Pre-Aerosol, Cloud, ocean Ecosystem (PACE) mission

- 2010 Report - *Responding to the Challenge of Climate and Environmental Change: NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space* (http://science.nasa.gov/earth-science/)
- PACE will make new, global ocean color radiometry measurements essential for understanding ocean biology and ecology, and the carbon cycle and its relationship to climate change, along with *plans for* polarimetry measurements to provide extended data records on clouds and aerosols
- Here we present results from the PACE Science Definition Team which has **nearly** completed its report
- Next step will be for NASA HQ to decide how it will implement the PACE mission **but** launch date is planned for 2019
- PACE’s name will likely change to reflect its marine focus – A SDT suggestion is “Pelagic And Coastal Ecosystem (PACE) mission”

Today's Session

Session 2. Ocean biogeochemistry from satellite data
Chair: *David Siegel (Univ. of California, Santa Barbara)*

14:00 A tutorial on satellite ocean color remote sensing *(David Siegel, Univ. of California, Santa Barbara)*

14:45 Science goals and objectives from the NASA PACE (Pre-Aerosol, Clouds, and ocean Ecosystem) Science Definition Team report *(Michael Behrenfeld, Oregon State Univ.)*

15:30 Break

16:00 NASA PACE Science Definition Team report approach and recommendations *(Carlos Del Castillo, Johns Hopkins Univ.)*

16:45 Panel discussion and community input to PACE

Satellite Ocean Color Overview & the PACE Science Definition Team

Dave Siegel – UC Santa Barbara

With help from Mike Behrenfeld, Stéphane Maritorena, Chuck McClain, Bryan Franz, Jim Yoder, David Antoine, Norm Nelson, Claudia Mengalt, Bob Evans, Carlos Del Castillo & many more

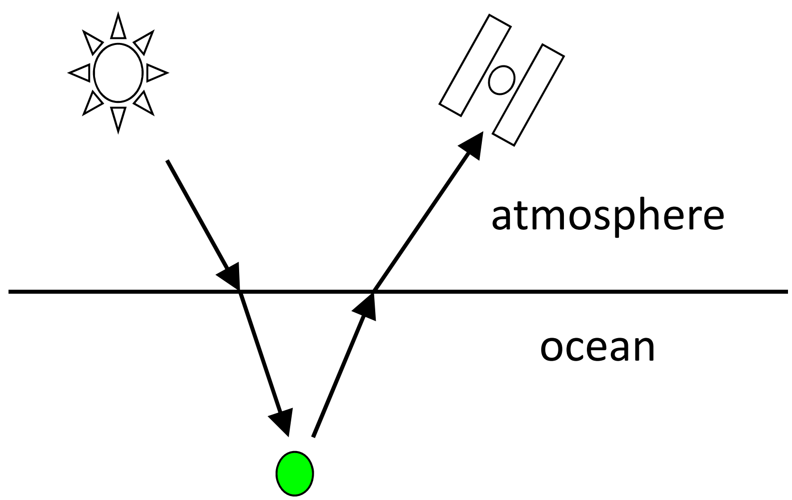
July 2012 – U.S. OCB Workshop, Woods Hole, MA

Talk Objectives

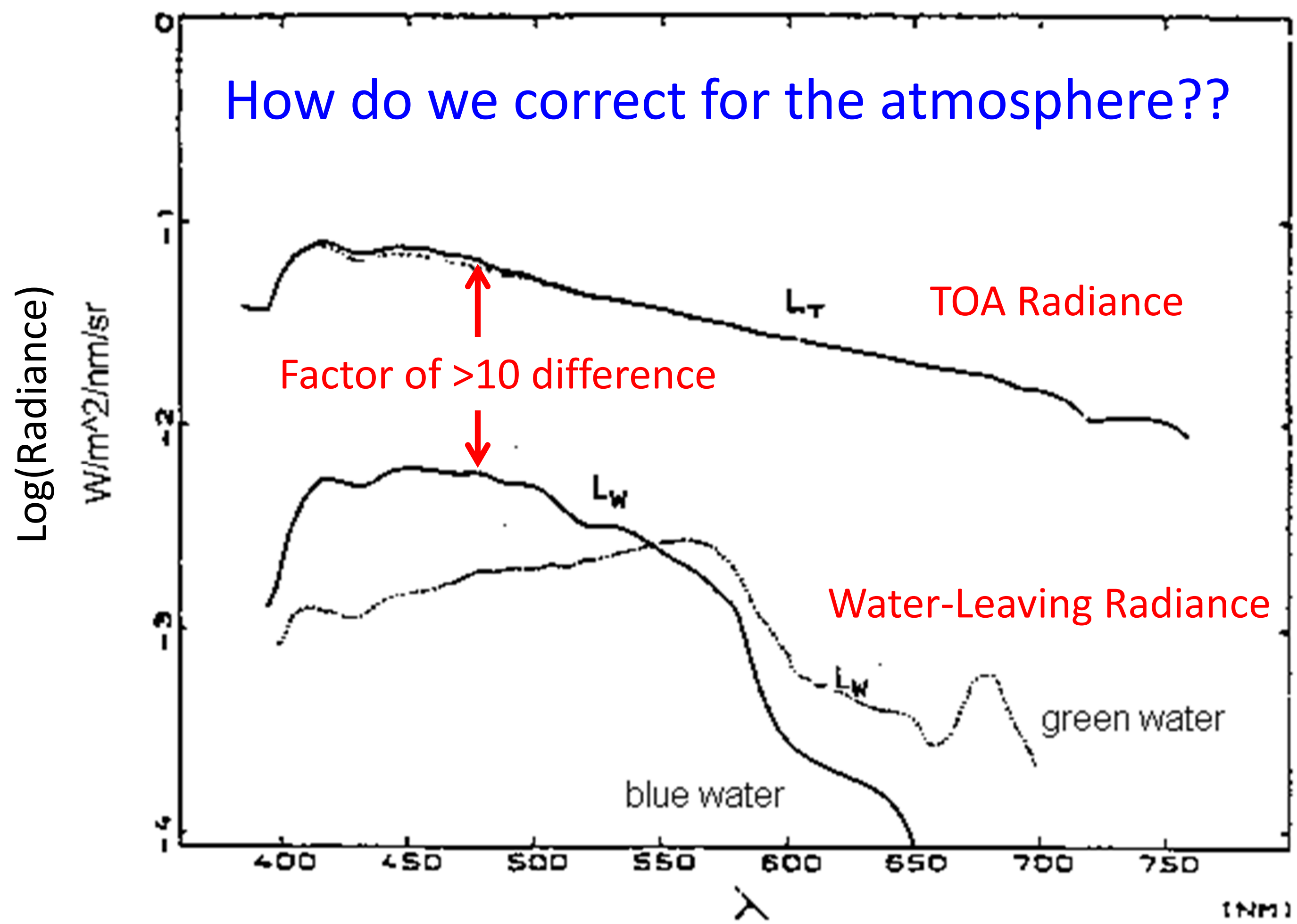
- Review satellite ocean color basics
- Highlight important findings from the SeaWiFS, MODIS & MERIS era
- Provide background for future missions such as PACE…

What is Satellite Ocean Color?

- The spectrum of the light reflected from the sea
- Water-leaving photons are backscattered & not absorbed *(ocean optics & relationship to ecology)*
- To see the oceans from space, we must account for the atmosphere *(atmospheric correction)*
- Ocean color signals are small *(great measurements require great care…)*



Bright Atmosphere – Dark Ocean



Atmospheric Correction

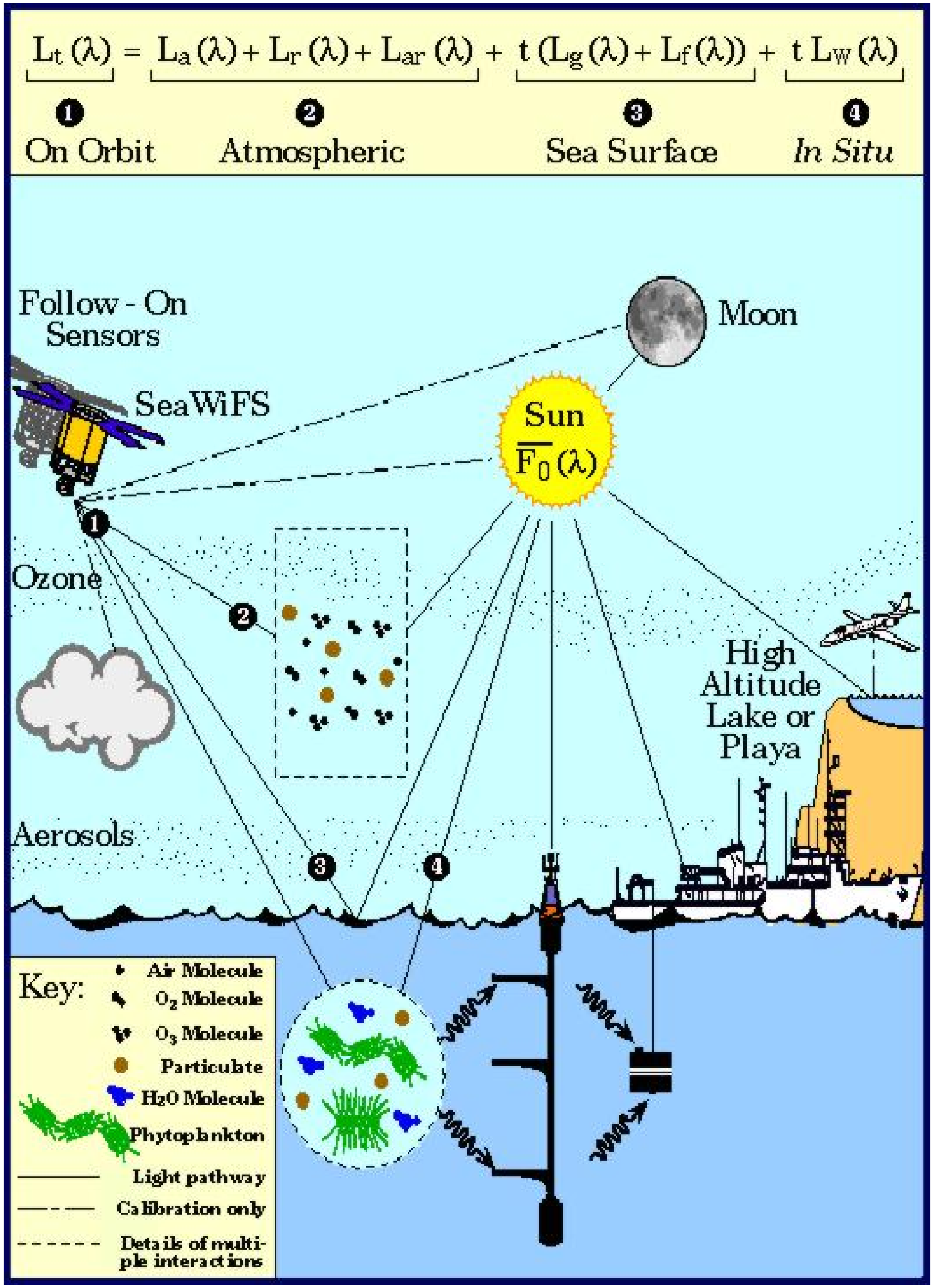
Radiance budget for satellite radiance

Measure $L_t(\lambda)$

Model $L_r(\lambda)$, $L_f(\lambda)$ & $L_g(\lambda)$

Unknowns are $L_w(\lambda)$, $L_a(\lambda)$ & $L_{ar}(\lambda)$

It is $L_w(\lambda)$ we need to know…



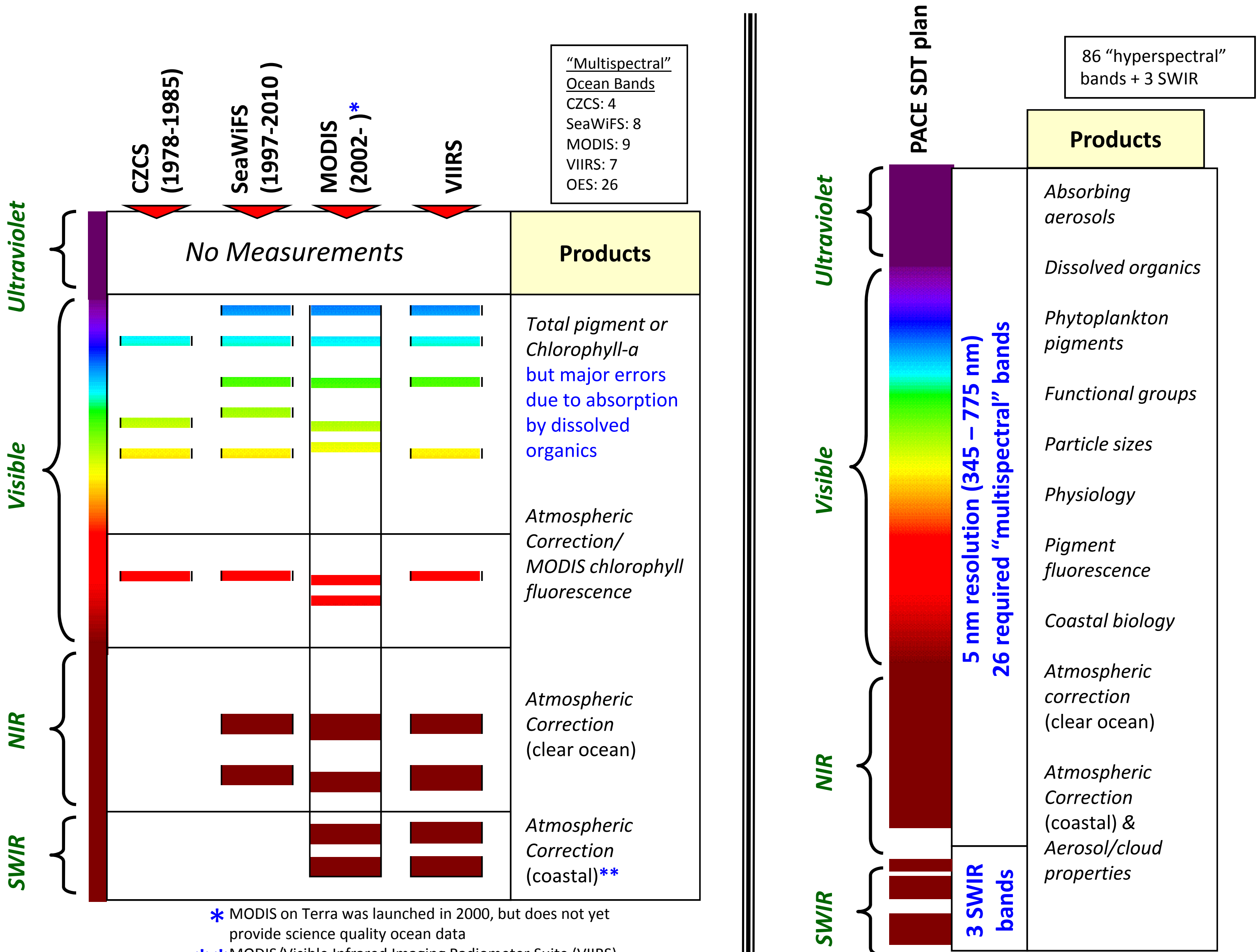
Atmospheric Correction Basics

- **Goal**: *Subtract off the atmospheric path signals from the satellite measurement*
- Model Rayleigh scattering, molecular absorption & interface reflectance terms
- Hard part is aerosol radiances
  - Use near-infrared bands to model aerosol radiances in the visible (in the future UV bands too)
  - Requires detailed models of aerosol optical properties that can be diagnosed from NIR

Ocean Color Sensor Requirements

- An ocean color sensor must…
  - Have *necessary* spectral resolution
  - Accurate (gains must be well known)
  - Stable (changes in gains must be known)
  - Well characterized (polarization, spectral, etc.)
- Devil is in the details…

Comparison of Spectral Coverage



* MODIS on Terra was launched in 2000, but does not yet provide science quality ocean data

** MODIS/Visible Infrared Imaging Radiometer Suite (VIIRS) SWIR bands are not optimized for oceans

Satellite Sensor Gains

- Accuracy requirements mean that satellite gains need to be known to better than 0.5%
- Accurate ground data are required

  End-to-end test -> vicarious calibration

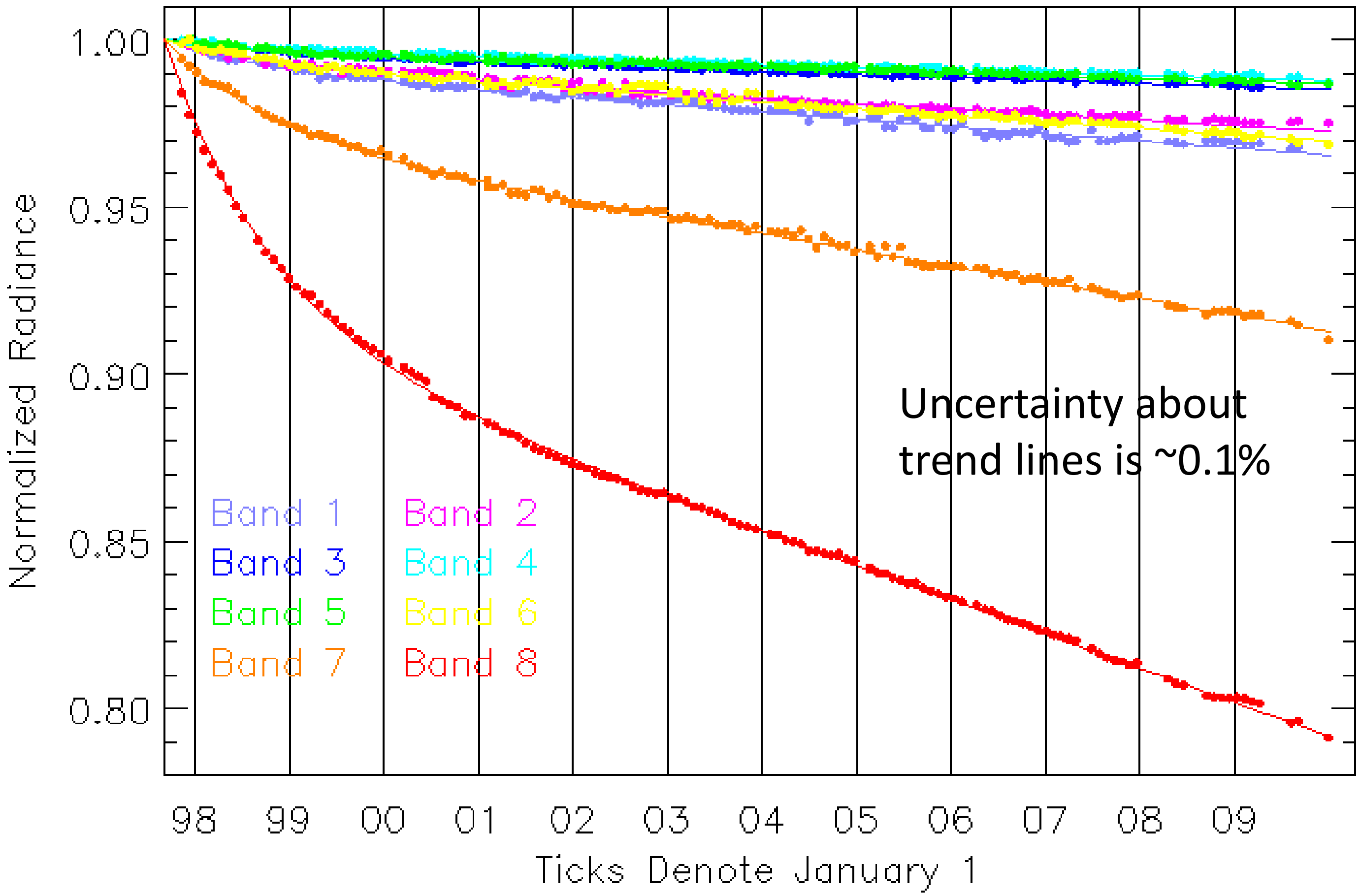
- Changes in these gains must be monitored

  Lunar viewing or multiple on-board sources

- Other "issues" creep in (like changes in polarization sensitivity or spectral responses)

SeaWiFS Lunar Calibration

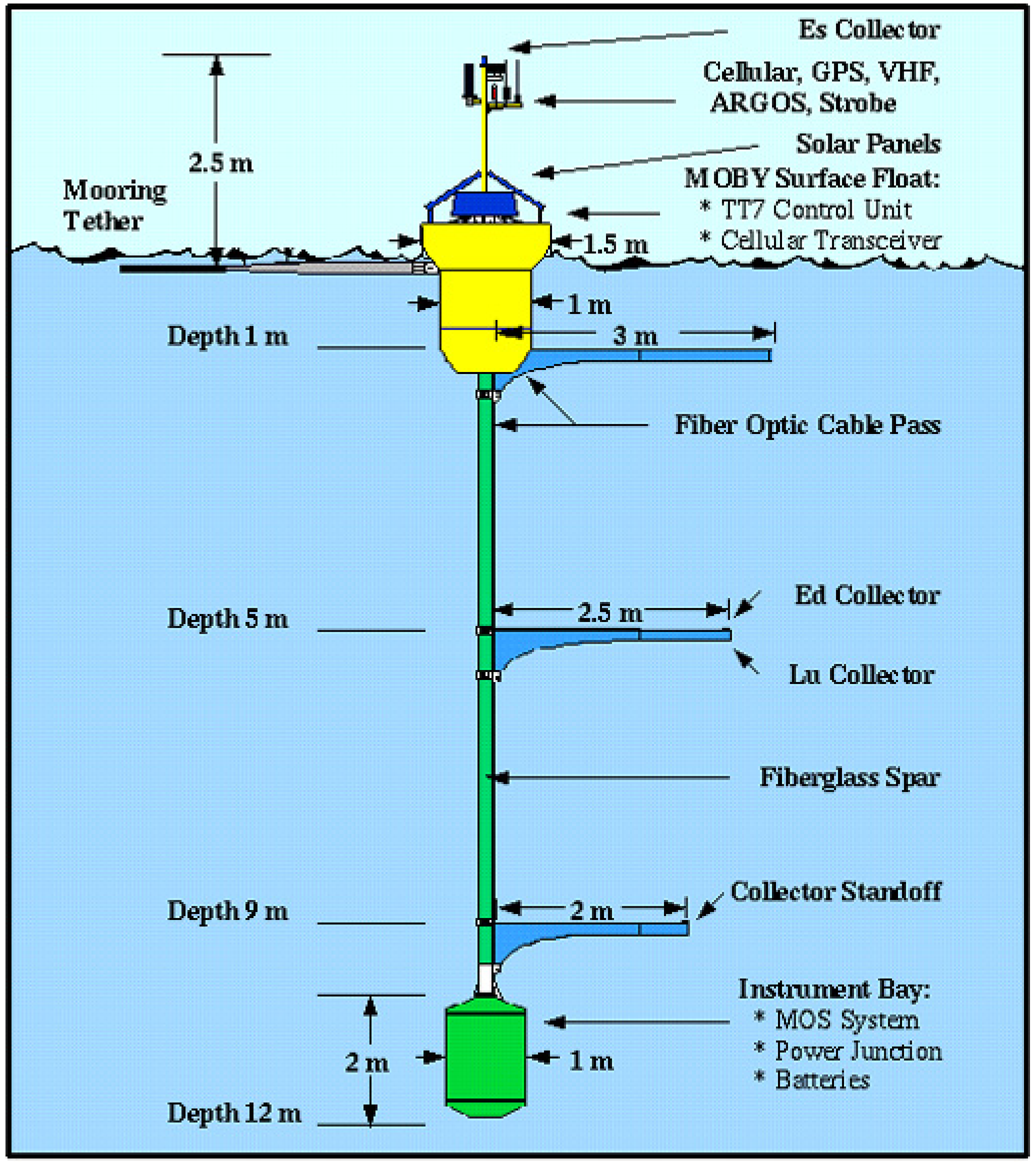
Used to monitor sensor gain *changes* over time



Fred Patt, GSFC

Marine Optical BouY

- Accurate source for vicarious calibration
- Used with models to set absolute gains
- Located off Hawaii and operational since 1996
- Difficulty with glint & nadir looking satellites (MODIS)
- Other ground obs are used as well



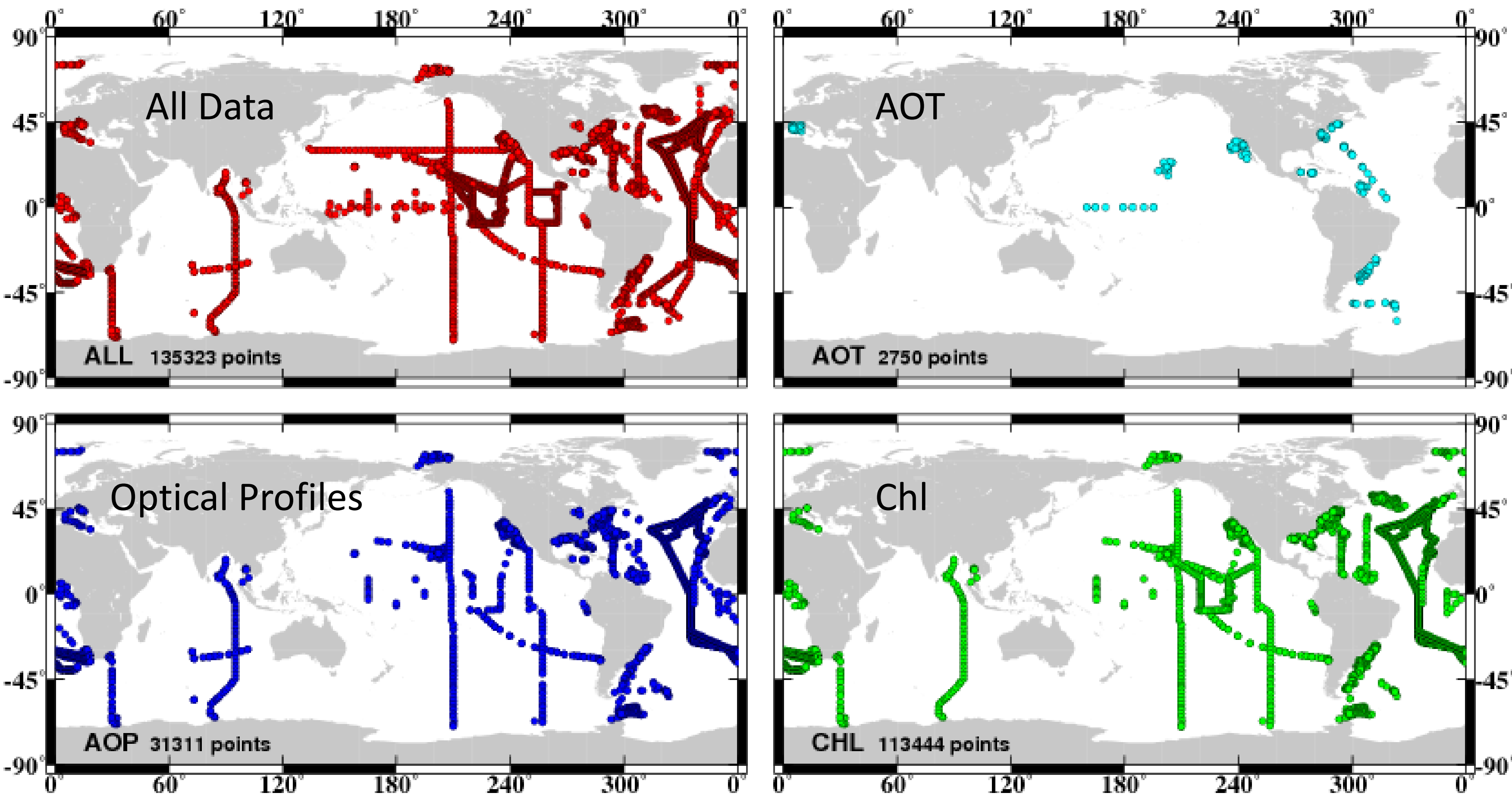
Satellite Sensor Issues

- Accuracy requirements mean that satellite gains need to be known to better than 0.005
- Accurate ground data are required - MOBY+
  End-to-end test -> vicarious calibration
- Changes in these gains must be monitored
  Lunar viewing or multiple on-board sources
- Other "issues" can creep in (like changes in polarization sensitivity or spectral responses)
- *Reprocessing is key…*

Bio-Optical Modeling

- **Goal**: *Relate water-leaving radiance spectra to useful in-water properties*
- Both empirical & semi-analytical approaches
- Need simultaneous measurements of water-leaving radiance & useful in-water properties

Global In Situ Data - SeaBASS

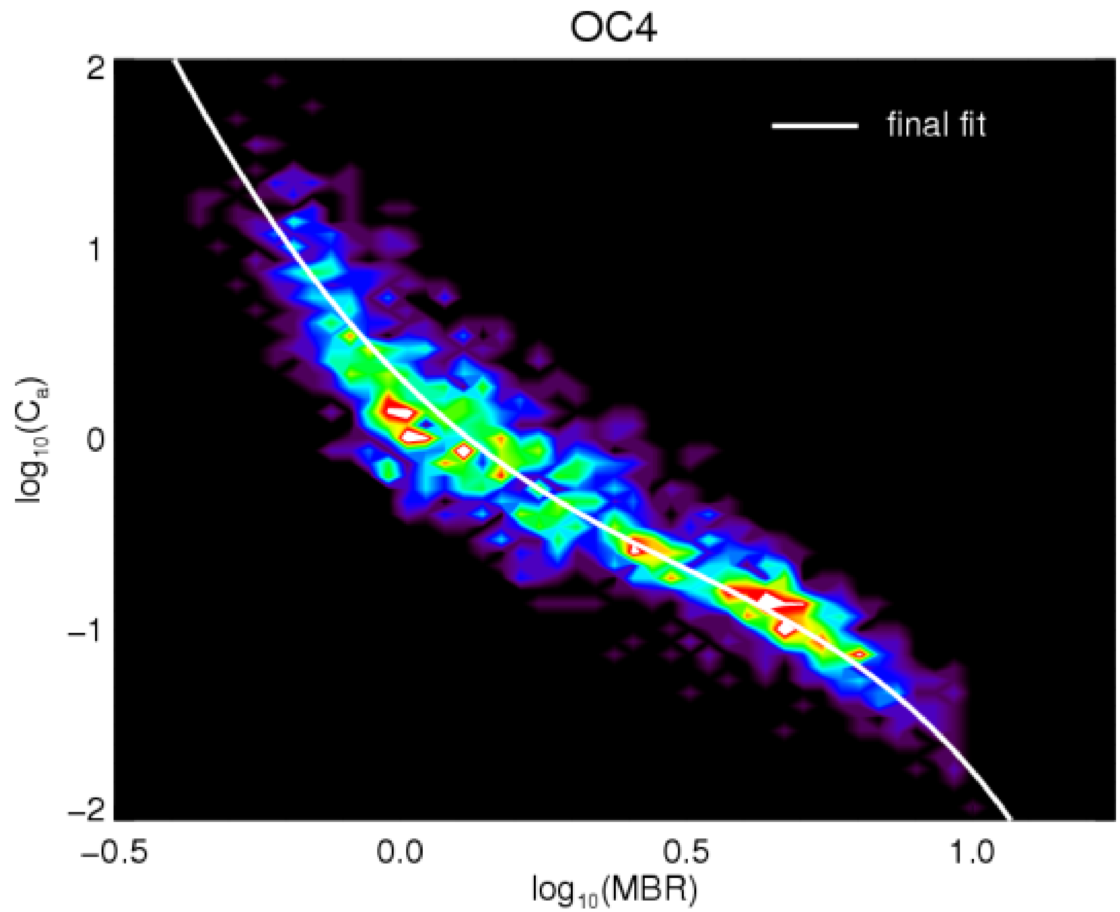


10 Jul 2009 ~ SeaBASS data points

Bio-Optical Algorithm

OC4v6 used for SeaWiFS

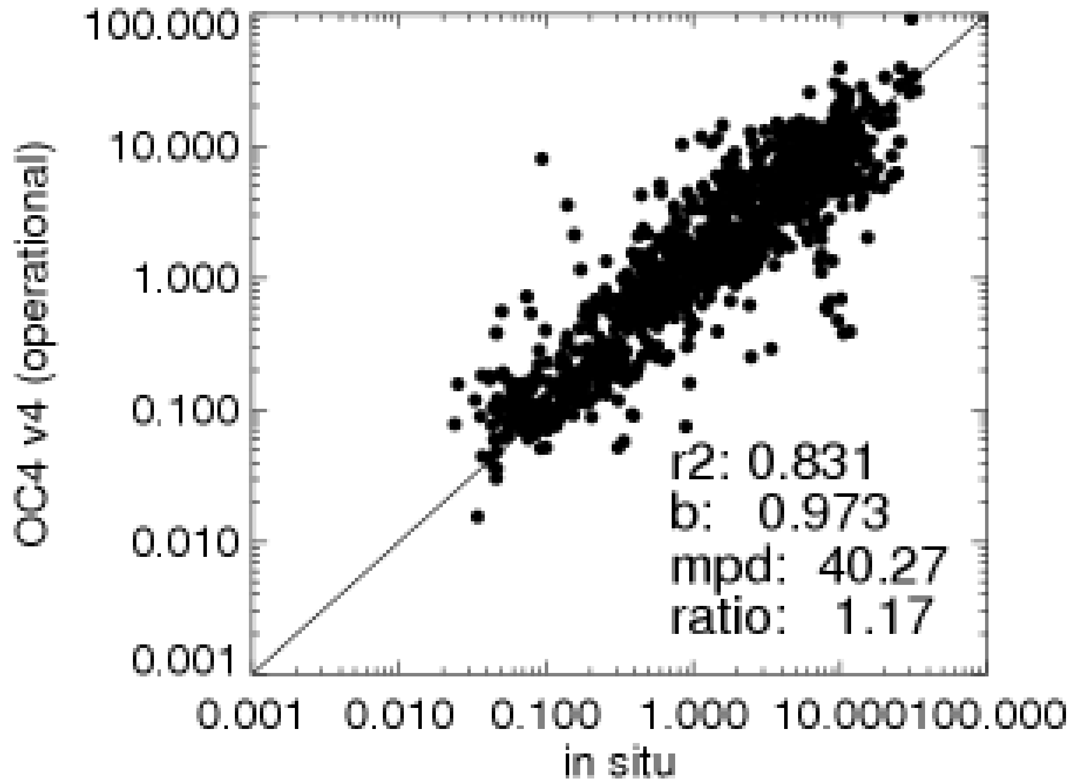
- Empirical
- Maximum Band Ratio of $L_{wN}(\lambda)$'s (443/555, 489/555 & 510/555)



From GSFC reprocessing page following O'Reilly et al. [1998] JGR

End-to-End Validation

- OC4v6 w/ SeaWiFS
- Global match-up data set of SeaWiFS & in situ Chl’s
- Regression & the fit slope are very good

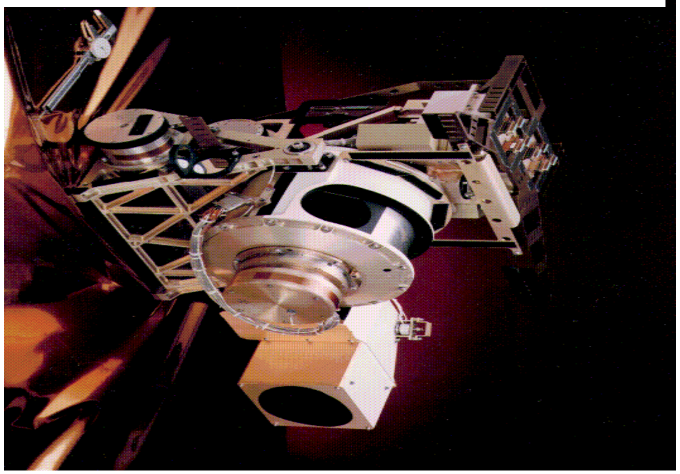


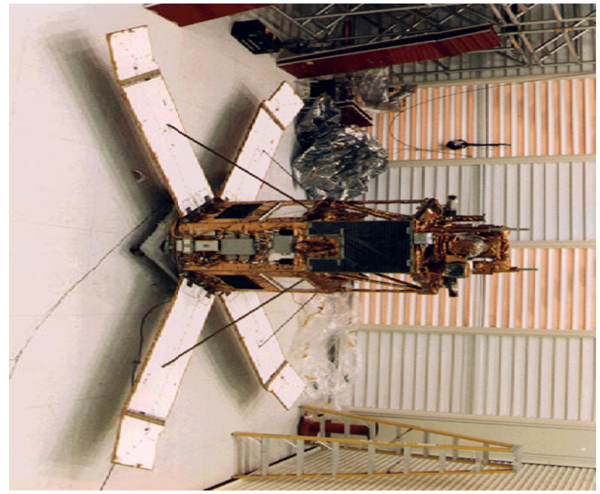
http://oceancolor.gsfc.nasa.gov/REPROCESSING/R2009/ocv6/

Ocean Color Components

- Ocean color signals are small *(great measurements require great care…)*
- We must account for the atmosphere *(radiative transfer in the atmosphere)*
- Relate water-leaving radiance to bio-optical properties*(ocean optics & relationship to ecology)*
- Validate we can do this end-to-end through the entire system *(this requires periodic reprocessing)*

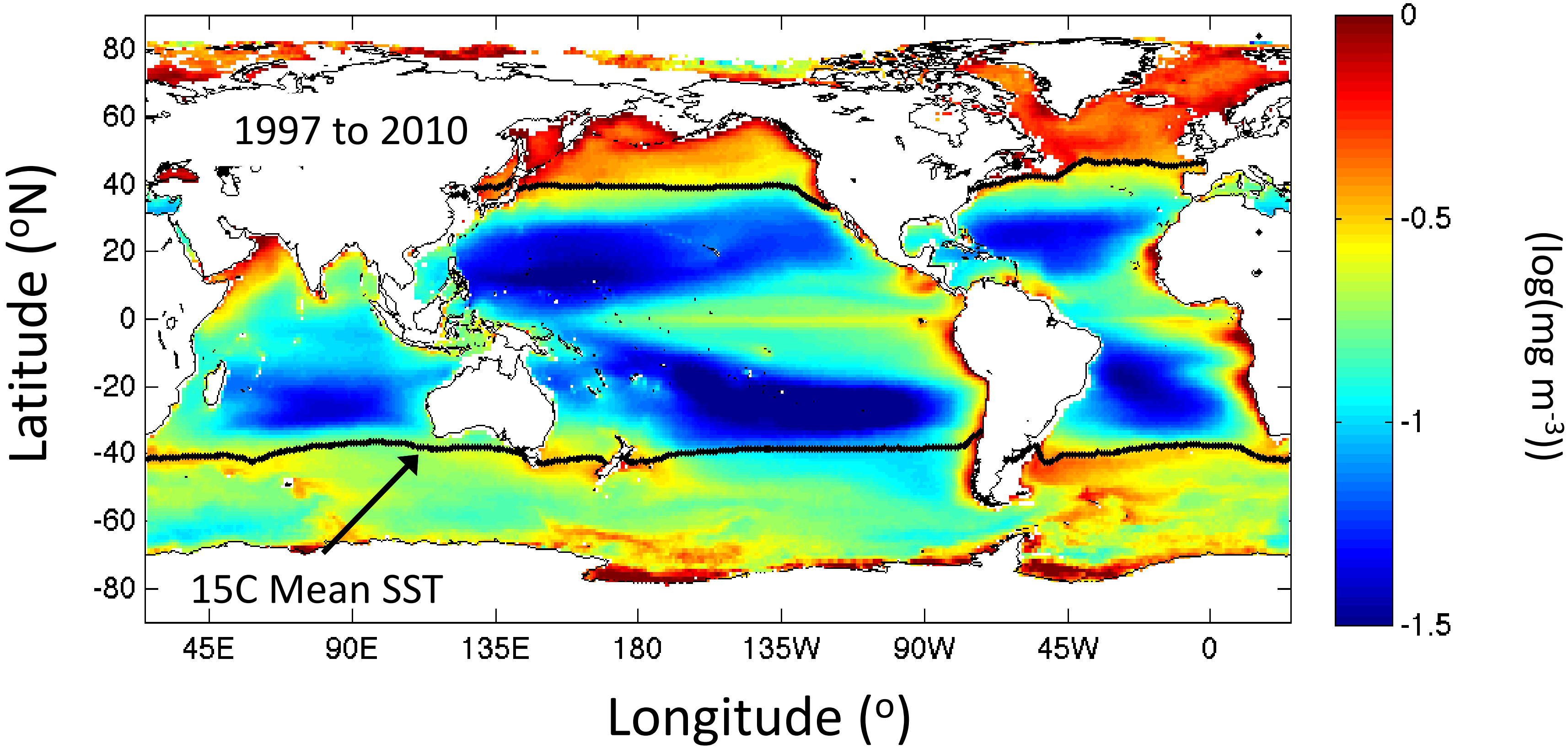
SeaWiFS: 1997-2010





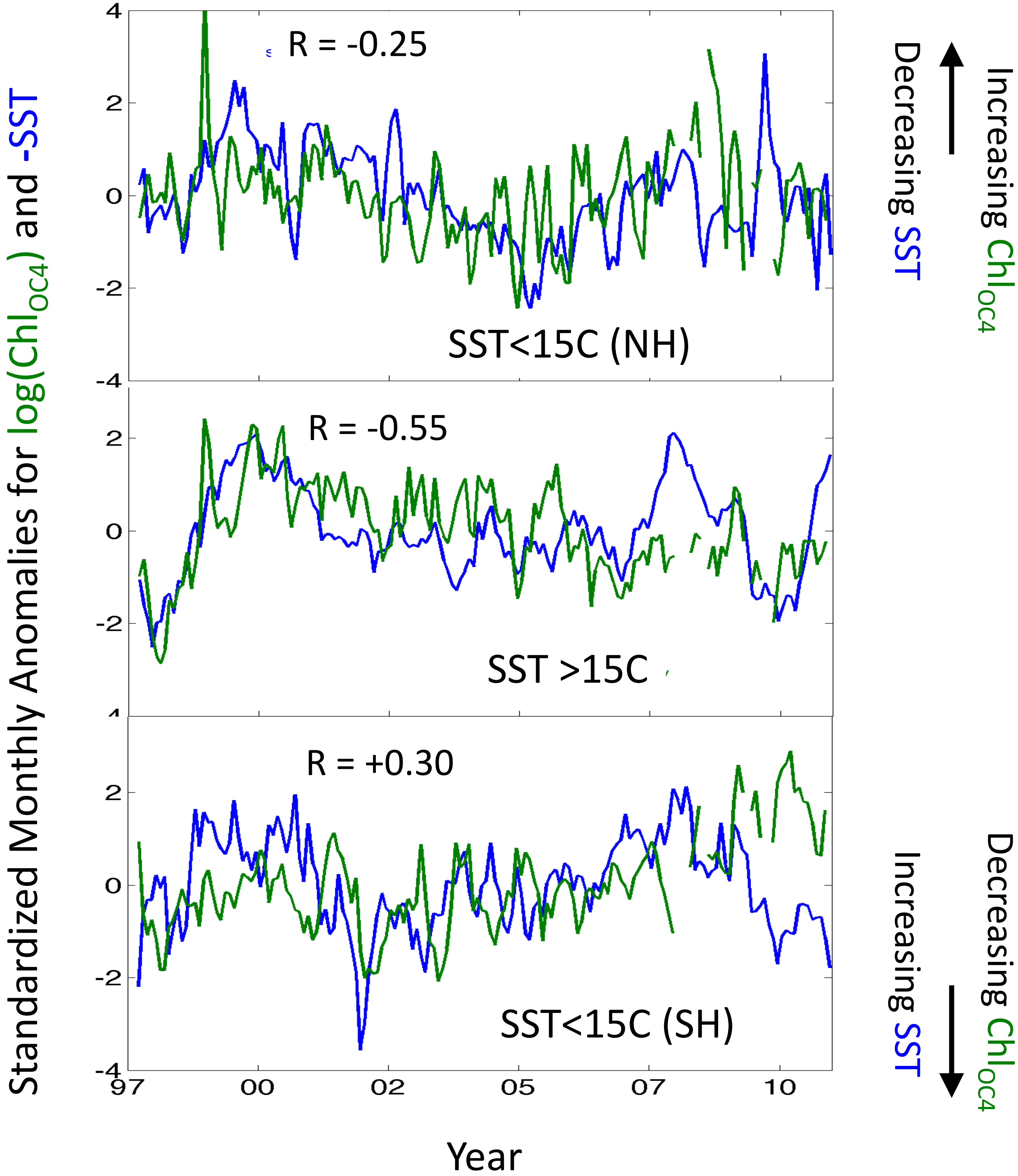
Death of SeaWiFS: 1997-2011

SeaWiFS Mission Mean Chlorophyll



Basic patterns are well predicted by large scale wind driven circulation as suggested by Harald Sverdrup > 50 years ago!!

What does SeaWiFS tell us about change over its 13 years in space?



Trends by Region

Not Significant
+0.035 °C/y

-0.18 %/y
+0.015 °C/y

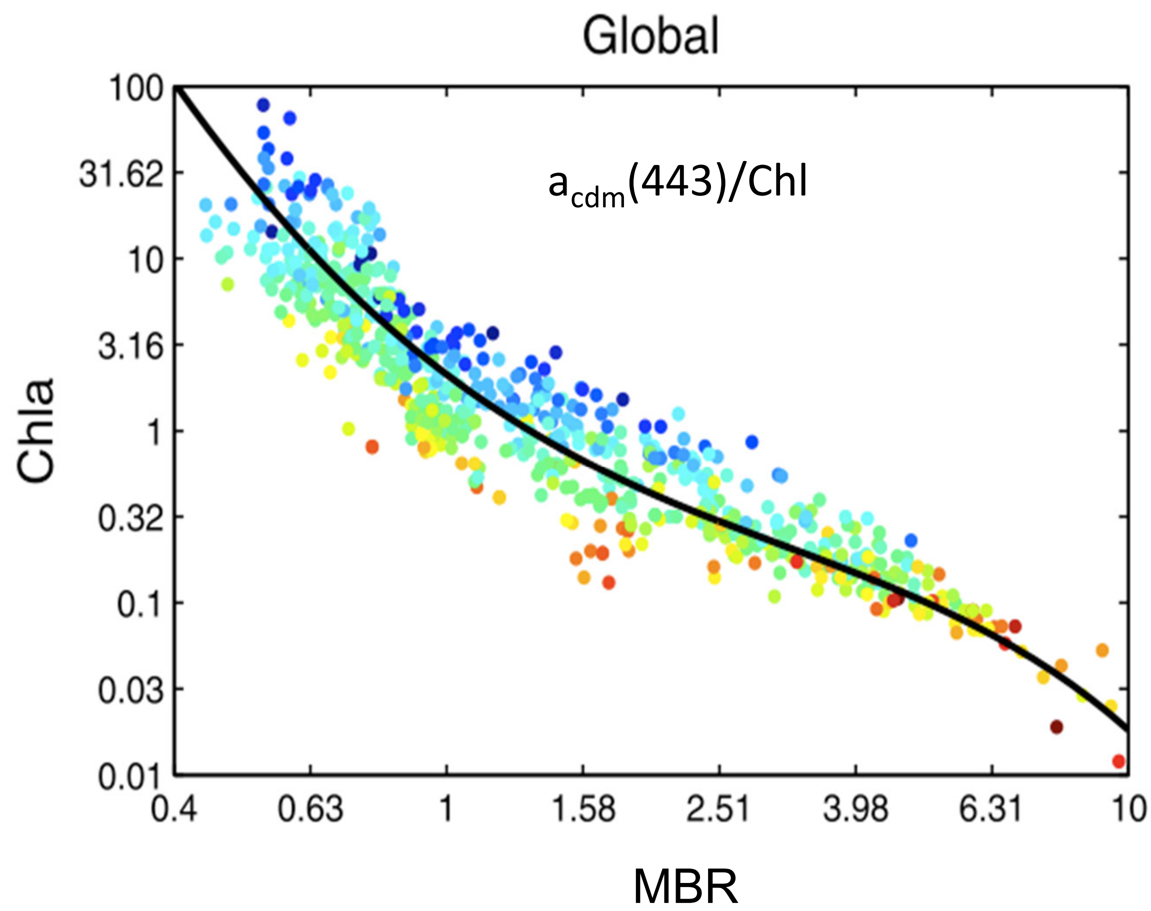
+0.83 %/y
+0.029 °C/y

Is this the whole story?

Operational Chlorophyll Algorithm

OC4v6 algorithm

- Empirical
- Maximum Band Ratio of $L_{wN}(\lambda)$'s (443/555, 489/555 & 510/555)



Szeto et al. JGR [2011] analysis of NOMAD data

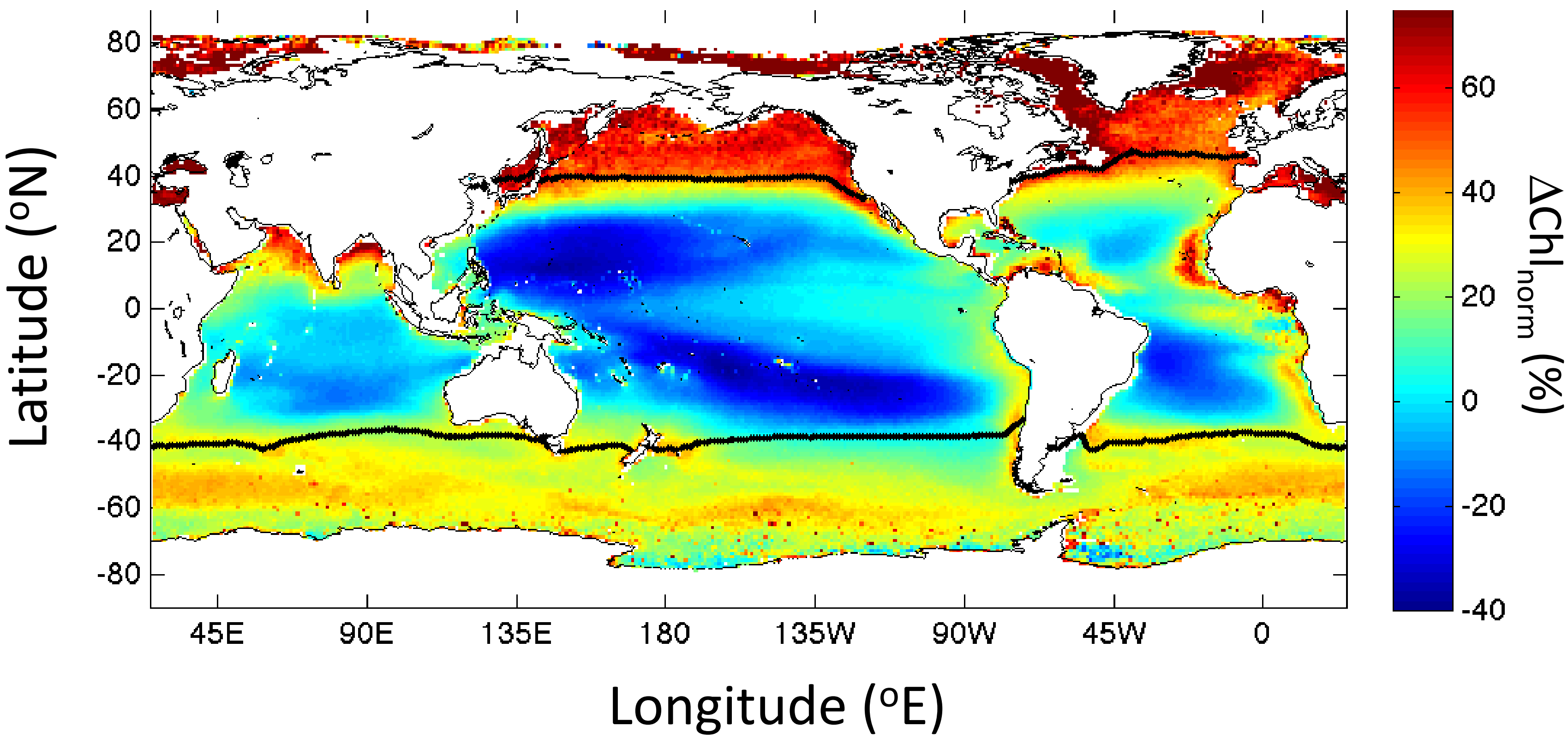
Need to remove the CDOM signal!

GSM Semi-Analytic Model

- Retrieves three relevant properties (CDM, BBP, Chl)
- Assumptions…
  - Relationship between $L_{wN}(\lambda)$ & IOP's is known
  - Component spectral shapes are constant
  - Water properties are known
  - In open ocean, CDM is almost entirely CDOM
- Model coefficients determined using field obs
- Validation statistics for Chl_{GSM} with SeaWiFS observations are nearly as good as for Chl_{OC4}

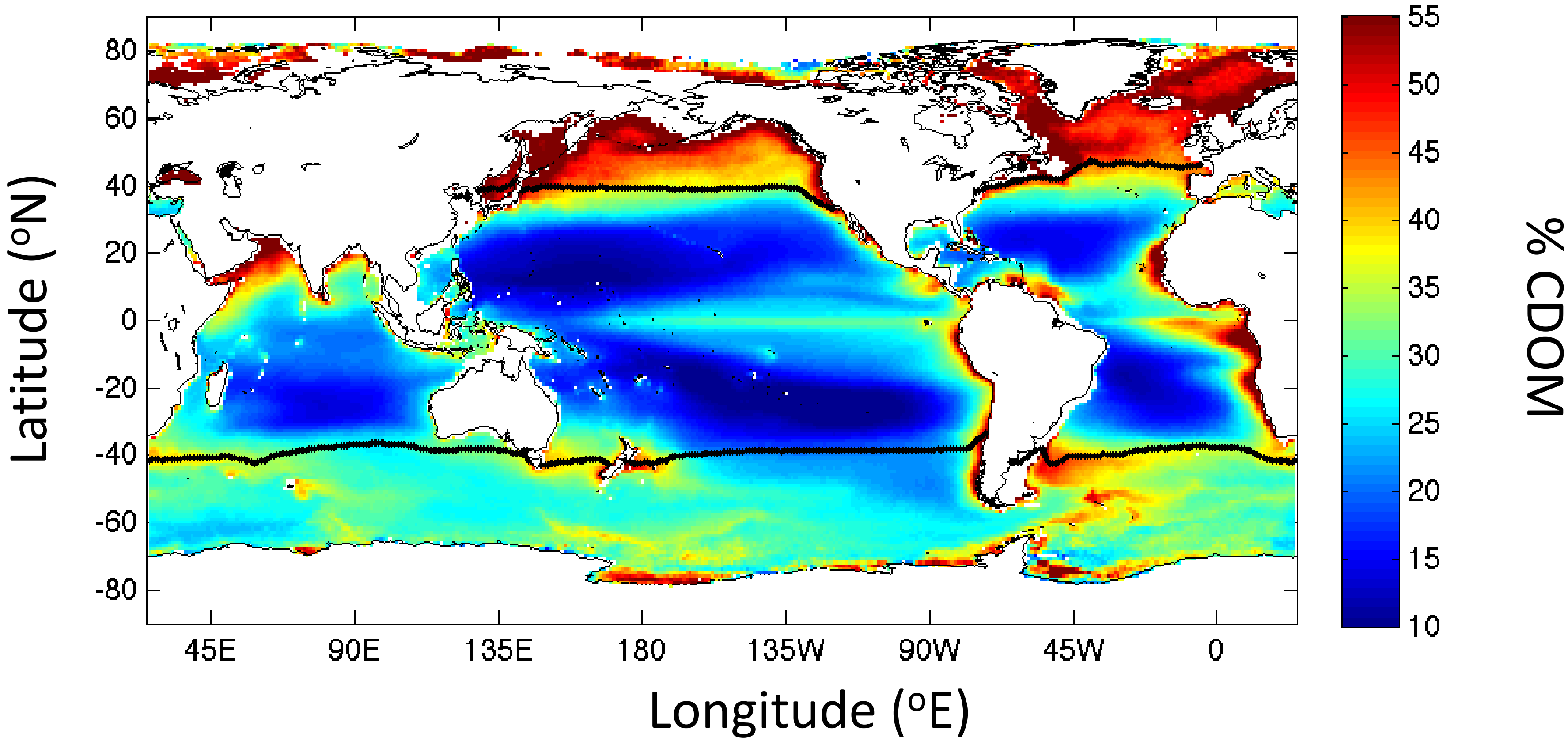
Following from Siegel et al. [in review]

Difference Between OC4v6 & GSM Chl's



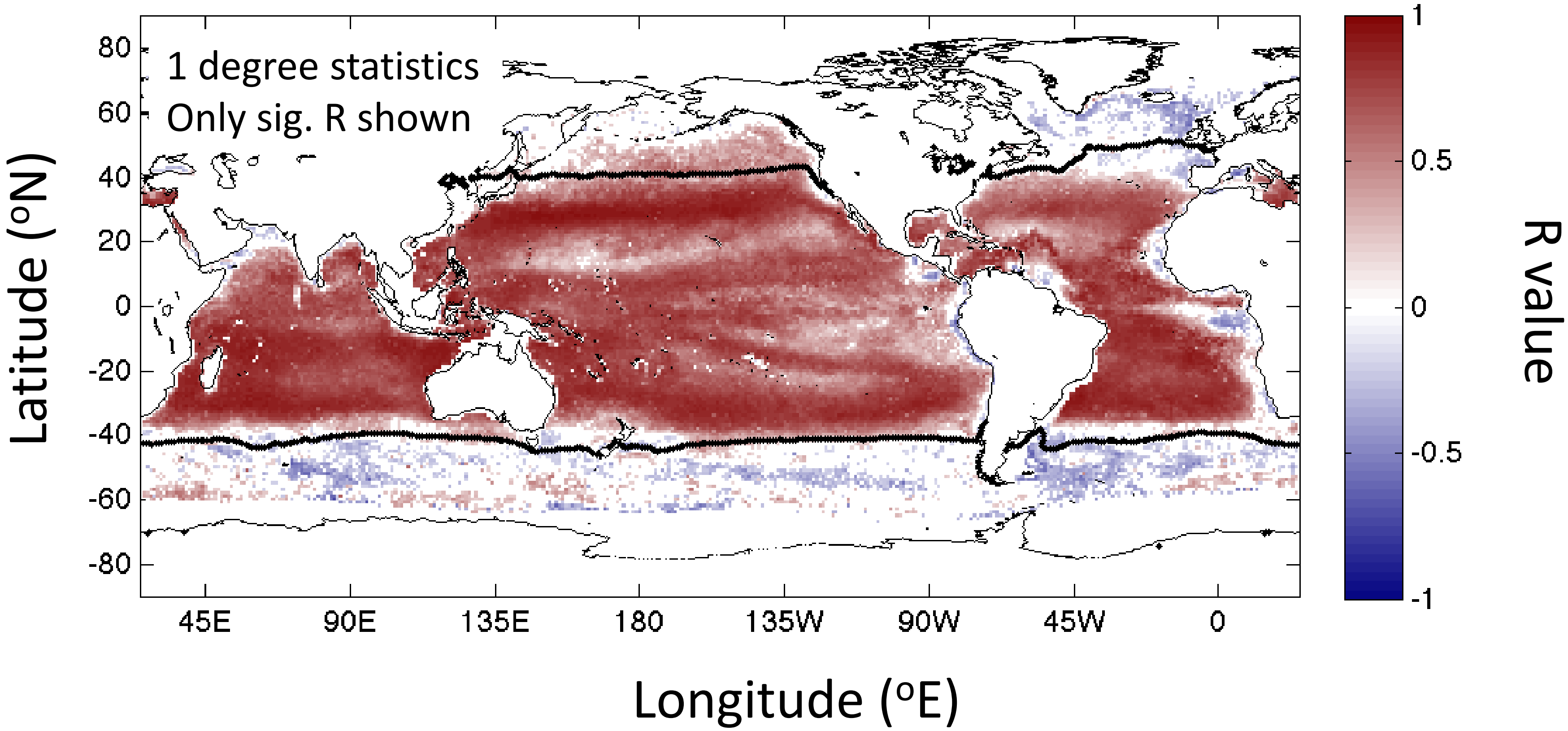
- $\Delta Chl_{norm} = 100 * (Chl_{OC4} - Chl_{GSM})/Chl_{GSM}$
- $Chl_{OC4} > Chl_{GSM}$ by ~60% in high NH, known riverine sources, etc.
- Chl_{OC4} ~20% lower in subtropical gyres
- Chl_{OC4} ~30% higher in the Southern Ocean

Mean Contribution of CDOM to Absorption



- Defined as $a_{cdm}(443) / (a_{cdm}(443)+a_{ph}(443))$ retrieved using GSM
- High in subpolar NH oceans & low in subtropical oceans
- Spatial patterns for %CDOM & ΔChl_{norm} are highly correlated (R=0.66)

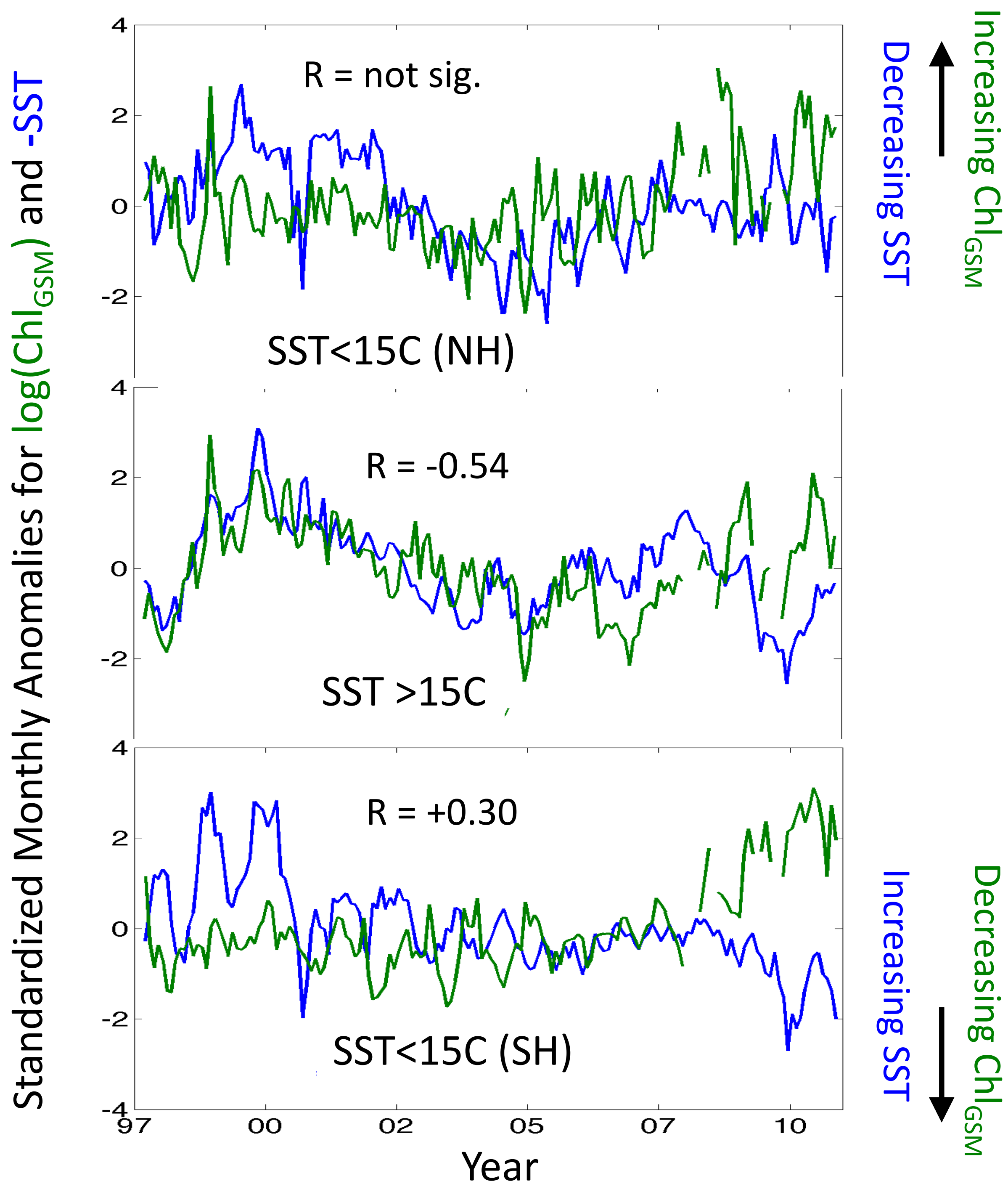
Temporal Correlation of ΔChl_{norm} & %CDOM



- High positive correlation between ΔChl_{norm} & %CDOM in warm ocean
- Correlations are mixed for regions where mean SST < 15^{o}C

Empirical Algorithms & CDOM

- Mean patterns in ΔChl_{norm} & %CDOM are well related especially for warm & NH cool oceans
- Changes in time of ΔChl_{norm} & %CDOM are well correlated for the warm ocean but not outside
- Both point to CDOM affecting Chl_{OC4} retrievals



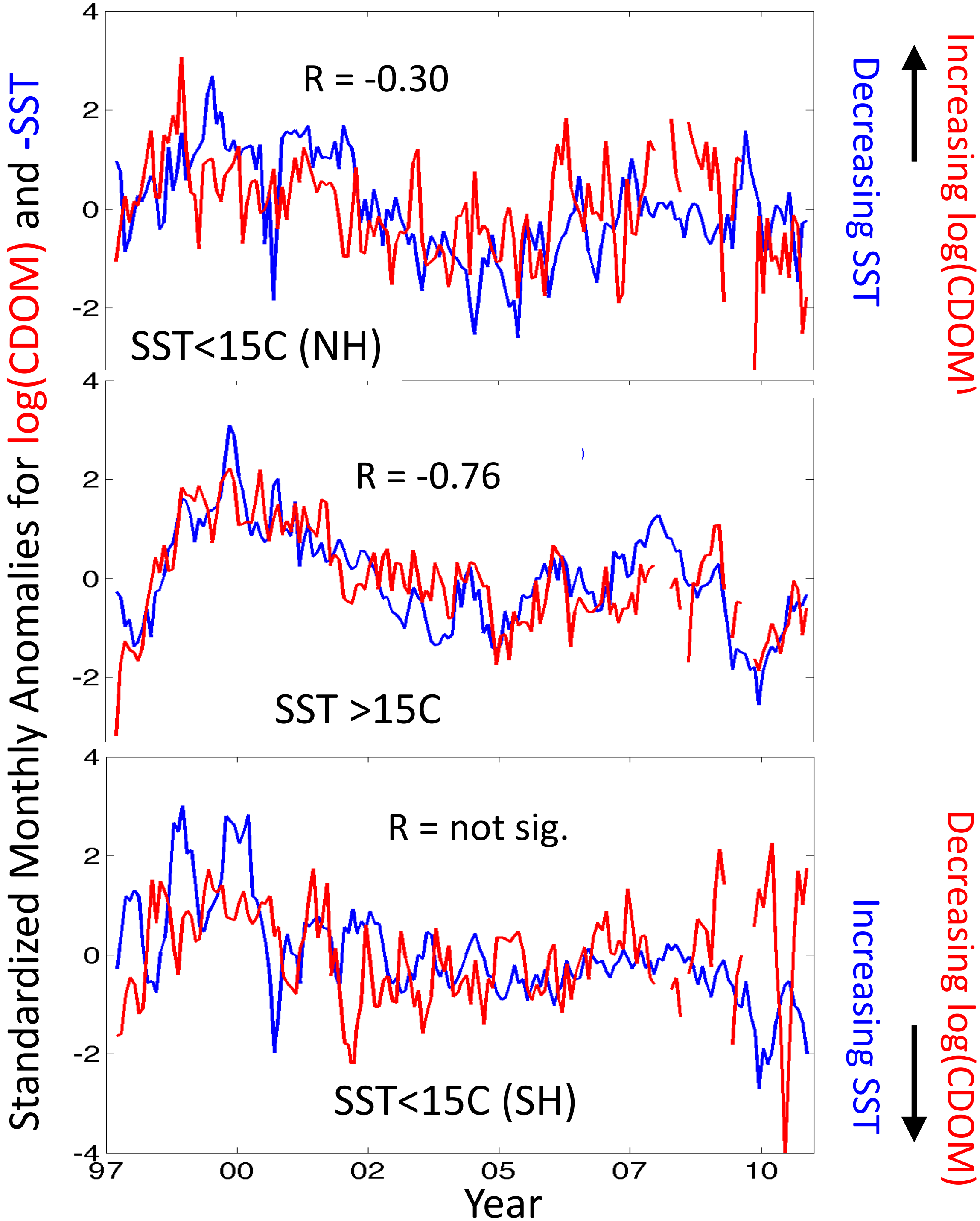
Trends by Region

+0.79 %/y
+0.035 °C/y

not significant
+0.015 °C/y

+1.03 %/y
+0.029 °C/y

OC4 Chl showed decreases in warm ocean!!



Trends by Region

-0.56 %/y
+0.035 °C/y

-0.31 %/y
+0.015 °C/y

not sig
+0.029 °C/y

OC4 Chl showed decreases in warm ocean!!

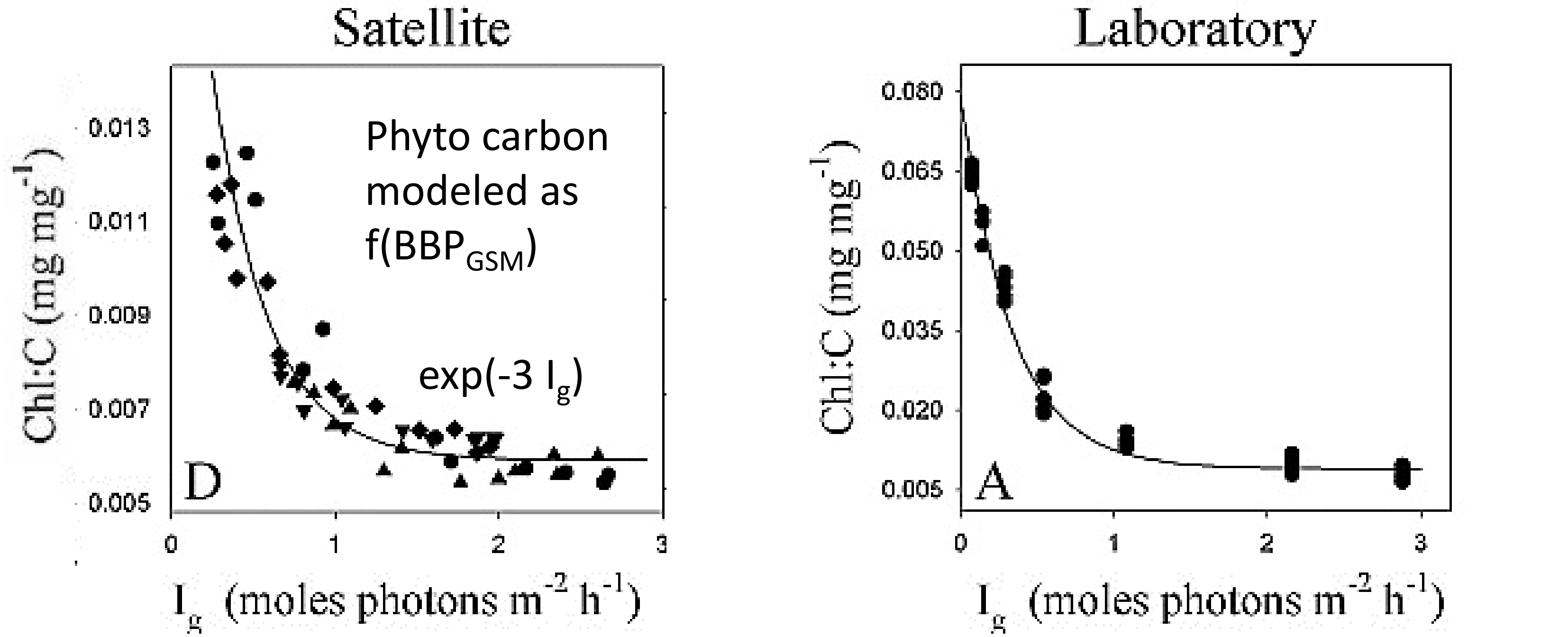
What do we learn about global trends?

- SeaWiFS trends are negative for Chl_{OC4} in the warm ocean but they are insignificant for Chl_{GSM}
- CDOM trends in the warm ocean are also negative (which may explains the Chl_{OC4} trends)
- Trends for Chl_{GSM} are increasing for cool oceans
- Correlations with SST are greatest with CDOM
- Don’t see the 1%/y decrease of Boyce et al. [2010]

So, What is Chlorophyll Really?

- Chlorophyll = f(phytoplankton abundance, physiological adaptations, community composition, …)
- Global patterns reflect abundance changes due to regional nutrient inputs
- But Chl/C’s can change more than five-fold
- Q: Are changes in Chl_{GSM} due to biomass or physiology?

Chl:C from satellite??



Satellite Chl:C for several subtropical regions vs. light

Chl:C vs. growth irradiance for *D. tertiolecta*

Opens the door to modeling phytoplankton growth rates & carbon-based NPP

Behrenfeld et al. (2005) GBC

Biomass vs. Physiology?

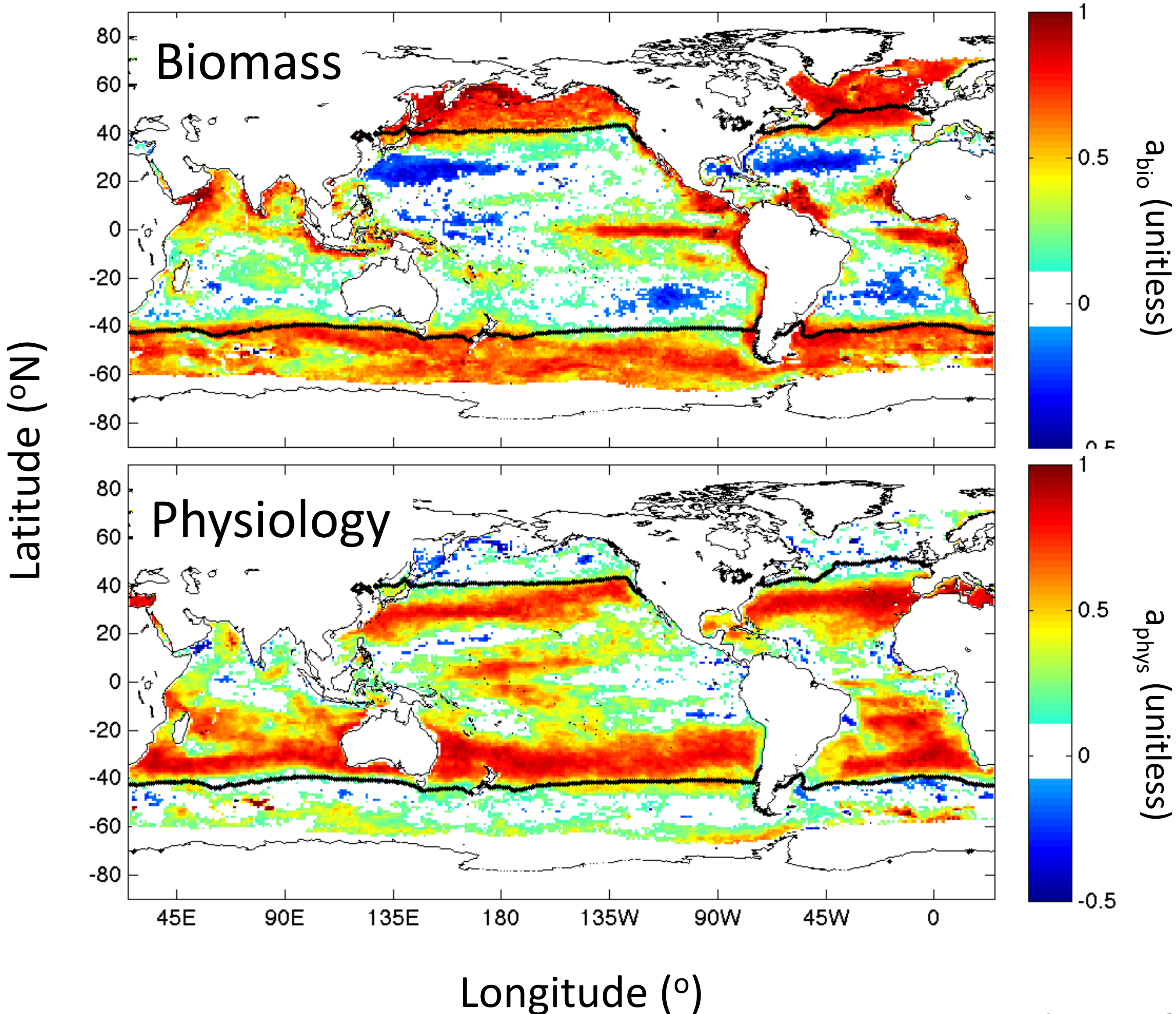
- Are changes in Chl_{GSM} due to biomass or physiology?
- Model changes in Chl_{GSM} as sum of biomass & physiological components

$$\log(\hat{Chl}_{GSM}) = a_{bio}\,(BBP) + a_{phys}\,(BBP * \exp(-3\ I_g))$$

biomass physiology

  - BBP = $b_b(443)$ retrieved from GSM (a proxy for phytoC)
  - $\exp(-3\ I_g)$ represents Chl:C ratio (as before)
  - Regression of standardized variables for each 1^o bin
  - a_{bio} & a_{phys} measure importance of each process

Chlorophyll is a Poor Metric for Biomass



Upwelling regions & the perpetually cool oceans

Subtropics

Only significant correlations shown

So, is it biomass or physiology?

- Biomass contributions dominate the high latitude oceans & regions of coastal & equatorial upwelling
- Physiology contributions dominate the subtropics
- Not much explained in the tropics (but not much variability in Chl_{GSM})
- Points to chlorophyll being a poor index for phytoplankton biomass for all regions

Need to Get Past Chlorophyll already!

- CDOM signals are huge – bias trends – mask phytoplankton signals
- Band ratio models are dangerous – especially with small signals due to climate variations
- For much of the oceans, chlorophyll is not useful as a metric for phytoplankton biomass
- Future missions (i.e., PACE) must be designed for this reality while enabling more extensive products (PFT's, PSD, physiology, etc.)


Thank You for
Your Attention!!
Special Thanx to the NASA Goddard
Ocean Biology Processing Group
and the
NRC Committee on Sustained Ocean Color Obs