# Refinement of global MODIS chlorophyll fluorescence quantum yields

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## ABSTRACT

- Chlorophyll fluorescence is the only remotely sensed property uniquely attributable to phytoplankton, and therefore conveys a wealth of information related to standing stocks, rates of photosynthesis, and important physiological processes.

- *The overarching goal of this proposal is to better characterize non-photochemical quenching (NPQ) processes that affect observed satellite fluorescence. Successful removal of the NPQ signal will result in satellite fluorescence products that provide a clearer picture of phytoplankton physiology over the entire surface ocean.*

- The research project proposed here seeks to merge a mechanistic cellular level understanding of NPQ with MODIS satellite data through 4 complimentary efforts:

  1. Extrapolation of laboratory findings on NPQ to satellite estimates of photoacclimation
  2. Establishment of constraints on NPQ dynamics observed in natural phytoplankton populations using an existing database of active fluorescence and passive radiometry
  3. Evaluation of NPQ behavior over the course of the daily irradiance cycle from a geostationary ocean color satellite (Korean GOCI)
  4. Use of MODIS fluorescence data at high latitudes where overlapping swaths provide multiple views on a given day

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## MODIS chlorophyll fluorescence

- Chl fluorescence can be measured from passive ocean color measurements in the red-nearIR
- The "efficiency" of fluorescence is given by the quantum yield (φ):

$$FLH = nL_w(678) - \tfrac{70}{81} nL_w(667) - \tfrac{11}{81} nL_w(748)$$

$$\varphi = \frac{4\pi n^2 C_f}{tF_o(678)} \frac{E_d(0^+, 678) FLH}{\int_{400}^{700} \frac{\lambda}{hc} \frac{1}{K(\lambda) + k_L(\lambda)} a_{ph} E_o(0^-, \lambda) d\lambda}$$

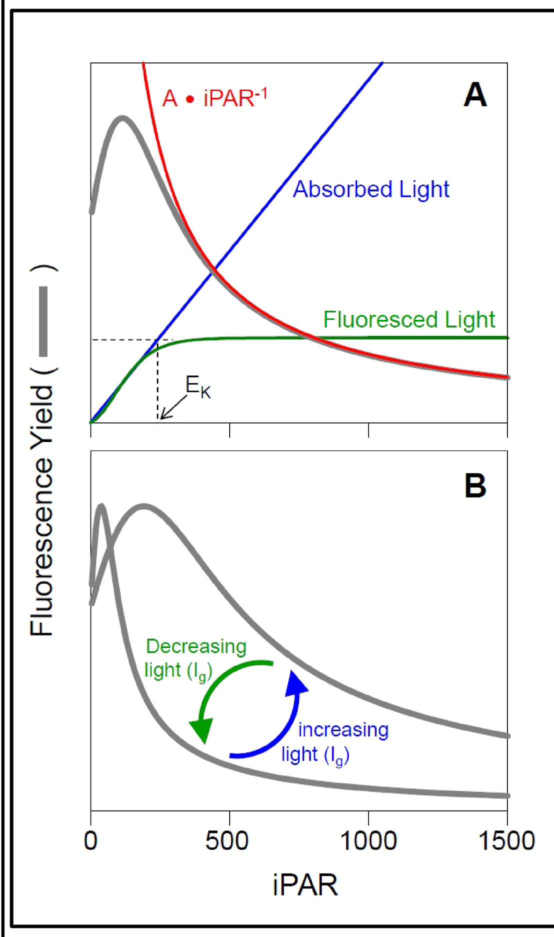


**Figure 1.** Relationship between incident light, absorption, and fluorescence. Absorbed light is a linear function of incident light, while fluoresced light saturates. At high light levels, the fluorescence yield closely approximates an inverse (1/iPAR) function of light (red line). As phytoplankton acclimate to different growth irradiances ($I_g$), their saturation point ($E_k$) changes causing NPQ to be engaged at different times. For example, phytoplankton acclimated to low light have a low $E_k$, and thus NPQ is engaged sooner, resulting in a more rapid reduction in φ.

## Non-photochemical quenching in MODIS fluorescence measurements

- NPQ often dominates FLH and φ variability
- It obscures other forms of interesting physiology contained in satellite fluorescence measurements

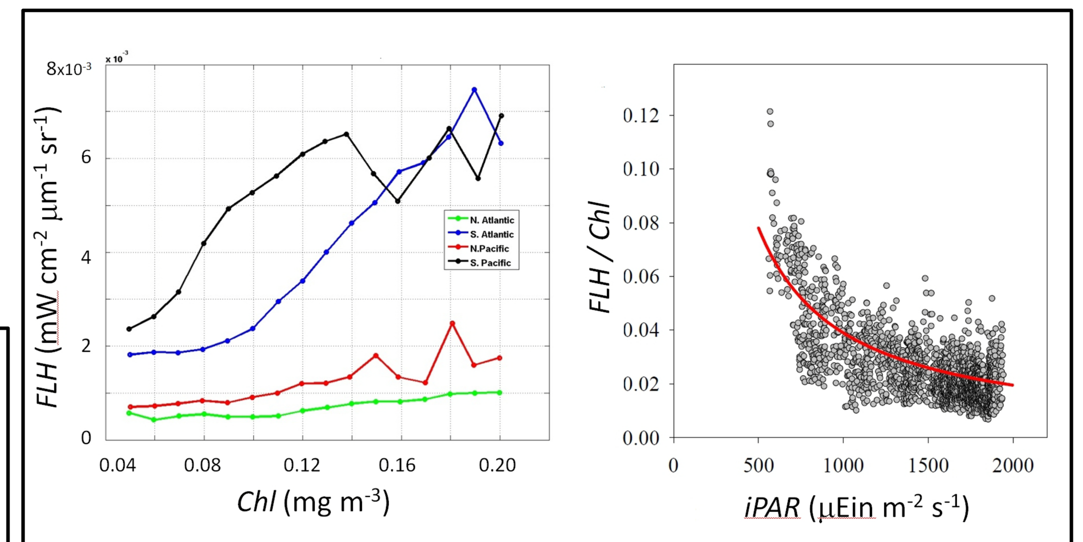


**Figure 2.** Non-photochemical quenching (NPQ) in MODIS chlorophyll fluorescence data. (Left) MODIS Level-3 FLH from June 2011 for discrete Chl bins averaged over the North and South Pacific and Atlantic Subtropical Gyres. For a given Chl concentration, FLH in the summertime hemisphere (red and green lines are N. Pacific and N. Atlantic, respectively) is significantly lower than in the low light, wintertime hemisphere (black and blue lines are S. Pacific and S. Atlantic, respectively). (Right) Five years of monthly, global MODIS Level-3 data binned regionally. Red line is scaled 1/iPAR relationship, which is the basis for the existing NPQ correction.

## MODIS fluorescence and iron stress

- Fluorescence is a well-known diagnostic of iron (Fe) stress
- This relationship presents a link between satellite fluorescence and climate

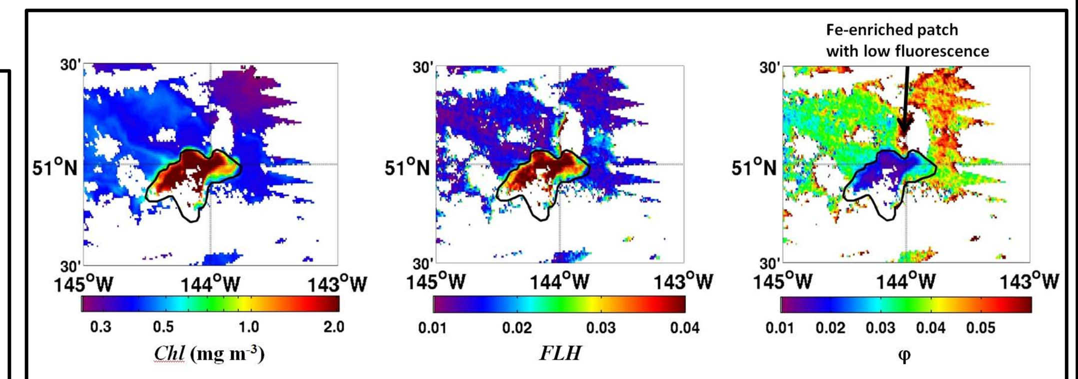


**Figure 3.** MODIS Terra daily composite imagery (July 29, 2002) around the SERIES experiment in Subarctic Northeast Pacific Ocean. The Fe-enriched patch is outlined in black and is >1000 km².

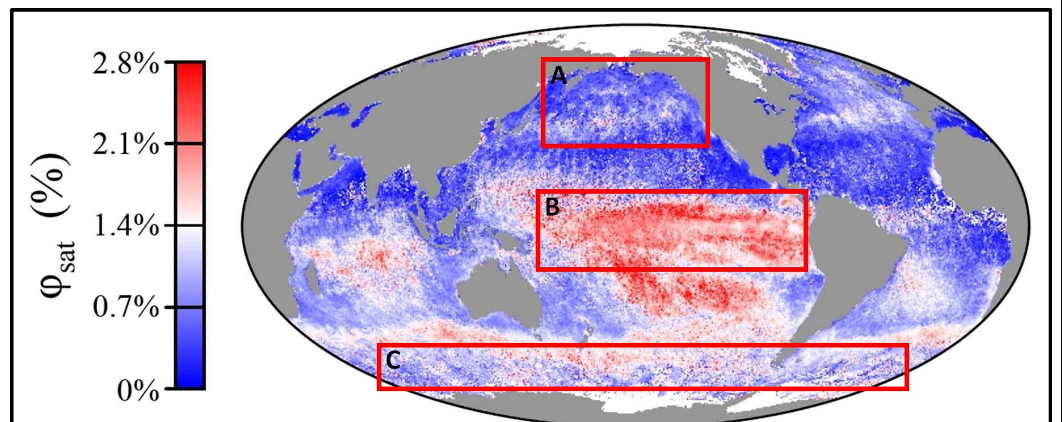


**Figure 4.** Global average φ during Spring 2004. φ >1.4% are shown in a shade of red to highlight areas of generally elevated fluorescence. Red boxes outline canonical Fe-limited regions. Only Equatorial Pacific (B) shows widespread elevated φ, while Subarctic Pacific (A) and Southern Ocean (C) do not.

## How can we remove non-photochemical quenching (NPQ) effects from MODIS fluorescence measurements?

### NPQ in Fast Repetition Rate fluorometry (FRRf) data

- Continuous measurements of active fluorometry displays NPQ behavior
- We have >500 sampling days worth of these data to characterize variability in NPQ

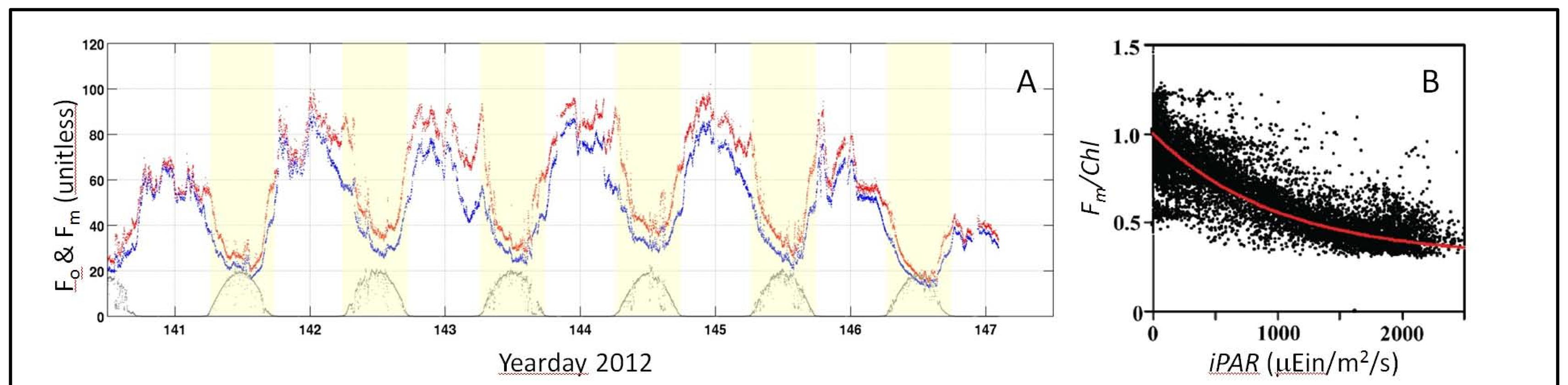


**Figure 5.** Time series of FRRf data. Fo (blue) and Fm (red) collected over 8 days during May 2012 in the eastern South Pacific. Periods of daylight are indicated by yellow regions and light gray dots are the daily cycles in incident irradiance at the sea surface. Note significant depression of fluorescence during mid-day. (Right) Same data, but each day of Fm has been normalized to Chl to account for changes in pigment biomass and expressed relative to the pre-dawn (unquenched) value. Viewed in this way, the ratio Fm/Chl equals unity at dawn and decreases with increasing irradiance.

### Evaluation of NPQ behavior from laboratory and field measurements

- NPQ can be characterized in a laboratory setting
- We can extrapolate results from past experiments

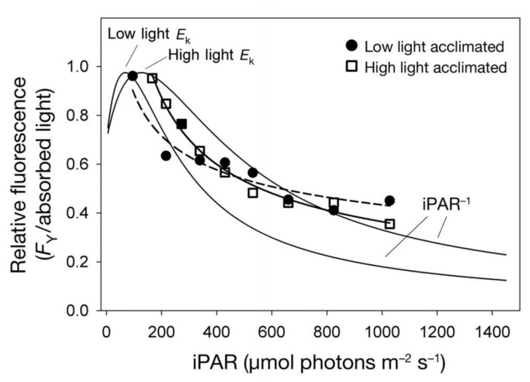


**Figure 5.** Relative fluorescence yield (~φ) as a function of iPAR for high and low light-acclimated cultures of *Thalassiosira weissflogii*. Theoretical curves from Behrenfeld et al. (2009) also shown. Reprinted with permission from Milligan et al. (2012).

### Analysis of geostationary ocean color data

- Geostationary satellite observations can resolve NPQ in hourly measurements of chlorophyll fluorescence
- We can use data from the Korean Geostationary Ocean Color Imager (GOCI)
- The NASA Ocean Biology Processing Group will soon be receiving, processing, and archiving GOCI data

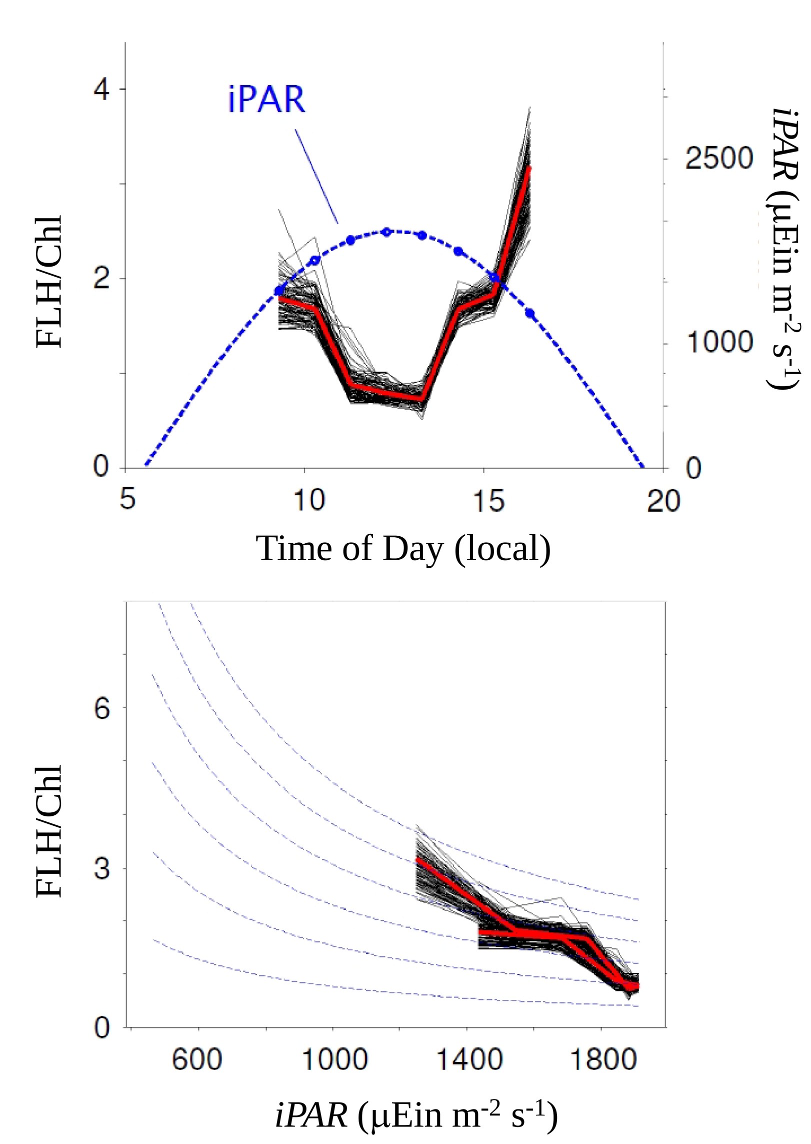


**Figure 6.** GOCI data collected on May 6, 2012 in a 100x100 pixel area centered on 26.7°N, 131.3°E. The red line is the average FLH/Chl over the entire region, individual black lines are averages over smaller 10x10 pixel regions within larger domain. Blue dashed line is incident clear-sky irradiance calculated by fitting geolocated MODIS iPAR data to a half-sine solar irradiance function. Open circles indicate time of day of GOCI sampling.

### MODIS data at high latitudes

- High latitude environments can be imaged by MODIS on several (3-5) orbits per day
- The range of light levels corresponding to these granules should allow us to resolve NPQ for a given day or set of consecutive days (e.g., during the winter MODIS Aqua will image the same pixel cycling through 50-100% of its daily maximal irradiance

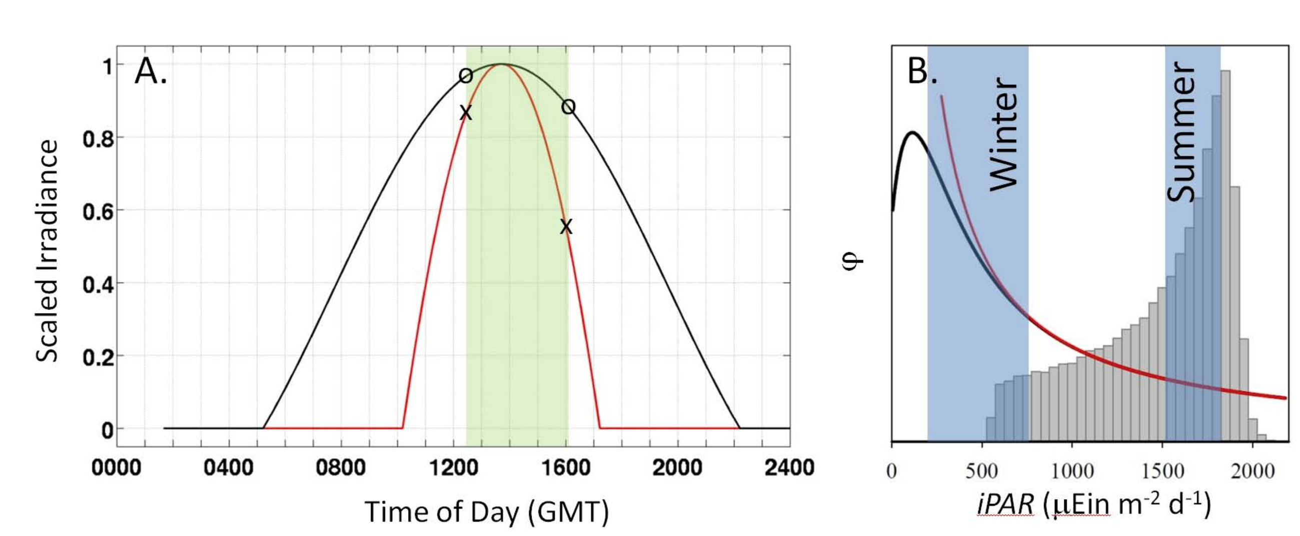


**Figure 7.** Daily irradiance at 55°N in summer (black line) and winter (red line). Green shaded area represents the window of MODIS coverage at 55°N, 25°W (similar in summer or winter). o's mark the relative irradiance level at the earliest/latest MODIS coverage times during summer, and x's indicate the relative irradiance levels for the same times of day during winter. B) Fluorescence quantum yield as a function of iPAR. Black line is theoretical curve of Behrenfeld et al. (2009), red line is scaled 1/iPAR NPQ correction. The blue shaded regions indicate the range of light levels corresponding to the MODIS coverage times in panel A. Wintertime coverage captures a broader range of iPAR in a more critical portion of the φ-iPAR curve. Grey histogram is a typical distribution of global monthly MODIS Level-3 iPAR.