A Next-Generation Net Primary Production Model for Application to MODIS Aqua

Toby K. Westberry[1], Michael J. Behrenfeld[1], Allen J. Milligan[1]

[1]Department of Botany & Plant Pathology, Oregon State University, USA

ABSTRACT

The research described here uses the advanced observational capabilities of the MODIS Aqua and Terra sensors to establish a next-generation approach for assessing global ocean productivity that addresses key physiological- and ecological attributes of the plankton, thereby yielding improved understanding of surface ocean carbon flow and a foundation for realizing both NASA's broad ocean science objectives and specific goals for upcoming ocean missions. The current research project encompasses the complete set of MODIS ocean ecosystem properties to first constrain global ocean NPP, and then address a specific science issue: the partitioning of newly formed organic carbon into new phytoplankton biomass versus transfer to other trophic levels.

The assessment and monitoring of global ocean NPP has always been recognized as a key objective in oceanographic research and it has been a primary motivation behind NASA's sustained ocean color record. Prior to satellite observations, the paucity of relevant field observations was the primary source of uncertainty in global NPP assessments. With the launch of CZCS and SeaWiFS, uncertainties in NPP assessments became dominated by the challenge of converting standing stocks of chlorophyll into rates of carbon fixation. With MODIS observations and recent advances in ocean color data analyses, it is now possible to combine information on phytoplankton carbon biomass (C), pigment absorption, chlorophyll fluorescence quantum yields, and phytoplankton size fractions to address the NPP assessment problem with a more sophisticated approach. This research project focuses on 4 key developmental activities:

- Physiological assessments based on absorption:carbon ratios, rather than Chl:C
- Correction for iron-stress effects by employing MODIS fluorescence quantum yield data
- Chlorophyll-independent partitioning of production among phytoplankton size groups
- Growth irradiance assessments using alternative mixed layer depth criteria

Following model development, we will quantify uncertainties in NPP estimates to identify specific issues for refinement. We will then focus our science analysis comparisons of NPP and net population growth rates to evaluate spatio-temporal changes in production-loss balances and their links to environmental forcing.

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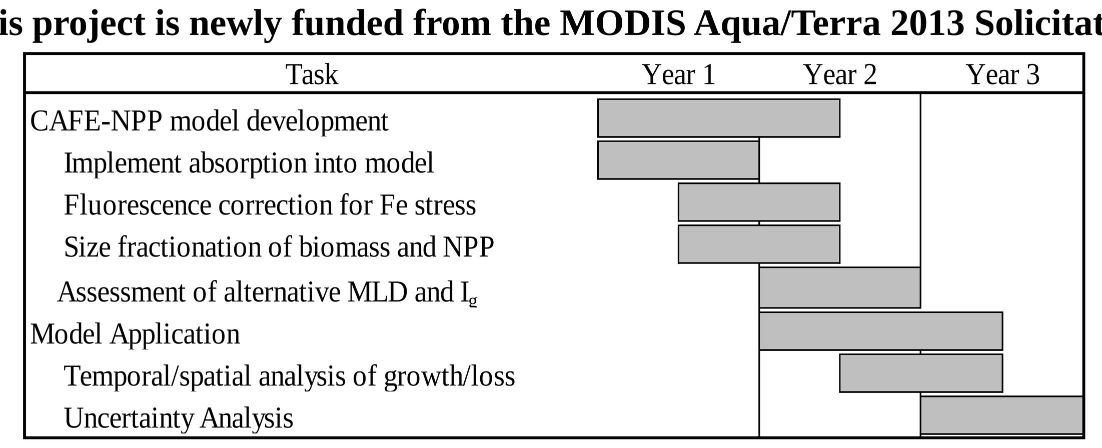


The Problem

- Historically, Chl has been used as an index of biomass, leaving all the phytoplankton physiology wrapped up in the assimilation efficiency, P_b^{opt}:

$$\sum NPP = Chl \cdot Z_{eu} \cdot DL \cdot f(E_o) \cdot P_b^{opt}$$

- Empirical expressions for P_b^{opt} are wildly divergent. Further, common predictors only serve as proxies for natural variability at best

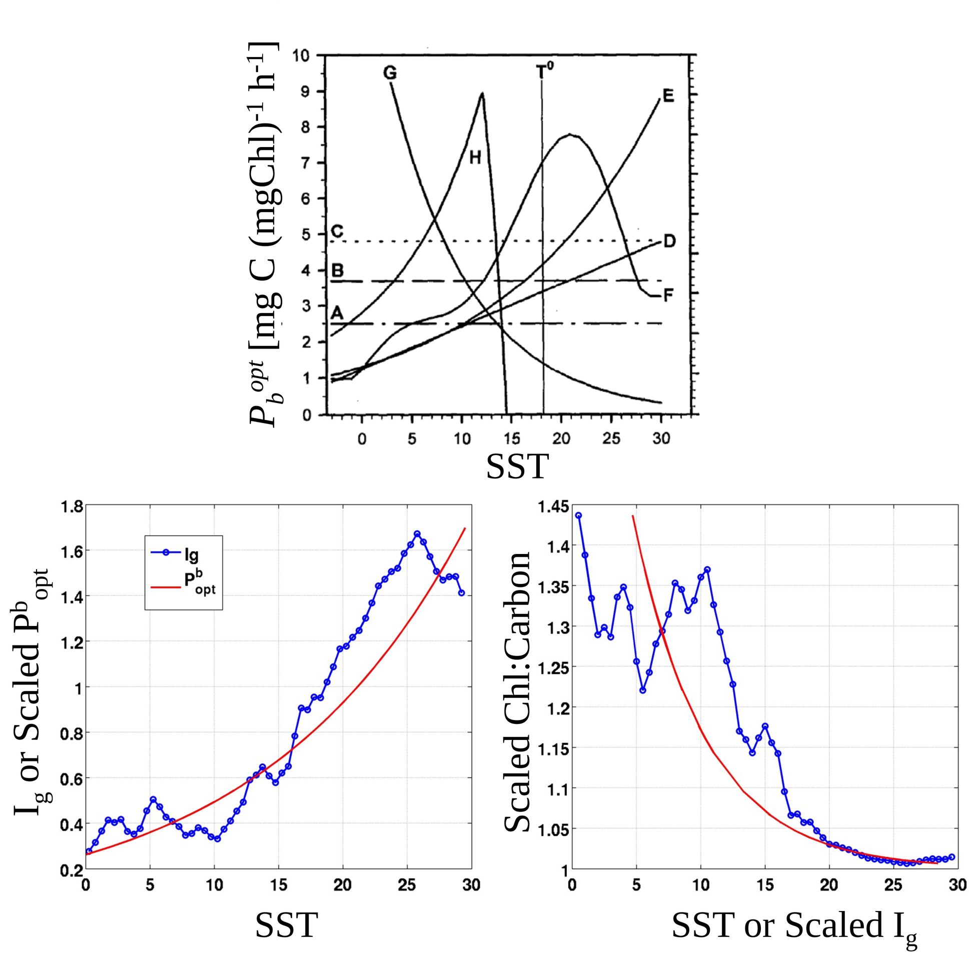
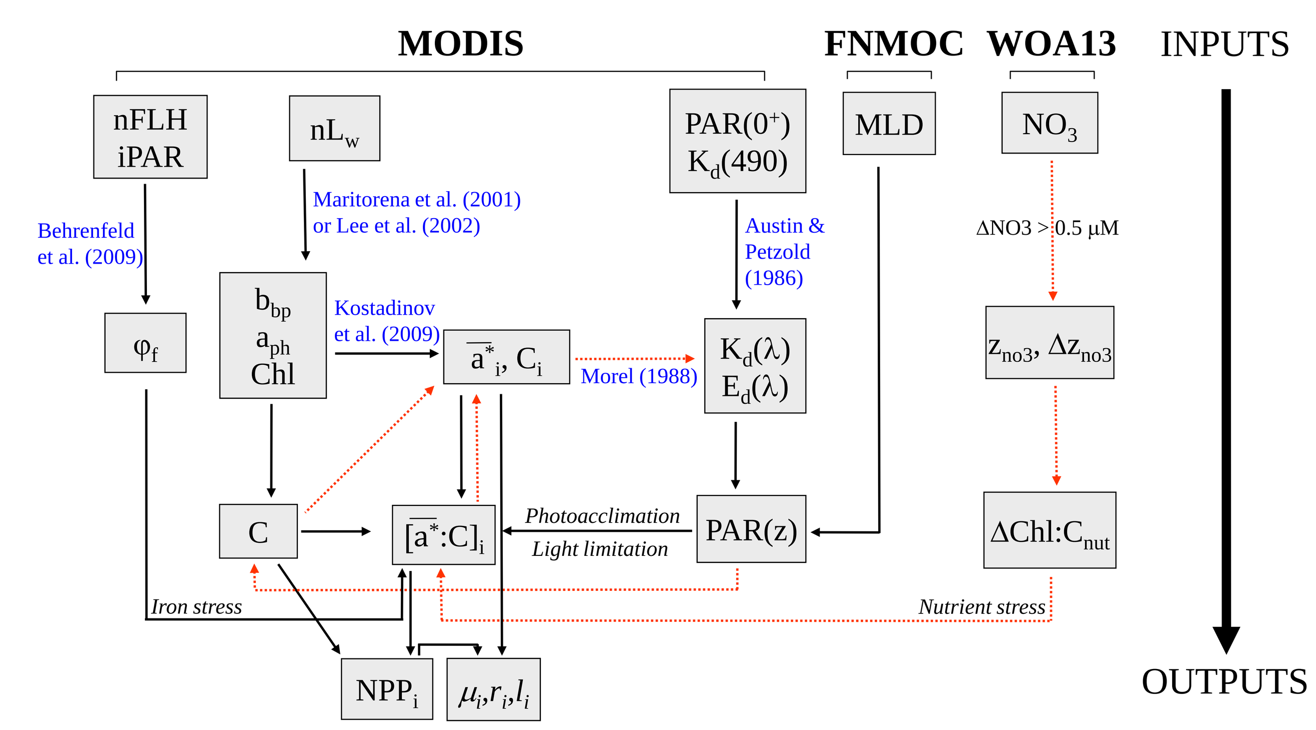


Figure 1. Estimation of P_b^{opt}. (Top) Various predictive relationships between P^b_{opt} and SST as compiled in Behrenfeld and Falkowski (1997). (Bottom Left) Illustration of covariance between acclimation irradiance (I_g) and P^b_{opt} as a function of SST. (Bottom right) Idealized photoacclimation response (Chl:C, red line), where the dependent variable, I_g, has been scaled to match the range of SST. Blue line shows the same Chl:C as a function of SST. In both cases, Chl:C is expressed relative to a high light value of 1 (units not important).

The Solution = <u>C</u>arbon <u>A</u>bsorption <u>F</u>luorescence, <u>E</u>uphotic-resolving <u>N</u>et <u>P</u>rimary <u>P</u>roduction model (CAFE-NPP)



Symbol	Definition/units	Comment
a_{ph}	Phytoplankton absorption coefficient, m^{-1}	Estimated from inversion model
$\bar{a}^*$	Spectrally averaged, Chl-specific phytoplankton absorption coefficient, m^2 (mg Chl)$^{-1}$	
b_{bp}	Particulate backscattering coefficient, m^{-1}	Estimated from inversion model
C	Phytoplankton biomass, mg C m^{-3}	Westberry et al. (2008)
Chl	Chlorophyll concentration mg Chl m^{-3}	
ΔChl:C_{nut}	Nutrient stress term	Westberry et al. (2008)
$E_d(\lambda)$	Spectral downwelling irradiance, W m^{-2} nm^{-1}	Estimated from spectral decomposition of PAR
iPAR	Instantaneous photosynthetically available radiation, μEin m^{-2} s^{-1}	Standard MODISA product
$K_d(\lambda)$	Diffuse attenuation coefficient of downwelling irradiance, m^{-1}	K_d(490) is a standard MODISA product, $K_d(\lambda)$ can be estimated
MLD	Mixed layer depth, m	Available from several sources
nFLH	Normalized fluorescence line height, mW cm^{-2} μm^{-1} sr^{-1}	Standard MODISA product
$nL_w(\lambda)$	Normalized water leaving radiance, mW cm^{-2} μm^{-1} sr^{-1}	Standard MODISA product
NO_3	Nitrate concentration, μM	World Ocean Atlas 2013
NPP	Net primary production rate, mg C m^{-2} d^{-1}	Westberry et al. (2008)
PAR	Daily integrated broadband irradiance (400-700nm), Ein m^{-2} d^{-1}	Standard MODISA product
z_{no3}	Nitracline depth, m	Calculated from WOA13
μ	Phytoplankton specific growth rate, d^{-1}	Production per biomass
r	Phytoplankton biomass accumulation rate, d^{-1}	Temporal change in biomass
l	Phytoplankton biomass loss rate, d^{-1}	Total losses (grazing, sinking, etc.)
φ_f	Quantum yield of fluorescence	Behrenfeld et al. (2009)

Use of absorption rather than Chl to better describe photoacclimation

- Alleviates error associated with empirical estimates of Chl
- Accounts for accessory pigment effects and pigment packaging on light harvesting

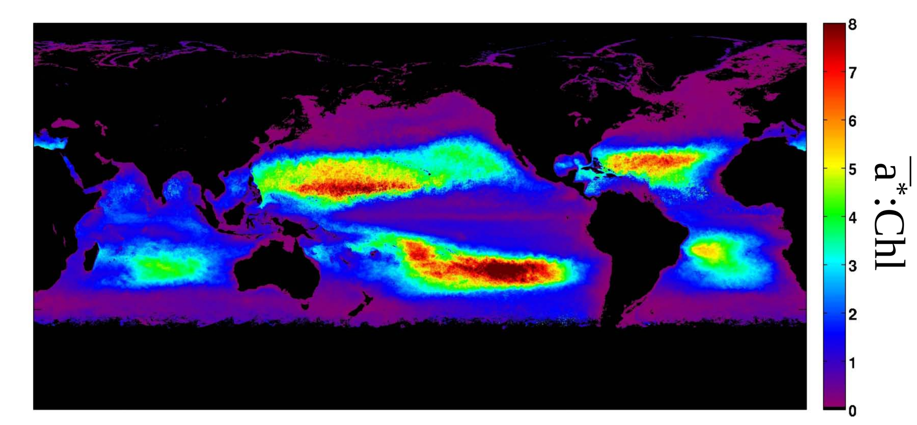


Figure 2. Ratio of $\bar{a}^*$ to Chl for a single climatological monthly composite (May 2003-2010). Values have been scaled so that the median equals 1. $\bar{a}^*$:Chl >1 implies significant contribution to absorption from accessory pigments and/or minimal pigment packaging.

Improved characterization of photoacclimation

- Calculation of acclimation irradiance (I_g) requires an estimate of mixing depth:

$$I_g = \frac{1}{DL}\int_{400}^{700} E_d(0^-,\lambda)e^{-K_d(\lambda)MLD/2}$$

- Use of oxygen profiles from ARGO-like floats may allow estimation of a "physiological" mixing depth. O_2-based mixing depths correspond to shallowest of conventional MLD estimates ($\Delta\sigma_\theta$=0.03 kg m-3).

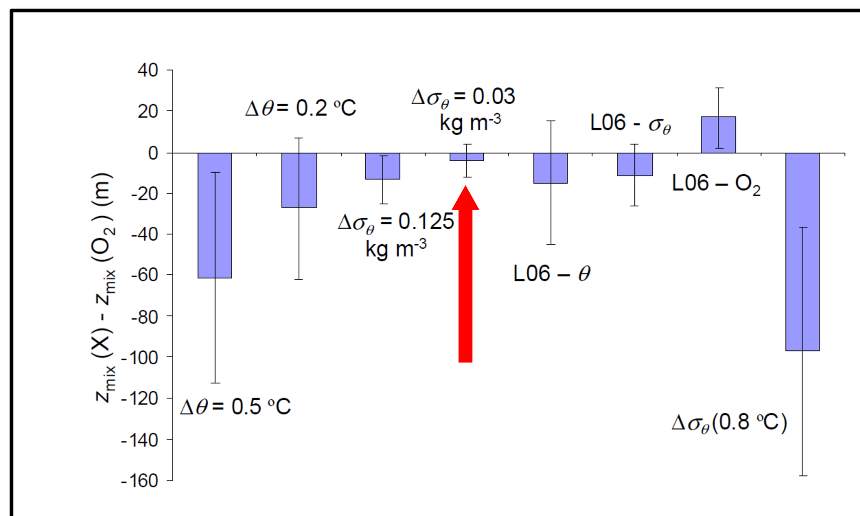


Figure 4. Differences between density- or temperature-based MLD calculated with differing criteria, versus an O_2-based mixing depth. Reproduced from Castro-Morales and Kaiser (2012).

Fe-stress correction using Chlorophyll fluorescence

- Fe-stress leads to significant fraction of Chl being functionally disconnected from photosystems (i.e., it fluoresces, but does not contribute to photosynthesis)
- We can correct for this, e.g.:

$$\Delta NPP_{corr} = NPP\left(\frac{\varphi}{\varphi_{thresh}} - 1\right), \text{ when } \varphi > \varphi_{thresh}$$

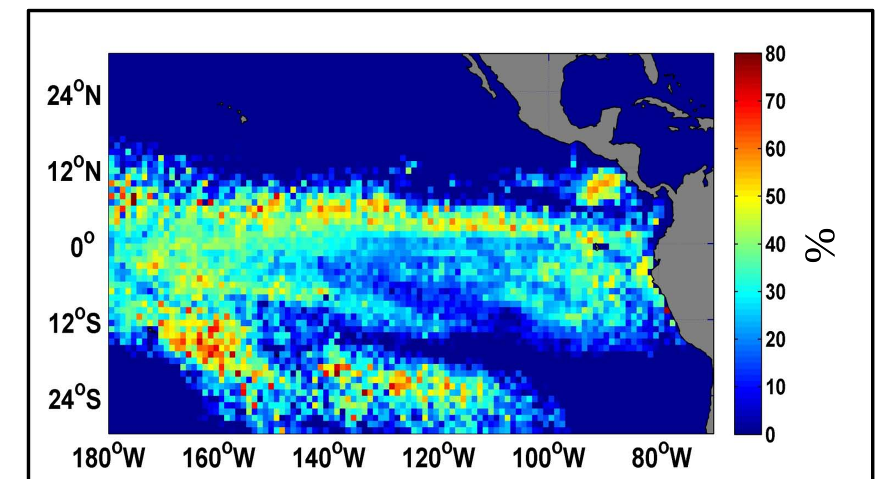


Figure 3. Example of iron stress correction using MODIS chlorophyll fluorescence data in the eastern Equatorial Pacific. **Quantity shown is the relative (%) reduction in NPP** (estimated from the CbPM for annual average 2004) due to "dysfunctional" Chl.

Size-group specific NPP

- There is a first order correspondence between cell size and functional role in ecosystem
- We can estimate fraction of total phytoplankton volume in each of 3 size classes:

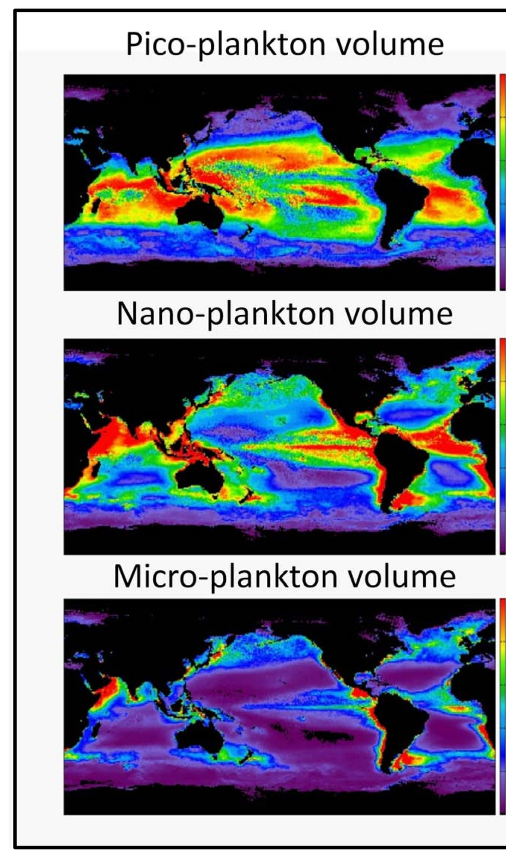


Figure 5. Fraction (percentage) of total particle volume in each of 3 size classes following model of Kostadinov et al. (2009). Results are based on retrieval of spectral particulate backscattering ($b_{bp}(\lambda)$) and a lookup table using Mie theoretical simulations. Pico-, nano-, and micro-fractions correspond to diameters between 0.2-2μm, 2-20μm, and >20μm respectively.

Model Application

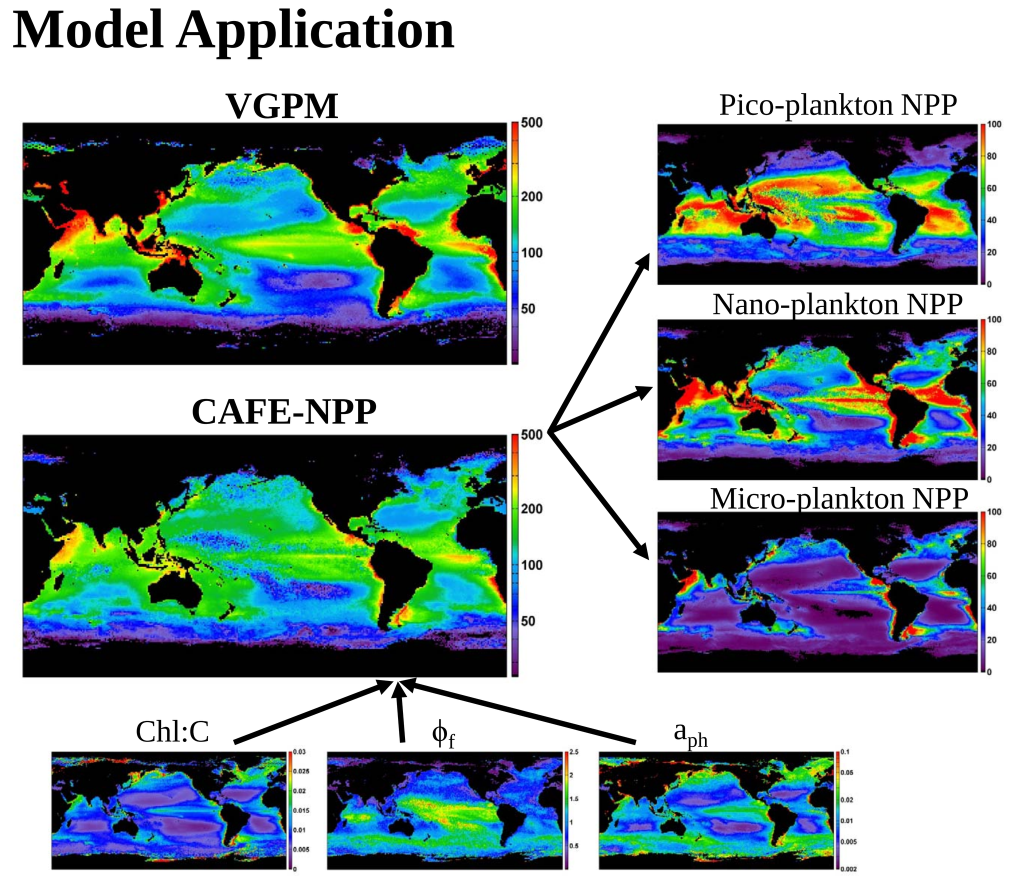


Figure 6. Illustration of current (VGPM) and next generation satellite-based marine NPP models. Additional satellite-derived inputs to CAFE-NPP model characterize photoacclimation (Chl:C), iron stress (φ_f), and phytoplankton absorption (a_{ph}). NPP can be resolved into coarse, size-based taxonomic groups (pico, nano, micro), yielding group-specific NPP.

Phytoplankton Growth, Loss and Accumulation Rates

- Accurate estimates of NPP can be used to examine other important ecological rates; phytoplankton growth, (μ) loss (l), and biomass accumulation (r)
- These rates allow investigation of phytoplankton bloom dynamics, their ecological basis, and links to climate forcing
- Partitioning of growth and loss into size-group specific rates will provide new insights into carbon partitioning in the ocean and essential products for contemporary models of export

$$l = u - r$$

$$\mu = NPP \Big/ \sum C$$

$$r = \frac{1}{C}\frac{dC}{dt} = \frac{1}{\int C}\frac{d\int C}{dt}$$

(To account for effects of dilution, r is calculated from concentration (C) when MLD is shoaling, and from stock (∫C) otherwise)