FINAL REPORT

NASA GRANT NAG5-12397 (Scripps Institution of Oceanography, University of California San Diego)
NASA GRANT NAG5-12396 (Hancock Institute for Marine Sciences, University of Southern California)

PROJECT TITLE:

Remote Sensing of Particulate Organic Carbon Pools in the High-Latitude Oceans

PRINCIPAL INVESTIGATORS:

Dariusz Stramski
Marine Physical Laboratory
Scripps Institution of Oceanography
La Jolla, CA 92093-0238
Tel: (858) 534 3353
Fax: (858) 553 7641
e-mail: dstramski@ucsd.edu

Malgorzata Stramska
Hancock Institute for Marine Sciences
University of Southern California
Los Angeles, CA 90089-0371
Tel: (213) 740 5813
Fax: (213) 740 8123
e-mail: stramska@usc.edu

Period of performance: 1 August 2002 - 31 July 2005

Table of Contents

Electronic attachments submitted with this report (pdf files of peer-reviewed articles):

(1) Stramska M., and D. Stramski. 2005. Effects of a nonuniform vertical profile of chlorophyll concentration on remote-sensing reflectance of the ocean, *Applied Optics*, 44, 1735-1747.

(2) Stramska M. 2005. Interannual variability of seasonal phytoplankton blooms in the north polar Atlantic in response to atmospheric forcing, *J. Geophys. Res.*, Vol. 110, C05016, doi: 10.1029/2004JC002457.

(3) Lee, Z.-P., M. Darecki, K. L. Carder, C. O. Davis, D. Stramski, and W. J. Rhea. 2005. Diffuse attenuation coefficient of downwelling irradiance: An evaluation of remote sensing methods. *J. Geophys. Res.*, 110, C02017, doi: 10.1029/2004JC002573.

(4) Stramska M., and D. Stramski. 2005. Variability of particulate carbon concentration in the north polar Atlantic based on ocean color observations with Sea-viewing Wide Field-of-view Sensor (SeaWiFS), *J. Geophys. Res.*, 110, in press.

(5) Stramska M., D. Stramski, S. Kaczmarek, D. B. Allison, and J. Schwarz. 2005. Seasonal and regional differentiation of bio-optical properties within the north polar Atlantic, *J. Geophys. Res.*, submitted.

1. Objectives of the project

The general goal of this project was to characterize spatial distributions at basin scales and variability on monthly to interannual timescales of particulate organic carbon (POC) in the high-latitude oceans. The primary objectives were:

(1) To collect in situ data in the north polar waters of the Atlantic and in the Southern Ocean, necessary for the derivation of POC ocean color algorithms for these regions.

(2) To derive regional POC algorithms and refine existing regional chlorophyll (Chl) algorithms, to develop understanding of processes that control bio-optical relationships underlying ocean color algorithms for POC and Chl, and to explain bio-optical differentiation between the examined polar regions and within the regions.

(3) To determine basin-scale spatial patterns and temporal variability on monthly to interannual scales in satellite-derived estimates of POC and Chl pools in the investigated regions for the period of time covered by SeaWiFS and MODIS missions.

2. Summary of completed tasks

During the course of this project we completed the following tasks:

(i) We made bio-optical and ancillary measurements on one Arctic cruise in April-May 2003 and one cruise in the Southern Ocean in January-March 2004.

(ii) We performed analysis of collected in situ data and satellite-derived ocean color data products. We derived regional ocean color algorithms for retrieval of POC concentration in the investigated polar waters, both for the north polar Atlantic and the Southern Ocean.

(iii) We applied our regional POC algorithm to a multi-year time series of SeaWiFS data in the north polar Atlantic to study the seasonal and interannual variability of surface POC in this region (Stramska and Stramski, 2005 in press). We also documented seasonal variability of bio-optical relationships in the north polar Atlantic (Stramska et al, 2005 submitted), and we investigated the influence of meteorological forcing on development of phytoplankton blooms in the north polar Atlantic (Stramska, 2005).

(iv) We applied our regional POC algorithms to the entire SeaWiFS data set for the Southern Ocean to characterize the seasonal and interannual variability of POC in this region (D. Allison, Ph.D thesis under Stramski's supervision to be completed in 2006).

(v) We completed a modeling study of the effects of a nonuniform vertical profile of chlorophyll concentration on remote-sensing reflectance of the ocean (Stramska and Stramski, 2005). As part of this project, we also participated in a paper on the evaluation of remote sensing methods for estimating the diffuse attenuation coefficient of downwelling irradiance (Lee et al., 2005).

(vi) We presented our results at several conferences and we published several peer-reviewed articles, which are listed in section 5.

3. Field measurements and data processing

Field data were collected in April-May 2003 during a cruise on R/V *Polarstern* operated by German Alfred Wegener Institute for Polar and Marine Research and during the AMLR (Antarctic Marine Life Resources) cruise on *R/V Yuzhmorgeologiya* in January-March 2004 in the Southern Ocean. The study area and the location of stations visited on the cruises are shown in Figure 1. During these cruises suspended particles for the analysis of POC and Chl were collected by filtration of water samples onto Whatman glass-fiber filters (GF/F) under low vacuum. The POC samples were collected on precombusted filters, dried at 55°C, and stored until post-cruise analysis in the laboratory. POC was determined by combustion of sample filters. Before this analysis, for removal of inorganic carbon, 0.25 ml of 10% HCl was applied to each sample filter and the acid-treated filters were dried at 55°C. Water samples from discrete depths were also taken to measure particulate absorption coefficient from 350 to 750 nm by means of filter pad technique with a bench-top dual beam spectrophotometer equipped with an integrating sphere. These measurements on filters were made in both the transmittance and the reflectance mode.

Additionally, in situ optical measurements were made down to a depth of 50 – 200 m in close proximity (location and time) to water samples collected from discrete depths. We used two underwater sensor packages:

(i) Multisensor Datalogger System (MDS) for measuring vertical profiles of physical properties and inherent optical properties of seawater. The system includes SeaBird Sealogger 25 (SB25) with temperature, conductivity, and pressure sensors, two single wavelength (488 and 660 nm) beam transmissometers (WetLabs), chlorophyll fluorometer (WetLabs), and PAR sensor (Biospherical). Hydroscat-6 sensor (HobiLabs) for measuring measurements of light backscattering at six wavelengths and two a-βeta instruments (HobiLabs) for measuring the backscattering and total absorption coefficient at single wavelengths were also integrated with this system.

(ii) SeaWiFS Profiling Multichannel Radiometer (SPMR, Satlantic) for measuring downwelling irradiance and upwelling radiance at 13 spectral wavebands in free fall mode away from ship perturbations. The instrument is equipped with a set of filters matching the SeaWiFS/MODIS bands as well as several wavelengths which are not included in the current satellite ocean color sensors (for example, in the UV region). Because of cruise schedule and sea ice conditions, only few such underwater irradiance and radiance measurements were made on R/V *Polarstern* in 2003. On the Antarctic cruise the Biospherical spectroradiometer was used.

Data processing including data quality control and conversion to physical units was completed. The pigment and POC determinations and calculations of various optical quantities that are relevant to ocean color algorithms such as the remote-sensing reflectance, water-leaving radiance, attenuation coefficients for downwelling irradiance and upwelling radiance, and absorption and backscattering coefficients were completed.

Both the methods of measurements and data processing are described in detail in our articles that are submitted with this report in the form of electronic pdf files.

4. Major results and accomplishments

Below we will summarize major results and research accomplishments. These results summarized in sections 4.1, 4.2, 4.3, and 4.5 are described in detail in the publications submitted with the report. Because the publications are submitted with this report, the sections 4.1, 4.2, 4.3, and 4.5 include only a brief summary of results with no graphs. The results summarized in section 4.4 are being included in the Ph.D. thesis of David B. Allison, which has not yet been completed nor published. Therefore, this section of our report includes a more detailed description of results supported by several representative graphs.

4.1. Development, testing, and application of POC algorithms in the north polar Atlantic

We used satellite data from SeaWiFS to investigate distributions of particulate organic carbon (POC) concentration in surface waters of the north polar Atlantic Ocean during the spring-summer season (April through August) over a 6-year period from 1998 through 2003. By use of field data collected at sea, we developed regional relationships for a purpose of estimating POC from remote-sensing observations of ocean color. Analysis of several approaches used in the POC algorithm development and match-up analysis of coincident in situ-derived and satellite-derived estimates of POC resulted in selection of an algorithm that is based on the blue-to-green ratio of remote-sensing reflectance R_{rs} (or normalized water-leaving radiance L_{wn}). The application of the selected algorithm to a 6-year record of SeaWiFS monthly composite data of L_{wn} revealed patterns of seasonal and interannual variability of POC in the study region. For example, the results showed a clear increase of POC throughout the season. The lowest values generally less than 200 mg m^{-3}, and at some locations often times less than 50 mg m^{-3}, were observed in April. In May and June, POC can exceed 300 or even 400 mg m^{-3} in some parts of the study region. Patterns of interannual variability are intricate as they depend on the geographic location within the study region and particular time of year (month) considered. By comparing the results averaged over the entire study region and the entire season (April through August) for each year separately, we found that the lowest POC occurred in 2001 and the highest POC occurred in 2002 and 1999.

4.2. Seasonal and regional bio-optical variability in the north polar Atlantic

Using data collected during spring and summer seasons in the north polar Atlantic we examined the variability of the spectral absorption, $a(\lambda)$, and backscattering, $b_b(\lambda)$, coefficients of surface waters and its relation to phytoplankton pigment concentration and composition. For a given chlorophyll *a* concentration (*TChla*), the concentrations of photosynthetic carotenoids (PSC), photoprotective carotenoids (PPC), and total accessory pigments (AP) were consistently lower in spring than in summer. The chlorophyll-specific absorption coefficients of phytoplankton and total particulate matter were also lower in spring, which can be partly attributed to lower proportions of PPC, PSC, and AP in spring. The spring values of the green-to-blue band ratio of the absorption coefficient were higher than the summer ratios. The blue-to-green ratios of backscattering coefficient were also higher in spring. The higher b_b values and lower blue-to-green b_b ratios in summer were likely associated with higher concentrations of detrital particles in summer compared to spring. Because the product of the green-to-blue absorption ratio and the blue-to-green backscattering ratio is a proxy for the blue-to-green ratio of remote-sensing reflectance, we conclude that the performance of ocean color band-ratio algorithms for estimating pigments in the north polar Atlantic is significantly affected by seasonal shifts in the relationships between absorption and *TChla* as well as between backscattering and *TChla*. Intriguingly, however, fairly good estimate of the particulate beam attenuation coefficient at 660 nm (potential measure of total particulate matter or particulate organic carbon concentration) can be obtained by applying a single blue-to-green band-ratio algorithm for both spring and summer seasons.

4.3. Relationships between meteorological forcing and phytoplankton blooms as derived from satellite data in the north polar Atlantic

We examined the year-to-year variability of timing, intensity, and spatial distribution of surface phytoplankton during spring-summer seasons in the north polar region of the Atlantic using satellite-derived chlorophyll *a* concentration (*Chl*) over seven years (1998-2004). Each year phytoplankton bloom differed in onset, temporal evolution, and intensity. Through analysis of coincident meteorological data, we showed that this interannual variability of *Chl* is to a large degree controlled by local weather. In our study, atmospheric forcing was parameterized in terms of the generation rate of turbulent kinetic energy (TKE_{RT}) supplied from the atmosphere to the ocean. We showed that timing of the bloom is delayed in years with high TKE_{RT} supplied to the ocean in March. In April, *Chl* (local and regionally averaged) and TKE_{RT} are inversely related to one another. The seasonal *Chl* patterns are also influenced by the late winter and early spring atmospheric conditions. The seasonal (April – August) *Chl* correlates well with net heat flux, wind energy, and TKE_{RT} in March and April, but the correlation can be negative or positive in different areas of the north polar Atlantic. The correlation between TKE_{RT} and seasonal *Chl* is positive in the Greenland Gyre (higher seasonal *Chl* corresponds to higher TKE_{RT} in March-April) and negative in the regions of East Greenland and North Atlantic/West Spitsbergen Currents. The most likely explanation for the positive correlation between TKE_{RT} and *Chl* within the Greenland Gyre is that higher TKE_{RT} in spring increases the seasonal supply of nutrients into surface waters.

4.4. Development, testing, and application of POC algorithms in the Southern Ocean

This portion of our project has been carried out as a major part of Ph.D. thesis of David B. Allison, who is a graduate student in Stramski's lab. This thesis has not yet been completed and these results have not yet been published. Therefore, in this report we include several representative graphs that summarize our accomplishments.

Our development of POC algorithms for the Southern Ocean is based on data collected on several cruises between 1997 and 2004, including the cruise on *R/V Yuzhmorgeologiya* in January-March 2004 (see lower graph in Figure 1). We explored two methods for estimating POC from ocean color data in the Southern Ocean, algorithm I and II. The first algorithm is a 2-step method, in which POC concentration is related to the remote sensing reflectance, $R_{rs}(555)$, via relationships between POC, particulate backscattering coefficient $b_{bp}(555)$, and $R_{rs}(555)$. The second algorithm uses a direct relationship between POC and a blue-to-green band ratio of R_{rs}.

The algorithm I is based on the observation that in the green region of the visible spectrum (~ 555 nm), the total absorption coefficient, a(555), shows a relatively weak variability over the measured range of POC concentration compared to the variability in the total backscattering coefficient, $b_b(555)$. Thus, at this wavelength, variations in remote sensing reflectance will be primarily determined by changes in the backscattering coefficient which is dependent upon the concentration of POC. This defines the two steps of the algorithm (Figure 2). It is important to note that although the POC and particulate backscattering $b_{bp}(555)$ data shown in Figure 2 are highly correlated for each of the cruises, the relation differs between these cruises. The high correlation is caused by the dominance of organic particles in controlling changes in both POC and b_{bp}. The difference between cruises is not surprising given the fact that the composition of particulate matter in the ocean can vary significantly with time and from one location to another. The variations in the particulate composition are accompanied by changes in particle size, shape, and refractive index, which all influence b_{bp}. Carbon content in individual planktonic cells (or more generally, in organic particles) is, however, coupled with particle size and refractive index which may be responsible for the good correlation between POC and b_{bp} on a cruise by cruise (or region/season) basis. On the other hand, the second step in the algorithm I utilizes the strong relationship between the AOP, $R_{rs}(555)$, and the IOP, $b_b(555)$, which does not appear to be variable between the cruises (or between the regions).

The algorithm II draws parallel reasoning to the common methods used to estimate chlorophyll from ocean color. The method uses a simple direct relationship between the in water constituent POC and a blue-to-green band ratio of remote-sensing reflectance, R_{rs}. Compared to the algorithm I, the use of a band-ratio of R_{rs} allows for the reduction of error (especially, atmospheric correction error) that is possible in the retrieval of the magnitude of R_{rs} at any single waveband. We choose to use the same wavelengths bands for the remote sensing reflectances as those used in the standard chlorophyll retrieval algorithm, namely the bands centered on 490 nm and 555nm. The choice of these bands takes advantage of the relatively weak variation of R_{rs} in the green and strong variation in the blue over the range of POC concentrations in our data. The strong variation in the blue is driven primarily by changes in the particulate absorption coefficient, $a_p(\lambda)$. This coefficient can be partitioned into contributions from detrital and phytoplankton absorption where the bulk of the POC is found. Both phytoplankton and detrital particles contain carbon and both exhibit absorption spectra that are characterized by an increase from 555 nm to 490 nm. This provides a basis for estimating POC from a blue-to-green band ratio of ocean color. For our field data from the Southern Ocean, there is indeed a strong relationship between POC and the band-ratio of $R_{rs}(490)$ and $R_{rs}(555)$ (Figure 3).

Figures 4 and 5 provide example results obtained by the application of our POC algorithms to SeaWiFS imagery in the Southern Ocean. There is a clear seasonal pattern of surface POC around Antarctica. Images presented in Figure 4 reveal the seasonal progression of POC, with zonal bands of elevated POC concentrations in December and January. Geographically, these bands of elevated POC often coincide with the Antarctic Polar Front Zone. The total amount of POC integrated within the surface layer from 0 to 100 m depth over the entire Southern Ocean can reach 0.65 Pg in the middle of the austral summer (Figure 5). At the beginning or at the end of the productive season this POC pool can be less than 0.35 Pg. Our results also show that the austral summer seasons 2001-2002 and 2002-2003 in the Southern Ocean were characterized by the lowest POC pool for the entire period of 7 years examined.

4.5. Modeling study of the effect of vertical structure in chlorophyll concentration on the spectral remote-sensing reflectance

Numerical simulations of radiative transfer were used to examine the effects of a nonuniform vertical profile of chlorophyll concentration, *Chl(z)*, on the spectral remote-sensing reflectance, $R_{rs}(\lambda)$, of the ocean. Using the Gaussian function describing the *Chl(z)* profile, we simulated a relatively broad range of open ocean conditions characterized by the presence of subsurface *Chl* maximum at depths greater or equal to 20 m. The simulations for a vertically nonuniform *Chl(z)* were compared with reference simulations for homogeneous ocean whose chlorophyll concentration was identical to the surface *Chl* of inhomogeneous cases. The results are thus relevant to empirical algorithms for retrieving chlorophyll from ocean color, which are based on correlating the field measurements of surface *Chl* with reflectance that depends on the vertical structure of the upper water column. For some vertical structures of *Chl(z)* considered, both the magnitude of $R_{rs}(\lambda)$ and the band ratios of $R_{rs}(\lambda)$ differ significantly (> 40% in extreme cases) from the reference values of homogeneous ocean. We determined a domain of values for the Gaussian profile parameters, which produce significant differences (>5%). We also determined that the differences become very small or negligible when the nonuniform profiles are characterized by the surface *Chl* greater than 0.4 mg m^{-3} or the depth of *Chl* maximum greater than 45 m (65 m in extremely clear waters with the surface *Chl* = 0.02 mg m^{-3} or less). Examples of field data from the Japan/East Sea and the north polar Atlantic are used to illustrate various nonuniform pigment profiles, including those affecting the common empirical approach for relating the surface *Chl* to the blue-to-green ratio of $R_{rs}(\lambda)$.

5. Publications supported by this project

5.1. Peer-reviewed research articles

Published and in press:

Stramska M., and D. Stramski. 2005. Variability of particulate carbon concentration in the north polar Atlantic based on ocean color observations with Sea-viewing Wide Field-of-view Sensor (SeaWiFS), *J. Geophys. Res.*, 110, in press.

Stramska M. 2005. Interannual variability of seasonal phytoplankton blooms in the north polar Atlantic in response to atmospheric forcing, *J. Geophys. Res.*, Vol. 110, C05016, doi: 10.1029/2004JC002457.

Stramska M., and D. Stramski. 2005. Effects of a nonuniform vertical profile of chlorophyll concentration on remote-sensing reflectance of the ocean, *Appl. Opt.*, 44, 1735-1747.

Lee, Z.-P., M. Darecki, K. L. Carder, C. O. Davis, D. Stramski, and W. J. Rhea. 2005. Diffuse attenuation coefficient of downwelling irradiance: An evaluation of remote sensing methods. *J. Geophys. Res.*, 110, C02017, doi: 10.1029/2004JC002573.

Submitted:

Stramska M., D. Stramski, S. Kaczmarek, D. B. Allison, and J. Schwarz. 2005. Seasonal and regional differentiation of bio-optical properties within the north polar Atlantic, *J. Geophys. Res.*, submitted.

5.1. Conference presentations

ASLO Summer Meeting 2005, Santiago de Compostela, Spain, June 19-24, 2005

Stramska, M. and D. Stramski, Particulate organic carbon concentrations in the north polar Atlantic from SeaWiFS ocean color observations.

NASA Ocean Color Research Team Meeting, Portland, April 12-14, 2005

Stramska, M., Interannual variability of seasonal phytoplankton blooms in the north polar Atlantic in response to atmospheric forcing.

Stramska, M. and D. Stramski, Development of ocean color algorithms for estimating particulate organic carbon concentration.

Stramska, M., D. Stramski, D. B. Allison, and S. Kaczmarek, Variability of the bio-optical relationships in the north polar Atlantic.

Allison, D. B., D. Stramski, and B. G. Mitchell, Estimating particulate organic carbon from satellite ocean color data in the Southern Ocean.

Ocean Optics XVII Conference, Fremantle, Australia, October25-29, 2004

Stramska, M., D. Stramski, D. B. Allison, and S. Kaczmarek. Interannual variability of surface chlorophyll and particulate organic carbon concentration in the north polar Atlantic.

Allison, D. B., D. Stramski, and B. G. Mitchell. Seasonal and interannual variability in particulate organic carbon and chlorophyll in the Southern Ocean from satellite ocean color data.

ASLO 2003 Aquatic Sciences Meeting, Salt Lake City, Utah,February 8-14, 2003

Allison, D. B., D. Stramski, and B. G. Mitchell. Satellite observations of variations in particulate organic carbon in the Southern Ocean.

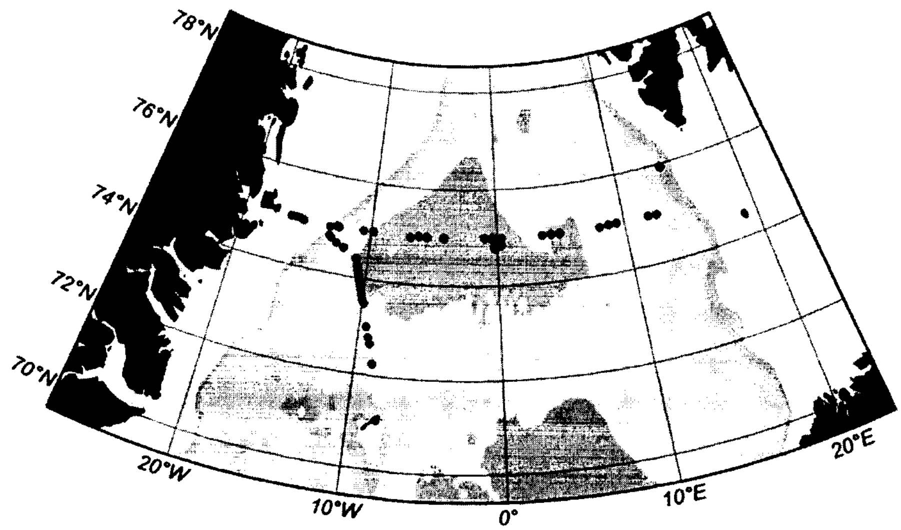

Figure 1. Maps showing the locations of optical stations during the *R/V Polarstern* cruise in April-May 2003 in the north polar Atlantic (the upper graph) and during the *R/V Yuzhmorgeologiya* cruise in January-March 2004 in the Southern Ocean (lower graph).

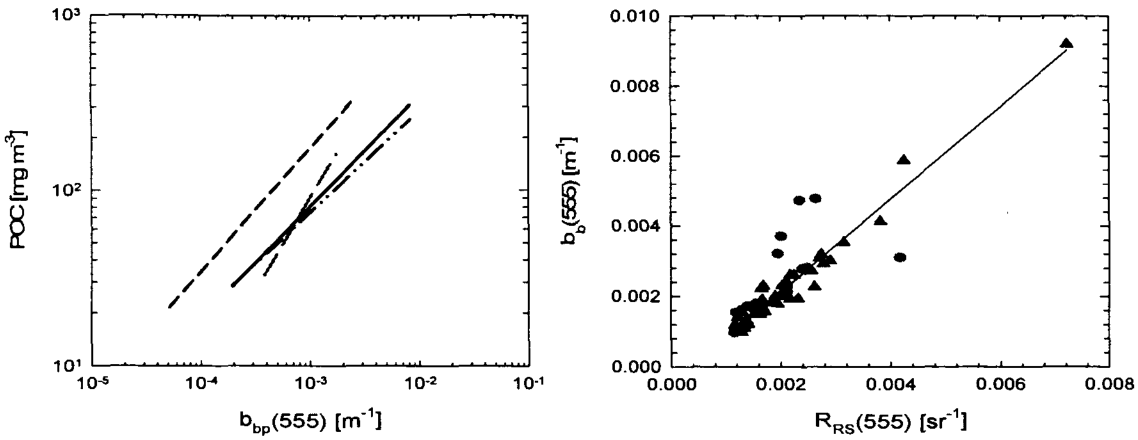

Figure 2. Left-hand panel. The best fit relationships for POC versus particulate backscattering $b_{bp}(555)$ obtained for each examined region of the Southern Ocean as well as the combined relationship for the open waters of the Southern Ocean (blue dash=Ross Sea, red dash=AMLR2004 cruise in the region of Antarctic Peninsula, black dash=Antarctic Polar Front Zone (APFZ) in the Pacific section of the Southern Ocean , solid line=combined open waters). The best fit for the open water data is POC = 6861.45 $[b_{bp}(555)]^{0.643}$ with $r^2 = 0.77$. Right-hand panel. The best fit relationship for the total backscattering $b_b(555)$ versus $R_{rs}(555)$ for all Southern Ocean data. Data with possibly low quality are marked as red circles. The best fit is $b_b(555) = 1.32\ R_{rs}(555) - 0.000533$ with $r^2 = 0.96$.

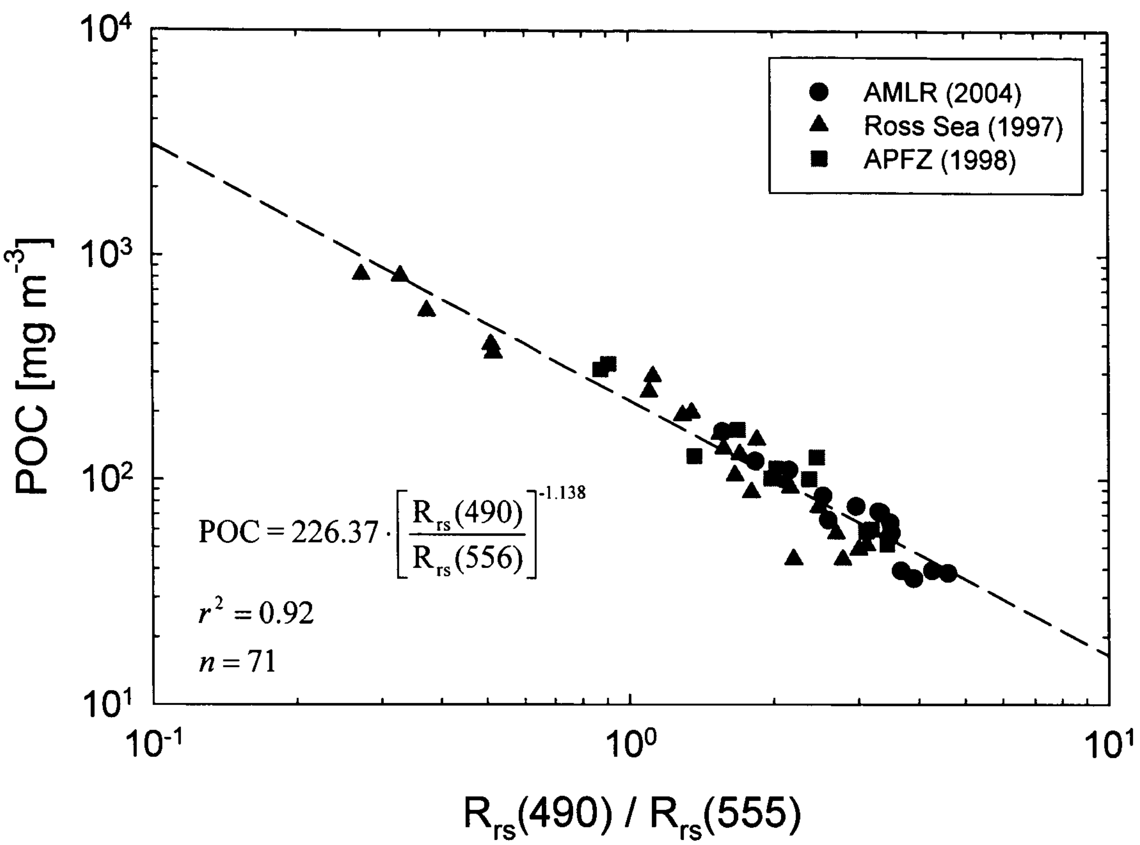

Figure 3. Relationship between POC and the reflectance ratio $R_{rs}(490)/R_{rs}$ (555). Data are plotted as points for the following cruises in the Southern Ocean: AMLR2004 cruise in the region of Antarctic Peninsula, and the Southern Ocean JGOFS cruises in the Ross Sea in 1997 and Antarctic Polar Front Zone (APFZ) in 1998.

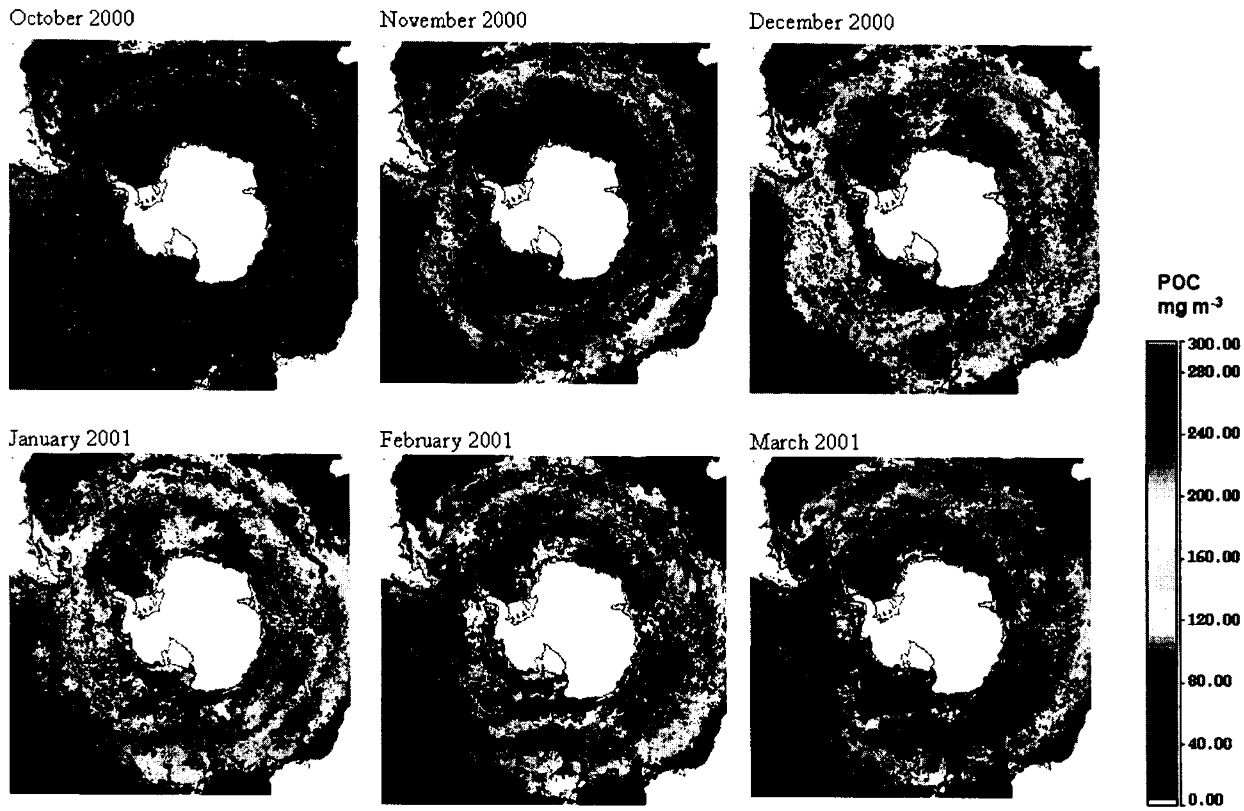

Figure 4. Seasonal progression of surface POC concentration in the Southern Ocean as determined by application of our POC algorithm I to SeaWiFS monthly imagery from October 2000 through March 2001.

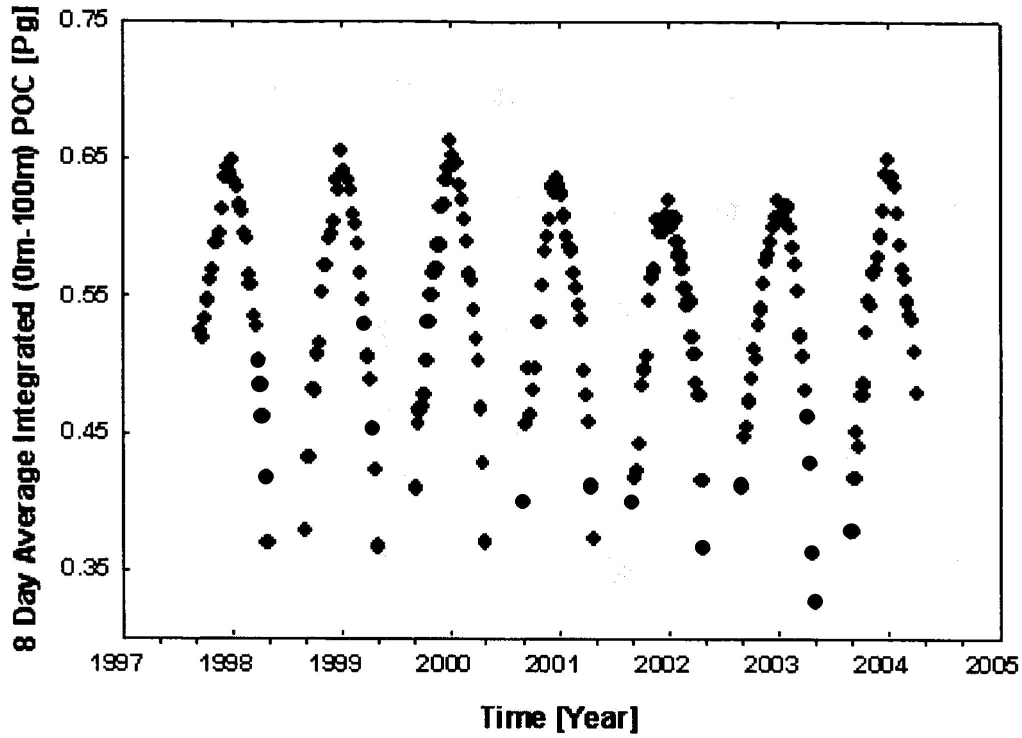

Figure 5. Time -series of POC pool integrated within the surface layer from 0 to 100 m depth over the entire Southern Ocean (40 - 70oS) for the period of SeaWiFS mission (with the exception of the last austral summer season). This result is based on the application of our POC algorithm II to 8-day composite imagery obtained with SeaWiFS for the entire period of time presented.