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Remote sensing observations of ocean physical and biological properties in the region of the Southern Ocean Iron Experiment (SOFeX)

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[1] Satellite remote sensing estimates of surface chlorophyll, temperature, wind speed, and sea ice cover are examined in the region of the Southern Ocean Iron Experiment (SOFeX). Our objectives are to place SOFeX into a regional context and highlight regional mesoscale spatial and monthly temporal variability. SOFeX fertilized two patches with iron, one south of the Antarctic Polar Front (PF) and one north of the PF but south of the Subantarctic Front (SAF). Satellite-observable phytoplankton blooms developed in both patches. The spring sea ice retreat near the south patch site was delayed in the 2001–2002 season, in turn delaying the naturally occurring, modest spring bloom in this region. Ambient surface chlorophyll concentrations for the area surrounding the southern patch during January 2002 are low (mean 0.26 mg/m^3) compared with climatological January values (0.42 mg/m^3). Regions east and west at similar latitudes exhibited higher mean chlorophyll concentrations (0.79 and 0.74 mg/m^3, respectively). These modest phytoplankton blooms were likely stimulated by melting sea ice via changes in the light-mixing regime and release of iron and were smaller in magnitude than the iron-induced bloom within the SOFeX southern patch (>3 mg/m^3). Iron inputs from melting ice may drive much of the natural spatial and temporal variability within the seasonal ice zone. Mean chlorophyll concentrations surrounding the SOFeX northern patch site were similar to climatological values during the SOFeX season. The northern patch was stretched into a long, thin filament along the southern boundary of the SAF, likely increasing the mixing/dilution rate with surrounding waters.

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1. Introduction

[2] The Southern Ocean (SO) is the largest of the high-nitrate, low-chlorophyll (HNLC) regions where the key macronutrients nitrate and phosphate are typically at high concentrations and thus do not limit biological production. Early researchers suggested that a micronutrient, perhaps iron, limited phytoplankton growth rates preventing the consumption of the available macronutrients [*Gran*, 1931; *Hart*, 1934]. Atmospheric deposition of mineral dust, the key source of iron to open ocean surface waters, is quite low throughout most of the SO [e.g., *Mahowald et al.*, 1999]. John Martin and coworkers using trace metal clean, bottle incubation experiments in this region demonstrated that the addition of iron stimulates phytoplankton biomass increase and strong macronutrient drawdown in the Southern Ocean [*Martin et al.*, 1990a, 1990b]. The satellite perspective also supported the hypothesis of iron limitation with phytoplankton blooms apparent mainly in coastal/shelf waters (where there is a sedimentary source for iron), downwind of Patagonia and Australia/New Zealand (where dust inputs are higher), and to a lesser extent in regions of retreating sea ice and near the major hydrographic fronts, where there are also additional iron inputs to surface waters (see discussion below) [*Sullivan et al.*, 1993; *Comiso et al.*, 1993; *Banse and English*, 1997; *Moore et al.*, 1999a, 2000; *Moore and Abbott*, 2000; *Tyrrell et al.*, 2005]. Last, several mesoscale, iron fertilization patch experiments have shown a clear response to iron additions both in the Atlantic (EISENEX experiment [*Bakker et al.*, 2005]) and in the Pacific sector (SOIREE [*Boyd et al.*, 2000] and SOFeX [*Coale et al.*, 2004]) (see also review by *de Baar et al.* [2005]).

[3] Yet it is also clear that at times the light regime and silicic acid availability can also influence phytoplankton growth rates, and that there can be interactions between these factors and iron, and at times simultaneous limitation by multiple factors [*Nelson and Smith*, 1991; *Mitchell et al.*, 1991; *Van Oijen et al.*, 2004; *Boyd et al.*, 1999; *Hutchins et al.*, 2001] (see *Boyd* [2002] for a recent review). Low light levels increase the cellular demand for iron, thus colimitation by iron and light may be common in this region, where

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mixed layers are often deep, particularly early and late in the growing season when surface irradiance levels are lower [*Raven*, 1990; *Sunda and Huntsman*, 1997; *Boyd et al.*, 2000, 2001; *Boyd*, 2002]. Diatoms increase their Si/NO_3^- uptake ratios and Si cell quotas under Fe-limiting conditions [*Hutchins et al.*, 1998; *Frank et al.*, 2000; *Watson et al.*, 2000; *Leynaert et al.*, 2004]. This effect can promote strong drawdown of silicic acid leading to Si limitation of the larger diatoms later in the growing season, particularly in subantarctic waters [*Boyd et al.*, 1999; *Hutchins et al.*, 2001; *Brzezinski et al.*, 2005].

[4] Phytoplankton blooms are more commonly observed in the southwest Pacific sector of the SO than in most other regions [*Sullivan et al.*, 1993; *Moore and Abbott*, 2000, 2002; *Meguro et al.*, 2004; D. T. Fitch and J. K. Moore, Phytoplankton bloom dynamics in the Southern Ocean marginal ice zone, submitted to *Deep-Sea Research, Part I*, 2006]. These blooms have been attributed to the effects of the retreating ice edge [*Smith and Nelson*, 1986; *Moore et al.*, 1999a; *Abbott et al.*, 2000; *Moore and Abbott*, 2002; *Buesseler et al.*, 2003; *Meguro et al.*, 2004] and to interactions between SO fronts and the Pacific-Antarctic Ridge [*Moore et al.*, 1999a; *Abbott et al.*, 2001]. The Antarctic Polar Front (PF) closely follows the northern flank of this ridge across the region [*Moore et al.*, 1999b]. Mesoscale meandering of jets such as the PF and SAF leads to localized areas of upwelling and downwelling that also can influence phytoplankton bloom dynamics [*Flierl and Davis*, 1993; *Olson et al.*, 1994; *Moore et al.*, 1999a; *Lima et al.*, 2002]. Elevated dissolved iron concentrations have been observed at SO fronts and attributed either to enhanced upwelling or advection from sedimentary sources upstream [*de Baar et al.*, 1995; *Measures and Vink*, 2001; *Croot et al.*, 2004].

[5] Retreating sea ice cover inputs fresh, low-density water at the surface often resulting in shallow surface mixed layers. This can improve the irradiance-mixing regime for phytoplankton, stimulating blooms [*Smith and Nelson*, 1986], and by reducing light stress can decrease the iron demand of the phytoplankton community [*Raven*, 1990; *Sunda and Huntsman*, 1997]. Melting sea ice may also release iron to surface waters [*Sedwick and DiTullio*, 1997; *Croot et al.*, 2004]. Sea ice may accumulate iron from atmospheric deposition of mineral dust [*Edwards and Sedwick*, 2001] and may also incorporate iron from sedimentary sources when forming in coastal/shelf regions [*Sedwick et al.*, 2000; *Fitzwater et al.*, 2000; *Grotti et al.*, 2005]. The analysis of *Meguro et al.* [2004] shows ice formed in the coastal/shelf Ross Sea advected directly toward the region of the southern SOFeX patch site. They suggest release of iron from melting sea ice along with seed stocks of ice algae drive phytoplankton blooms in this region during the 1996–1997 season. An intense, natural phytoplankton bloom (in situ chlorophyll observations >3 mg/m^3) was also observed in this region following the retreating ice edge, during the recent U.S. JGOFS study in 1997–1998, AESOPS [*Smith et al.*, 2000; *Buesseler et al.*, 2003]. The highest surface layer dissolved iron concentrations (0.25–0.29 nM) during the AESOPS early summer cruise were observed adjacent to the ice edge, coincident with high chlorophyll and POC concentrations, suggesting substantial iron release and biological uptake prior to sampling [*Measures and Vink*, 2001]. The strong correlation between ice retreat and southward bloom propagation [*Buesseler et al.*, 2003] can be viewed as indirect evidence of substantial iron release of melting ice fueling the AESOPS bloom. *Croot et al.* [2004] report evidence for iron release from sea ice as a key factor driving a *Phaeocystis* sp. bloom at the spring ice edge in the Atlantic sector. *Löscher et al.* [1997] also suggest release of dissolved iron from melting sea ice along 6°W during 1992 the ANT X/6 JGOFS expedition. In addition, ice bergs derived from continental glacial sources can also release significant amounts of dissolve iron as they melt [*Löscher et al.*, 1997].

[6] The 2002 Southern Ocean Iron Experiment (SOFeX) involved the purposeful fertilization, with dissolved iron additions, of two mesoscale ocean patches (15 km × 15 km), one north and one south of the Antarctic Polar Front (PF) in the southwest Pacific sector of the Southern Ocean (SO) [*Coale et al.*, 2004]. Phytoplankton blooms developed in both iron-fertilized patches with increases in chlorophyll concentrations, particulate organic carbon (POC), and POC export, and decreases in surface nitrate, silicate, and pCO_2 values relative to surrounding waters [*Coale et al.*, 2004; *Buesseler et al.*, 2004; *Bishop et al.*, 2004].

[7] The SOFeX experiments were designed to examine the effects of iron fertilization in both the high-silicate waters south of the PF, and in the low-silicate waters north of the PF. Thus the southern SOFeX patch was in a region with high concentrations of nitrate (28 μM) and silicate (60 μM), while the northern patch region had high nitrate (20 μM) but relatively low ambient silicate concentrations (<3 μM) [*Coale et al.*, 2004]. A key goal of the experiment was to test how iron additions would affect the ecosystems in these high- and low-silicate regions. Iron additions to the south patch were made on year days 24, 29, 32, and 36, and to the north patch on year days 10, 16, 41. Iron concentrations reached 1.2 nM in the north patch and 0.7 nM in the south patch [*Coale et al.*, 2004]. In the southern patch (66°S, 172°W) the result of iron fertilization was a bloom dominated by diatoms (as in most other fertilization experiments to date, i.e., IronEx II [*Coale et al.*, 1996]; SOIREE [*Boyd et al.*, 2000]; SEEDS [*Tsuda et al.*, 2003; *de Baar et al.*, 2005]). In the northern patch a bloom developed composed of diatoms and a mix of other flagellated phytoplankton groups [*Coale et al.*, 2004]. After fertilization maximum observed rates of photosynthesis (mmolC/m^3/day) increased by factors of 23.8 for the south patch and 15.9 for the north patch, and chlorophyll concentrations increased by factors of 20 and 10 for the south and north patches [*Coale et al.*, 2004].

[8] Dilution of the fertilized patch with surrounding waters will act to lower iron and chlorophyll concentrations, but increase macronutrient concentrations as these are depleted within the patch [*Boyd et al.*, 2000; *Abraham et al.*, 2000]. *Hiscock and Millero* [2005] reported an observed depletion within the southern patch at day 20 after fertilization of 3.5 μmol/kg nitrate, 0.21 μmol/kg phosphate, and 4.0 μmol/kg silicate. However, correcting for the increases due to dilution with surrounding waters, the drawdowns by the bloom increase to 9.2, 0.55, and 10.6 μmol/kg, respectively. At the north patch the observed depletion on Day 39 were 1.4 μmol/kg nitrate, 0.09 μmol/kg phosphate, and 1.1 μmol/kg silicic acid (with dilution corrected estimates

of 7.4, 0.48, and 5.8 μmol/kg, respectively [*Hiscock and Millero*, 2005]). Given that initial silicic acid concentrations at the North patch were only ~2.8 μmol/kg, roughly half of the silicic acid required by the bloom came from mixing in of surrounding waters [*Hiscock and Millero*, 2005; *Brzezinski et al.*, 2005]. The generally low silicic acid concentrations at the north patch significantly limited biogenic silica production both within and outside of the patch [*Brzezinski et al.*, 2005]. The addition of iron increased maximum uptake rates and decreased the half-saturation constant for silicic acid uptake at the north patch indicating that both silicic acid and iron were limiting the production of biogenic silica by the diatoms, and likely controlling their contribution to export production [*Brzezinski et al.*, 2005].

[9] The increases in export flux associated with the patches were generally more modest than the increases in biomass and production. Particulate organic carbon (POC) and biogenic silica (bSi) export from the southern patch increased by a factor of ~3 from the upper 50 m, with larger increases of 7 and 6 estimated for the flux at 100 m by the ^{234}Th method [*Buesseler et al.*, 2005]. The natural bloom observed in this region during AESOPS had significantly higher POC export than the SOFeX southern patch (roughly a factor of 2 [*Buesseler et al.*, 2005]). These authors note that export may have increased after the sampling period for the southern patch. *Bishop et al.* [2004] concluded that export increased significantly within the northern SOFeX patch as well, using profiling autonomous floats calibrated with data from the southern patch. All of the above results clearly indicate that iron was strongly limiting phytoplankton growth and biomass accumulation at both the north and south SOFeX patch locations. *Coale et al.* [2004] suggest that as the blooms developed light limitation due to self-shading may have prevented full depletion of available macronutrients.

[10] The northern patch (56°S, 172°W) was stretched into a long, thin filament extending approximately 7 km by >340 km, while the southern patch experienced less shear and expanded in all directions roughly equally [*Coale et al.*, 2004]. The shear due to currents and the stretching into a thin filament of the northern patch was also observed in the SOIREE fertilization experiment [*Boyd et al.*, 2000]. Despite the stronger shear at the northern site that elongated the patch, *Coale et al.* [2004] estimated only moderately higher dilution rates for the northern patch (0.11 day^{-1} versus 0.08 day^{-1}, although a larger dilution rate difference was observed based on SF6 data alone).

[11] Here we examine satellite remote sensing data from the SW Pacific to assess (1) What was the natural seasonal cycle outside the SOFeX patches during the 2001–2002 growing season? (2) How typical was this seasonal cycle compared to other years? (3) How representative were the patch locations for this region? (4) How did regional-scale circulation and other physical forcings influence the two iron-fertilized patches and surrounding waters? and (5) What are the driving forces of natural variability in phytoplankton chlorophyll in this region? Remote sensing data can help place the SOFeX fertilizations into a larger context, and through comparison of in patch chlorophyll with surrounding unfertilized waters, provide insight into the relative roles of iron, light, sea ice cover, winds, frontal dynamics, and other forcings in driving ocean biogeochemical cycling in this region.

[12] In brief, we show that the background biological conditions around the SOFeX southern patch in the austral summer of 2002 were somewhat atypical relative to either the multiyear climatological state or to conditions east and west of the site in 2001–2002. The adjacent regions both east and west of the southern SOFeX fertilization site had elevated chlorophyll concentrations (approaching 1 mg/m^3); we refer to these as "modest" blooms to distinguish them from the intense blooms observed within the southern patch and during AESOPS (chlorophyll >3 mg/m^3). Because of the late sea ice retreat, the initiation of the modest spring bloom often observed in this region was delayed from December into January. The high spatial and temporal variability observed in the satellite data highlight the degree to which modest, natural perturbation "experiments" continually occur in the Southern Ocean, a fact that could be exploited in future field projects to better understand iron and ecosystem dynamics in the SO.

[13] Background conditions at the northern patch were more representative of climatological conditions. The PF and SAF in this part of the SO are commonly associated with filaments of elevated surface chlorophyll, at times exceeding 1 mg/m^3 [e.g., *Moore et al.*, 1999a], and the stretching of the northern SOFeX patch appears to have been associated with eastward advection along the southern edge of the Subantarctic Front.

2. Methods

[14] Monthly and daily SeaWiFS images were obtained from the Goddard Space Flight Center Distributed Active Archive Center at ~9 km resolution (SeaWiFS version 4.0 [*McClain et al.*, 2004]) and at ~4 km and ~1 km from MODIS (Terra, for chlorophyll and sea surface temperature (SST)). Monthly mean sea ice concentrations (NASA Team algorithm) at ~25 km resolution from the Special Sensor Microwave Imager (SSM/I) were obtained from the National Snow and Ice Data Center Distributed Active Archive Center [*Cavalieri et al.*, 2004] and remapped to the ~9 km equal-angle grid used for SeaWiFS and the sea surface temperature (SST) data for comparison. Monthly images of sea surface temperature (SST) (ascending pass) were obtained from the NOAA/NASA Pathfinder Project at the Jet Propulsion Laboratory Distributed Active Archive Center [*Brown et al.*, 1993; *Kilpatrick et al.*, 2001]. QuikSCAT L3 estimates of daily surface wind speeds (0.25 degree resolution) were also obtained from the Jet Propulsion Laboratory Distributed Active Archive Center. To create climatologies for assessing the SOFeX growing season (2001–2002), we averaged SeaWiFS chlorophyll, sea surface temperature, and percentage sea ice cover data from five other growing seasons (1997–1998, 1998–1999, 1999–2000, 2000–2001, 2002–2003).

[15] Several studies have attempted to assess the accuracy of the SeaWiFS global chlorophyll algorithms in Southern Ocean waters for versions OC2 [*Moore et al.*, 1999a; *Abbott et al.*, 2000] and OC4v4 [*Murphy et al.*, 2001; *Clementson et al.*, 2001; *Arrigo and van Dijken*, 2004; *Garcia et al.*, 2005]. Reaching similar conclusions, these studies found relatively good agreement between in situ measurements

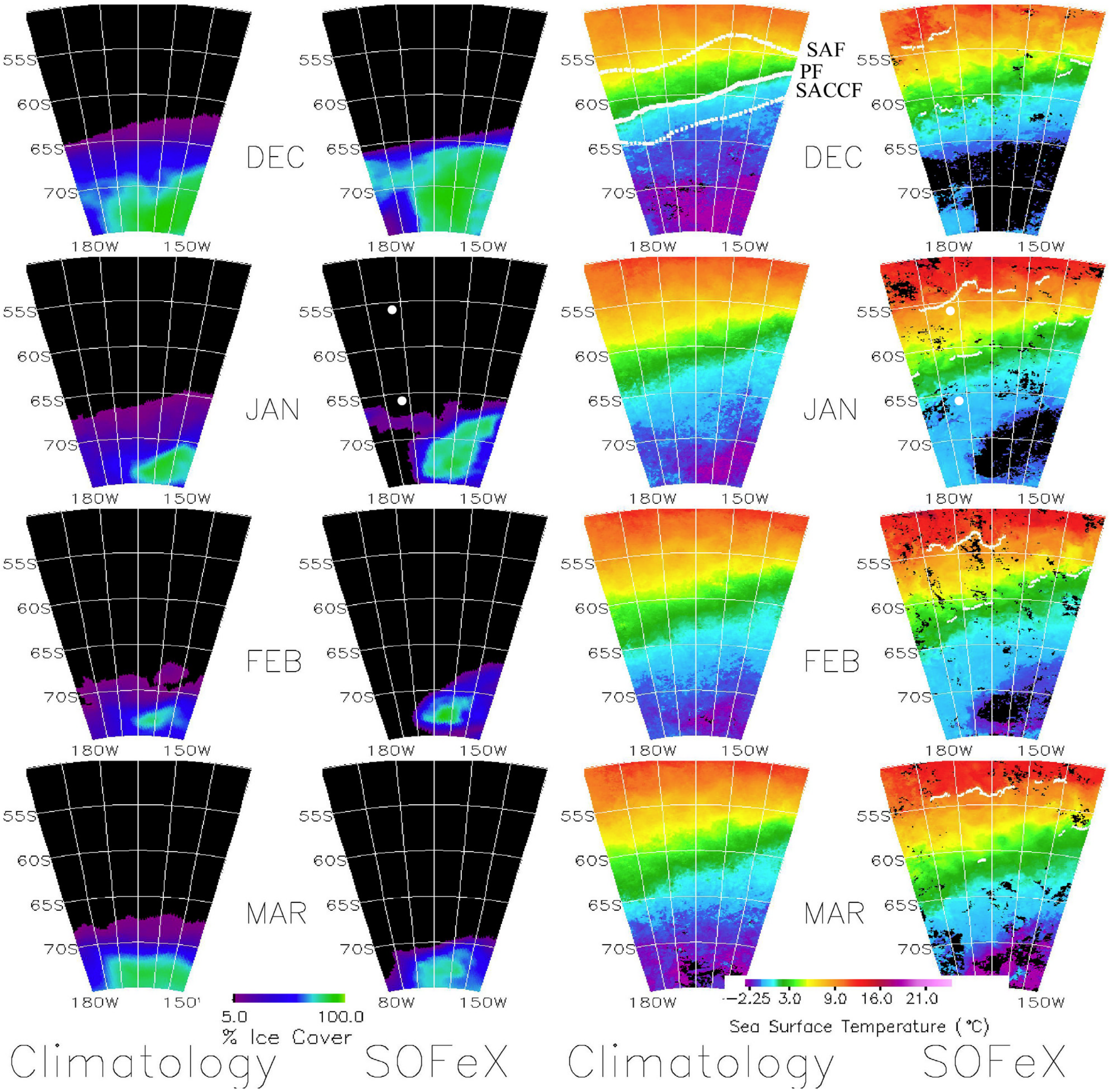

Figure 1. Monthly sea ice concentration and sea surface temperature (SST) from our climatology are compared with those observed during the SOFeX season (December 2001 to March 2002). White spots indicate the location of initial iron additions during January 2002. The white lines on the sea the surface temperature images indicate frontal locations from climatology or our analysis of SST during 2001–2002.

and the satellite estimates (r^2 correlations from Type II linear regressions of ~0.6–0.86) with a consistent tendency for SeaWiFS to underestimate chlorophyll, particularly at higher chlorophyll concentrations (regressions slopes from satellite vs. in situ between 0.52 and 0.88). This underestimation tendency was also present in the earlier generation Coastal Zone Color Scanner (CZCS) satellite sensor global algorithm [*Mitchell and Holm-Hansen*, 1991; *Sullivan et al.*, 1993], but the problem seems less severe with SeaWiFS [*Moore and Abbott*, 2000; *Garcia et al.*, 2005]. The goal of the SeaWiFS project is to estimate chlorophyll concentrations within ±35% (a goal not always met in the above cited studies). *Garcia et al.* [2005] estimated a bias of −21.7% for the OC4v4 algorithm in SO waters. Here we use the satellite data to examine spatial and temporal patterns in the SW Pacific with a focus more on variations rather than absolute chlorophyll concentrations. We note that absolute concentrations are likely underestimated, particularly for mid to high concentrations (>~0.5 mg/m^3). Another difficulty in interpreting the SeaWiFS imagery is that there is no way to distinguish changes in phytoplankton biomass (changes in phytoplankton particulate organic carbon) from changes in the C/chlorophyll ratios, due to photoadaptation or varying iron stress. In general, we assume that chloro-

Table 1. Monthly Mean Satellite Estimated Chlorophyll Concentrations, Sea Surface Temperature Values, and Percentage Sea Ice Coverage (for South Patch Site Only) During the SOFeX Season and in Our Climatologies[a]

Month	C-Chl, mg/m^3	S-Chl, mg/m^3	C-SST, °C	S-SST, °C	C%ICE	S%ICE
			South Patch Area (65°–67°S, 174°–170°W)			
December	0.65	0.27	−0.033	−0.98	23	36
January	0.42	0.26	−0.011	−0.33	1.4	0
February	0.27	0.46	0.31	0.18	0	0
March	0.23	0.45	−0.25	0.34	0	0
			North Patch Area (52°–57°S, 174°–164°W)			
December	0.29	0.31	9.0	7.6		
January	0.20	0.17	8.0	9.4		
February	0.20	0.19	8.2	9.2		
March	0.20	0.18	7.9	9.3		

[a] C-Chl, climatological chlorophyll; S-Chl, SOFeX chlorophyll, etc.

phyll variations are mainly due to changes in biomass, particularly across regions where SST, wind speeds, and ice melt influence are similar (i.e., where there is no reason to assume large changes in mixed layer depths). However, this complicating factor does add some additional uncertainty to our analysis.

[16] The monthly SST data was used to map the locations of Antarctic Polar Front (PF) and the Subantarctic Front (SAF) using methods developed previously for the PF [*Moore et al.*, 1997, 1999b; *Moore and Abbott*, 2002]. In this method, the location of the poleward of edge of the strong SST gradient associated with frontal features is subjectively digitized. There is some potential for error associated with the approach because frontal locations in this region can shift substantially over the course of a month [*Moore et al.*, 1999b], and this can smear or obscure the SST gradient signal in the monthly images. At times the cross frontal temperature gradient can also be too weak to be detected with our technique [*Moore et al.*, 1999b].

3. Results

[17] Wintertime sea ice cover directly influences the southern SOFeX patch site. The spring sea ice retreat in this region was delayed during the SOFeX season compared with other years (Figure 1). Heavier sea ice cover (concentrations >~70%), particularly just south of the injection site, persisted in this region through December 2001 during the SOFeX campaign relative to the climatology (Figure 1 and Table 1). The ice edge extends farther north in the climatology but at low concentrations (<~25%). The effect of heavy sea ice cover can also be seen in the monthly sea surface temperature (Figure 1) and chlorophyll data (Figure 2) from the region. There are few valid SST observations between 65°–70°S due mainly to heavy sea ice cover during December 2001 (Figure 1). Sea surface temperatures tend to be somewhat cooler than the climatology at the southern patch site, and generally warmer than the climatology at the northern patch site (Table 1). In Table 1, we compare the SOFeX season sea ice cover, chlorophyll concentration and sea surface temperature for two boxes centered on the south and north patch sites with data from our climatologies. The box averaged for the north patch is larger to encompass the elongation and substantial drift observed for the north patch [*Coale et al.*, 2004].

[18] The mean location of the major fronts of the Antarctic Circumpolar Current (ACC) are overlain on the climatological temperature field for December in Figure 1. These frontal locations are determined by satellite SST for the position of the PF [*Moore et al.*, 1999a], and by historical hydrographic data for the SAF and the Southern Antarctic Circumpolar Current Front (SACCF) [*Orsi et al.*, 1995]. The SACCF is the most southerly of the three fronts followed by the PF and then the SAF. The locations of the SAF and PF during the SOFeX season are shown over the SST images in Figure 1, where the frontal locations could be determined in the monthly satellite SST data using the methods developed previously for the PF [*Moore et al.*, 1997, 1999b]. The PF is located quite close to its long-term mean position for the period December through February, and we were unable to determine the position over most of this region during March 2002 as sufficiently strong SST gradients were not observed. The stability of the PF location is not surprising as topographic control of the PF location is quite strong in this region [*Moore et al.*, 1999b]. The satellite derived SAF was located several degrees of latitude north of the mean position determined from hydrography by *Orsi et al.* [1995], and can be seen in the same general location in each monthly SST image. In subsequent sections, we will show that the SOFeX northern patch was stretched into a long thin filament along the southern boundary of this front.

[19] Examining the regional monthly surface chlorophyll values for this region from SeaWiFS, we can see a strong impact in the southerly areas from the delayed sea ice retreat. In our climatology, a modest spring bloom is apparent in the general latitudes of the southern patch location that is strongest during December, declining in magnitude during January, and nearly spent by February (at least north of 70°S, below this latitude high chlorophyll concentrations persist into March) (Figure 2). This bloom is initiated as sea ice melts, and then moves poleward as the sea ice retreats further south (compare Figures 1 and 2). This general pattern is also what was observed in situ and in the satellite data during AESOPS [*Moore et al.*, 1999a; *Smith et al.*, 2000; *Buesseler et al.*, 2003]. During the 2001–2002 growing season, the ice edge induced bloom did not begin until January 2002 and extended well into February 2002 in the general region between 65° and 70°S. The southern SOFeX patch (66°S and 172°W) was located

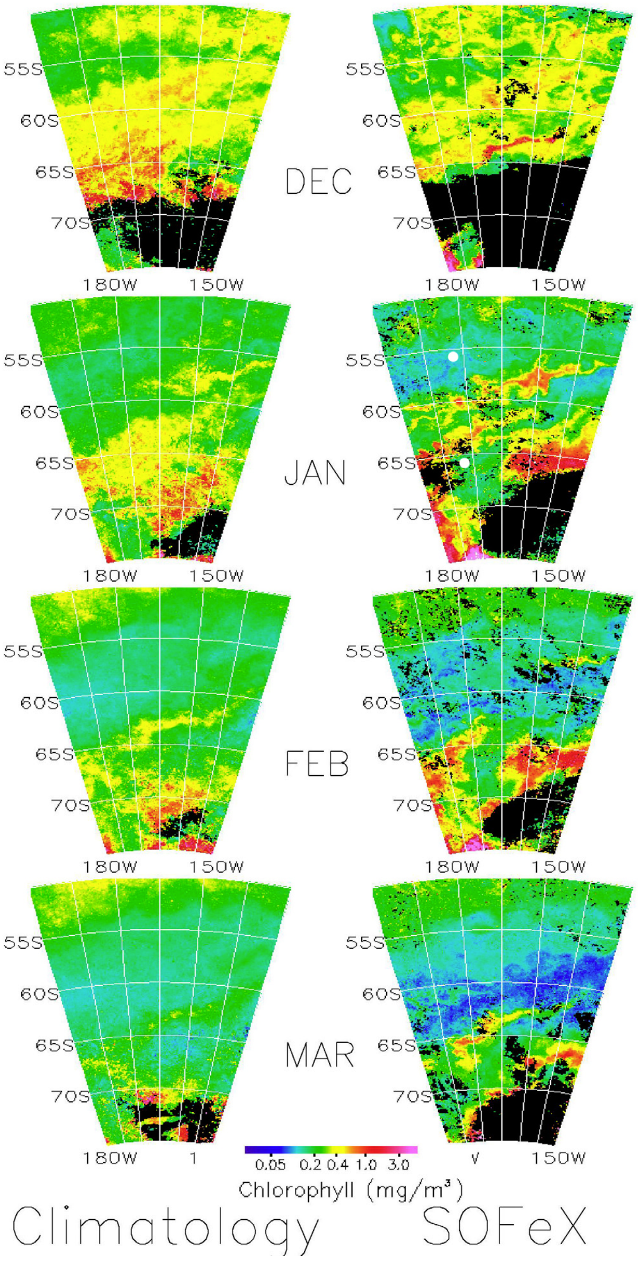

Figure 2. Monthly surface chlorophyll concentrations (SeaWiFS) from our climatology are compared with those observed during the SOFeX season. White spots indicate the location of initial iron additions during January 2002.

in an area of relatively low chlorophyll that can be seen in the January 2002 monthly data covering most of the area between 65° and 70°S and 165° and 175°W (Figure 2). Areas with higher ambient chlorophyll concentrations can be seen both to the east and west of this low chlorophyll region in the January 2002 and February 2002 monthly images (Figure 2). It is notable that these areas were able to achieve chlorophyll concentrations as high as ~1 mg/m^3 without artificial iron additions, while the SOFeX results suggest that the waters in the immediate vicinity of the south patch were strongly iron-limited to the extent that surface chlorophyll concentrations remained low (~0.3 mg/m^3), despite relatively shallow mixed layer depths of ~35 m [*Coale et al.*, 2004]. *Coale et al.* [2004] argued that light was not limiting initially but may have become limiting as the bloom developed. *Boyd et al.* [2000, 2001] found that light levels corresponding to mixed layer depths as deep as 65m did not seriously limit growth rates under iron-replete conditions.

[20] Farther north in the vicinity of the northern SOFeX patch site (56°S, 172°W), in general chlorophyll concentrations were slightly lower than the climatology from January through March south of the fertilization site, while concentrations north of the fertilization site were quite similar to the climatological values (Figure 2). Chlorophyll concentrations to the north of ~60°S are similar to the climatology during the month of December, while during January the region between 55° and 60°S and 180° and 170°W, which includes the northern patch fertilization site, chlorophyll concentrations were slightly below the climatological values (Figure 2). This region of somewhat lower than typical chlorophyll concentrations is expanded during February and March covering much of the region between 55° and 65°S.

[21] Chlorophyll distributions in the southwest Pacific sector of the SO occur within a background spatial pattern structured by the locations of the major fronts [*Moore et al.*, 1999a; *Smith et al.*, 2000]. Elevated chlorophyll associated with the major fronts can be seen in several of the monthly images from the 2001–2002 growing season and in the climatology. During January elevated chlorophyll concentrations relative to surrounding waters can be seen at the PF across the entire region (compare frontal paths in Figure 1 with Figure 2). Similarly, elevated chlorophyll along the mean location of the SACCF can be observed to some extent in each monthly image during SOFeX (compare mean location from Figure 1 with Figure 2). In December a strong bloom is visible in the vicinity of the mean SACCF location at ~63°–64°S between ~168° and 157°W. In the January image the bloom seen south of ~64°S between 180° and 175°W then extends for hundreds of km to the northeast along the mean location of the SACCF (compare Figures 1 and 2).

[22] If we compare the climatology and SOFeX monthly values in the immediate vicinity of the southern patch site, it is apparent that chlorophyll was anomalously low during December and January, and anomalously high during February and March (Figure 3). Because of the patchy nature of these data sets because of extensive cloud cover, the bloom induced by iron additions in the southern patch was not observed during the month of January by SeaWiFS. However, elevated chlorophyll is seen in the monthly image for February at the south patch site (~66.1°–65.7°S, ~172.5°–171.8°W in Figure 3). (Our ~9 km monthly composite data does not resolve the patch accurately, but see *Coale et al.*, 2004 for a high-resolution SeaWiFS image of the southern patch bloom). Also visible is the modest phytoplankton bloom to the west of the southern patch site. It appears that this bloom was advected eastward into the original location of the southern patch fertilization by March (Figures 2 and 3). This is consistent with the observed eastward drift of the southern patch [*Coale et al.*, 2004, Figure S1].

[23] We also compare chlorophyll concentrations in the immediate vicinity of the northern patch with the SeaWiFS

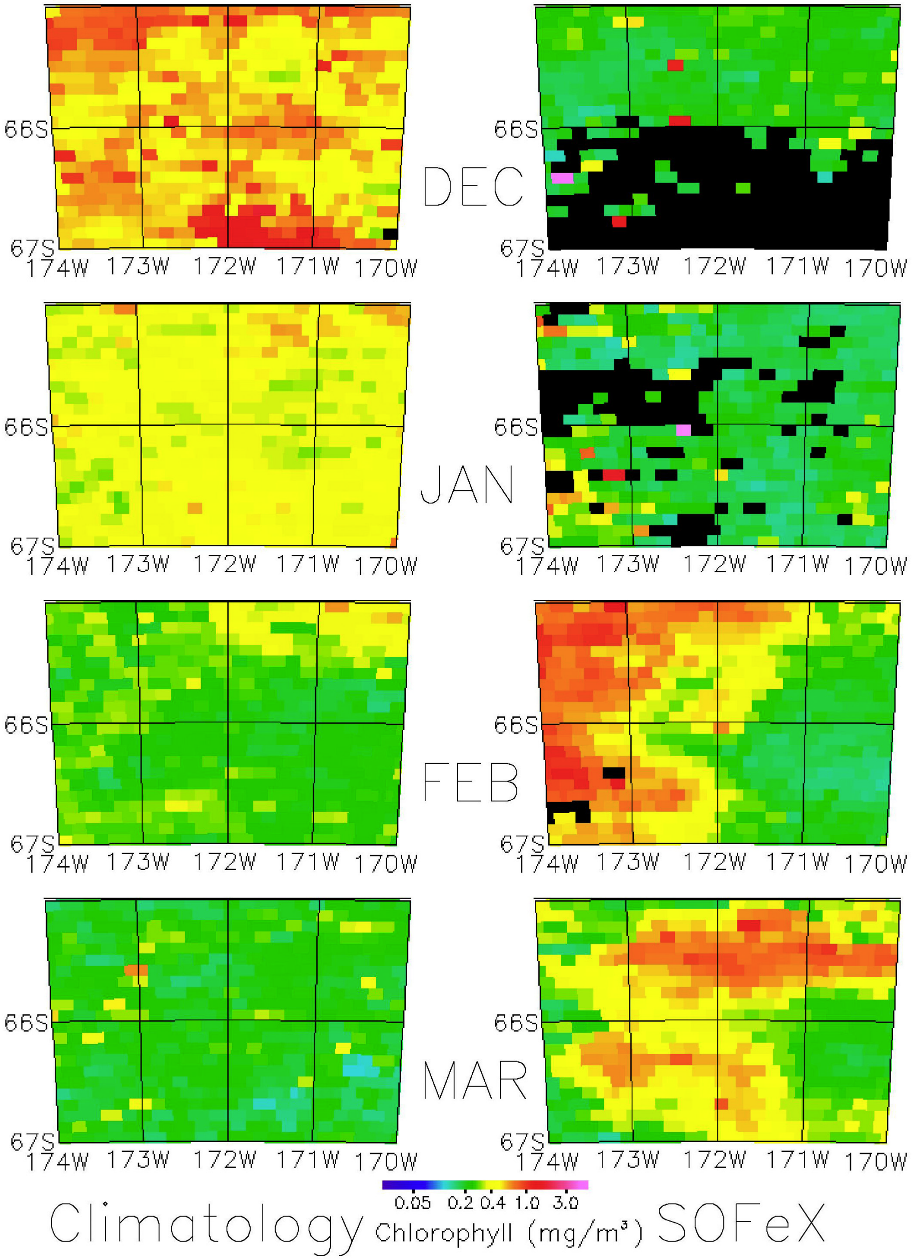

Figure 3. Monthly surface chlorophyll concentrations (SeaWiFS) from our climatology are compared with those observed during the SOFeX season in the vicinity of the southern fertilization patch.

climatology in Figure 4. Our estimated position for the southern edge of the SST gradient associated with the SAF is shown over the chlorophyll image for February in Figure 4. Chlorophyll concentrations are consistently lower on the poleward side of this front than to the north by ~0.1–0.2 mg/m^3 (Figures 4 and 5). The northern patch was originally fertilized at 56°S, 172°W, but over the course of the next several weeks as the phytoplankton bloom was developing, this patch was stretched into a long thin filament and advected hundreds of km to the northeast of the original fertilization site [*Coale et al.*, 2004, Figure S1]. Because of the patchy coverage of the SeaWiFS data this bloom is not apparent in any image we examined (in the ~9 km or the LAC ~ 1km data sets). The bloom is apparent in several images from the MODIS Terra sensor [see *Coale et al.*, 2004] (Figure 5). Comparing the chlorophyll and sea surface temperature data from MODIS on 5 February 2002 (Figure 5) with the monthly SST, chlorophyll and SAF position from Figures 1 and 4, it is apparent that the northern patch bloom is being stretched out along the southern boundary of the SAF.

[24] To better understand the mesoscale spatial patterns in the southern portion of our study area, we computed mean chlorophyll concentration, wind speed, percent sea ice

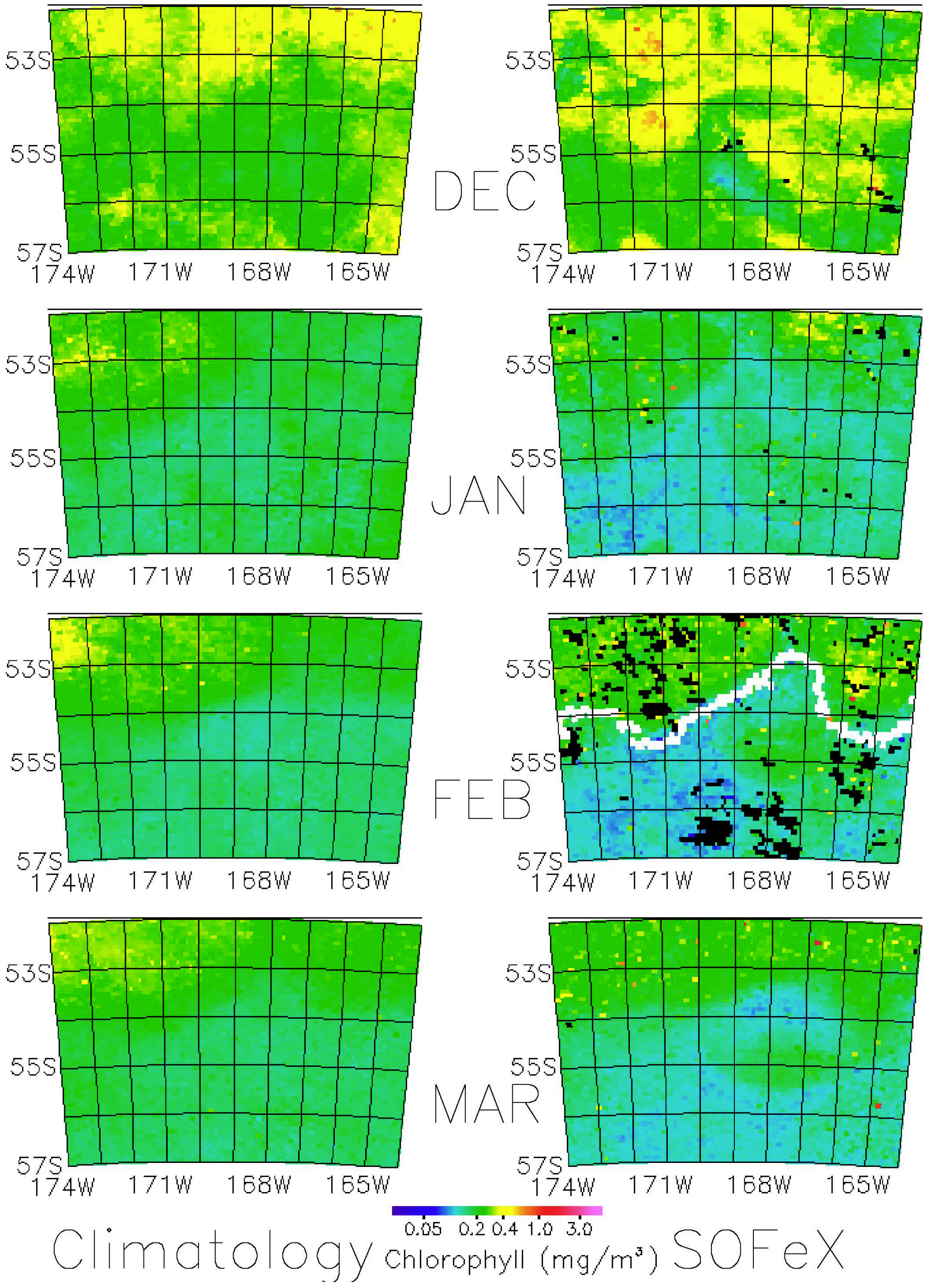

Figure 4. Monthly surface chlorophyll concentrations (SeaWiFS) from our climatology are compared with those observed during the SOFeX season in the vicinity of the northern fertilization patch.

cover, and sea surface temperature for an area encompassing the southern patch site, and for representative locations within the naturally blooming regions to the east and west of the patch site (Table 2). One possibility for the elevated chlorophyll concentrations during January 2002 to the west (area 1) and east (area 3) relative to the climatology and the 2002 SOFeX southern patch region (area 2, see Table 2) is that shallower mixed layers allowed for reduced light limitation, decreased iron quotas, and increased phytoplankton growth. Mean wind speeds were nearly identical for the three regions, but there seem to have been different levels of freshwater input from melting sea ice in 2001–2002 that could have affected mixed layer depths (Table 2). Melting sea ice can also release dissolved iron into surface waters [*Sedwick and DiTullio*, 1997; *Measures and Vink*, 2001; *Croot et al.*, 2004]. Area 3 to the east of the SOFeX site had substantially higher sea ice cover during December of 2001, and cooler mean sea surface temperatures during December 2001 and January 2002, probably indicative of cold meltwater release from sea ice (Table 2). Area 1 also had modestly higher sea ice cover during December than area 2. The blooms seen in area 1 (apparent in Figures 2 and 3) may partly reflect advection from farther west. The mean January chlorophyll in the region 5 degrees to the west of area 1 (65°–68°S by 175°–180°E) was quite high at 1.04 mg/m3, and the January sea ice was also elevated at

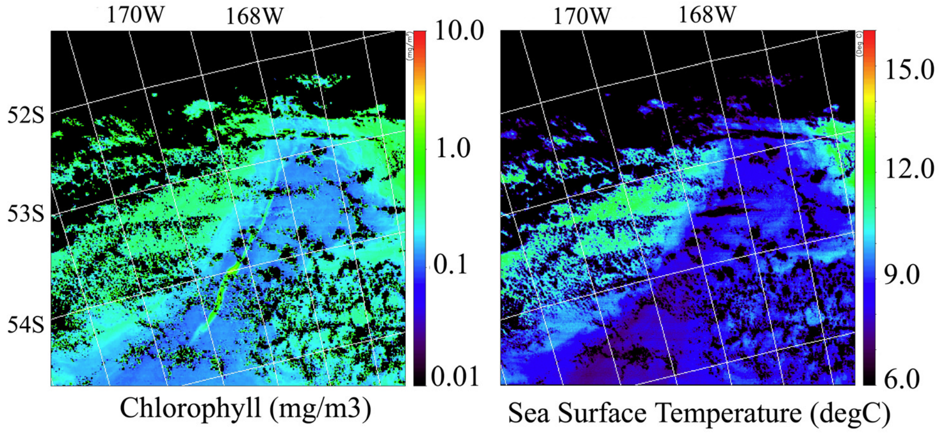

Figure 5. Surface chlorophyll concentrations and sea surface temperatures from MODIS (Terra) are shown at high resolution in the vicinity of the north fertilization patch from 5 February 2002.

28% (compare with values in Table 2). Thus the satellite data is consistent with the idea that the modest blooms seen both to the east and west of the southern SOFeX patch site were driven by the generally delayed sea ice retreat seen during the 2001–2002 growing season. In the vicinity of the southern patch chlorophyll concentrations were lower than in these more strongly ice-influenced areas (Table 2). These ambient concentrations of ~0.3 mg/m3 (Table 2 and Figures 2 and 3) are similar to the values typically observed in open ocean regions of the Southern Ocean away from the ice edge blooms [*Moore and Abbott*, 2000] and likely reflect reduced ice retreat influence and strong iron limitation. In addition to variations in meltwater and iron release, the timing of the ice edge retreat may also influence bloom dynamics in this region as it interacts with seasonal patterns in solar forcing, sea surface temperature, wind speeds and direction.

4. Discussion

[25] The SOFeX fertilizations clearly demonstrate that iron availability was limiting phytoplankton growth rates and biomass accumulation at both the south and north patch sites. The satellite data presented here shows that natural, modest blooms, though smaller in magnitude than observed in the iron-fertilized south patch, occurred over wide areas both just to the west and several degrees of longitude to the east of the south patch fertilization site. Blooms of this magnitude seem to be a relatively common occurrence in this region of the SW Pacific [*Moore et al.*, 1999a; *Moore and Abbott*, 2000, 2002; *Meguro et al.*, 2004]. Notably, we did not observe such mesoscale variability in chlorophyll concentrations in the vicinity of the north patch. We hypothesize that the key difference was that the southern region benefited from increased stratification and iron inputs from melting sea ice and icebergs.

[26] At larger spatial scales, the question remains why are there consistently modest spring phytoplankton blooms in this sector of the Southern Ocean, while other areas of ice retreat show little elevated chlorophyll? The source for the sea ice melting in this region is likely the Ross Sea. Much of the ice may be formed nearshore as winds move ice away from the coast. It is well established that dissolved iron concentrations in the Ross Sea and other shelf regions are often elevated due to diffusion and mixing of shelf iron into the water column [*Nolting et al.*, 1991; *Martin et al.*, 1990b]. Sea ice formed in this region may have elevated iron content [*Sedwick and DiTullio*, 1997; *Grotti et al.*, 2005]. Icebergs discharged from the Ross ice shelves may also release large amounts of iron from dust and rock accumulated through glacial processes on the continent [*Martin et al.*, 1990b; *Nolting et al.*, 1991]. *Martin et al.* [1990a] measured dissolvable iron in a glacial iceberg from the Gerlache Strait at 26.7 nm/kg. *Löscher et al.* [1997] reported iceberg concentrations from 10 to 100 nM. The southern portion of our study is encompasses the maximum extent of the seasonal ice zone. The mesoscale spatial variations seen in our analysis are most likely due to both varying influence of sea ice melting (variable fresh water inputs to surface waters) and to variations in the iron released from the ice which would be a function of ice formation region (nearshore versus offshore) and atmospheric dust deposition.

[27] Returning to the questions laid out in our introduction: (1) What was the natural seasonal cycle outside the SOFeX patches during the 2001–2002 growing season? (2) How typical was this seasonal cycle compared to other years? (3) How representative were the patch locations for this region? (4) How did regional-scale circulation and other

Table 2. Mean Chlorophyll Concentration, Percentage Sea Ice Cover, and Sea Surface Temperature for Three Areas in the Southern Portion of the SOFeX Region[a]

	Area 1	Area 2	Area 3
December percent sea ice cover	52	47	66
January percent sea ice cover	13	8	10
January chlorophyll, mg/m^3	0.74	0.29	0.79
December sea surface temperature, °C	−0.79	−0.99	−1.1
January sea surface temperature, °C	−0.081	−0.39	−0.55
January mean wind speed, m/s	8.4	8.4	8.3

[a] The areas are as follows: area 1, 65°–68°S, 180°–175°W; area 2, 65°–68°S, 175°–170°W; area 3, 65°–68°S, 165°–160°W. The southern SOFeX fertilization site was within area 2.

physical forcings influence the two iron-fertilized patches and surrounding waters? (5) What are the driving forces of natural variability in phytoplankton chlorophyll in this region? The seasonal cycle in surface chlorophyll concentrations in the vicinity of the northern SOFeX patch was quite similar to our climatology (Figure 4), and similar to the pattern seen over much of the Southern Ocean north of the SIZ [*Moore and Abbott*, 2000]. The patch was significantly impacted by advection associated with the SAF which may have increased the dilution rate between patch and surrounding waters, helping to fuel the observed bloom. In particular, had the patch been sited within quieter waters with less shear, the diatoms might have been more strongly impacted by Si limitation [*Brzezinski et al.*, 2005; *Hiscock and Millero*, 2005] and contributed less to the north patch bloom. Much of the natural variability in chlorophyll concentrations in this area appear to be associated with the location and dynamics of the major oceanographic fronts [*Moore et al.*, 1999a; *Moore and Abbott*, 2000, 2002; this study].

[28] The seasonal cycle in the waters encompassing the southern SOFeX patch was marked by anomalously low chlorophyll values during December and January (Figures 2 and 3). Our analysis suggests that this area was somewhat less impacted by sea ice retreat than the regions just to the west and east which exhibited higher chlorophyll concentrations. We suggest that variable iron content within the sea ice also likely played a role. These modestly blooming regions adjacent to the southern fertilization site had chlorophyll concentrations well below those observed within the SOFeX patch or during AESOPS, and thus were likely still iron limited. It is not clear that the SOFeX bloom would have progressed much differently if it had been cited in these regions, or if chlorophyll concentrations at the fertilization site had been more typical of other years. Although, the initial biomass might have been higher with perhaps an altered community composition.

[29] Satellite observations of the SOFeX iron-fertilized patches were limited due to extensive cloud cover. The available images for both patches, however, do show chlorophyll concentrations much higher than in the surrounding waters [*Coale et al.*, 2004; this study]. These images, model simulations, and all of the extensive in situ data collected during the SOFeX and EisenEx, and SOIREE experiments clearly illustrate the key role that iron plays in this region in limiting phytoplankton growth rates and biomass accumulation [*Boyd et al.*, 2000; *Fung et al.*, 2000; *Coale et al.*, 2004; *Moore et al.*, 2002, 2004; *Bakker et al.*, 2005; *de Baar et al.*, 2005]. Observations from the southern patch [*Coale et al.*, 2004], and from a recent synthesis of iron fertilization experiment results [*de Baar et al.*, 2005] also point to light as a limiting factor, even during summer months, in areas of moderate to high chlorophyll concentrations. Although, in vitro experiments *Boyd et al.* [2000] found evidence little evidence of light limitation of the SOIREE bloom at a mixed layer depth of 65m with indication of strong light limitation at light regimes corresponding to mixed layer depths of 100 m. In the SEEDS experiment, in the subarctic North Pacific, mixed layers were substantially shallower than in SOFeX, and the bloom magnitude and nutrient decreases in surface waters observed were much larger [*Coale et al.*, 2004; *Tsuda et al.*, 2003; *de Baar et al.*, 2005]. In their review of eight iron fertilization experiments *de Baar et al.* [2005] found in general a strong inverse correlation between wind mixed layer depth and maximum chlorophyll concentrations, dissolved inorganic carbon (DIC) removal, and the overall DIC/Fe efficiency.

[30] More measurements of dissolved and particulate iron concentrations within sea ice, icebergs, and around the retreating ice edge are needed to quantify the role of sea ice and icebergs as iron sources, and to assess the relative importance of mixed layer shoaling (including its effects on both light regime and iron quotas), and iron release in the generation of ice edge phytoplankton blooms. Ongoing ecological/biogeochemical model simulations and analysis of a longer time series of satellite wind speed, ice dynamics, and chlorophyll data should also provide further insights on these processes.

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