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Satellite-measured net primary production in the Chesapeake Bay

SeungHyun Son [a,b], Menghua Wang [a,*], Lawrence W. Harding Jr.[c]

[a] *NOAA National Environmental Satellite, Data, and Information Service, Center for Satellite Applications and Research, E/RA3, 5830 University Research Court, College Park, MD 20740, USA*
[b] *CIRA, Colorado State University, Fort Collins, CO 80523, USA*
[c] *Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, CA 90095-1565, USA*

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ABSTRACT

The regional daily-integrated net primary production (NPP) model for the Chesapeake Bay, Chesapeake Bay Production Model (CBPM), has been improved for use with ocean color products from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the satellite Aqua. A polynomial regression formula for the photosynthetic parameter (i.e., optimal carbon fixation rate, P^B_{opt}) as a function of sea surface temperature (SST) was derived for the Chesapeake Bay. Results show that the CBPM-derived NPP using the new model for P^B_{opt} are improved for the Chesapeake Bay. Comparisons of MODIS-Aqua-derived and in situ-measured NPP show that the satellite-derived data correspond reasonably well to in situ measurements, although MODIS-Aqua-derived NPP values may be slightly overestimated for the upper Bay, primarily due to uncertainties in the bio-optical algorithm for satellite ocean color products for that region. We also generated MODIS-Aqua-derived NPP maps using the improved CBPM for the period of 2002 to 2011 to characterize NPP in the Chesapeake Bay. Spatial distributions of MODIS-Aqua-derived NPP products show that higher NPP values are generally found in the southern upper Bay and northern middle Bay (regions around 38.3°N–39.0°N), including the Potomac River, while relatively low NPP values were found in the northern upper Bay, the eastern area of middle Bay, and lower Bay. The temporal pattern of MODIS-Aqua-derived NPP showed lowest values in winter (December to February) over the entire Bay, while high NPP values were in late spring to summer (May to August), depending on location. Furthermore, there is a strong interannual variability in NPP for the Chesapeake Bay, and an apparent increasing trend from 2003 to 2011.

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1. Introduction

The Chesapeake Bay, the largest estuary in the U.S., contains some of the most productive waters along the U.S. East Coast. A large amount of fresh water (~2300 $m^3 \cdot s^{-1}$ on average), including dissolved and particulate materials, flows into the Chesapeake Bay (Schubel & Pritchard, 1986), and strongly influences phytoplankton production (Harding, Mallonee, & Perry, 2002; Malone et al., 1986). Daily-integrated net primary production (NPP) plays an important role as the basis of the marine food web and a mediator of carbon flux in the marine ecosystem. There have been several studies of phytoplankton NPP with in situ measurements in the Chesapeake Bay (Harding, Meeson, & Fisher, 1985, 1986; Kemp, Smith, Marvin-DiPasquale, & Boynton, 1997; Malone, Crocker, Pike, & Wendler, 1988; Malone et al., 1986). However, it is difficult to estimate NPP for the entire Chesapeake Bay with in situ measurements alone because these data have spatial and temporal limitations. Satellite-based primary production models provide high spatial and temporal resolutions at basin and global scales and for the coastal ocean (Antoine & Morel, 1996; Behrenfeld & Falkowski, 1997; Platt & Sathyendranath, 1988). However, most standard primary production algorithms for ocean color satellite data are generally only suitable for clear open ocean waters. Therefore, it is required and necessary to develop and improve regional primary production algorithms for estuarine and coastal waters.

A tuned daily-integrated NPP algorithm based on the vertically generated production model (VGPM) (Behrenfeld & Falkowski, 1997) was developed for the Chesapeake Bay using extensive in situ data, resulting in the Chesapeake Bay production model (CBPM) (Harding et al., 2002). However, some issues remain to accurately quantify NPP using satellite ocean color data for turbid coastal waters involving uncertainties in satellite ocean color products traceable not only to bio-optical and biogeochemical algorithms, but also to atmospheric correction algorithms for the region. Thus, additional work to address these issues is essential to improve local NPP algorithms for satellite data in estuarine and coastal waters, such as the Chesapeake Bay.

Appropriate bio-optical algorithms for turbid coastal waters remain an outstanding issue for satellite ocean color remote sensing, although there has been considerable progress to develop bio-optical models for ocean-color products in the region (Gitelson, Schalles, & Hladik, 2007; Magnuson, Harding, Mallonee, & Adolf, 2004; Tzortziou et al., 2007; Werdell et al., 2009). Satellite-measured chlorophyll-a (Chl-a) concentrations using bio-optical models for open ocean (Case-1) waters (O'Reilly et al., 1998) are often overestimated in Chesapeake Bay waters

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* Corresponding author.
E-mail address: Menghua.Wang@noaa.gov (M. Wang).

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(Magnuson et al., 2004; Son & Wang, 2012; Werdell et al., 2009) due to complex bio-optical constituents, including high phytoplankton concentrations, colored dissolved organic matter (CDOM), and total suspended sediment (TSS) (Gallegos, Correll, & Pierce, 1990; Gitelson et al., 2007; Harding, Magnuson, & Mallonee, 2005; Son & Wang, 2012; Tzortziou et al., 2007), especially in the upper Bay. In addition to the issues with the bio-optical algorithms, effective atmospheric correction to derive accurate normalized water-leaving radiance spectra, $nL_w(\lambda)$ (Gordon, 2005; IOCCG, 2010; Morel & Gentili, 1991; Wang, 2006) is a challenge for turbid coastal waters, particularly as the black-pixel assumption for near-infrared (NIR) bands used for atmospheric correction may not apply (Gordon & Wang, 1994; Ruddick, Ovidio, & Rijkeboer, 2000; Shi & Wang, 2009; Siegel, Wang, Maritorena, & Robinson, 2000; Wang & Shi, 2005).

To address the issue of non-negligible NIR radiance contributions in productive or turbid waters, a new approach for atmospheric correction using the shortwave infrared (SWIR) bands was proposed (Wang, 2007) that achieves significantly improved MODIS ocean color products for coastal and inland waters (Wang, Nim, Son, & Shi, 2012; Wang, Shi, & Tang, 2011; Wang, Son, & Shi, 2009; Wang, Son, Zhang, & Shi, 2013; Wang, Tang, & Shi, 2007). However, because of considerable sensor noise in the MODIS SWIR bands (Wang & Shi, 2012; Werdell, Franz, & Bailey, 2010; Xiong, Sun, Xie, Barnes, & Salomonson, 2010), a NIR–SWIR combined atmospheric correction algorithm was developed (Wang & Shi, 2007), specifically for the Chesapeake Bay. The NIR–SWIR atmospheric correction approach (Wang & Shi, 2007) uses the NIR atmospheric correction (Gordon & Wang, 1994) with two MODIS NIR bands for non-turbid waters, while for the turbid waters the MODIS SWIR 1240 and 2130 nm bands are used (Wang, 2007). A recent study showed that the existing bio-optical model works reasonably well in the lower Bay using the NIR–SWIR atmospheric correction algorithm for satellite ocean color data processing (Son & Wang, 2012). Overall, using the NIR–SWIR ocean color data processing, satellite-derived ocean color data (e.g., $nL_w(\lambda)$, Chl-a) from the Chesapeake Bay have been significantly improved (Son & Wang, 2012).

In this study, we have used extensive in situ data for Chesapeake Bay to develop an improved regional NPP algorithm based on CBPM for application to satellite ocean color data and to evaluate its effectiveness. We included additional in situ data that were not used to develop the original model and a new formulation for the optimal photosynthesis term, P^B_{opt}, that led to improved outputs. The new model is applied to MODIS-Aqua ocean color data from 2002 to 2011 to characterize seasonal and interannual variability in the Bay, and the time series is used to characterize spatial and temporal distributions of NPP in the region. The regional NPP algorithm developed for the Chesapeake Bay using MODIS-Aqua data can be readily applied to ocean color data derived from the Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi National Polar-orbiting Partnership (SNPP) that was successfully launched on October 28, 2011. Some recent studies show that VIIRS can potentially provide high quality (comparable to MODIS-Aqua) ocean color products (Arnone et al., 2012; Hlaing et al., 2013; Wang, Liu, et al., 2013).

2. Data and methods

Both satellite and in situ data used in the study of a NPP product for the Chesapeake Bay are described and discussed in this section. Three regions in the Chesapeake Bay are defined, i.e., the lower Bay (region south of 37.6°N), middle Bay (region in 37.6–38.6°N), and upper Bay (region north of 38.6°N), and followed the approach of Magnuson et al. (2004) and others (Shi, Wang, & Jiang, 2013; Son & Wang, 2012) (Fig. 1). The three regions are defined by the salinity gradient along the main stem of the Bay as oligohaline, mesohaline, and polyhaline salinity zones (Magnuson et al., 2004). Water quality of the upper Bay near the input of the Susquehanna River is high nutrient concentrations (N, P, Si) and high turbidity dominated by sediment loadings, with progressively lower nutrient concentrations and lower turbidity in the middle and lower Bay regions (Fisher, Harding, Stanley, & Ward, 1988; Shi et al., 2013; Son & Wang, 2012).

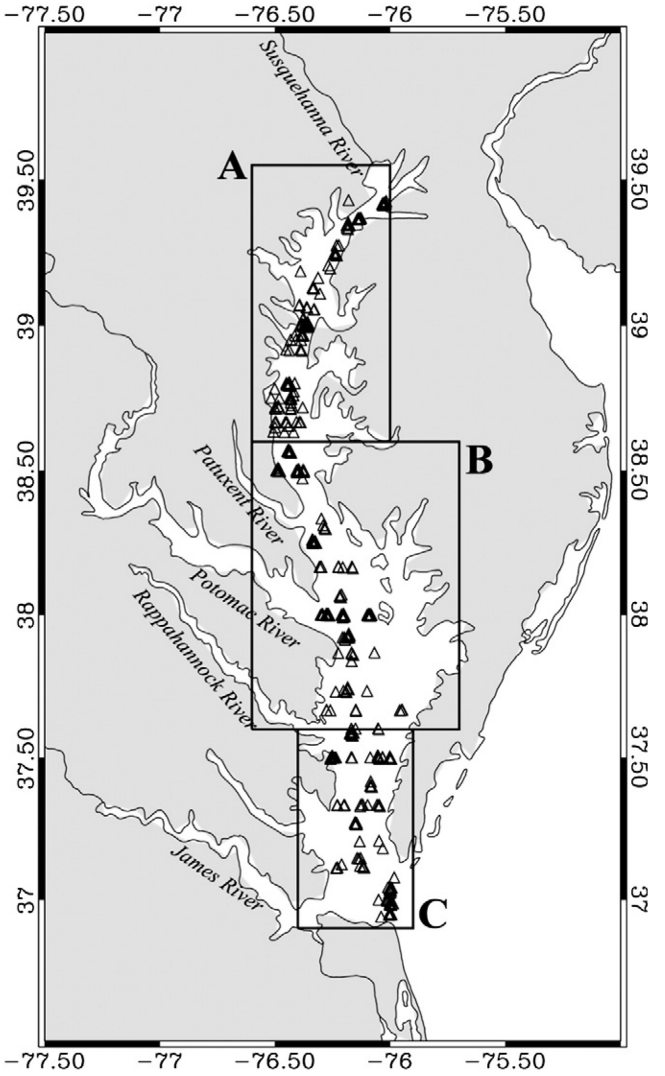

Fig. 1. Map of the Chesapeake Bay with stations occupied for in situ NPP measurements shown as triangles. The three boxes (A, B, and C) indicate the upper, middle, and lower Bay, respectively.

2.1. In situ data

In situ NPP data used in this study were accompanied by data on sea surface temperature (SST), Chl-a, euphotic depth (Z_{eu}), optimal carbon fixation rate (P^B_{opt}), photosynthetically available radiance (PAR) (E_0), and diffuse light attenuation coefficient for PAR (K_d (PAR)). These data were used to develop an improved NPP model for the Chesapeake Bay and for model validation. Most of the in situ NPP data (April 1987 to October 2000) were used previously to develop a regional NPP model for the Chesapeake Bay, i.e., the Chesapeake Bay Production Model (CBPM) (Harding et al., 2002). Additional in situ NPP data ($n = 95$) from 10 cruises in April 2001 to November 2003 were used in work described here. Because values of the optimal carbon fixation rate P^B_{opt} from April 1987 to March 1989 were significantly lower than those from April 1989 to November 2003, we excluded P^B_{opt} data before April 1989 ($n = 72$) in this analysis. The total number of the NPP measurements from April 1989 to November 2003 used in this study is 558, with $n = 463$ from April 1989 to October 2000 and $n = 95$ from April 2001 to