Spectral Weighting Functions for the Effects of Solar Ultraviolet Radiation on Phytoplankton Photosynthesis

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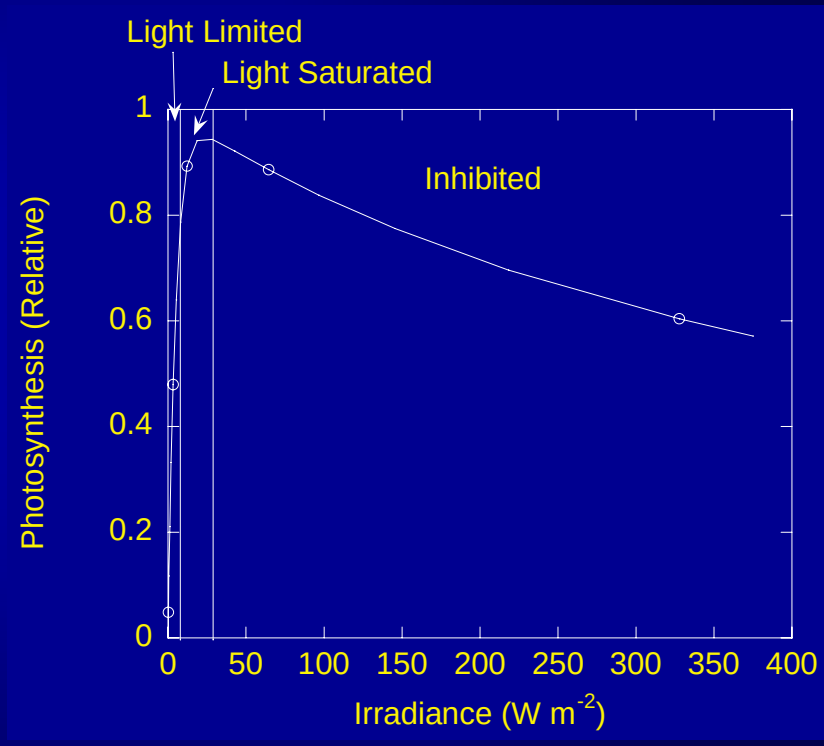
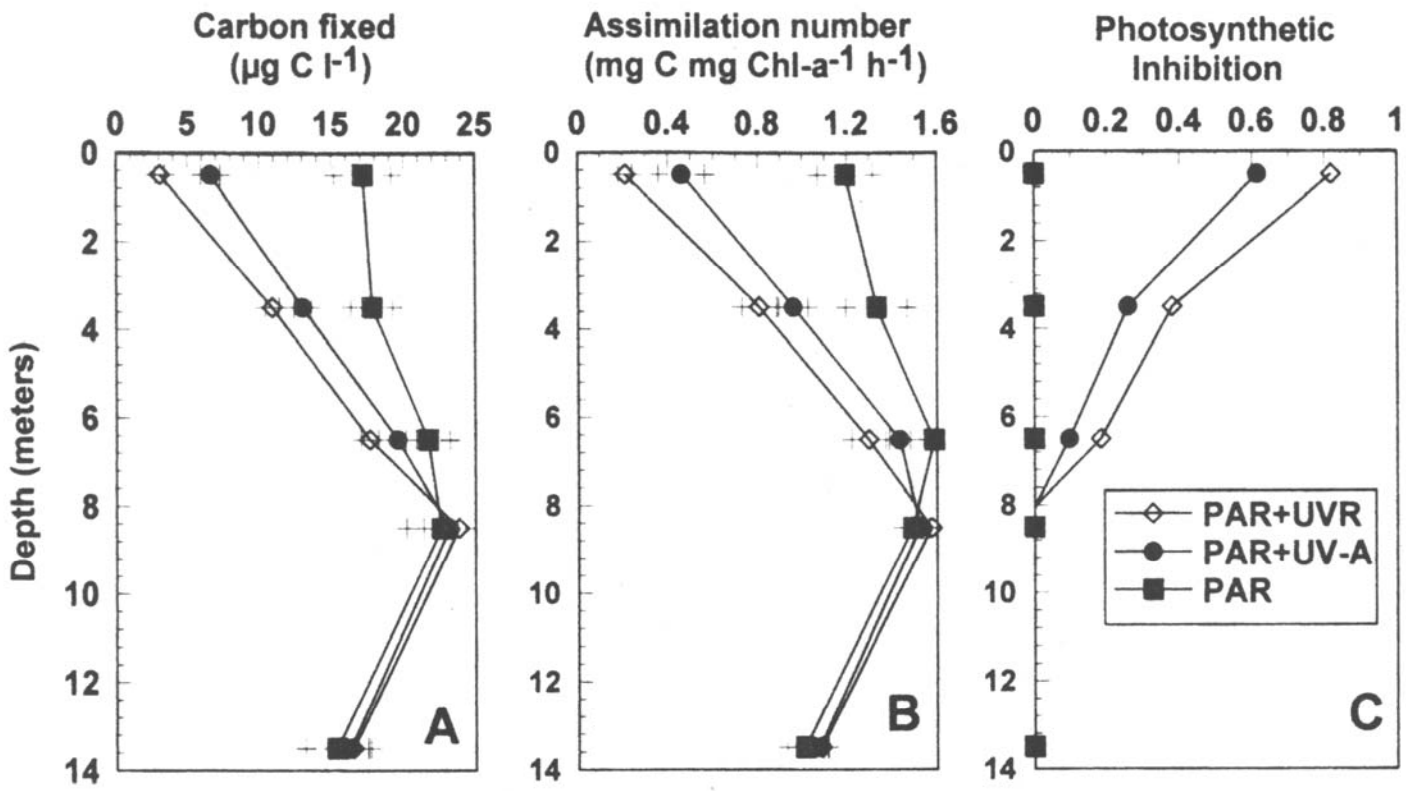
Supported by US-NSF(OPP & OCE), EPA and Smithsonian Institution

Inhibition of Phytoplankton Photosynthesis

- Photosynthesis is limited by low irradiance (~ 1% incident)
- Photosynthesis attains a maximum, saturated rate at moderate irradiance (~10% incident)
- Photosynthesis decreases from a maximum as irradiance nears midday levels (50-100%)



Near-Surface Photosynthesis is inhibited in Lago Titicaca



Villafañe, et al. 1999 Freshwater Biol. 42: 215

Investigations of UV effects on phytoplankton photosynthesis

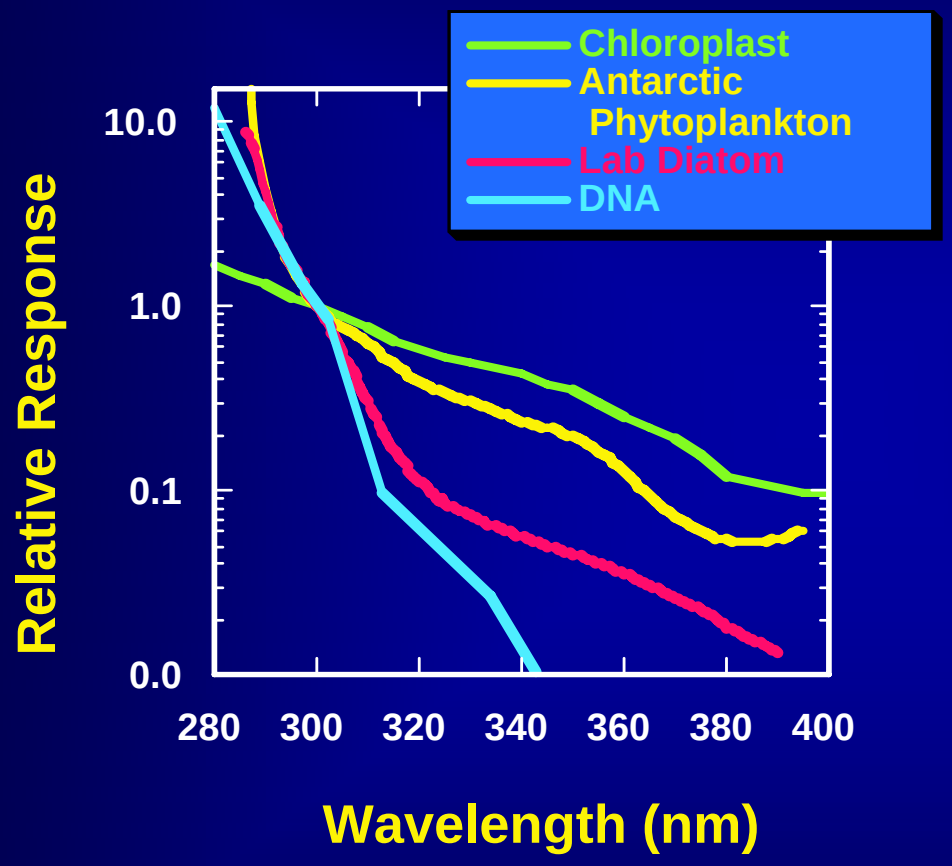
1964 Comparison of 14C photosynthesis in quartz vs. glass bottles shows that solar UV inhibits (Steeman-Nielsen, J. Cons. Perm. Int. Explo. Mar)

1980 Initial work with spectral treatments, showed that both UVA and UVB were important (e.g. Smith et al, Photochemistry and Photobiology)

1990s Several groups define weighting functions for UV inhibition of phytoplankton in culture and natural assemblages in Antarctica

From the beginning, the approach is based on combined exposures to PAR and varying amounts of UV

Biological Weighting Functions quantify wavelength-dependent effects

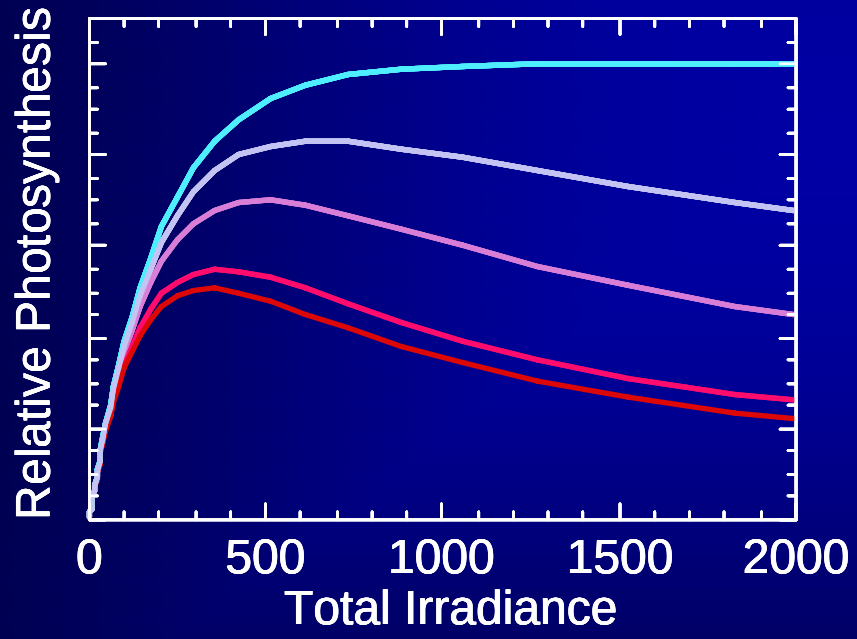


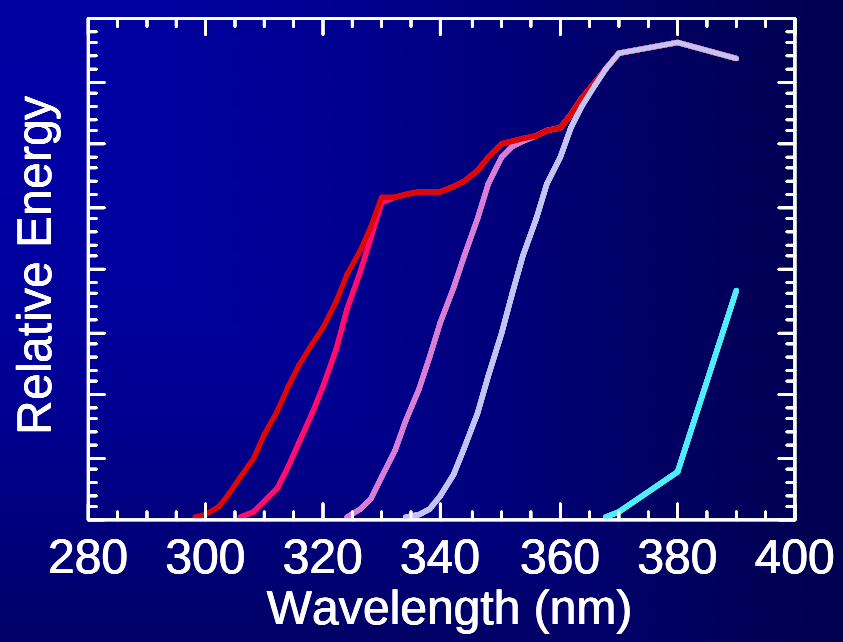
UV Affects Multiple Trophic Levels:

- **Bacterial Assimilation**
- **Phytoplankton Production**
- **Zooplankton and Fish Larvae Survival**

A tool to assess the effect of wavelength dependent changes in UV (climate change, O3 depletion)

Photosynthetic Response to UV + PAR

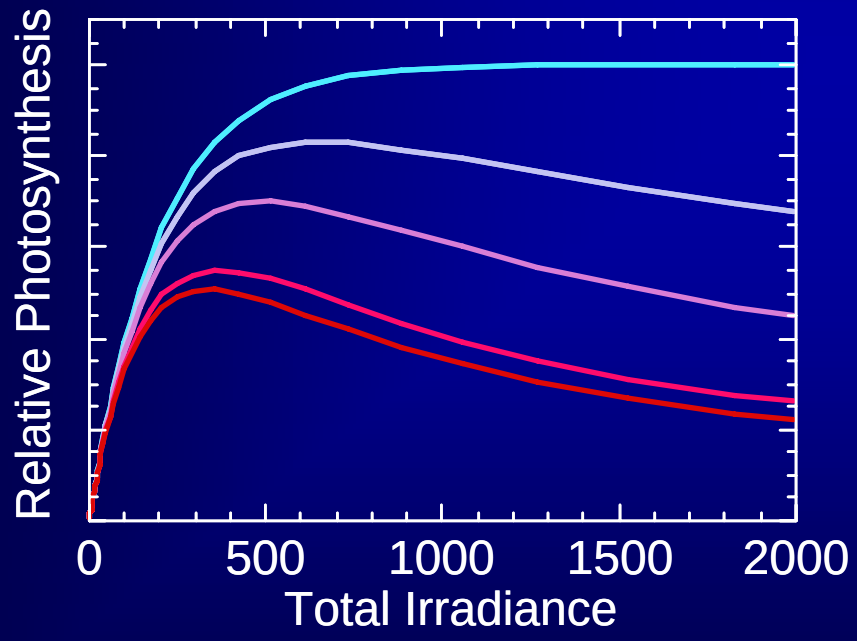


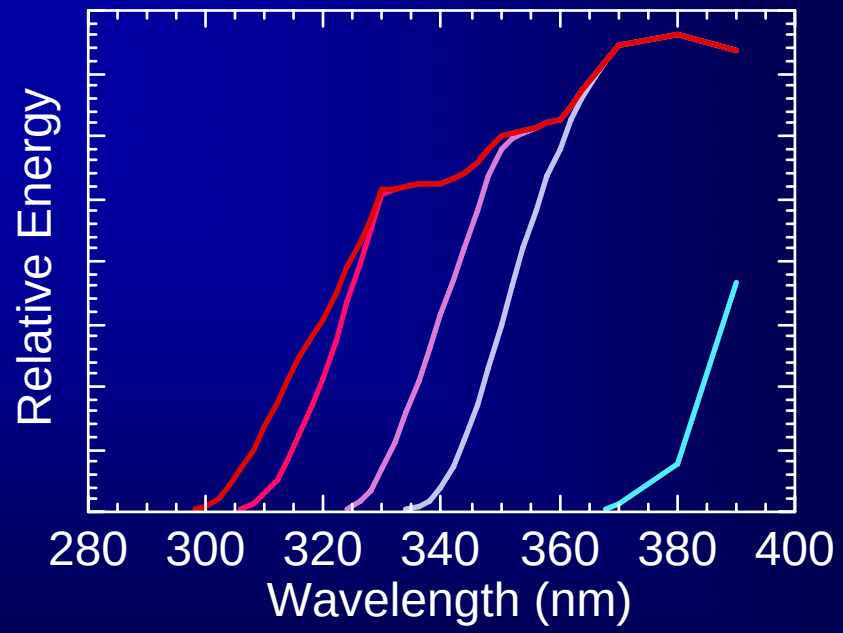


$$P^B = P_s^B \left(1 - e^{-E_{PUR}/E_k}\right) \frac{1}{1 + E_{inh}^*}$$

$$E_{inh}^* = \sum_{\lambda = 280\,\mathrm{nm}}^{700\,\mathrm{nm}} \varepsilon(\lambda) \cdot E(\lambda) \cdot \Delta\lambda$$

BWF/P-I model





Cullen et al. 1992 Science 258: 646

Production Model for the Rhode River

- *Measured BWFs May-Jul (n=8)*
- *Irradiance Spectra*
  - 28 d, June-July 1999
  - Measured with SR18 290-324 nm
  - Extended with full RT 325-400 nm
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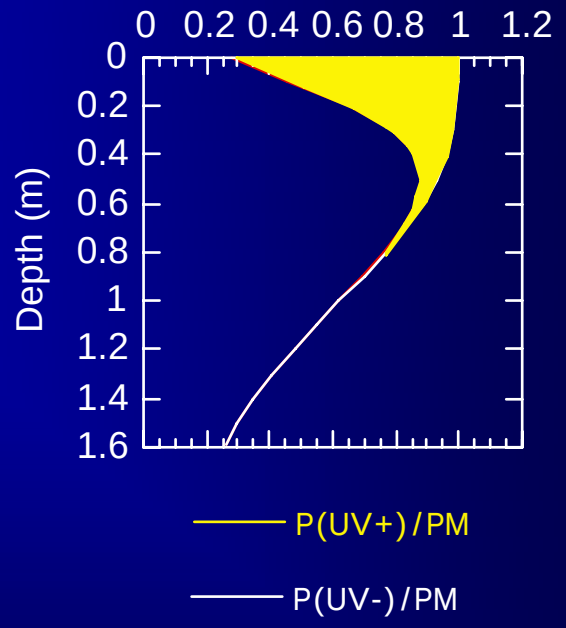
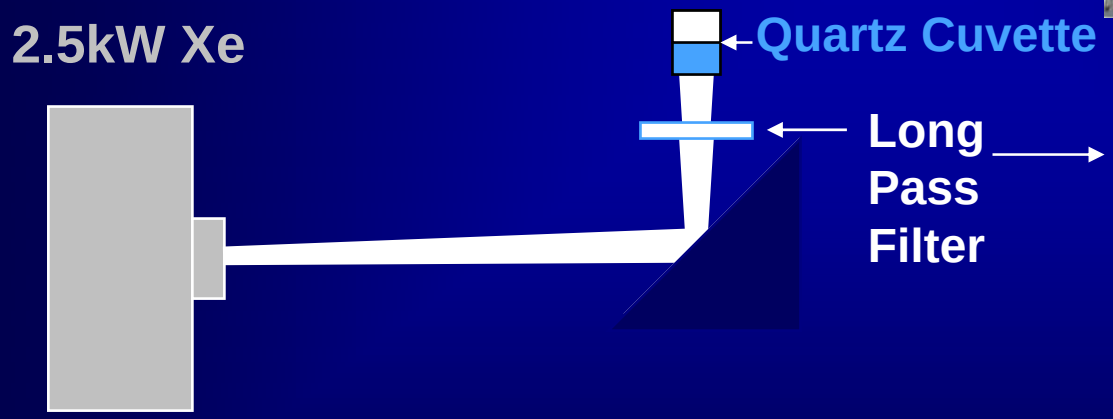
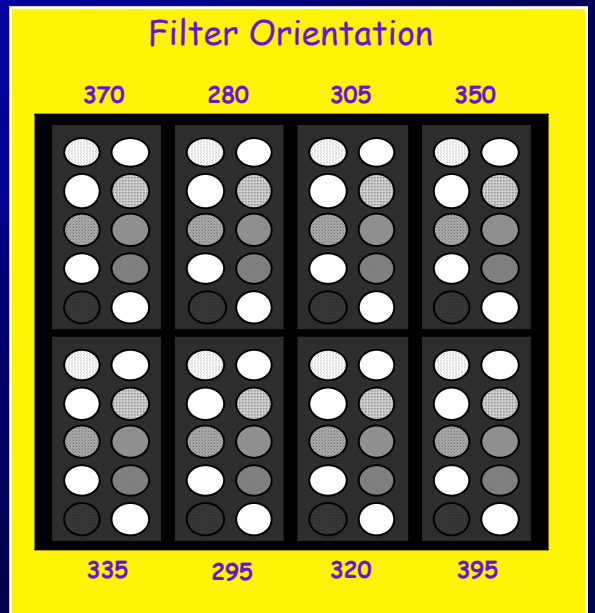


Describing the effects of solar UV on phytoplankton photosynthesis

- Responses are a composite of effects at multiple wavelengths (UV-B, UV-A, PAR)
- Near-surface residence times can vary from minutes to hours

The Photoinhibitron





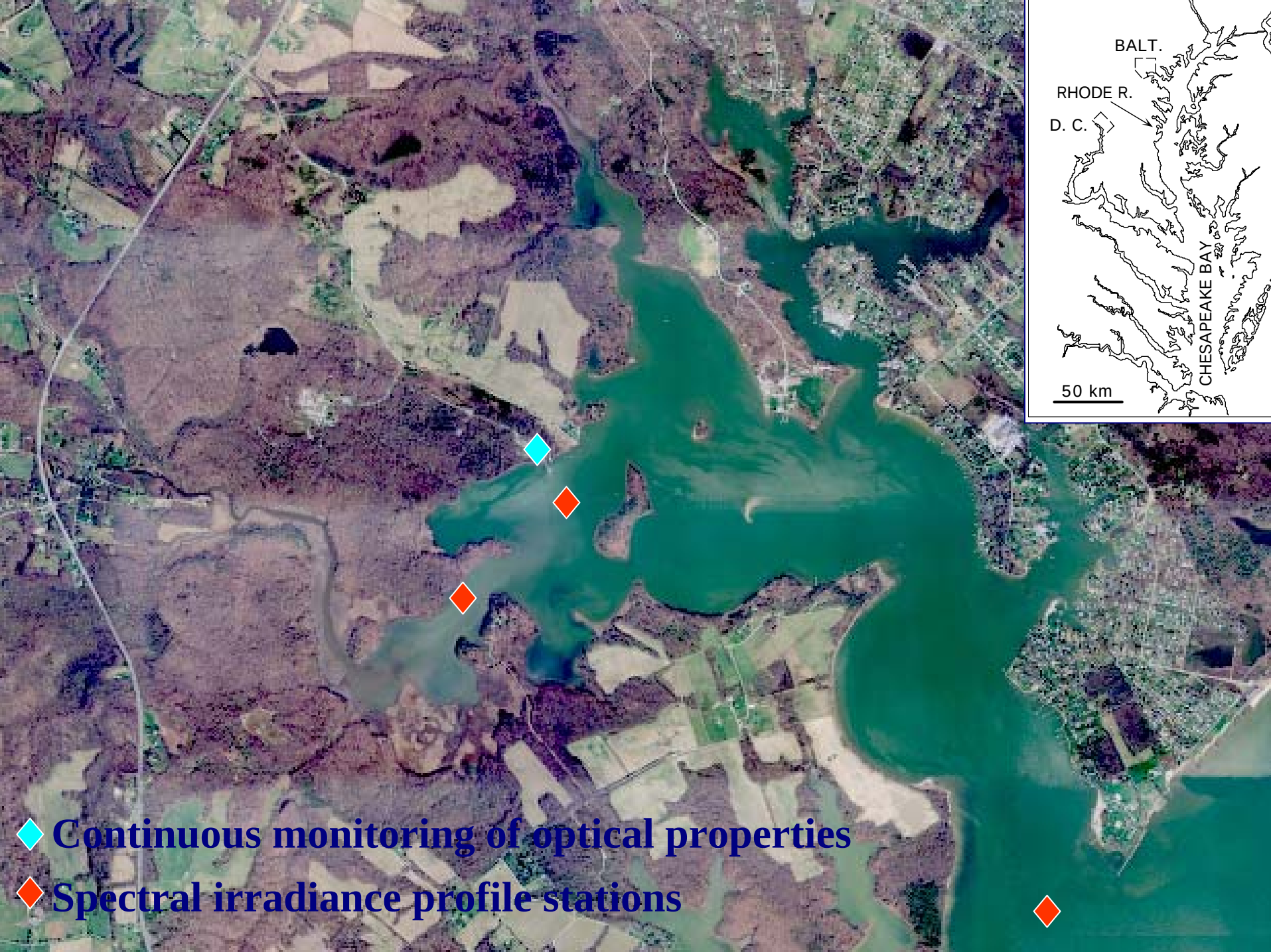
A Polychromatic Incubator for Experimental UV Exposures

Photoinhibitron Travelogue
1. A Temperate Estuary

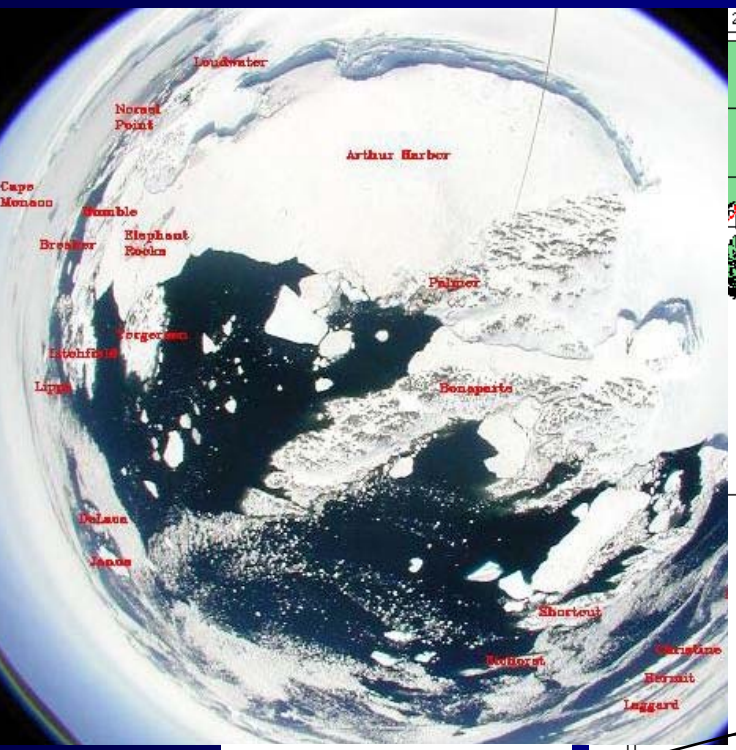
The Rhode River: Shallow Subestuary of Chesapeake Bay

BWFs on monthly samples during 1995-1996 (n=23)

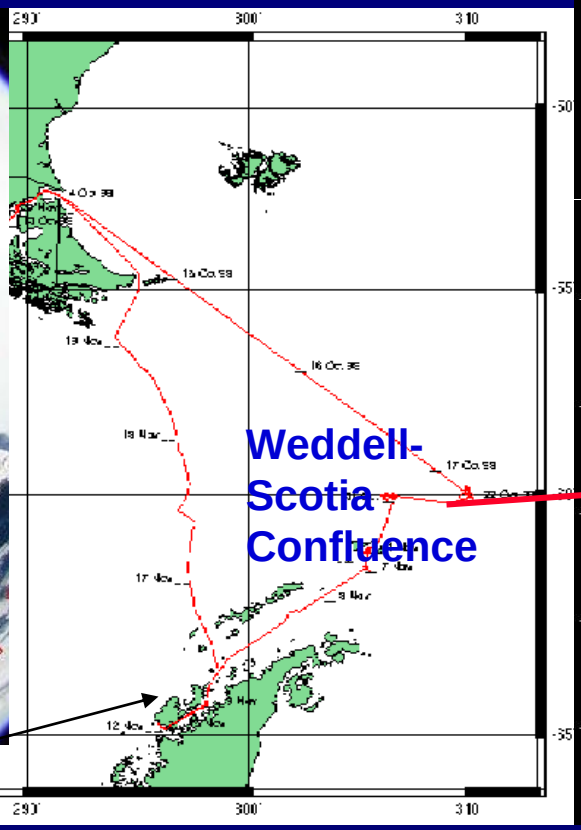
See: Banaszak and Neale, Limnol. Oceanogr. *2001*

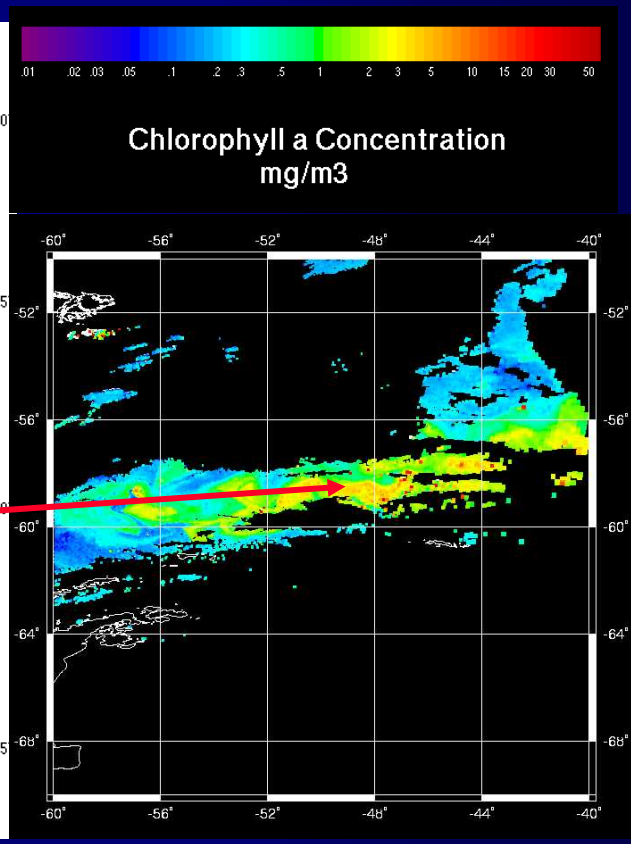

BALT.
RHODE R.
D. C.
CHESAPEAKE BAY
50 km
Continuous monitoring of optical properties
Spectral irradiance profile stations

Photoinhibitron Travelogue
2. Antarctica



Palmer Station



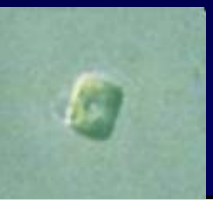


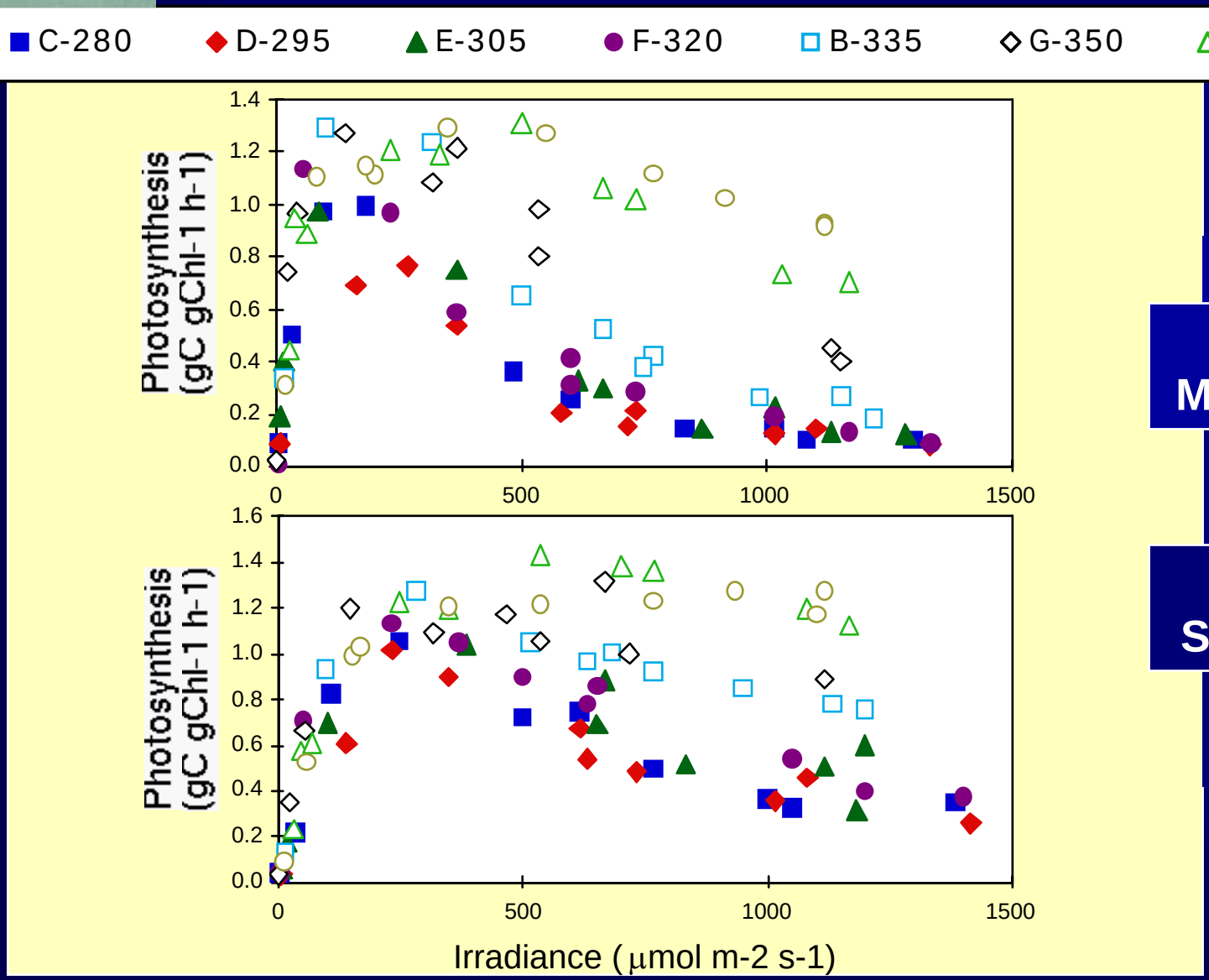
Field Seasons: October-December 1991, 1993, 1997-1999

About 40 BWFs in all

Our Research Platform: The RV Laurence M. Gould

There are clear variations in the sensitivity of photosynthesis to UV



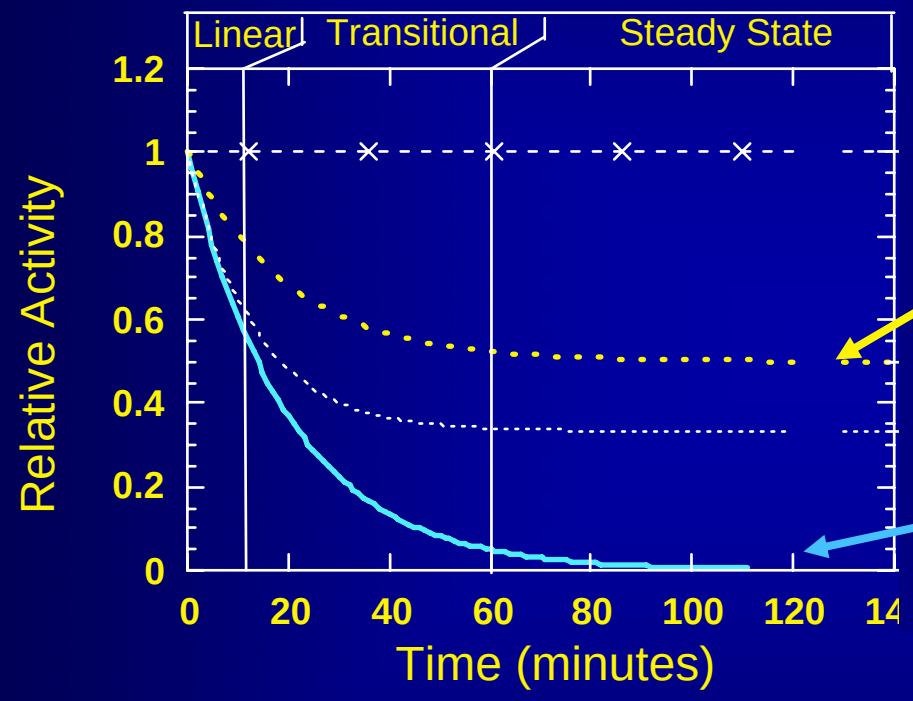


Palmer Station, Antarctica

Phytoplankton, Moderate Pack Ice

Ice Algae in Surface Ice Slurry

Photosynthetic response to UV is non-linear



Irradiance (BWF_E)

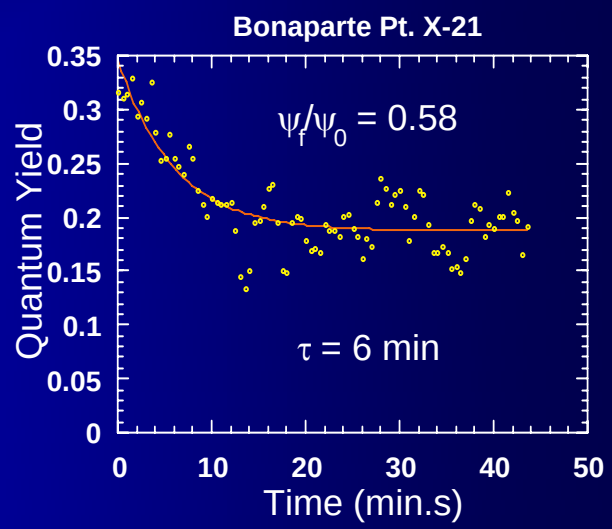
Cumulative Exposure (BWF_H)

The BWF_E/P-I model

P_{pot} f

$$P^B = P_s^B \left(1 - e^{-E_{PUR}/E_k}\right) \frac{1}{1 + E^*_{inh}}$$

$$E^*_{inh} = \sum_{\lambda = 280\,\text{nm}}^{700\,\text{nm}} \varepsilon(\lambda) \cdot E(\lambda) \cdot \Delta\lambda$$

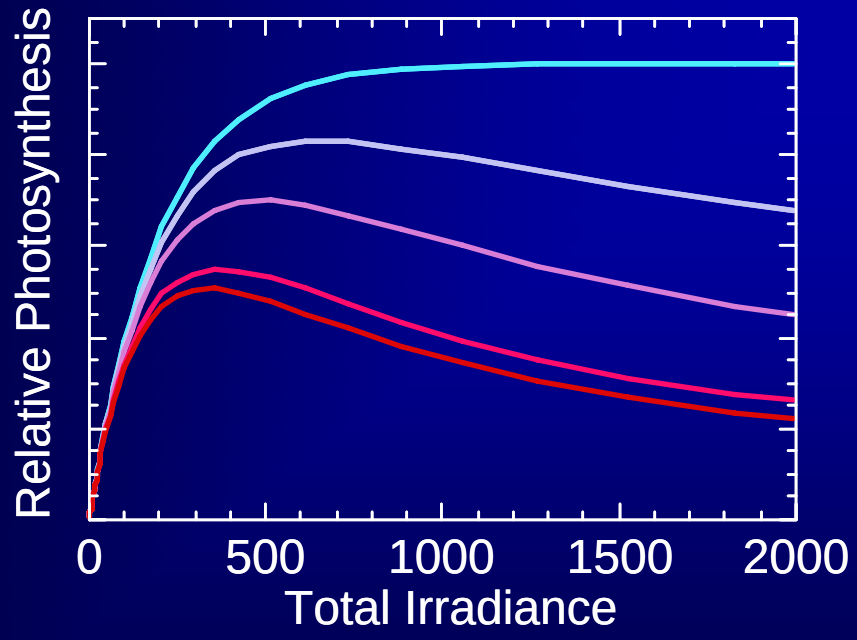


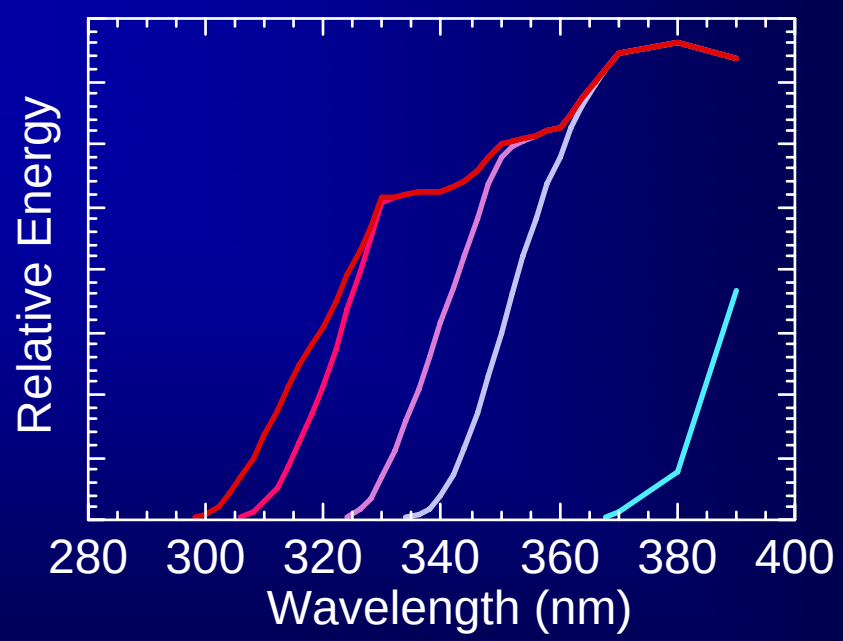
- **Inhibition is a function of dose-rate when damage and recovery balance**
- **Kinetics of F'_v/F'_m (PAM): P steady after 15 min**
- **Good model of P^B over 1 h exposure to UV-B,UV-A+PAR ($R^2 > 0.9$)**

$$P^B = P_s^B \left(1 - e^{-E_{PUR}/E_k}\right) \frac{1}{1 + E_{inh}^*}$$

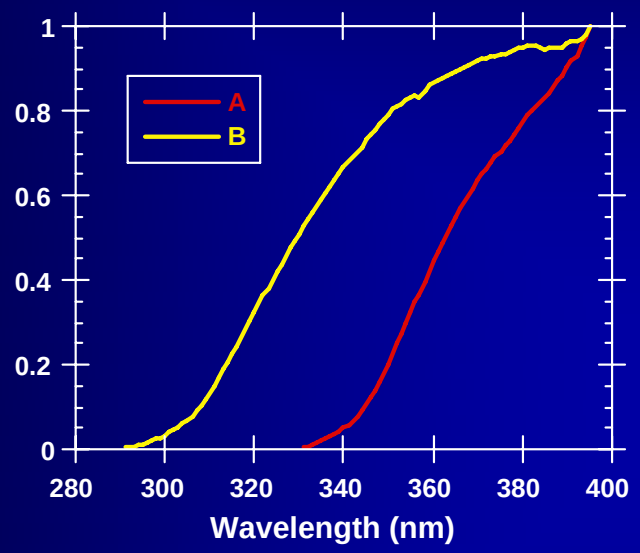
$$E_{inh}^* = \sum_{\lambda = 280\,\mathrm{nm}}^{700\,\mathrm{nm}} \varepsilon(\lambda) \cdot E(\lambda) \cdot \Delta\lambda$$

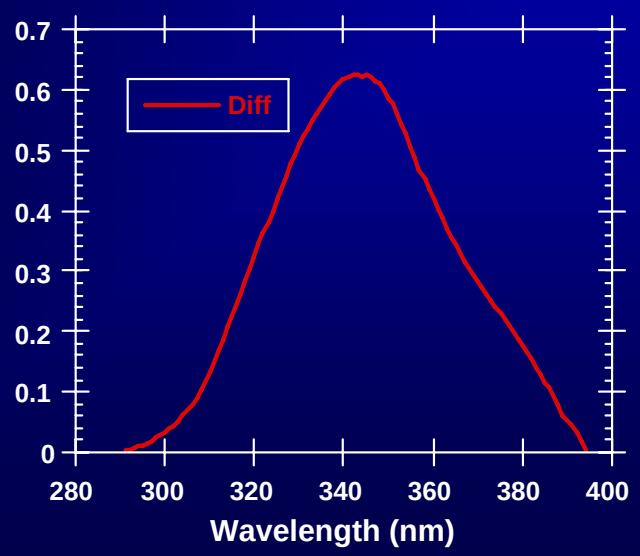
BWF/P-I model



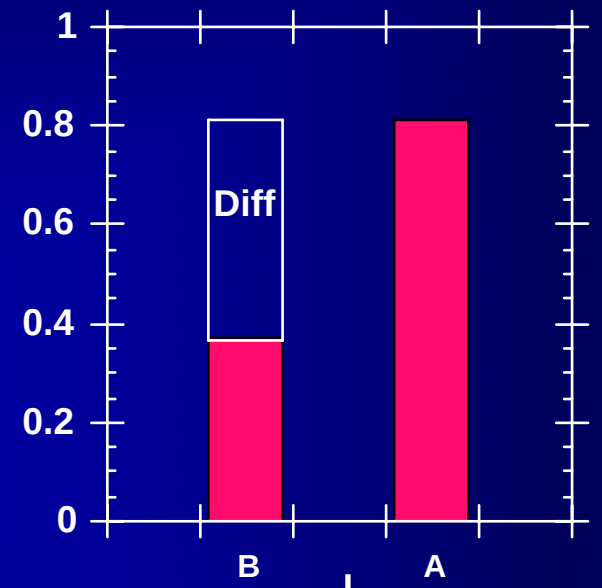


Estimating a BWF - Difference Method





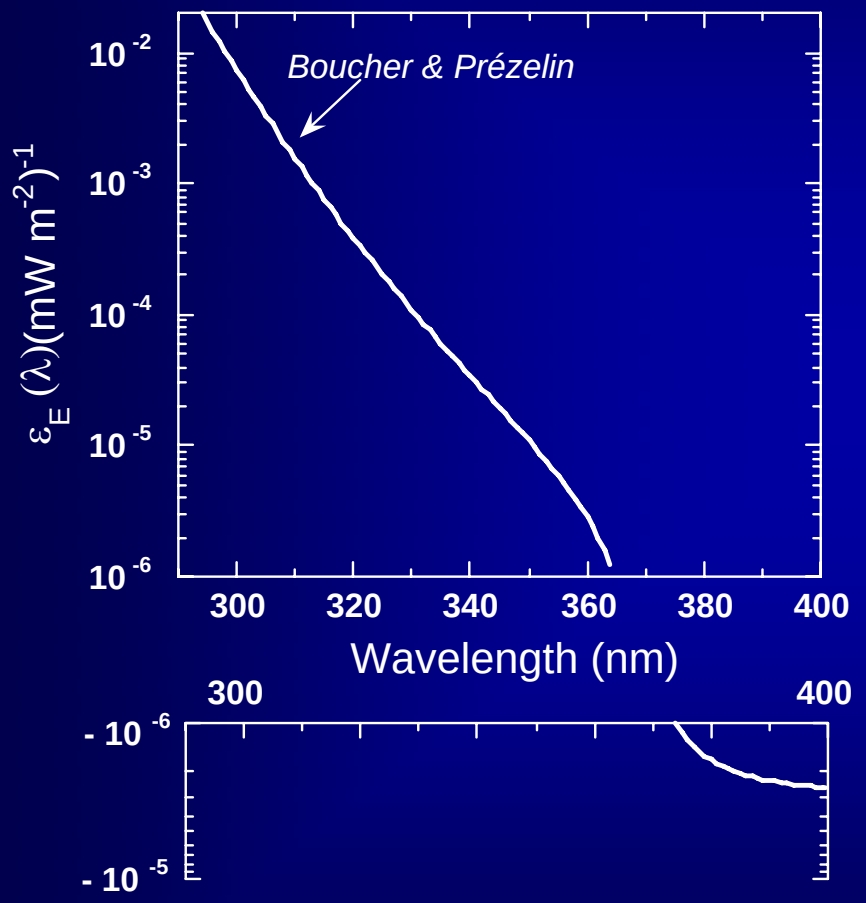
Effect →



Sum Energy →

$$\textit{Weight} = \frac{\text{Diff}}{\text{Sum Energy}}$$

Another Approach: Fit BWF to a general equation



As described by Rundel (1983)

Simple

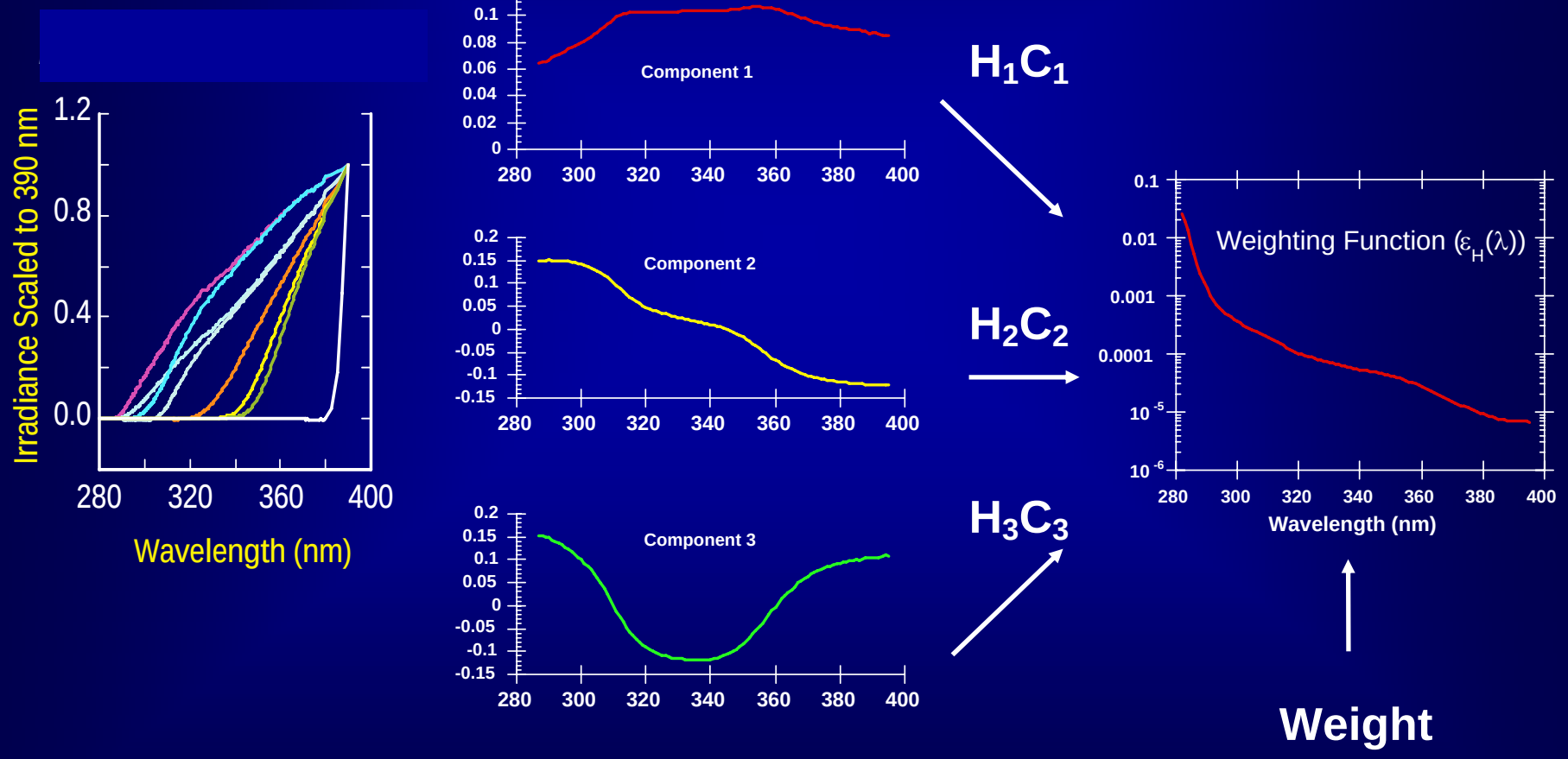
$$\varepsilon(\lambda) = e^{(m_0 + m_1\lambda)}$$

Complex

$$\varepsilon(\lambda) = e^{(m_0 + m_1\lambda + m_2\lambda^2)} + c$$

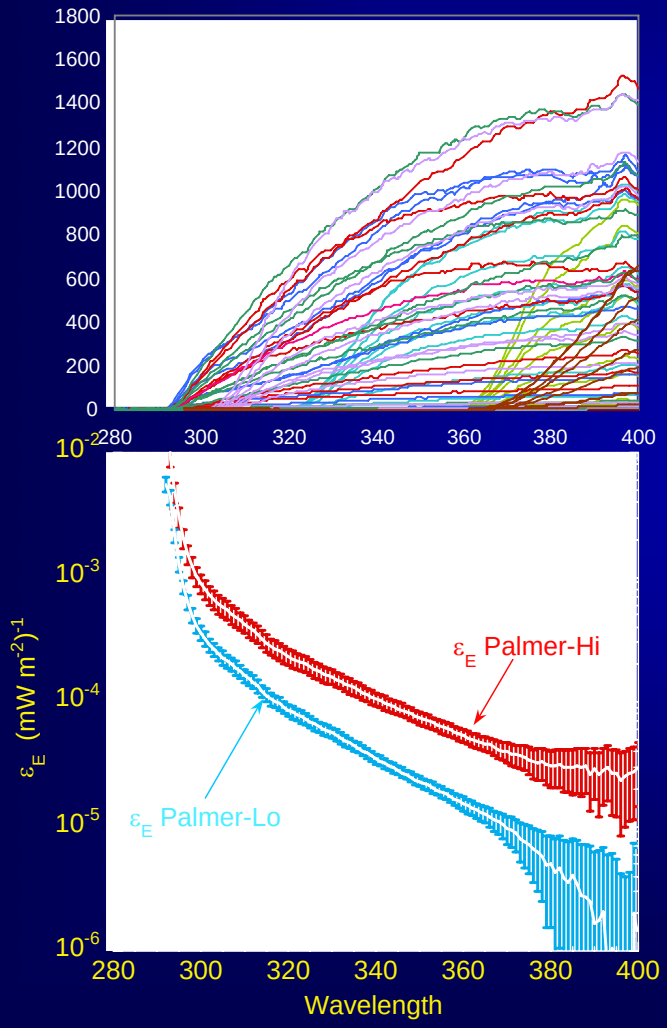
N. P. Boucher, B. B. Prézelin, *Mar. Ecol. Prog. Ser.* **144**, 223-236 (1996)

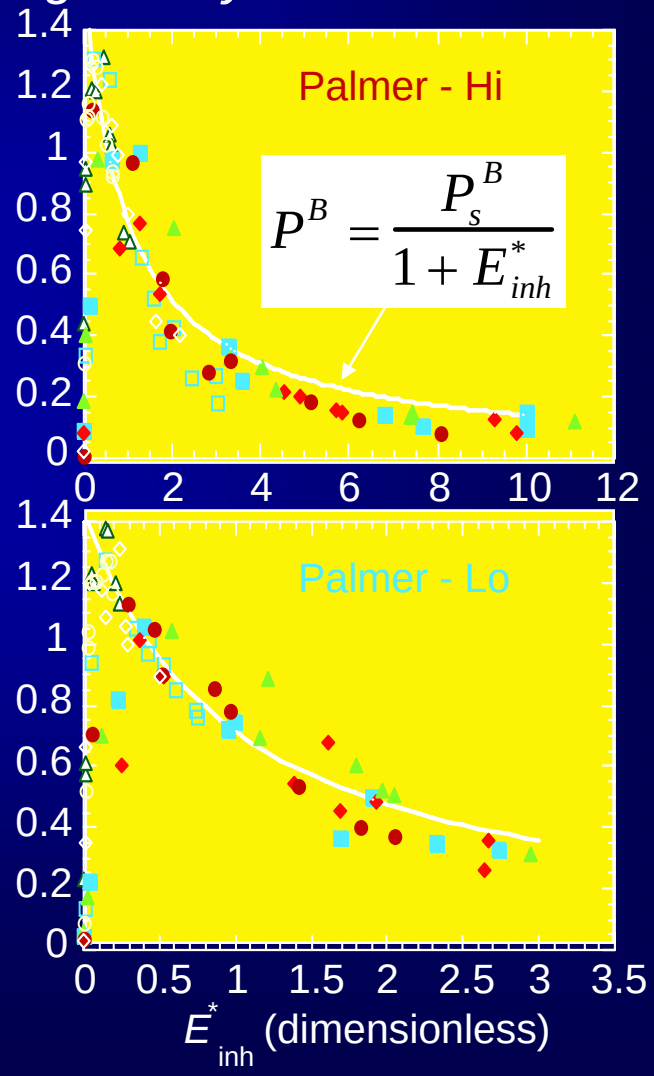
Estimating a BWF - PCA Method



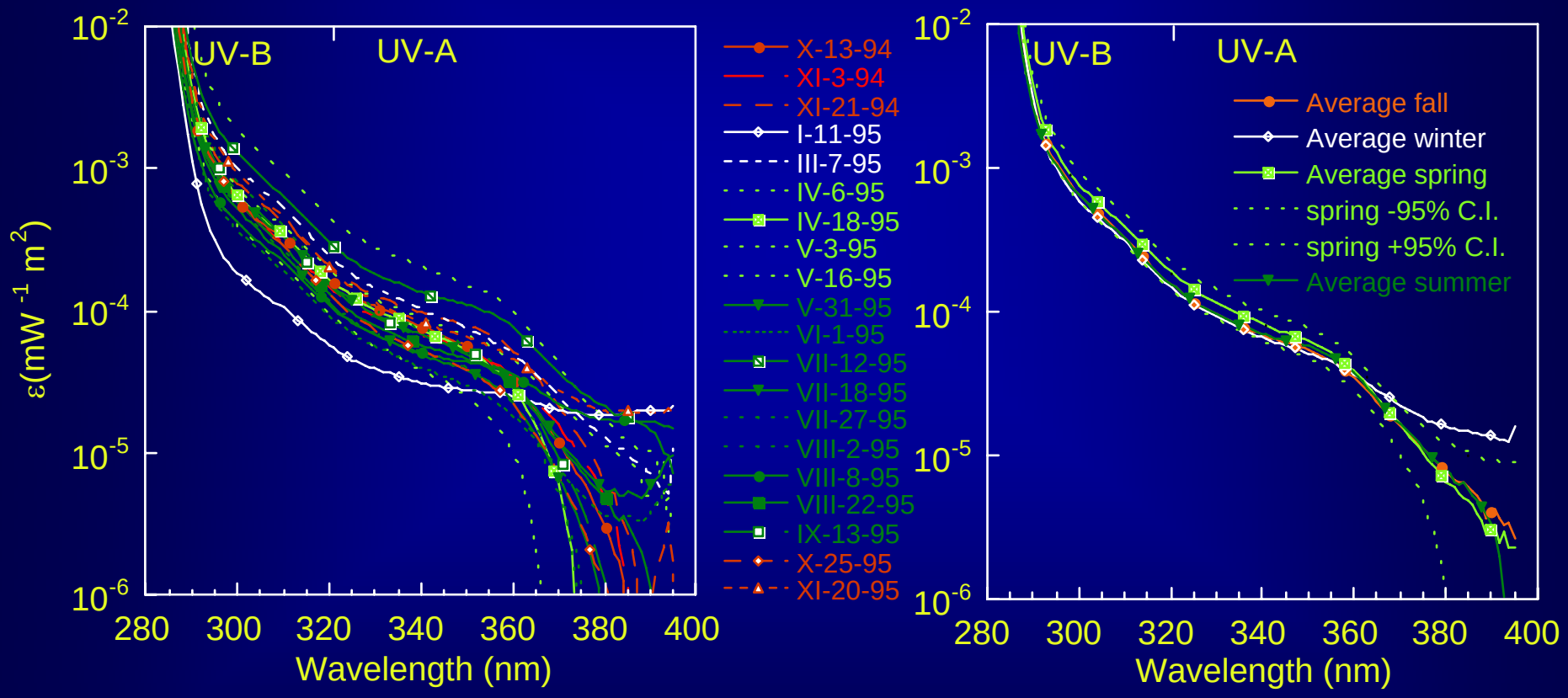
BWF/P-I model provides accurate predictions of UV response

Photosynthesis is inversely related to UV weighted by estimated BWFs



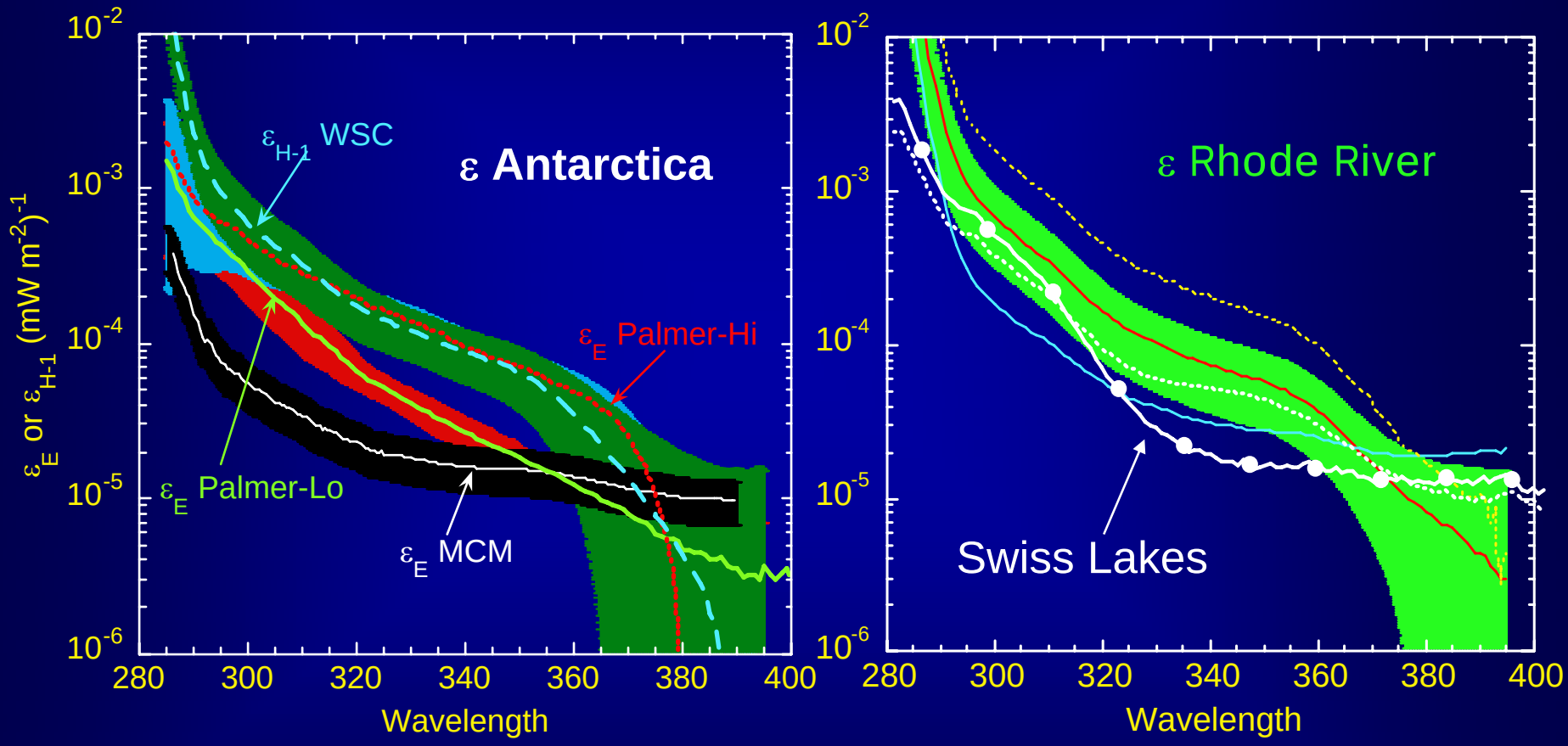


Sensitivity of Chesapeake Bay Phytoplankton varies by an order of magnitude



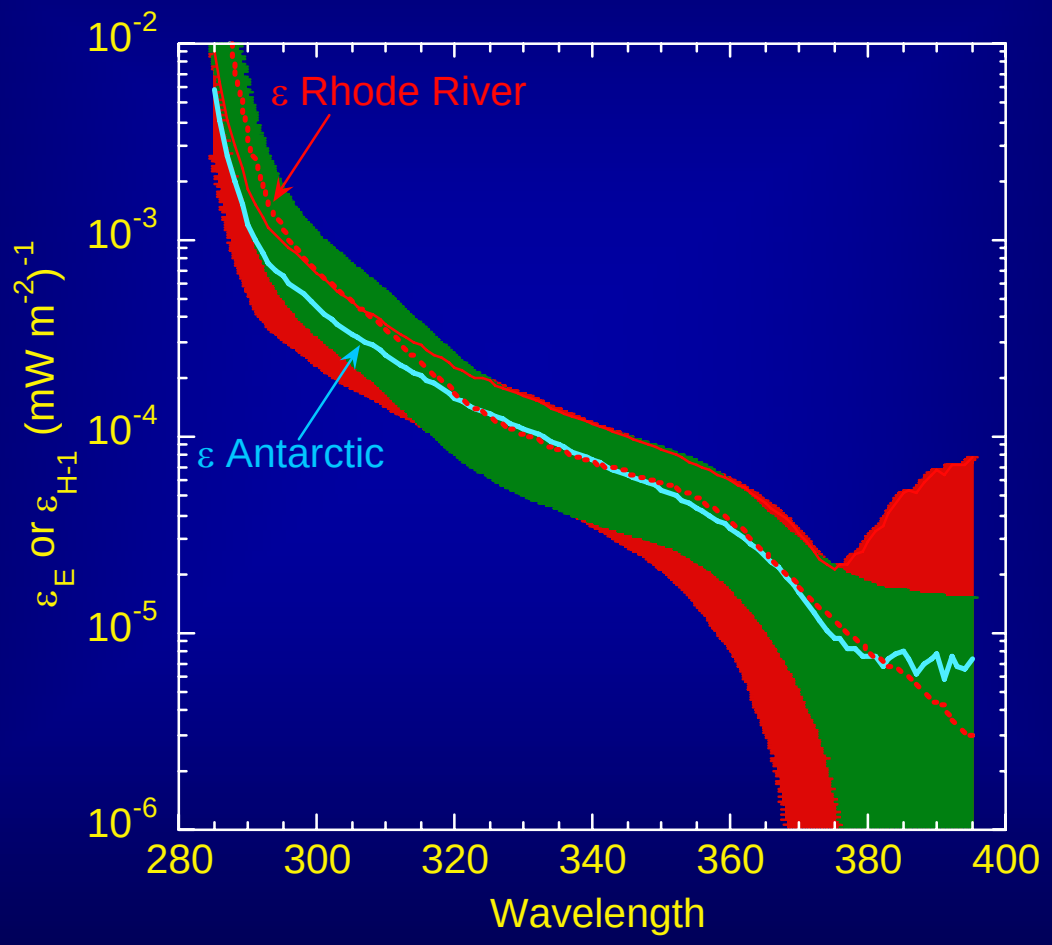
But seasonal average sensitivity is less variable!

BWFs vary 10 fold in All Environments



Weight of 1 h Exposure for Cumulative Exposure (H) BWFs

Average Sensitivity is Similar in Temperate and Polar Environments



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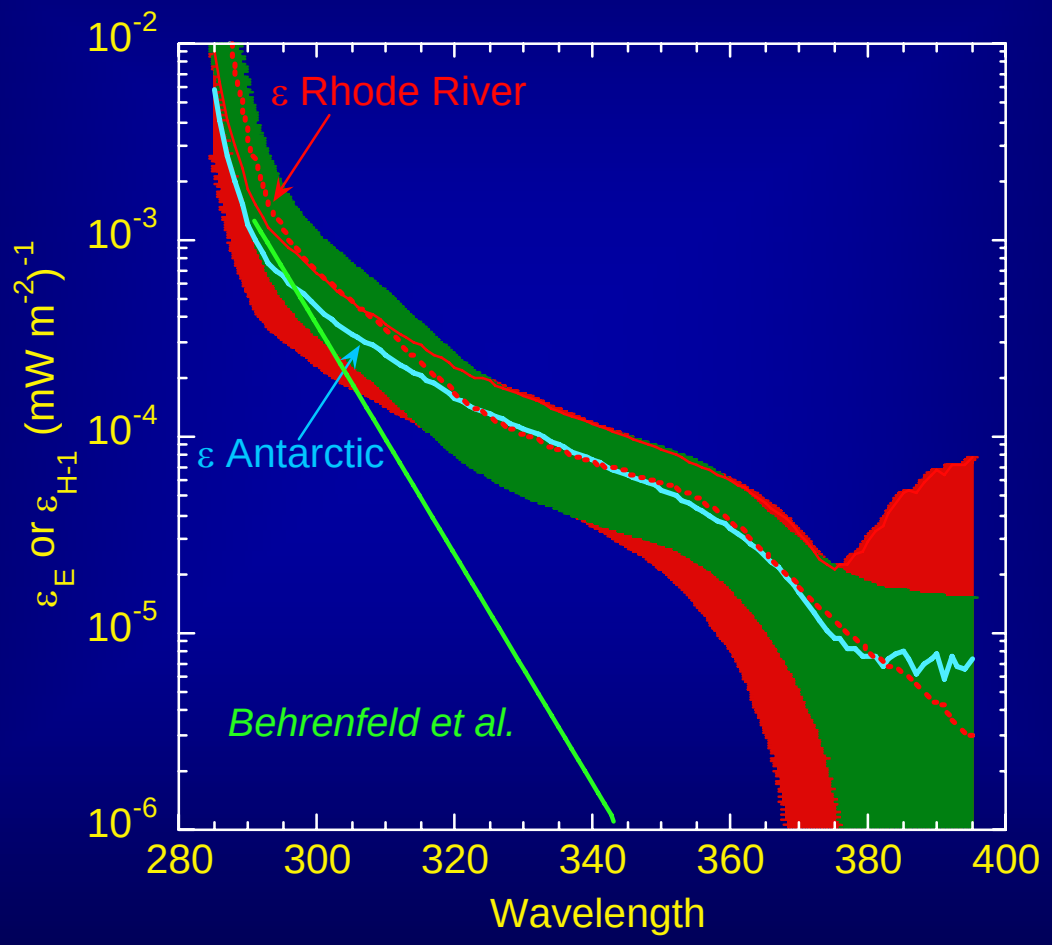
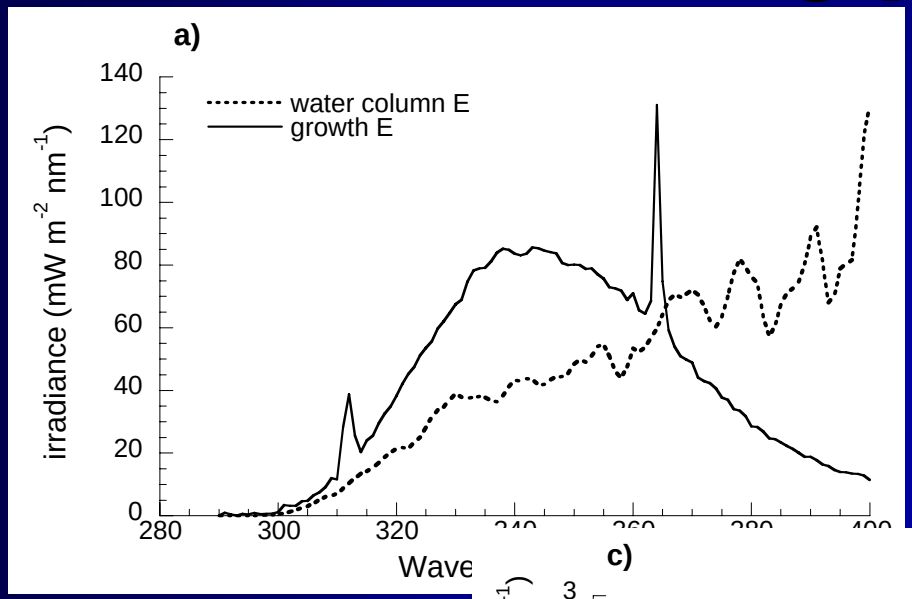
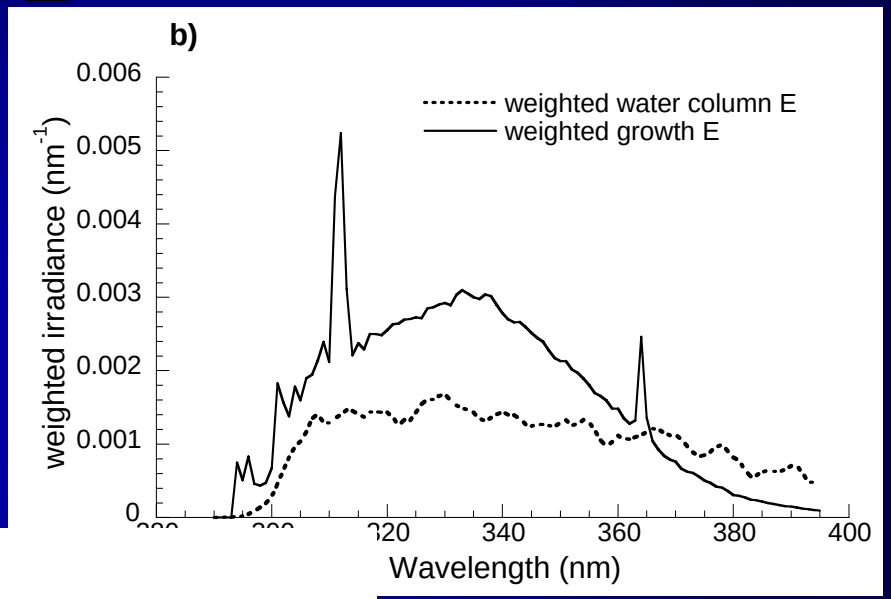
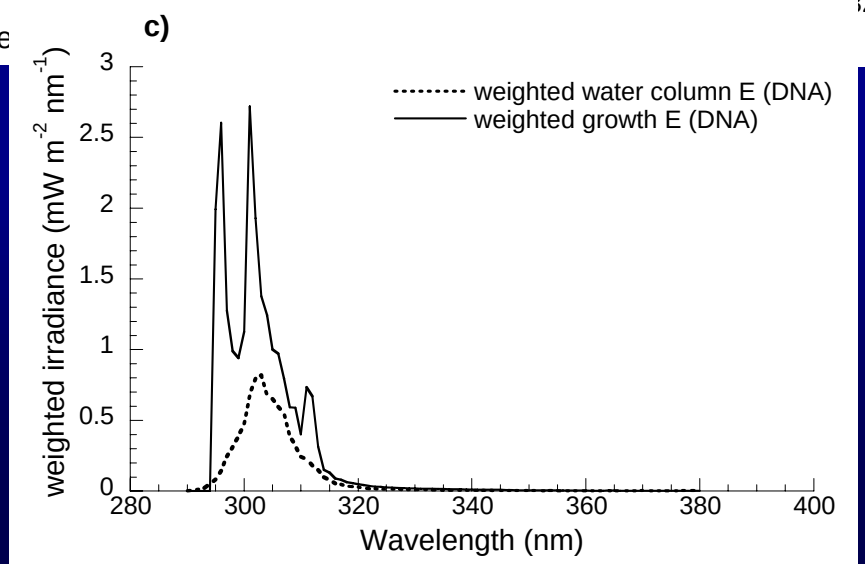


Cf. Behrenfeld, et al. 1993

UV-A is more important than UV-B







UV Effects on WSC (S. Ocean) Productivity

Factor	Average range of integral daily water column production (±46% overall)
Ozone Depletion (50%)	-1 to -8%
Mixed Layer Depth	± 24%
Sensitivity (BWF)	± 28%

(± is the half range of (max-min)/avg)

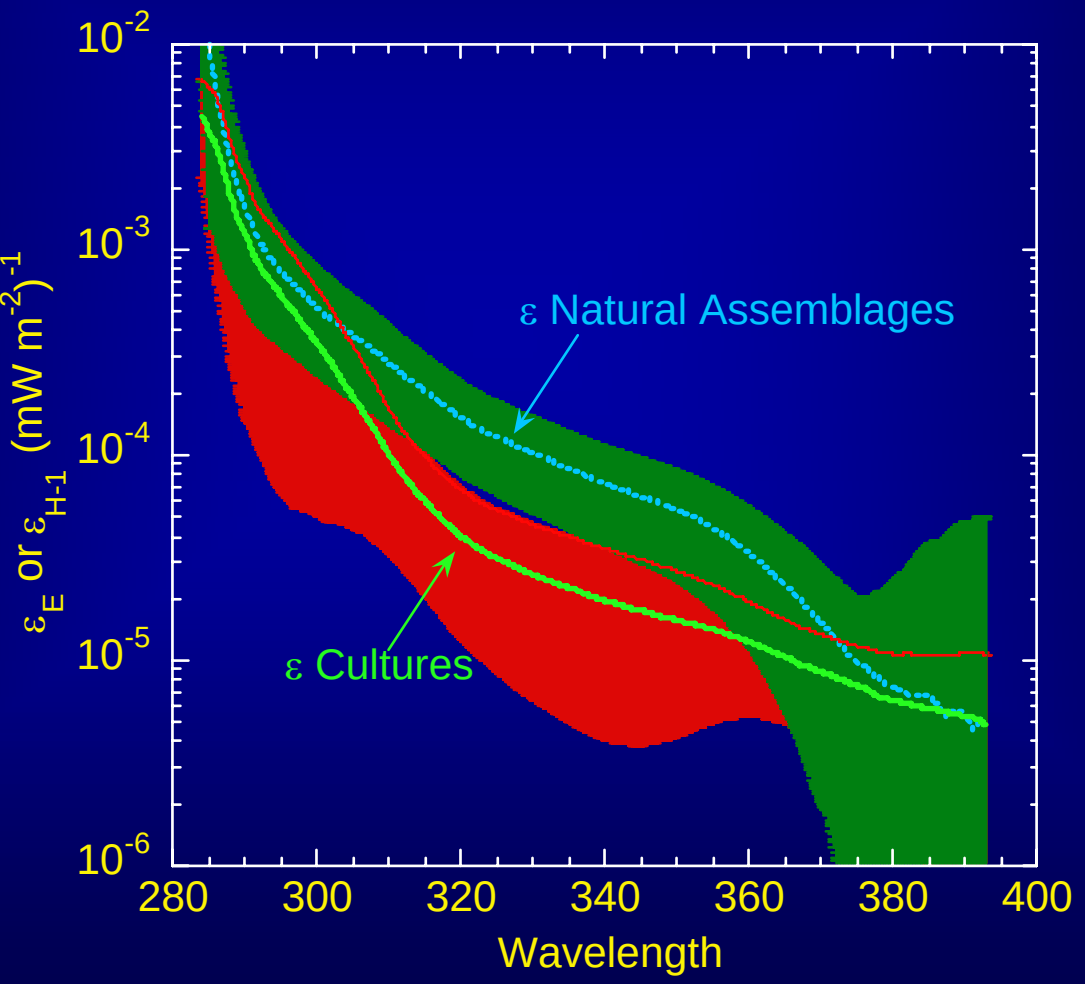
See: Neale,Cullen, Davis, Nature 1998

What are the sources of variation in BWFs?

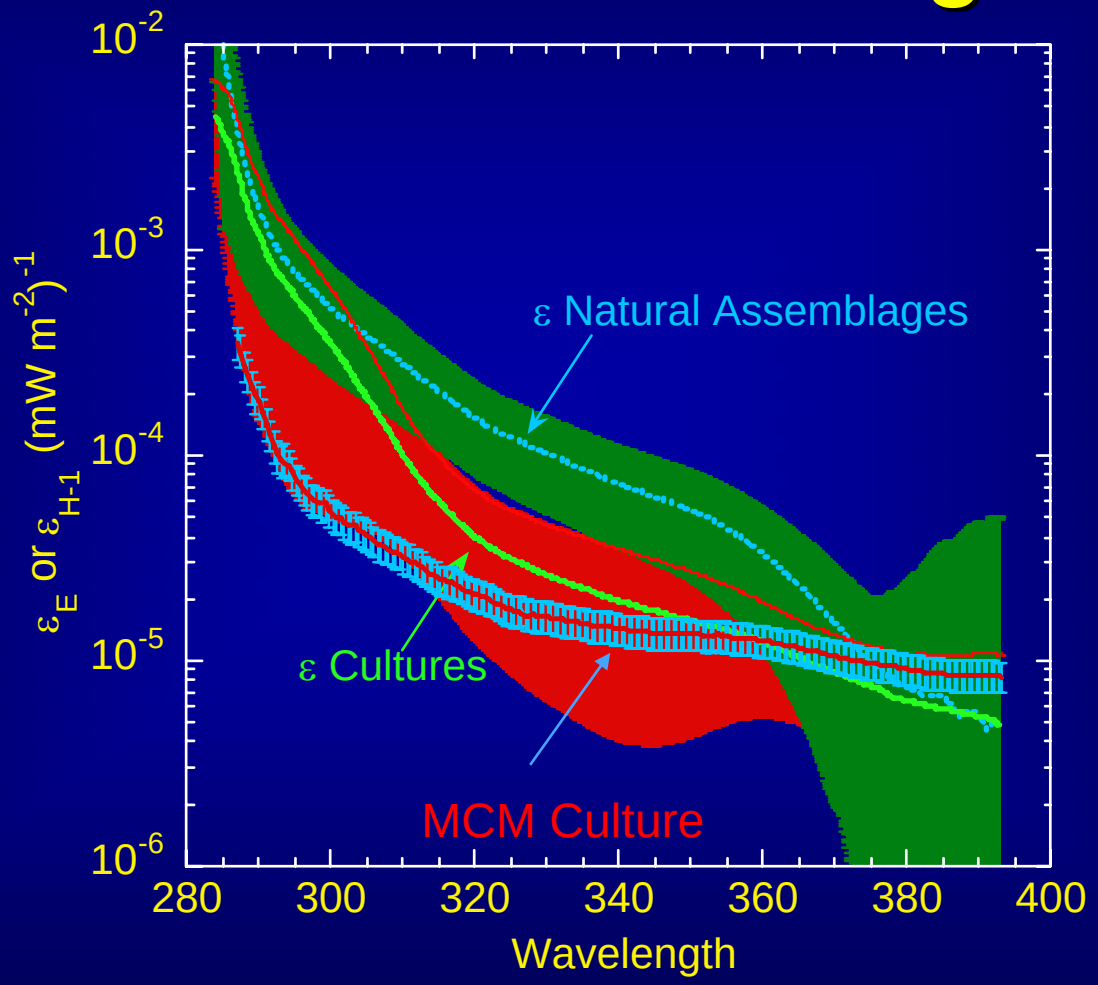
- Inherent differences between taxa
- Nutrient availability
- Resource tradeoffs (survival vs. defense)

Here's where culture studies are useful!

Natural Assemblages are More Sensitive than Cultures



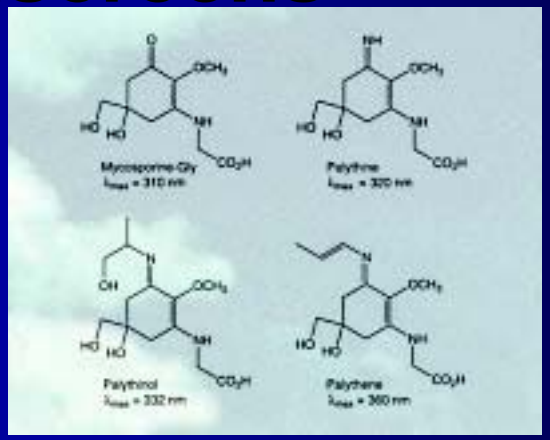
Strong Exposure Does Result in Resistant Assemblages



What is contribution of Differential Survival vs. Acclimitization?

Can Aquatic Organisms Modify their Sensitivity to UV ?

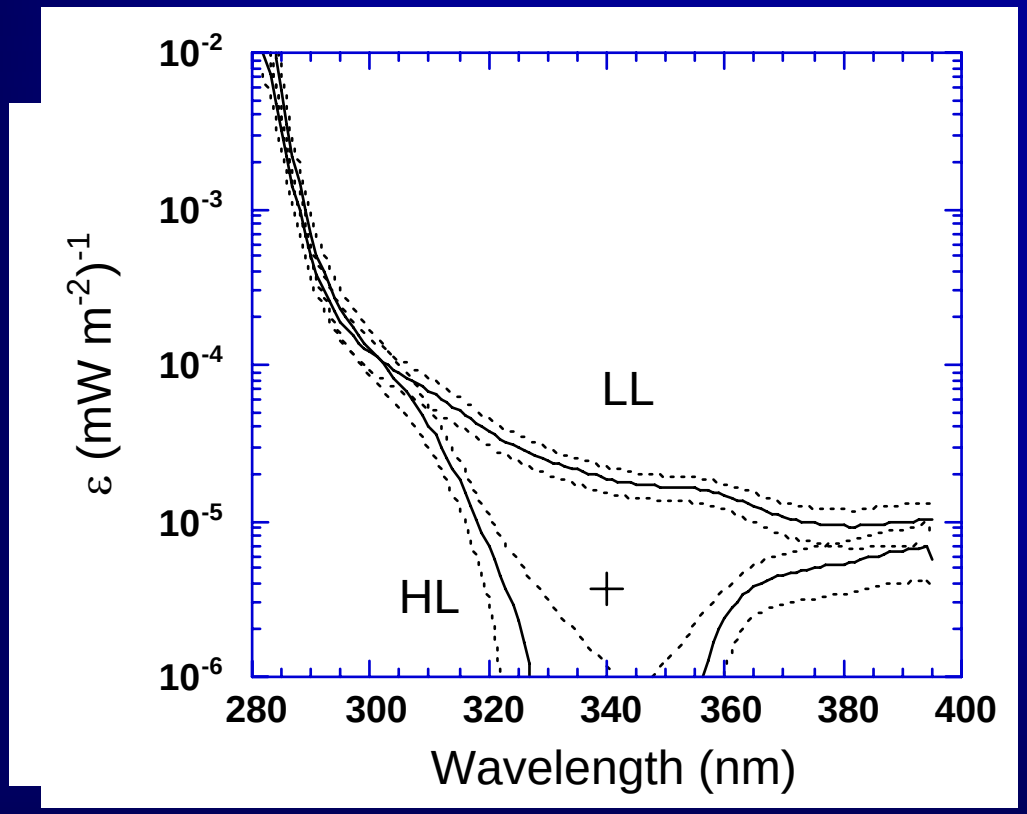
- **Accumulation of sunscreens (MAAs)**
- **Anti-oxidants**
- **Repair capacity**
  - **DNA**
  - **Proteins, lipids, etc**



Corals on Great Barrier Reef photo from Walt Dunlap, AIMS

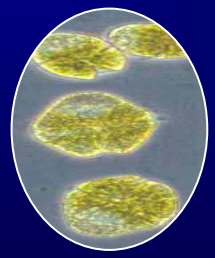
Variation in Photoprotection

MAAs accumulation decreases sensitivity in wave band of absorbance

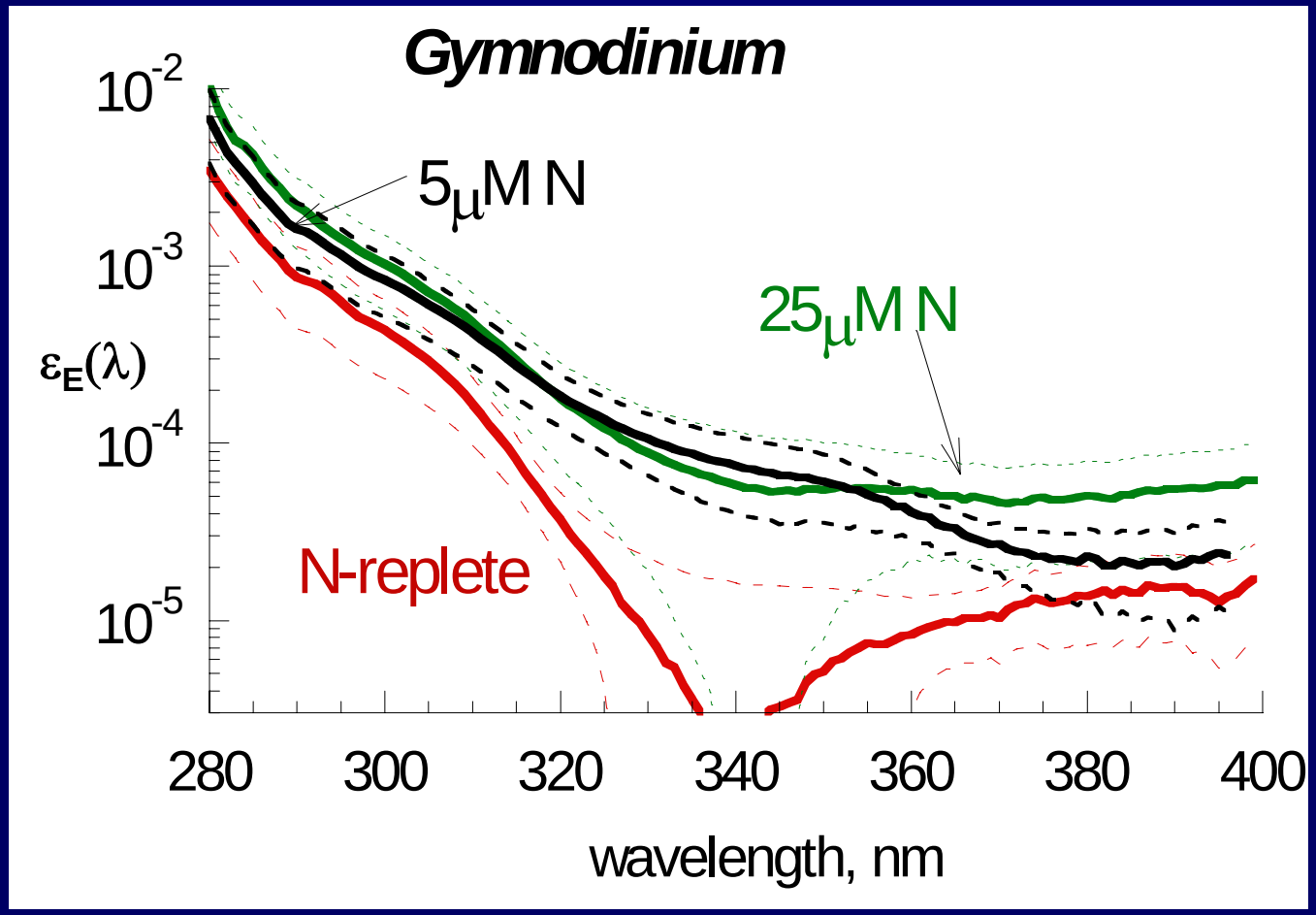


Neale et al. (1998) J. Phycol.34:928

Estuarine dinoflagellate, *Akashiwo sanguineum* grown in high vs low PAR



Sensitivity to UV increases under N-limitation



Litchman, Neale & Banaszak Limnol. Oceanogr. (2002) 47:86-94

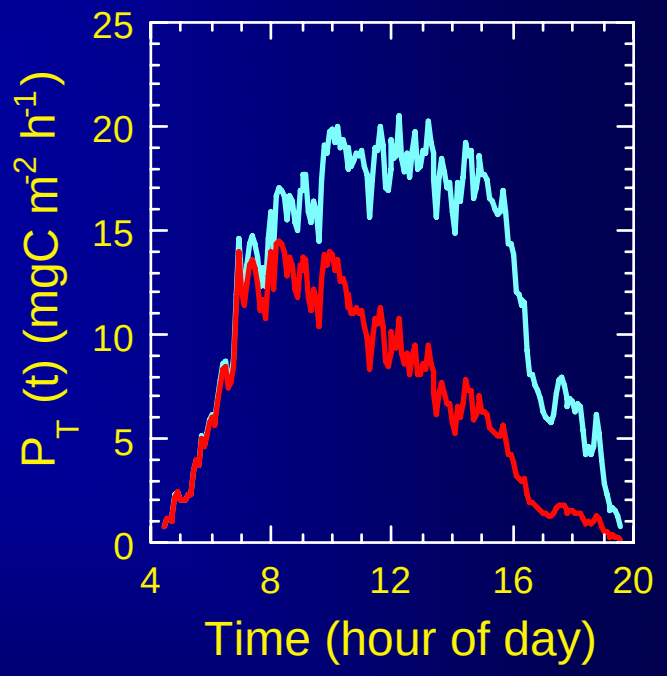
Polychromatic vs Monochromatic Experimental Approaches

- Polychromatic more appropriate to predicting responses to solar radiation
- Monochromatic studies more appropriate to mechanistic studies of damage and repair mechanisms
  - Mechanisms of inhibition by UVA exposure
  - Regulation of photorepair
  - Efficacy of photoprotection at cellular length scales
- Poly vs Mono comparison: Generality of spectral shape (Flint & Caldwell)
- Advantage of FEL – high output in the UVA, narrow bandwidth, flexibility in time of exposure

Thanks!

Production Model for the WSC

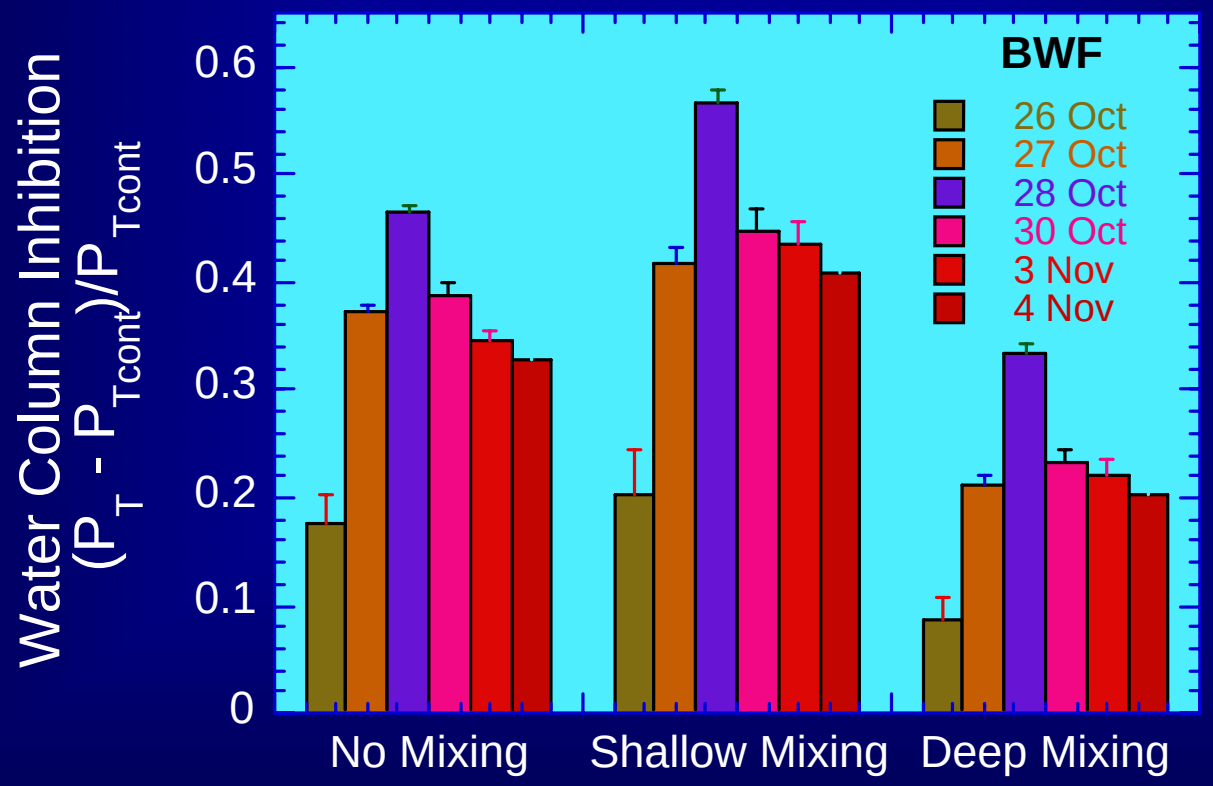
- *Measured BWFs*
- *Broad Band Irradiance Measurements*
- *Modeled Irradiance Spectra*
  - Single Day Climatology
  - Range of Ozone
- *Average Attenuation Spectra*
- *Range of Mixing Depths and Speeds*



Next Steps

- Establish a simple assay system to measure effect of monochromatic exposure (e.g. PSII fluorescence)
- Test for non-linear (2) photon processes

BWF variation modifies inhibition and the effect of O_3 depletion



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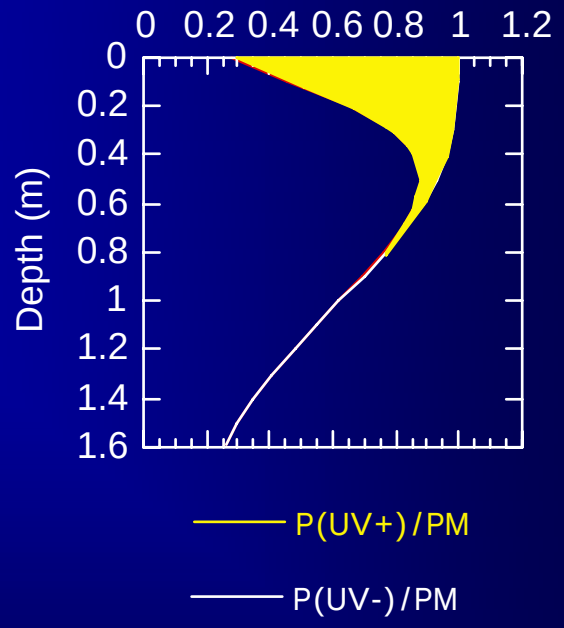

UV Effects on Rhode River Productivity

Factor	Average range integral midday water column production (±18% overall)
Irradiance	± 5%
Transparency	± 7%
Sensitivity (BWF)	± 8%

"±" is the half range of (max-min)/average

See: Neale 2001 J. Photochem. Photobiol. B 62:1-8

The Next Steps

- **UV Responses Under Realistic Mixing Regimes**
  - *Kinetics of Damage and Repair*
  - *Measurements of Mixing Rates*
- **Systematic Understanding of BWF Variation**
  - *Consistent differences between taxa*
  - *Nutrient limitation (cultures and natural populations)*
  - *Resource tradeoffs (survival vs. defense)*

Long Term Objectives

- **BWFs for multiple trophic levels**
  - *Photochemical transformations*
  - *Bacteria*
  - *Zooplankton*
- **Predictions of Ecological Responses**
  - *Shifts in Community Structure*
  - *Shifts in Trophic Structure*

It couldn't have been done without a lot of help!

- **Rhode River**
  - **Ania Banaszak, UNAM marine lab, Puerto Morelos, MX**
- **Culture Studies, Swiss Lakes**
  - **Elena Litchman, Rutgers University, NJ**
- **Antarctica**
  - **Jennifer Fritz, RSMAS, Miami, FL**

Thank you!