USING THE MODERATE RESOLUTION IMAGING SPECTRORADIOMETER (MODIS) TO ESTIMATE PHYTOPLANKTON PROCESSES IN THE ROSS SEA, ANTARCTICA

Jill A. Peloquin, Virginia Institute of Marine Science, Gloucester Point, VA
(*jillp@vims.edu*)
Mentor: Dr. Tiffany Moisan, NASA WFF, Code 972

Abstract. *The Southern Ocean has been identified as critical in the global carbon cycle and will unequivocally be affected by changes in global temperature. Thus, it is critical to understand carbon dynamics in the Southern Ocean. The Ross Sea, Antarctica is amongst the most productive areas of the Southern Ocean and represents an area of Deep Water formation. Because of this, the magnitude and interannual variation of carbon production is an important system component to constrain. The first-order goal of this project is to quantitatively estimate chlorophyll a pigment as a proxy for phytoplankton abundance in the Ross Sea, Antarctica. These estimates will then be used in a vertically generalized primary production model to estimate the seasonal potential of the Ross Sea phytoplankton assemblage to fix carbon dioxide into organic matter. In addition, regional estimates of photochemical efficiency will be made in order to strengthen primary production models and determine when the phytoplankton assemblage becomes nutrient limited (presumably by trace metals). Data from images will be sea-truthed with discrete measurements made in conjunction with a field program called interannual variability in the Ross Sea (IVARS). Several years (2000-2004) will then be compared in order to ascertain and constrain interannual variability. These data will be put into the context of a larger field program in order to determine what drives the potential and magnitude of the seasonal phytoplankton bloom. At present, the MODIS Terra images are being reprocessed, thus the primary thrust of this summer's work has been to establish the infrastructure needed to complete the project goals and learn the processing/analysis language. It is clear from browse images that chlorophyll –a and chlorophyll efficiency does change from year to year.*

INTRODUCTION

The first-order goal of this project is to quantitatively estimate chlorophyll *a* pigment as a proxy for phytoplankton abundance in the Ross Sea, Antarctica. These estimates will then be used in a vertically generalized primary production model (Behrenfeld and Falkowski 1997a) to estimate the seasonal potential of the Ross Sea phytoplankton assemblage to fix carbon dioxide into organic matter. In addition, regional estimates of photochemical efficiency will be made in order to determine when the phytoplankton assemblage becomes nutrient limited (presumably by trace metals). Several years (2000-2003) will then be compared in order to ascertain and constrain interannual variability. These data will be put into the context of a larger field program in order to determine what drives the potential and magnitude of the seasonal phytoplankton bloom. At present, the MODIS Terra images are being reprocessed, thus the primary thrust of this summer's work has been to establish the infrastructure and tools needed to complete the project goals and learn the processing/analysis language (Interactive Data Language). This project will continue past the GEST fellowship period and comprise a significant portion of the author's dissertation work. A considerable amount of this paper is dedicated to describing the ultimate fate of the images that will be processed in order to relate this summer's work to the larger project.

Ross Sea Biogeochemistry

The Southern Ocean refers to the waters found south of a convergence zone at approximately 40° S. The primary current structure, the Antarctic Circumpolar Current (ACC) is forced clockwise around the Antarctic continent by westerly winds. The Southern Ocean is characterized as the largest high nutrient low chlorophyll region (HNLC), although biomass tends to be higher in coastal, shelf, frontal and ice edge regions. Most of the Antarctic continent is perpetually covered by snow and ice. Thus, deposition of iron from aerolian dust is limited in this area. As a result, low concentration of phytoplankton biomass is driven by low inputs of biologically available iron (Martin *et al.* 1991; Boyd *et al.* 1999). The Southern Ocean carbon cycle is critical to global climate because it represents an area of intermediate and deep-water formation and sequesters carbon naturally (Sarmiento and Orr 1991, Sarmiento *et al.* 1998). Models coupling atmospheric and oceanic processes have also suggested that this region may be particularly sensitive to climatic fluctuations (Sarmiento *et al.* 1998*)*. Thus, it is of critical importance to understand the factors driving carbon dynamics in the Southern Ocean (Smith *et al.* 2000).

In particular, the Ross Sea, Antarctica is a highly productive region of the Southern Ocean system and supports a predictable seasonal phytoplankton bloom (Comiso *et al.* 1993). Increased phytoplankton biomass begins in late October (Smith and Gordon 1997; Arrigo *et al.* 1998) and is maximal in late December (Asper and Smith 1999; Smith *et al.* 2000). Primary productivity follows a similar trend with the maximum occurring in December (Smith *et al.* 2000). The Ross Sea is further characterized by having taxonomically discrete areas. The first is the south-central region where *Phaeocystis antarctica* dominates the phytoplankton assemblage. The second is along the coast of Victoria Land where diatoms dominate (DiTullio and Smith 1996; Arrigo *et al.* 1999). Although the spatial floristic trends have not yet been attributed to a single nutrient or physical feature (Arrigo *et al.* 1999; Olson *et al.* 2000), the taxonomic distribution clearly has profound biogeochemical consequences on vertical flux and elemental removal ratios (DeMaster *et al.* 1992; Smith and Dunbar 1998; Arrigo *et al.* 1999).

Remote Sensing of Ocean Color

Phytoplankton are the base of marine food webs, providing organic matter for all trophic transformations. Furthermore, they are an integral part of the global carbon cycle and fundamental regulators of the ocean's "biological pump" (see Figure 1). Phytoplankton primary production, the reduction of inorganic carbon into organic carbon by photosynthesis, is an integral process in both biological oceanography and marine biogeochemistry. Ocean color image analysis provides a powerful means to estimate global and local phytoplankton biomass and derived primary production and remains the only means to derive large-scale phytoplankton processes.

Spectral reflectance, a formalized name for ocean color, measures the radiance backscattered from water through the earth's atmosphere at one or several wavebands of light. The primary absorbers of light *in situ* at biologically relevant wavebands are particulate detritus, chromophoric dissolved organic matter (CDOM), phytoplankton pigments, and water molecules (Yoder *et al.* 2001). The first satellite dedicated to measuring ocean color was the Coastal Zone Color Scanner (CZCS) (Mitchell 1994).

Although the satellite's radiance sensors degraded through the course of the mission, the first satellite-based estimates of regional scale chlorophyll distribution (Esaias *et al.* 1986) and global primary productivity (Longhurst *et al.* 1995) were made. In 1997, the Sea Wide Field of View Sensor (SeaWiFS) was launched with numerous technological advances and improvements. For example, the SeaWiFS sensor is calibrated on board for long- and short-term shifts, there are six wavebands that are measured (two more than CZCS), and its signal to noise ratio is greater (Joint and Groom 2000).

The latest satellite sensor launched by NASA for ocean color was the Moderate-Resolution Imaging Spectrophotometer (MODIS) and is the sensor that will be used for this project. MODIS has a large viewing swath (2330 km), 36 discrete spectral bands (Table 1) and covers the earth every 1-2 days. The MODIS sensor is on two separate satellites, AQUA and TERRA. TERRA-based measurements are relative to this project as AQUA images are still in provisional status. An exciting advancement for the MODIS sensor is that the quantum yield of photochemistry as well as the concentration of chlorophyll *a* (Esaias *et al.* 1997) can be estimated. Important advancements in the understanding of large-scale biogeochemical cycles have been made in concert with remote sensing of ocean color for the field of biological oceanography. The temporal and spatial coverage with remote monitoring are greater than any other method of sampling. There are, however, limitations to remote sensing estimates of ocean color as cloud cover, sunglint and aerosols can mask the sea surface. Also, since satellites can only "see" to one optical depth (14% of surface intensity), the subsurface chlorophyll maximum is often poorly observed (thus integrated chlorophyll will be underestimated). Nonetheless, the use of satellite remote sensing is an outstanding tool in biological oceanography, and much progress has been made with it since its conception. Studies include the use of CZCS data to quantify phytoplankton blooms for the Southern Ocean (Sullivan *et al.* 1993), SeaWiFS images to estimate primary production for El-Nino and La Nina years (Turk *et al.* 2001) and POC concentrations for the Southern Ocean (Stramski *et al.* 1999). An ocean color study by Moore and Abbott (2001) for the Southern Ocean showed that regionally high chlorophyll concentrations are constrained to the coastal zone, the MIZ (marginal ice zone), and along the watermass fronts.

For the Ross Sea estimates of phytoplankton distributions have been determined with CZCS remote sensing imagery (Arrigo and McClain, 1994; Arrigo *et al.* 1998). Shortcomings in these last two studies are that they both lacked appropriate field measurements and early bloom remote sensing images for the Ross Sea. For polar systems, acquiring early bloom images is difficult as ice, snow and cloud cover restrict satellite sensors. However, comparing discrete measurements of chlorophyll to ocean color estimates is extremely useful in an area where algorithms are still being developed. Thus, for optimal confidence in the processed images, it is necessary to have a series of *in situ* measurements during the period that images are processed.

Modeling Primary Production from Ocean Color

Primary production (g C $m^{-2}d^{-1}$) is the process in which phytoplankton convert inorganic carbon through photosynthesis into organic carbon. There have been few global and regional estimates of primary production (Eppley and Peterson 1979; DeVooys 1979: Pauly and Christiansen 1995) since the original estimate by Kolblentz-Mischke *et al.* (1970) of 25 – 30 pg C y-1. By integrating ocean color chlorophyll estimates, extrapolating to carbon production via remote sensing is possible (Longhurst *et al.* 1995; Behrenfeld and Falkowski 1997a; Antoine *et al.* 1996; Arrigo *et al.* 1998). There are essentially two approaches for estimating primary production from remotely sensed chlorophyll concentrations, empirical (Behrenfeld and Falkowski 1997a) and semi-analytical (Platt *et al.* 1990; Platt *et al.* 1991; Morel 1991). Empirical models for primary production tend to be regionally specific (from the areas which they were generated, whereas semi-analytical models take light absorption and physiological considerations into account to extrapolate to a global context (Joint and Groom 2000). One of the most promising empirical primary production models that have specifically been designed to integrate with satellite remote sensing is the Vertically Generalized Production Model (VGPM) (Behrenfeld and Falkowski 1997a). This model is depth independent, light dependent and is fairly simple to apply. Uncertainties still remain with estimates of primary production from satellite remote sensing specifically for the Southern Ocean (Schlitzer 2002). However, if estimates of primary production derived from ocean color are coupled and regionally constrained with *in situ* measurements of primary production these models can be used confidently.

Photochemical Competency

Evaluation of the quantum yield of photochemistry by the use of fluorometry is a commonly used technique. Measuring fluorescence and relating it back to photochemistry is based on a very simple photobiological theory. A photon penetrating the cell wall will have one of three fates: it will be used to drive photosynthesis, be dissipated as heat, or re-emitted at a longer wavelength as fluorescence. These cellular processes are competitive (light energy is conserved), such that by measuring fluorescence, one can estimate the importance of photochemistry and heat dissipation. This fluorescence yield from PSII is highly variable, dependent on the physiological state of the phytoplankton cell, and can be affected by a number of factors, including light and nutrient stress. One of the advancements of MODIS is that 3 bands (665, 676, 746 nm) have been added that can be used to evaluate the fluorescence properties of the phytoplankton assemblages. This added functionality will allow the MODIS consumer to be able to estimate health of phytoplankton assemblage on variable temporal and spatial scales.

OBJECTIVES

In order to work with the highest quality images from the MODIS sensor, the author has to wait until mid-September for the first set of images to be reprocessed. Despite the fact that images were not available, the summer's goals were still challenging. The author had no previous experience with IDL or the process required to analysis MODIS images. Thus, a realistic amount of time was allotted this summer towards understanding fundamental processing approaches and how to program in IDL. The specific summer goals and future objectives are found below:

A. Summer Goals

1. Compile the MODIS products that will be necessary to complete the project goals and understand the algorithm calculations

2. Understand exactly how to use and manipulate level 2 and level 3 images in order for them to be accurately utilized

3. Learn Interactive Data Language (IDL)

4. Acquire available IDL code and write the rest needed for image analysis

5. Set up subscription with NASA Data Archive in order to receive images as soon as they are reprocessed in the most efficient manner

6. Preview browse MODIS images to determine whether it appears that interannual variability will be found in the Ross Sea, Antarctica.

B. Future Project Goals

1. Quantify the MODIS-based chlorophyll a product for the Ross Sea, Antarctica over seasonal and interannual time scales.

2. Relate the seasonal chlorophyll a product to a vertically generalized primary production model (Berenfeld and Falkowski 1997a).

3. Quantify the MODIS-based quantum efficiency product for the Ross Sea and utilize it to predict when the local phytoplankton assemblage undergoes trace metal limitation and strengthen primary production models.

*4**.** Compare the larger spatial and temporal changes in chlorophyll a and modeling primary production with the IVARS program discrete measurements to begin linking changes in yearly carbon production to local environmental factors.*

METHODS

The Ross Sea

In order to validate MODIS ocean products, remote sensing image analysis will be paired with an on going field effort called Interannual Variability in the Ross Sea (IVARS). Funding for this 5 year project is provided by N.S.F. to Dr. Walker O. Smith. The main thrust of this program is to deploy and retrieve moorings from taxonomically distinct sites in the Ross Sea (*P. Antarctica*- and diatom-dominated locations; 77º S, 177º W (*Xiphias*), and 77º S, 172º E (*Calinectes*), respectively (see Figure 2). The moorings will contain *in situ* nitrate analyzers, silcate analyzers, sediment traps, current meters, temperature/salinity sensors, transmissometers, fluorometers, fast repetition rate fluorometers and whole water samplers. These moorings will be deployed each year starting mid-December 2001 and retrieved at the end of the growing season in mid-February (although sediment traps will be redeployed for the full year. In addition to the mooring operations, discrete measurements of biogeochemical parameters will be made (see Table 2).

Images

At present (August-October 2003, MODIS Terra images (August 2000-December 2002) are being reprocessed to correct for sensor shifts not accounted for in the present calibration. Thus, quantitative image analysis is delayed until reprocessing is complete.

Two different levels of DAAC image processing will be utilized. Daily (1 km pixel resolution) Level 2 images will be used for validation of ship-based station data. Level 2 are images that have been processed by the DAAC, atmospherically corrected, and adjusted according to the product specific algorithm. These swath images (5 second granules) will be geolocated, quality filtered (0; best quality) and sub-sampled using Interactive Data Language (IDL). It is unclear at this time whether daily passes will be binned for a Level 2 daily average or the closest swath to the sampling time will be used. A regression will be established between the value of the MODIS and ship-based product. This algorithm offset will then be applied as a post- processing correction to Level 3 images. The products that will be initially ordered are compiled in Table 3.

Level 3 mapped images (global; 8-day temporal bin) at approximately 5 km resolution will be used as the primary data product. Mapped Level 3 images are useful (Figure 3); they are straightforward to work with, to systematically sub-sample and they can be spatially binned (polar areas tend to have poor image coverage due to ice and cloud formation). The Level 3 images will be quality controlled for best pixels (Q, 0) and then corrected as explained above. These images will then comprise the time-series from October 1st-March 1st for the Ross Sea for the years 2000, 2001, 2002, and 2003.

Product Algorithms and Models

The algorithm approach to remotely sensed ocean color and fluorescence efficiency merits a brief explanation. The general approach of the VGPM will also be reviewed. Put simply, phytoplankton are evaluated according to chlorophyll because of the ease of its measurement. A consumer of such products needs to be aware of the potential problems with assuming that chlorophyll concentration is always a reliable indicator of phytoplankton biomass. Changing chlorophyll: phytoplankton cell ratio with nutrient, light, age, cell size and assemblage structure can be considerable issues. Nonetheless, the potential for predicting chlorophyll concentrations from remotely-sensed ocean color is extremely compelling and valuable. One of the strengths of modern phytoplankton pigment algorithms is that it only required an accurate spectrum of water leaving radiance, not the actual intensity of the radiance. This is because primary chlorophyll *a* algorithms utilize ratios at certain wavelengths of light from the returned spectrum to determined concentrations. For the purposes of this study, the Chlor_MODIS algorithm (D. Clark) will be used. This is an empirical algorithm for optically clear (Case "1") waters based on the ratio between 443:551 nm in the water leaving spectral radiance.

A photon of light enters a cell has one of three fates: it can be used to drive photosynthesis, be re-emitted as heat, or reemitted at a longer wavelength as fluorescence. Thus, fluorescence by phytoplankton light harvesting complex is major de-excitation processes for photo-system II (PSII). If we consider the fact that light harvested obeys conservative laws, then the following relationship holds:

$$1 = \phi_{\text{photochemistry}} + \phi_{\text{fluorescence}} + \phi_{\text{heat}}$$

(Equation 1)

Thus, by understanding something about the variability in photochemical fluorescence characteristics, one can start to understand photosynthesis. Consider the following bio-optical model (Abbot and Letelier, date unknown)

$$F = \text{Chl-a} \bullet \text{PAR} \bullet a^* \bullet \phi_{\text{fluorescence}}$$

(Equation 2)

where:

F = fluorescence

Chl a = chlorophyll concentration

PAR = photosynthetically available radiation

a^* = chlorophyll specific absorption

$\phi_{\text{fluorescence}}$ = Fluorescence quantum yield

ARP= chl x a^* x PAR

Then if you rearrange this equation, you can estimate ϕ by the ratio F/ARP. Thus, by good estimates of ARP and measurements of fluorescence one can estimate how efficient the phytoplankton assemblage is at utilizing light for photosynthesis. A variety of factors can reduce photochemical quenching, including light and nutrient stress.

The following equation is the VPGM model (Behrenfeld and Falkowski 1997a):

$$PP_{eu} = 0.66125 \bullet P^{B}\,\text{opt} \bullet [\, E_o / E_o + 4.10] \bullet C_{SAT} \bullet Z_{eu} \bullet D_{IRR} \qquad \text{(Equation 3)}$$

where:

C_{SAT} are satellite derived surface chlorophyll concentrations

-Z_{eu} is the depth of the euphotic zone (1% light penetration depth) derived from C SAT (Morel and Berthon 1989)

-D_{IRR} is daily photoperiod

- E_o is sea surface daily PAR

-P^bopt is the optimal rate of carbon fixation

This vertically generalized model has been systematically used in conjunction with remote sensing image analysis of ocean color. In fact, it is included and processed as a Level 4 MODIS product. For this study, it will be necessary to run the model locally as we hope to use chlorophyll a products that have undergone a post-processing correction. Thus, we will use the locally corrected Level 3 images as input for the VGPM model.

RESULTS/DISCUSSION

The summer's project goals were successfully met, with some advancement in the ease of which image analysis can be completed. At present, the author has a solid handle on IDL, understands how to use and analyze MODIS images and has a subscription set for the required MODIS products. All the code that is required has been compiled and is working. Several sub-routines had to be locally written and some that was needed was available from the MODIS group. In addition, everything that is needed to analyze images was transferred over to a Windows platform in order to analyze images on a more local basis.

It is clear that interannual variability of the phytoplankton bloom does exist in the Ross Sea (Figure 4). This is an early January 8-day binned browse image provided by the DAAC of the MODIS Terra chlorophyll a product (2000-2002). Something to consider is that this is on a 36 km spatial scale, thus the detail available from 5 or 1 km images will be relatively impressive. It is clear from this series of images that phytoplankton concentrations can widely vary from year to year. The phytoplankton bloom was severely attenuated in January 2003, whereas in 2002 and 2001 it was more impressive. Several factors may cause these changes in bloom dynamics; variability in ice, presence of large icebergs, degree of trace metal limitation, phytoplankton taxa present (or favored) amongst several other environmental factors. It is necessary to examine the full series of images in more detail to determine that the changes that seem apparent here are not reflections of cloudiness or ad pixels. Nonetheless, these images are encouraging and it seems likely that we will be able to quantify the seasonal phytoplankton bloom from MODIS images.

The quantum efficiency fields for the same time periods have also been downloaded from the DAAC (Figure 5). *A priori*, one might think that even if the magnitude of the phytoplankton differs from year to year, that the efficiency of the phytoplankton assemblage should be approximately similar. It is clear that interannual variability exists for phytoplankton physiology. This can be due to changes in micronutrient concentrations because of increased sea ice or changes in water circulation. Another possibility is that the phytoplankton assemblage was different during each year and that the algorithm is not strong enough to consider different light harvesting physiology.

With time, and by interfacing with a robust series of discrete measurements, we can determine what is driving these changes in bloom dynamics. Remote sensing image analysis serves as a powerful compliment to the IVARS field program as large temporal and spatial fields of phytoplankton can be directly compared from year to year. With that knowledge, we can start linking what biogeochemical and physical factors explain the magnitude of change from year to year. This study will unequivocally serve as a powerful segue towards understanding what drives and changes carbon dynamics in the Ross Sea.

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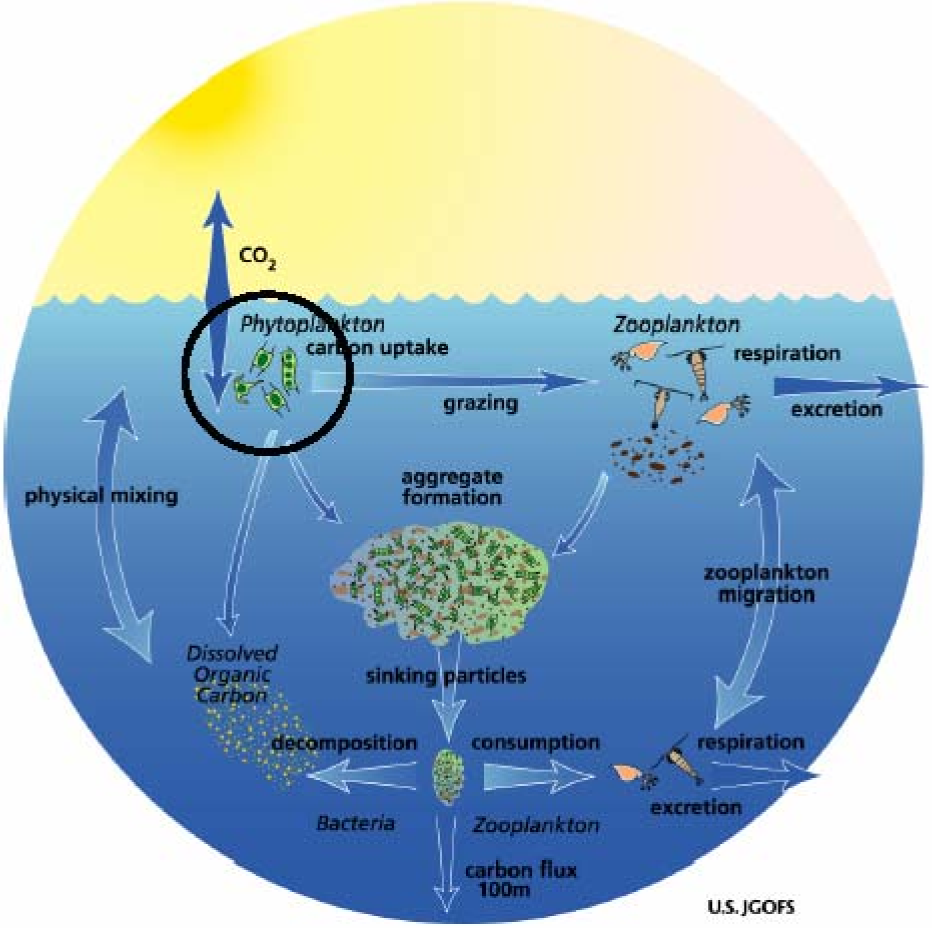


Figure 1. Cartoon of the global carbon cycle. Note the position of oceanic phytoplankton as a primary control for carbon dioxide flux.

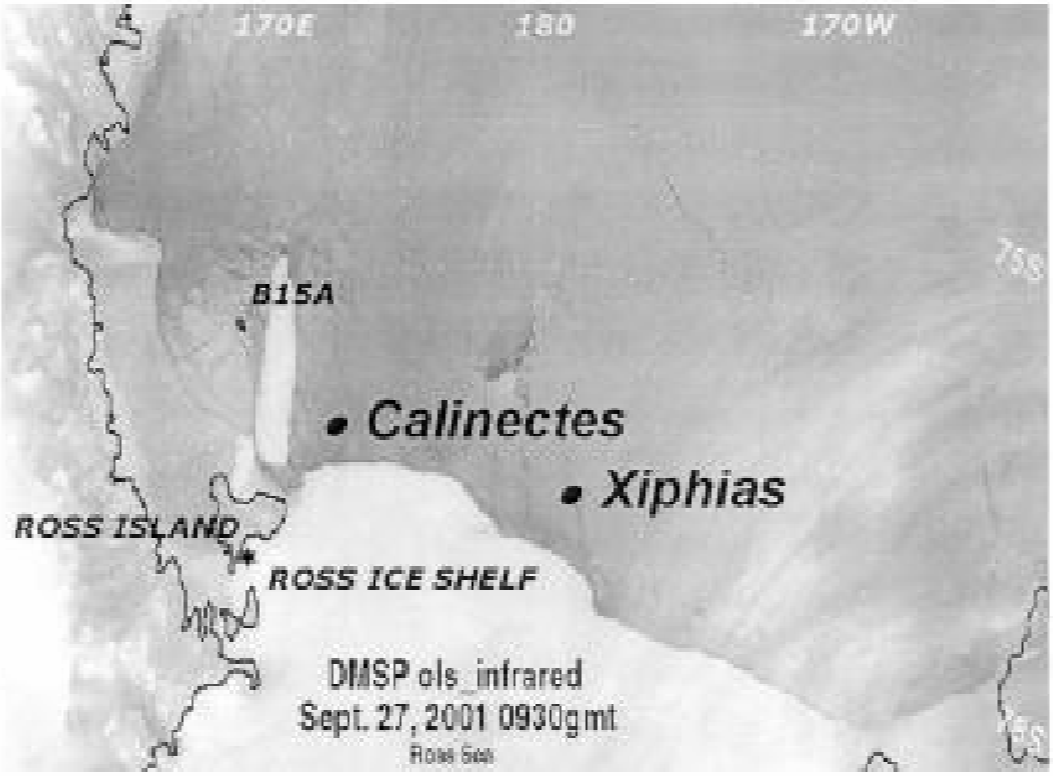


Figure 2. The location of the IVARS field program in the Ross Sea. Calinectes and Xiphias represent major stations and mooring locations.

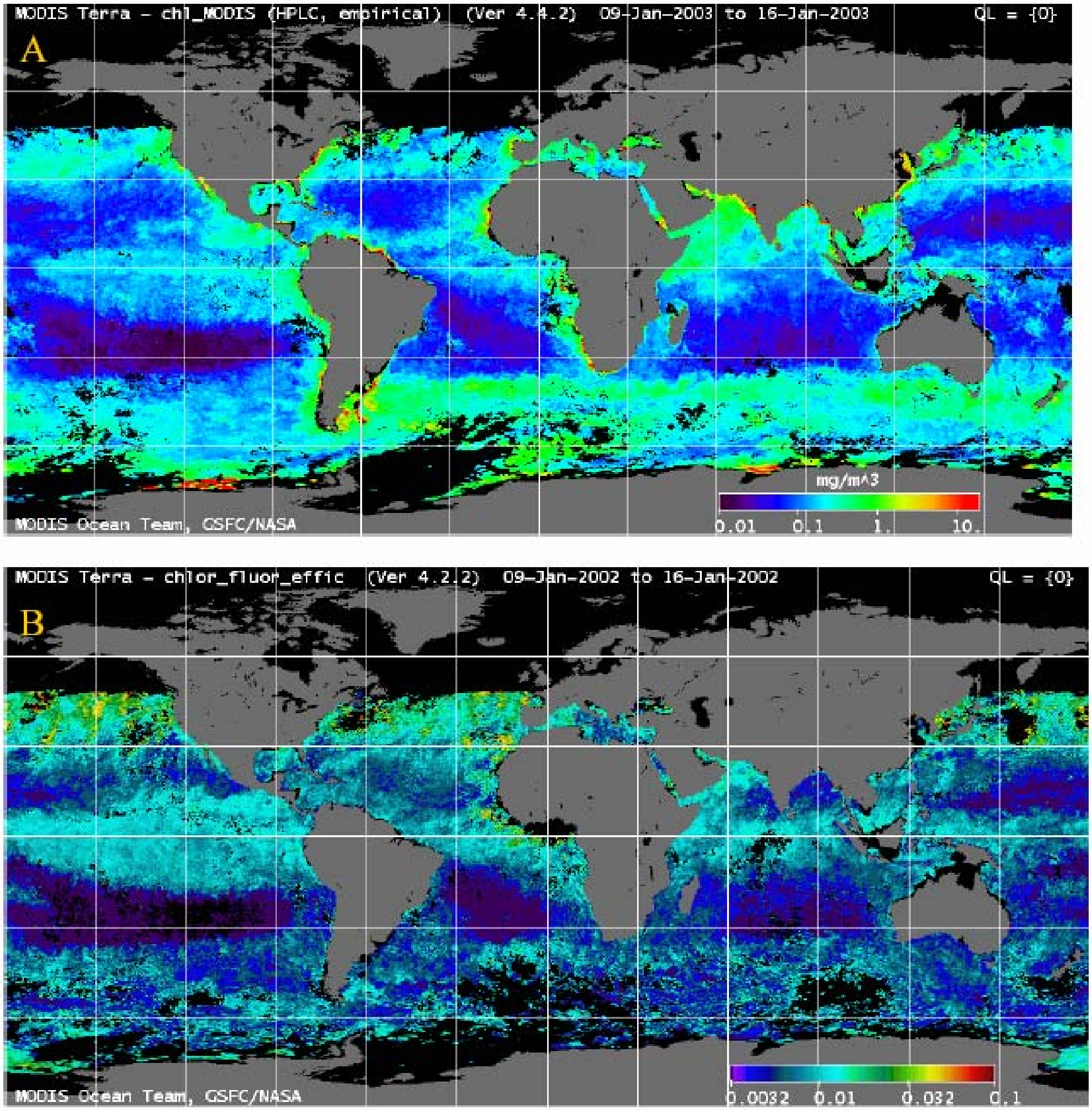


Figure 3. Example of MODIS Terra Level 3 mapped images for chlorophyll-a (A) and chlorophyll efficiency (B). These images are 36 km pixel, quality level 0 (best images). Images provided by NASA DAAC.

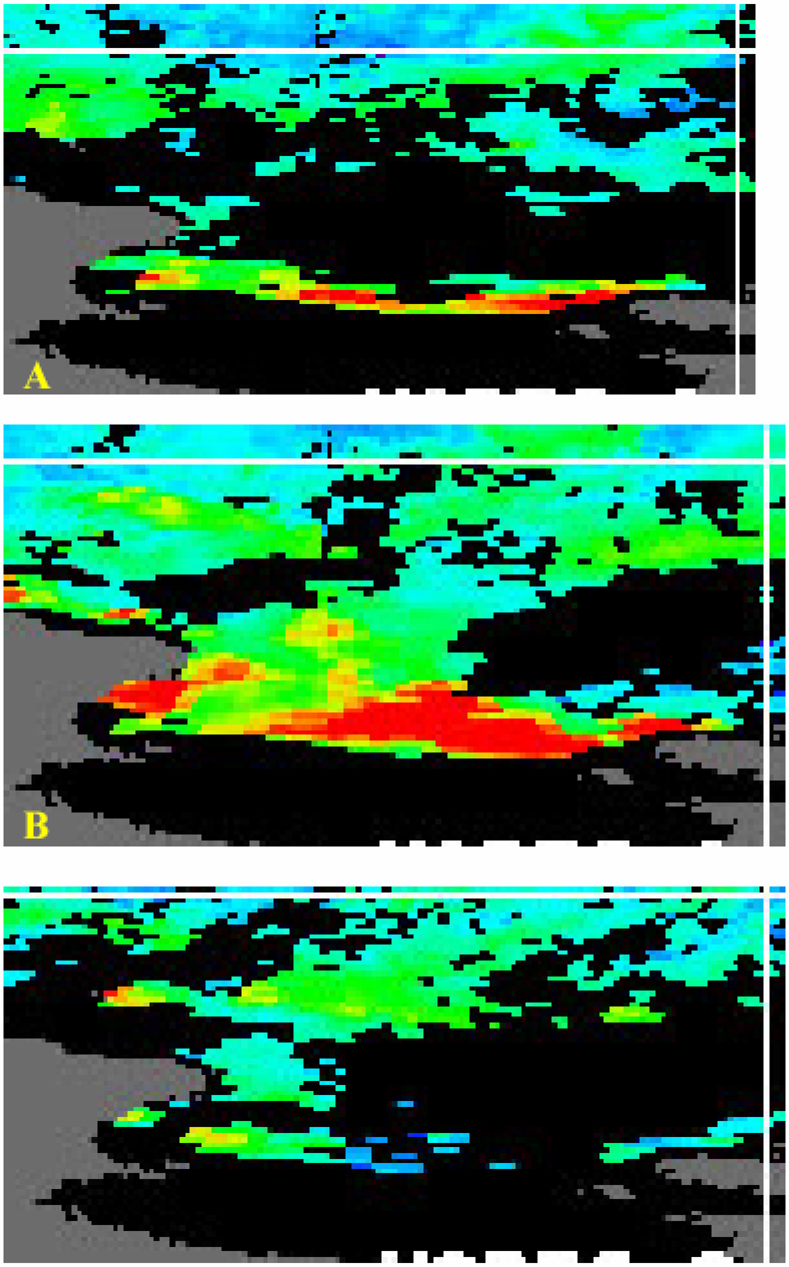


Figure 4. Chlorophyll *a* MODIS product for the Ross Sea, Antarctica. Image was extracted from a Level 3 global browse image for an 8-day bin from January 9-16th. A-C are years 2001, 2002, 2003, respectively. Note the change in pigment quantity (red is highest) from year to year.

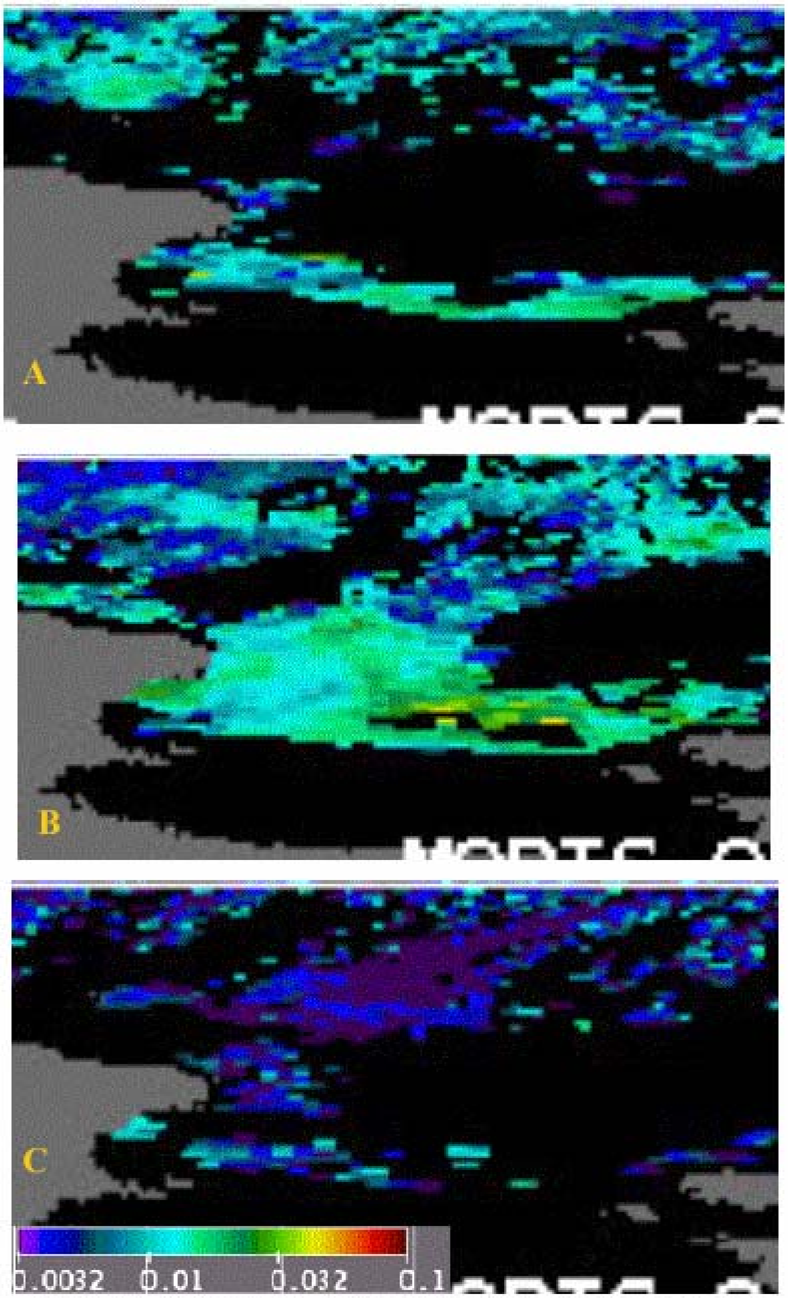
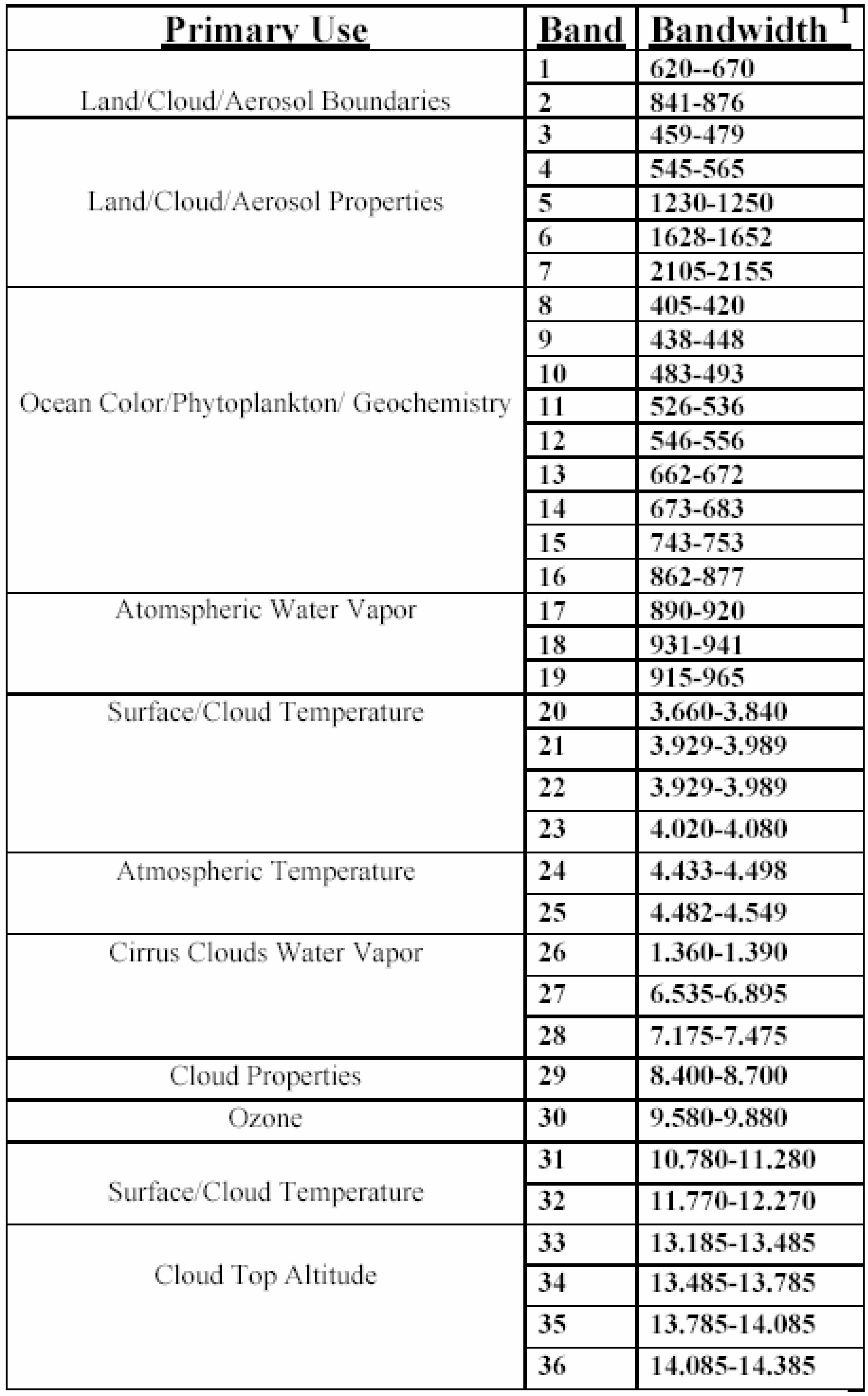


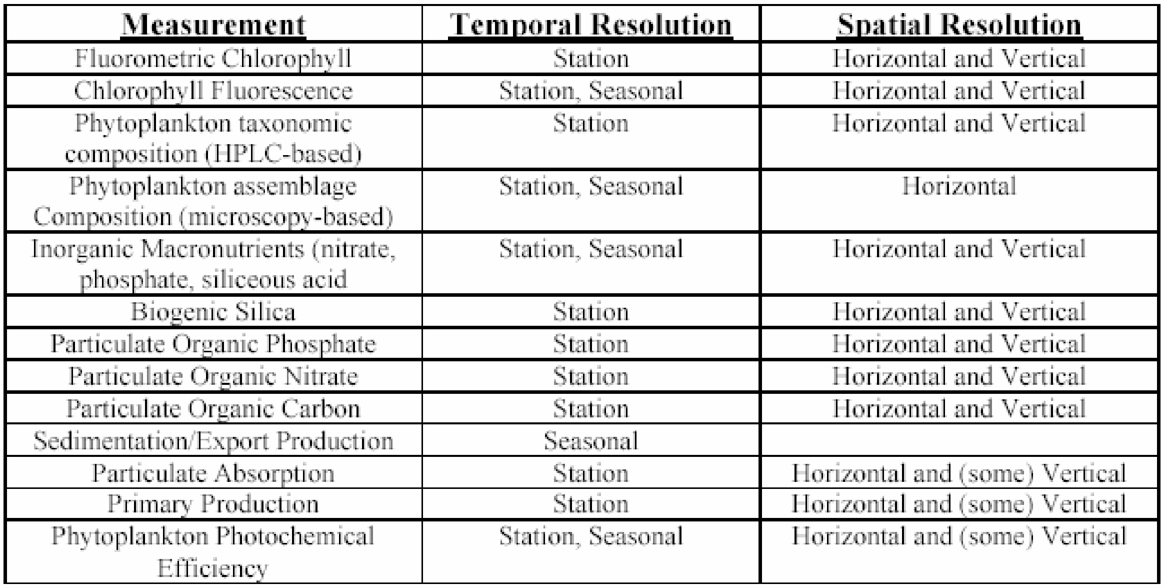
Figure 5. Chlorophyll *a* efficiency product for the Ross Sea, Antarctica. Image was extracted from a Level 3 global browse image for an 8-day bin from January 9-16th. A-C are from years 2001, 2002, 2003, respectively. Note the decease in efficiency in 2003.



Primary Use	Band	Bandwidth [1]
Land/Cloud/Aerosol Boundaries	1	620--670
	2	841-876
Land/Cloud/Aerosol Properties	3	459-479
	4	545-565
	5	1230-1250
	6	1628-1652
	7	2105-2155
Ocean Color/Phytoplankton/ Geochemistry	8	405-420
	9	438-448
	10	483-493
	11	526-536
	12	546-556
	13	662-672
	14	673-683
	15	743-753
	16	862-877
Atomspheric Water Vapor	17	890-920
	18	931-941
	19	915-965
Surface/Cloud Temperature	20	3.660-3.840
	21	3.929-3.989
	22	3.929-3.989
	23	4.020-4.080
Atmospheric Temperature	24	4.433-4.498
	25	4.482-4.549
Cirrus Clouds Water Vapor	26	1.360-1.390
	27	6.535-6.895
	28	7.175-7.475
Cloud Properties	29	8.400-8.700
Ozone	30	9.580-9.880
Surface/Cloud Temperature	31	10.780-11.280
	32	11.770-12.270
Cloud Top Altitude	33	13.185-13.485
	34	13.485-13.785
	35	13.785-14.085
	36	14.085-14.385

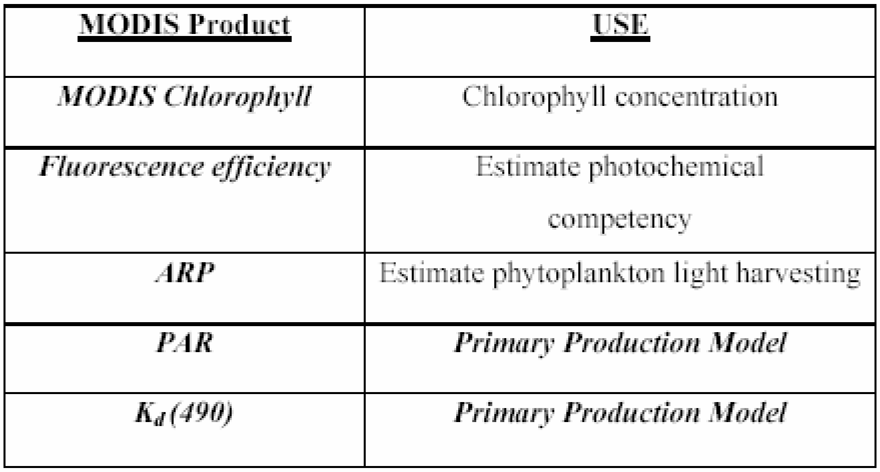
Table 1. MODIS bands and related product

[1] Bands 1-19 are in nm; Bands 20-36 are in µm.



Measurement	**Temporal Resolution**	**Spatial Resolution**
Fluorometric Chlorophyll	Station	Horizontal and Vertical
Chlorophyll Fluorescence	Station, Seasonal	Horizontal and Vertical
Phytoplankton taxonomic composition (HPLC-based)	Station	Horizontal and Vertical
Phytoplankton assemblage Composition (microscopy-based)	Station, Seasonal	Horizontal
Inorganic Macronutrients (nitrate, phosphate, siliceous acid	Station, Seasonal	Horizontal and Vertical
Biogenic Silica	Station	Horizontal and Vertical
Particulate Organic Phosphate	Station	Horizontal and Vertical
Particulate Organic Nitrate	Station	Horizontal and Vertical
Particulate Organic Carbon	Station	Horizontal and Vertical
Sedimentation/Export Production	Seasonal	
Particulate Absorption	Station	Horizontal and (some) Vertical
Primary Production	Station	Horizontal and (some) Vertical
Phytoplankton Photochemical Efficiency	Station, Seasonal	Horizontal and (some) Vertical

Table 2. List of Biogeochemical parameters measured in conjunction with IVARS. Station means that samples are taken discretely during the cruise, and seasonal means that they are measured by an instrument on the mooring.



MODIS Product	**USE**
MODIS Chlorophyll	Chlorophyll concentration
Fluorescence efficiency	Estimate photochemical competency
ARP	Estimate phytoplankton light harvesting
PAR	***Primary Production Model***
K_d(490)	***Primary Production Model***

Table 3. Primary MODIS data products for project use.