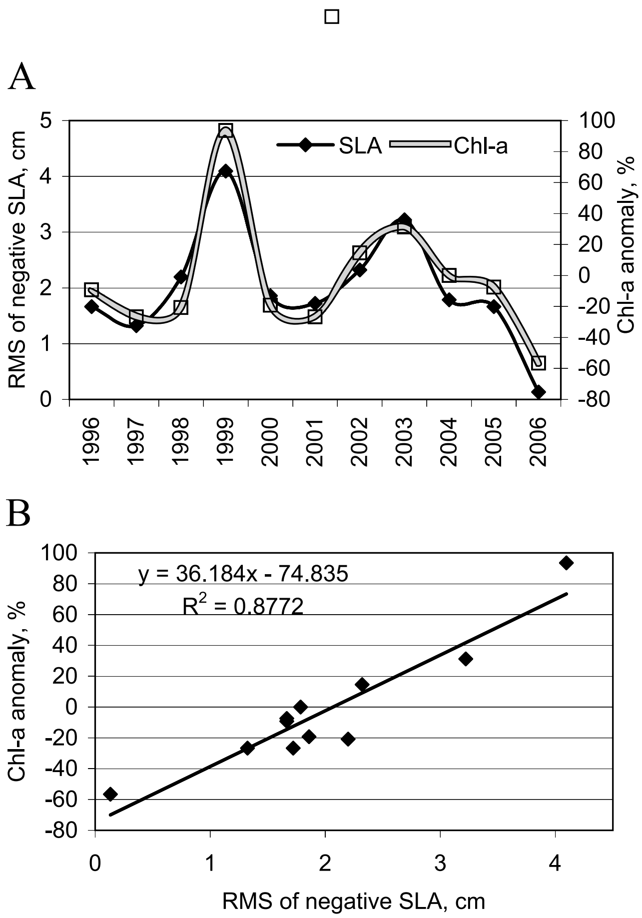


**Figure 5.** Relationships between cyclonic eddy activity (RMS of the negative sea-level anomaly, SLA, in the SACCF zone between 36–40° W, area 1 in Figure 1b) and monthly Chl-a anomaly (between 40–44° W, area 2 in Figure 1b). Chl-a anomalies are regressed against SLA anomalies one month earlier. (a) Annual time series of Chl-a anomaly in October (green line, right axis) and RMS of negative SLA in September (blue line, left axis). (b) Scatter plot between Chl-a anomaly in October and RMS of negative SLA in September.

of the presumed mean currents one month later. The general flow direction shown by arrow in Figure 1b is consistent with both observational and model data [e.g., *Korb et al.*, 2004, Figure 1]. The lag of about 1 month in the Chl-a response can be explained by the relatively slow growth rate of phytoplankton at very low temperatures [*Neori and Holm-Hansen*, 1982].

## 4. Conclusions

[14] The area in the Scotia Sea and around South Georgia centered on the mean position of the Southern ACC Front is the largest and most persistent productive area in the Southern Ocean. The abundant iron input from the Weddell Sea and the local shelf areas combined with the stratification provided by cyclonic eddies and the interleaving of different water masses create favorable conditions for phytoplankton growth there. Cross-frontal mixing mediated by eddies is likely an important factor contributing to the increased productivity and Chl-a in the frontal zone. Cyclonic eddies have increased Chl-a in their cores while anticyclonic eddies have low Chl-a in their cores but increased Chl-a in the periphery. A significant part of the interannual Chl-a variability during the spring bloom around South Georgia is explained by the cyclonic eddy activity in the SACCF zone.

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