# Remote Sensing Reflectance and Derived Products: MODIS & VIIRS

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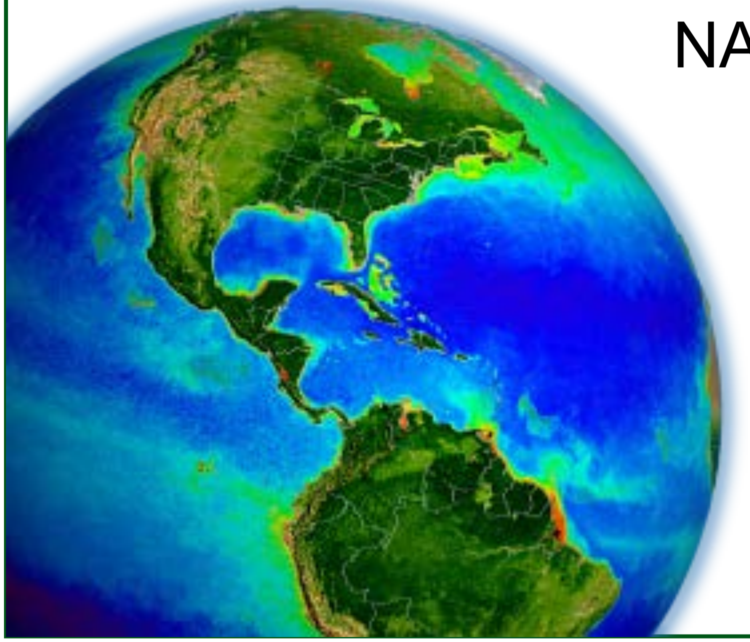


MODIS/VIIRS Science Team Meeting

6-10 June 2016, Silver Spring, MD

# Definition

Remote Sensing Reflectance, Rrs($\lambda$; $sr^{-1}$), is water-leaving radiance, Lw($\lambda$), corrected for bidirectional effects of the air-sea interface and sub-surface light field, and normalized by downwelling solar irradiance, Ed($\lambda$), just above the sea surface.

Rrs($\lambda$) is the fundamental measurement from which ocean color (OC) products such as phytoplankton chlorophyll concentration and marine inherent optical properties are derived.

Primary purpose of our work is to develop a stable and consistent, long-term OC time-series spanning multiple mission lifetimes to support global change research and applications.

# Proposal Team: MODIS & VIIRS

| Team Member | Primary Role |
|---|---|
| Bryan Franz | project lead & quality assessment |
| Zia Ahmad | atmospheric correction |
| Sean Bailey | vicarious calibration & software |
| Gene Eplee | VIIRS calibration |
| Gerhard Meister | MODIS calibration |
| Chris Proctor | in situ validation |
| Kevin Turpie | VIIRS prelaunch |
| Jeremy Werdell | bio-optical algorithms |

and the Ocean Biology Processing Group ...

# Contents

# R2014.0 Multi-Mission Ocean Color Reprocessing

## Scope

- CZCS, OCTS, SeaWiFS, MERIS, MODIS(A/T), and VIIRS

## Motivation

1. improve interoperability and sustainability of the product suite by adopting modern data formats, standards, and conventions (netCDF4, CF and ISO conventions, etc.)
2. incorporate algorithm updates and advances from community and science teams
3. incorporate knowledge gained in instrument-specific radiometric calibration and updates to vicarious calibration

## Status

- CZCS, OCTS, **VIIRS, MODISA, MODIST**, SeaWiFS (& GOCI) **done**
- MERIS in progress

# PRODUCT AND ALGORITHM CHANGES

| | |
|---|---|
| $R_{rs}(\lambda)$ | *calibration updates, ancillary data updates, improved land/water masking, terrain height, other minor fixes* |
| Ångstrom | |
| AOT | |
| Chlorophyll *a* | *standard chlor_a product now OCI algorithm (Hu et al. 2012)*<br>*original OC3/OC4 product still being distributed as chl_ocx* |
| $K_d(490)$ | *no change* |
| POC | *no change* |
| PIC | *updated algorithm and LUT* |
| CDOM_index | *remove product (redundant with new IOP suite)* |
| PAR | *consolidated algorithm, minor fixes* |
| iPAR | *MODIS-only, no change* |
| nFLH | *MODIS-only, flagging changes (allow negatives)* |
| IOPs | *added suite of inherent optical properties (Werdell et al. 2013)* |

# INSTRUMENT CALIBRATION CHANGES

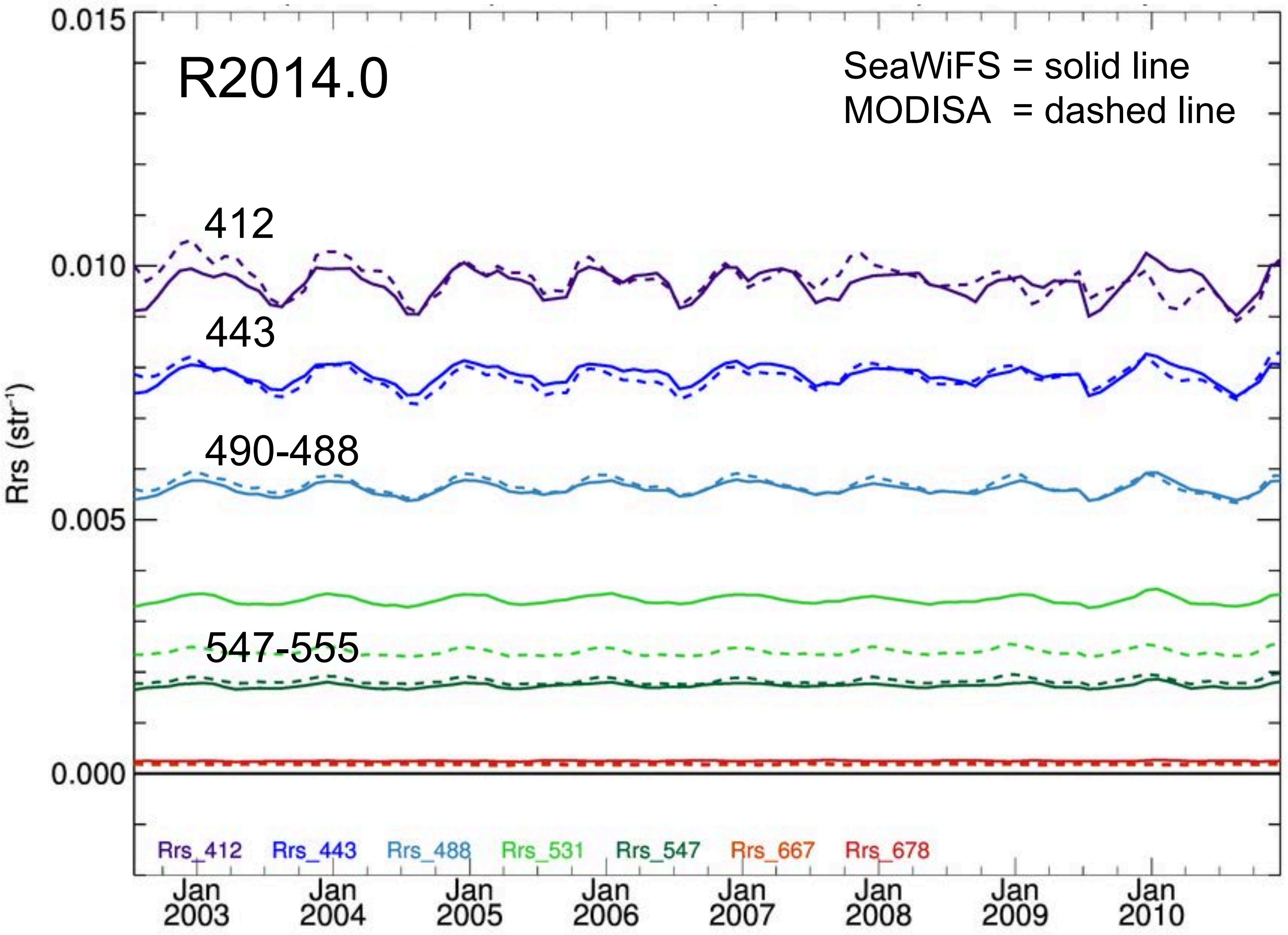
| | |
|---|---|
| SeaWiFS | • *correcting dark offset changes at the sub-count level*<br>• *correction for time-dependent change in system spectral response*<br>• *Patt et al. (in prep), Eplee et al. (in prep)* |
| MODISA | • *updated temporal calibration from MCST (V6.1.35.17_OC2)*<br>• *updated temporal corrections to response versus scan angle*<br>• *Meister and Franz 2014.* |
| MODIST | • *updated temporal calibration from MCST (V6.1.20.16)*<br>• *updated temporal corrections for response versus scan angle and polarization sensitivity (crosscal to SeaWiFS and MODISA)* |
| VIIRS | • *first use of lunar calibration trends to track temporal degradation of VIIRS (lunar calibration is used to correct more frequent but more uncertain solar calibration trends)*<br>• *solar diffuser stability corrections.*<br>• *additional statistical correction for detector striping.*<br>• *Eplee et al. 2015* |

Reprocessed to utilize new NASA-developed 6-minute Level-1A and Level-1B granule format and calibration code. (R2014.0.2)

# Contents

# SeaWiFS & MODISA Rrs(λ) Deep-Water Time-Series

showing good agreement



Mean Ratio

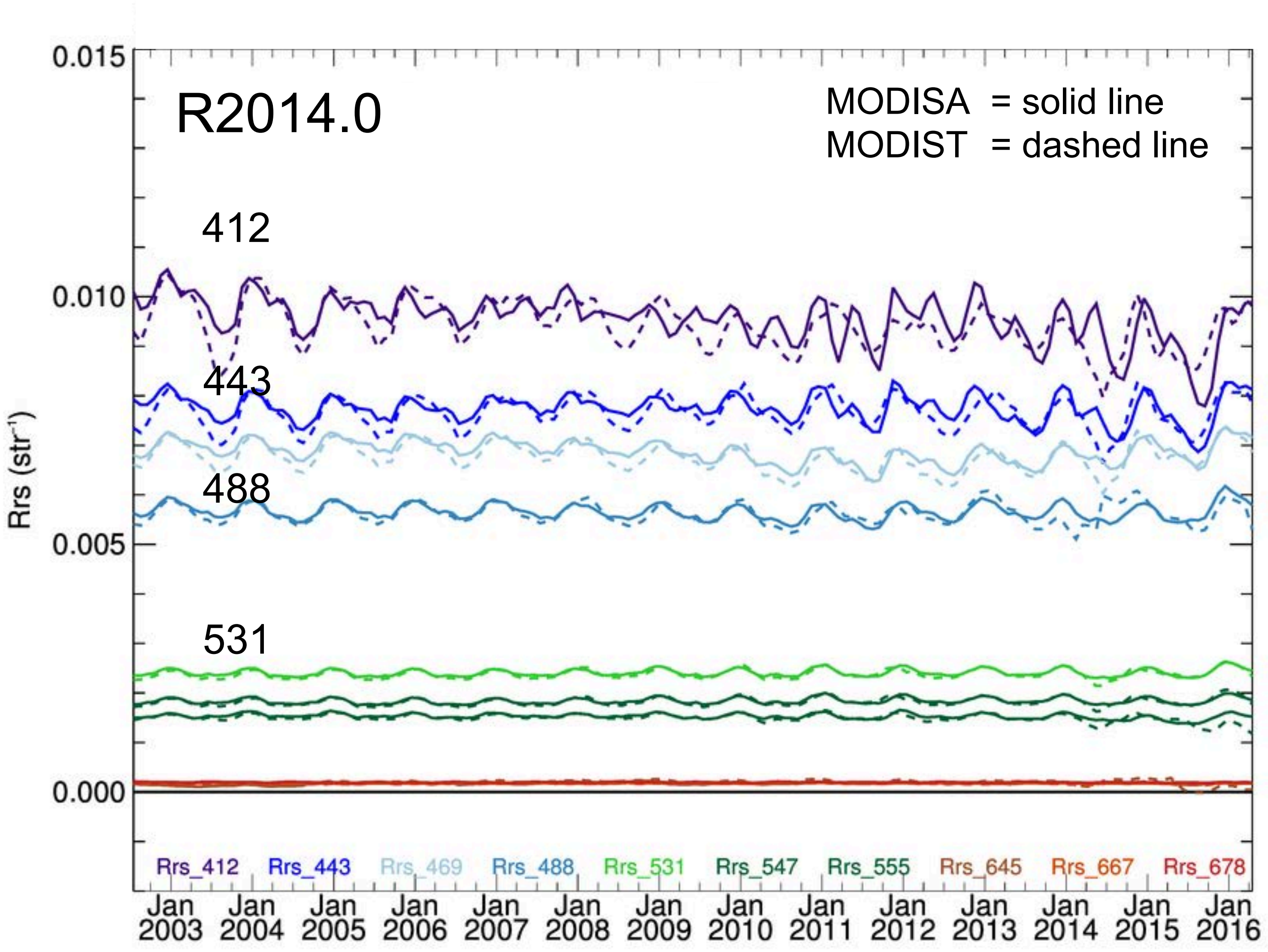
1.01

0.99

1.01

# MODIST & MODISA Rrs(λ) Deep-Water Time-Series

## showing “mostly” good agreement



Mean Ratio

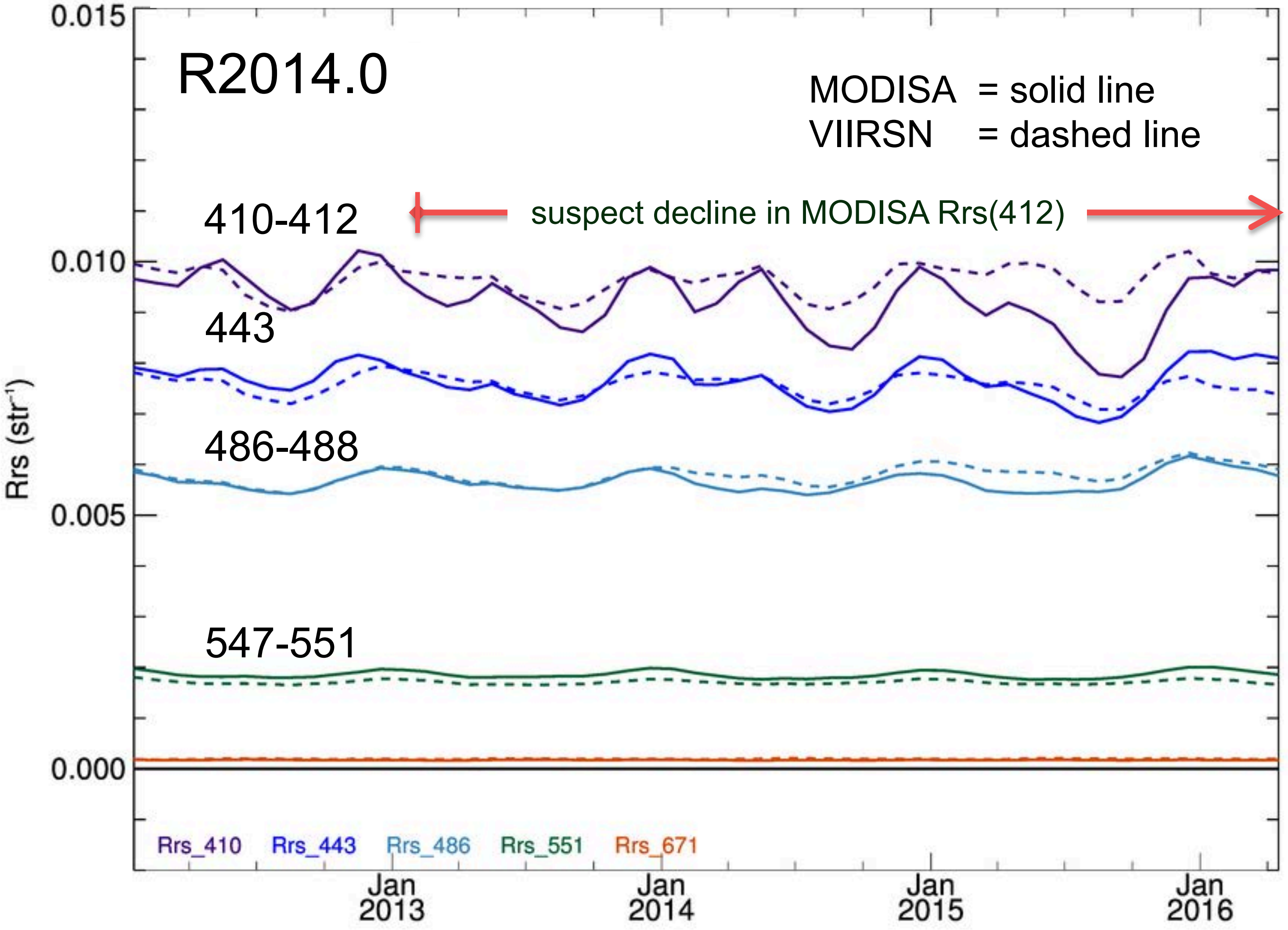
0.99

0.99

0.99

# MODISA & VIIRS Rrs(λ) Deep-Water Time-Series

## showing “mostly” good agreement



Mean Ratio

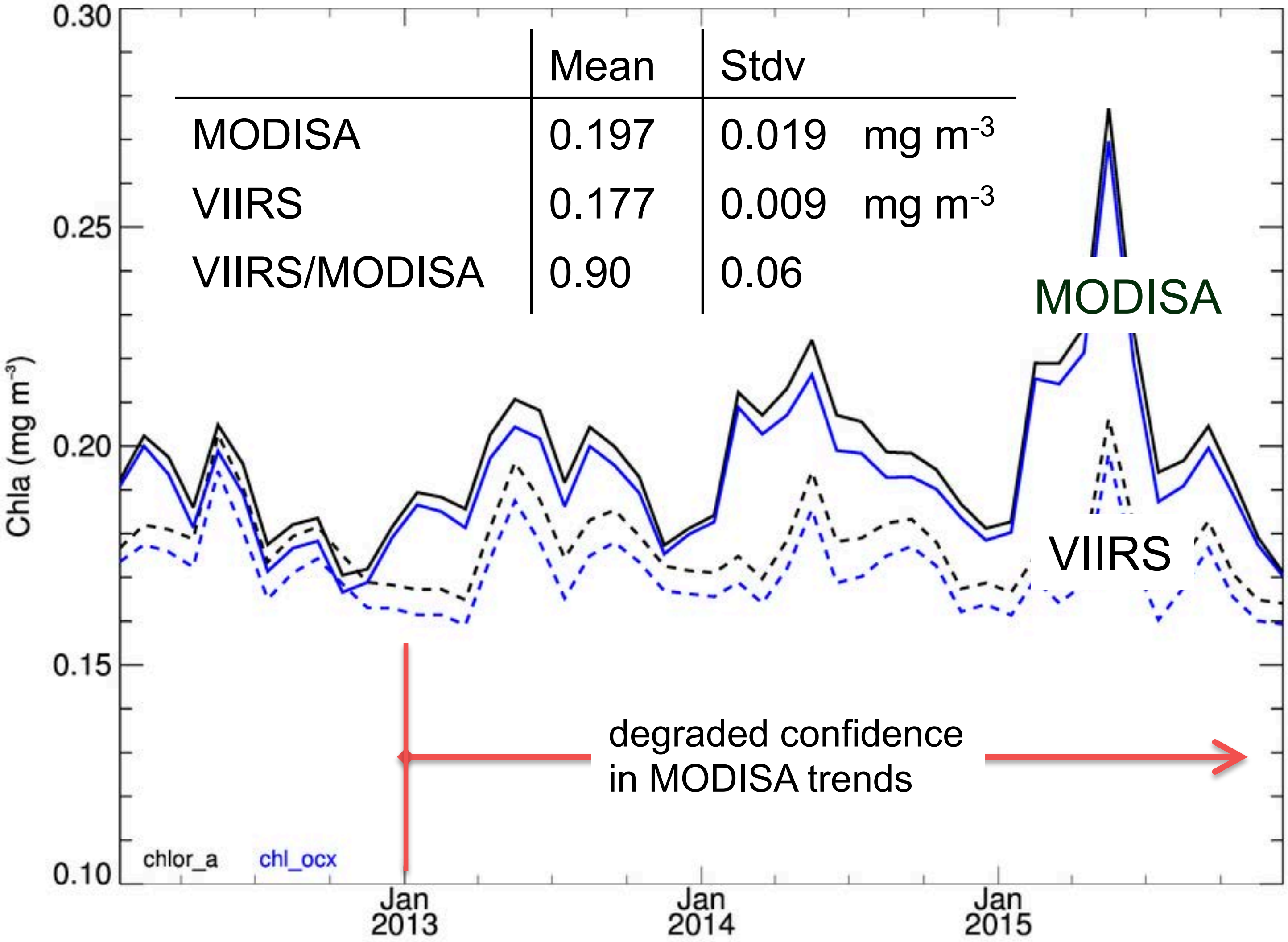
1.04

0.99

1.02

# MODISA and VIIRS R2014.0

## Chlorophyll Deep-Water Time-Series



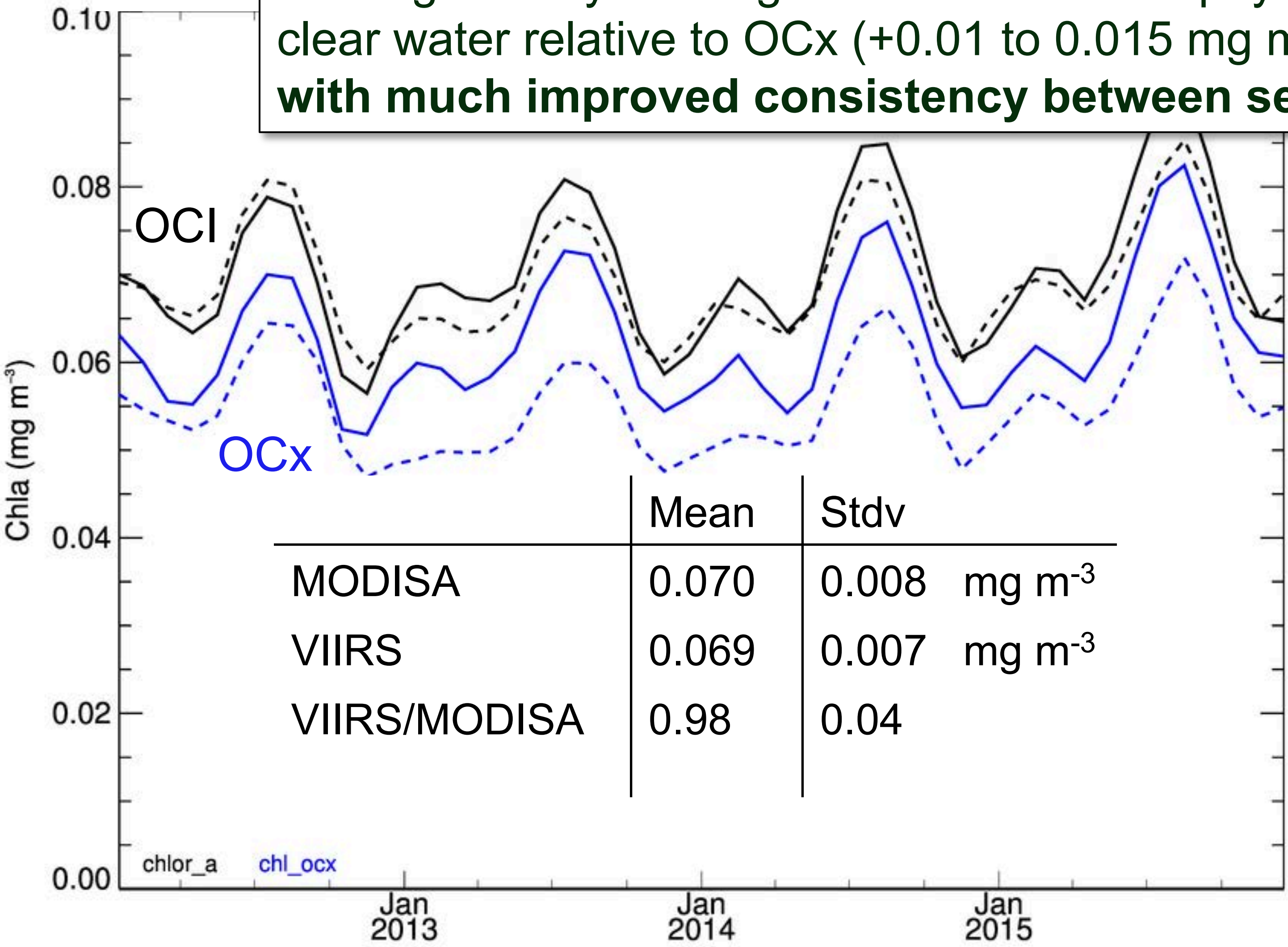
| | Mean | Stdv | |
|---|---|---|---|
| MODISA | 0.197 | 0.019 | mg m$^{-3}$ |
| VIIRS | 0.177 | 0.009 | mg m$^{-3}$ |
| VIIRS/MODISA | 0.90 | 0.06 | |

degraded confidence in MODISA trends

# MODISA and VIIRS R2014.0

## Chlorophyll Clear-Water Time-Series

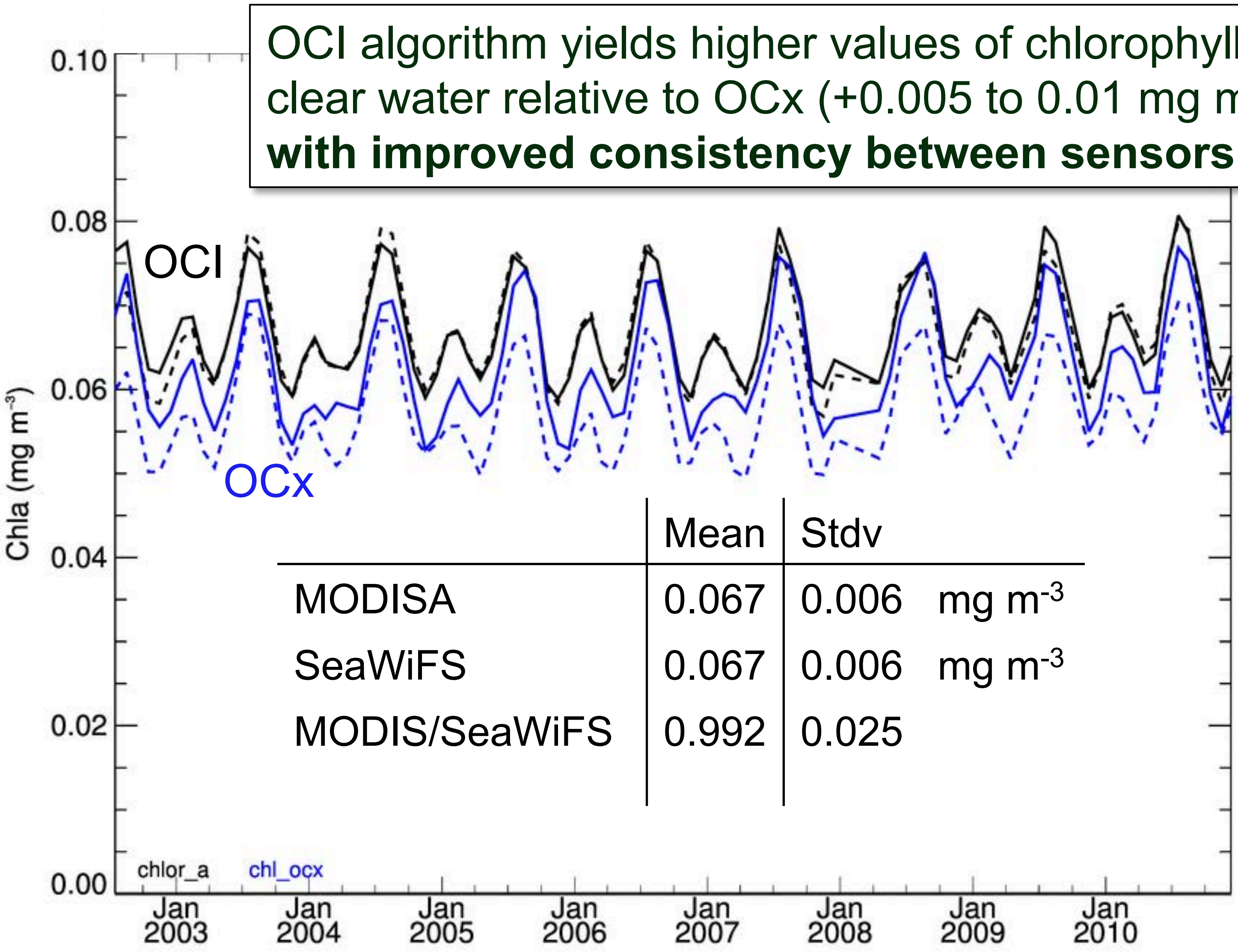
OCI algorithm yields higher values of chlorophyll in clear water relative to OCx (+0.01 to 0.015 mg $m^{-3}$), **with much improved consistency between sensors**.



| | Mean | Stdv | |
|---|---|---|---|
| MODISA | 0.070 | 0.008 | mg $m^{-3}$ |
| VIIRS | 0.069 | 0.007 | mg $m^{-3}$ |
| VIIRS/MODISA | 0.98 | 0.04 | |

# SeaWiFS and MODISA R2014.0

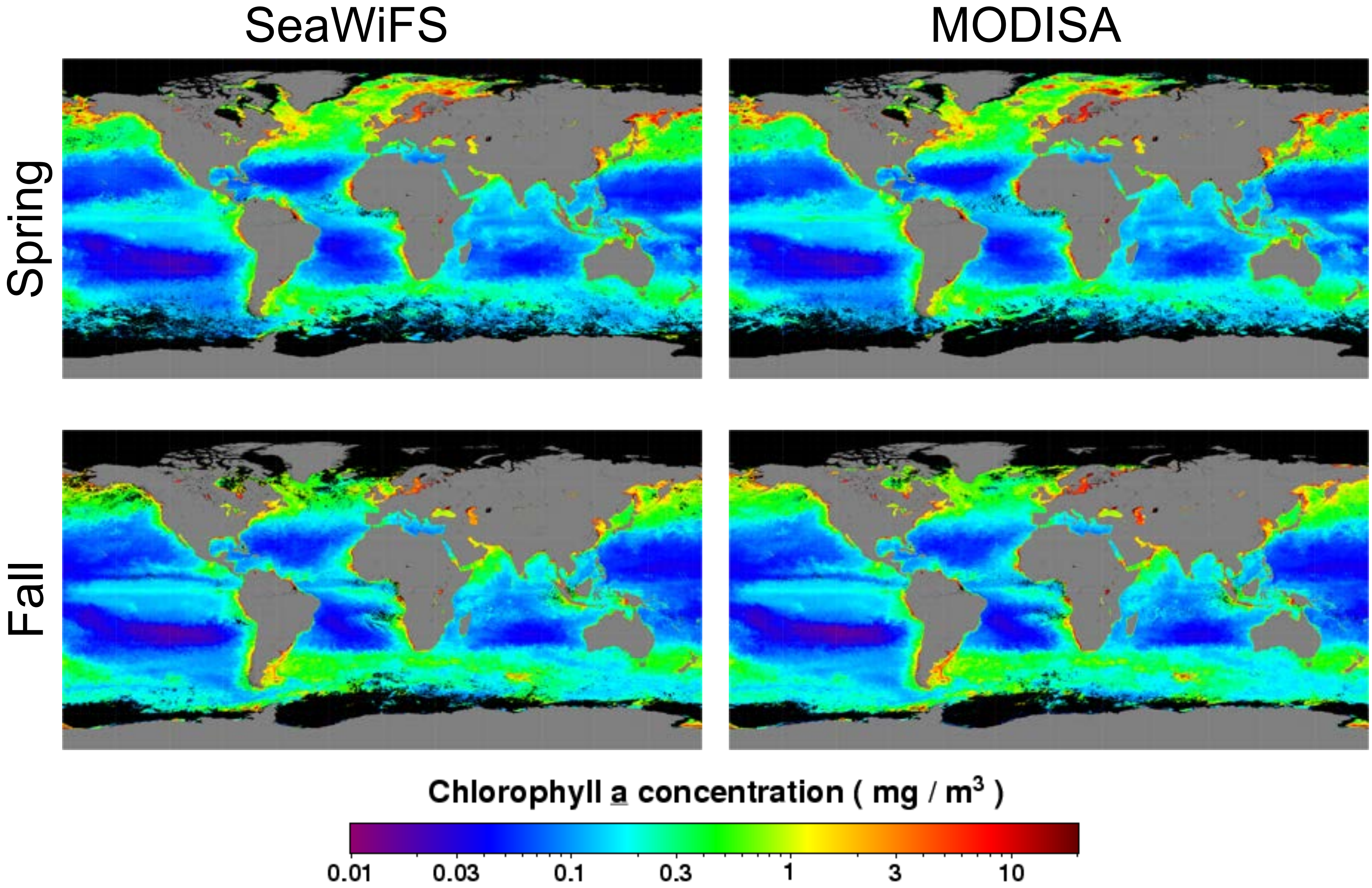
## Chlorophyll Clear-Water Time-Series



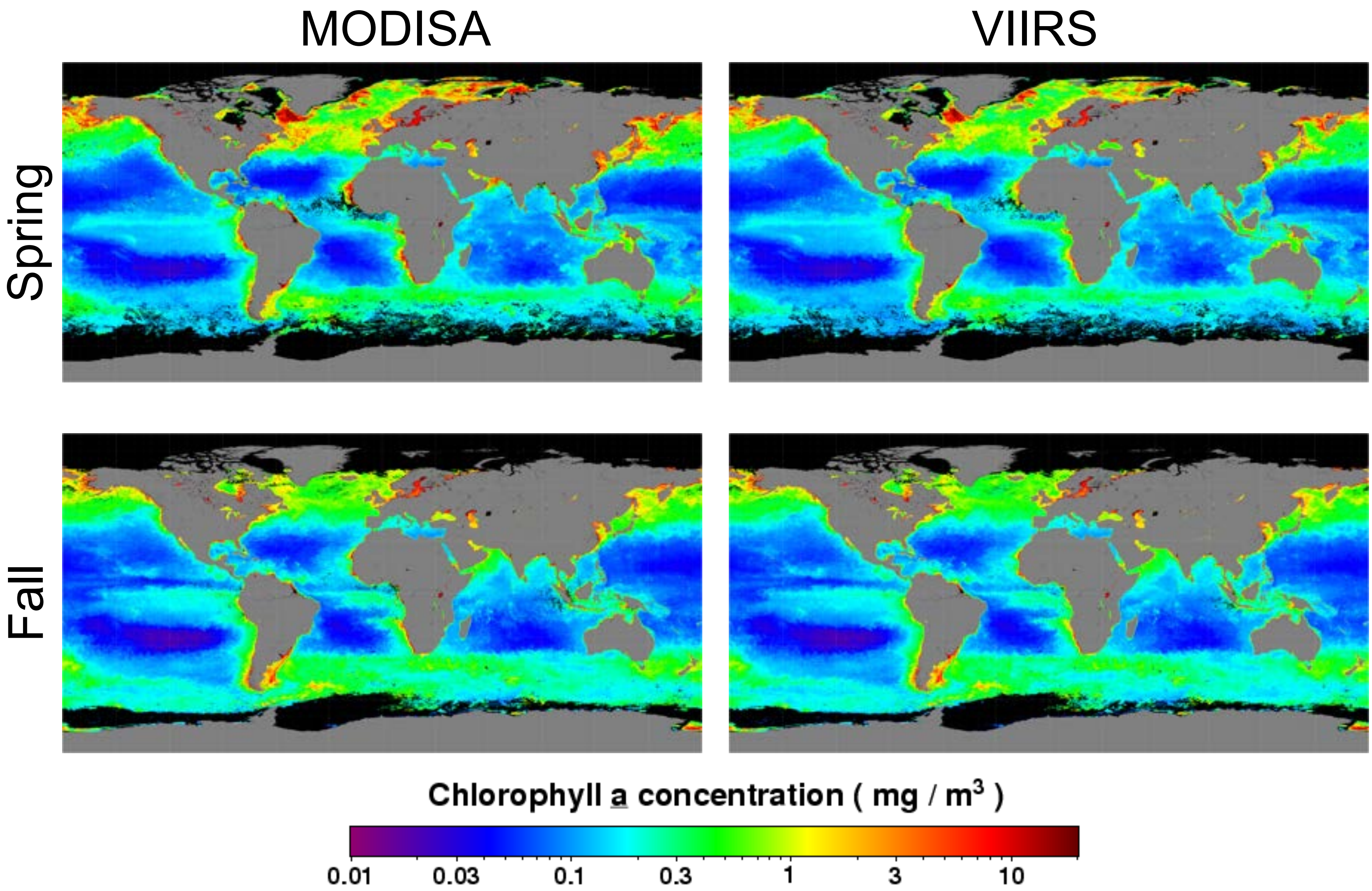
OCI algorithm yields higher values of chlorophyll in clear water relative to OCx (+0.005 to 0.01 mg m$^{-3}$), **with improved consistency between sensors**.

| | Mean | Stdv | |
|---|---|---|---|
| MODISA | 0.067 | 0.006 | mg m$^{-3}$ |
| SeaWiFS | 0.067 | 0.006 | mg m$^{-3}$ |
| MODIS/SeaWiFS | 0.992 | 0.025 | |

# Seasonal Chlorophyll Comparison (2005)



# Seasonal Chlorophyll Comparison (2015)



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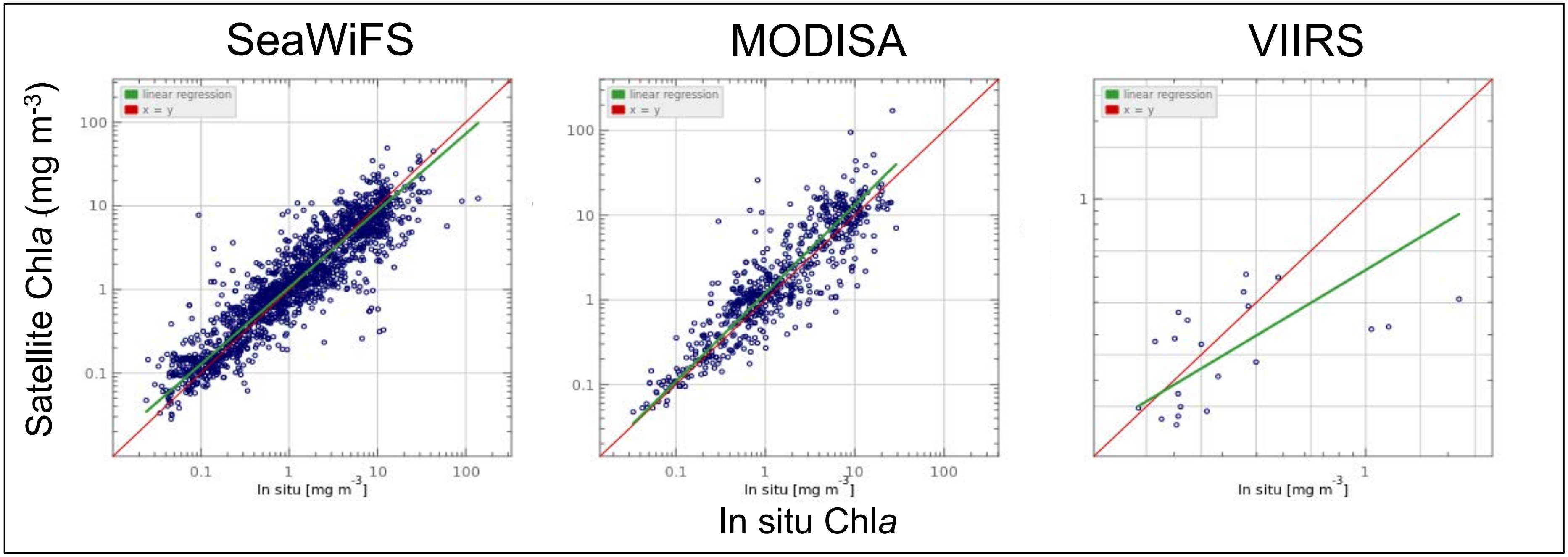
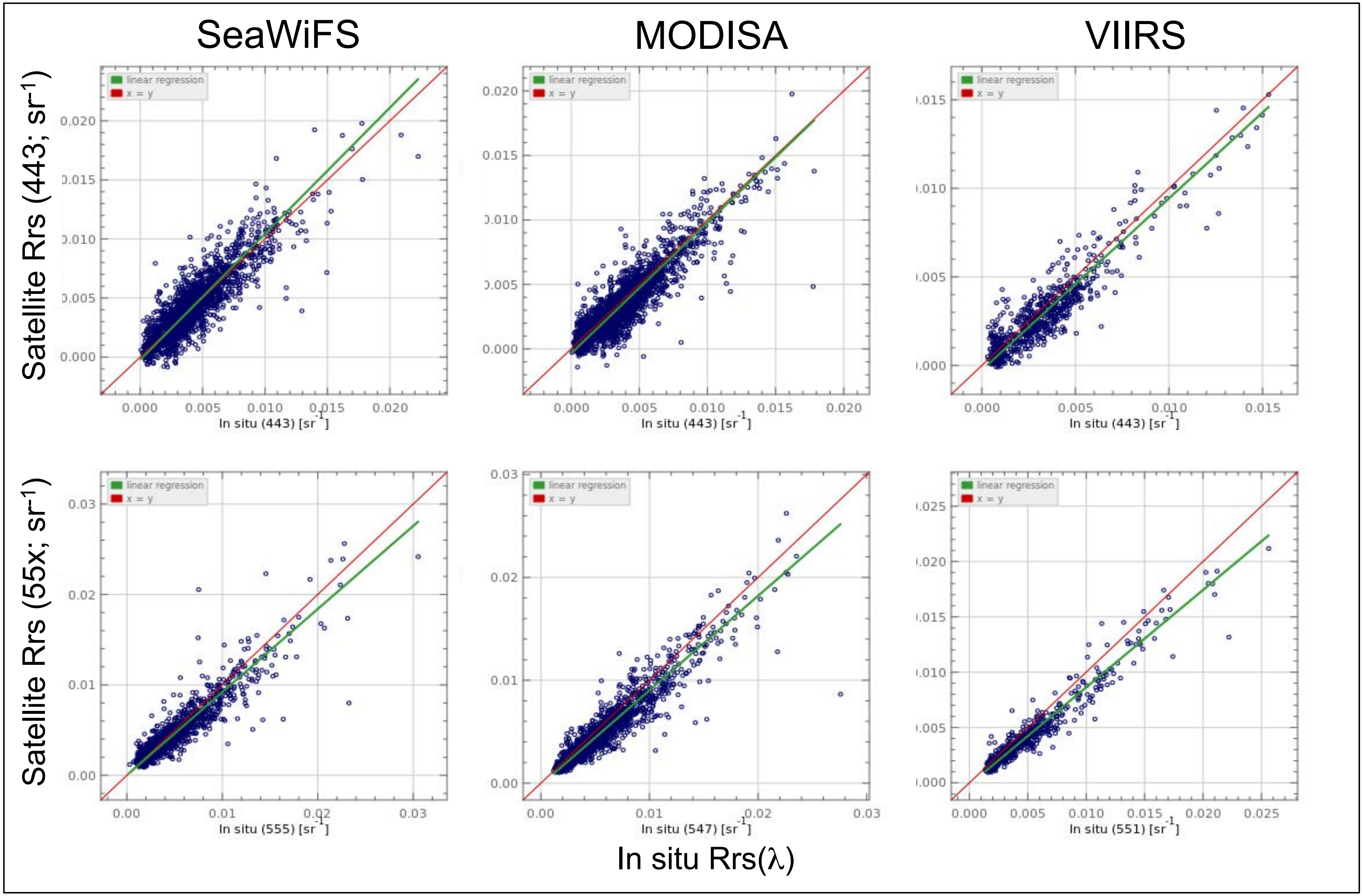
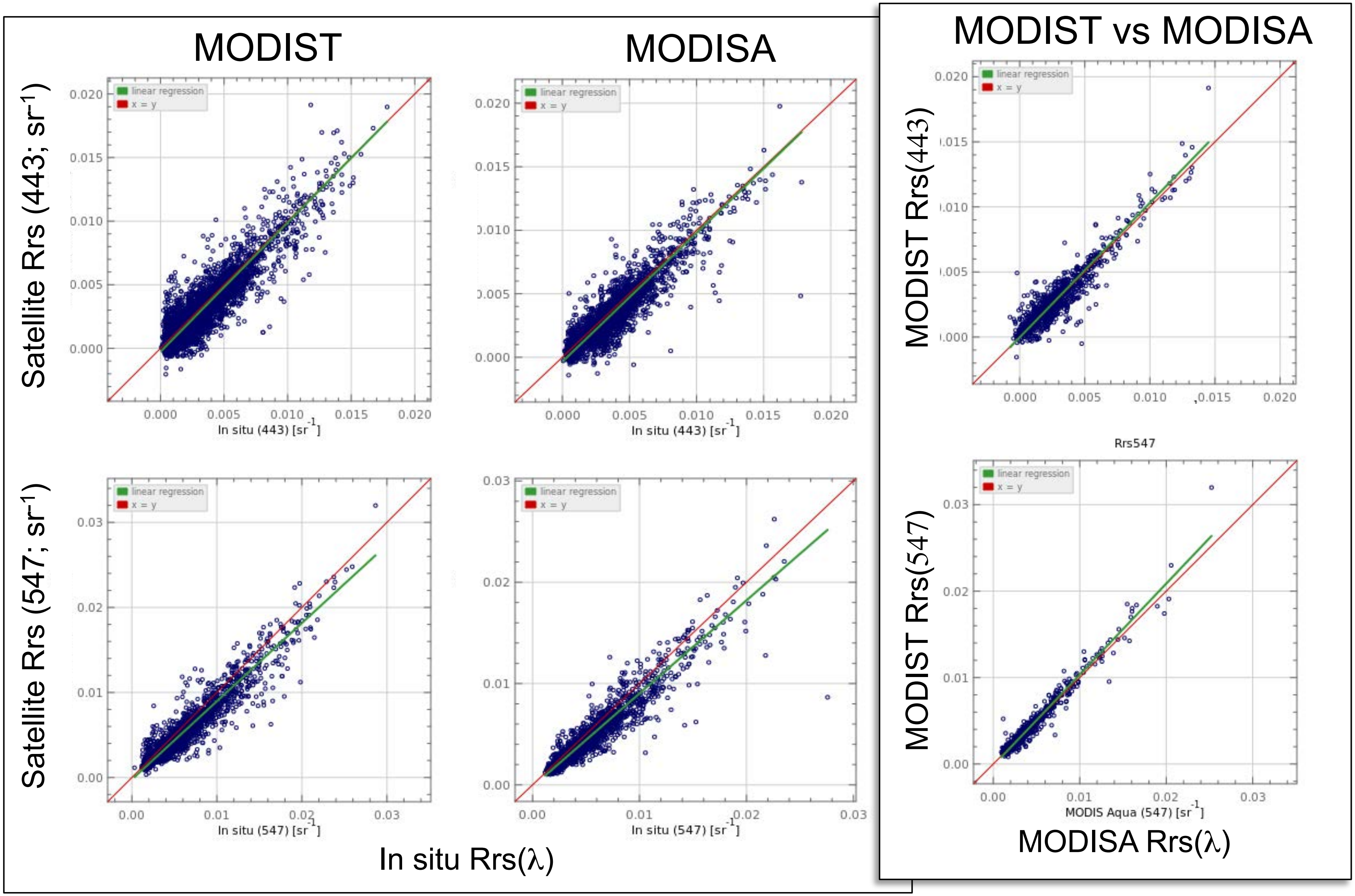
1. MODIS & VIIRS OC Reprocessing Overview
2. Multi-mission OC Time-series Consistency
3. Product Validation and Uncertainties
4. Chlorophyll Climate Data Record and Application
5. Summary



| | | PRODUCT | COUNT | SLOPE | INT (mg m$^{-3}$) | R$^2$ | MED RATIO | APD (%) | RMSE (mg m$^{-3}$) |
|---|---|---|---|---|---|---|---|---|---|
| **Chlorophyll a** | **All** | SeaWiFS | 1739 | 0.92 | 0.02513 | 0.83 | 1.07 | 37.3 | 0.29030 |
| | | MODISA | 653 | 1.04 | 0.07814 | 0.80 | 1.19 | 40.7 | 0.30814 |
| | | VIIRS | 21 | 0.63 | -0.27375 | 0.27 | 0.86 | 34.9 | 0.27166 |
| | **Deep** | SeaWiFS | 363 | 0.83 | -0.09787 | 0.74 | 1.01 | 32.4 | 0.24365 |
| | | MODISA | 113 | 0.87 | -0.10674 | 0.85 | 0.97 | 22.5 | 0.19605 |
| | | VIIRS | 17 | 0.50 | -0.37107 | 0.30 | 0.79 | 40.9 | 0.29676 |



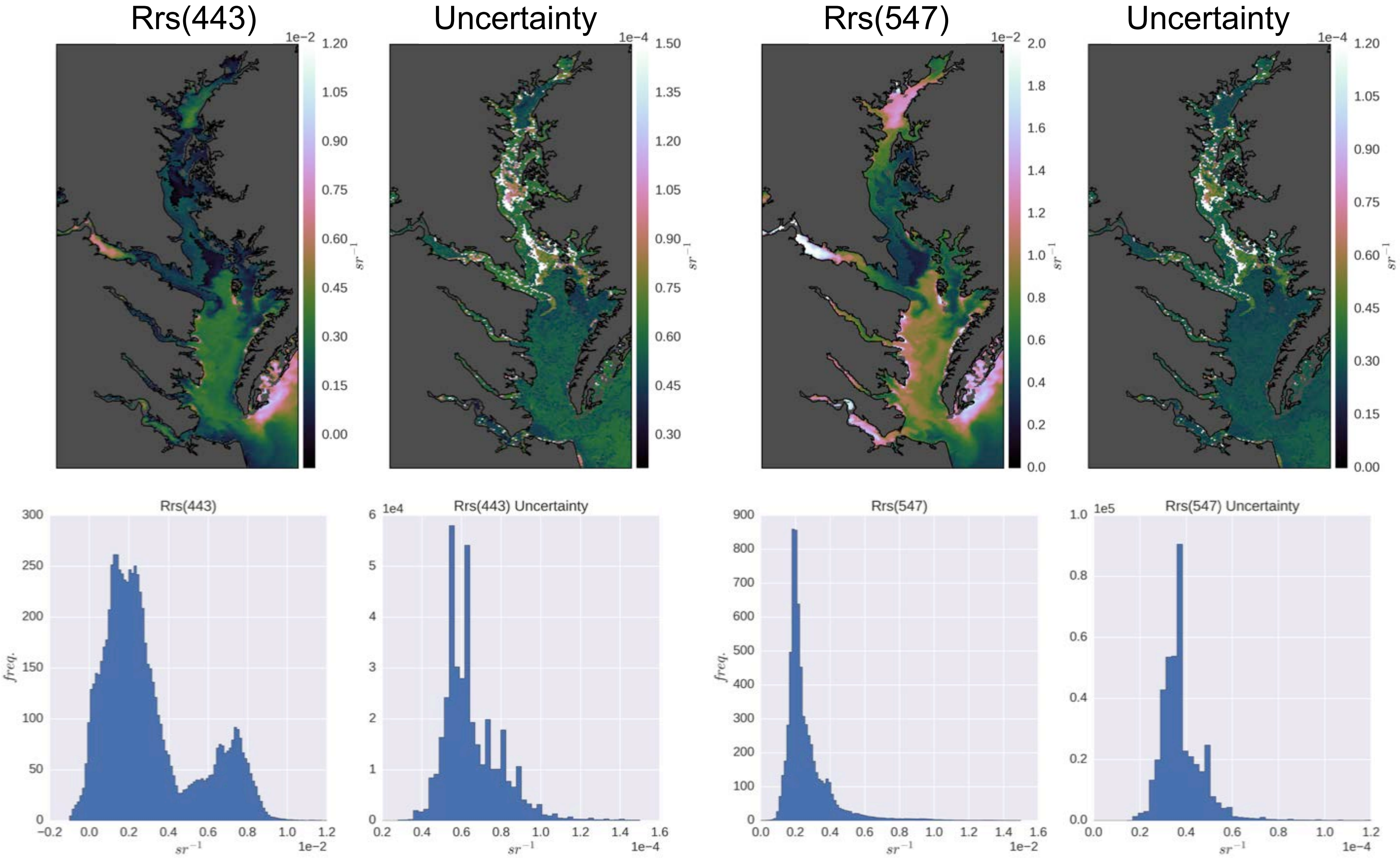
*Comparison between R2014.0 satellite retrievals and in situ measurements for Rrs at 443nm and near 550nm. Match-up is for all available in situ data from SeaBASS and AERONET-OC.*



*Comparison between R2014.0 satellite retrievals and in situ measurements for Rrs at 443nm and near 547nm. Match-up is for all available in situ data from SeaBASS and AERONET-OC.*

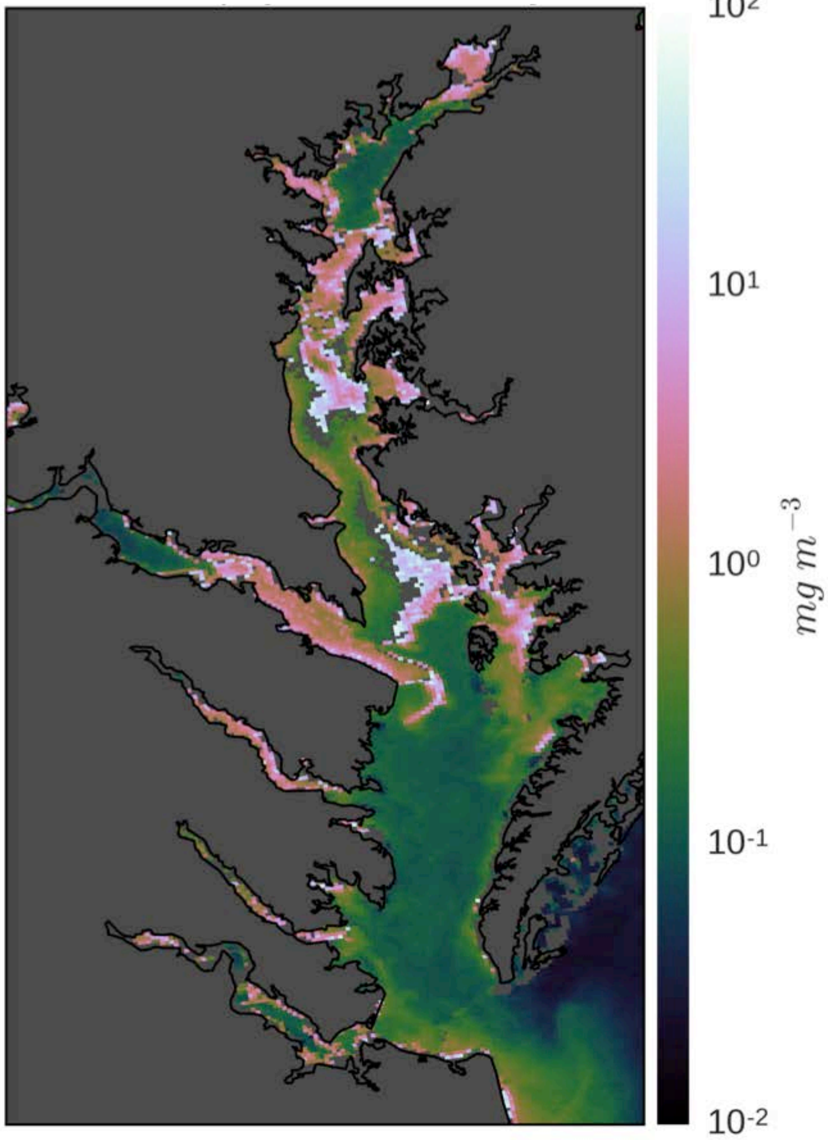
# Developing per-pixel Rrs(λ) uncertainty estimates

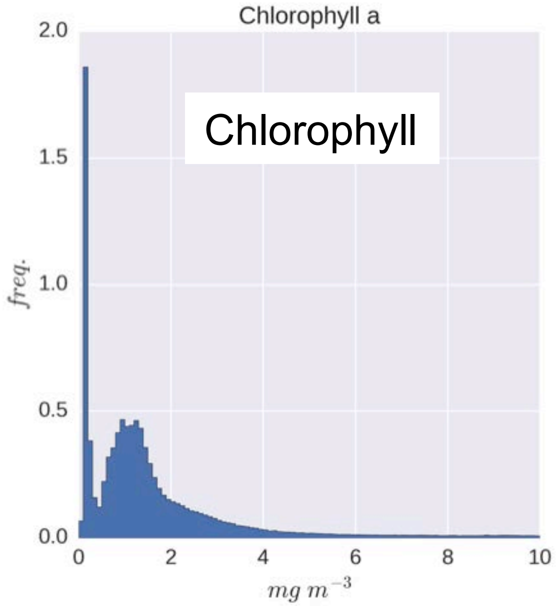
instrument noise propagated through atmospheric correction via Monte Carlo simulation (MODIS-Aqua Ches. Bay, 1000 iterations)

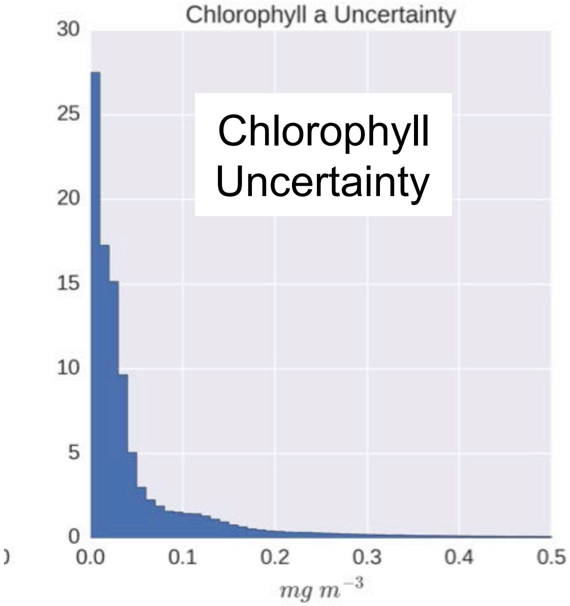


# Developing per-pixel chlorophyll uncertainty

Chlorophyll Uncertainty

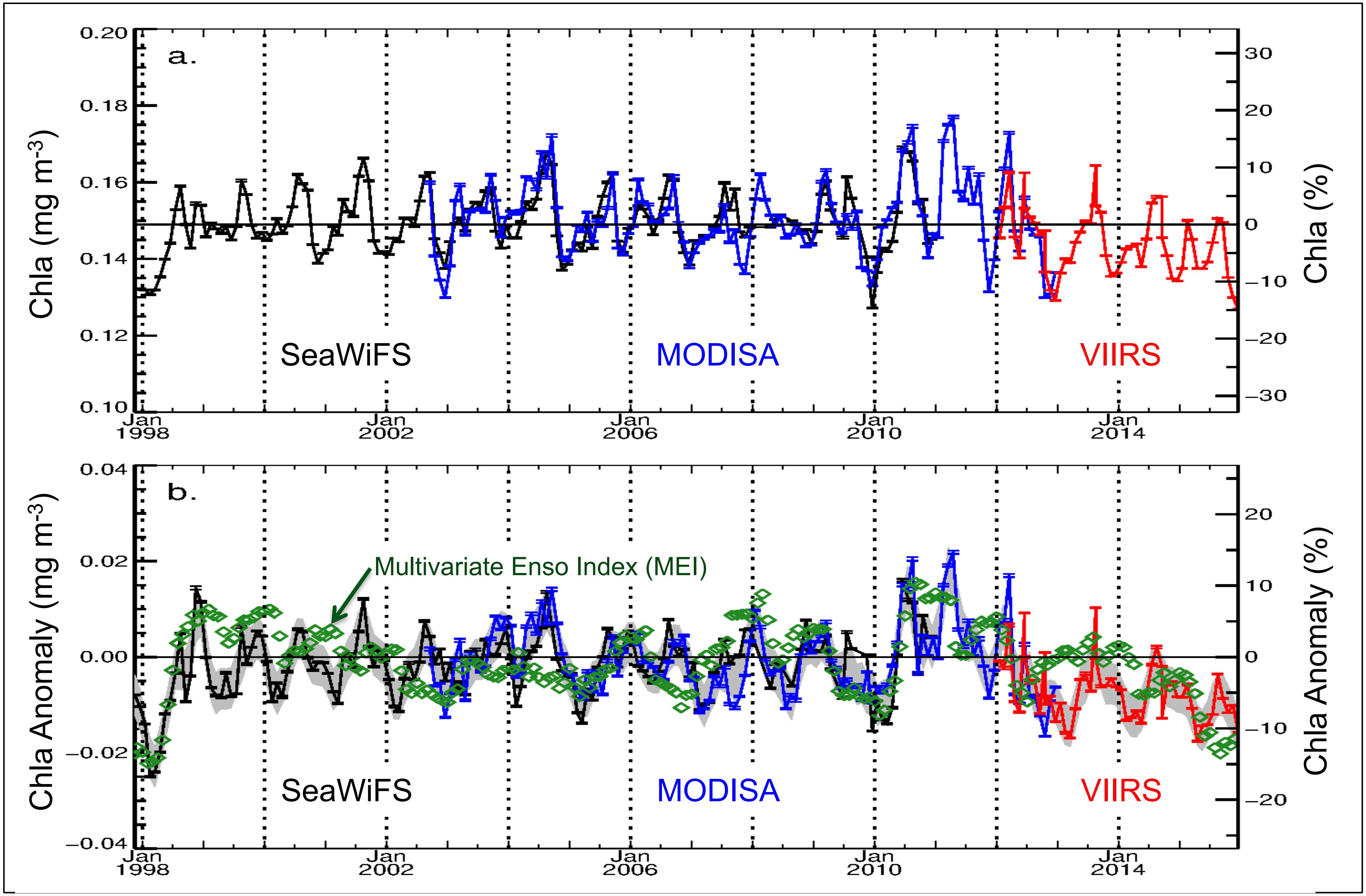




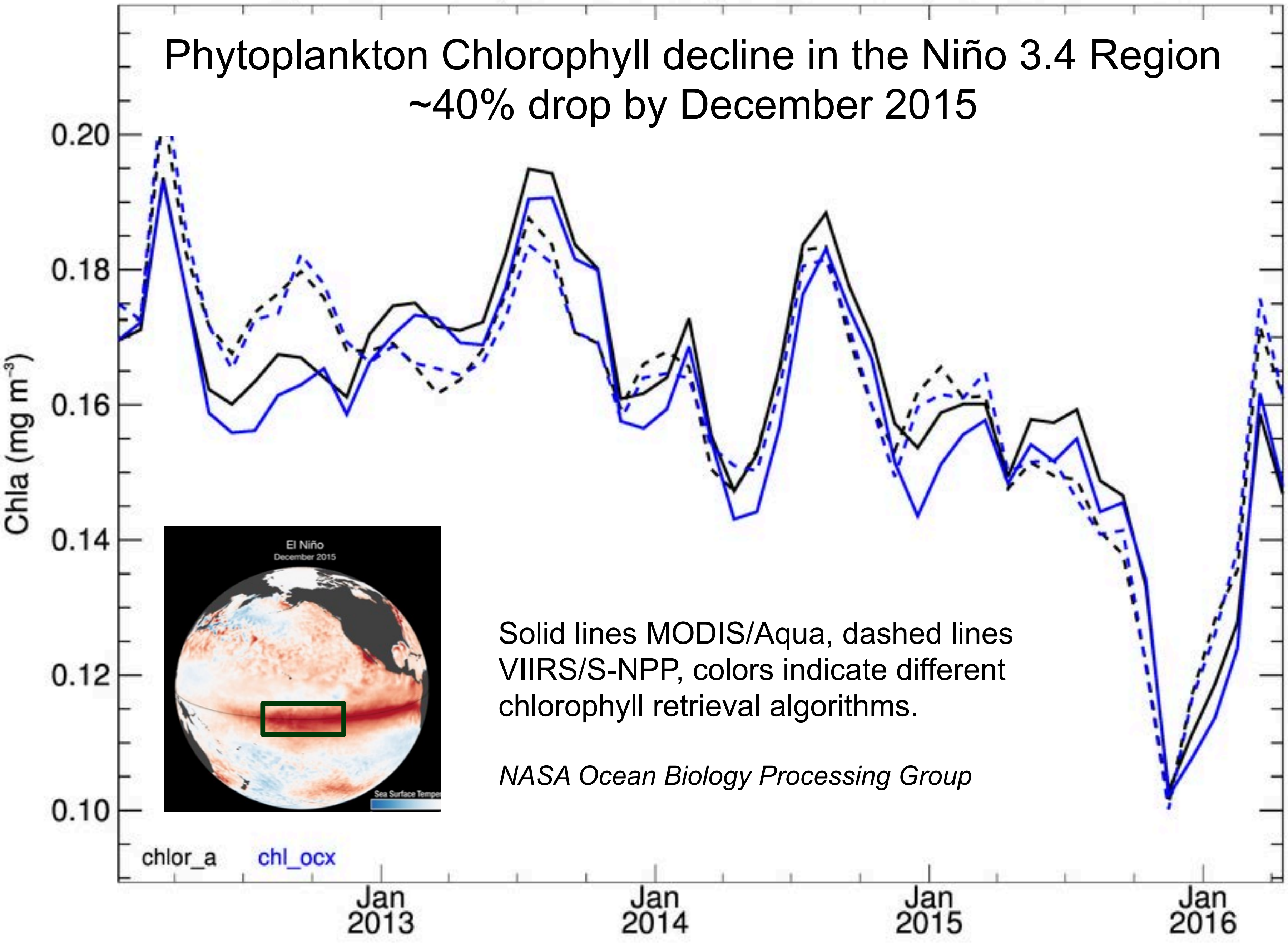


# Contents

# Long-term (18-year) record of phytoplankton chlorophyll a for mid-latitude oceans (± $40^0$), constructed from R2014.0



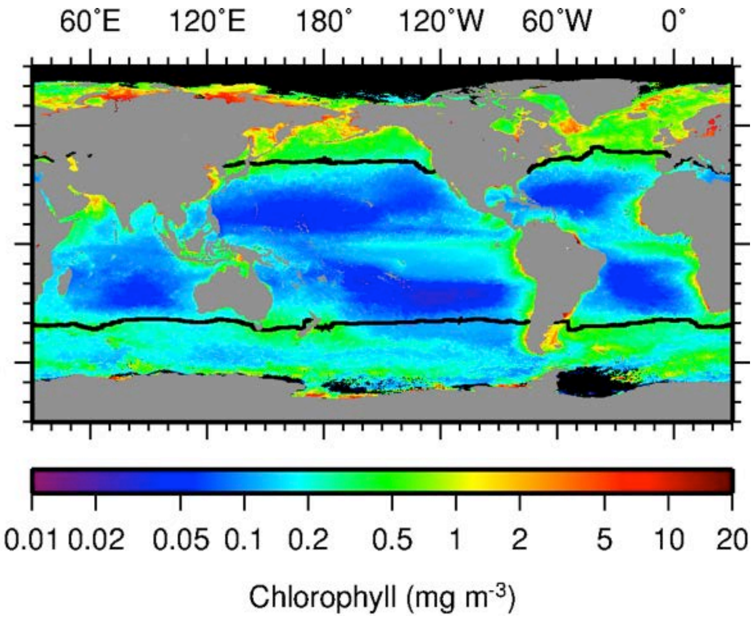
# Phytoplankton Chlorophyll decline in the Niño 3.4 Region
~40% drop by December 2015



Solid lines MODIS/Aqua, dashed lines VIIRS/S-NPP, colors indicate different chlorophyll retrieval algorithms.

*NASA Ocean Biology Processing Group*

# 2015 El Niño Anomaly (VIIRS)



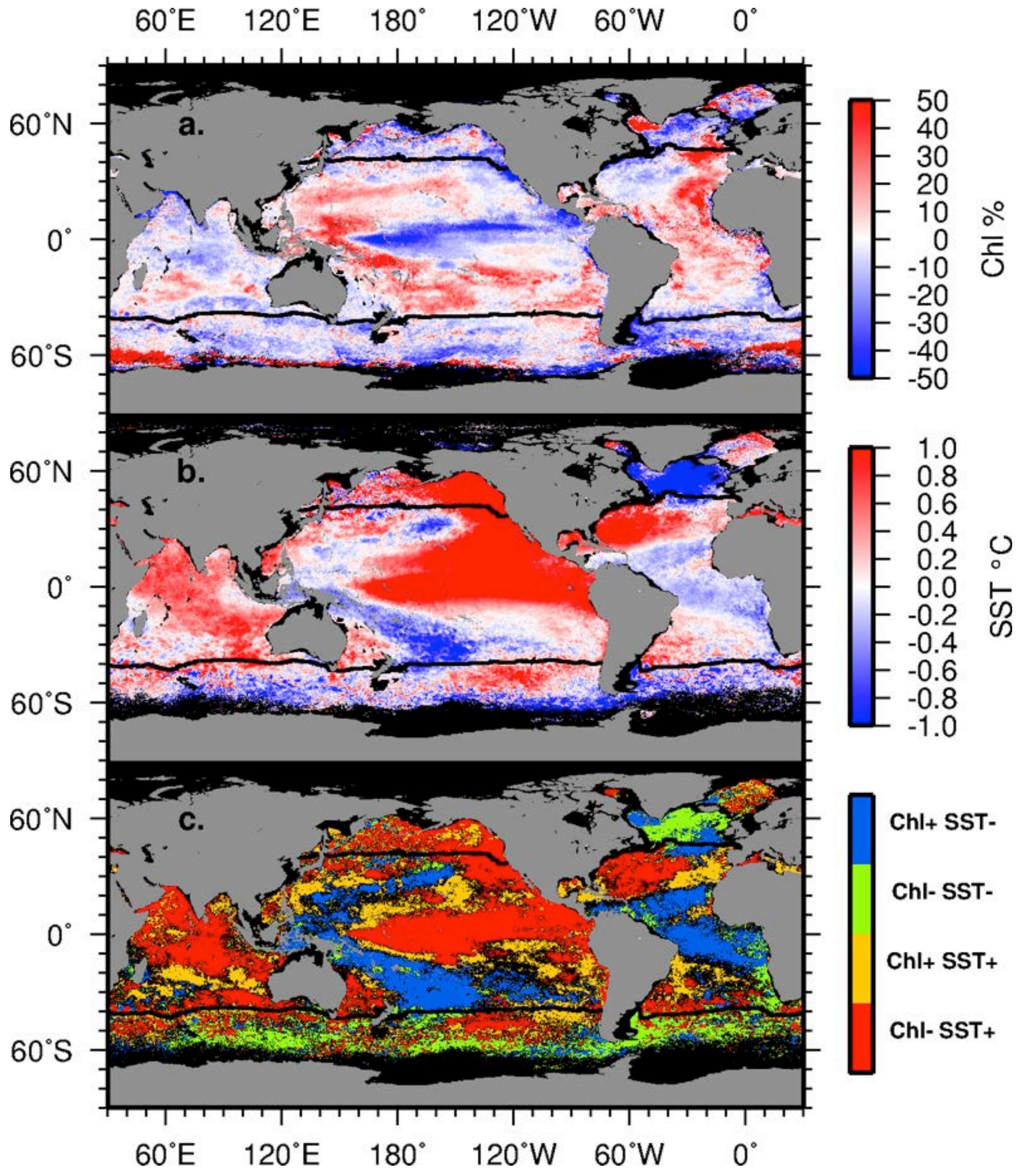
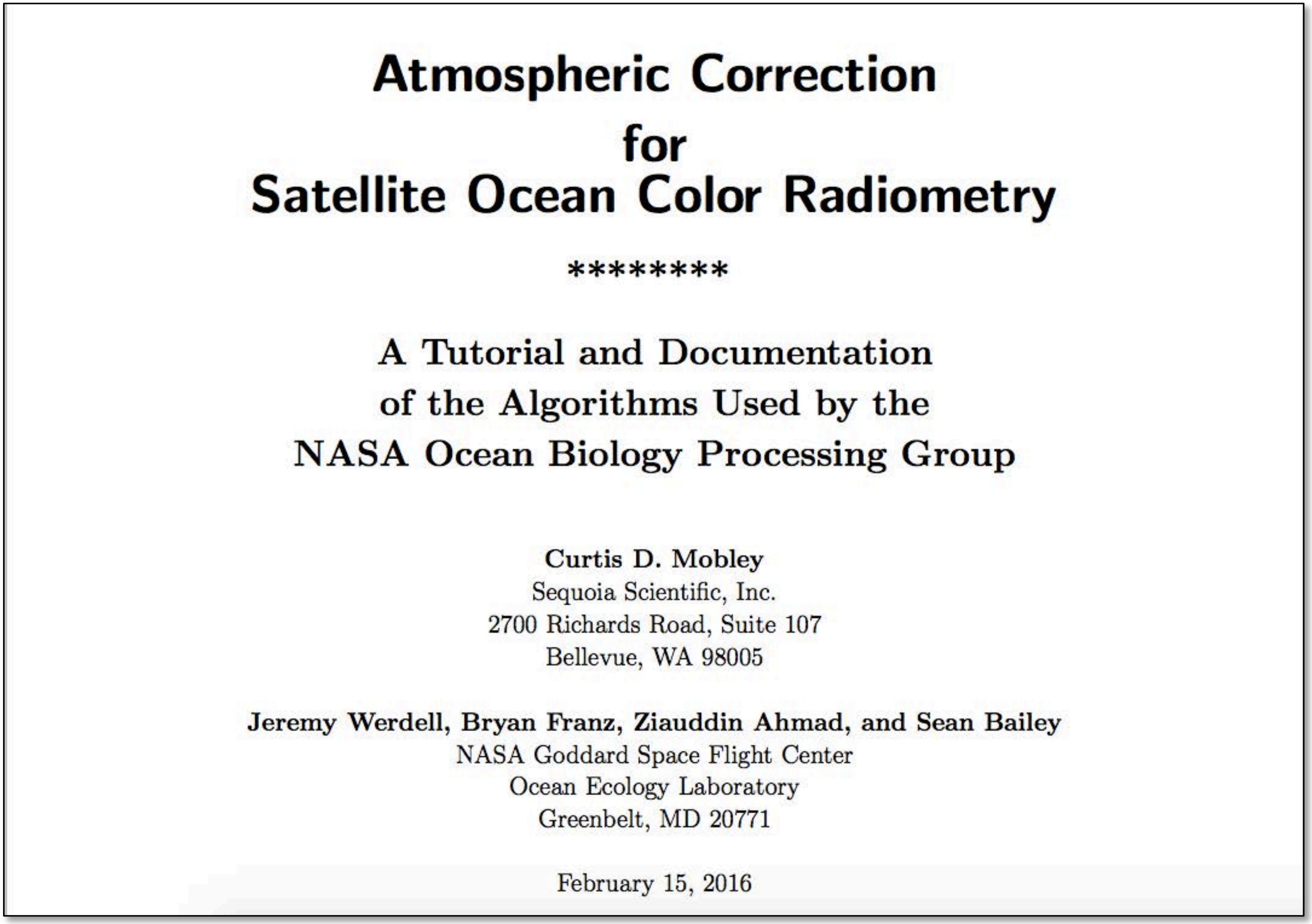


Image above shows mean phytoplankton chlorophyll distribution for 2015, from VIIRS processed by NASA. Images to right show change in chlorophyll in 2015 relative to the climatological norm, and correlated changes in sea surface temperature from MODIS on Aqua.

# Summary

- R2014.0 multi-mission ocean color reprocessing completed for VIIRS, MODIS/Aqua, and MODIS/Terra (& CZCS, OCTS, SeaWIFS).
- High degree of mission-to-mission consistency achieved for Rrs, with some exceptions in the blue (412nm).
- New OCI algorithm contributes to significant improvement in consistency of chlorophyll time-series for clearest ocean waters.
- Validation of Rrs and Chl retrievals against in situ measurements shows equivalent performance for SeaWiFS, MODIS, and VIIRS.
- We have produced a long-term ocean color time-series of sufficient length (18 years), continuity, and consistency to assess climate-driven trends in ocean biology.



# Atmospheric Correction for Satellite Ocean Color Radiometry

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## A Tutorial and Documentation of the Algorithms Used by the NASA Ocean Biology Processing Group

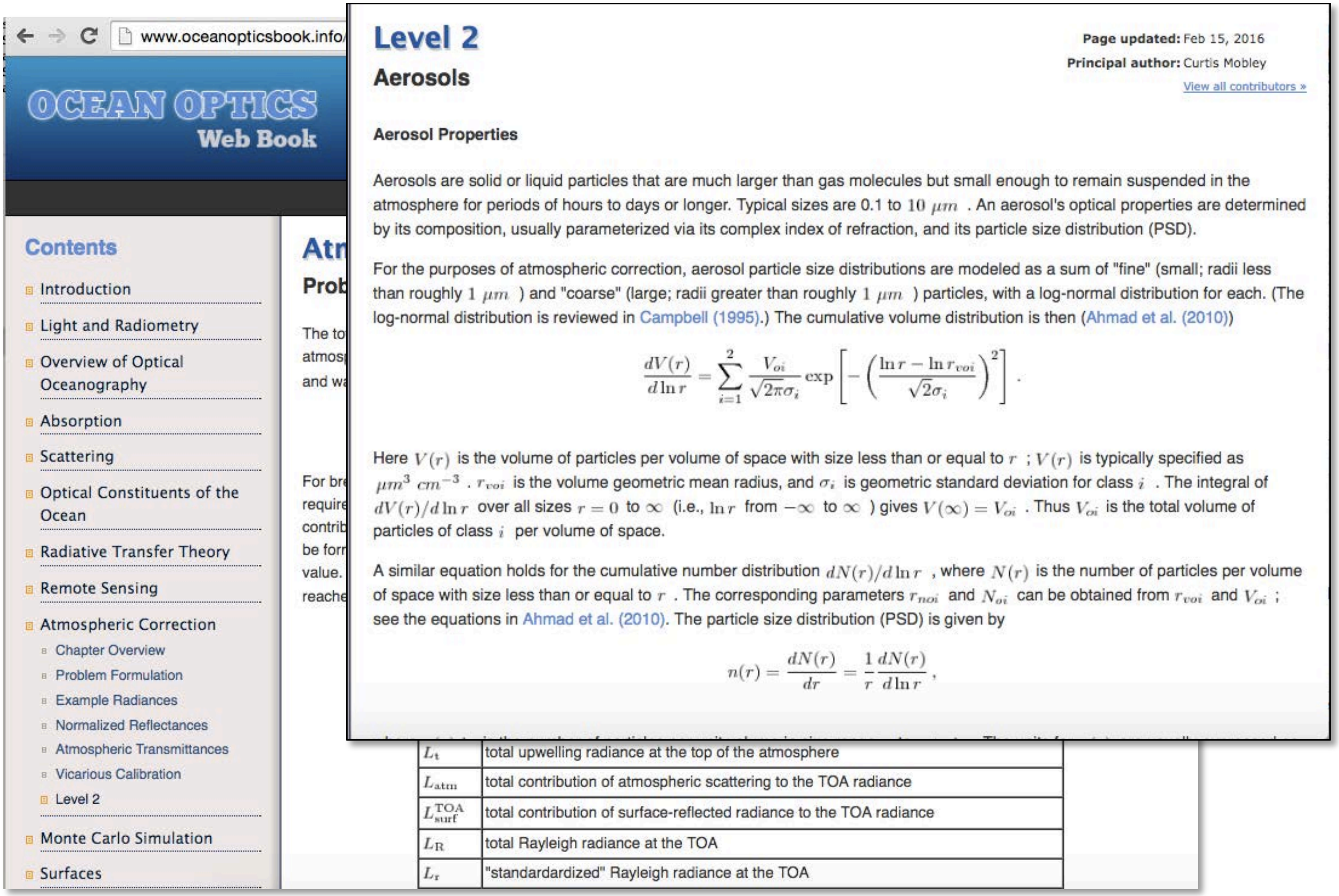
**Curtis D. Mobley**
Sequoia Scientific, Inc.
2700 Richards Road, Suite 107
Bellevue, WA 98005

**Jeremy Werdell, Bryan Franz, Ziauddin Ahmad, and Sean Bailey**
NASA Goddard Space Flight Center
Ocean Ecology Laboratory
Greenbelt, MD 20771

February 15, 2016

http://soap.siteturbine.com/webbook/file.php?id=345

# New on-line book: NASA Standard Atmospheric Correction Algorithm for Ocean Color Retrieval



## Level 2

### Aerosols

**Aerosol Properties**

Aerosols are solid or liquid particles that are much larger than gas molecules but small enough to remain suspended in the atmosphere for periods of hours to days or longer. Typical sizes are 0.1 to $10\ \mu m$ . An aerosol's optical properties are determined by its composition, usually parameterized via its complex index of refraction, and its particle size distribution (PSD).

For the purposes of atmospheric correction, aerosol particle size distributions are modeled as a sum of "fine" (small; radii less than roughly $1\ \mu m$ ) and "coarse" (large; radii greater than roughly $1\ \mu m$ ) particles, with a log-normal distribution for each. (The log-normal distribution is reviewed in Campbell (1995).) The cumulative volume distribution is then (Ahmad et al. (2010))

$$\frac{dV(r)}{d\ln r} = \sum_{i=1}^{2} \frac{V_{oi}}{\sqrt{2\pi}\sigma_i} \exp\left[-\left(\frac{\ln r - \ln r_{voi}}{\sqrt{2}\sigma_i}\right)^2\right] .$$

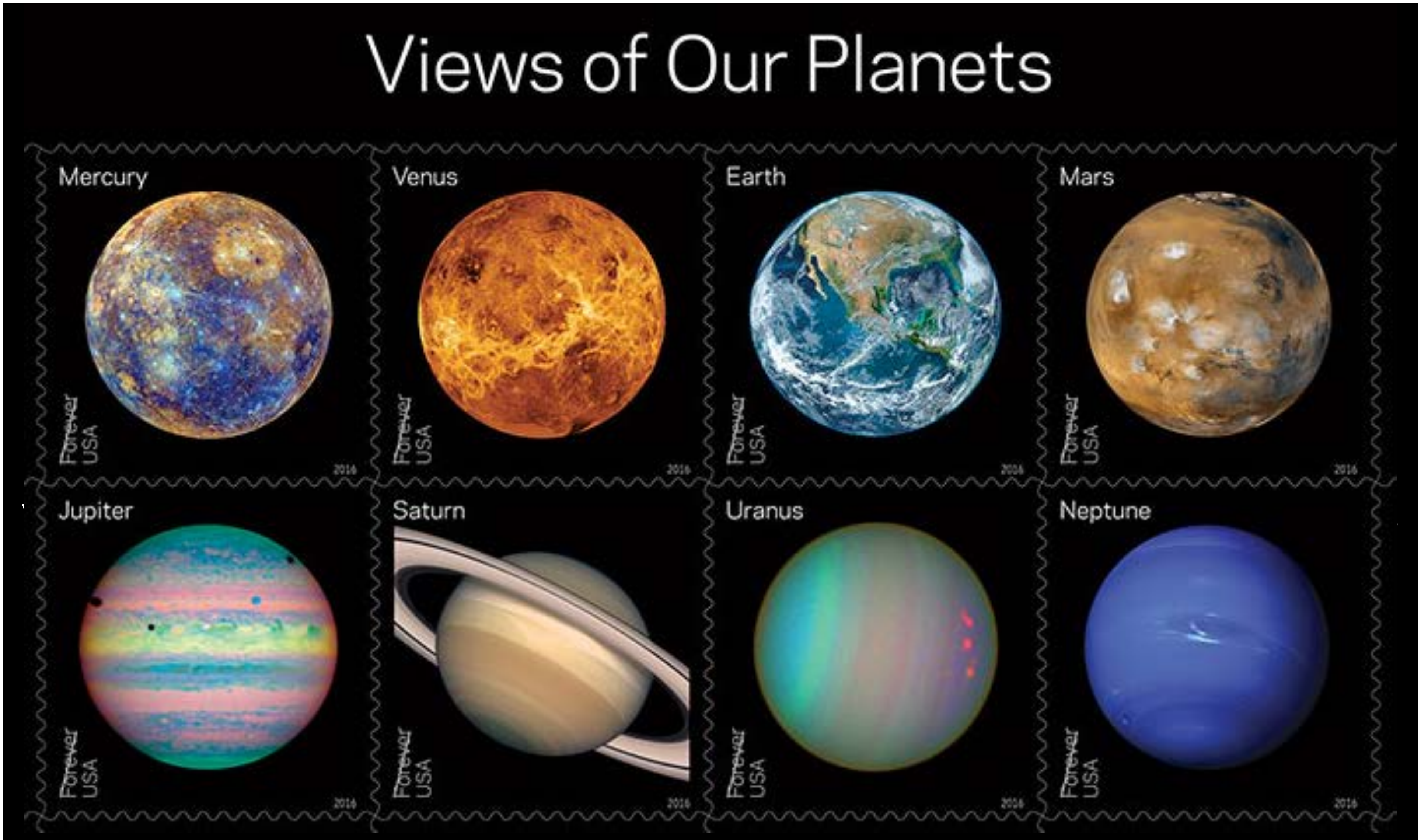
Here $V(r)$ is the volume of particles per volume of space with size less than or equal to $r$ ; $V(r)$ is typically specified as $\mu m^3\ cm^{-3}$ . $r_{voi}$ is the volume geometric mean radius, and $\sigma_i$ is geometric standard deviation for class $i$ . The integral of $dV(r)/d\ln r$ over all sizes $r = 0$ to $\infty$ (i.e., $\ln r$ from $-\infty$ to $\infty$ ) gives $V(\infty) = V_{oi}$ . Thus $V_{oi}$ is the total volume of particles of class $i$ per volume of space.

A similar equation holds for the cumulative number distribution $dN(r)/d\ln r$ , where $N(r)$ is the number of particles per volume of space with size less than or equal to $r$ . The corresponding parameters $r_{noi}$ and $N_{oi}$ can be obtained from $r_{voi}$ and $V_{oi}$ ; see the equations in Ahmad et al. (2010). The particle size distribution (PSD) is given by

$$n(r) = \frac{dN(r)}{dr} = \frac{1}{r}\frac{dN(r)}{d\ln r} ,$$

| | |
|---|---|
| $L_t$ | total upwelling radiance at the top of the atmosphere |
| $L_{atm}$ | total contribution of atmospheric scattering to the TOA radiance |
| $L_{surf}^{TOA}$ | total contribution of surface-reflected radiance to the TOA radiance |
| $L_R$ | total Rayleigh radiance at the TOA |
| $L_r$ | "standardardized" Rayleigh radiance at the TOA |

www.oceanopticsbook.info



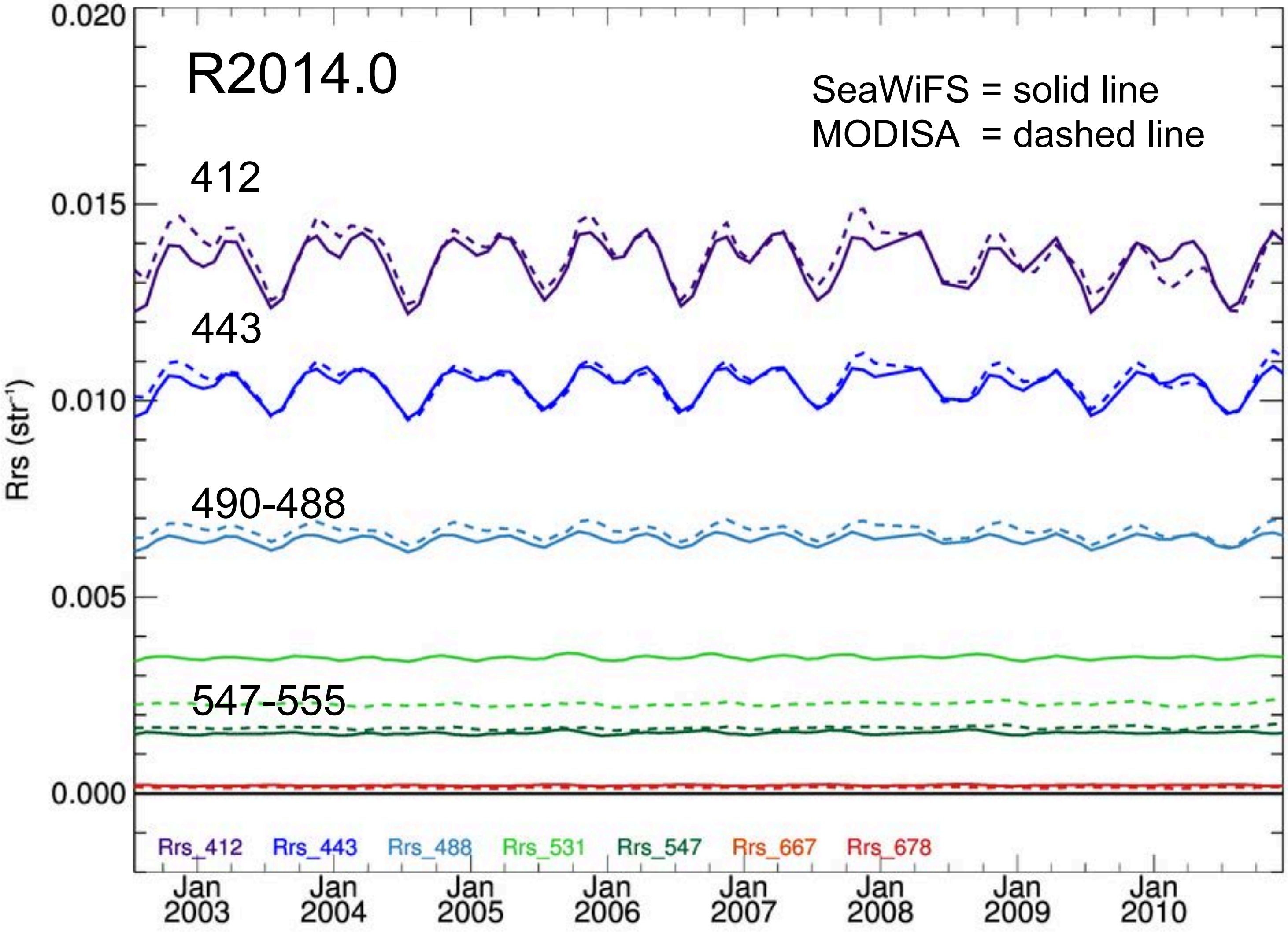
Views of Our Planets” Forever stamps featuring iconic images of the planets in our solar system, including the well-known “Blue Marble” image of Earth” were released on 31 May 2016 at the World Stamp Show in New York City, an international gathering of stamp collectors that occurs only once each decade in the U.S. with more than 250,000 visitors attending.

Norman Kuring of the OBPG created the new “Blue Marble” using data taken by VIIRS on the NOAA/NASA Suomi NPP satellite soon after it began orbiting our home planet in 2011.

# Questions?

# MODISA & SeaWiFS Rrs($\lambda$) Clear-Water Time-Series

## showing “good” agreement



Mean Ratio

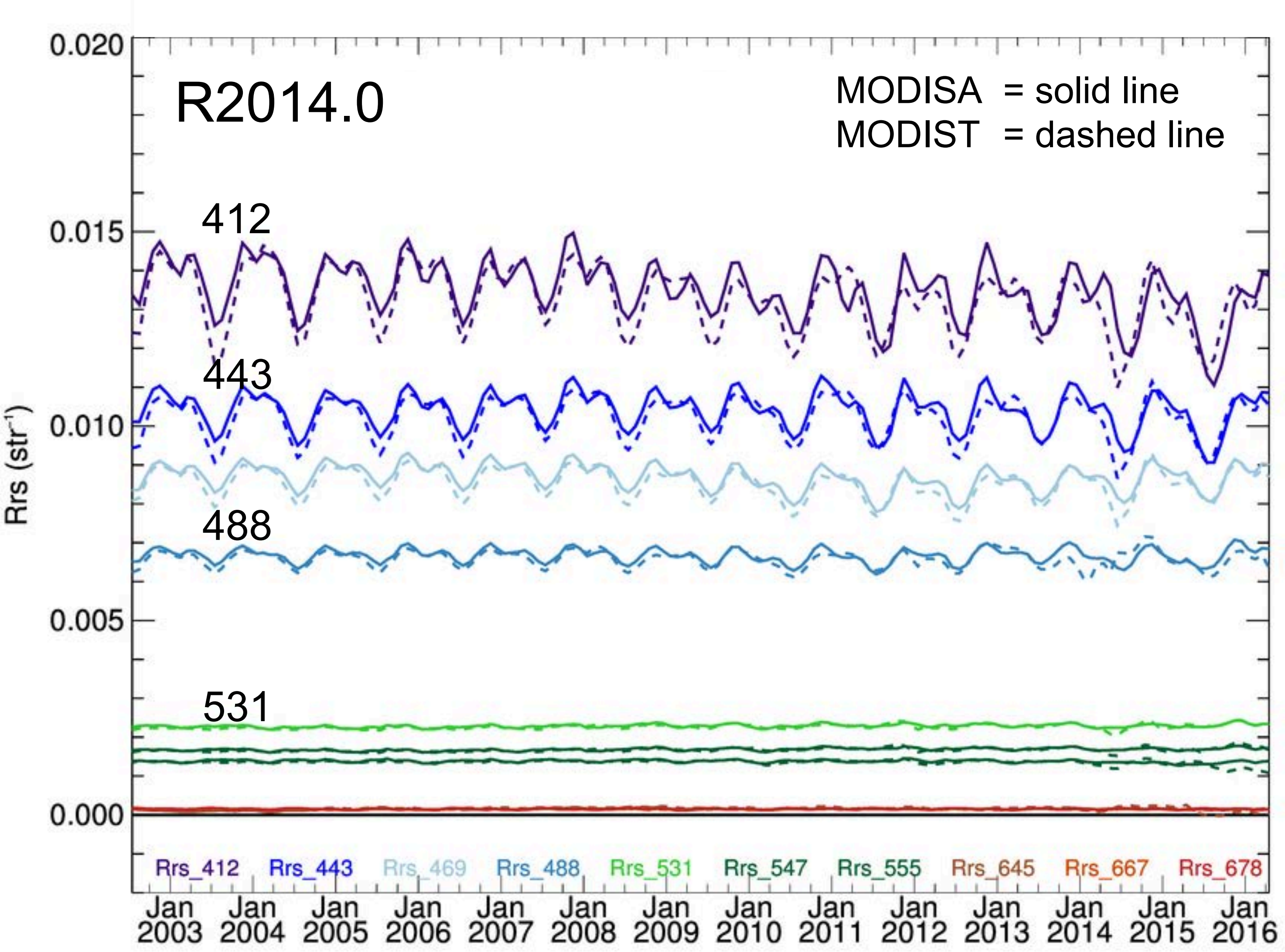
1.01

1.01

1.03

# MODIST & MODISA Rrs(λ) Clear-Water Time-Series

showing “good” agreement



Mean Ratio

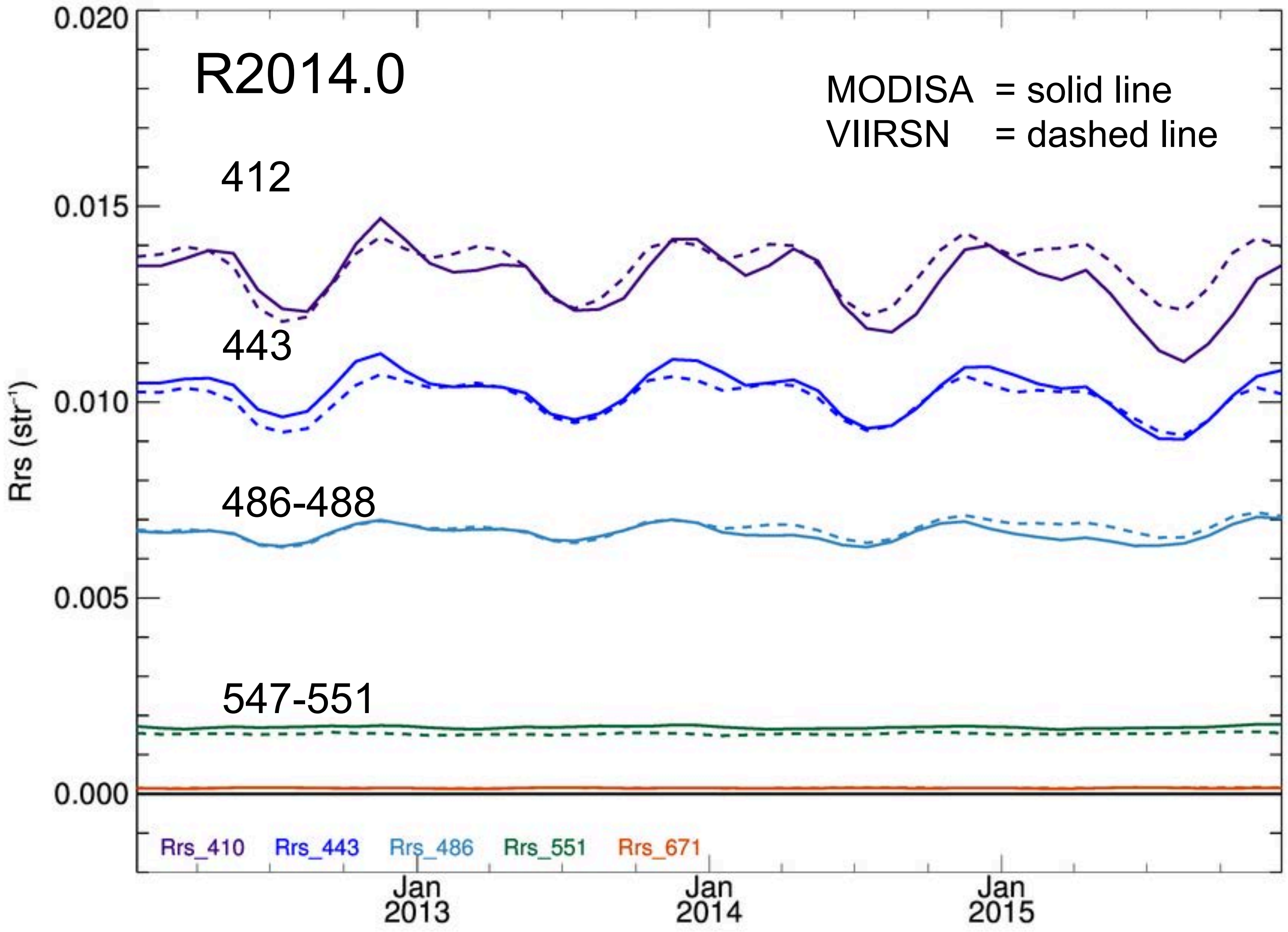
0.98

0.98

0.99

# MODISA & VIIRS Rrs(λ) Clear-Water Time-Series

## showing “good” agreement



Mean Ratio

1.03

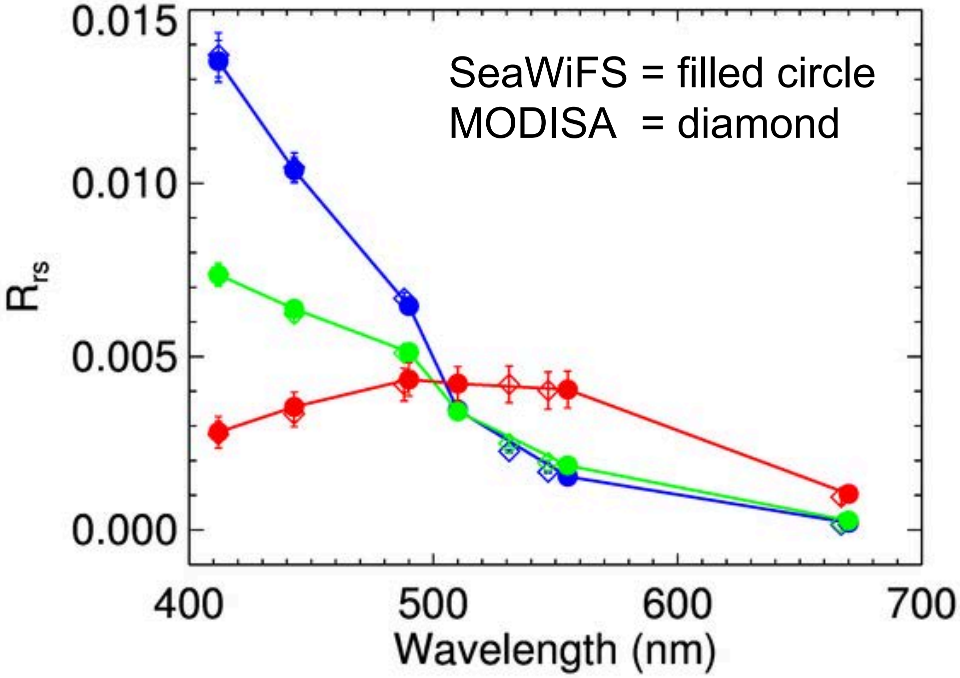
0.98

1.02

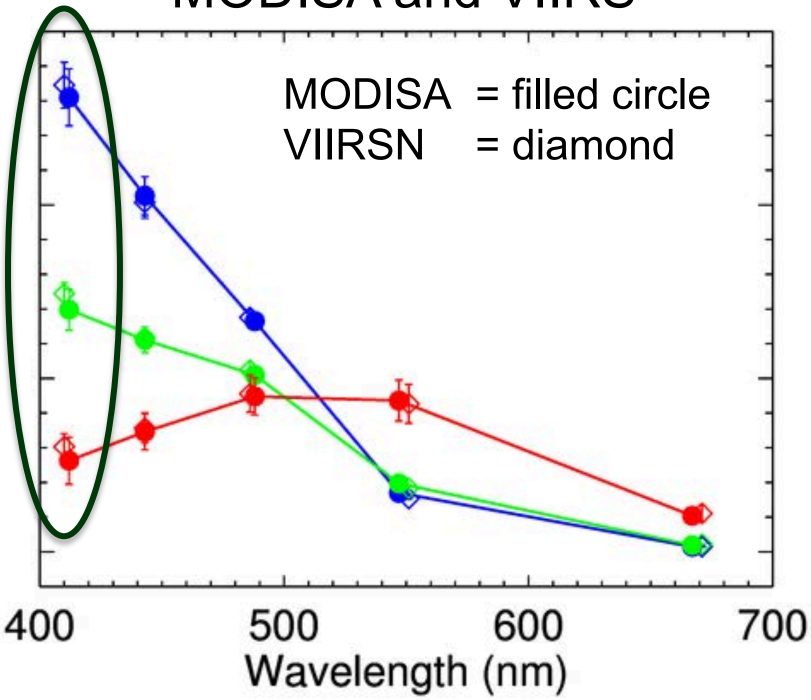
# Rrs(λ) Spectral Comparison

## common mission mean by water type

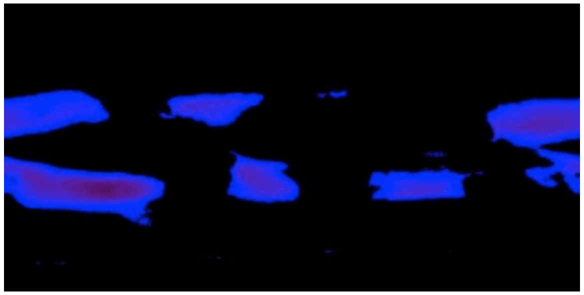
SeaWiFS and MODISA



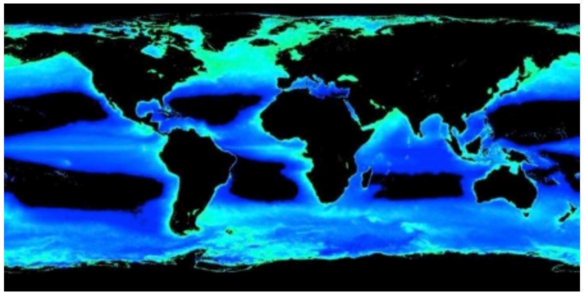
MODISA and VIIRS



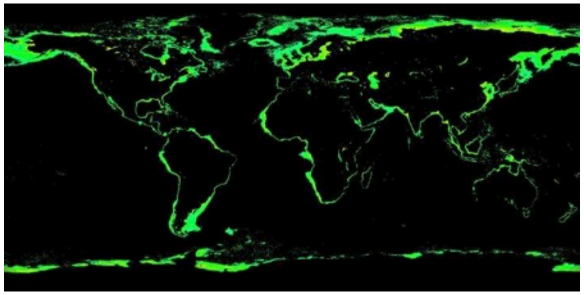
Oligotrophic



Mesotrophic

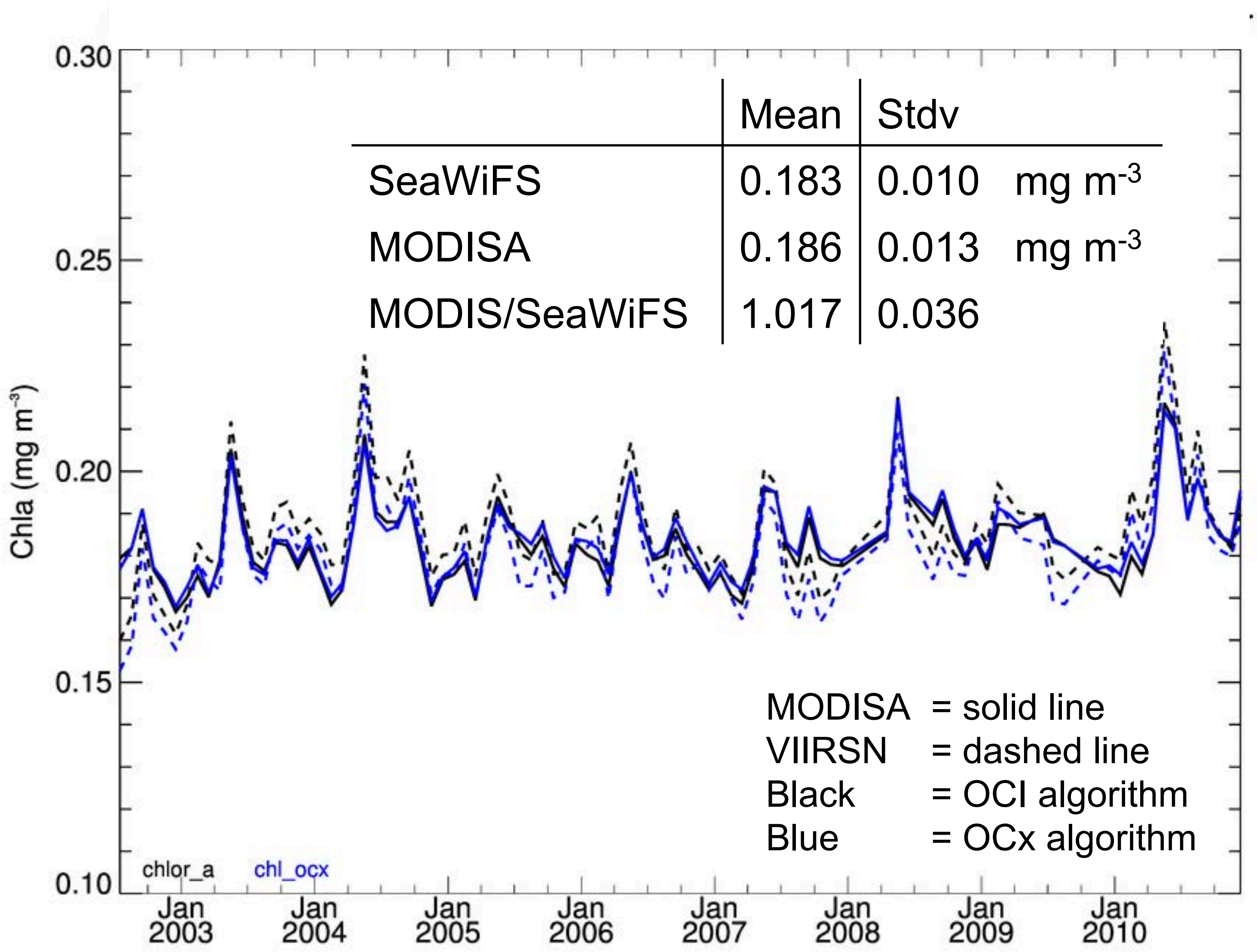


Eutrophic



# SeaWiFS and MODISA R2014.0

## Chlorophyll Deep-Water Time-Series



| | Mean | Stdv | |
|---|---|---|---|
| SeaWiFS | 0.183 | 0.010 | mg $m^{-3}$ |
| MODISA | 0.186 | 0.013 | mg $m^{-3}$ |
| MODIS/SeaWiFS | 1.017 | 0.036 | |

MODISA = solid line
VIIRSN = dashed line
Black = OCI algorithm
Blue = OCx algorithm

# Algorithm

# Remote Sensing Reflectance (Rrs; sr$^{-1}$)

Rrs is the ratio of upwelling “water-leaving” radiance to downwelling irradiance, just above the sea surface

Rrs is the fundamental remote sensing quantity from which most ocean color products are derived (e.g., chlorophyll, particulate organic and inorganic carbon, inherent optical properties)

**Atmospheric Correction**

$$\overset{\text{observed TOA}}{L_t} = \left( \overset{\text{Rayleigh}}{L_r} + \boxed{\overset{\text{aerosol + Ray-aer}}{\left[ L_a + L_{ra} \right]}} + \overset{\text{foam \& whitecaps}}{t_{dv} L_f} + \overset{\text{Sun glint}}{T_s T_v L_g} + \overset{\text{water-leaving}}{t_{dv} L_w} \right) t_{gv}\, t_{gs}\, f_p$$

$$R_{rs} = \frac{L_w}{F_0 \cos(\theta_s)\, t_{ds}\, f_s} f_b\, f_\lambda$$

$$\boxed{nL_w = F_0 R_{rs}}$$

# determining aerosol contribution

assume $L_w(\lambda) = 0$ at two NIR (or SWIR) bands, **or that it can be estimated with sufficient accuracy**.

retrieve aerosol reflectance in each NIR band as

$$\left[L_a + L_{ra}\right] = \frac{L_t}{t_{gv}\,t_{gs}\,f_p} - \left(L_r + t_{dv}L_f + T_sT_vL_g + t_{dv}\cancelto{\text{known}}{L_w}\right)$$

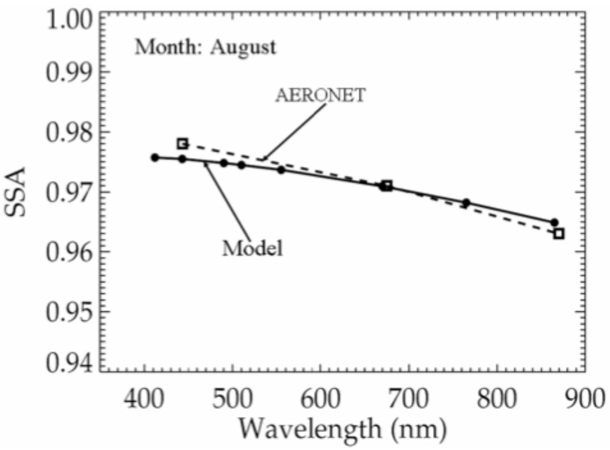
$$\rho_a = \left[L_a + L_{ra}\right]\frac{\pi}{F_0\cos(\theta_0)}$$

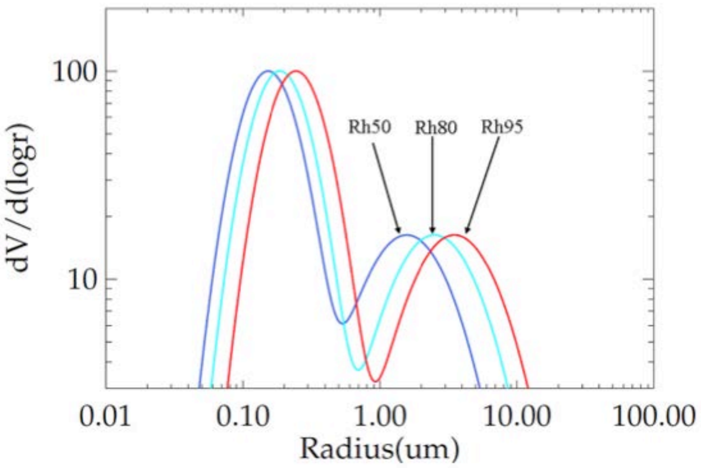
use spectral dependence of retrieved NIR aerosol reflectance ($\varepsilon$) to select the most appropriate aerosol model from a suite of pre-computed models

use NIR aerosol reflectance and selected aerosol model to extrapolate aerosol reflectance to visible wavelengths

# aerosol model tables

- vector RT code (Ahmad-Fraser)
- based on AERONET size distributions & albedos
- 80 models (10 size fractions within 8 humidities)
    - 100% coarse mode to 95% fine mode
    - non- or weakly absorbing
- LUT: extinction, albedo, phase function, ss->ms, $t_d$
    - function of path geometry (or scattering angle)
- model selection discriminated by relative humidity


Fine Mode Albedo


Typical Size Distributions

Mean AERONET Fine & Coarse Modal Radii

| $Rh$ | $r_{vf}$ | $\sigma_f$ | $r_{vc}$ | $\sigma_c$ | $r_{vf}/r_{ovf}$ | $r_{vc}/r_{ovc}$ |
|---|---|---|---|---|---|---|
| 0.30 | 0.150 | 0.437 | 2.441 | 0.672 | 1.006 | 1.009 |
| 0.50 | 0.152 | 0.437 | 2.477 | 0.672 | 1.019 | 1.024 |
| 0.70 | 0.158 | 0.437 | 2.927 | 0.672 | 1.063 | 1.210 |
| 0.75 | 0.167 | 0.437 | 3.481 | 0.672 | 1.118 | 1.439 |
| 0.80 | 0.187 | 0.437 | 3.966 | 0.672 | 1.255 | 1.639 |
| 0.85 | 0.204 | 0.437 | 4.243 | 0.672 | 1.371 | 1.753 |
| 0.90 | 0.221 | 0.437 | 4.638 | 0.672 | 1.486 | 1.917 |
| 0.95 | 0.246 | 0.437 | 5.549 | 0.672 | 1.648 | 2.293 |

*Ahmad et al. 2010, Appl. Opt.*

# aerosol model selection & application

select the two sets of 10 models (10 size fractions) with relative humidity (RH) that bound the RH of the observation.

find the two models that bound the observed epsilon within each RH model family.

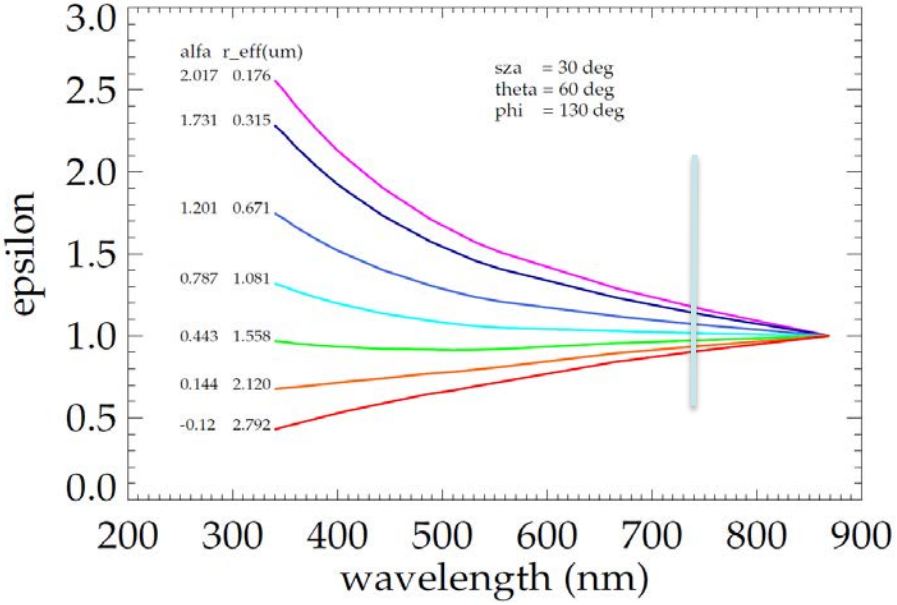
$$\varepsilon^{obs}(748,869) = \frac{\rho_a(748)}{\rho_a(869)} \rightarrow \varepsilon^{\mathrm{mod}}(748,869)^{*}$$

use model epsilon to extrapolate to visible.

$$\rho_a(\lambda) = \rho_a(869)\varepsilon^{\mathrm{mod}}(\lambda,869)$$

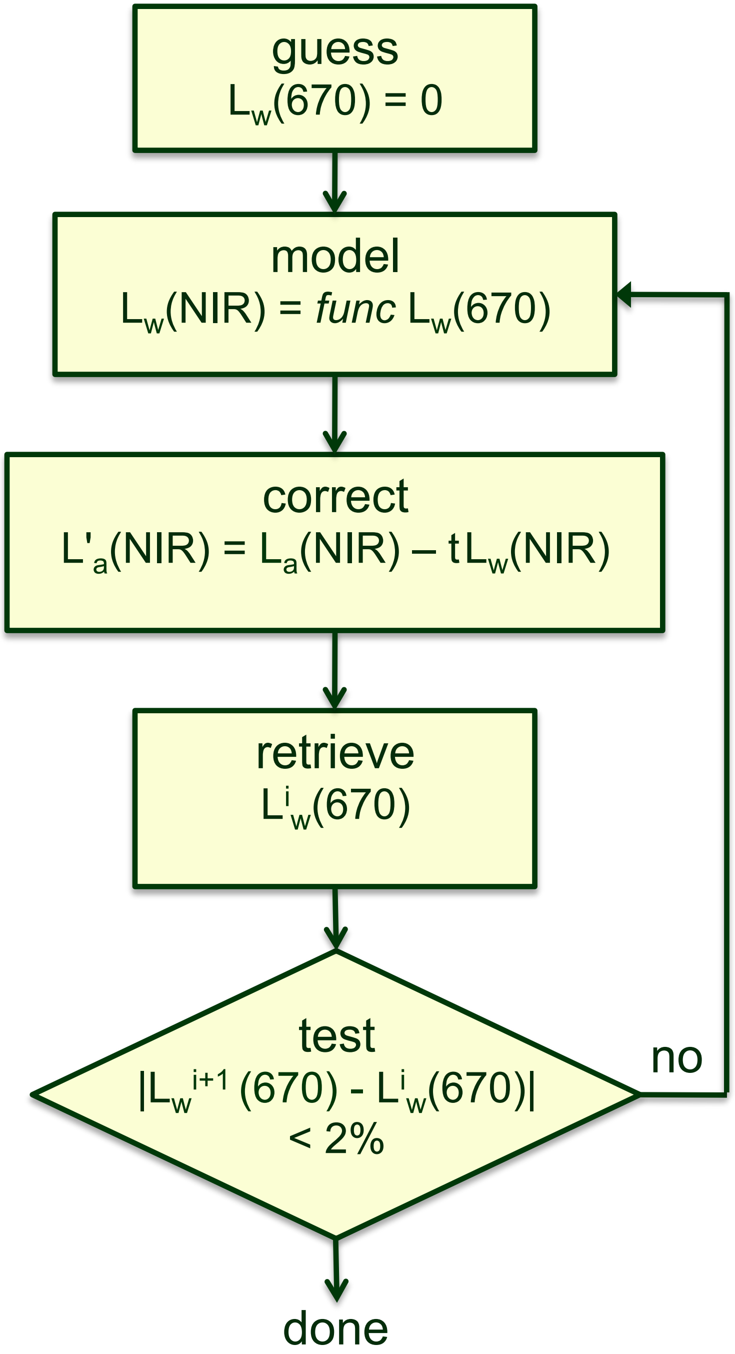
compute weighted average, $\bar{\rho}_a$, between models within each RH family, and then again between bounding RH solutions.

$$\left[L_a + L_{ra}\right] = \bar{\rho}_a(\lambda)\frac{F_0\cos(\theta_0)}{\pi}$$



model epsilon

**actually done in single scattering space and transformed to multi-scattering*



guess
$L_w(670) = 0$

model
$L_w(NIR) = \mathit{func}\ L_w(670)$

correct
$L'_a(NIR) = L_a(NIR) - t\,L_w(NIR)$

retrieve
$L^i_w(670)$

test
$|L_w^{i+1}(670) - L^i_w(670)| < 2\%$

no

done

# we estimate $L_w$(NIR) using a bio-optical model

1) convert $L_w(670)$ to $b_b/(a+b_b)$

via Morel f/Q and retrieved $Chl_a$

2) estimate $a(670) = a_w(670) + a_{pg}(670)$

via NOMAD empirical relationship

$$a(670) = e^{\left(\ln(C_a)*0.9389-3.7589\right)} + a_w(670)$$

3) estimate $b_{bp}(NIR) = b_{bp}(670)\ (\lambda/670)^{\eta}$

via Lee et al. 2002

$$\eta = 2.0 * \left[1. - 1.2 * e^{\left(-0.9*R_{rs}(443)/R_{rs}(555)\right)}\right]$$

4) assume $a(NIR) = a_w(NIR)$

5) estimate $L_w(NIR)$ from $b_b/(a+b_b)$

via Morel f/Q and retrieved $Chl_a$

Bailey et al., Optics Express, 2010

# brdf correction

to account for shape of sub-surface light-field due to position of the Sun and optical properties of the water column.

based on pre-computed look-up tables from hydrolight simulations of Morel et al. 2002, Appl. Opt.

given radiant path geometry ($\theta_0,\theta,\Delta\varphi$), windspeed (w) and **Chl**

$\mathrm{Chl} = f(R'_{rs}(\lambda))$

$$R'_{rs} = \frac{L_w}{F_0 \cos(\theta_s) t_{ds} f_s} f_\lambda$$

iteration

$f_b(\lambda,\theta_0,\theta,\Delta\varphi,\mathrm{Chl},w) = (\overset{\theta_0=0,\ \theta=0,\Delta\varphi=0}{\mathcal{R}_0\, f_0/Q_0}) / (\mathcal{R}\, f/Q)$

f/Q relates subsurface irradiance reflectance to radiance reflectance
$\mathcal{R}$ includes all reflection/refraction effects of the air-sea interface

$R_{rs}(\lambda) = R'_{rs}(\lambda)\, f_b(\lambda,\theta_0,\theta,\Delta\varphi,\mathrm{Chl},w)$

$\mathrm{Chl} = f(R_{rs}(\lambda))$

# adaptation to VIIRS

- standard MODIS atmospheric correction software was modified (previous S-NPP science team) to also process VIIRS
- starts from VIIRS pseudo Level-1A, and applies instrument calibration in Level-1A to Level-2
  - Level-1A developed by multi-disciplinary NASA team
  - instrument calibration developed by OBPG (Eplee et al. 2015)
- algorithm modifications limited to adjustment for sensor-specific spectral band centers and relative spectral responses
- same Ahmad-Fraser vector radiative transfer code used to derive MODIS & VIIRS-specific Rayleigh and aerosol model tables
- bands used for aerosol determination
  - MODIS: 748 & 869 nm
  - VIIRS: 745 & 862 nm