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Wind speed influence on phytoplankton bloom dynamics in the Southern Ocean Marginal Ice Zone

Dillon T. Fitch^{1,2} and J. Keith Moore¹

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[1] Analysis of satellite ocean color and wind speed data within the seasonal ice zone (SIZ) of the Southern Ocean sheds light on the physical processes that influence phytoplankton biomass distributions. A compilation of monthly averaged chlorophyll and percent sea ice cover data within the SIZ from 1997 to 2005 has been compared with monthly average wind speed data from 1999 to 2005. The size of the marginal ice zone (MIZ, areas of recent ice retreat) was fairly consistent from year to year, always peaking in December, with a mean area of 6.0 million km². The mean area within the MIZ with phytoplankton blooms (chlorophyll exceeding 0.8 mg/m³) was 0.36 million km². While the bloom areal extent seems small compared to the MIZ, in reality, because of gaps in the chlorophyll data, blooming regions comprise a much larger fraction of the MIZ. Considering only areas with valid chlorophyll data, the percentage of the MIZ with blooms was 17%, 21%, and 24% for the months of December, January, and February, respectively. December always has the largest MIZ area, but MIZ mean chlorophyll concentrations sometimes do not peak until February. Wind speed strongly impacts phytoplankton bloom dynamics within the MIZ. There is an inverse relation between wind speed and bloom occurrence, with blooms largely suppressed at high wind speeds. At low wind speeds (~5 m/s), blooms are observed over about one third of the MIZ. Blooms are also much more frequent near the continent than in offshore waters, likely due to increased iron availability. Open ocean phytoplankton blooms in the Southern Ocean are likely to become iron-light co-limited except in regions where the mixed layer depth is relatively shallow.

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1. Introduction

[2] Within the Southern Ocean (SO) lies a region where ecological dynamics vary from the usual High Nutrient, Low Chlorophyll (HNLC) regime. During the seasonal retreat of sea ice, relatively high chlorophyll concentrations are often observed within the marginal ice zone (MIZ), with blooms extending over thousands of kilometers in area [i.e. *Smith and Nelson*, 1986; *Moore and Abbott*, 2000]. Interestingly, this high chlorophyll anomaly is also extremely variable temporally and spatially. The size and location of the MIZ, defined as areas of recent ice melting/retreat, will vary by time of season and from year to year. The phytoplankton blooms within the MIZ are an important food source for higher trophic levels and significantly impact biogeochemical cycling in the region [*Smith and Nelson*, 1986; *Arrigo et al.*, 1998a].

[3] The physical process of melting sea ice has important implications for phytoplankton bloom dynamics. Because of brine rejection during ice formation, the melt will input low-salinity water causing an increase in vertical stratification. This will decrease the mixed layer depth, improving the irradiance regime and promoting phytoplankton growth [*Smith and Nelson*, 1986]. As a limiting factor to production in the MIZ, *Moline and Prézélin* [1996] suggest that strong wind forcing will break down vertical stratification and lead to deep mixed layers, with light limitation of phytoplankton growth rates. Wind direction and the curl of the wind stress can result in Ekman-pumping induced upwelling. Wind forcing along the edge of heavy ice cover may also induce upwelling, depending in part on wind direction [*Niebauer*, 1982]. Strong wind-driven mixing and upwelling in coastal waters may help entrain iron from sedimentary sources into the euphotic zone. Thus, spatial and temporal variability in MIZ chlorophyll concentrations may be due in part to variable wind forcing.

[4] Iron control of phytoplankton production and growth rates is another very important dynamic within the MIZ because it lies within the general HNLC region of the Southern Ocean [*Martin et al.*, 1990]. Several mesoscale iron fertilization experiments have illustrated the strong

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influence of iron on phytoplankton biomass and community composition in the SO [Boyd *et al.*, 2000; Coale *et al.*, 2004]. Direct deposition of iron from mineral dust is generally low to the Southern Ocean, particularly at the higher latitudes where the MIZ is found [Luo *et al.*, 2003; Zender *et al.*, 2003]. However, some atmospheric dust particles do accumulate in the winter snow fall that solidifies with the sea ice providing a pulse input of iron during melting [Sedwick and DiTullio, 1997; Grotti *et al.*, 2005]. Perhaps more importantly as the MIZ approaches the continental shelf, there is a mixing of iron rich sediments with surface waters [Schoemann *et al.*, 1998; Johnson *et al.*, 1999]. The highest concentrations of chlorophyll are seen in the shelf regions of the Weddell and Ross Seas [Moore and Abbott, 2000; Arrigo *et al.*, 1998b; Arrigo and van Dijken, 2004]. Iron from sediment re-suspended by vertical mixing is also captured within sea ice during formation in winter [Grotti *et al.*, 2005]. It has been proposed that this iron-rich sea ice could be advected away from the continental shelf, releasing iron far from coastal regions [Sedwick *et al.*, 2000; Fitzwater *et al.*, 2000; Grotti *et al.*, 2005]. Croot *et al.* [2004] report evidence of iron release from sea ice as an important factor in driving the *Phaeocystis* sp. bloom at the spring ice edge along 6°E. Similarly, Loscher *et al.* [1997] also suggest release of dissolved iron from melting sea ice along 6°W during the 1992 ANT X/6 JGOFS expedition. Moore and Doney [2006] suggest that variable iron content and release from melting sea ice is a significant source of the observed, mesoscale chlorophyll concentration variability in the SW Pacific sector of the SO. An additional source of iron within the MIZ is release from ice bergs [Croot *et al.*, 2004; Loscher *et al.*, 1997]. Ice bergs can hold significant amounts of iron due to their formation by glacial processes on the continent, but it is uncertain as to the quantitative significance of them as sources of iron for open ocean phytoplankton production.

[5] It is also important to note the interactions between iron and light, and the possibility of iron-light co-limitation within the MIZ [Boyd, 2002]. It was theorized by Raven [1990] that when mixed layer depths increase and thus mean light levels experienced by the phytoplankton decrease, the cellular demand for iron increases as phytoplankton photoadapt to lower light levels. Sunda and Huntsman [1997] found evidence for this interaction between light and iron in a laboratory setting. Thus, increased stratification and shallower mixed layer depths following the retreating ice edge would reduce the cellular demands for iron, in addition to possibly releasing iron. Summarizing results from eight iron-fertilization experiments, de Baar *et al.* [2005] noted that there was a strong inverse relation between maximum chlorophyll/dissolved inorganic carbon drawdown and mixed layer depths. They suggested that as mixed layer depth increases, light-limitation of phytoplankton becomes increasingly important in restraining the bloom due to self-shading (light absorption by phytoplankton) within the mixed layer. Krishnamurthy *et al.* [2007] conducted 1D simulations of the Southern Ocean Iron Experiment (SOFEX) to examine the relative roles of light and nutrients with iron additions and with ambient nutrients. At the South Patch location (within the SIZ) there was a strong impact of wind speed and corresponding changes in mixed layer depth

under iron-fertilized conditions. The simulated bloom magnitude after iron addition was inversely related to wind speed and mixed layer depth. With deeper mixed layers, both iron and light availability limited bloom development due to self-shading. In contrast under the low-iron, background conditions, light-limitation played a minor role as biomass was kept low due to iron stress with minimal self-shading by the phytoplankton.

[6] The US JGOFS AESOPS study area along 170°W longitude both offers confirmation of previous physical process theories, and allows a comparison of satellite data with in-situ measurements from the MIZ. Buesseler *et al.* [2003] show that during AESOPS the ice melt in the MIZ dramatically decreased mixed layer depths leading to a classic ice-edge phytoplankton bloom which moved southward during the study following the retreating sea ice. This study also suggests that the in-situ chlorophyll concentrations were generally consistent with estimates from satellite sensors. It should be noted that the AESOPS bloom was of unusually high chlorophyll concentrations for Southern Ocean waters away from coastal regions (in-situ measurements $>3.0 \text{ mg/m}^3$) [Smith *et al.*, 2000; Buesseler *et al.*, 2003]. Elevated dissolved iron concentrations (0.25–0.29 nM) were found near the retreating ice-edge in conjunction with high particulate organic carbon (POC) and chlorophyll concentrations, suggesting substantial release of dissolved iron from the ice and subsequent significant biological uptake prior to sampling [Measures and Vink, 2001].

[7] Previous satellite measurements of both the CZCS and SeaWiFS instruments have shown similar spatial patterns of chlorophyll distributions for the Southern Ocean. Phytoplankton blooms are most commonly found in coastal/shelf regions, particularly in the Ross Sea, and in the southwest Pacific sector of the Southern Ocean, as well as the southwest Atlantic sector [Sullivan *et al.*, 1993; Arrigo and McClain, 1994; Comiso *et al.*, 1993; Arrigo *et al.*, 1998a, 1998b; Moore and Abbott, 2000, 2002; Meguro *et al.*, 2004; Arrigo and van Dijken, 2004]. Outside these areas, generally low chlorophyll concentrations have been observed in open-ocean waters. These satellite observations support the iron-limitation hypothesis for the Southern Ocean with phytoplankton blooms apparent mainly in iron rich waters such as coastal/shelf waters, and areas downwind of Patagonia and Australia/New Zealand [Sullivan *et al.*, 1993; Comiso *et al.*, 1993; Moore and Abbott, 2000]. To a lesser extent than in coastal regions, areas of retreating sea ice and areas near the major hydrographic fronts, where there are also additional iron inputs to surface waters, yield more modest phytoplankton blooms [Arrigo *et al.*, 1998b; Moore *et al.*, 1999a; Moore and Abbott, 2000, 2002]. Arrigo *et al.* [1998a] calculated much higher productivity in the MIZ and shelf areas relative to open ocean waters, and estimated the MIZ accounted for 23% of total Southern Ocean ($>50^\circ\text{S}$) primary production during December, and about 10% annually.

[8] It is important to better understand how physical forcings and seasonal timescale sea ice dynamics influence the MIZ phytoplankton blooms given their importance for marine ecology and biogeochemical cycling in this region. Marsland and Wolff [2001] suggest that even in the wake of

global increases in mean temperature associated with the ongoing global warming, the seasonal formation and retreat of sea ice will be only modestly affected. They argued that increases in surface air temperatures and increasing surface freshwater flux from the atmosphere under global warming scenarios, would at least partially offset each other and therefore preserve the role of sea ice in the Southern Ocean. *Cavaliere et al.* [2003] and *Parkinson* [2004] show that while there have been large decreases in the summertime areal sea ice extent in the Arctic in recent decades, similar trends across the Southern Ocean have not been observed. Regionally there have been areas of increasing and decreasing trends in sea ice cover [*Liu et al.*, 2004].

[9] In this study we analyze the physical dynamics of the MIZ in an attempt to better understand the growth patterns of phytoplankton in the Southern Ocean. Monthly mean remote sensing estimates of surface chlorophyll, percentage sea ice cover, and wind speeds are examined. We wanted to test the hypothesis that wind speed variations are a key factor in driving the large spatial and temporal variations observed within the MIZ, and to also gain insights into the possible role of iron in driving these patterns. Output from the biogeochemical elemental cycling (BEC) model [*Moore et al.*, 2004] is used to aid our interpretation of the satellite data.

2. Methods

[10] Monthly mean sea ice concentrations from the Spatial Sensor Microwave Imager (SSM/I) DMSP -F13 satellite sensor for the austral melting season from 1997 to 2005 were obtained from the National Snow and Ice Data Center (NSDIC) Distributed Active Archive Center, at the University of Colorado at Boulder (National Snow and Ice Data Center, 1998). In determining sea ice extent, a minimum of 5% sea ice cover was used. A decrease in sea ice between months from greater than 70% to less than 70% in the subsequent month was used to define the marginal ice zone. As noted in *Moore et al.* [2000], percentages ranging from 30 to 70% give similar results due to the rapid speed of ice-edge retreat during austral summer. Each month's MIZ was created by masking the ice extent of a month and subtracting the ice extent of a previous month to determine the monthly melt region. In most cases this definition for the MIZ will track the general southward retreat of the seasonal ice cover highlighting regions with substantial meltwater inputs at the surface. In some cases though, particularly near the continent, the decrease in ice cover may be due mainly to advection, with less local release of freshwater. Either way the removal of the ice marks the beginning of the pelagic growing season, but the effects on mixed layer depths would be different. The sea ice data was remapped from the polar stereographic grid to the SeaWiFS ~ 9 km equal-angle grid.

[11] Monthly mean surface chlorophyll concentrations from the SeaWiFS sensor (V5.1, OC4v4 algorithm) from 1997 to 2005 were obtained from the Distributed Active Archive Center at the Goddard Space Flight Center (Level 3 standard mapped image monthly data). SeaWiFS data in the Southern Ocean is known to underestimate chlorophyll, especially at mid to high concentrations ($> \sim 0.5$ mg/m³) [*Moore et al.*, 1999a; *Abbott et al.*, 2000; *Murphy et al.*, 2001; *Garcia et al.*, 2005]. *Garcia et al.* [2005] estimated a bias of -21.7 % for the OC4v4 algorithm in Southern

Ocean waters. We define a bloom as chlorophyll concentrations > 0.8 mg/m³ rather than the ~ 1.0 mg/m³ cutoff commonly used for other areas of the globe, in part because of this underestimation tendency. Chlorophyll concentrations of 0.8 mg/m³ are still significantly elevated above typical open ocean values within the Southern Ocean (~ 0.2 – 0.4 mg/m³, i.e., *Moore and Abbott*, 2000). We are more interested in the spatial patterns and variability in chlorophyll and their relations to physical forcings than the absolute values estimated by SeaWiFS. Another source of some uncertainty in our analysis arises because chlorophyll concentration variability may be due to variations in phytoplankton biomass or result from variations in C/chlorophyll ratios modified by photoadaptation, and perhaps iron availability. C/chlorophyll (g/g) ratios typically range between 50 and 150 [i.e. *Behrenfeld et al.*, 2005].

[12] Quikscat derived estimates of wind speed from each growing season from 1999–2005 were obtained from Remote Sensing Systems (sponsored by the NASA Ocean Vector Winds Science Team). Band 1 from the multiple band, time-averaged, Quikscat product is estimated wind speed at 10 meters above the water surface, derived from surface roughness (wind stress) roughly equivalent to an 8–10 minute mean surface wind. Each image was remapped from its original 0.25 degree grid to the ~ 9 km equal angle grid for comparison with the sea ice and chlorophyll data.

[13] The biogeochemical elemental cycling (BEC) ocean model includes four phytoplankton functional groups, light limitation, and multiple potentially growth limiting nutrients (N, P, Fe, and Si), and runs within the ocean component of the Community Climate System Model (CCSM3.0) developed at the National Center for Atmospheric Research [*Moore et al.*, 2004]. The coarse resolution circulation model (3.6 degree in longitude; 0.9–2.0 degree in latitude, with finer resolution at the Equator) has 8 levels in the upper 103 m and does a good job of capturing the seasonal variations in mixed layer depth [*Yeager et al.*, 2006] such that no restoring of surface temperature and salinity to observations is necessary. We use BEC model output to estimate a relation between monthly mean wind speed and mixed layer depth for the Southern Ocean region. We also examine the relative roles of light and iron in limiting phytoplankton growth rates in this region to aid interpretation of the remote sensing data. Growth is computed in the model based on a temperature determined maximum growth rate that is multiplied times a light limitation factor (0.0–1.0) and by a nutrient limitation factor (0.0–1.0). Whichever nutrient is most limiting for growth determines the nutrient limitation factor, typically iron for this region. Note that the light and nutrient terms are multiplicative, allowing for iron-light co-limitation (for further details see *Moore et al.*, 2002, 2004). For the simulation used here, the winds and other climate forcings are from a late 20th century NCAR-NCEP climatology [*Large and Yeager*, 2004]. Climatological dust deposition [*Luo et al.*, 2003] delivers iron to the oceans assuming 3.5% iron by weight and a constant 2% surface solubility (for further details on the BEC model, see *Moore et al.*, 2004).

3. Results

[14] There is a general progression of the MIZ that holds for all eight years of our study. The significant ice retreat

Table 1. Mean Monthly Statistics for the Marginal Ice Zone (MIZ) are Listed (mChl, Mean Chlorophyll Concentration Over Eight-year Period (mg/m^3), WS, Mean Wind Speed (m/s, Over Six-year Period), sMIZ, Areal Extend of the MIZ ($\times 1\text{e}6 \text{ km}^2$), bMIZ, Area Within the MIZ With Blooms ($\times 1\text{e}3 \text{ km}^2$), vMIZ, Area Within the MIZ With Valid Chlorophyll Data ($\times 1\text{e}3 \text{ km}^2$), %BmV, % of MIZ With Valid Chlorophyll Data With Blooms, %Bm, % of Total MIZ With Blooms)^a

	mChl	WS	sMIZ	bMIZ	vMIZ	%BmV	%Bm
SEP	0.19 (0.035)	11.7 (2.3)	0.56 (0.19)	0.54 (0.46)	39.1	1.4	0.096
OCT	0.25 (0.085)	11.6 (1.4)	1.1 (0.40)	4.7 (3.2)	231	2.0	0.42
NOV	0.50 (0.22)	9.30 (0.79)	3.0 (0.31)	56.0 (38)	713	7.8	1.9
DEC	0.85 (0.37)	7.58 (0.48)	6.0 (0.41)	36.0 (120)	2140	17	6.0
JAN	0.81 (0.17)	7.50 (0.44)	2.9 (0.37)	280.0 (71)	1340	21	9.5
FEB	0.89 (0.20)	9.23 (0.37)	1.1 (0.17)	99.0 (30)	417	24	8.7
MAR	0.43 (0.16)	10.7 (0.87)	0.23 (0.052)	3.6 (2.9)	37.3	9.6	1.6

^aStandard deviations are shown in parentheses.

begins in October and continues through February. We have included measurements from September and March to show the boundaries of the melting season, and to look for possible temporal shifts. Mean MIZ areas have been averaged over the eight-year period and begin in September at $5.6\text{e}5 \text{ km}^2$, peak in December at $6.0\text{e}6 \text{ km}^2$, and end in March at $2.3\text{e}5 \text{ km}^2$ (Table 1). Areal extent in November and January is typically about half that of December, with generally small MIZ area in other months (Table 1). As the

melt reaches its peak, the MIZ size becomes more and more predictable, as the timing and magnitude of the minimum ice extent varies little from year to year (Table 1).

[15] The location of monthly MIZs are more variable than their total areal extent. Eight year time series of MIZ locations and mean chlorophyll distributions for December (Figure 1) and January (Figure 2) show similarities in spatial distribution as well as significant differences in the size and location of blooms within the MIZ. We first discuss

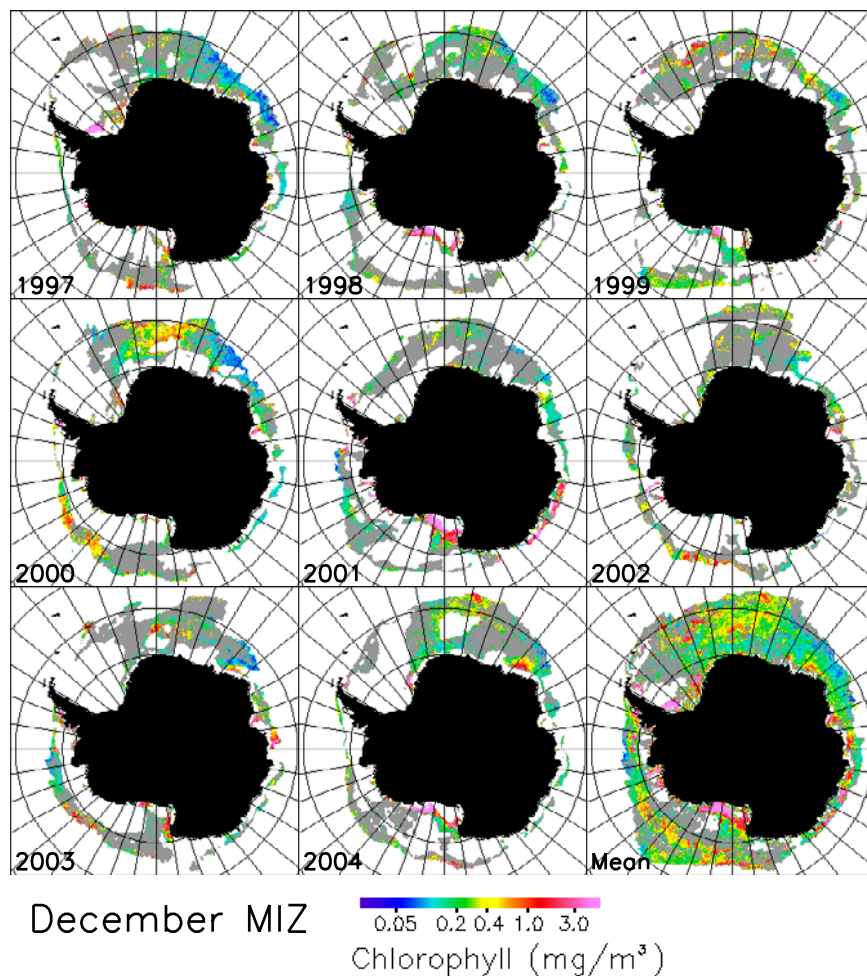


Figure 1. Displayed are the December MIZ's for each year, plus an 8-year mean MIZ. The MIZ for each figure includes both the area of color and that in gray. The gray area indicates MIZ areas where chlorophyll data was unavailable. Latitude lines shown indicate 50°S , 60°S , and 70°S .

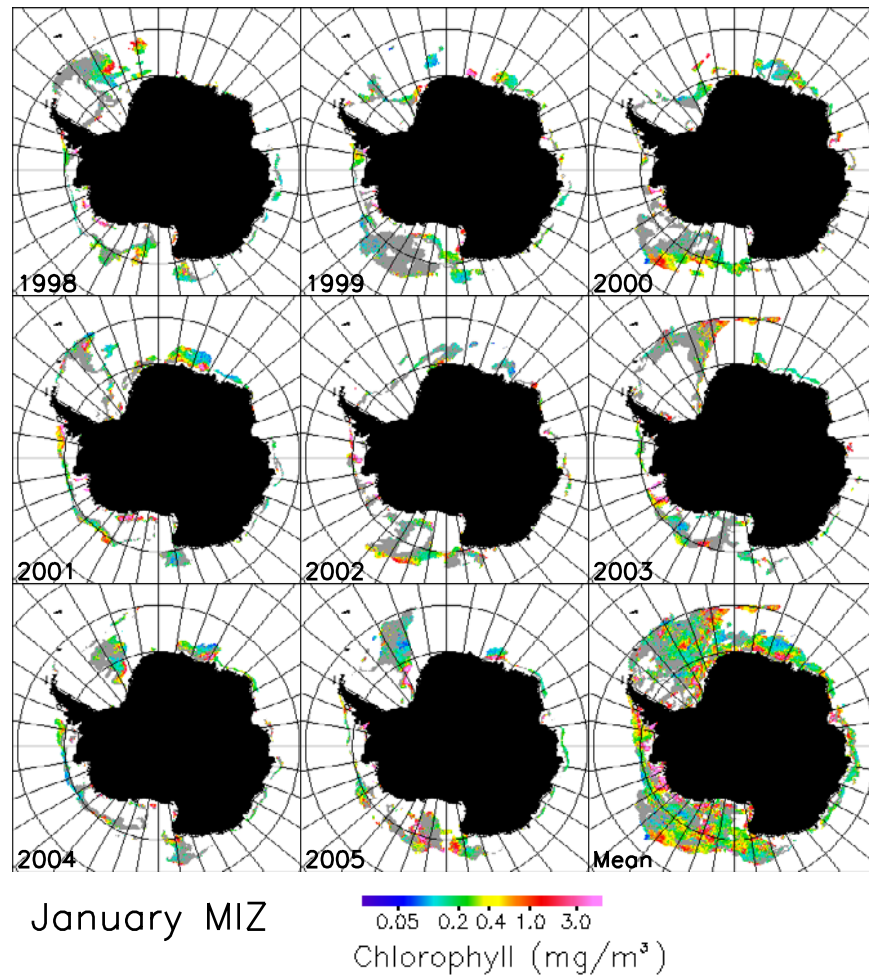


Figure 2. Displayed are the January MIZ equivalents of Figure 1.

the size and location of the MIZ in these figures, followed by chlorophyll distributions. These images clearly show the significantly larger ice retreat in December compared to January. In the early season (October-November) the Ross and Weddell Sea have the most variability between months. The area of 50°W–30°E has the most range in geographic extent, often monthly MIZ regions fluctuate by more than 10 degrees latitude inter-annually. All other areas of the MIZ are fairly consistent, with a regular large melt in the southern Indian Ocean, particularly 70–110°E. Melting in the outer Ross Sea is consistent in its latitude, as is the massive melt in the Weddell region of the Atlantic sector. MIZ area is relatively small from 90–150°E (Figures 1 and 2). By the end of the melting season (January-February) the MIZ in the Weddell Sea becomes erratic with years 1998, 1999, and 2002 lacking in area, where other years a large MIZ areas exist in this region (Figure 2). Generally, the MIZ during the later part of the season is spatially more consistent than the early part, except for in the Weddell Sea where there is a high degree of variability.

[16] The highest chlorophyll concentrations and most persistently blooming regions are located in the MIZ areas of the southern Ross Sea, and also in the southern Weddell Sea (Figures 1 and 2). More sporadic blooms are also observed along the outer limb of both seas during January

and February. Sporadic blooms are also seen closer to Antarctica between 70 and 135°E during December, and between the Antarctic Peninsula and 130°W during January (Figures 1 and 2). This last region, along with areas at the

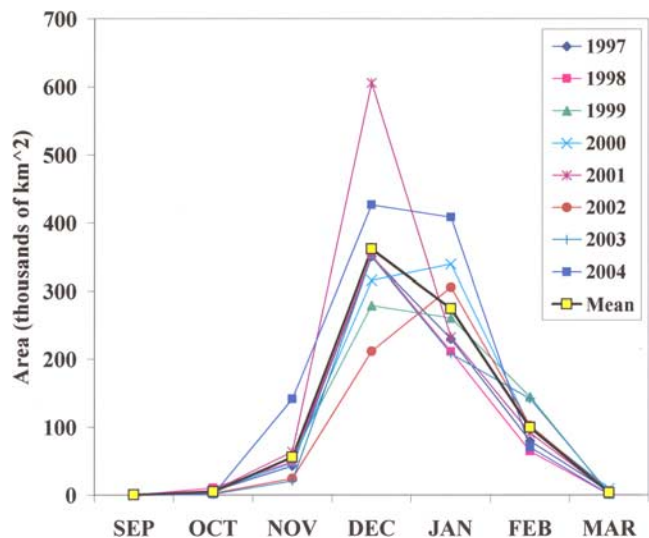


Figure 3. Displayed are the areal extents of the blooms within the MIZ for each year as well as an eight year mean.

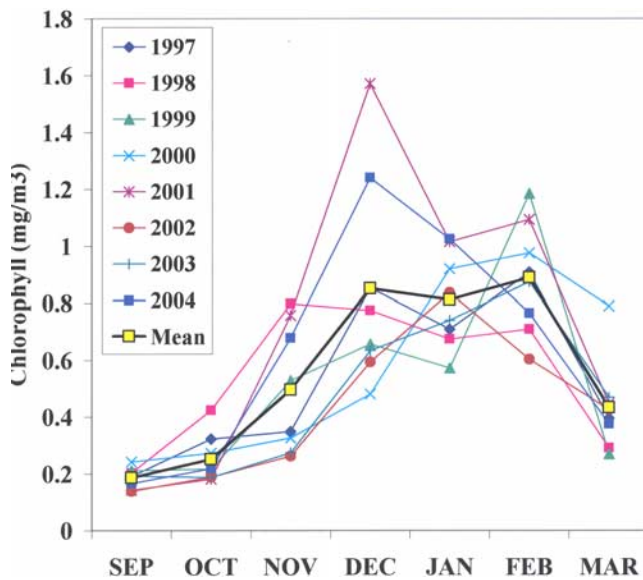


Figure 4. Displayed are the monthly mean chlorophyll concentrations for each year as well as an 8-year mean.

margins of the permanently ice-covered portions of the Weddell Sea, are the sites of most MIZ blooms during February (not shown).

[17] Monthly mean bloom areal extent ranges from 530 km² in September to 3.6e5 km² in December (Figure 3, Table 1). Bloom extents generally follow the overall size of the MIZ, peaking during December most years, or in January (2000 and 2002) (Figure 3, Table 1). Our observations of bloom extent give lower bounds, as gaps in the chlorophyll dataset (due to cloud cover) prevent observations of some blooms. Normalizing the bloom area to MIZ area with valid chlorophyll data likely gives a better estimate of the region within the MIZ that blooms. The percentage of the MIZ that blooms each month increases as the season progresses and areal extent declines, reaching values of 17%, 21%, and 24% for the months December, January, and February, respectively (Table 1). Mean MIZ chlorophyll concentrations are elevated over these same months (Figure 4).

[18] Chlorophyll concentrations within the MIZ range from less than 0.1 mg/m³ to more than 20 mg/m³, although monthly means have much less disparity. Eight year monthly means show high mean concentrations from

Table 2. Monthly Mean Statistics for the Marginal ice Zone for Eight Year Study Period (mChl, Mean Chlorophyll Concentration (mg/m³), sMIZ, Areal Extent of the MIZ (×1e6 km²), bMIZ, Blooming Area Within MIZ (×1e3 km²), %Bm, % of Total MIZ With Blooms, %BmV, % of MIZ With Valid Chlorophyll Data With Blooms)^a

	mChl	sMIZ	bMIZ	%BmV	%Bm	mChl	sMIZ	bMIZ	%BmV	%Bm		
	1997–1998					1998–1999						
SEP	0.19	0.78	1.2	1.1	0.15	0.20	0.29	0.17	0.97	0.057		
OCT	0.32	0.84	5.6	4.0	0.64	0.42	1.1	11.0	4.6	0.97		
NOV	0.35	3.0	43.0	5.6	1.4	0.80	3.1	48.0	9.5	1.6		
DEC	0.85	6.3	350.0	16.0	5.5	0.77	6.1	350.0	18.0	5.8		
JAN	0.71	2.7	230.0	17.0	8.7	0.68	3.3	210.0	16.0	6.4		
FEB	0.91	1.2	80.0	21.0	6.8	0.71	1.1	65.0	17.0	6.0		
MAR	0.40	0.29	4.8	10.0	1.6	0.29	0.19	0.86	3.7	0.45		
	mChl	WS	sMIZ	bMIZ	%BmV	%Bm	mChl	WS	sMIZ	bMIZ	%BmV	%Bm
	1999–2000						2000–2001					
SEP	0.21	12.0	0.70	0.86	4.5	0.12	0.24	11.6	0.40	0.46	5.9	0.12
OCT	0.22	13.5	1.1	3.2	1.6	0.30	0.27	11.8	1.2	6.5	2.9	0.57
NOV	0.53	9.83	3.3	56.0	6.7	1.7	0.33	8.69	3.2	47.0	5.9	1.5
DEC	0.66	8.14	6.0	280	13.0	4.7	0.48	7.71	6.0	320	11.	5.3
JAN	0.57	7.74	3.3	260	16.0	7.8	0.92	6.96	2.7	340	24.	13.
FEB	1.2	9.24	1.1	14.0	35.0	14.0	0.98	8.97	1.3	100	24.	7.9
MAR	0.27	10.4	0.17	1.3	2.7	0.74	0.79	9.39	0.17	9.2	19.	5.4
	mChl	WS	sMIZ	bMIZ	%BmV	%Bm	mChl	WS	sMIZ	bMIZ	%BmV	%Bm
	2001–2002						2002–2003					
SEP	0.14	12.5	0.40	0.0	0	0	0.14	7.64	0.75	0.63	0.72	0.084
OCT	0.18	12.1	2.1	6.5	1.0	0.31	0.19	9.34	0.98	2.8	1.3	0.28
NOV	0.76	10.6	2.4	64.0	14	2.7	0.26	9.30	2.7	24	3.4	0.91
DEC	1.6	8.09	6.4	610	29	9.5	0.59	7.13	5.1	210	14.	4.2
JAN	1.0	8.23	2.4	230	24	9.6	0.84	7.35	3.2	310	23.	9.7
FEB	1.0	9.48	0.96	91.0	26	9.5	0.60	8.70	1.2	100	20.	8.8
MAR	0.45	11.1	0.27	3.5	12	1.3	0.43	10.8	0.29	5.6	11.	2.0
	mChl	WS	sMIZ	bMIZ	%BmV	%Bm	mChl	WS	sMIZ	bMIZ	%BmV	%Bm
	2003–2004						2004–2005					
SEP	0.19	11.8	0.71	0.99	1.7	0.14	0.17	14.7	0.47	0	0	0
OCT	0.19	12.0	0.82	1.5	1.1	0.19	0.22	10.8	0.91	1.1	1.4	0.12
NOV	0.27	9.03	3.2	21.	3.3	0.65	0.68	8.40	3.1	140	14	4.5
DEC	0.64	7.44	5.8	350	20.	6.0	1.2	6.98	6.2	430	19	6.8
JAN	0.74	7.24	2.5	210	19.	8.3	1.0	7.50	3.1	410	27	13.
FEB	0.88	9.76	1.5	140	26.	9.7	0.77	9.23	0.94	71.	21.	7.5
MAR	0.47	12.1	0.21	2.5	9.4	1.2	0.38	10.5	0.25	0.93	3.9	0.37

^aMean MIZ wind speed (m/s) is shown for 1999–2005 (WS).

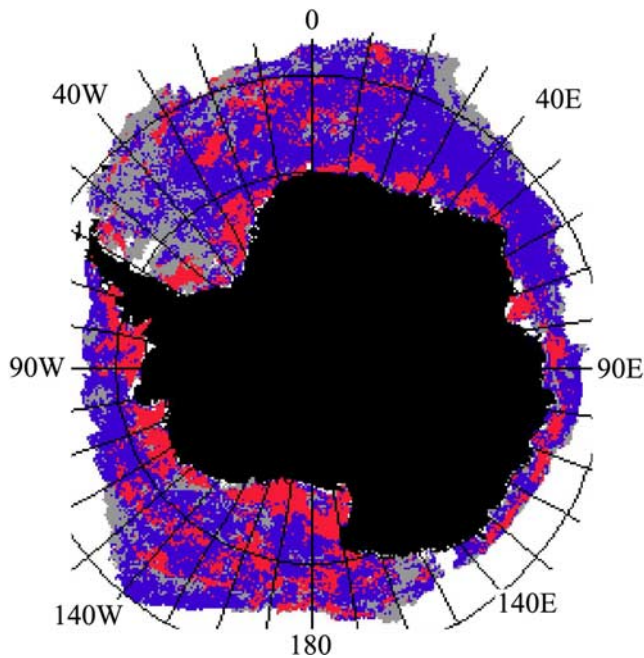


Figure 5. Marginal ice zone areas where phytoplankton blooms were observed during summer months (Dec.–Feb.) over the 8-year summer period are shown in red. MIZ areas where blooms were not observed are shown in purple, and the areas in gray were part of the MIZ but had no valid chlorophyll observations.

December to February, and then a sharp drop at the end of the growing season (Figure 4). The February MIZ is largely restricted to small areas on the fringes of areas with permanent sea ice cover. As the most significant blooms in terms of areal extent are seen in December and January, we focus our analysis on these months. The December MIZ is the most variable in mean chlorophyll concentration, especially compared to the other main bloom months, January and February (Table 1). This is likely related to interannual variations in sea ice retreat. Differences in melt from early December to later December and gaps in chlorophyll coverage can effect the satellite chlorophyll concentrations by delaying the ice-retreat induced blooms or by delaying satellite observations of December blooms into January.

[19] The highest monthly MIZ chlorophyll concentrations were observed in December of 2001 at 1.6 mg/m^3 , where 29% of valid pixels showed blooms, chlorophyll was also elevated in 2004 at 1.2 mg/m^3 (Table 2). The minimum December mean value was during 2000 at 0.48 mg/m^3 (Table 2). In general, December had the greatest variability in chlorophyll concentrations (Tables 1 and 2) driven largely by the extent of coastal/shelf blooms with very high chlorophyll concentrations in the southern Weddell and Ross seas, as well as some offshore blooms (Figure 1). *Arrigo and van Dijken* [2004] showed that Southern Ross sea blooms were depressed and delayed from December into February during our low chlorophyll year of 2000 by heavy sea ice cover (also in 1997). Peak January concentrations were seen in 2001, following the low value for December 2000, and also exceeded 1 mg/m^3 during 2005,

driven by offshore blooms in the Ross Sea, and in 2002 (Table 2, Figure 2). Highest February chlorophyll was 1.2 mg/m^3 in 2000, following low mean chlorophyll concentrations in the preceding two months (Table 2).

[20] A composite seasonal figure was created marking all locations where a bloom was observed during the eight-year period (areas in red, Figure 5). In Figure 5, areas in gray were part of the MIZ where no valid chlorophyll data was observed, and areas in blue had some valid MIZ chlorophyll observations, but no blooms were observed. Blooms are consistently seen near the Antarctic continent, most often in the Weddell and Ross shelf regions, likely driven in part by increased iron availability (Figures 1, 2, and 5). Indeed nearly all coastal areas had at least one observed phytoplankton bloom (Figure 5). Blooms are seen more sporadically in the offshore waters, mainly in portions of the Weddell and Ross seas. A large area between 20°E and $\sim 70^\circ\text{E}$ is almost completely lacking of bloom occurrence in waters away from the continent (Figure 5). Mean chlorophyll concentrations are quite low in this region ($\sim 0.1\text{--}0.2 \text{ mg/m}^3$), lower by a factor of 2–4 compared with Weddell Sea waters west of 20°E (Mean panel of Figure 1).

[21] Wind speeds within the MIZ follow a predictable pattern. Six year averages shown in Table 1 reveal an inverse pattern to that of MIZ area. During both the early and later portions of the melting season, wind speeds are relatively high ($>10 \text{ m/s}$) compared with speeds in December and January that average 7.6 and 7.5 m/s. The variability of wind speed strength is elevated in early spring, with less variability in December and January (smaller standard deviation relative to mean value), and ending with a more variable February and March, likely driven by early and late season storms (Table 1). During December mean wind speed exceeds 10 m/s from $\sim 130\text{--}160^\circ\text{W}$ otherwise wind speeds generally are below 10 m/s (Figure 6). The lowest wind speeds are consistently seen in the eastern portions of the Weddell gyre (Figures 6 and 7). Comparing Figures 1 and 6, the strong blooms in the southern Ross Sea during 2001 and 2004 are both associated with anomalously low wind speeds ($\sim 5 \text{ m/s}$). Areas of moderate to high chlorophyll concentrations in the Weddell Sea between $\sim 10^\circ\text{E}$ and 10°W during 2000, 2002, and 2003 during December also appear associated with lower wind speeds. Mean December winds over all years are considerably lower in the high productivity regions of the southern Weddell and Ross seas relative to more open ocean waters (Figure 6).

[22] A common pattern noted in previous Southern Ocean studies and in the discussion above (Figures 1, 2, and 5) is one of increased phytoplankton bloom frequency near the Antarctic continent. We averaged all of the MIZ chlorophyll observations for the months of January and December as a function of the distance from land (N-S direction) within 20 km wide bins (0–20 km, 20–40 km, etc. . .). There was a strong correlation between mean MIZ chlorophyll concentration and the distance from the Antarctic continent (Figure 8). MIZ chlorophyll concentrations were highest within $\sim 140 \text{ km}$ of the continent, declined rapidly between ~ 140 and 400 km offshore, and were relatively constant at greater distances from land (Figure 8). These observations closer to land also had a higher percentage ($>35\%$) of bloom observations where chlorophyll exceeded 0.8 mg/m^3 (Figure 8). The most likely explanation for this pattern is

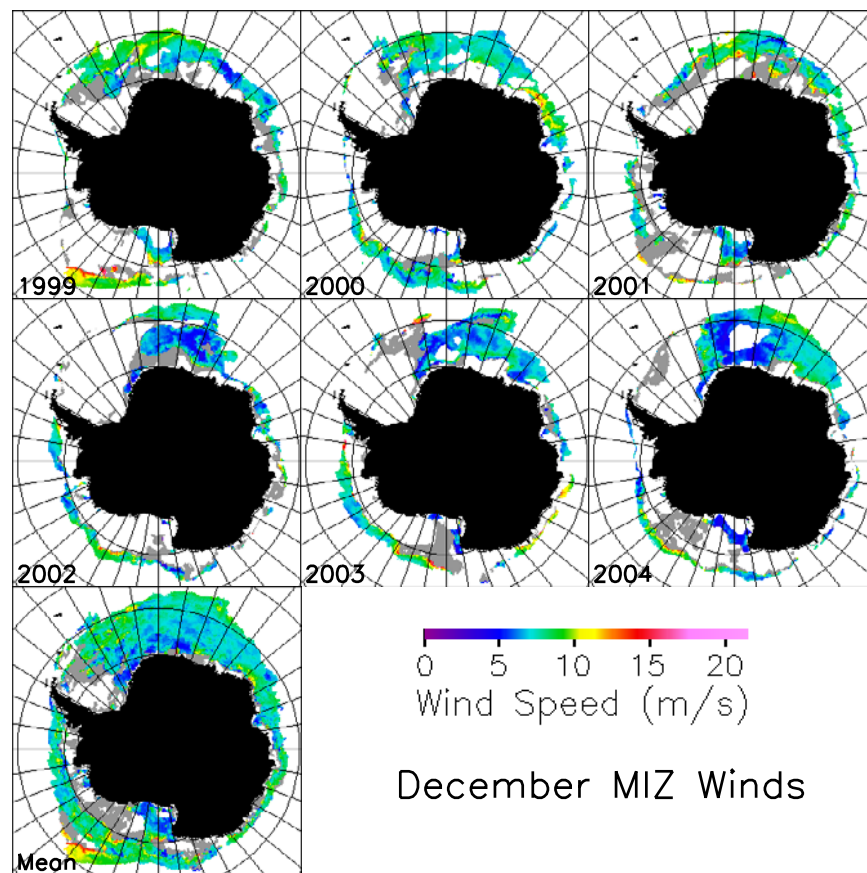


Figure 6. Displayed are the December MIZ monthly mean wind speed for each of year, plus a six year MIZ mean. The MIZ for each figure includes both the area of color and that in gray. The gray area indicates where wind speed data was unavailable. Latitude lines indicate 50°S, 60°S, and 70°S.

reduced iron-stress closer to the continent with inputs from melting ice and ice bergs, and entrainment from below of iron from sedimentary sources. Wind speeds were also consistently lower in some near-shore areas (Weddell and Ross Seas) where high chlorophyll was observed (Figures 1 and 6).

[23] To provide a more quantitative estimate of the relations between wind speed and bloom dynamics, we binned all MIZ chlorophyll observations during December and January (December 1999-January 2005) according to Quikscat wind speed within 0.5 m/s bins (0–0.5, 0.5–1.0, etc.). Figure 9 shows the mean chlorophyll concentration (A), the percentage of chlorophyll observations with blooms (B), and the total number of chlorophyll-wind observations within each bin (C). Error bars for mean chlorophyll indicate the 95% confidence interval assuming a normal distribution. In some cases the error bars are smaller than the plotted symbol, due to the large number of observations in those bins (Figures 9A and 8C). The bins where wind speed is <3 m/s and where wind speed is $>\sim 15$ m/s had few observations and are likely not accurate means (Figure 9C). Mean chlorophyll concentration peaks at wind speeds of ~ 5 m/s and generally declines as wind speed increases. Mean chlorophyll may not be the best metric to evaluate the influence of wind speed on bloom dynamics due to photo-acclimation by the phytoplankton. As wind speed increases and mixed layers deepen, the mean light level experienced by phytoplankton will decrease. As this leads to light stress

the phytoplankton will synthesize more chlorophyll to adapt to low light conditions. $C/\text{chlorophyll}$ (g/g) ratios can range over a factor of >3 typically from 50 to 150 [i.e. *Behrenfeld et al.*, 2005]. Thus, under increasing wind speeds, phytoplankton carbon biomass and productivity could actually decline without an observed decrease in chlorophyll. However, light-limited phytoplankton in a deeper mixed layer would be less likely to actually bloom, achieving high chlorophyll concentrations. Thus, the percentage of observations in each bin where high (blooming) chlorophyll levels are observed is a better metric of wind influence on bloom dynamics. This metric shows a strong inverse relationship between wind speed and bloom occurrence (Figure 9B). At lower wind speeds more than 1/3 of the observations were blooms, and this fraction declines steadily as wind speed increases. Few blooms are observed as wind speeds approach 15 m/s (here we ignore the bins with few observations at very high and low wind speeds). The few observations of very low wind speed <2 m/s may be contaminated by some remaining sea ice, leading to underestimation of wind speed and catching the phytoplankton very early before blooms could develop.

[24] The percentage of observation with blooms declines at wind speeds above ~ 10 m/s (Figure 9B). If we divide the observations (again for December and January) into lower wind areas (<10 m/s) and high wind regions (>10 m/s), the mean percentage of observations blooming declines from

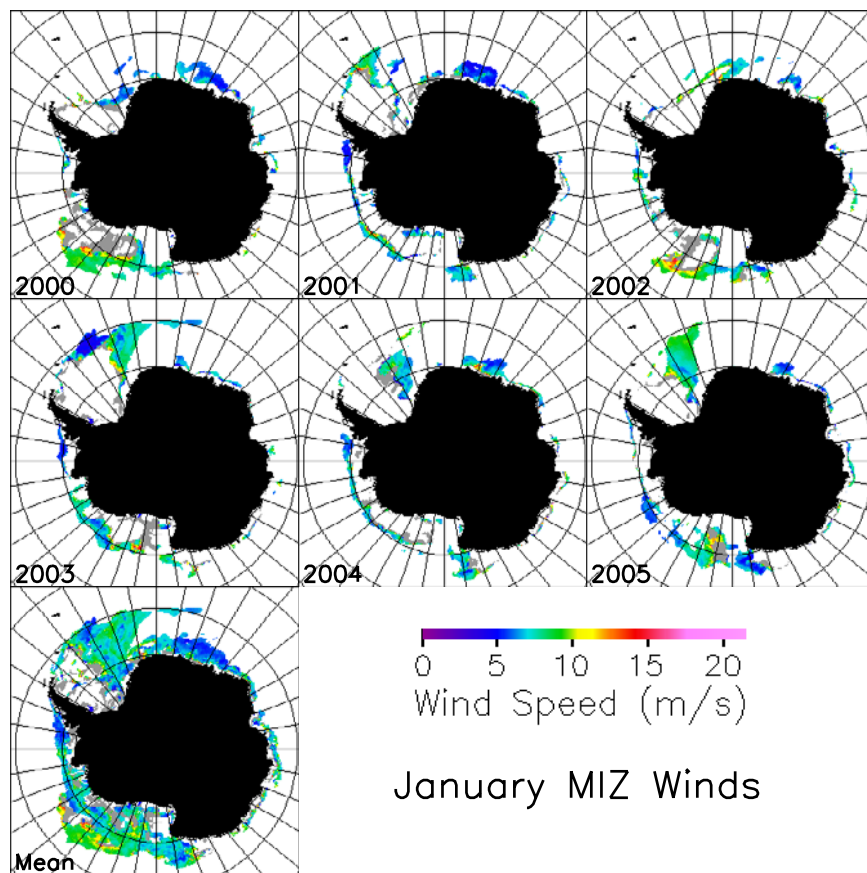


Figure 7. Shown here are the January MIZ equivalents of Figure 7.

19% at lower wind speeds to 12% at high wind speeds. The mean chlorophyll concentration at lower wind speeds was 0.86 mg/m^3 and 0.61 mg/m^3 at high wind speeds (significantly different at 99% confidence).

[25] There were a few blooms associated with high mean wind speeds ($>17 \text{ m/s}$, Figure 9). A total of 38 such observations were seen in the December and January satellite data with most (76%) occurring within 185 km of the Antarctic continent. These high-wind, high-chlorophyll observations were from pixels within four distinct bloom events, only one of these was in offshore waters ($>185 \text{ km}$). Thus, they were mostly within the zone of generally elevated chlorophyll near the continent (Figure 8). The strong winds may have resulted in enhanced entrainment of iron from sedimentary sources into surface waters, leading to a bloom. Alternatively, in areas of high meltwater inputs and very strong vertical density gradients, these winds may not have led to the deep mixed layers one would expect in other areas.

[26] We can examine output from the BEC model to test whether increasing light limitation with increasing wind speeds (and mixed layer depths) is a likely explanation for these patterns. Significant light limitation during phytoplankton blooms due to self-shading has been suggested for HNLC regions based on results from in situ iron fertilization experiments [de Baar et al., 2005] and 1D ecosystem simulations at the southern SOFeX patch location [Krishnamurthy et al. 2007]. We extracted the monthly mean BEC light limitation and iron limitation

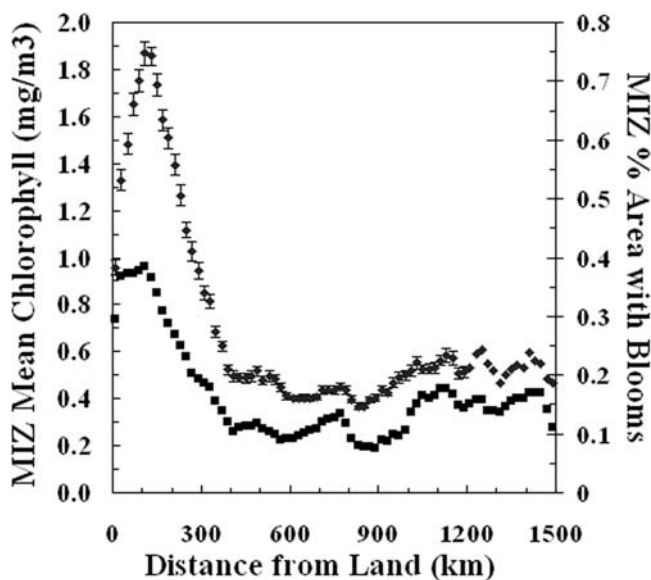


Figure 8. Marginal Ice Zone SeaWiFS chlorophyll concentrations (diamonds) and the % of pixels where chlorophyll $>0.8 \text{ mg/m}^3$ (blooms, squares) are averaged within 20 km bins based on distance from the Antarctic continent for the months of December and January over the eight-year study period. Error bars show 95% confidence interval for mean chlorophyll concentration assuming normal distribution (bars smaller than symbols in some cases).

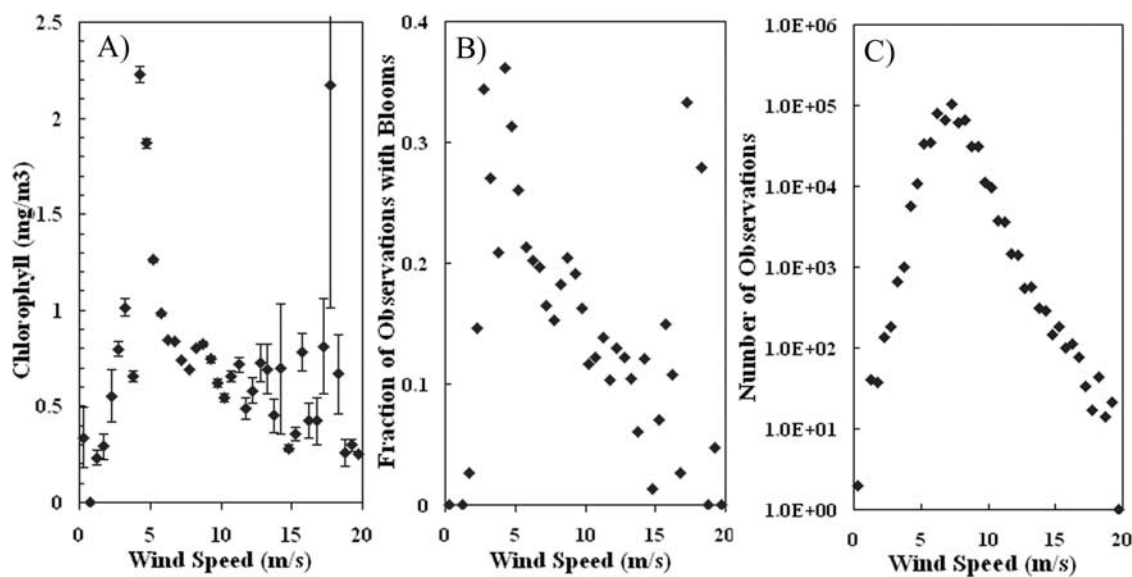


Figure 9. All Marginal Ice Zone SeaWiFS chlorophyll observations during the months of January and December (during 6 year overlap period with Quikscat) are examined within wind speed bins of 0.5 m/s. Panel A shows the mean chlorophyll concentration within each bin (error bars are 95% confidence interval). Panel B shows the percentage of observations within each bin where chlorophyll is greater than 0.8 mg/m^3 . Panel C shows the total number of observations within each bin.

factors from December and January averaged over the mixed layer, and also plotted the monthly mean mixed layer depths as a function of monthly mean wind speed (from model regions where latitude $>54^\circ\text{S}$, Figure 10). In Figure 10 the light and iron limitation factors plotted are the biomass-weighted average of the diatom and small phytoplankton groups [see Moore *et al.*, 2004]. When chlorophyll concentrations are low ($<0.2 \text{ mg/m}^3$ Figure 10A) light limitation only reduces maximum growth rates by about 10% when mixed layers are $\sim 58 \text{ m}$ deep, and light limitation is a minor factor at shallower depths. However, when chlorophyll concentrations are higher ($>0.6 \text{ mg/m}^3$, Figure 10B) the degree of light limitation increases more rapidly with increasing mixed layer depths, due to self-shading of the bloom. Thus, growth rates are reduced by $\sim 10\%$ at a depth of $\sim 40 \text{ m}$ and by nearly $\sim 20\%$ at 50 m (Figure 10B).

[27] In general iron is more limiting for growth than light in this region, reducing phytoplankton growth rates in the model by $\sim 25\text{--}60\%$ (Figure 10D). The open squares in Figure 10D are from the low chlorophyll areas (Figure 10A) and the solid diamonds are from the higher chlorophyll areas (Figure 10B). Because biomass is higher, there has generally been stronger drawdown of ambient dissolved iron at the high chlorophyll sites, resulting in a stronger iron-limitation (lower iron limitation factor, Figure 10D). A similar process accounts for the relation between iron limitation factor and mixed layer depths across both high and low chlorophyll regions, with the high chlorophyll regions having generally shallower mixed layer depths. Where mixed layers are deeper, light limitation is stronger (Figures 10A and 10B) and this reduces the uptake and drawdown of dissolved iron, resulting in relatively higher iron limitation factors (Figure 10D). Where mixed layers are shallow, light is not limiting and the iron depletion is

much greater leading to much lower iron limitation factors (Figure 10D). Recall from Figure 9B that fewer blooms were observed at wind speeds greater than $\sim 10 \text{ m/s}$. This would correspond to mixed layer depths of about 40 m in this region (Figure 10C). Thus, the model results are consistent with the interpretation that increasing light limitation inhibits blooms at higher wind speeds (with deeper mixed layer depths).

4. Discussion

[28] We find a strong inverse relation between wind speeds and bloom occurrence within the Southern Ocean marginal ice zone. This suggests that wind forcing plays an important role in driving the considerable spatial and temporal variations in MIZ phytoplankton bloom distributions (Figures 1 and 2). Another likely key factor is the degree of iron stress of the phytoplankton community. Blooms were much more common close to the Antarctic continent (Figures 1, 2, 5, and 8) where higher dissolved iron concentrations are often observed [Sedwick and DiTullio, 1997; Schoemann *et al.*, 1998; Fitzwater *et al.*, 2000] than in offshore waters. Mean MIZ chlorophyll concentrations during December and January were nearly fourfold higher close to the Antarctic continent ($<140 \text{ km}$) than in offshore waters ($>400 \text{ km}$) (Figure 8). Phytoplankton are better able to adapt to low light conditions when iron is not limiting, and iron stress will exacerbate the sensitivity to deeper mixed layers [Sunda and Huntsman, 1997].

[29] Phytoplankton blooms along the retreating ice edge have been observed in the marginal ice zone from both in situ and satellite studies [i.e. Smith and Nelson, 1986; Moore and Abbott, 2000; Buesseler *et al.*, 2003]. The water column stability and shallow mixed layer depths imparted by the melting sea ice, and iron release from melting ice

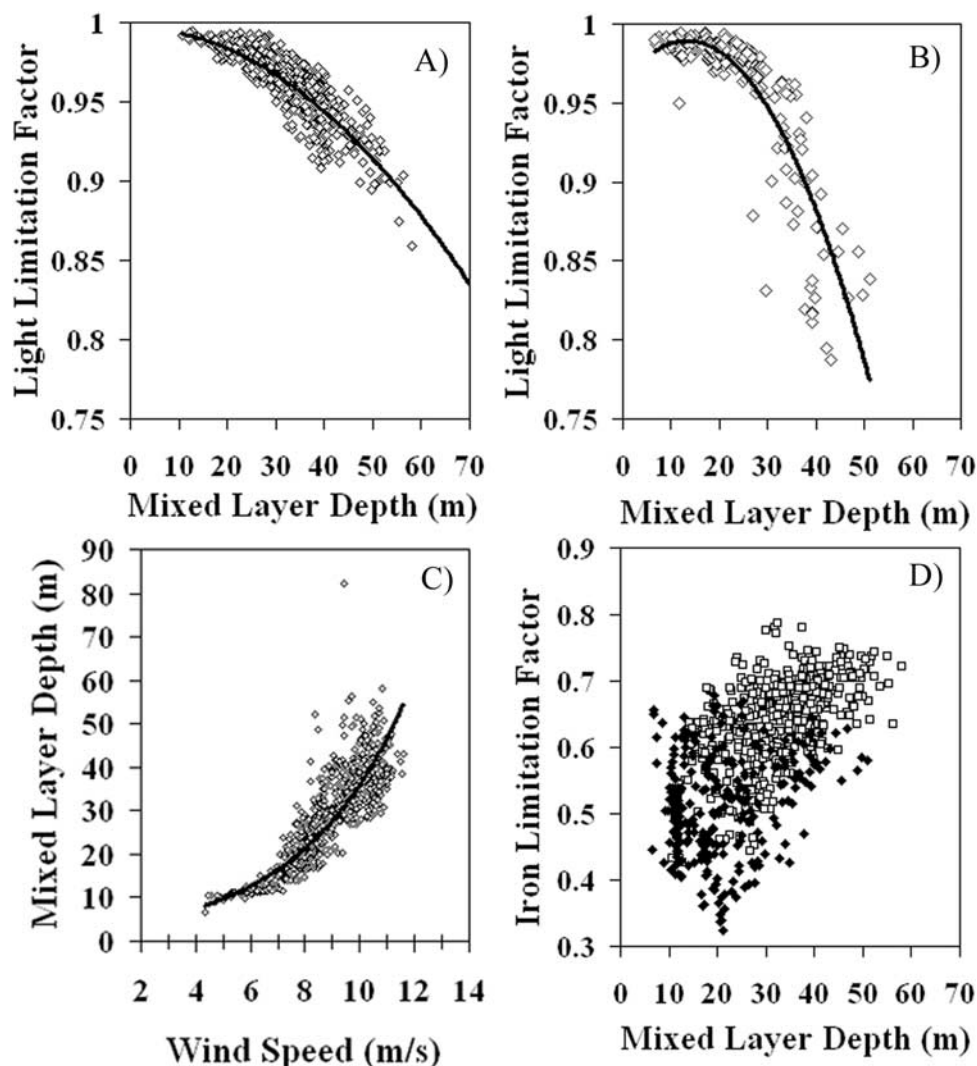


Figure 10. Output from the Biogeochemical Elemental Cycling Model (BEC) displays the phytoplankton light limitation factor from locations where total chlorophyll $< 0.2 \text{ mg/m}^3$ (A), and where total chlorophyll $> 0.6 \text{ mg/m}^3$ (B). Also shown is the model estimated mixed layer depths for Southern Ocean areas ($> 54^\circ\text{S}$) shown as a function of monthly mean wind speed (C), and the iron limitation factor (D), where open squares show low chlorophyll regions from panel A, and the solid diamonds show the high chlorophyll areas from panel B (see text for details). Regression lines were fit for the data from panel A ($y = -3e - 5x^2 + 3e - 5x + 0.9965$, $r^2 = 0.51$), from panel B ($y = -2e - 4x^2 + 0.004x + 0.9623$, $r^2 = 0.78$), and from panel C ($y = 2.612 * e^{0.2621x}$, $r^2 = 0.80$).

appear to be the main drivers of these phytoplankton blooms. Wind forcing has long been suggested as a potentially important factor in governing phytoplankton bloom distributions through impacts on the mixing and the irradiance regime, and on the input of nutrients to surface waters through mixing or upwelling. *Arrigo et al.* [1998b] suggested that strong winds could delay the initiation of the spring bloom in the Ross Sea, while calmer winds promoted bloom formation. They also suggested that stratification and mixed layer depths could play a role in determining the phytoplankton species composition, with diatoms favored under reduced winds/mixing. This study demonstrates a strong impact of wind forcing on phytoplankton bloom distributions throughout the Southern Ocean marginal ice zone.

[30] The clear relation between wind speed and bloom occurrence seen in Figure 9 is somewhat surprising given the potential for temporal mismatch between the chlorophyll and wind speed observations. Cloud cover severely restricts chlorophyll coverage in this region. Thus, our monthly images often include only a couple of data points at any one location. Ideally, weekly or eight-day temporal scale data could be used to better understand the dynamics and evolution of the blooms. However, our preliminary analysis suggests strong limits to this approach due to cloud-induced gaps in the chlorophyll data. Also, one might not expect as strong of a relation between wind speed and chlorophyll/blooms in weekly data as blooms typically take several weeks to develop in this region [i.e. *Abbott et al.*, 2000]. Another factor not addressed in the present study is the

directional influence of wind forcing which can lead to coastal upwelling, Ekman-induced upwelling and downwelling due to wind stress curl, and possibly upwelling at the edge of heavy sea ice cover [Niebauer, 1982]. Arrigo and Weiss [1998] suggested intense offshore winds in the Ross Sea could be lead to substantial upwelling in the spring and early summer polynyas.

[31] This study is the first multi-year look at the entire MIZ and sets a baseline for future research in a time of changing climate. The distribution of blooms found here was similar to that described in previous studies [Sullivan *et al.*, 1993; Comiso *et al.*, 1993; Arrigo *et al.*, 1998a; Moore *et al.*, 1999a; Moore and Abbott, 2000; Meguro *et al.*, 2004; Arrigo and van Dijken, 2004]. Moore and Abbott [2000] look at the MIZ from the first SeaWiFS season (1997–98). MIZ sizes for this season match up fairly close considering there are discrepancies between definitions. While both studies use the 70% sea ice percentage cutoff to define the MIZ, Moore and Abbott [2000] define the area below 73 degrees south as the Weddell/Ross sea region, and exclude that data from their MIZ calculations. Chlorophyll concentrations between the two studies show discrepancies. This could be due to different versions/algorithms for the chlorophyll data, as well as the difference in defining the MIZ. The general chlorophyll concentration progression displayed by Moore and Abbott [2000] is a close match to the eight-year averages, except that of the relatively high October mean value in their study.

[32] The results from this study offers a more thorough understanding of the main processes that control phytoplankton biomass and primary production within the Southern Ocean MIZ. Monthly mean bloom percentages within the MIZ range from 2–24% for available data during each melting season. This suggests that only a portion of the MIZ is highly productive during the spring/summer sea ice retreat. Mean MIZ chlorophyll concentrations in offshore waters are roughly double typical values for the offshore SO [Figure 8, Moore and Abbott, 2000]. Wind forcing accounts for some of the variability within the MIZ, with iron also likely playing a key role. Maximum bloom areal extents are in December and January, but the highest mean MIZ chlorophyll concentrations are often not seen until January or February (Figure 4). While mean chlorophyll concentrations can increase later in the melt season, it should be noted that in terms of integrated primary production, biogeochemical cycling, and ecological value for higher trophic levels, December is the most important MIZ period due to the large areal extent and frequent phytoplankton blooms.

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