Scaling-Up: Satellite-Based Budgets of Productivity

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One of the single most important mathematical formalisms in oceanography, Riley’s development of his first differential equation:

Performance of “$P_m^b/K$” models

Surface chlorophyll explained about 6% of the variability in integral productivity (n=2595)

$P/B = \left[ \ln(Io/(0.5Ik^*)) \right] (1/1.33^*) \frac{P_m^b}{K}$

$r^2 = 0.27$

$P/B = R^* \frac{P_m^b}{K}$

$r^2 = 0.60$

$P/Ck = 2.3 \frac{P_m^b}{K}$

$r^2 = 0.65$

$P/Ck = \frac{Io/Ik}{P_m^b/K}$

$r^2 = 0.65$

$P/Ck = 2.3 \frac{P/Chlopt}{K}$

$r^2 = 0.67$

Balch et al., 1992; JGR v97p2279
Photoadaptive parameters vary dramatically and fast!

**Fig. 1.** Photosynthesis versus light (PAR, photosynthetically available radiation) for *Emiliania huxleyi* (strain 88E) cells in early stationary phase. There were two treatments: control with no NO$_3$ addition (triangles) and experimental with 2 µM NO$_3$ (diamonds) added 4 hours before the experiment. Modified from Figure 4A of Balch et al. [1992b] with permission from Pergamon Press, see that paper citation for experimental details.
A consumer's guide to phytoplankton primary productivity models

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I. Wavelength-resolved models (WRMs)

\[
\sum PP = \int_{\lambda=400}^{700} \int_{t=sunrise}^{sunset} \int_{z=0}^{z_{eu}} \Phi(\lambda, t, z) \times PAR(\lambda, t, z) \times a^*(\lambda, z) \times Chl(z) \, d\lambda \, dt \, dz - R
\]

II. Wavelength-integrated models (WIMs)

\[
\sum PP = \int_{t=sunrise}^{sunset} \int_{z=0}^{z_{eu}} \varphi(t, z) \times PAR(t, z) \times Chl(z) \, dt \, dz - R
\]

II. Time-integrated models (TIMs)

\[
\sum PP = \int_{z=0}^{z_{eu}} P^n(z) \times PAR(z) \times DL \times Chl(z) \, dz
\]

IV. Depth-integrated models (DIMs)

\[
\sum PP = P^b_{opt} \times f[PAR(0)] \times DL \times Chl \times z_{eu}
\]
Key Conclusions

- models can be related to a single formulation equating depth-integrated primary production ($\Sigma$ PP) to surface Chl($C_{surf}$), a photoadaptive variable ($P_{b_{(opt)}}$), euphotic depth ($Z_{(eu)}$), an irradiance-dependent function ($F$), and daylength ($DL$).

- Primary difference between models is description of $F$, and irradiance had a relatively minor effect on variability in $\Sigma$ PP.

- Only small fraction of variability in $\Sigma$ PP can be attributed to vertical variability in phytoplankton biomass or variability in the light-limited slope for photosynthesis.

- Differences between or within any model category have the potential to improve estimates of $\Sigma$ PP by ~10%, so long as equivalent parameterizations are used for $C_{surf}$ and $P_{b_{(opt)}}$.

- Differences in estimates of global annual primary production are due almost entirely to differences in input biomass fields and estimates of the photoadaptive variable, $P_{b_{(opt)}}$, not to fundamental differences between model constructs.
➢ 12 algorithms tested
➢ Algorithm input: surface [chlorophyll], SST, PAR, latitude, longitude, and day of the year.
➢ Algorithm results compared with IP estimates derived from 14C uptake measurements at 89 stations.
➢ Four model categories: (WRM) Wavelength-resolved; (TIM) Depth-resolved, time-integrated and wavelength integrated; (DIM) Depth-Integrated Model
➢ Best-performing algorithms were generally within a factor of 2 of the 14C-derived estimates.
➢ Algorithm performance and degree of correlation with each other were independent of the algorithms’ complexity
Figure 2. Scatterplots of algorithm-derived primary production (IP_{alg}, mg C m^{-2}) versus production measured in situ (IP_{meas}, mg C m^{-2}) for 12 algorithms tested. Solid line represents perfect agreement, and dashed lines represent factor-of-2 relative errors. Algorithm category [Behrenfeld and Falkowski, 1997b] is shown in upper left corner of each plot.
A comparison of global estimates of marine primary production from ocean color

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Pairwise correlation and RMS between model types

Carr et al., 2006; DSRII
**PPAR 3 Key Conclusions: Carr et al., 2006**

- Compared global $\Sigma$PP output from 8 months, 1998-1999 using common input fields: PAR, SST, MLZ, and [chl]; **24 models**. Not looking at performance but model behavior
- Model correlations did not follow model complexity w.r.t. $\lambda$ or $z$, though they are related to the manner in which temperature is used to parameterize photosynthesis.
- Global average PP varies by a factor of two between models.
- Models diverged most in the Southern Ocean, SST < 10°C, and [chl] > 1mg m$^{-3}$
- GCMs performed as well as ocean color based estimates
- Progress in modeling $\Sigma$PP requires better understanding of the effect of temp. on photosynthesis & better parameterization of $P_{\text{max}}$
Assessing the uncertainties of model estimates of primary productivity in the tropical Pacific Ocean

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Fig. 4. Taylor diagram of log(PP). The distance from the origin is the standard deviation of the modeled productivities. The azimuth angle represents the correlation between the observations and the modeled productivities, and the distance between each model symbol and the data (black diamond) is the RMSD_{CP}. Dashed lines are isolines of RMSD_{CP}=0.25 and RMSD_{CP}=0.15. Dotted line represents the standard deviation of the data. Colors as in Fig. 3.
PPARR 3 Conclusions- Friedrich et al., 2009

• Goal to compare PP estimates obtained from 30 different models (21 SatPPMs and 9 BOGCMs) to a tropical Pacific PP database with ~1000 $^{14}$C measurements spanning more than a decade (1983–1996)

• Simplest models characterized by significantly less bias than those that resolved wavelength and depth.

• Skill varied significantly between models, but performance was not a function of model complexity or type

• Nearly all models underestimated the observed variance of PP, specifically yielding too few low PP ($<0.2$ g Cm$^{-2}$ d$^{-1}$) values

• Interdecadal and global changes will be a significant challenge for both SatPPMs and BOGCMs
High Latitude Prim. Prod.

455 stations across Arctic

Lee et al., 2015; JGR Oceans
Arctic waters
Lower $r^2$, greater RMSD

Lee et al., 2015; JGR Oceans
Summary Lee et al., 2015

- 32 net primary productivity (NPP) models by assessing skills to reproduce integrated NPP in the Arctic Ocean
- models most sensitive to uncertainties in surface chlorophyll, generally performing better with in situ chlorophyll than with satellite-derived values; much less sensitive to uncertainties in PAR, SST, and MLD,
- most models significantly underestimated the variability of NPP, often by more than a factor of two, regardless of model type or complexity
Inorganic Carbon Production (Calcification) from Space...

Prediction of pelagic calcification rates using satellite measurements

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Inorganic Carbon Production (Calcification) from Space...

Algorithm based on PIC, Chl, SST, Depth, Day Length

Balch et al., 2007; DSRII
A New Approach to Estimating Coccolithophore Calcification Rates From Space

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Key Points:
- Estimates of global calcification rate are essential for understanding the efficiency of both the alkalinity and biological carbon pumps.
- A simple model parameterized with remotely sensed data can be used to estimate global calcification rates.
- Average, global, coccolithophore calcification rate is estimated to be 1.42 Pg C/year.

RMSE = 0.53 mg C m\(^{-3}\) d\(^{-1}\)

Hopkins and Balch, 2017; JGR Biogeosciences
Performance of Hopkins & Balch (2018; JGR Biogeosciences) calcification algorithm

![Graphs showing calcification rate vs. depth](image-url)