BIO-OPTICAL MODELING OF PRIMARY PRODUCTION FROM SEAWIFS OCEAN COLOR DATA FOR THE WESTERN ANTARCTIC PENINSULA REGION

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Waters of the Southern Ocean are bio-optically distinct. These waters are characterized by a pronounced seasonal variability in incoming solar radiation, low temperatures, generally high inorganic nutrients, as well as the presence, formation, and melting of sea ice. Phytoplankton populations in waters of the Southern Ocean have a maximum chlorophyll-specific carbon fixation rate within the water column which, consistent with low water temperatures, is low compared to those in more temperate waters. The corresponding optical properties of these waters generally show both low chlorophyll-specific absorption and low back-scattering which leads to significantly distinct remote sensing reflectance. As a consequence, algorithms for the estimation of satellite derived chlorophyll and subsequent modeling of primary production are unique for these waters. In this work, we evaluate the spatial and temporal variability of primary production (determined *in-situ* aboard ship as well as estimated from SeaWiFS ocean color satellite data). We also present the spatial and temporal variability of sea ice extent (estimated from passive microwave satellite data). Even though persistent spatial patterns have been observed over the many years of study (e.g., an onshore to offshore gradient in biomass and a growing season characterized by episodic phytoplankton blooms), this marine ecosystem displays extreme interannual variability in both phytoplankton biomass and primary production. This high interannual variability at the base of the food chain influences organisms at all trophic levels.

INTRODUCTION

Mounting evidence suggests that the world climate is changing and that polar regions, with their associated ecosystems, may be especially sensitive to this change. In particular, the western Antarctic Peninsula (WAP) region has experienced a statistically significant warming trend during the past half century (King, 1994; Stark, 1994; Smith *et al.*, 1996b; King and Harangozo, 1998; Smith and Stammerjohn, 2001). Thus, this region is proving to be an exceptional area to study ecological response to climate variability. Ecosystem research in the marine system (Fraser *et al.*, 1992), and paleoecological records from this area (Emslie *et al.*, 1998) show that ecological transitions have occurred in response to climate change.

Primary production in the WAP area follows closely the distribution of phytoplankton biomass measured as chlorophyll a (chl-a) concentration, and published values show a wide range of spatial and temporal variability (Smith *et al.*, 1996a; Moline and Prezelin, 1996). Concentrations are greatest nearshore with an onshore/offshore gradient of decreasing biomass towards the continental slope, that follows a gradient in bottom topography and physical and optical properties (Smith *et al.*, 1998a). While a number of physical and biological factors (e.g., light, temperature, nutrients, water column stability, advection, grazing, sinking) have been hypothesized as controls of cell and population growth, it is likely that no single factor dominates, and environmental variability can significantly influence these various factors.

Sea ice coverage in the WAP area shows high spatial and temporal variability and has important implications for the marine ecosystem (Stammerjohn and Smith, 1996; Smith *et al.*, 1998b). Therefore, a central hypothesis of the Palmer LTER is that the advance and retreat of sea ice is a major physical determinant of spatial and temporal changes in the structure and function of the Antarctic marine ecosystem. For example, air temperature and sea ice are strongly linked in the WAP area (Jacka, 1990; Smith *et al.*, 1996b), and there is evidence for decreasing trends in sea ice corresponding to statistically significant warming trends (Smith and Stammerjohn, 2001). In addition, the high variability in the frequency of storm events in the WAP region explains a significant amount of the variability in sea ice. The variability in circumpolar deep water intrusions onto the continental shelf mediates sea ice formation and decay as well as influences the supply of nutrients to the shelf (Jacobs and Comiso, 1997). It is within the context of this highly variable physical environment, that we consider the spatial and temporal variability of pigment biomass and phytoplankton production.

Our goal is to estimate the spatial and temporal variability of primary production in the WAP region. The need to synoptically characterize physical and biological properties of this large, inhospitable and remote ocean (i.e., Southern Ocean) over long time periods leads to the use of satellite data. We use a multiplatform sampling approach (Smith *et al.*, 1987) whereby surface shipboard observations are used to develop in-water bio-optical algorithms, and these algorithms are then used with SeaWiFS ocean color data to estimate pigment biomass (Dierssen and Smith, 2000). We then use a depth-integrated primary production model that was developed specifically for these waters to estimate primary production from the satellite derived chl-a data (Dierssen *et al.*, 2000). Results are compared with independent shipboard observations to optimize in-water and satellite algorithms for estimation of primary production in the WAP. This extended abstract is a subset of a manuscript currently submitted for publication in American Zoologist (Smith *et al.*, submitted). Please refer to the submitted document for a more complete bibliography.

METHODS

Our long-term regional observations are structured by a sampling grid that lies along the west coast of the Antarctic Peninsula. This fixed grid provides station locations that can be visited repeatedly over time scales of many years. Within the large-scale peninsula grid we have embedded a smaller sampling grid in the area adjacent to Palmer Station. Stations within this smaller grid are visited at least weekly (weather and sea ice conditions permitting) throughout the period of maximum phytoplankton production (typically October to March). In this work, shipboard phytoplankton biomass is characterized by total chl-a concentration using standard fluorometer techniques (Smith *et al.*, 1981).

We also utilize monthly SeaWiFS Level-3 Standard Mapped Images of chl-a provided from the NASA Goddard Space Flight Center's Distributed Active Archive Center (Version 3). These images are global-area coverage data that have been averaged over each month using the maximum likelihood estimator mean. The resolution of each pixel in the image is approximately 0.088 degrees latitude and longitude, which translates roughly to a resolution of 9.77 km per pixel in the north-south and 4.2 km per pixel in the east-west direction. Dierssen et al. (2000) using a large *in-situ* data set (>1000 stations from the Palmer LTER program) assessed the general processing algorithms for ocean color satellites and then created a revised SO-algorithm for use in Antarctic waters (Dierssen and Smith, 2000). These authors discuss in detail both the biological and optical methods used in their work. A validation of the SO-algorithm using SeaWiFS data (Version 2) shows that satellite-derived chl-a can be used to accurately estimate chl-a in these waters (Dierssen, 2000). For this analysis, all satellite-derived chl-a is adjusted using the SO algorithm.

Duplicate productivity samples were estimated by 24-hour simulated *in situ* incubations with ^{14}C-bicarbonate (Smith *et al.*, 1998a). These shipboard production data were then used to optimally parameterize a standard depth-integrated primary production model (Behrenfeld and Falkowski, 1997) to fit the relatively uniform chl-normalized production profile and low photoadaptive variable (characteristic of low-light adapted phytoplankton) found in Antarctic waters. so as to enhance model performance for the WAP area. Our formulation of this model (Dierssen *et al.*, 2000) is as follows:

$$PP_{eu} = P^{B}_{opt}\ D\ Z_{eu}\ C_o\ F$$

$$Z_{eu} = 46.8\ \ C_o^{-0.36}$$

where PP_{eu} is daily integrated primary production (mg C m^{-2} d^{-1}), D is daylength (h), Z_{eu} is the euphotic depth (m), F is the irradiance-dependent function taken here as a constant equal to 0.64, P^{B}_{opt} is the photoadaptive variable and set to 1.09 mg C mg chl-a^{-1} h^{-1} for these waters, and C_o is surface chl-a. This standard production model was optimized using Palmer LTER bio-optical data It was developed using Palmer LTER 1994/95 and 1995/96 field data and then tested using both other Palmer LTER data and historic data from the WAP region (r^2>0.70) (Dierssen *et al.*, 2000; Dierssen, 2000).

Remotely sensed passive microwave data was used to characterize sea ice extent. Data were provided by the National Snow and Ice Data Center (NSIDC) which distributes data from the Defense Meteorological Satellite Program's (DMSP) Special Sensor Microwave/Imager (SSM/I) (Stammerjohn and Smith, 1996)

RESULTS AND DISCUSSION

The Palmer LTER field data show significant variation in the timing (+/- several weeks) and magnitude (roughly +/- a factor of 5) of annual biomass accumulation, both alongshore and on/offshore. Simple correlations (not shown) indicate that roughly 60% of the variability in production can be explained by biomass alone (Dierssen *et al.*, 2000). Therefore variability in biomass is generally related to variability in primary production. Making use of the production model described in the methods, production is calculated using estimates of chl-a from SeaWiFS and compared with shipboard primary production measurements. Figure 1 provides such a comparison and shows annual primary production (g C m^{-2} y^{-1}), determined for the nearshore area of Palmer Station, estimated three different ways as described in the figure legend. As Fig. 1 shows, there is good agreement between the three methods for estimating the high interannual variability (roughly seven-fold) in production for the Palmer area.

In addition to the temporal variability at Palmer Station, the SeaWiFS satellite data also can be used to estimate production over larger spatial scales. Figure 2 acutely illustrates both the seasonal and interannual variability as well as the spatial variability of phytoplankton production in this region, and several observations can be made about primary production in this area. First, the spatial patterns within the Palmer LTER grid during those years for which there is ocean color satellite data (1998-2000) can be directly compared with the corresponding January cruise (data not shown). To first order, there is good agreement between the patterns observed in both the *in situ* and satellite data. Second, within the larger WAP region (including the Drake Passage) we generally observe three separate zones that are a composite of Treguer and Jacques (1992) biogeochemical provinces:

1. a coastal shelf zone of consistently high biomass and a strong onshore to offshore gradient along the coastal Palmer LTER grid (Coastal Shelf Zone);
2. a pelagic region of low biomass northwest of the grid (Pelagic Zone); while biomass may be limited in this zone by factors such as iron, stability, or even silica concentrations (Treguer and Jacques, 1992), phytoplankton blooms associated with the retreat of sea ice in the early spring (September-October) can occur;
3. a region of increasing biomass to the far north associated with the Polar Front (Frontal Zone); blooms in this region generally occur in the summer months from December through February.

Third, similar to our nearshore measurements, we also observe high levels of interannual variability throughout all three of the zones. Fourth, the spatial variability within the grid is relatively high from year to year. For example, coastal biomass in Marguerite Bay (most southern inlet shown on the western side of the Peninsula) peaked in different

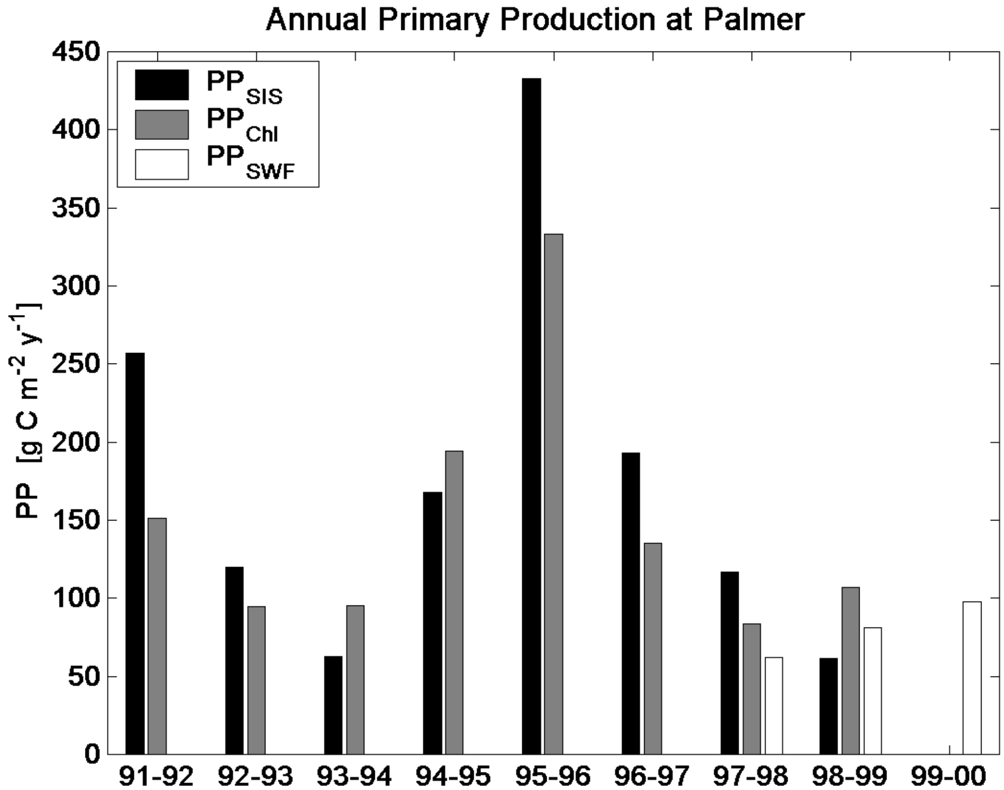

Figure 1. Annual primary production (g C m^{-2} y^{-1}) determined near Palmer Station for each growing season from 1991/92 to 1998/1999. First, annual estimate have been made from integrated near-weekly surface sampling over the growing season from November to March (152 days) at Palmer Station (PP_{SIS}). Data for the 1991/92 through 1993/94 season are estimated using photosynthesis irradiance curves integrated to 60 m (Moline and Prezelin 1996). Data from 1994/95 through 1999/00 estimated from simulated in situ observations (SIS), as described in the text, integrated to the depth representing 2% of surface irradiance. Second, annual production estimated based on Palmer Station chl-a measurements using our production model and integrated over the same growing season (PP_{CHL}). Third, estimates from modeled primary production based on average monthly chl-a retrieved from SeaWiFS ocean color data (for the three years the satellite has been in orbit) (PP_{SWF}).

months for all three seasons (February 1998, December 1998, and March, 2000). In December of 1997, we witnessed a massive bloom in the (more northward) frontal zone that is not evident in the later two years. In November 1999, a large ice-edge bloom was evident in the pelagic zone that runs nearly the length of the Palmer LTER grid. Finally, the sub-regions show variable production rates ranging from 50 to 100 gC m^{-2} y^{-1}. With the addition of more SeaWiFS data (and hence a longer satellite time series) we would like to investigate next the production of the various biogeochemical provinces, estimate their space/time variability and then sum these results to provide both Southern Ocean regional and total estimates of productivity.

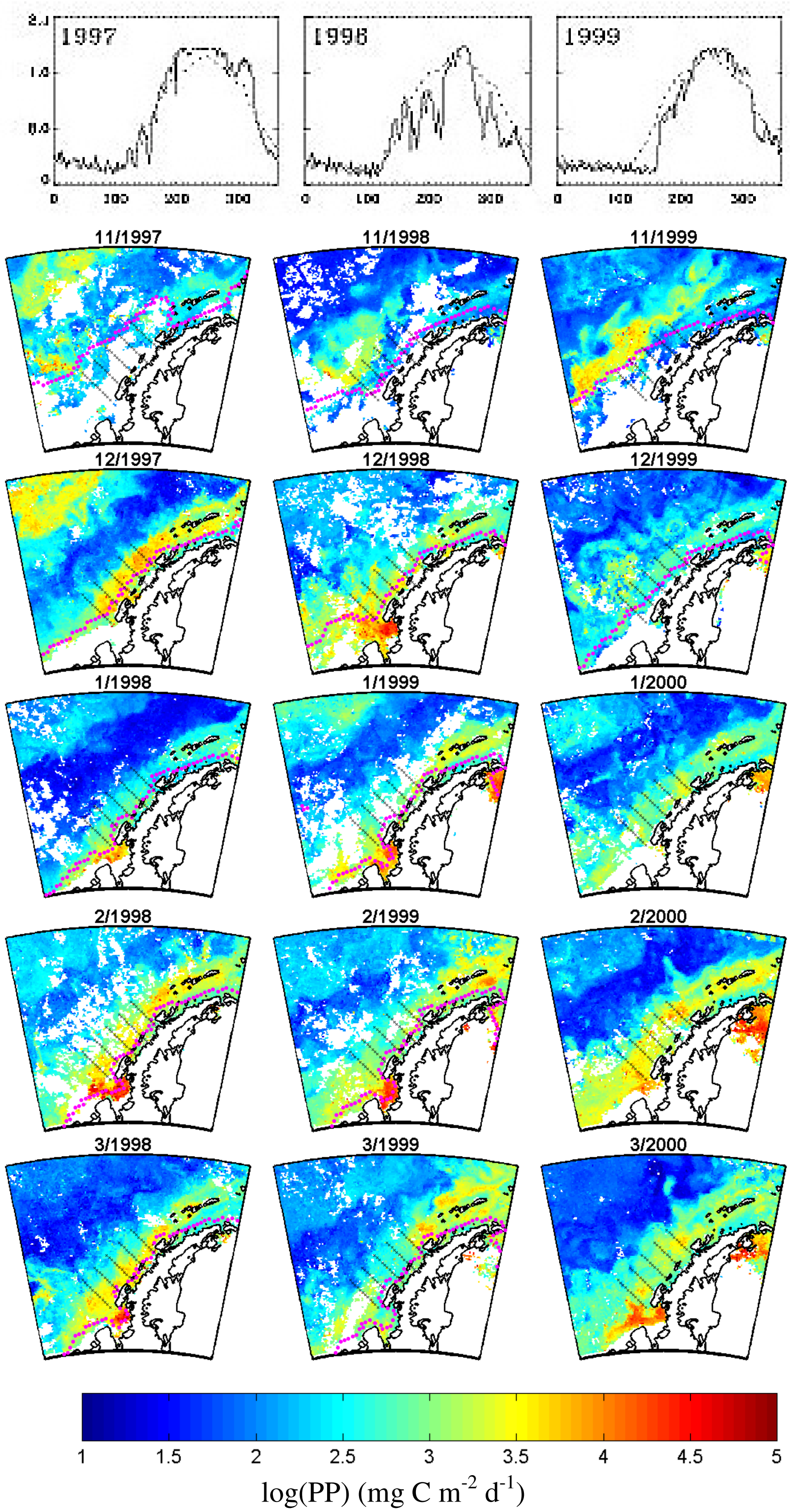

Figure 2. Monthly estimates of daily primary production for the WAP region from the SeaWiFS chl-a adjusted using our SO-algorithm and a depth-integrated production model. Figures compare three years of available SeaWiFS data for the growing season (Nov.-Mar.). Purple contours show the average sea ice extent for each individual month. The top row shows the daily sea ice extent for the preceding winter through the beginning of the field season depicted in the SeaWiFS images.

SUMMARY

Our planet may be viewed as a dynamic collection of interacting earth systems. While there is a growing understanding of the need to define the ecosphere as a whole and to identify the human impacts on its balance, it remains difficult to quantify trends or system changes given the wide range of natural variability within each component. The Palmer LTER bio-optical data focus on the coastal continental shelf zone of the WAP region, an area swept by the annual advance and retreat of sea ice. From shipboard sampling, we find that interannual variability in primary production is extremely high (7-fold) in Palmer nearshore waters. The SeaWiFS satellite data extends our observations seasonally and regionally and shows an even larger temporal and spatial variability of biomass than previously thought. Our multiyear observations demonstrate again that the most effective (and perhaps only) way to adequately sample the space/time variability of the Southern Ocean is by means of remote sensing. Hence there is a strong motivation for the development and refinement of bio-optical models for ocean color satellite and aircraft data as well as for time series data from ship and mooring observations.

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