Phytoplankton physiology diagnosed from MODIS chlorophyll fluorescence

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With (lots of) help from
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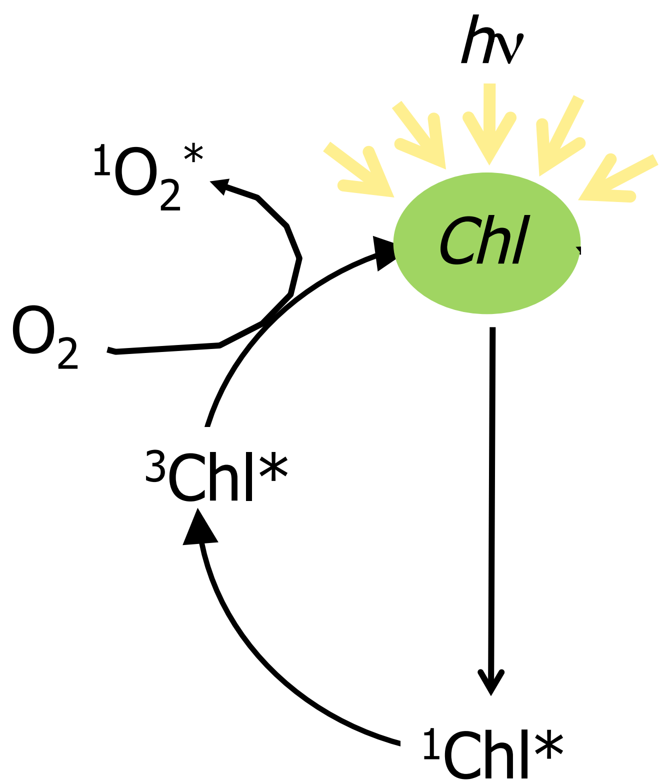
What is Chlorophyll fluorescence?

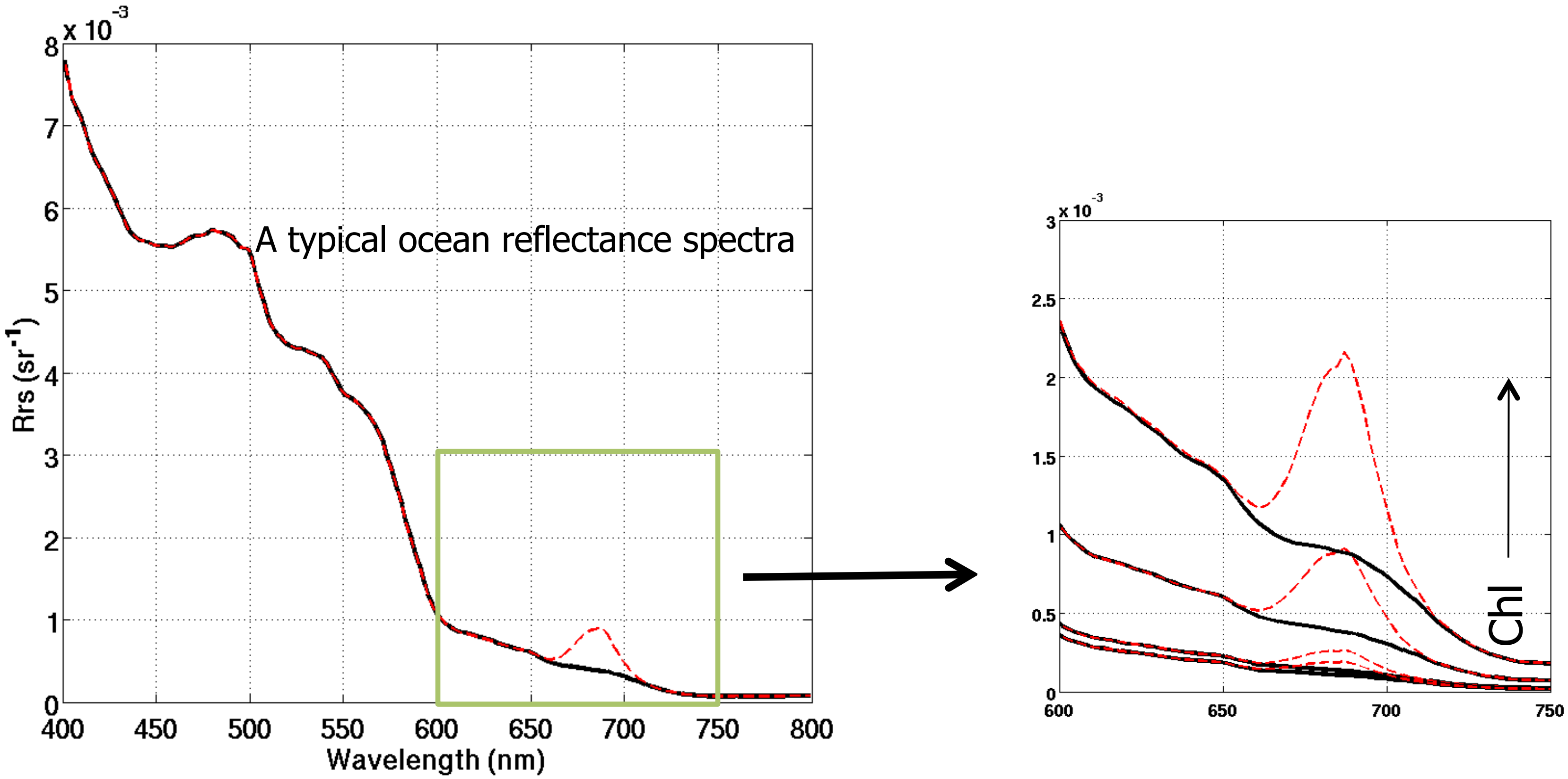
- Chlorophyll-a (Chl) is a ubiquitous plant pigment
- It dissipates some of its absorbed energy as photons (i.e., fluorescence)



⇒
1. Photochemistry
2. Heat
3. Fluorescence

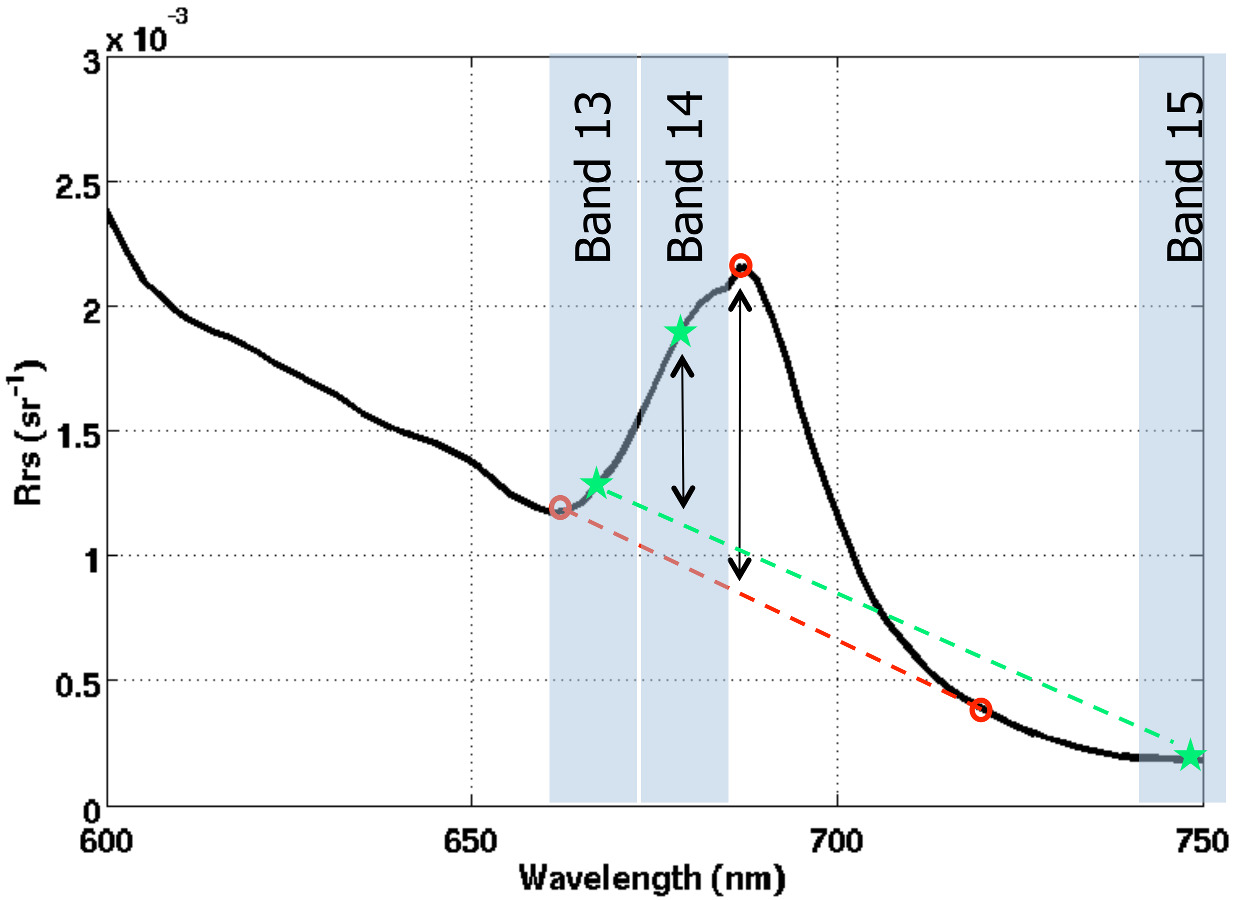
What is Chlorophyll fluorescence?

- Chlorophyll-a (Chl) is a ubiquitous plant pigment
- It dissipates some of its absorbed energy as photons (i.e., fluorescence)
- Fluorescent even under natural sunlight
- Fluoresced radiation is discernable in upwelled radiant flux



MODIS Fluorescence Line Height (FLH)

- A geometric definition
- Can be related to total fluoresced flux (e.g., Huot et al., 2005)



Why MODIS FLH?

- Alternative & independent measure of chlorophyll (particularly in coastal environments)
- Improved NPP estimates
- Index of phytoplankton physiology
  - Pigment Packaging
  - Non-photochemical quenching
  - Nutrient stress effects
  - Photoacclimation

Fluorescence Basics

Three primary factors regulate global phytoplankton fluorescence distributions:

(1) pigment concentrations

(2) “pigment packaging”, a self-shading phenomenon influencing light absorption efficiencies (Duysens 1956; Bricaud et al., 1995, 1998).

(3) a photoprotective response aimed at preventing high-light damage (i.e., “nonphotochemical quenching”, NPQ)

Derivation of ϕ (Fluorescence quantum yield)

Absorbed energy

$$FLH = \overbrace{Chl_{sat} \times \langle a_{ph}^{*} \rangle \times PAR}^{\text{Absorbed energy}} \times \varphi \times \mathbf{S}$$

Chl_{sat}: satellite chlorophyll

$\langle a_{ph}^{*} \rangle$: chlorophyll-specific absorption

φ: fluorescence quantum yield

- subtract small *FLH* value of 0.001 mW cm^{-2} μm^{-1} sr^{-1} to satisfy requirement that *FLH* = 0 when Chl = 0

A little more complicated

full spectral fluorescence emission relative to 683 nm

air-sea interface

Isotropic emmission

incident scalar PAR

FLH

$$\varphi_{\mathrm{sat}} = \frac{4\pi n_w^2 C_f}{t F_0(678)} \frac{E_d(0^+, 678) F_{\mathrm{sat}}}{\int_{400}^{700} \frac{\lambda}{hc} \frac{1}{K(\lambda)+k_L(678)} a_{ph}(\lambda) E_0(0^-, \lambda) d\lambda}$$

TOA irradiance

attenuation of downwelling radiation

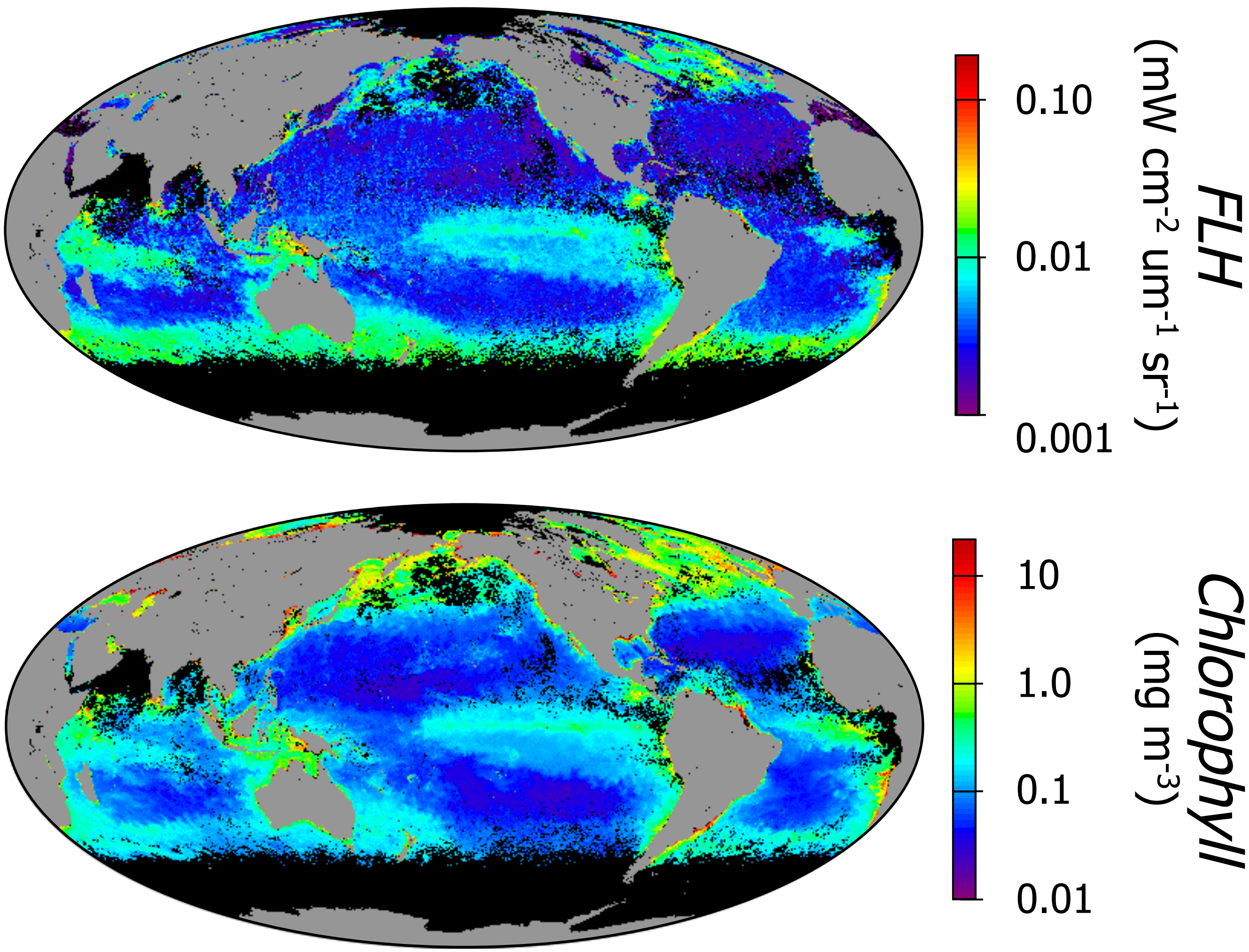
attenuation of upwelling fluorescence

phytoplankton absorption

spectral irradiance

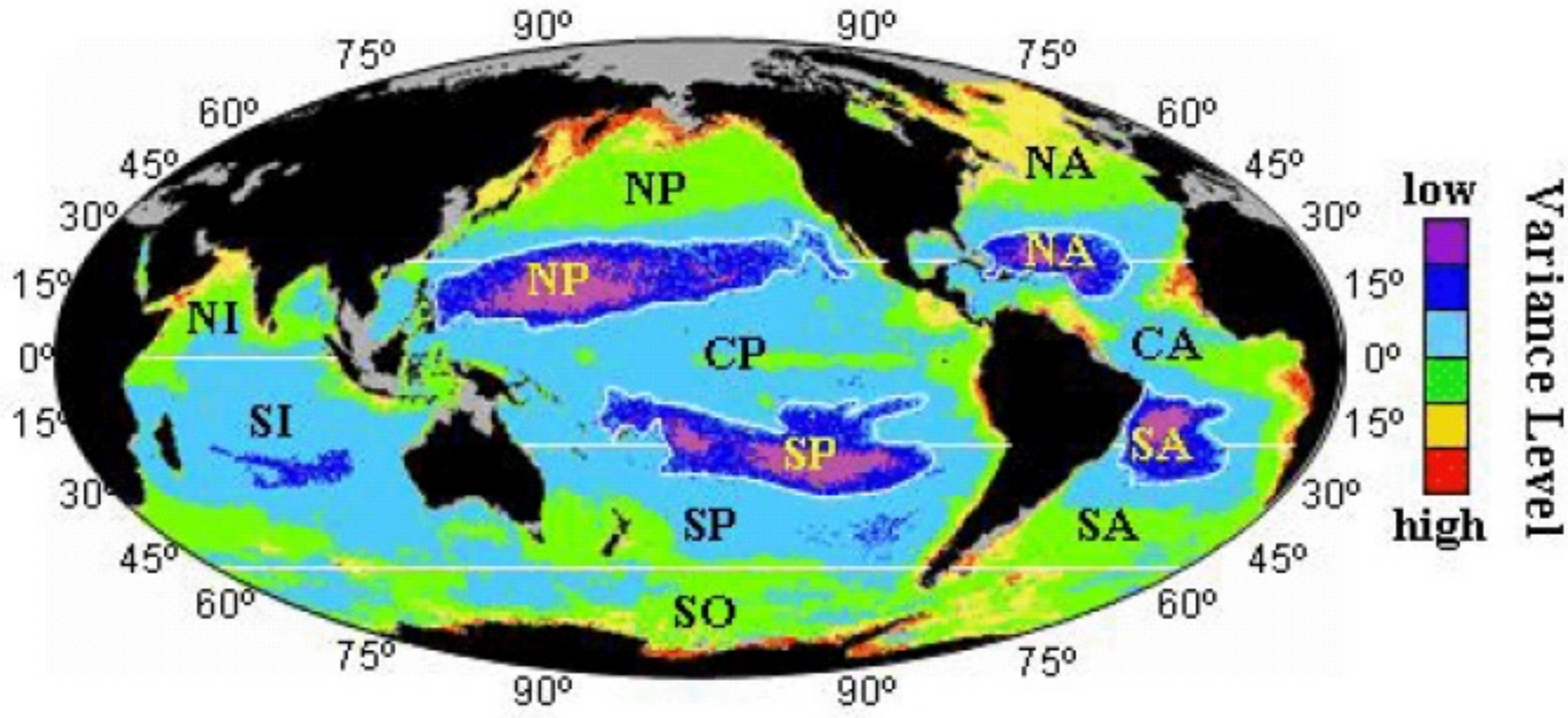
Results

Global MODIS FLH



Global MODIS FLH

- Compute averages within bins of similar Chl σ^2
- 2003 – 2009 Monthly MODIS OC3 Chl
- 43 regional bins



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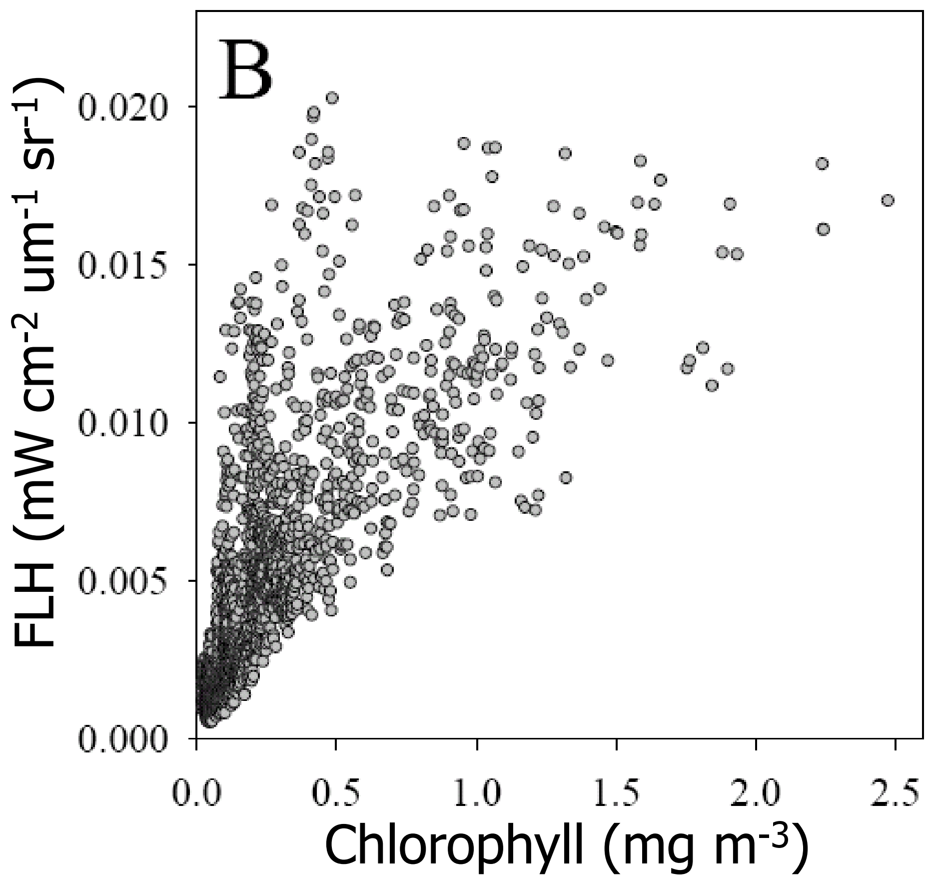

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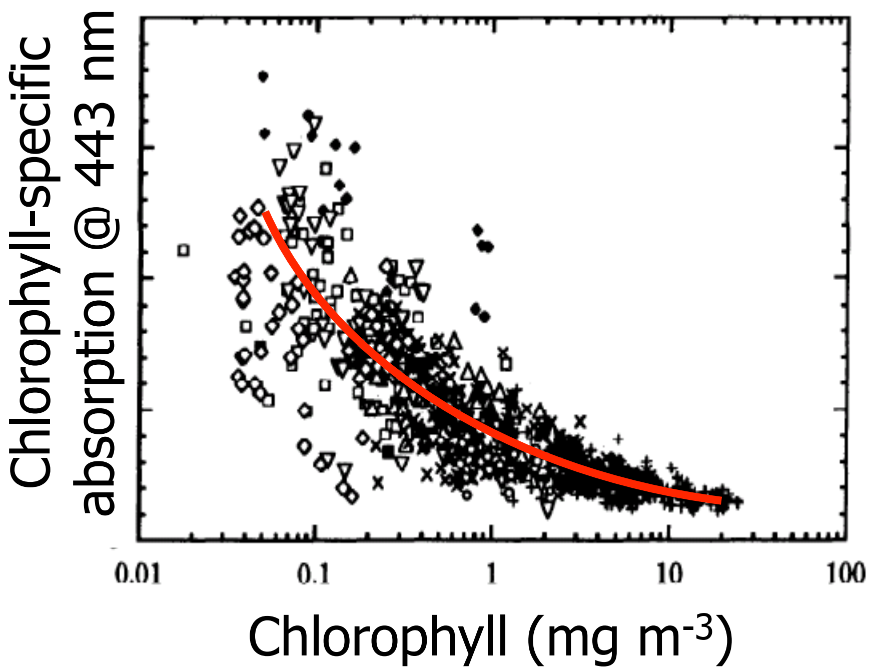
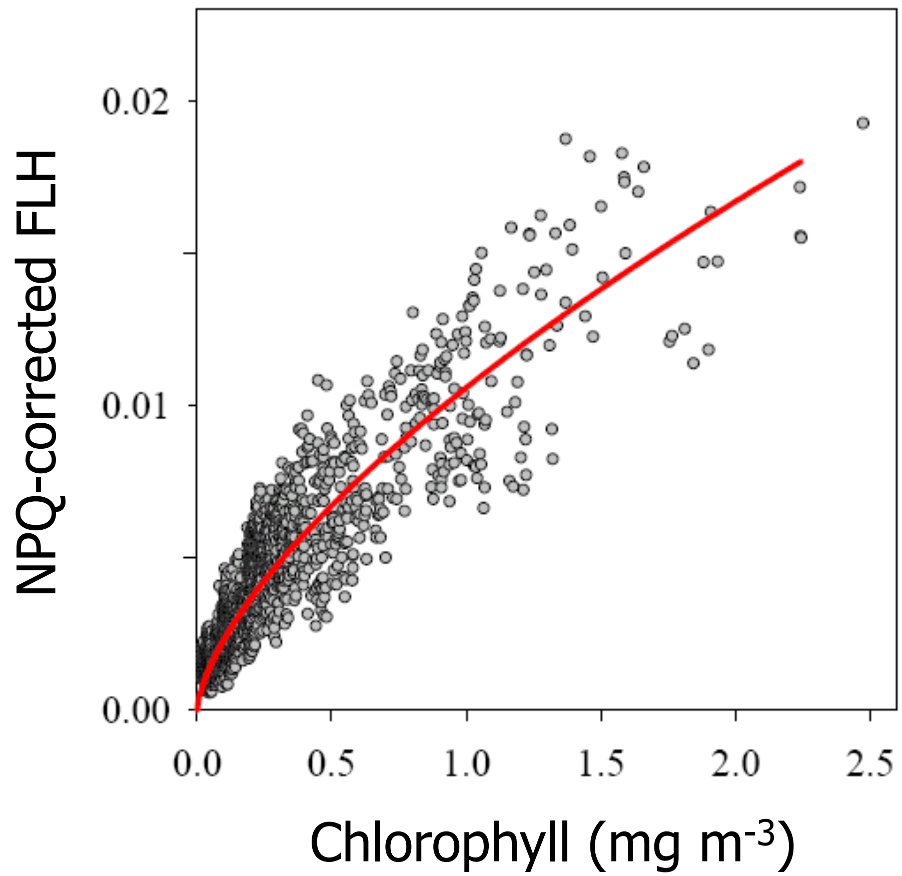
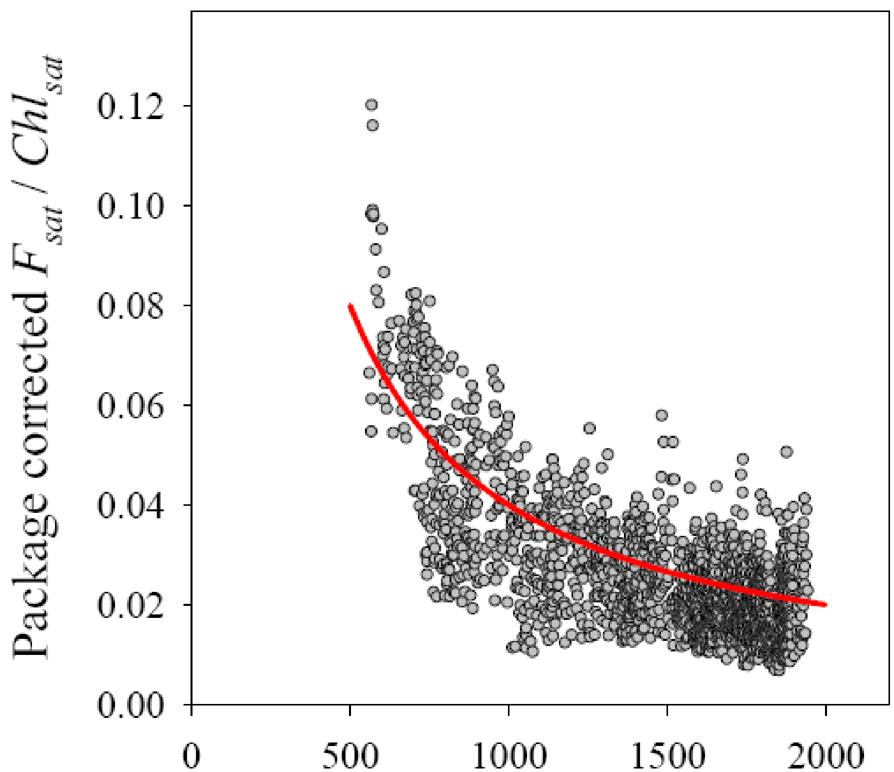
Pigment Packaging

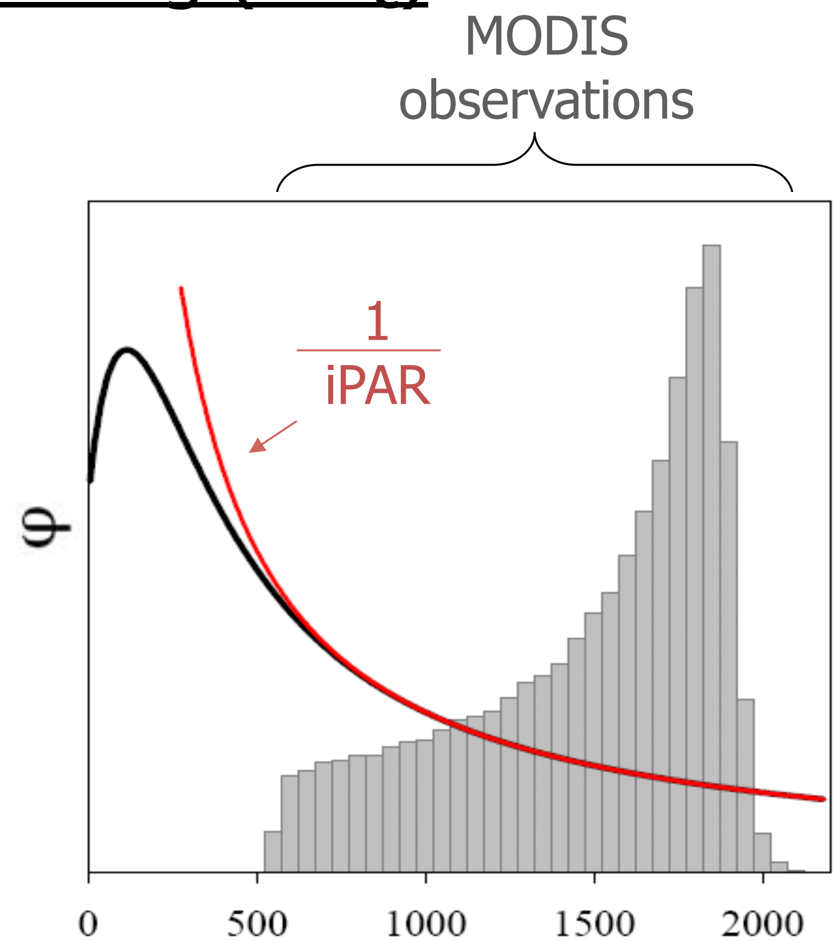


Bricaud *et al.* (1998), *J. Geophys. Res.*, 103, 31,033-31,044.



Non-photochemical quenching (NPQ)





iPAR (μmol photon m^{-2} s^{-1})

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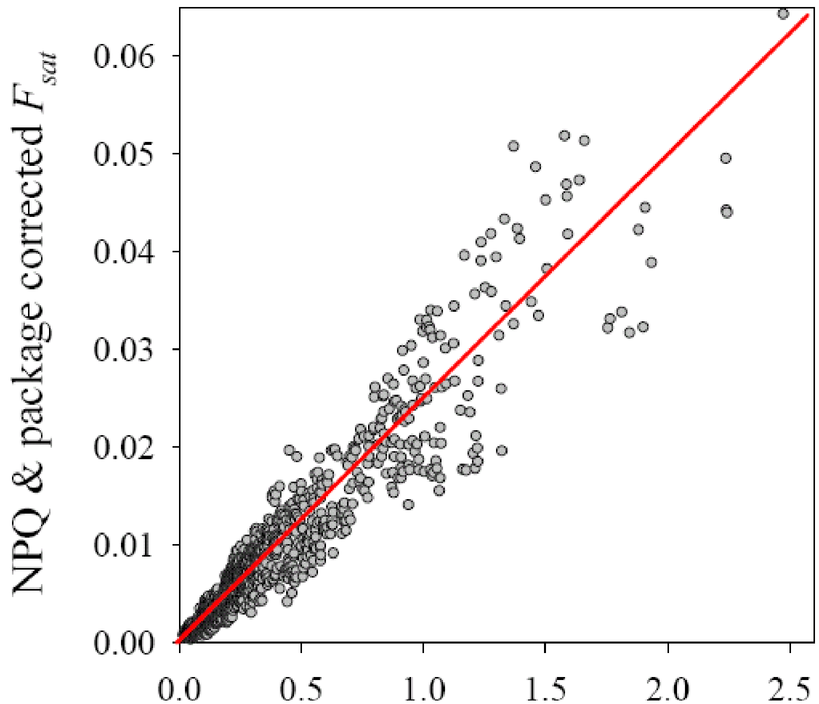
Remaining variability in $FLH_{corrected}$



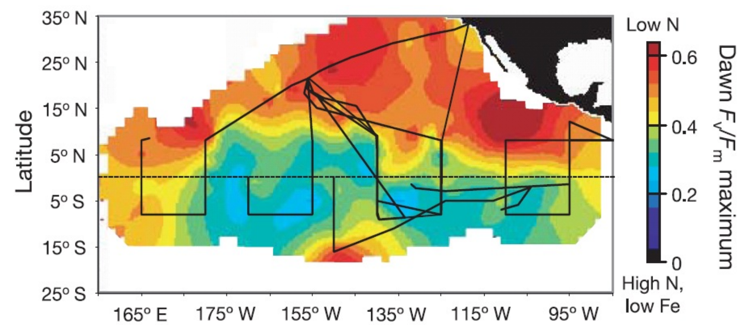
Chlorophyll (mg m^{-3})

Chlorophyll (mg m^{-3})

What do we expect in remaining variability?

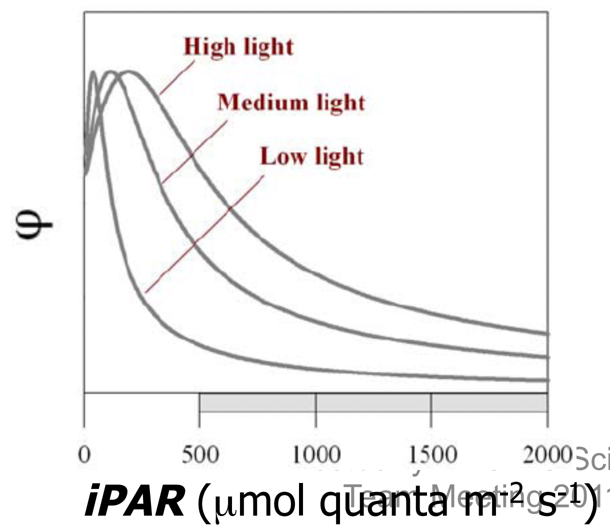
#1: Unique consequences of iron stress

- Over-expression of pigment complexes
- Increases in PSII:PSI ratio
  1. Chlorophyll = PSII & PSI
  2. Fluorescence = PSII
  3. ϕ increases with PSII:PSI ratio

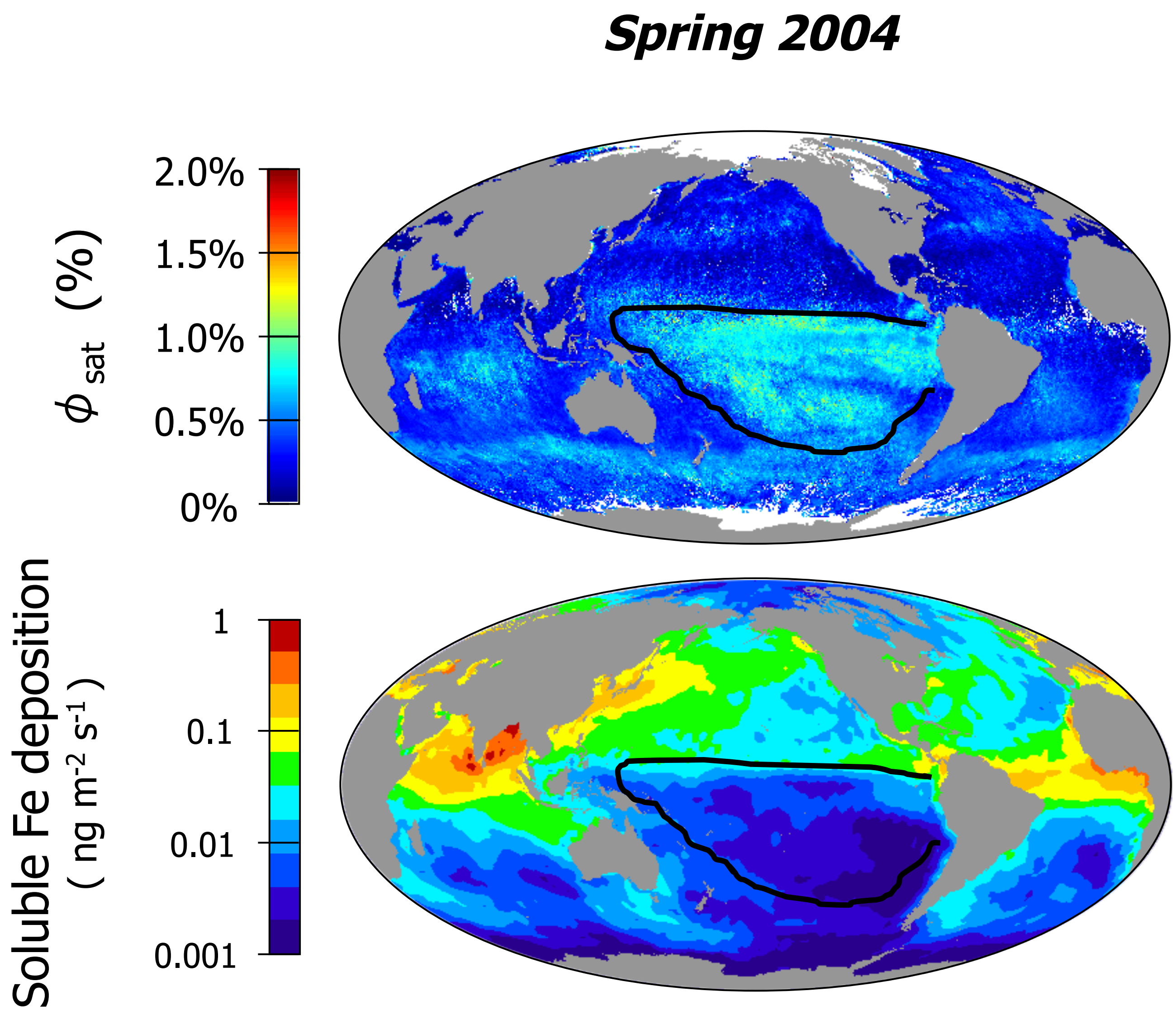


#2: Photoacclimation

- Low light = enhanced NPQ at any given *iPAR*
  → lower ϕ



Fluorescence Quantum Yields (φ, or FQY)



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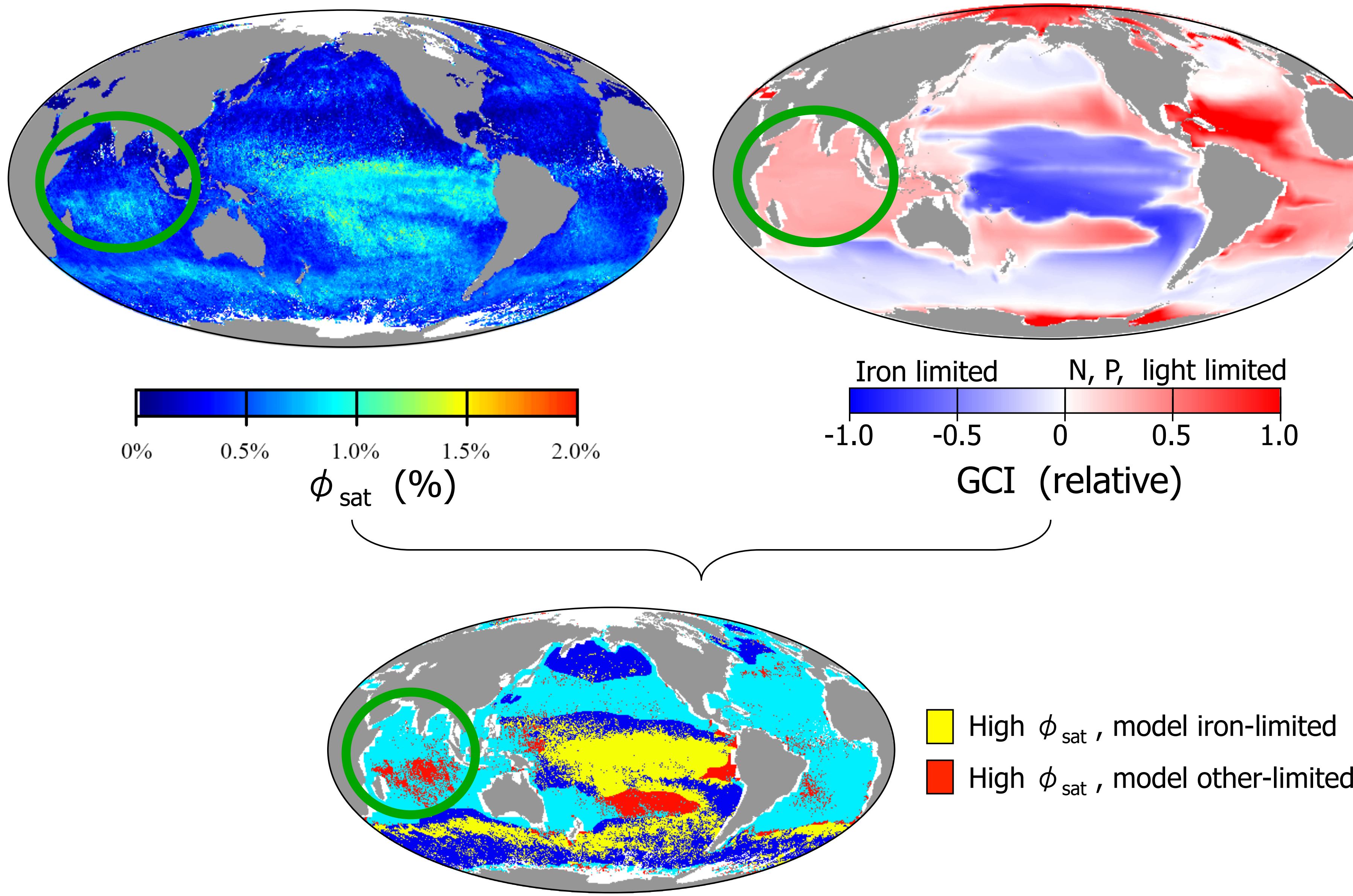
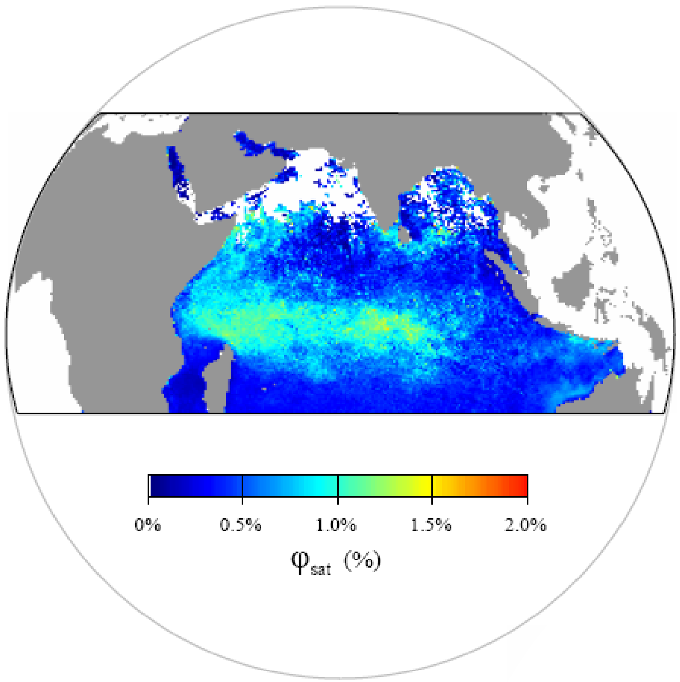
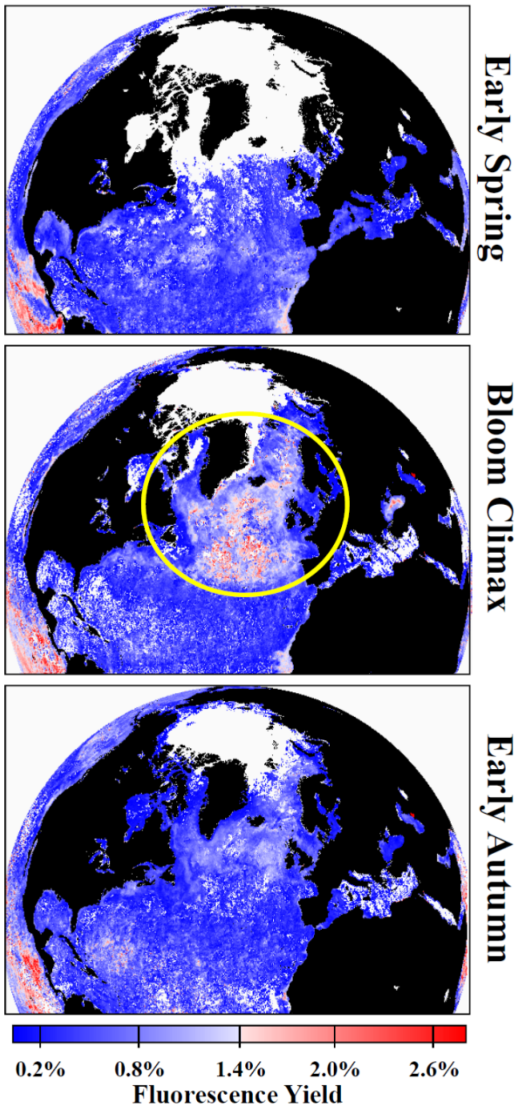


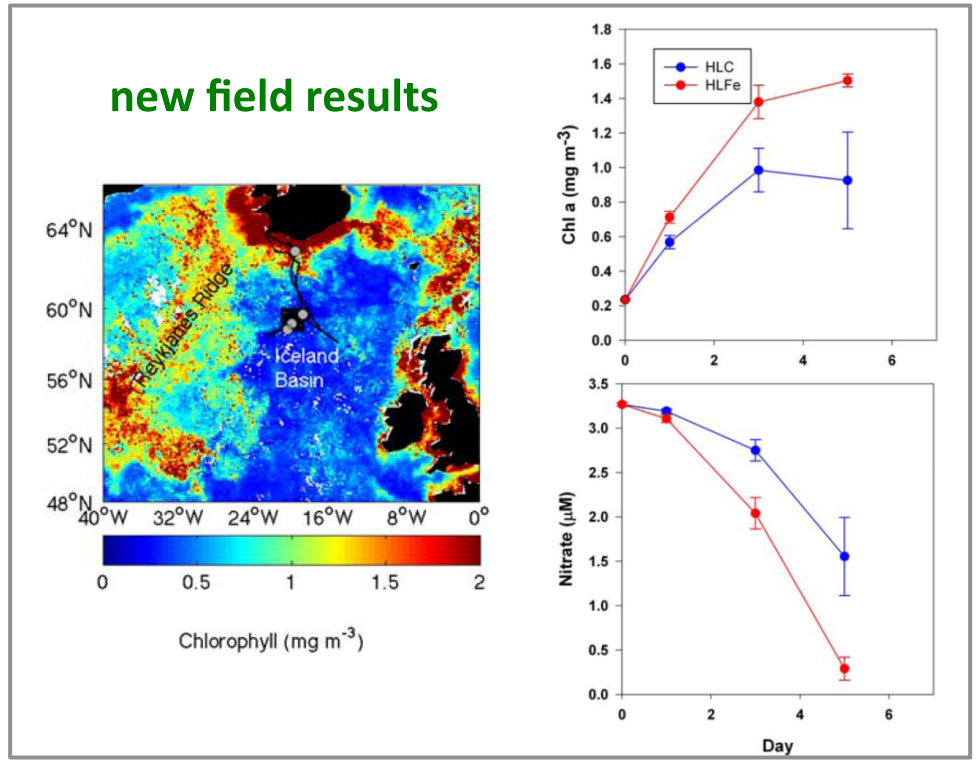
Indian Ocean FQY



North Atlantic FQY

new satellite findings





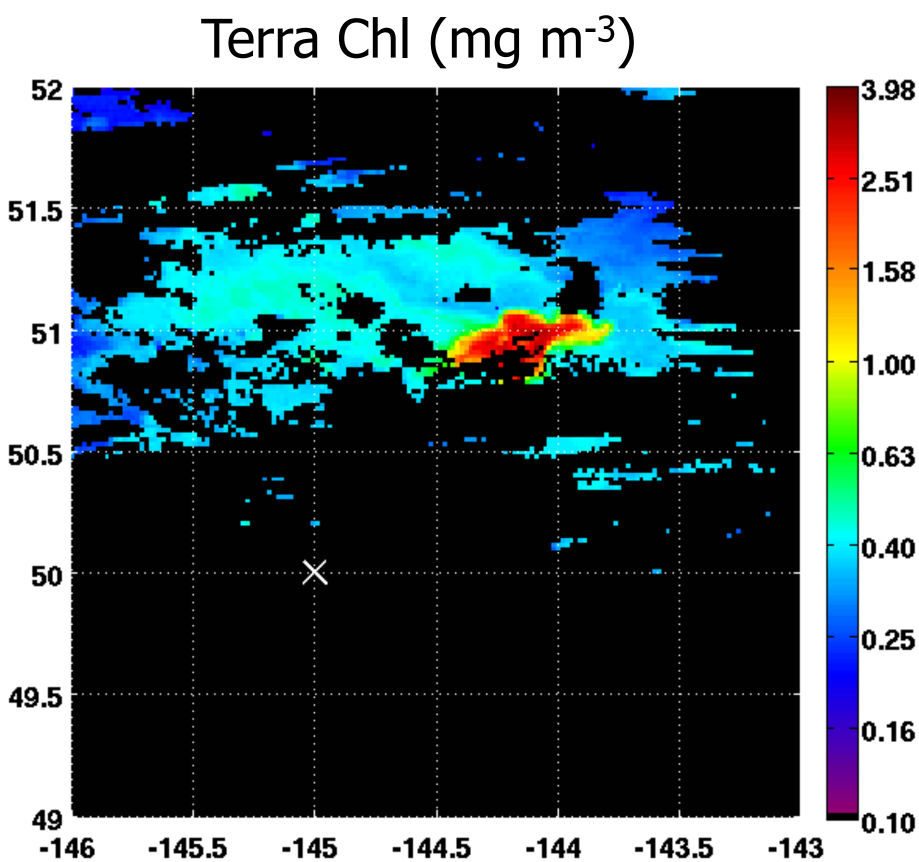
Iron limitation of the postbloom phytoplankton communities in the Iceland Basin

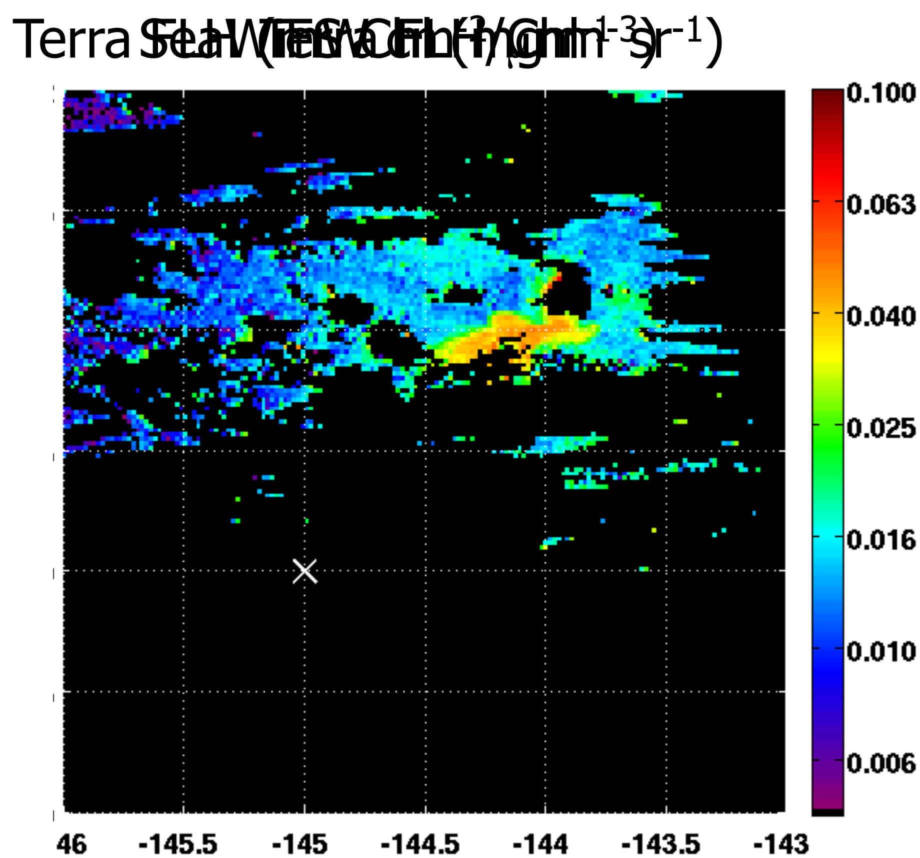
GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 23, GB3001, doi:10.1029/2008GB003410, 2009

Maria C. Nielsdóttir,[1] Christopher Mark Moore,[1] Richard Sanders,[1] Daria J. Hinz,[1] and Eric P. Achterberg[1]

Fluorescence and Fe enrichment experiments

- Example from SERIES
- July 2002 at Station Papa (50°N, 145°W)





Conclusions and Future Directions

1. Ironically, it is the global ocean that is easy, not productive waters

2. Hierarchy: [Chl] > $^{1}/iPAR_{NPQ}$ > packaging > { Fe stress, E_k }

3. Solve E_k to expand iron diagnostic

4. Solve iron stress to derive Ek – then apply to Chl:C !

5. New tool for evaluating (i) Chl_{sat}, (ii) climate models, (iii) responses to natural and purposeful iron enrichments

6. Opportunity to view physiological changes over time

Thank you!

References:

Abbott, M. R. and Letelier, R.M.: Algorithm theoretical basis document chlorophyll fluorescence, MODIS product number 20, NASA, http://modis.gsfc.nasa.gov/data/atbd/atbdmod22.pdf, 1999.

Babin, M., Morel, A. and Gentili, B.: Remote sensing of sea surface sun-induced chlorophyll fluorescence: consequences of natural variations in the optical characteristics of phytoplankton and the quantum yield of chlorophyll a fluorescence, Int. J. Remote Sens., 17, 2417–2448, 1996.

Behrenfeld, M.J., T. K. Westberry, E. S. Boss, R. T. O'Malley, D. A. Siegel, J. D. Wiggert, B. A. Franz, C. R. McClain, G. C. Feldman, S. C. Doney, J. K. Moore, G. Dall'Olmo, A. J. Milligan, I. Lima, and N. Mahowald (2009), Satellite-detected fluorescence reveals global physiology of ocean phytoplankton, *Biogeosciences* v6, 779-794.

Boyd, P. W., et al. (2004), The decline and fate of an iron-induced subarctic phytoplankton bloom, Nature, 428, 549– 553.

Bricaud, A., Morel, A., Babin, M., Allalli, K. and Claustre, H. Variations of light absorption by suspended particles with chlorophyll a concentration in oceanic (case 1) waters: Analysis and implications for bio-optical models, J. Geophys. Res,103, 31,033–31,044, 1998.

Huot, Y., Brown, C. A. and Cullen, J. J.: New algorithms for MODIS sun-induced chlorophyll fluorescence and a comparison with present data products, Limnol. Oceanogr. Methods, 3, 108–130, 2005.

Mahowald, N., Luo, C., Corral, J. D., and Zender, C.: Interannual variability in atmospheric mineral aerosols from a 22-year model simulation and observational data, J. Geophys. Res., 108, 4352, doi:10.1029/2002JD002821, 2003.

Moore, J. K., Doney, S. C., Lindsay, K., Mahowald, N. and Michaels, A. F.: Nitrogen fixation amplifies the ocean biogeochemical response to decadal timescale variations in mineral dust deposition, Tellus, 58B, 560–572, 2006.

Morrison, J. R.: In situ determination of the quantum yield of phytoplankton chlorophyll fluorescence: A simple algorithm, observations, and model, Limnol. Oceanogr., 48, 618–631, 2003.

Westberry T. K. and Siegel, D.A.: Phytoplankton natural fluorescence in the Sargasso Sea: Prediction of primary production and eddy induced nutrient fluxes, Deep-Sea Research Pt. I, 50, 417–434, 2003.

Wiggert, J. D., Murtugudde, R. G., and Christian, J. R.: Annual ecosystem variability in the tropical Indian Ocean: Results from a coupled bio-physical ocean general circulation model, Deep-Sea Res. Pt. II, 53, 644–676, 2006.