Scaling-Up: Satellite-Based Budgets of Productivity

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One of the single most important mathematical formalisms in oceanography, Riley's
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Riley, G. A. (1946),
controlling phytopl
populations on Georges Bank, *J. Mar. Res.*, *6*(1), 54-73.

Guillard

GORDON A. RILEY:

FACTORS CONTROLLING PHYTOPLANKTON POPULATIONS ON GEORGES BANK

Reprint from:
SEARS FOUNDATION: JOURNAL OF MARINE RESEARCH
Vol. VI, No. 1, December 31, 1946. Pp. 54–73, figs. 14–21.

Conclusions. The original equation

$$\frac{dP}{dt} = P\,(P_h - R - G)$$

can now be expanded by substituting the right hand terms of equations (5), (6) and (7):

$$\frac{dP}{dt} = P\left[\frac{pI_\circ}{kz_1}\,(1 - e^{-kz_1})\,(1 - N)\,(1 - V) - R_\circ e^{rT} - gZ\right]. \quad (8)$$

The rate of change of the population is dependent on six ecological variables: the incident solar radiation, transparency of the water, the quantity of phosphate, the depth of the mixed layer, the surface temperature and the quantity of zooplankton. The results of the applica-

Performance of “P_m^b/K” models

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

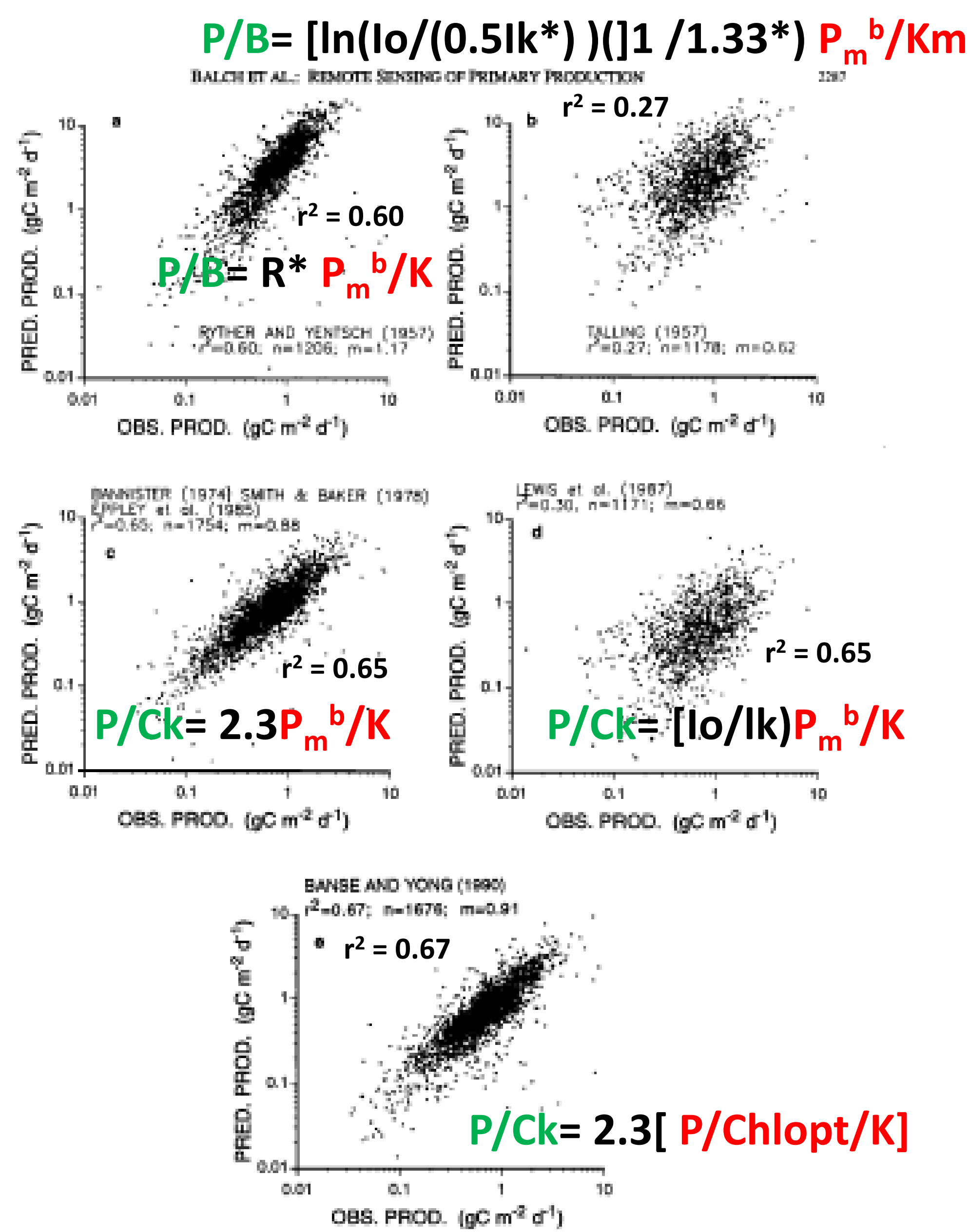

Fig. 10. Predicted versus observed integral production for family of five "P_m^b/K" models described in text: (a) model of *Ryther and Yentsch* [1957 equation (1)], (b) model of *Talling* [1957, equations (5) and (5)], (c) model of *Bannister* [1974, equation (28)], *Smith and Baker* [1978, equation (16)], and *Eppley et al.* [1985, equation (2)], (d) model of *Lewis et al.* [1987, equation (8)], and (e) *Banse* [1990, equation (2)]. Statistical parameters are given on each figure as well as number of stations having necessary data to apply to the model.

Balch et al., 1992; JGR v97p2279

Photoadaptive parameters vary dramatically and fast!

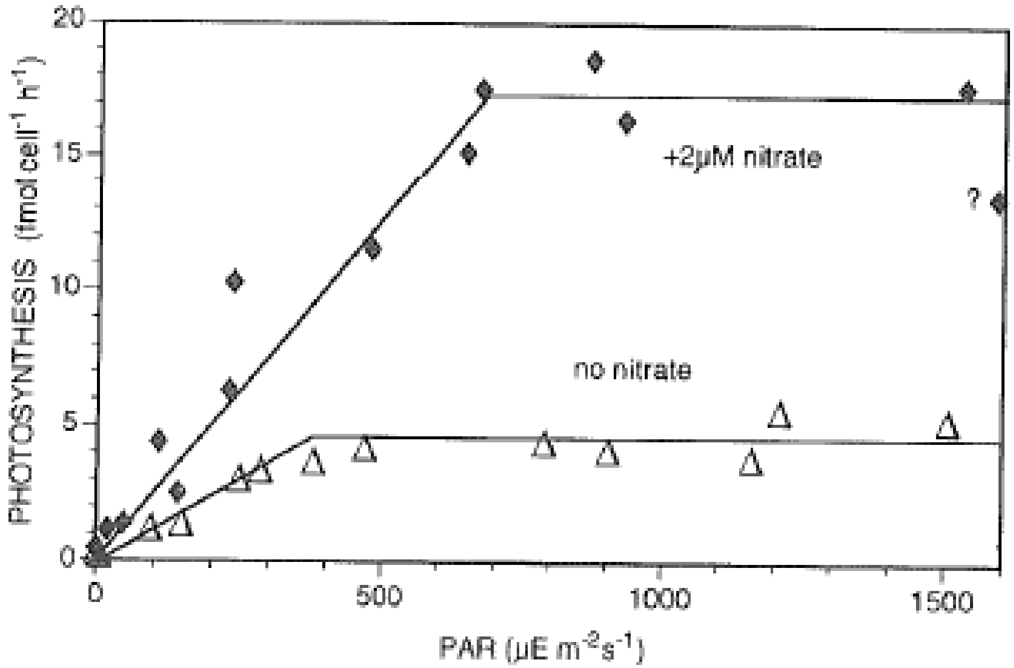

Fig. 1. Photosynthesis versus light (PAR, photosynthetically available radiation) for *Emiliania huxleyi* (strain 88E) cells in early stationary phase. There were two treatments: control with no NO_3 addition (triangles) and experimental with 2 μM NO_3 (diamonds) added 4 hours before the experiment. Modified from Figure 4A of *Balch et al.* [1992*b*] with permission from Pergamon Press, see that paper citation for experimental details.

Balch, 1992 Cont. Shelf Res. v12; p1353

LIMNOLOGY
AND
OCEANOGRAPHY

November 1997
Volume 42
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A consumer's guide to phytoplankton primary productivity models

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I. Wavelength-resolved models (WRMs)

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

II. Wavelength-integrated models (WIMs)

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

II. Time-integrated models (TIMs)

$$\sum PP = \int_{z=0}^{Z_{eu}} P^b(z) \times \text{PAR}(z) \times DL \times \text{Chl}(z)\, dz$$

IV. Depth-integrated models (DIMs)

$$\sum PP = P^b_{opt} \times f[\text{PAR}(0)] \times DL \times \text{Chl} \times Z_{eu}$$

Behrenfeld & Falkowski 1997 Key Conclusions

- **models can be related to a single formulation equating depth-integrated primary production (Σ PP) to surface Chl(C(surf)), a photoadaptive variable (Pb(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 Σ PP.**
- **Only small fraction of variability in Σ 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 Σ PP by ~10%, so long as equivalent parameterizations are used for C(surf) and Pb(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, Pb(opt), not to fundamental differences between model constructs.**

GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 16, NO. 3, 10.1029/2001GB001444, 2002

Comparison of algorithms for estimating ocean primary production from surface chlorophyll, temperature, and irradiance

Janet Campbell,[1] David Antoine,[2] Robert Armstrong,[3] Kevin Arrigo,[4]
William Balch,[5] Richard Barber,[6] Michael Behrenfeld,[7] Robert Bidigare,[8]
James Bishop,[9] Mary-Elena Carr,[10] Wayne Esaias,[7] Paul Falkowski,[11]
Nicolas Hoepffner,[12] Richard Iverson,[13] Dale Kiefer,[14] Steven Lohrenz,[15] John Marra,[16]
Andre Morel,[2] John Ryan,[17] Vladimir Vedernikov,[18] Kirk Waters,[19] Charles Yentsch,[5]
and James Yoder[20]

Received 21 May 2001; revised 8 March 2002; accepted 8 March 2002; published 17 July 2002.

- 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 ^{14}C-derived estimates.
- Algorithm performance and degree of correlation with each other were independent of the algorithms’ complexity

Factor of 2 relative errors

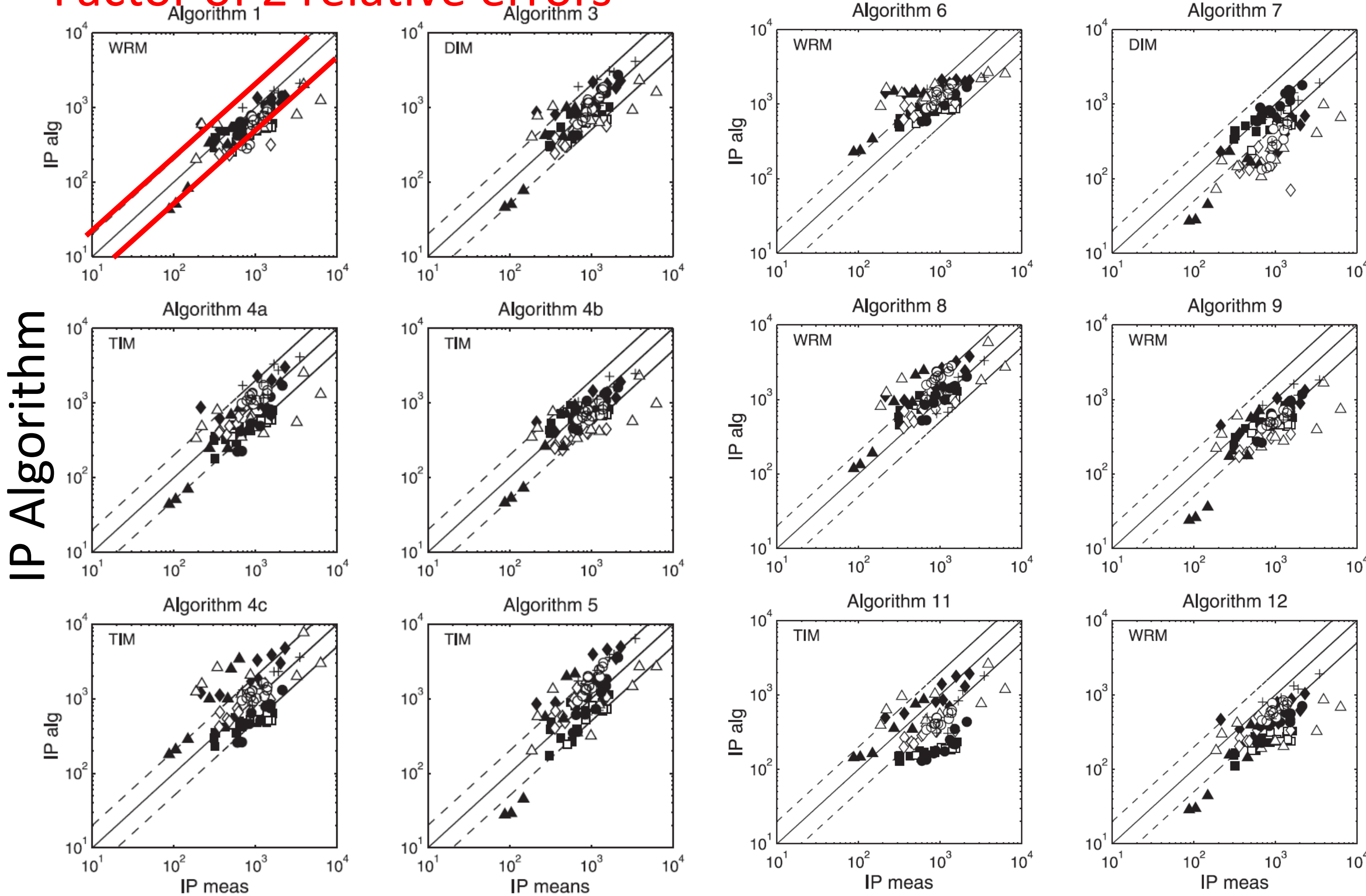


Figure 2. Scatterplots of algorithm-derived primary production (IP_{alg}, mg C m^{-2}) versus production measured in situ (IP_{meas}, mg C m^{-2}) for 12 algorithms tested. Solid line represents perfect agreement, and dashed lines represent factor-of-2 relative errors. Algorithm category [*Behrenfeld and Falkowski*, 1997b] is shown in upper left corner of each plot.

IP Measured

Campbell et al., GBC 2002

Comparing Prim Prod algorithm behavior: Carr et al. 2006

ELSEVIER

Deep-Sea Research II 53 (2006) 741–770

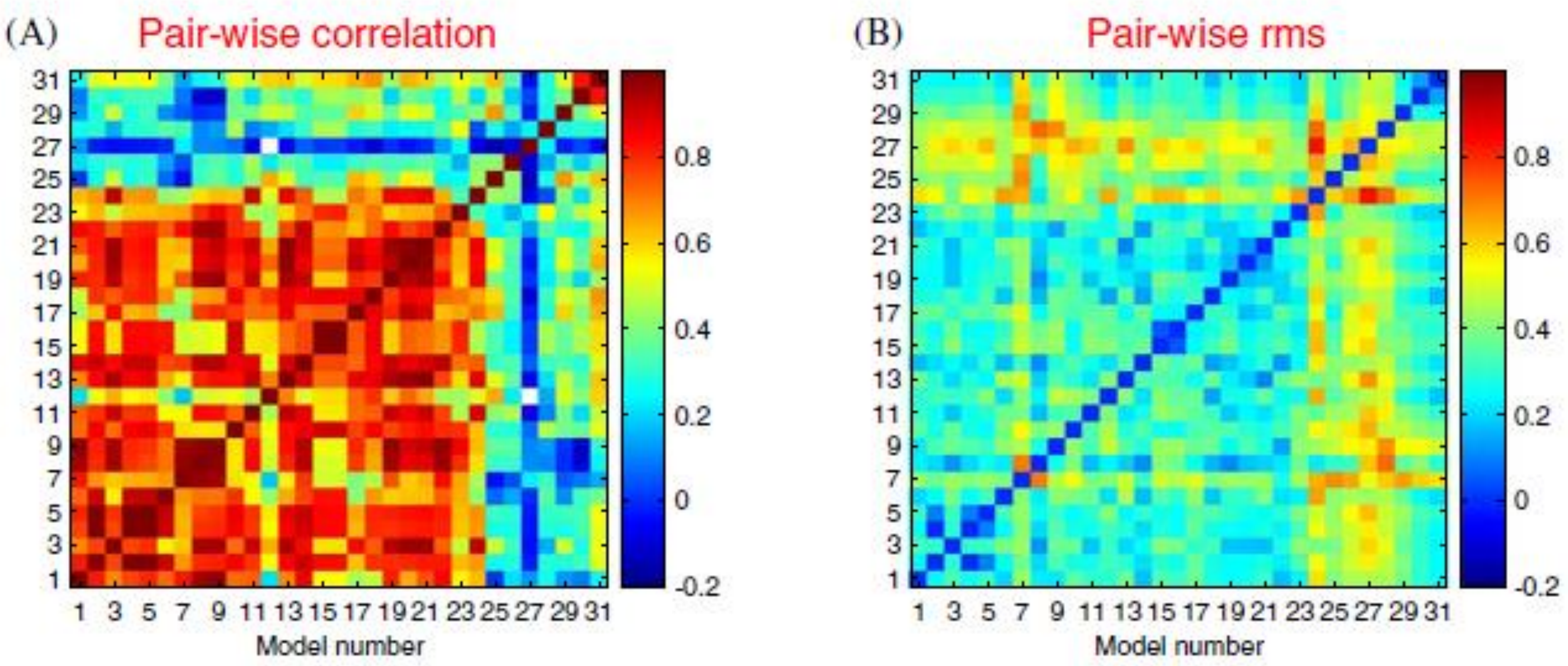
DEEP-SEA RESEARCH
PART II

www.elsevier.com/locate/dsr2

A comparison of global estimates of marine primary production from ocean color

Mary-Elena Carr[a,*], Marjorie A.M. Friedrichs[b,bb], Marjorie Schmeltz[a], Maki Noguchi Aita[c], David Antoine[d], Kevin R. Arrigo[e], Ichio Asanuma[f], Olivier Aumont[g], Richard Barber[h], Michael Behrenfeld[i], Robert Bidigare[j], Erik T. Buitenhuis[k], Janet Campbell[l], Aurea Ciotti[m], Heidi Dierssen[n], Mark Dowell[o], John Dunne[p], Wayne Esaias[q], Bernard Gentili[d], Watson Gregg[q], Steve Groom[r], Nicolas Hoepffner[o], Joji Ishizaka[s], Takahiko Kameda[t], Corinne Le Quéré[k,u], Steven Lohrenz[v], John Marra[w], Frédéric Mélin[o], Keith Moore[x], André Morel[d], Tasha E. Reddy[e], John Ryan[y], Michele Scardi[z], Tim Smyth[r], Kevin Turpie[q], Gavin Tilstone[r], Kirk Waters[aa], Yasuhiro Yamanaka[c]

Pairwise correlation and RMS between model types



Carr et al., 2006; DSRII

PPAR 3 Key Conclusions: Carr et al., 2006

- Compared global ΣPP 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. λ 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^{o}C, and [chl]>1mg m^{-3}
- GCMs performed as well as ocean color based estimates
- Progress in modeling ΣPP requires better understanding of the effect of temp. on photosynthesis & better parameterization of P_{max}

PPARR3-model performance
Friedrichs et al., 2009

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Journal of Marine Systems

journal homepage: www.elsevier.com/locate/jmarsys

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Assessing the uncertainties of model estimates of primary productivity in the tropical Pacific Ocean

Marjorie A.M. Friedrichs [a,*], Mary-Elena Carr [b,1], Richard T. Barber [c], Michele Scardi [d], David Antoine [e], Robert A. Armstrong [f], Ichio Asanuma [g], Michael J. Behrenfeld [h], Erik T. Buitenhuis [i], Fei Chai [j], James R. Christian [k], Aurea M. Ciotti [l], Scott C. Doney [m], Mark Dowell [n], John Dunne [o], Bernard Gentili [e], Watson Gregg [p], Nicolas Hoepffner [n], Joji Ishizaka [q], Takahiko Kameda [r], Ivan Lima [m], John Marra [s], Frédéric Mélin [n], J. Keith Moore [t], André Morel [e], Robert T. O'Malley [h], Jay O'Reilly [u], Vincent S. Saba [a], Marjorie Schmeltz [b], Tim J. Smyth [v], Jerry Tjiputra [w], Kirk Waters [x], Toby K. Westberry [h], Arne Winguth [y]

Friedrichs et al., 2009

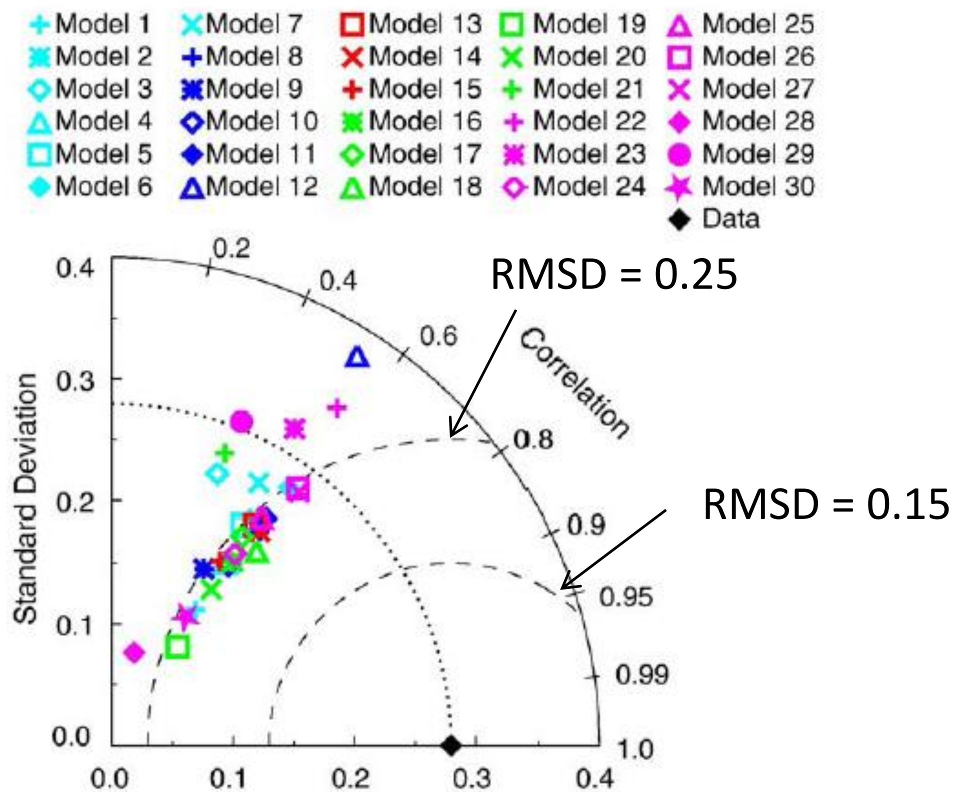


Fig. 4. Taylor diagram of log(PP). The distance from the origin is the standard deviation of the modeled productivities. The azimuth angle represents the correlation between the observations and the modeled productivities, and the distance between each model symbol and the data (black diamond) is the $RMSD_{CP}$. 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.

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Oceans

RESEARCH ARTICLE

10.1002/2015JC011018

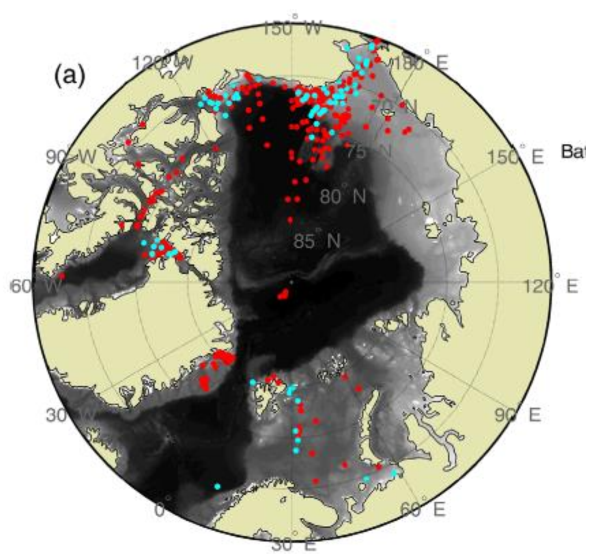
Special Section:
Forum for Arctic Modeling and Observing Synthesis (FAMOS): Results and Synthesis of Coordinated Experiments

Key Points:
- The models reproduced primary productivity better using in situ

An assessment of phytoplankton primary productivity in the Arctic Ocean from satellite ocean color/in situ chlorophyll-*a* based models

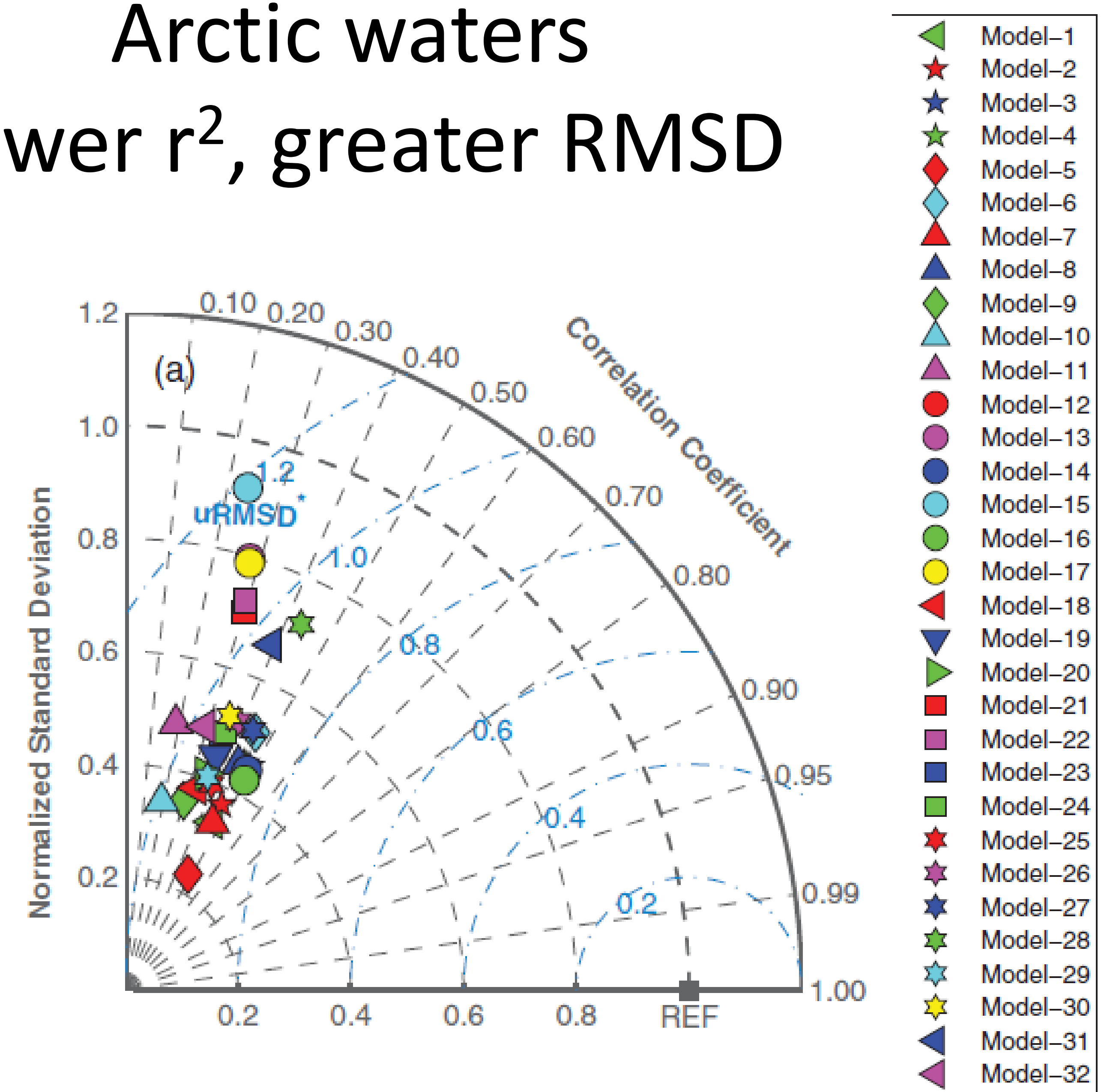
Younjoo J. Lee[1], Patricia A. Matrai[1], Marjorie A. M. Friedrichs[2], Vincent S. Saba[3], David Antoine[4,5], Mathieu Ardyna[6], Ichio Asanuma[7], Marcel Babin[6], Simon Bélanger[8], Maxime Benoît-Gagné[6], Emmanuel Devred[6], Mar Fernández-Méndez[9], Bernard Gentili[4], Toru Hirawake[10], Sung-Ho Kang[11], Takahiko Kameda[12], Christian Katlein[9], Sang H. Lee[13], Zhongping Lee[14], Frédéric Mélin[15], Michele Scardi[16], Tim J. Smyth[17], Shilin Tang[18], Kevin R. Turpie[19], Kirk J. Waters[20], and Toby K. Westberry[21]

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…

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Available online at www.sciencedirect.com

ScienceDirect

Deep-Sea Research II 54 (2007) 478–495

DEEP-SEA RESEARCH
PART II

www.elsevier.com/locate/dsr2

Prediction of pelagic calcification rates using satellite measurements

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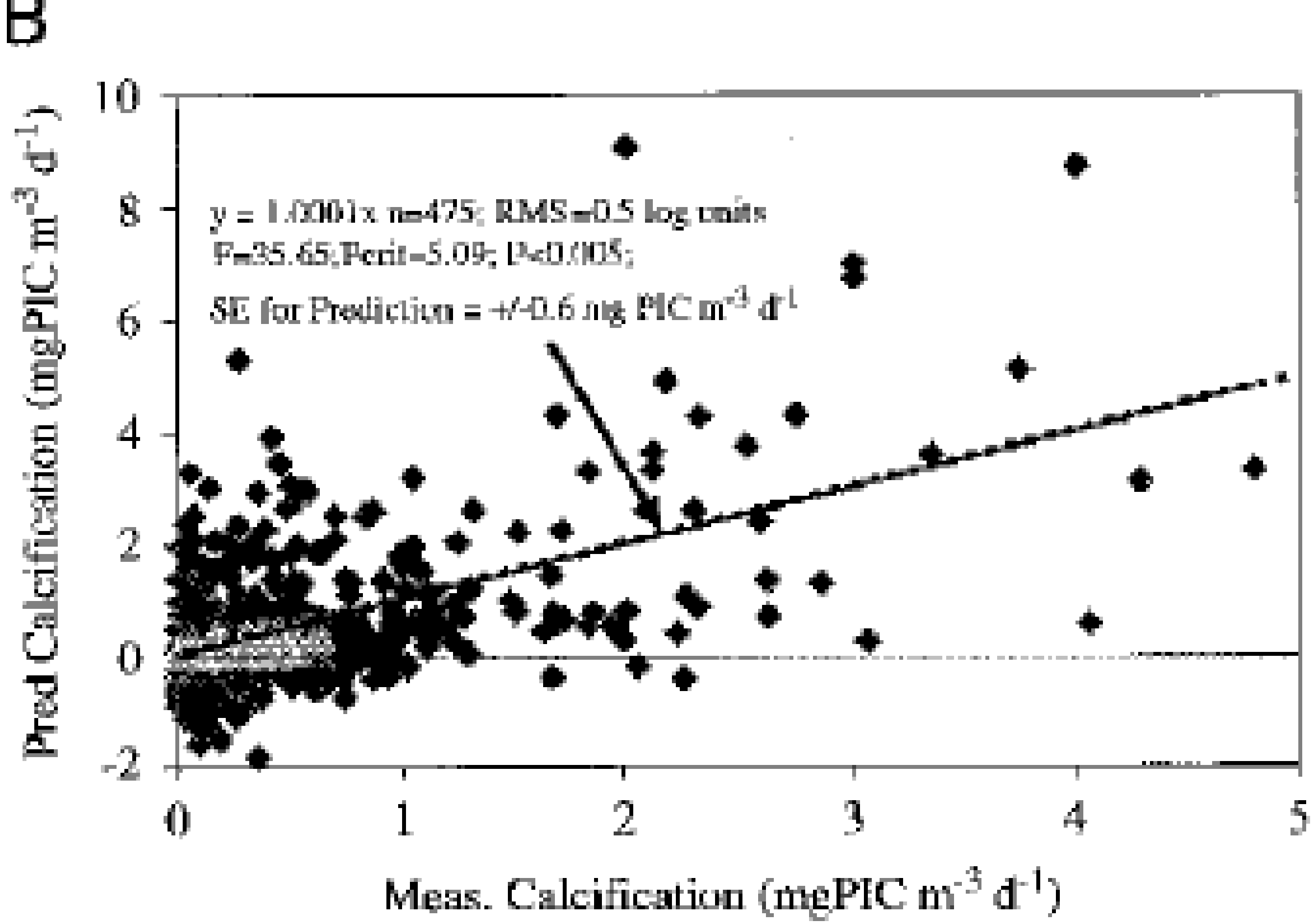
Accepted 10 December 2006
Available online 14 March 2007

Inorganic Carbon Production (Calcification) from Space…



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

Balch et al., 2007; DSRII

New calcification algorithm…
Hopkins and Balch 2017

AGU100 ADVANCING EARTH AND SPACE SCIENCE

JGR

Journal of Geophysical Research: Biogeosciences

RESEARCH ARTICLE
10.1002/2017JG004235

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

A New Approach to Estimating Coccolithophore Calcification Rates From Space

Jason Hopkins[1] and **William M. Balch**[1]

[1]Bigelow Laboratory for Ocean Sciences, East Boothbay, ME, USA

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

Hopkins and Balch, 2017; JGR Biogeosciences

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