Ocean Productivity

Where?

How Much?

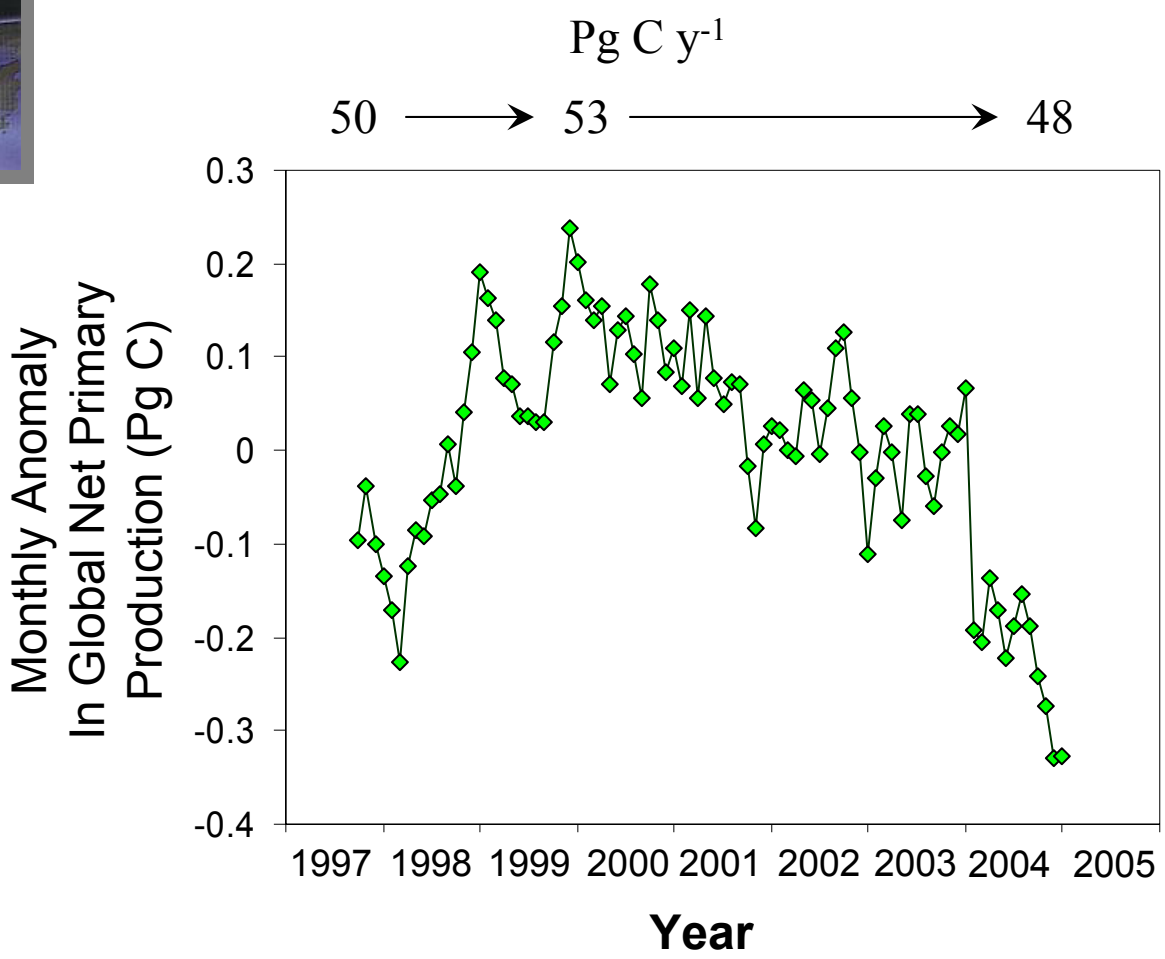
Is it Changing?

Why is it Changing?

What is its fate?

Emmanuel Boss
David Siegel

Current Trends



Overview

- *Historical Approaches*

- *The Carbon-based Approach*
  - **What is it?**
  - **Challenges**
  - **Validation**

- *SeaWiFS Trends Revisited*

- *Where to go from Here?*

^{14}C Database Approach

Date	Author	NPP (Pg y^{-1})	Method
1952	Steemann Nielsen	20	few ^{14}C measurements
1957	Fleming & Laevastu	20	FAO production data (O_2, ^{14}C, etc)
1957	Steemann Nielsen	20-25	few ^{14}C measurements
1958	Fogg	32	FAO production data (O_2, ^{14}C, etc)
1968	Koblentz-Mishke *et al.*	23	Synthesis of many ^{14}C stations
1969	Bogorov	25	Synthesis of many ^{14}C stations
1969	Ryther	20	^{14}C & spatial model
1970	Koblentz-Mishke *et al.*	25-30	revision of '68 paper
1975	Platt & Subba Rao	31	new ^{14}C synthesis
1985	Shushkina	**56**	new ^{14}C & biomass data
1987	Martin *et al.*	**51**	revision of Koblentz-Mishke *et al.*
1989	Berger *et al.*	27	new ^{14}C synthesis

From: Barber & Hilting (2002) In: *Phytoplankton Productivity: Carbon assimilation in marine and freshwater ecosystems* [Williams, Thomas, Reynolds eds.] Blackwell

Pigment-based Approach

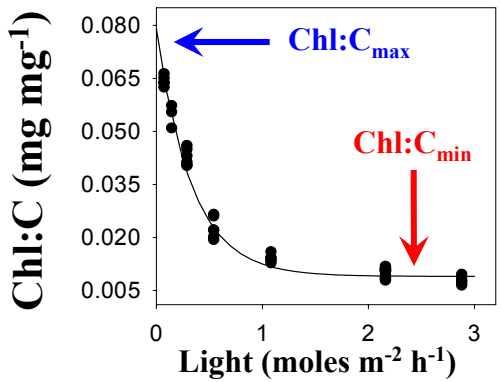
Basics: surface pigment concentration * assimilation efficiency * light function

Issues:

- Pigment biomass
  - chlorophyll *not* = carbon biomass
  - empirical ratio algorithms – semi-analytic algorithms

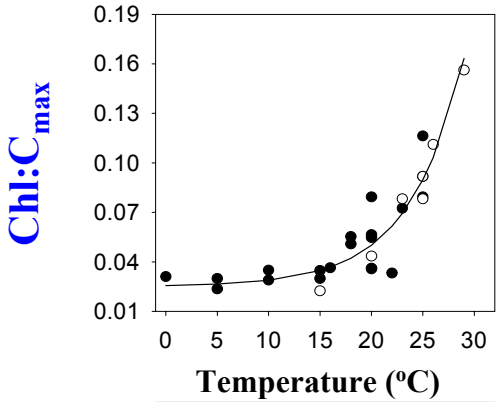
- Assimilation Efficiency
  - frequently dominates NPP variability
  - 'Conservation of Misery'
  - light, nutrients, temperature are critical drivers

Pigment-based: Physiology



Light

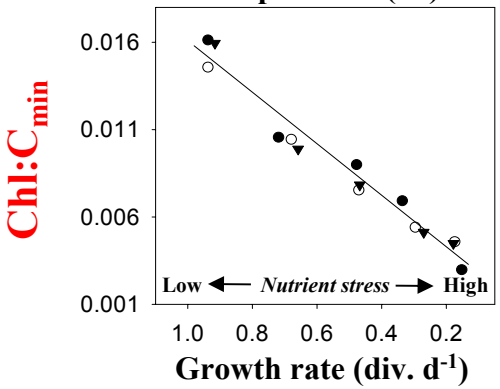
Dunaliella tertiolecta
20 °C
Replete nutrients
Exponential growth phase



Temperature

Geider (1987) *New Phytol*. **106**: 1-34

16 species
● = Diatoms
○ = all other species



Nutrients

Laws & Bannister (1980)
Limnol. Oceanogr. **25**: 457-473

Thalassiosira fluviatilis
● = NO_3 limited cultures
○ = NH_4 limited cultures
▼ = PO_4 limited cultures

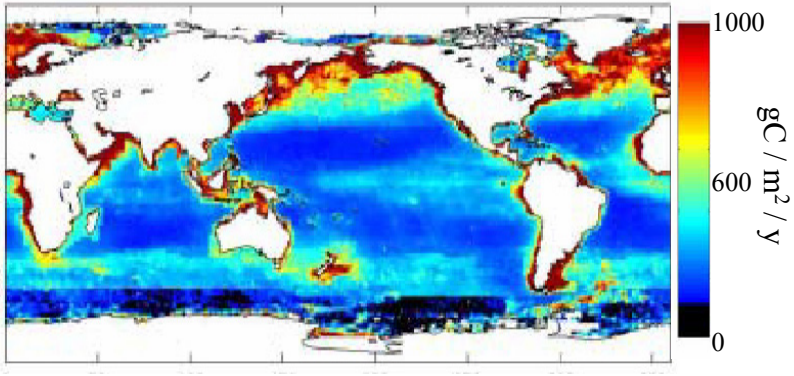
Pigment-based: Physiology

Basics: surface pigment concentration * assimilation efficiency * light function

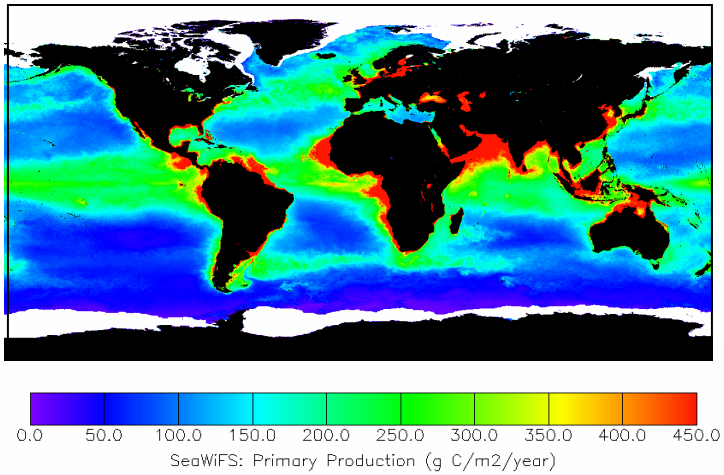
Approaches:

- Constant
- Biogeographical Provinces
- Temperature Functions
  - Linear
  - Exponential
  - Polynomial
- Fuzzy Logic / Blending
- Physiological 'Dynamic' Models
  - E_0, K_d, MLD…
  - Nutrient stress: degree & type
  - Temperature
  - Taxonomic Groups (?)

Longhurst & Platt (1995) – CZCS, provinces, PI data



VGPM with Eppley



Model Summary

- Pigment-based Global Annual NPP = 40's to 60's Pg C y^{-1}
- ^{14}C-based = 20 to 30 Pg C y^{-1}, but 2 recent @ 51 to 56 Pg C y^{-1}
- Oxygen data suggests ^{14}C might be factor of 2 to 3 too low
- Carbon-based = 7 to 16% of Pigment based estimates*

  (w/ equivalent shared inputs)

  - CZCS < SeaWiFS > GSM (…. other)
  - $K_{par} < K_{\lambda} < K490$
  - Regional physiology

*67 vs 60 Pg C y-1 in 2005 GBC

The 'Carbon-based' Approach

Carbon-based Approach

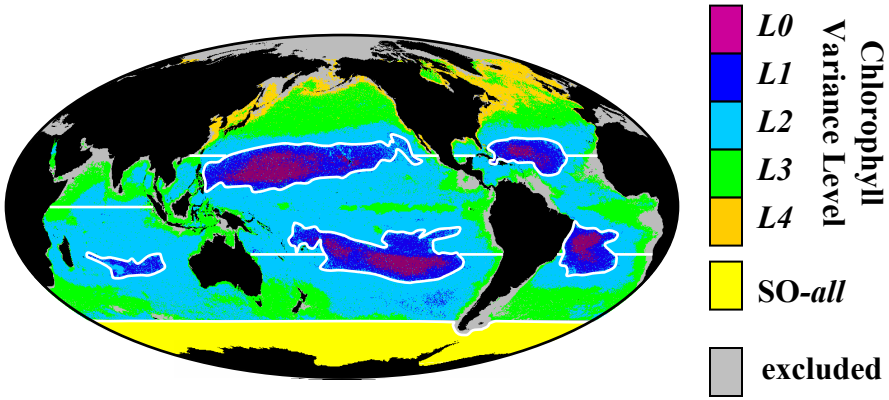
Basics: phytoplankton carbon biomass * growth rate * light function

Approach:

- Semi-analytic algorithms provide estimates of particulate backscatter (b_{bp}) and phytoplankton chlorophyll concentration

- Particulate backscattering is due to phytoplankton- and smaller sized particles
- Conserved nature of particle size spectrum allows phytoplankton C biomass to be estimated from b_{bp}
- Division of chlorophyll by carbon biomass is an index of intracellular pigmentation
- Intracellular pigmentation registers variations in growth rate and photoacclimation
- Yields 2 useful products for modeling: algal carbon biomass & growth rates

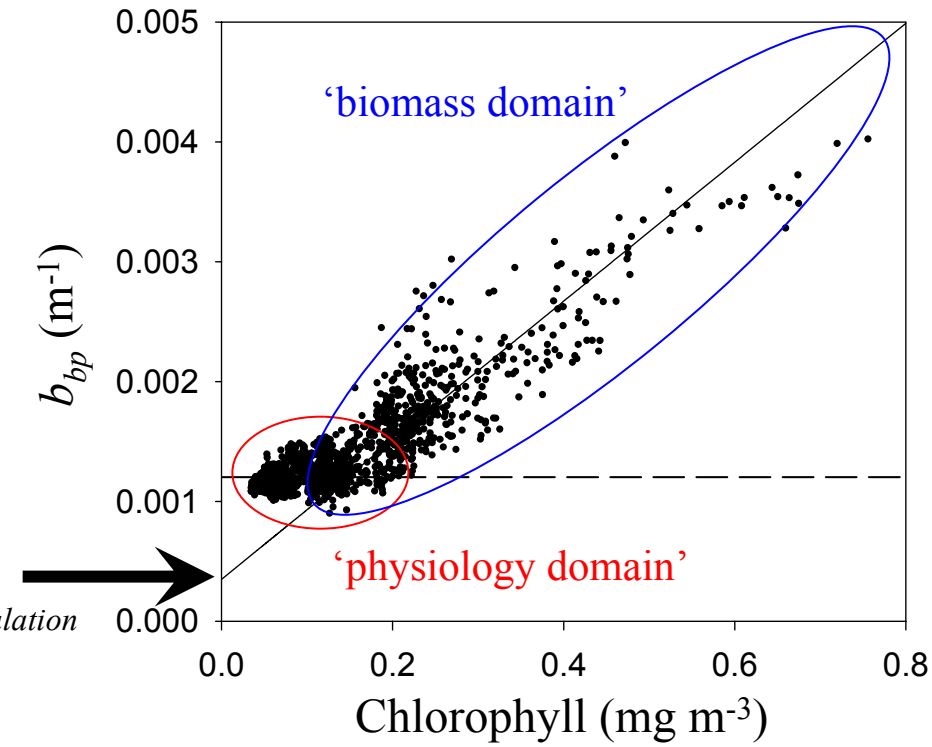
28 Regional Bins



Behrenfeld et al. GBC 2005
reprints

Carbon-based Approach

Basics: phytoplankton carbon biomass * growth rate * light function



Intercept = b_{bp} *from stable component of the bacterial population*

$$C = \text{scalar} \times (b_{bp} - \text{intercept})$$
$$= 13{,}000 \times (b_{bp} - 0.00035)$$

Intercept = **0.00017 m^{-1}**

Stramski & Kiefer (1991) *Prog. Oceanogr.* 28, 343-383

Cho & Azam (1990) *Mar. Ecol. Prog. Ser.*, 63, 253-259

Phytoplankton Carbon = **25 – 35% POC**

Eppley et al. (1992) *J. Geophys. Res.*, 97, 655-661

DuRand et al. (2001) *Deep-Sea Res. II*, 48, 1983-2003

Gundersen et al. (2001) *Deep-Sea Res. II* 48, 1697-1718

Carbon-based Approach

Basics: phytoplankton carbon biomass * growth rate * light function

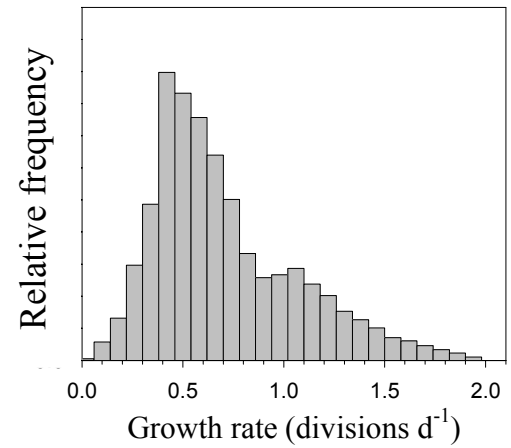
Growth rate (μ) =

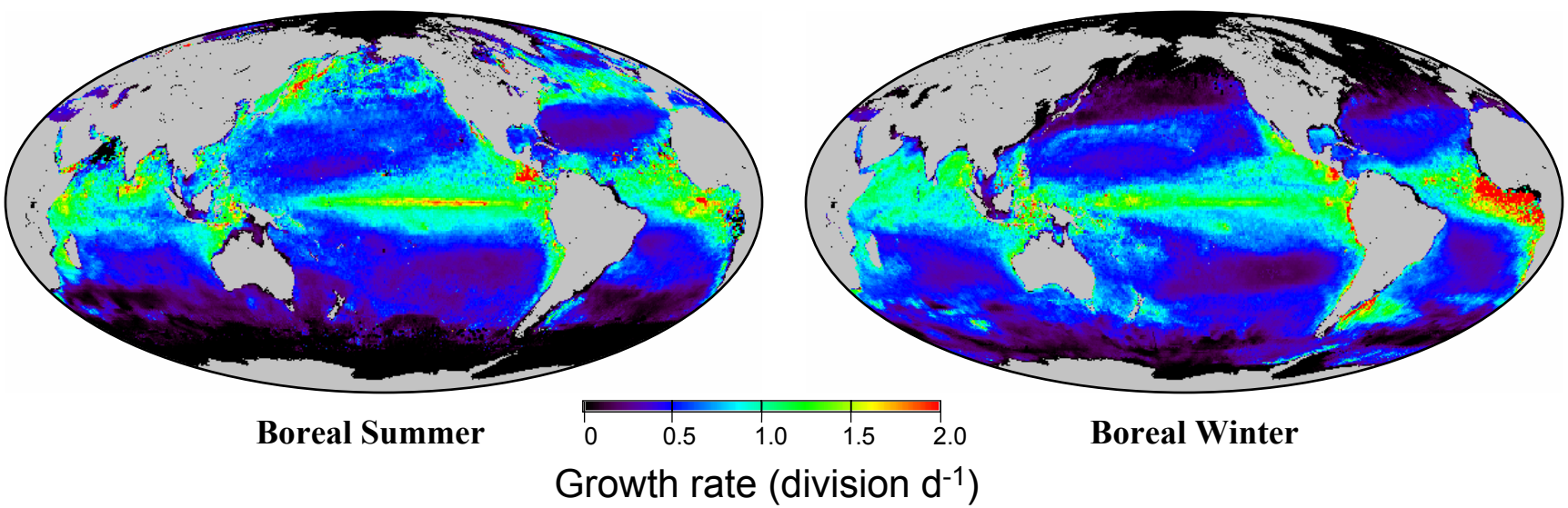
$$\mu_{max} \times f(\text{nuts, temp}) \times g(\text{light})$$

μ_{max}: 2 divisions d^{-1} Banse (1991)

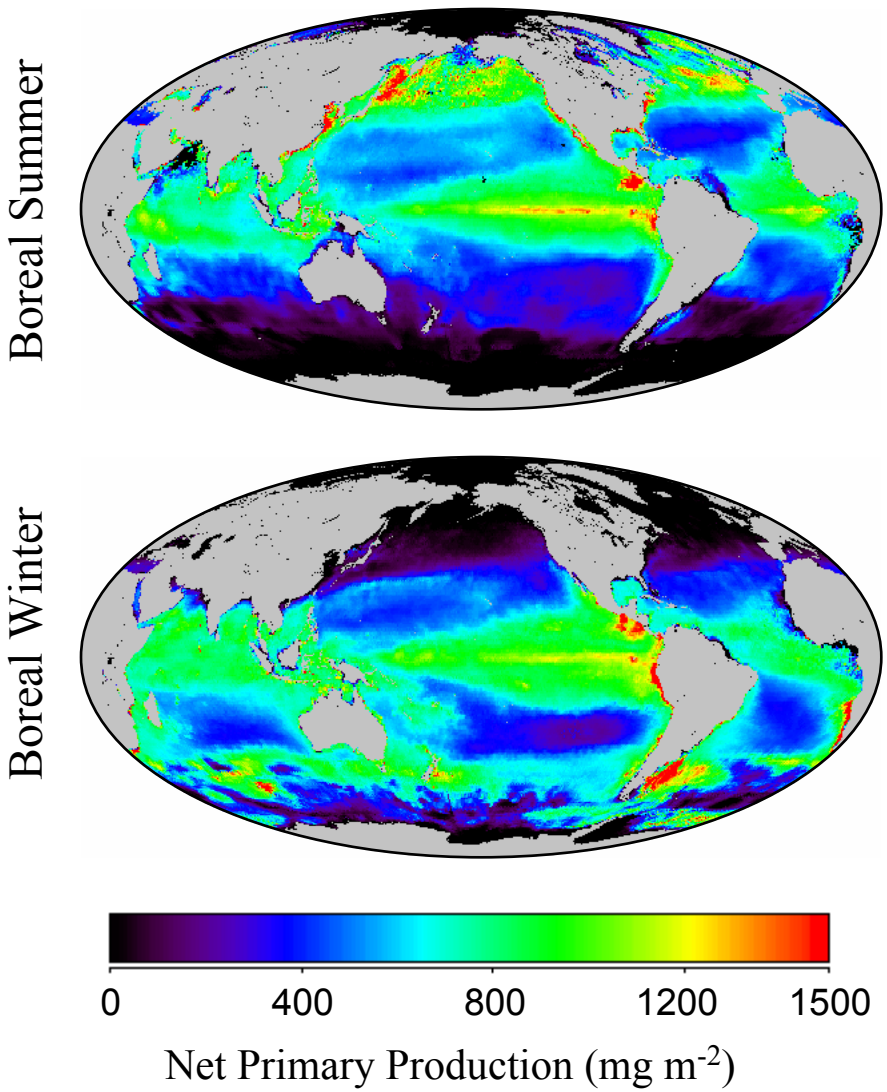
$f(\text{nuts, temp})$: $\dfrac{\text{Chl:Csat}}{(\text{Chl:C}_{N,T\text{-max}})_{\text{Light}}}$

$g(\text{light})$: $1 - \exp^{-3\text{light}}$





Carbon-based: Results

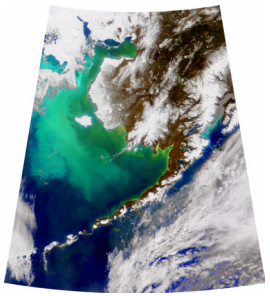


Carbon-based: Biomass

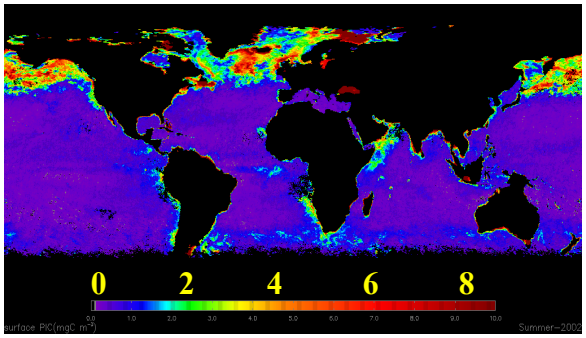
Basics: phytoplankton carbon biomass * growth rate * light function

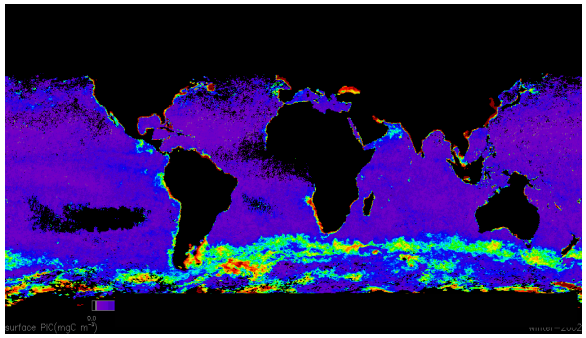
Issues:

- Particulate backscatter is not uniquely algal in origin (…unlike chlorophyll…)
- Conserved / predictable nature of particle size distribution
- Stability of background particle load
- Difficult in Case II waters
- Little data on phytoplankton Carbon
- Little consensus on phytoplankton carbon measurement
- Validation of semi-analytic products: data limited
- Spectrally inadequate remote sensing data
- PIC – '*one person's signal is another one's noise*'



Summer





Winter

W.Balch, Bigelow Laboratory

Carbon-based: Physiology

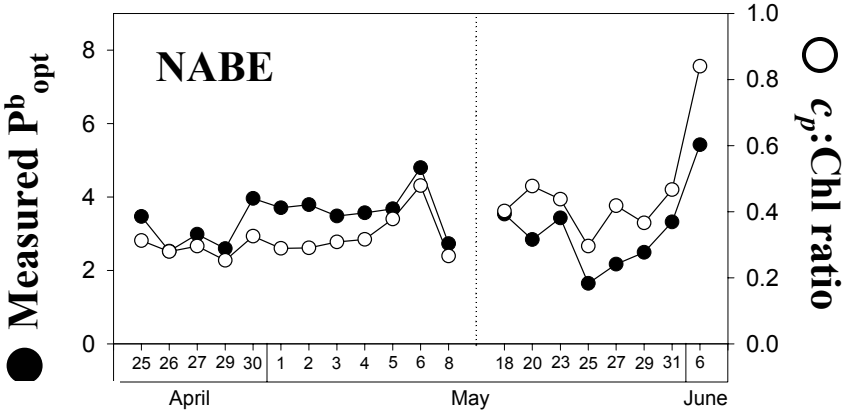
Basics: phytoplankton carbon biomass * growth rate * light function

Issues:

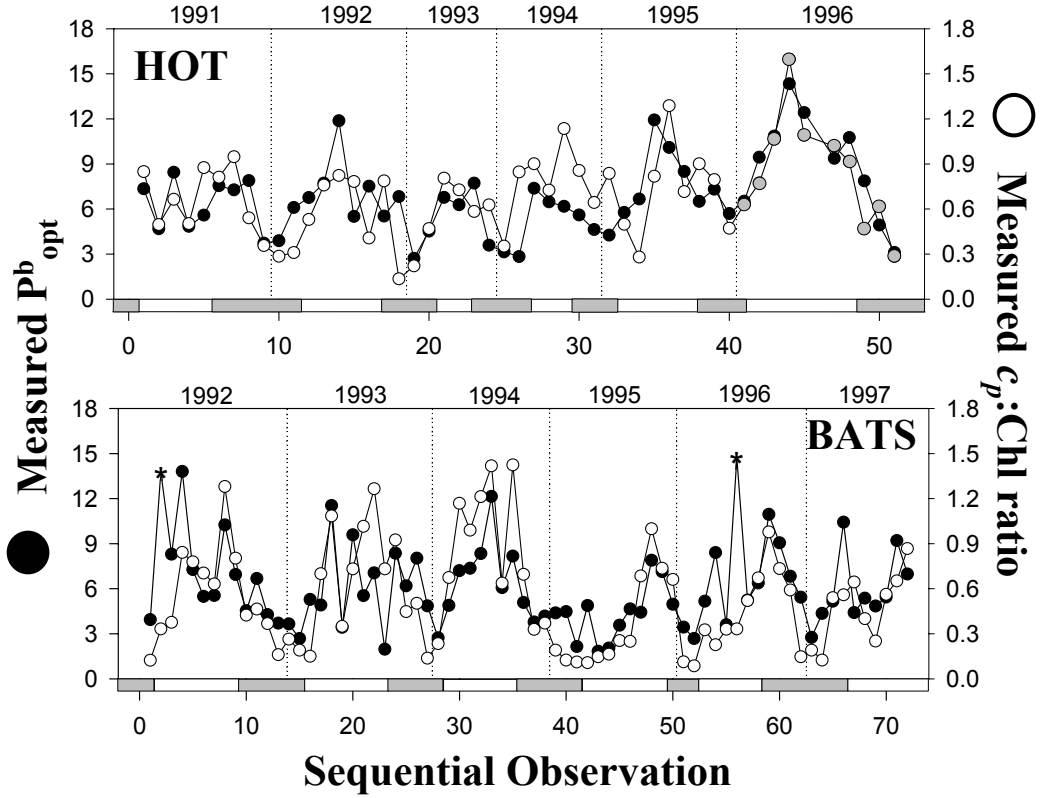
- Ratio of two biomass terms
- Critically dependent on accurate separation of absorbing components
- Limited test data – growth rates, acclimation of natural populations,…etc
- ^{14}C-based assimilation and growth rate share dependence on photoacclimation but differ in response to nutrient stress
- f (N,T) shape and intercept?
- recalibration with each reprocessing
- μ_{max} not well resolved
- μ difficult to determine in the field
- type of nutrient stress can be important (e.g., Fe)

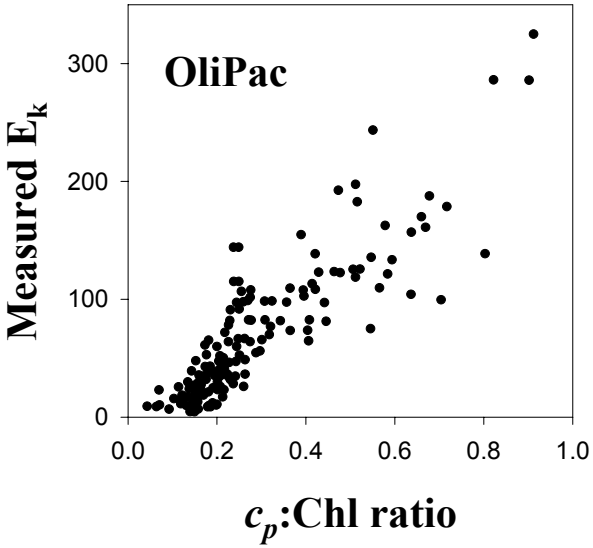
Carbon-based: Validation

^{14}C physiology *vs* optical C:Chl



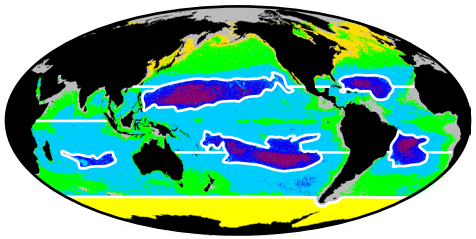
NABE Time Series

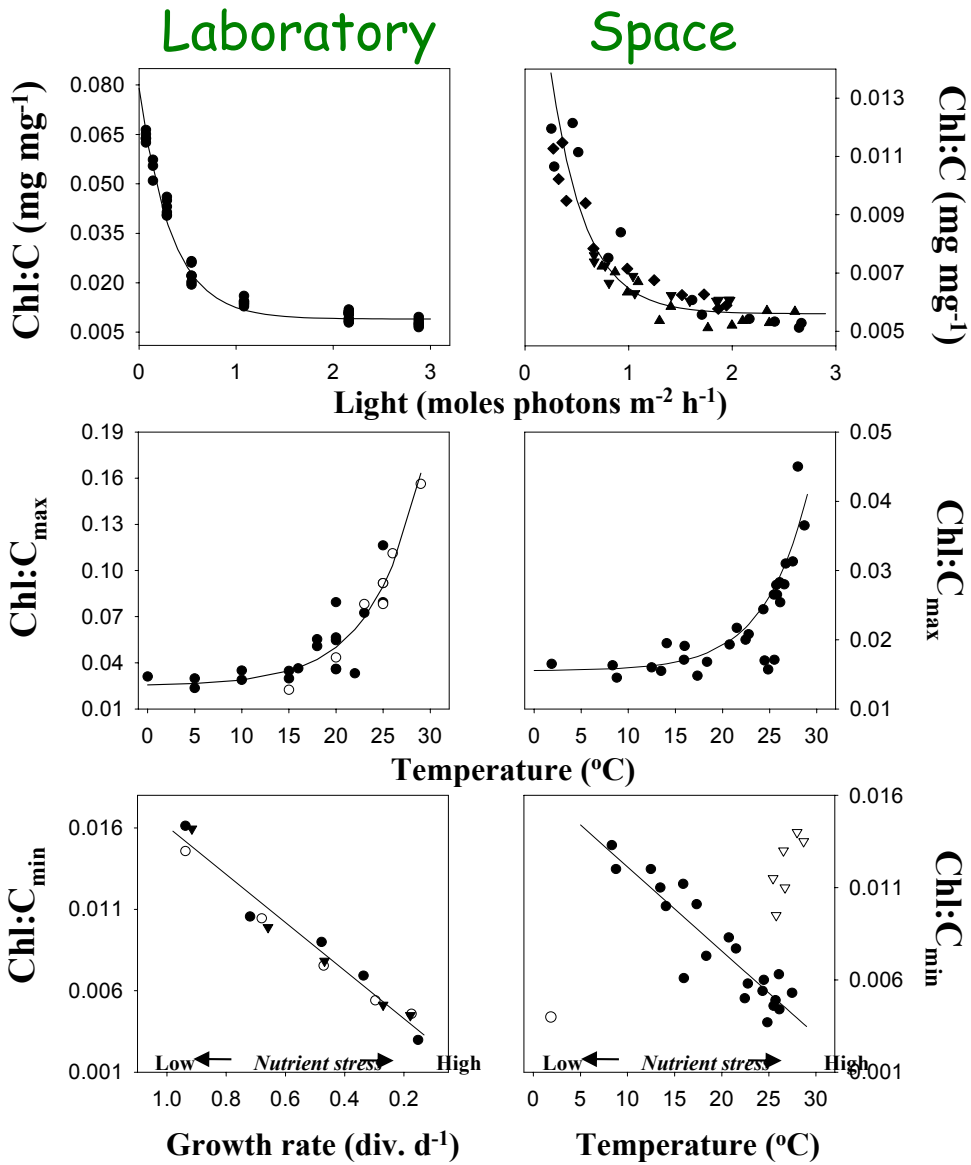




Carbon-based: Validation

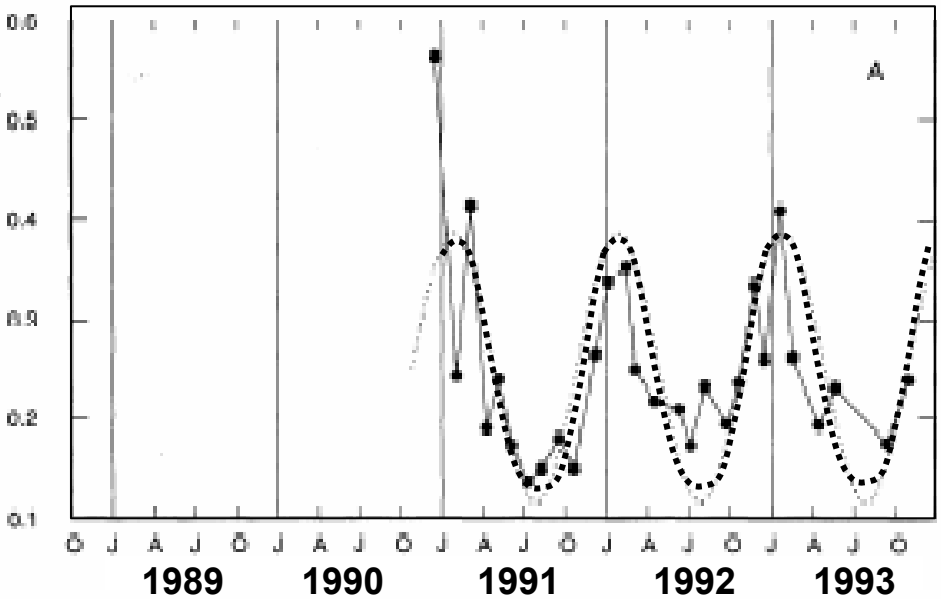
Chl:C
Regional Behavior





Carbon-based: Validation

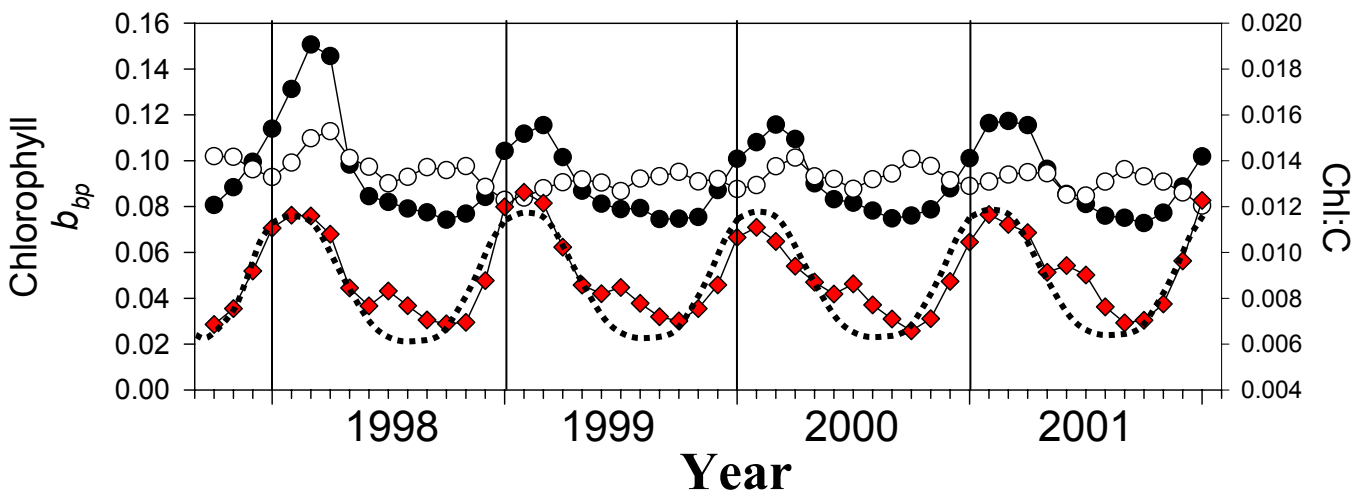
North Pacific: HOT



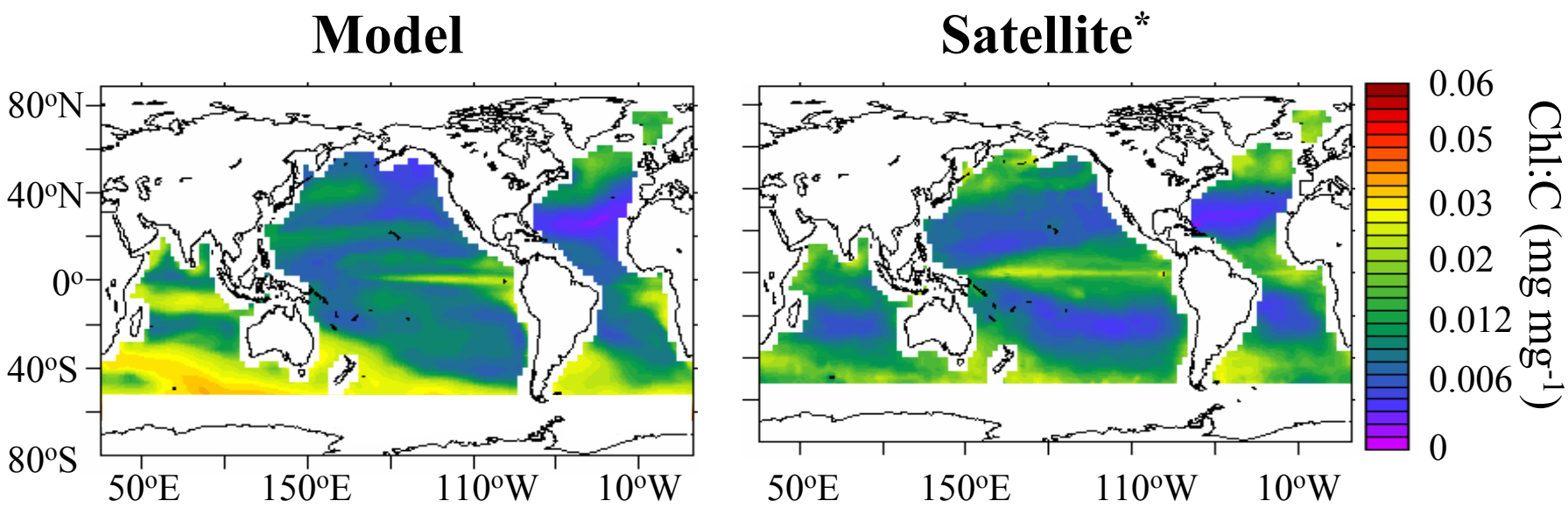
References:

Winn, Campbell, Christian, Letelier, Hebel, Dore, Fujieki, Karl. 1995. ***Global Biogeochem. Cycles*** 9:605-620.

Figure 6. (a) Time series of mean *Prochlorococcus* cellular fluorescence (arbitrary units) in the upper euphotic zone (0-50 m) from December 1990 through December 1993.

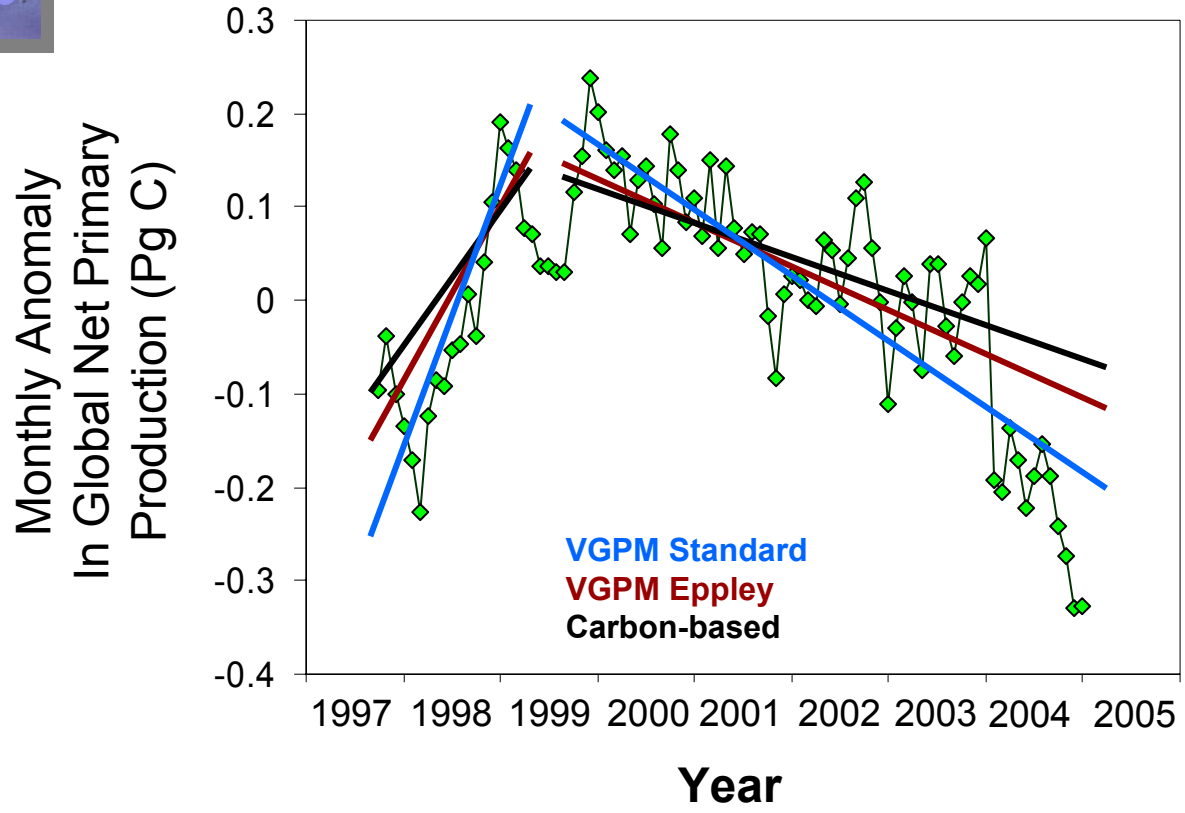


Carbon-based: Validation



Remote sensing data: Average June values for SeaWiFS time series

Current Trends



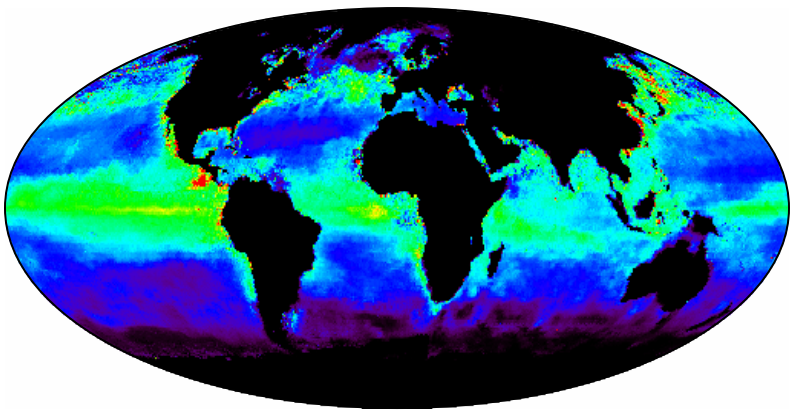
Current Issues

- Availability & interpretation of data
  - Unresolved respiratory pathways
  - Growth Rate & Phytoplankton Carbon
  - Community-level acclimation
  - Unique nutrient stress effects
  - Algorithm development – a_{ph}, cDOM, chlorophyll, b_{bp}, taxon, etc.
- Atmospheric corrections
  - Absorbing aerosols & Aerosol Heights
  - 'Bright waters'
- Optically active components
  - cDOM *vs* Pigment absorption
  - PIC and detritus *vs* living particles
  - taxonomic groups
  - particle size spectra
- Mixed layer depths
- Future Remote Sensing

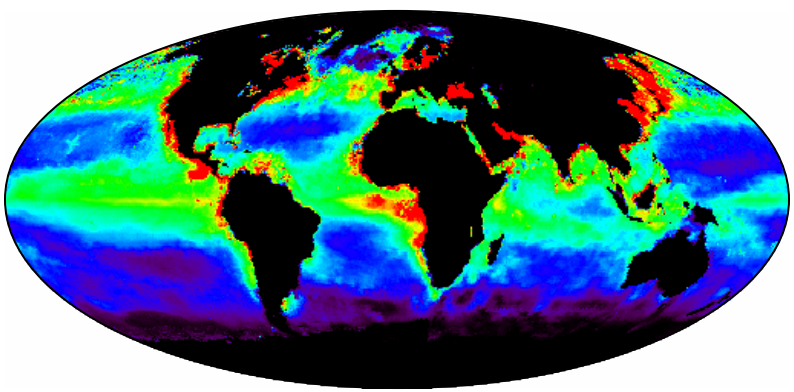
Current Issues: cDOM

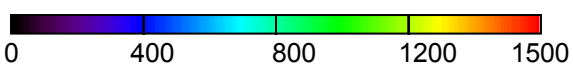
Siegel et al. 2005

GSM semi-analytic algorithm



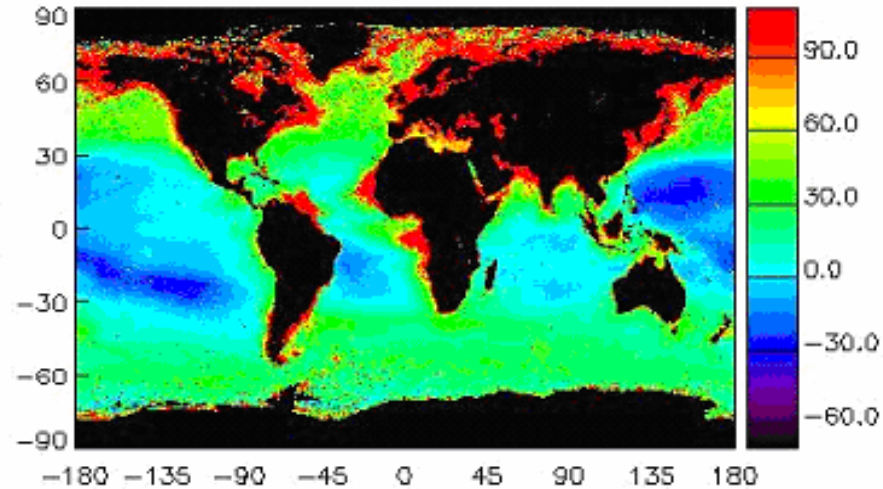
NASA Standard Ratio Algorithm (OC4-V4)



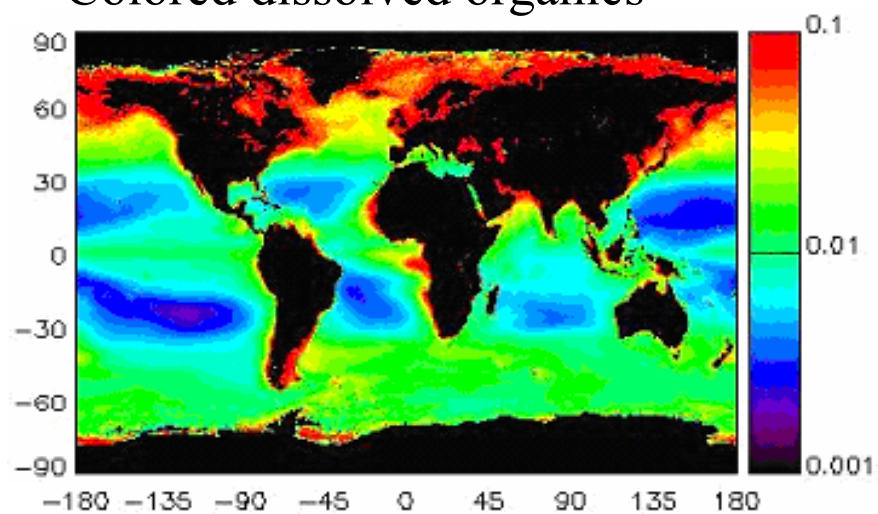


Boreal Summer Production (mg m^{-2} d^{-1})

NPP difference

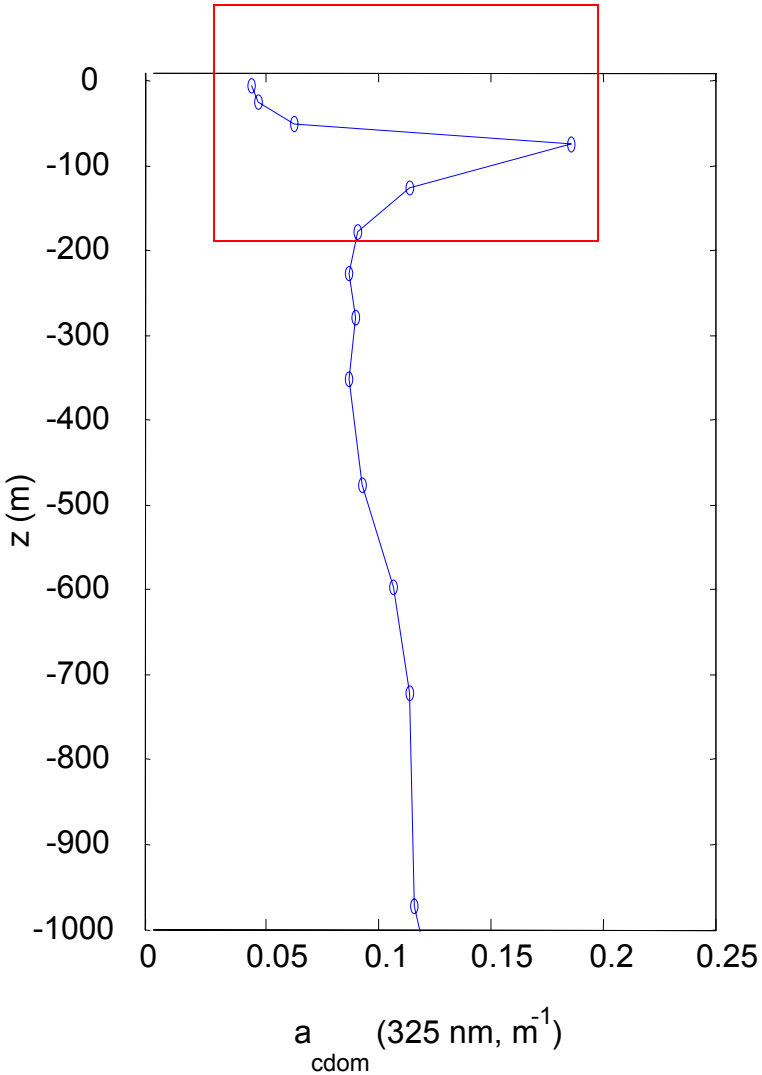


Colored dissolved organics



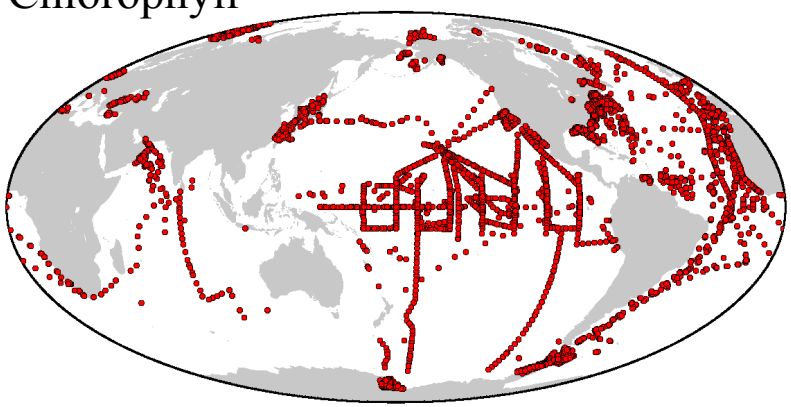
Current Issues: cDOM

*also note resuspension

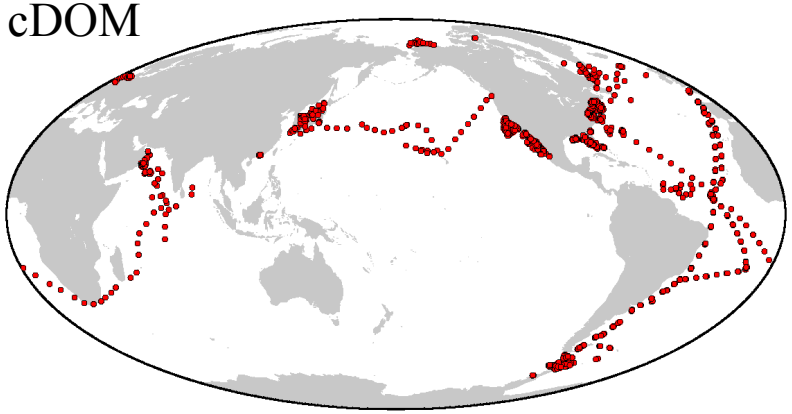


Current Issues: cDOM

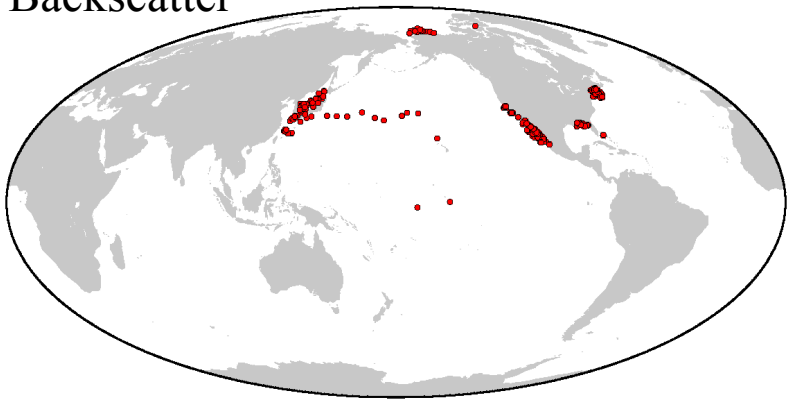
Chlorophyll



cDOM

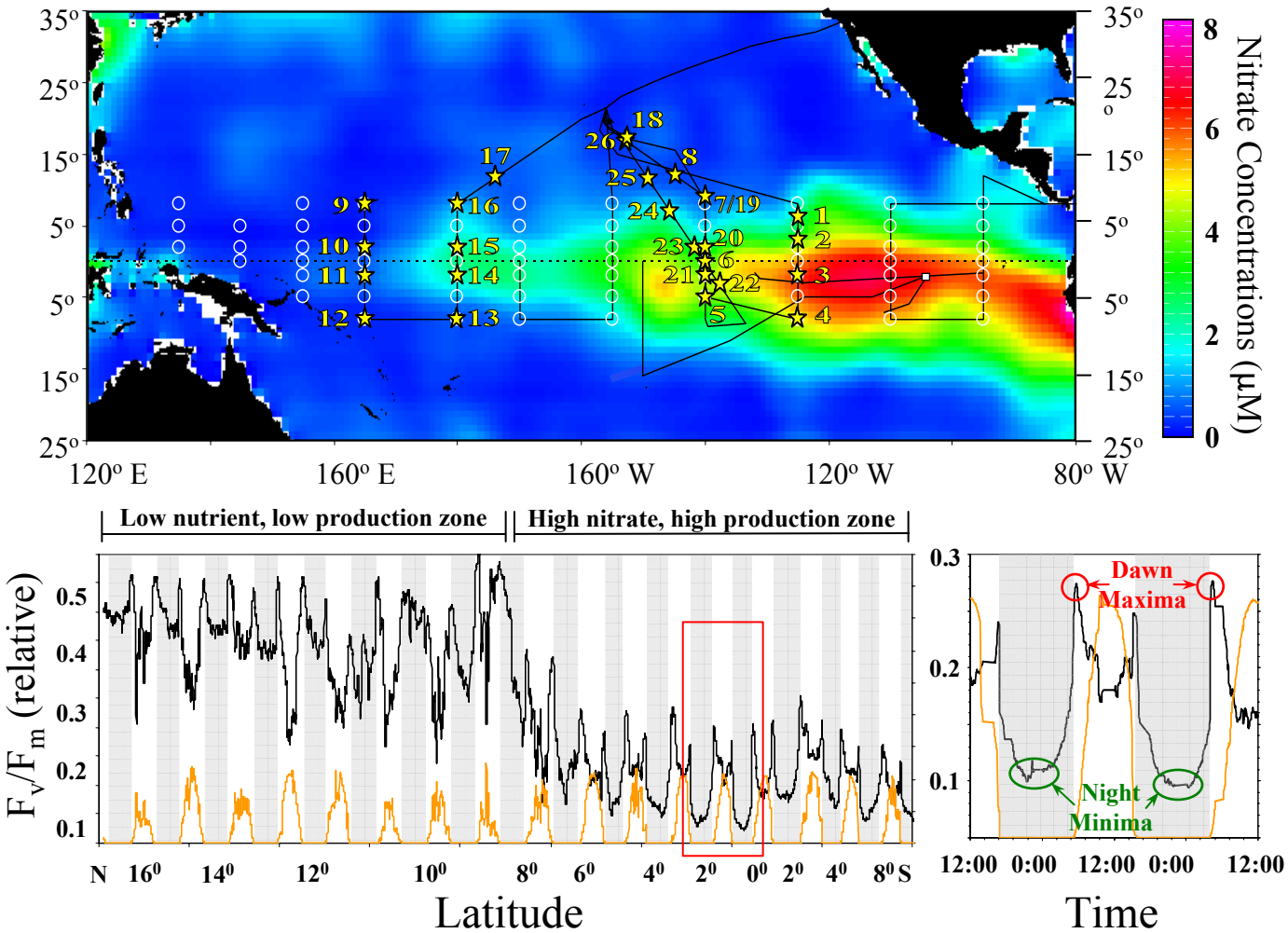


Backscatter

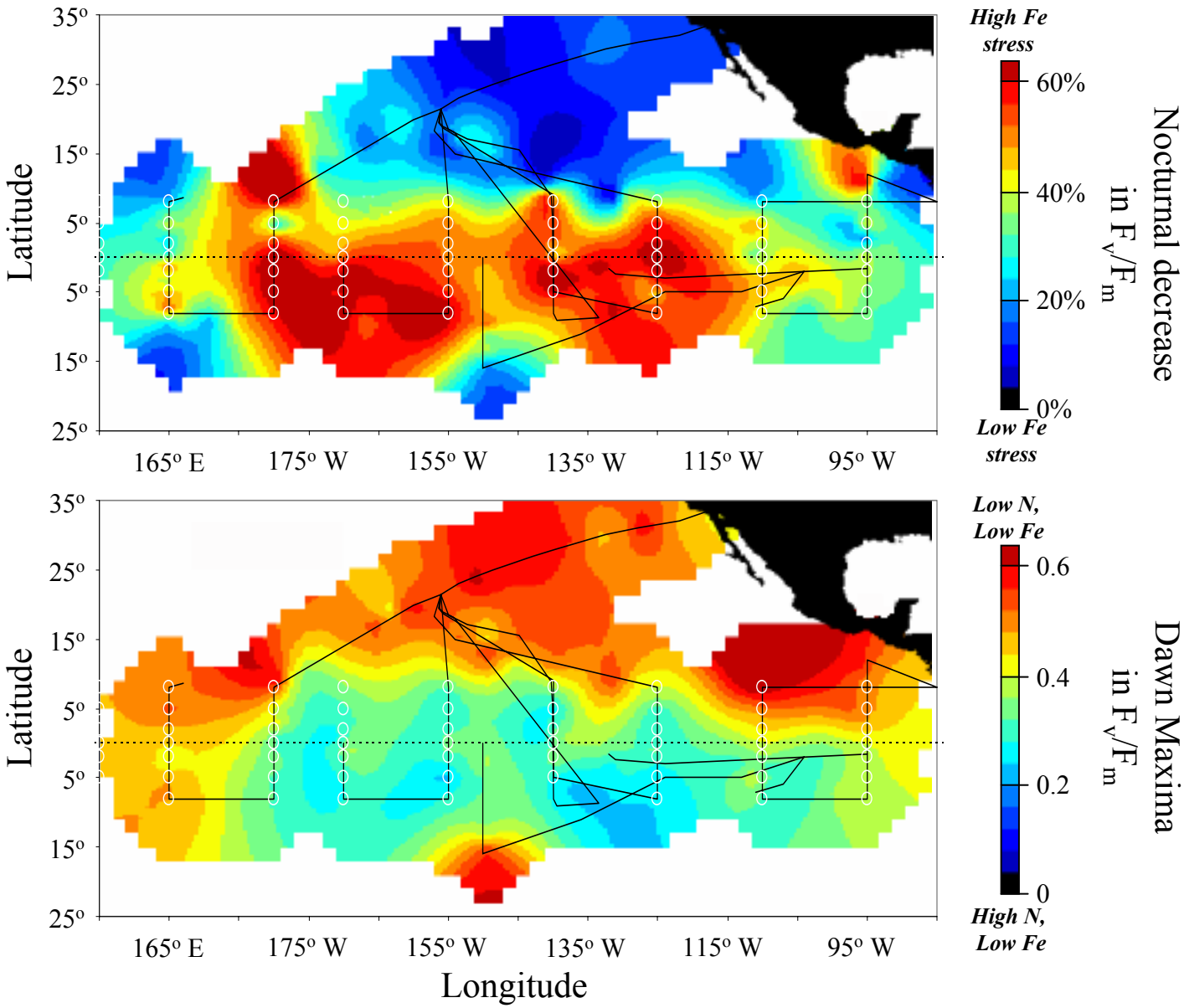


SeaBASS Dataset for remote sensing algorithm development and testing

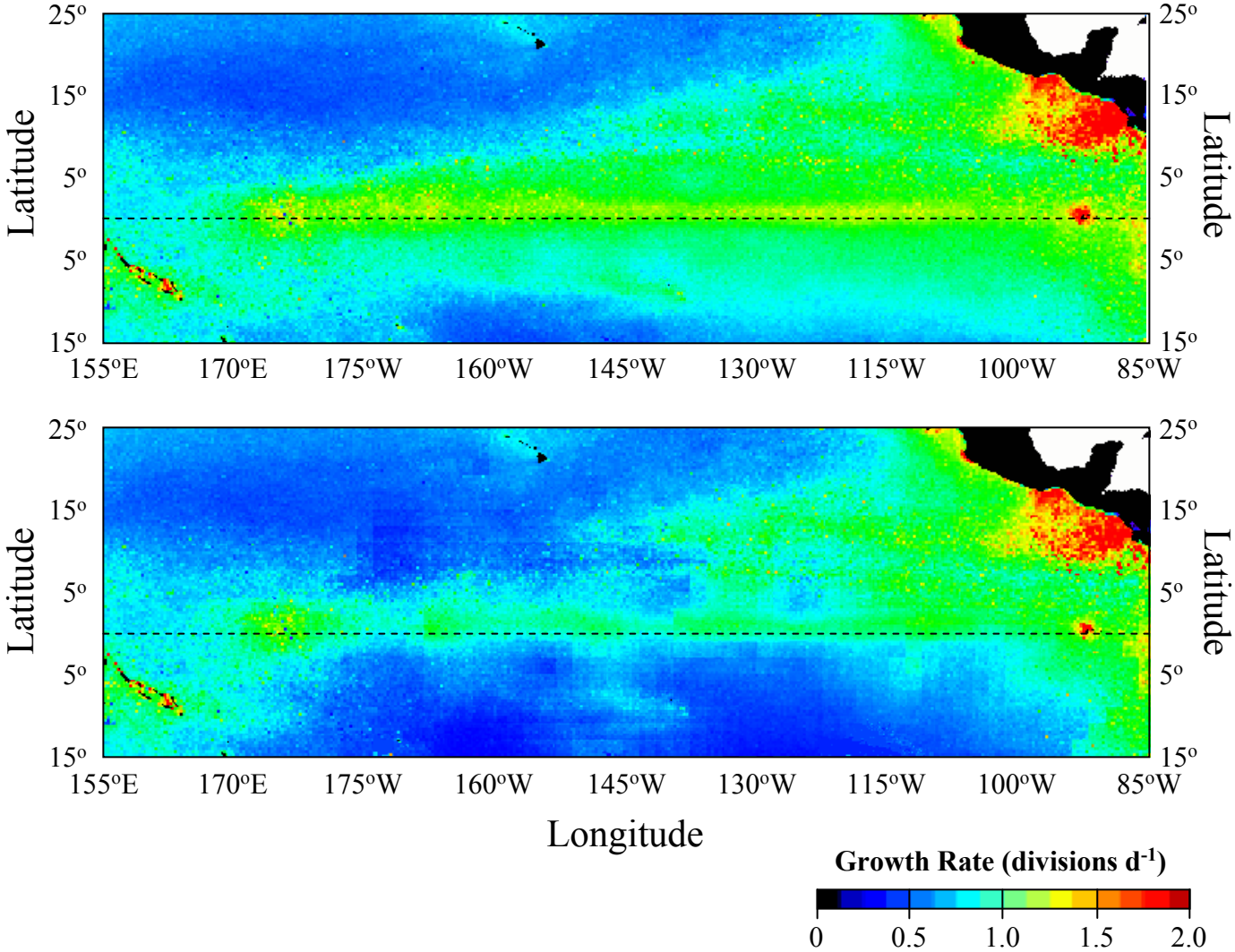
Current Issues: Unique nutrients



Current Issues: Unique nutrients



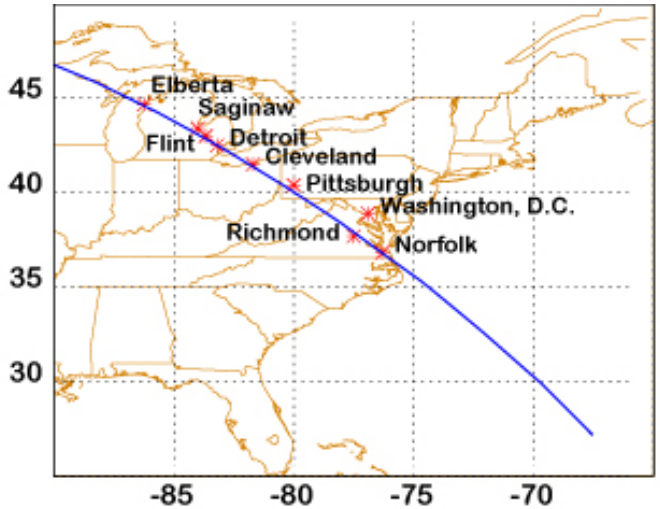
Current Issues: Unique nutrients

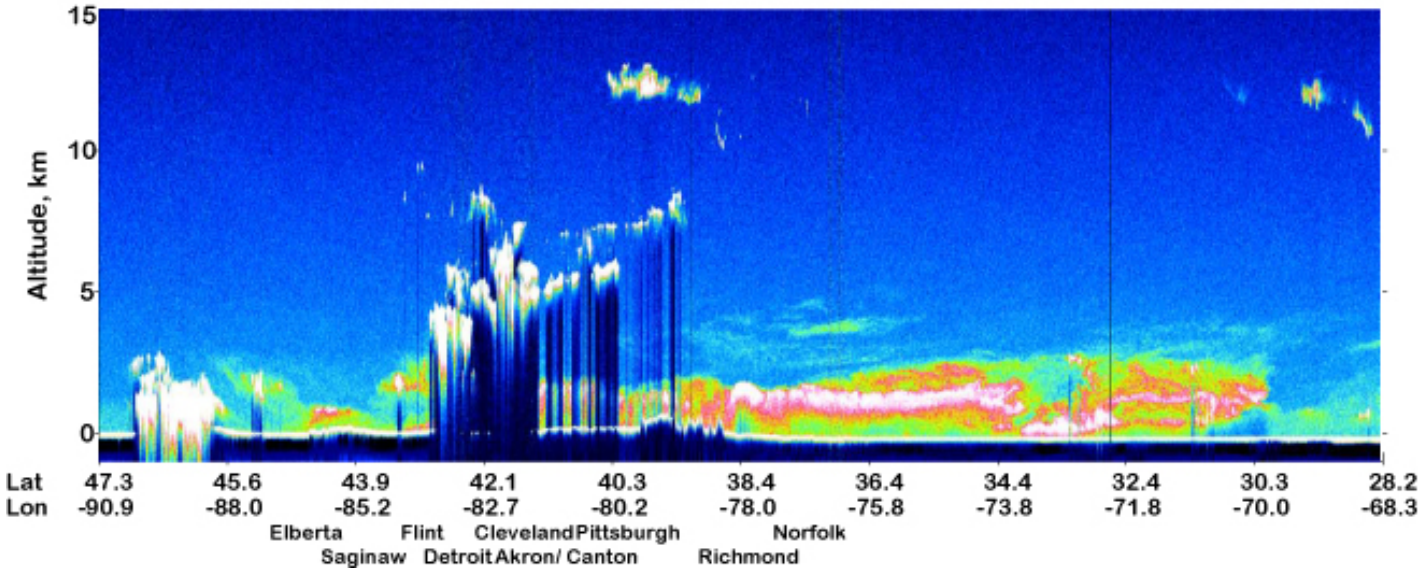


Current Issues: Absorbing Aerosols

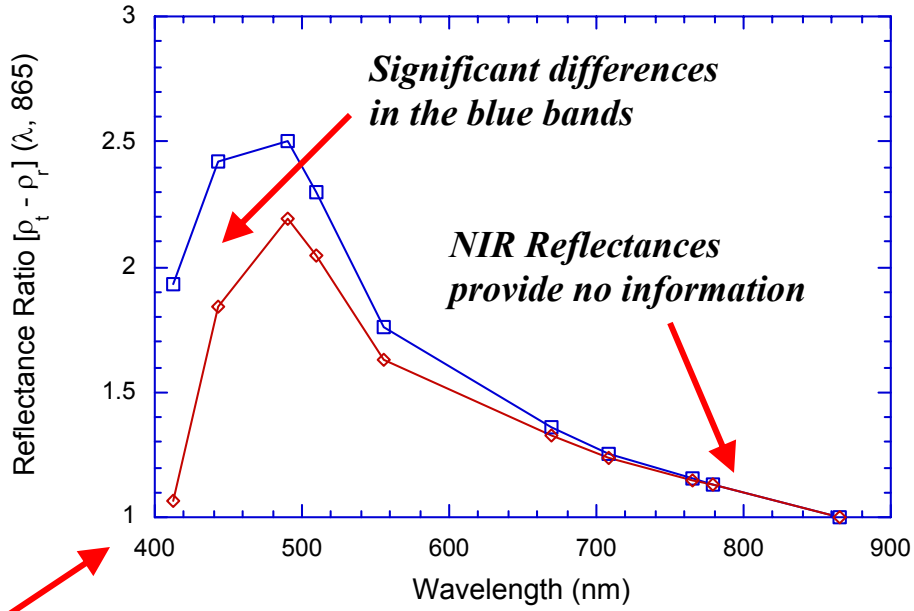
Observations of Continental Haze by LITE

September 17, 1994
Orbit 117

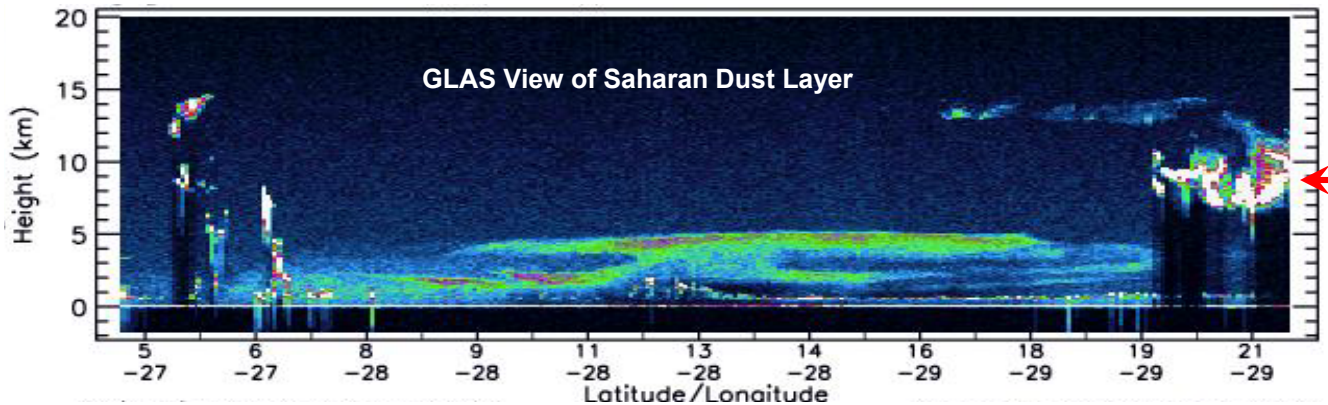


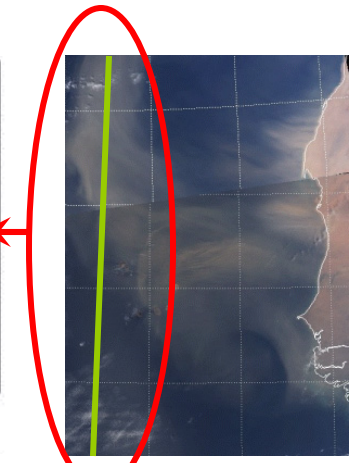


Current Issues: Absorbing Aerosols

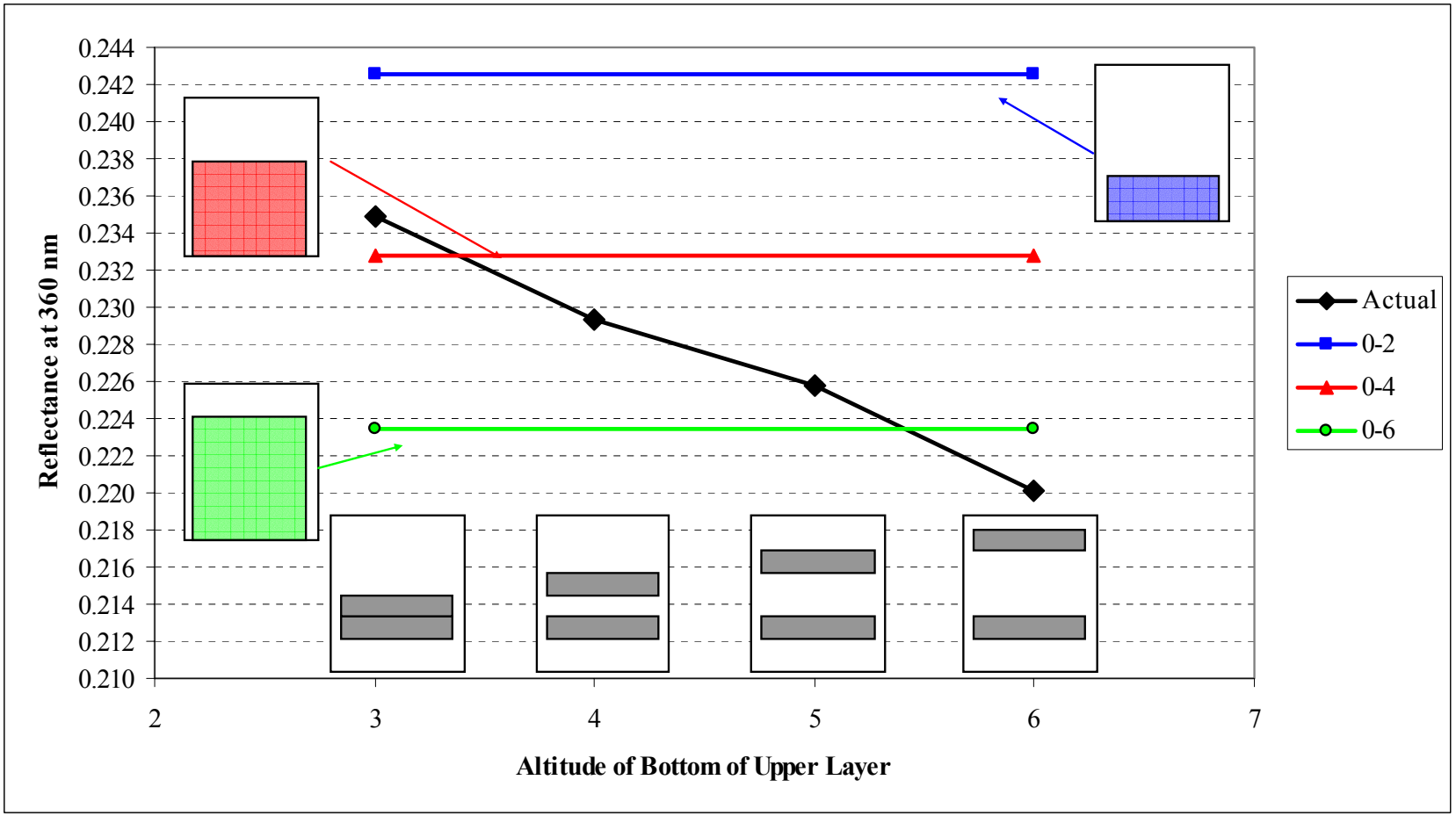


Problem is worse in UV bands – an important region for future sensors





Current Issues: Absorbing Aerosols



AOD = 0.8 at 865 nm

SeaWiFS processing models: Moulin et al (2004), Banzon et al (2004)

Future Remote Sensing

- we can't take it for granted
- is where we're headed where we want to go?
- role for carbon planning groups

Remote Sensing Future

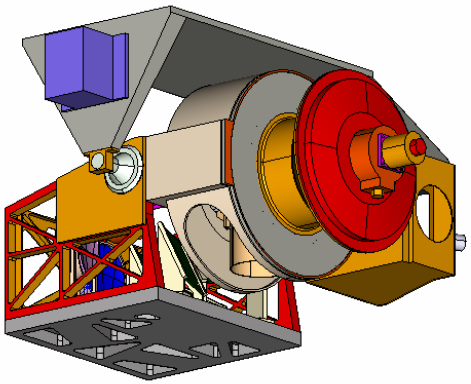
- Atmospheric corrections
  - Absorbing aerosols & Aerosol Heights
  - 'Bright waters'
- Optically active components
  - cDOM *vs* Pigment absorption
  - particle concentration (b_{bp}, c_p)
  - PIC and detritus *vs* living particles
  - taxonomic/functional groups
  - particle size spectra
- Mixed layer depths
- Active & Passive measurements
- Spatial Resolution
  - Global & geostationary – sequence is important!
- Roadmapping
  - Current & Operational sensors are inadequate
  - 'One Mission, One Product'

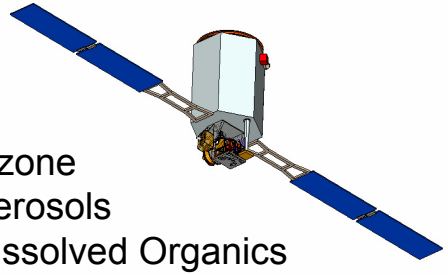
Global Passive

OCEaNS

Ocean Carbon, Ecosystems and Near-Shore

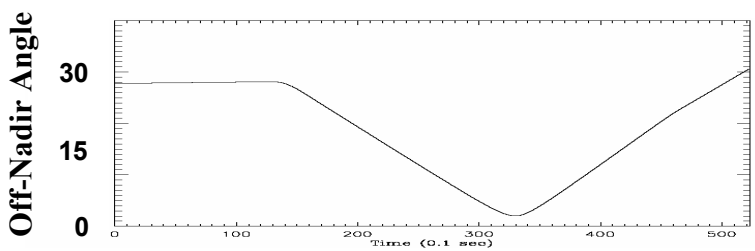
Discovery Science
- Pigment composition
- Functional Groups
- Particle size spectrum
- Beam-attenuation
- Harmful Algal Blooms
- Terrestrial Vegetation
- Land Productivity
- …more…



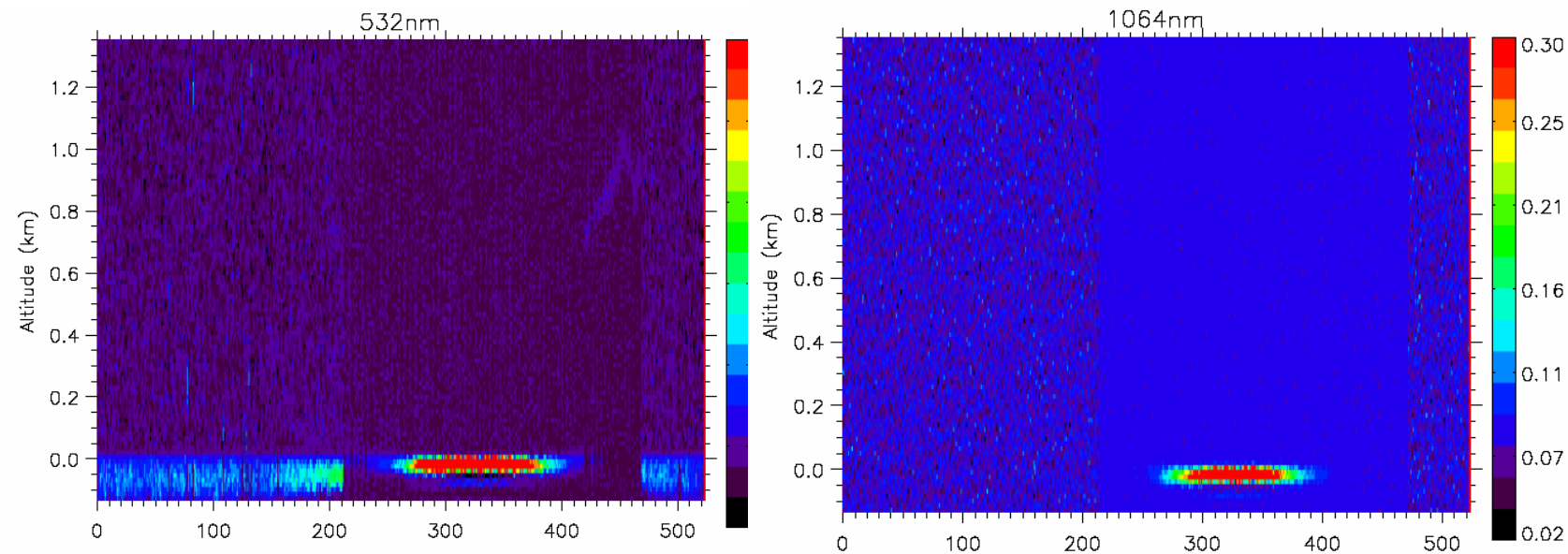


Full global L1 data set	Aggregates Center	Band	
B318	B318	2	•Ozone •Aerosols •Dissolved Organics •'Bright' Waters
	B345	20	
	B360	20	
	B380	20	
	B412	20	•Pigment absorption •Particle backscatter •Open ocean to Near shore conditions
	B443	20	
	B460	20	
	B490	20	
	B510	20	
	B532	20	
	B555	20	
	B595	20	
	B620	20	
	B667	10	•Biomass in high productive regions
	B678	10	
	B748	40	
	B865	40	•Atmospheric correction 'bright' & clear waters
B1000	B1000	50	
B1240	B1240	50	
B1375	B1375	30	

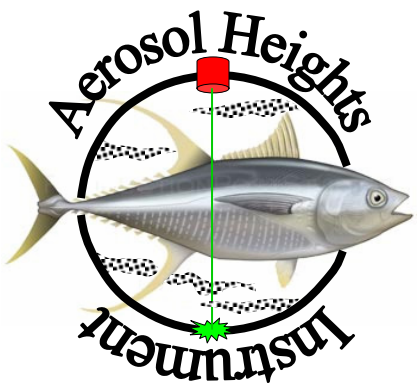
Active Measurements



Subsurface Scattering From the Space Shuttle

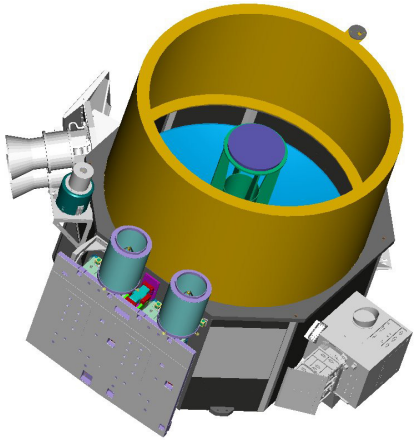


Along-track multi-angle view LITE data of Lake Superior. Off-Nadir Angle changes between 28 degree and 2 degree (upper left). The fixed gain 355nm shows only surface reflectance for small off-nadir angles; The high-gain 532nm shows good sub-surface signals down to 75 meters (lower left) for large off-nadir angles. We do not see signals from high gain 1064nm with large off-nadir angles – which indicates the surface return for both 1064nm and 532nm are negligible, since the two channels have similar real-part of refractive indices and thus similar surface returns.



In-water Lidar Photon Return Calculations

Energy_per_pulse_in_Joules = 0.0500
Mirror_aperture_in_m = 1
Orbit_altitude_in_km = 600
Detector_quantum_efficiency =0.8000
Spectral_analyzer_losses = 0.1000
Atmospheric_losses =0.2000



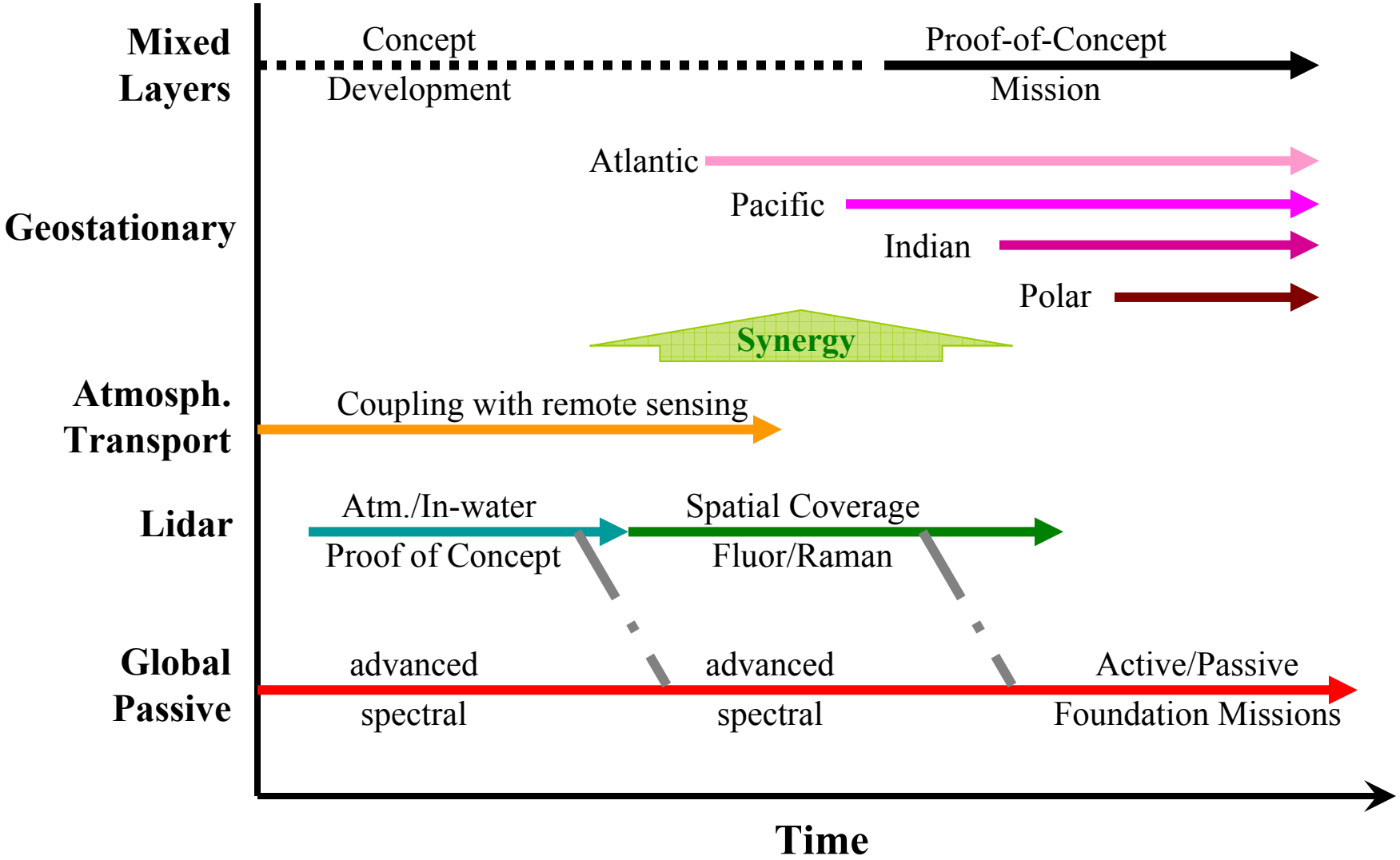
Total Number Of Photons Received per Pulse*

GoMOOS 1	**308.09**
GoMOOS 2	**388.83**
GoMOOS 3	**228.99**
Gulf of Cal 1	**232.36**
Gulf of Cal 2	**349.29**
Gulf of Cal 3	**1761.49**
Oligo 1	**176.25**
Oligo 2	**195.96**
Meso 1	**217.22**
Meso 2	**301.95**
Coastal 1	**336.99**
Coastal 2	**381.07**
Coastal 3	**386.22**

Ron Zaneveld

*** Note: These results were not corrected for the 1/n2 effect at the surface. Photon counts should thus be reduced by a factor of 1/(1.33)2 = 0.565.**

Remote Sensing Future*



* Does not reflect in any way agency objectives

Ocean Productivity

Where?
How Much?
Is it Changing?
Why is it Changing?
What is its fate?

Pg C y^{-1}

50 → 53 → 48