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Satellite-derived estimates of primary production during the Sargasso Sea winter/spring bloom: Integration of *in-situ* time-series data and ocean color remote sensing observations

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HIGHLIGHTS

- Data on both surface and vertical distributions of chlorophyll biomass were examined.
- The radioisotope ^{14}C photosynthesis–irradiance curve parameters were calculated.
- Underwater light transmission was modelled using a shifted Gaussian model.
- We estimate integrated primary production during the Sargasso Sea winter/spring.
- The patterns in chlorophyll biomass and primary production affecting the Sargasso Sea.

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ABSTRACT

Accurate estimates of primary production from satellite-derived data on both regional and global scales are one of the most important goals of international ocean color remote-sensing programs. This manuscript presents surface concentrations and vertical distributions of chlorophyll-a (Chl-a) data as a proxy for phytoplankton biomass, and calculated photosynthesis–irradiance (P–E) curve parameters, which were used to estimate integrated monthly primary production in the Sargasso Sea euphotic zone from 2004 to 2009. The measured surface Chl-a in the Sargasso Sea was low but exhibited strong seasonal variation, and correlated well with satellite estimates of Chl-a. Underwater light transmission was modeled using a shifted Gaussian model from 69 vertical Chl-a profiles, which were collected in the Sargasso Sea. The P–E curve parameters were experimentally derived; the maximum photosynthetic rate, P_m^B ranged from 1.51 to 3.05 (mgC(mgChl-a)$^{-1}$h^{-1}) and the maximum light utilization coefficient, α^B, ranged from 0.017 to 0.806 (mgC(mgChl − a)$^{-1}$(Wm^{-2})$^{-1}$ h^{-1}). These data and previously published P–E curve parameter estimates were used in a spectrally varying model to estimate integrated primary production in the Sargasso Sea euphotic zone. Output from two of the four primary production models agreed well with *in-situ* measurements (±20%) and captured the strong seasonal variation.

1. Introduction

Phytoplankton biomass and rates of primary production are the foundation of pelagic ocean ecosystems. Phytoplankton are responsible for ∼50% of global primary production (Falkowski et al., 1998; Emilio et al., 2012), and are fundamental for understanding the ocean carbon cycle and interactions between the atmosphere and oceans (Aguirre-Hernandez et al., 2004). However, *in-situ* measurements of primary production offer a restricted perspective of carbon cycling, due to limitations in capturing spatial and temporal variability (Platt et al., 1995; Kahru et al., 2009). The integration of spatial and temporal ocean color data and field observations to estimate marine primary production using empirical and semi-analytical algorithms/models has been well studied and applied to a wide variety of marine systems (e.g. Platt, 1986, Platt et al., 1988,

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Fig. 1. The Sargasso Sea area covered by satellite images surrounding the Bermuda islands. The red circle represents the location of the Bermuda Atlantic Time-series Study (BATS) site (31°40′N, 64°10′W) and the satellite data box (31°04′–31°14′N, 64°54′–64°44′W). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Balch et al., 1989a,b, Longhurst et al., 1995 and Sathyendranath et al., 2007).

Phytoplankton photosynthesis parameters, such as the initial slope (α^B) and light-saturated, biomass (B) normalized primary production (also referred to as assimilation number, P_m^B), are derived from photosynthesis–irradiance (P–E) curves and are the basic components of semi-analytical models used for estimating ocean primary production on the regional and global scale (Platt, 1986; Platt et al., 1988; Platt and Sathyendranath, 1988). Understanding the factors that control the relationship between light (photon flux) and photosynthesis is critical to the success and refinement of these primary productivity algorithms. In practice, a simple model can be used to describe this relationship; however, a model that also considers other characteristics that impact primary production, such as light, nutrients, temperature, and species composition might provide a more accurate relationship (Platt et al., 1995; Eppley et al., 1985; Cullen, 1990). In this study, the semi-analytical non-spectral, non-uniform-biomass model developed by Platt and Sathyendranath (1993) was chosen as one of the best-fit models for calculating integrated primary production (IPP) in the water column (Platt and Sathyendranath, 1993); this model uses P–E parameters and chlorophyll vertical biomass profiles to estimate primary production.

The Sargasso Sea is an oligotrophic region of the north Atlantic subtropical gyre. In the northwestern Sargasso Sea at the Bermuda Atlantic Time-series Study (BATS) site, physical, chemical, and biological parameters have been measured on monthly research cruises with bi-weekly sampling during the winter/spring bloom (JGOFS, 1994; Michaels and Knap, 1996). Due to this wealth of data, much is known regarding carbon and nutrient cycles in the oligotrophic ocean (e.g. Michaels and Knap, 1996, Nelson and Brzezinski, 1997, Westberry and Siegel, 2003, Nelson et al., 2004, McGillicuddy et al., 2007, Lomas et al., 2009, 2010, 2013 and Saba et al., 2010), especially during the winter/spring bloom period, when rates of primary production are highest. Relatively few studies have coupled satellite remote sensing with bio-optical and physical–biological models to estimate and examine variability in primary production (e.g., Siegel et al., 2001, 2008, McGillicuddy et al., 2001 and Mattern et al., 2010).

The integration of remote sensing data and field observations in the Sargasso Sea to understand the inter-annual variation in phytoplankton photosynthesis and primary production during the winter/spring bloom remains an important venture. In this study, ^{14}C radioisotope incubations and P–E curve experiments were used to estimate phytoplankton photosynthesis parameters, which were then applied to a semi-analytical primary production model for the years 2004–2009. In addition, a spectral, non-uniform biomass model was used to calculate the integrated primary production during the winter/spring bloom season.

2. Materials and methods

2.1. Study area

The Bermuda Atlantic Time-series Study (BATS) site is located in the northwestern corner of the Sargasso Sea at 31°40′N and 64°10′W (Fig. 1). This location was used as the center of a grid to obtain satellite and validation data (mean area of 1° × 1° centered on BATS). A flow-chart outlining the data sources and processing steps used to calculate primary production from ocean color remote sensing data is presented (Fig. 2) and described in more detail in the sections below.

2.2. In-situ data

Monthly primary production and Chl-a data at BATS from 2004 to 2009 were used for this study (http://bats.bios.edu). Methods for relevant *in-situ* measurements are briefly described below and are based on the JGOFS protocols (JGOFS, 2002). The photosynthesis parameters P_m^B and α^B are not available for the entire period due to constraints of the research program. Photosynthetic performance, P_m^B, defined as the maximum volumetric photosynthesis normalized to chlorophyll, was previously measured at BATS from 1988 to 1995 (see Table 1 for the list of symbols and acronyms).

2.2.1. Chlorophyll-a biomass profiles

For each cruise, Chl-a and phaeo-pigment concentration depth profiles were collected at 12 depths and 20-m intervals from 1 to 250 m, which is at the level of ∼0.1% photosynthetically active radiation (PAR) (e.g., Siegel et al., 2001). Chl-a samples were collected from Go-Flo (General Oceanics, Inc.) samplers into