Ocean color satellite atmospheric correction

Jeremy Werdell
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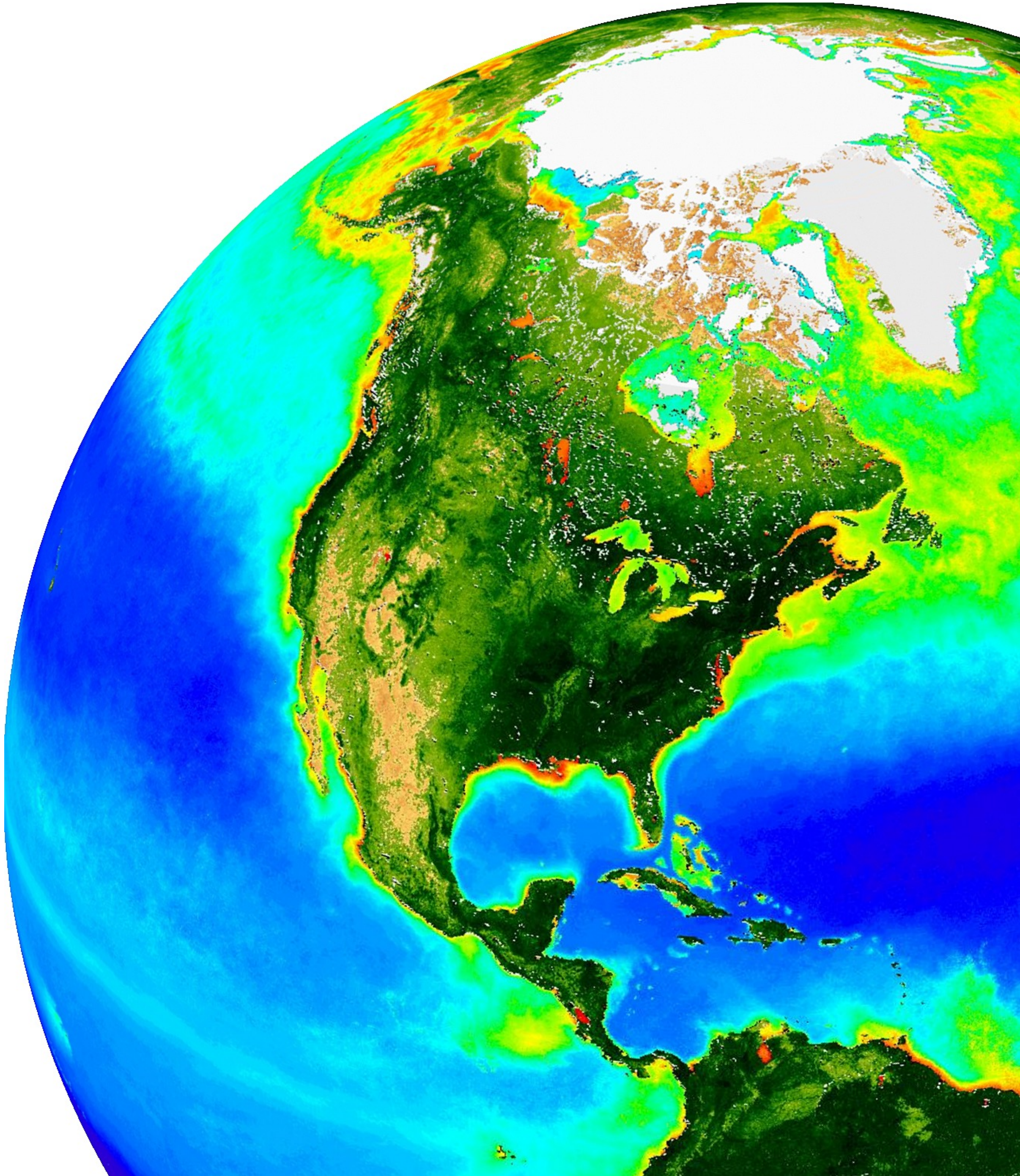
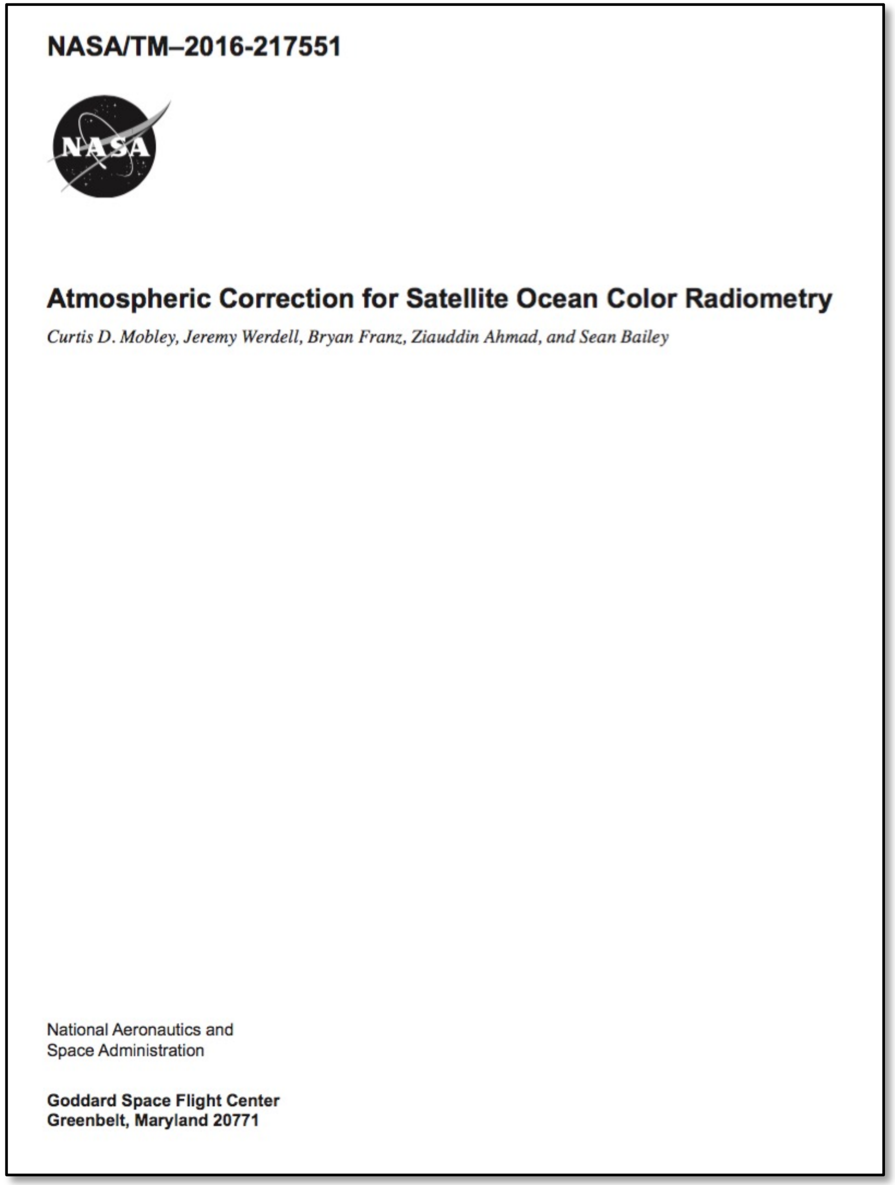
Acknowledgements: Zia Ahmad, Sean Bailey, Bryan Franz, Amir Ibrahim, & **Curt Mobley**

2023 Ocean Optics Summer Course



Learn more

"And as your tour guide, I'd now like to point out that we're **completely** lost."



NASA/TM–2016-217551

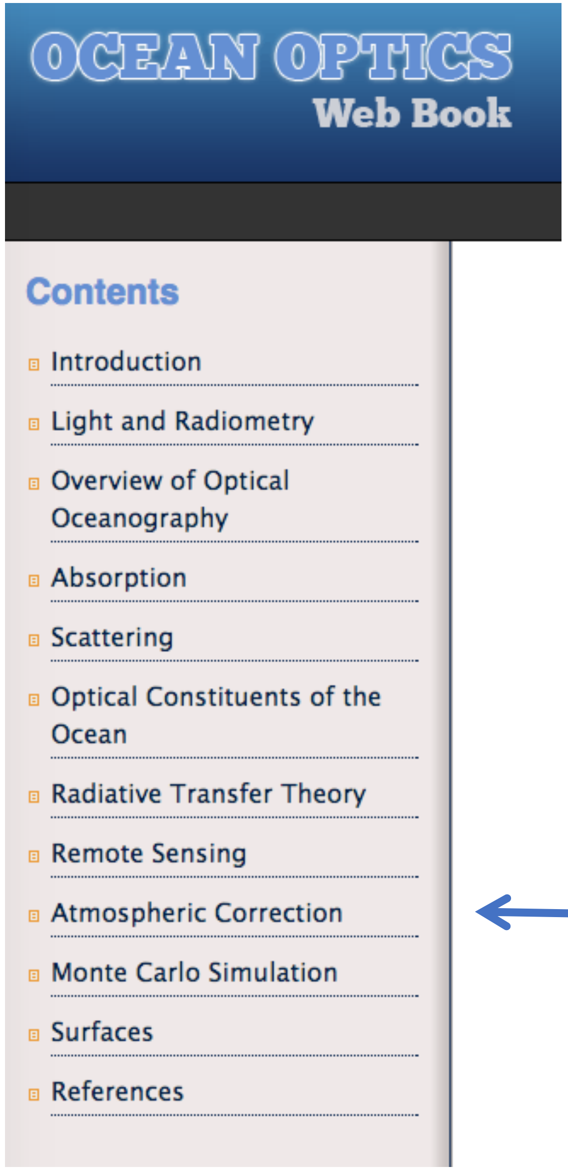
Atmospheric Correction for Satellite Ocean Color Radiometry

Curtis D. Mobley, Jeremy Werdell, Bryan Franz, Ziauddin Ahmad, and Sean Bailey

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

https://oceancolor.gsfc.nasa.gov/docs/technical/NASA-TM-2016-217551.pdf



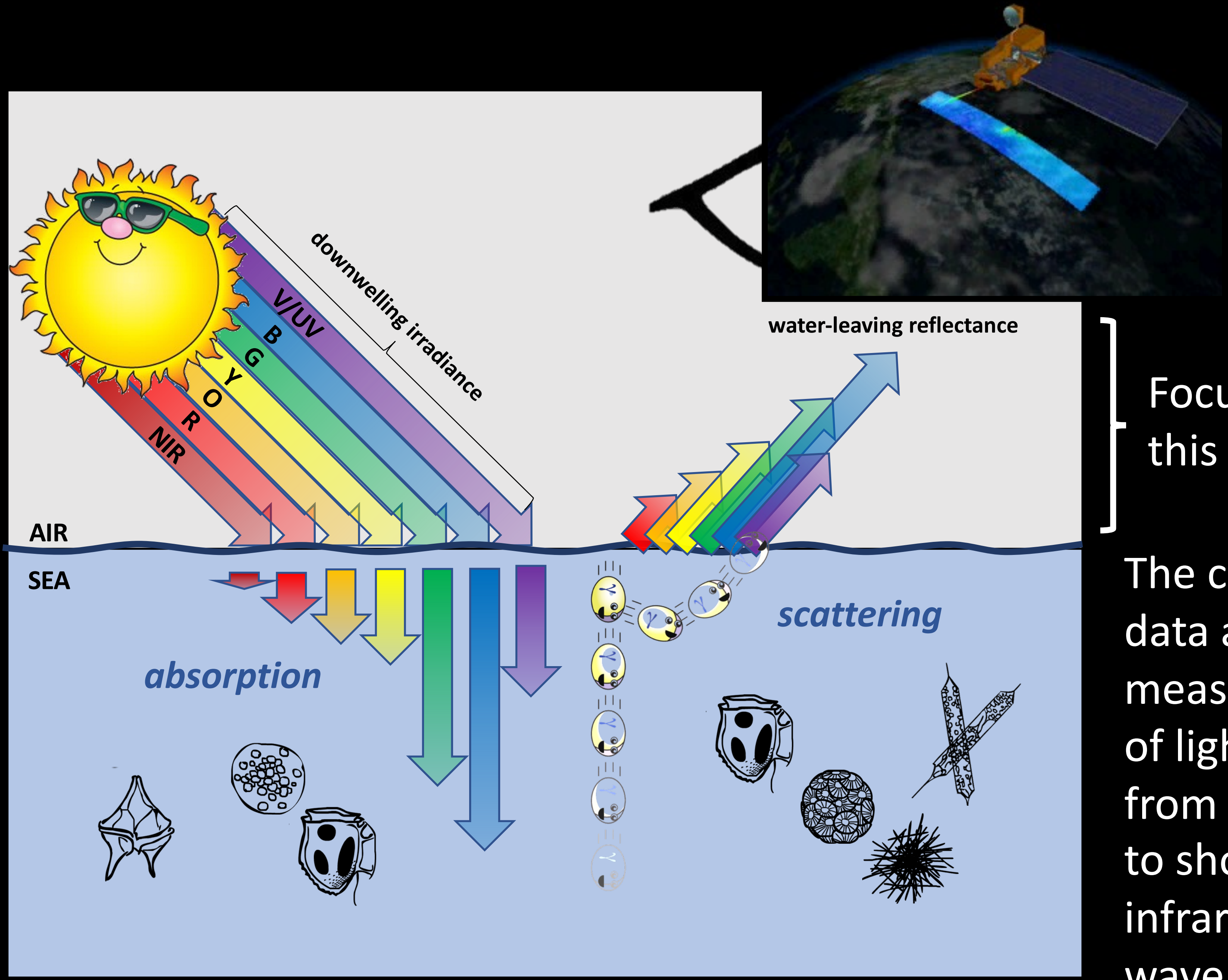
http://www.oceanopticsbook.info

understand the mechanical steps of ocean color atmospheric correction
(as performed by NASA in heritage – this is only one solution, but touches on common issues)

identify places where ancillary (external) data is required

identify places where in situ data & bio-optical models are used

The "color" of the ocean or atmosphere is determined by the interactions of incident light with substances or particles present in the water or atmosphere.



Focus of this lecture

The core satellite data are accurate measurements of light intensity from ultra-violet to shortwave infrared wavelengths.

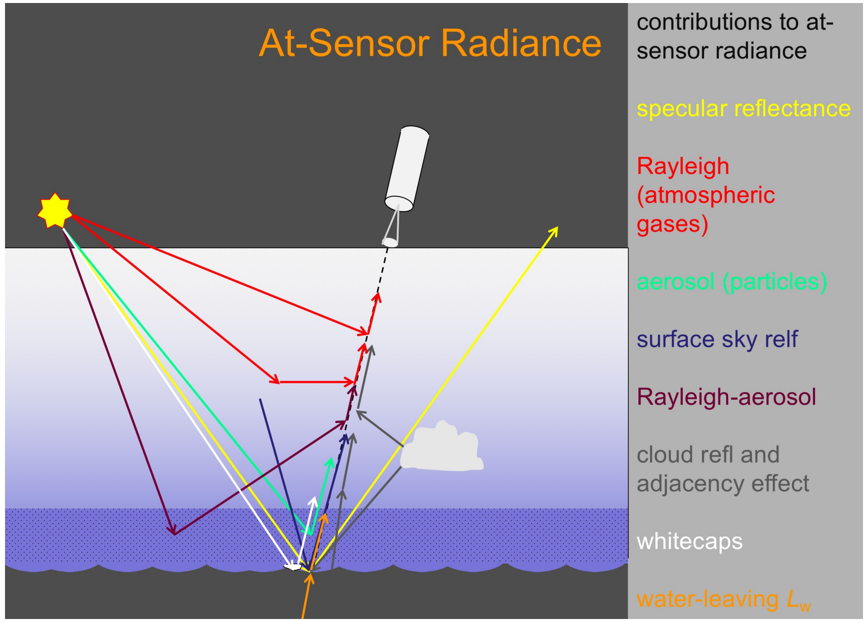
satellite ocean color

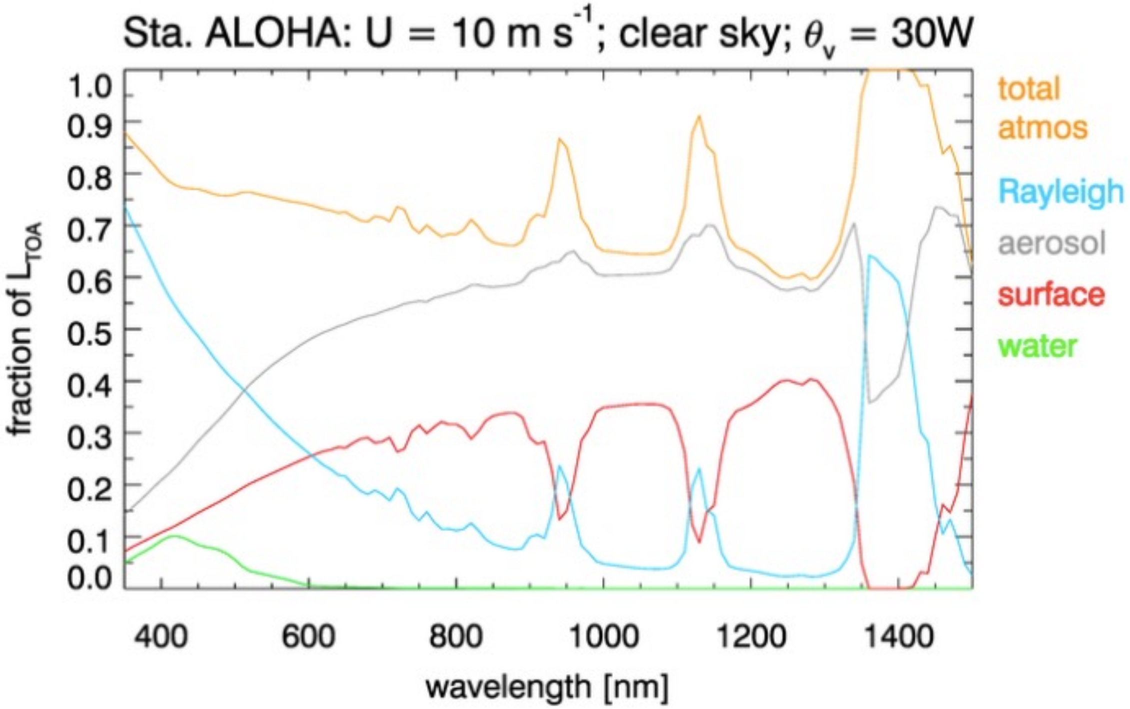
ocean color satellites measure top-of-atmosphere radiances

Rayleigh, aerosols, aerosols+Ray, Sun glint, background sky radiance, white caps, water-leaving

$$(1) \quad L_t = L_R + [L_a + L_{aR}] + L_g + L_{sky} + L_f + L_w$$

where all radiances are defined at the top-of-atmosphere (TOA)





processing constraints

Order of magnitude estimate:

Global ocean area: 5.1×10^8 km^2

MODIS, VIIRS, etc. give global coverage in < 2 days (MODIS data acquisition rate is 10.5 Mbytes/sec)

VIIRS pixel size is 375 m, so ~ 7 pixels/km^2, so must process 35×10^8 pixels every 2 days

All of this times all of the instruments now in orbit (2 MODIS, 3 VIIRS) or planned (PACE, 2 OLCI)

Every pixel gets its own atmospheric correction, which must be done in near real time

This is a severe constraint on what atmospheric correction algorithms are used. You WANT the AC algorithms to be as accurate as possible, but they MUST BE computationally FAST

satellite ocean color

ocean color satellites measure top-of-atmosphere radiances

Rayleigh *aerosols* *aerosols+Ray* *Sun glint* *background sky radiance* *white caps* *water-leaving*

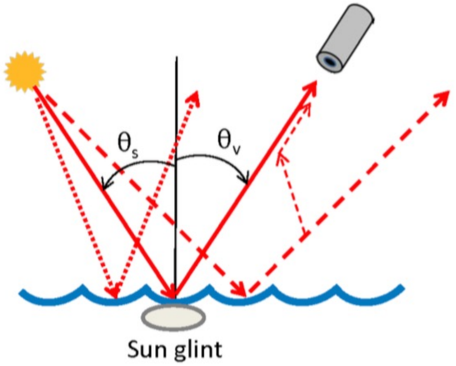
(1) $$L_{\mathrm{t}} = L_{\mathrm{R}} + [L_{\mathrm{a}} + L_{\mathrm{aR}}] + L_g + L_{\mathrm{sky}} + L_f + L_{\mathrm{w}}$$

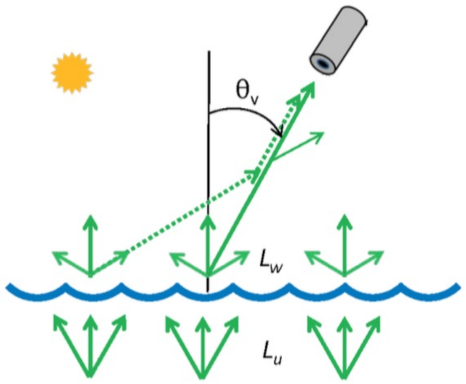
where all radiances are defined at the top-of-atmosphere (TOA)

(2) $$L_t = L_{\mathrm{R}} + [L_a + L_{\mathrm{Ra}}] + TL_g + tL_f + tL_w$$

where $\mathbf{L_g}$, $\mathbf{L_f}$, and $\mathbf{L_w}$ are now defined at the sea surface and $\mathbf{L_{sky}}$ is accounted for in Rayleigh correction. **T** and **t** are the direct and diffuse transmittance.

Direct: one particular path connects the source & observer





Diffuse: radiance from all locations & directions can be scattered into the direction of interest

satellite ocean color

ocean color satellites measure top-of-atmosphere radiances

Rayleigh · aerosols · aerosols+Ray · Sun glint · background sky radiance · white caps · water-leaving

(1) $$L_t = L_R + [L_a + L_{aR}] + L_g + L_{sky} + L_f + L_w$$

where all radiances are defined at the top-of-atmosphere (TOA)

(2) $$L_t = L_R + [L_a + L_{Ra}] + TL_g + tL_f + tL_w$$

where $\mathbf{L_g}$, $\mathbf{L_f}$, and $\mathbf{L_w}$ are now defined at the sea surface and $\mathbf{L_{sky}}$ is accounted for in Rayleigh correction. **T** and **t** are the direct and diffuse transmittance.

factor out gaseous diffuse transmissions: (3) $$L_t = (\, L_r + [L_a + L_{ra}] + t_{dv}L_f + t_{dv}L_w \,)\, t_{gv}t_{gs}f_p + TL_g$$

$\mathbf{t_{gv}}$ is the diffuse transmission by atmos. gases in the viewing direction
$\mathbf{t_{gs}}$ is the diffuse transmission by atmos. gases in the Sun's direction
$\mathbf{t_{dv}}$ is the diffuse transmission along viewing path of the sensor

This "factoring" is done for reasons of computational efficiency. Theoreticians often use (1) or (2); OBPG works with (3).

justification for the latter

Consider the Rayleigh term: $L_{\mathrm{R}} = L_{\mathrm{r}} t_{\mathrm{gv}} t_{\mathrm{gs}} f_{\mathrm{p}}$

The TOA Rayleigh contribution L_R depends on Sun and viewing geometry, absorbing and non-absorbing atmospheric gasses, sea-level pressure, and polarization. This is a serious RT calculation, including polarization.

The L_r term is a "standard" Rayleigh contribution computed using a standard atmosphere and only non-absorbing gases N_2 and O_2, for various Sun & viewing geometries. This can be computed once and placed in a look-up table.

The gaseous transmittances are computed by use of gas absorption coefficients, computed path lengths, and gas concentrations for the various absorbing gases. Compute once and put in a LUT.

The f_p term is a polarization correction, which depends on atmosphere and surface polarization states (modeled Rayleigh and glint Stokes vectors) and the sensor-specific polarization sensitivity with viewing direction. Again, compute once for various inputs and make a LUT.

L_r, the diffuse transmittances, and f_p are pre-computed and stored in look-up tables as functions of Sun and viewing geometry, gas concentrations, instrument polarization sensitivity, etc. **Evaluation of L_R then requires no real-time radiative transfer calculations.**

Ditto for the other terms in the L_t equation

atmospheric correction is the process of estimating R_{rs} from L_t

ocean color satellites measure top-of-atmosphere radiances

$$L_t = \left(L_r + [L_a + L_{ra}] + t_{dv} L_f + t_{dv} L_w\right) t_{gv}\, t_{gs}\, f_p \; + T\, L_g$$

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

we desire (normalized)
remote sensing reflectances

lecture outline: sequentially step through the meaning & derivation of each term in these equations

measured

not known

calculated

$$L_t = \left(L_r + [L_a + L_{ra}] + t_{dv} L_f + t_{dv} L_w\right) t_{gv}\, t_{gs}\, f_p + T L_g$$

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

desired

top-of-atmosphere radiance

$$L_t = \left(L_r + \left[L_a + L_{ra}\right] + t_{dv} L_f + t_{dv} L_w\right) t_{gv}\, t_{gs}\, f_p + T L_g$$

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

top-of-atmosphere radiance

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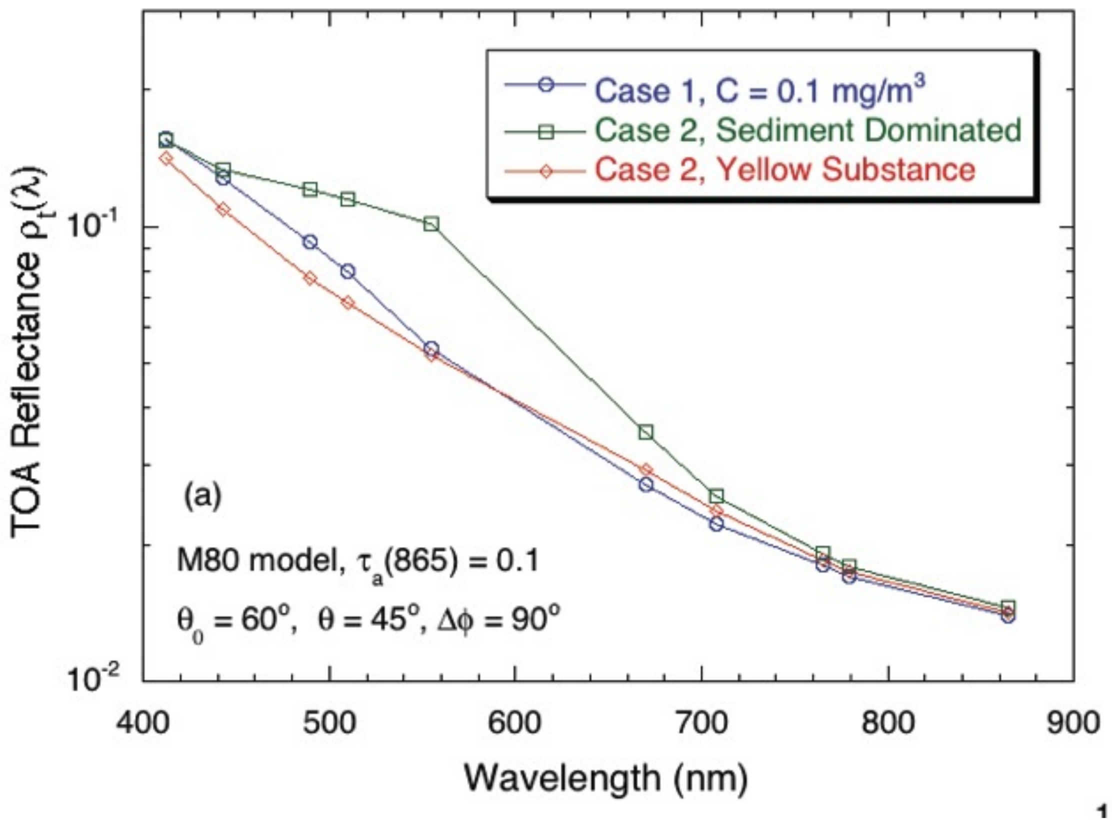
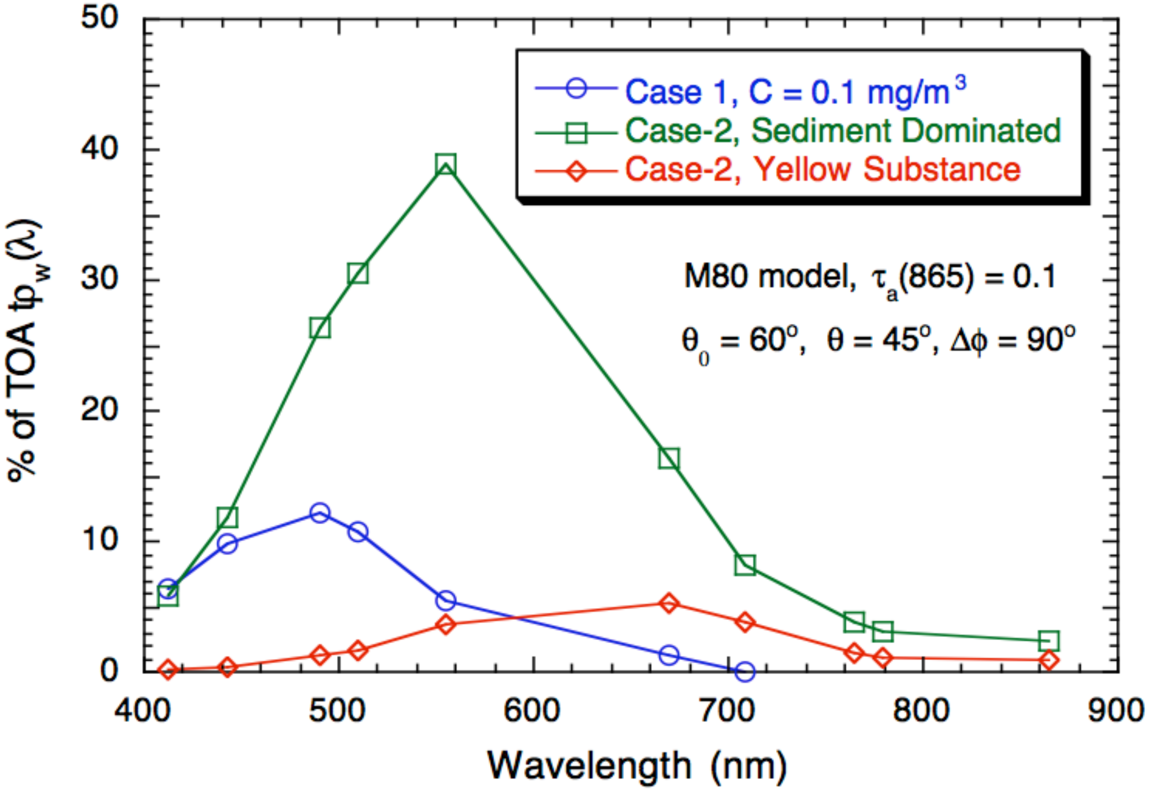
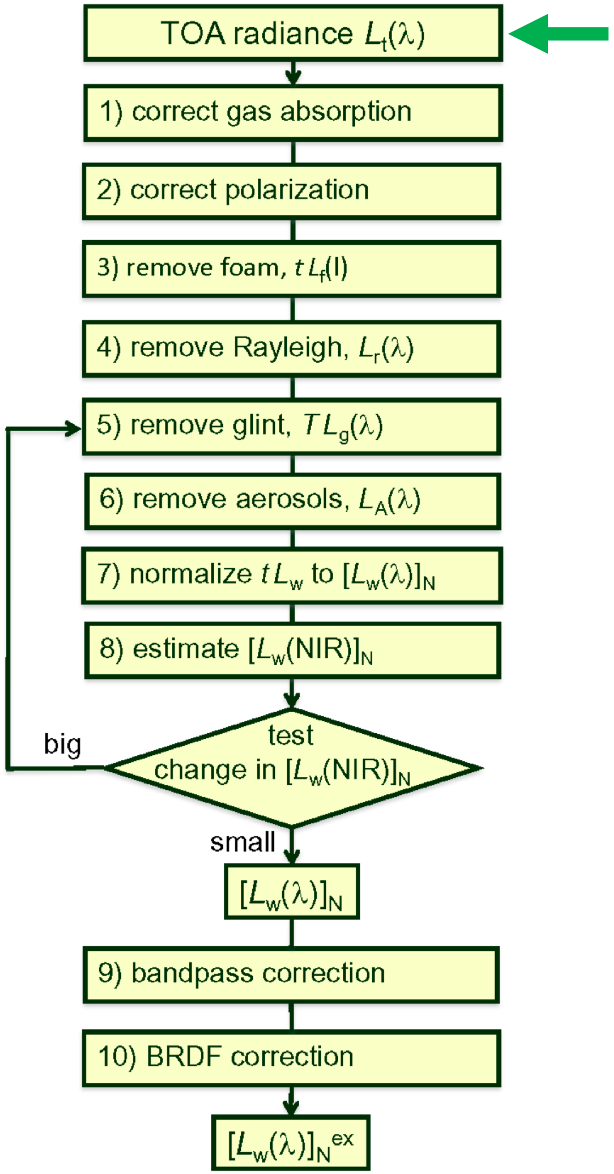


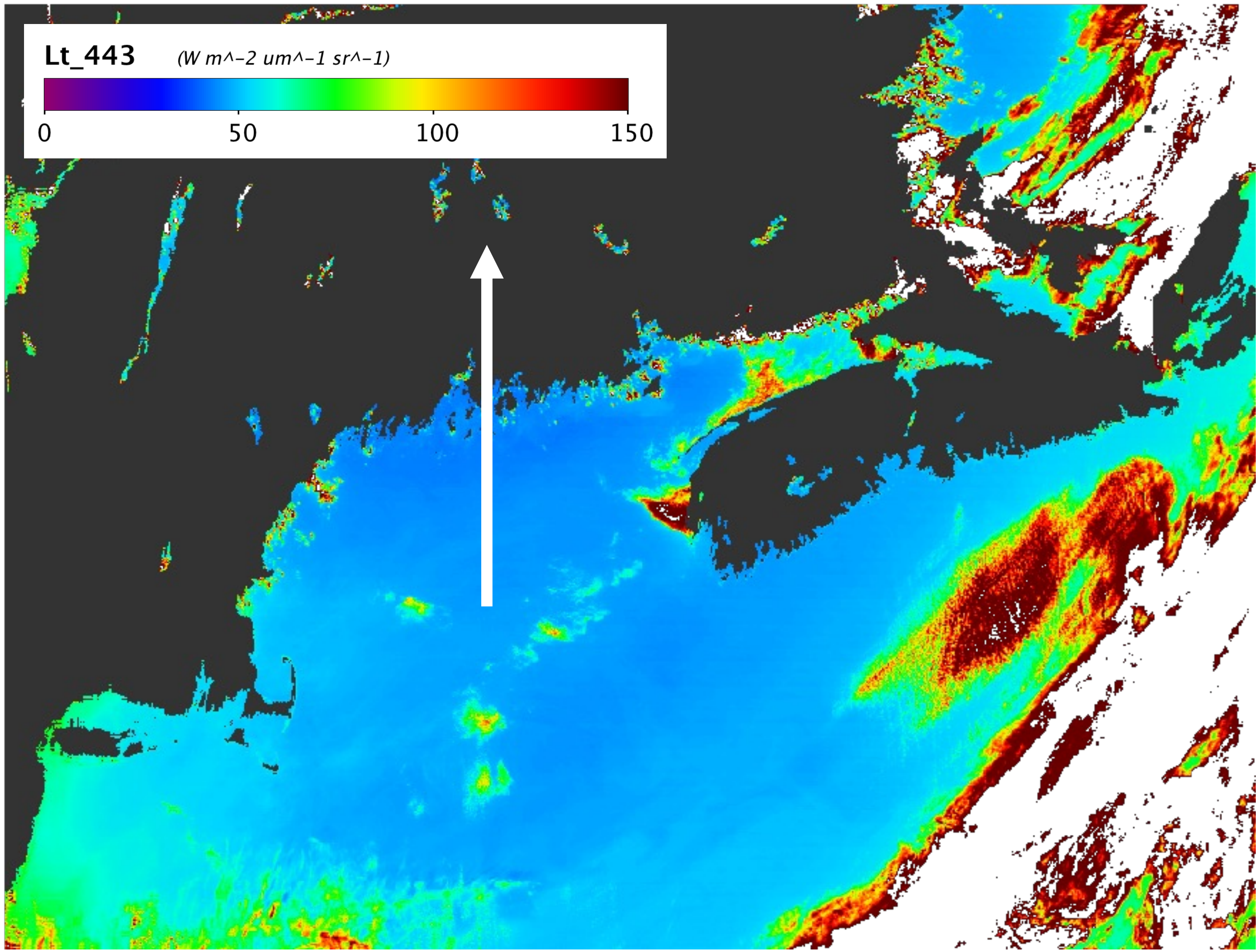


L_w is often <10% of L_t !

0.5% error in atmospheric correction or calibration → 5% error in L_w

processing cadence: L_t





known terms

✓

$$L_t = \left(L_r + [L_a + L_{ra}] + t_{dv} L_f + t_{dv} L_w\right) t_{gv} t_{gs} f_p + T L_g$$

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

cosine of the
instrument view angle

solar constant (irradiance) & an
adjustment for the Earth-Sun distance

transmittances

diffuse transmittance of gases (g)
in direction of Sun (s) or satellite (v)

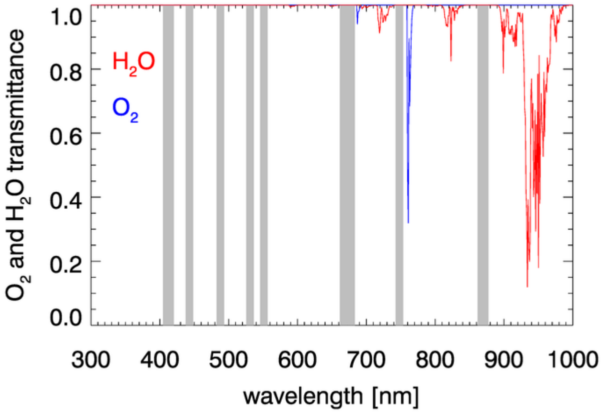
$$L_t = \left(L_r + [L_a + L_{ra}] + t_{dv} L_f + t_{dv} L_w\right) t_{gv} t_{gs} f_p + T L_g$$

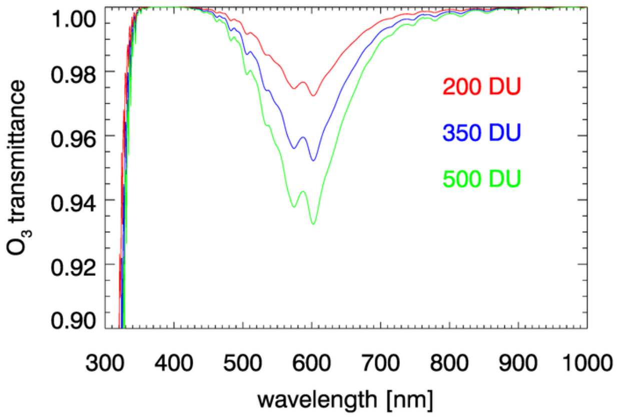
$$R_{rs} = \frac{L_w}{F_0 \cos(\theta_s) t_{ds} f_s f_b f_\lambda}$$

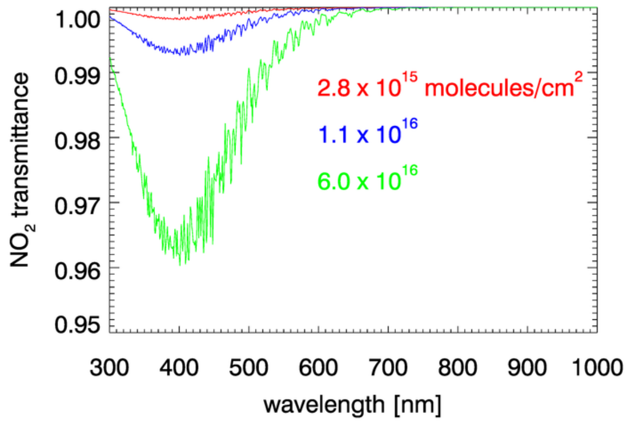
Rayleigh / aerosol diffuse
transmittance (d) in direction
of Sun (s) or satellite (v)

gaseous transmittance

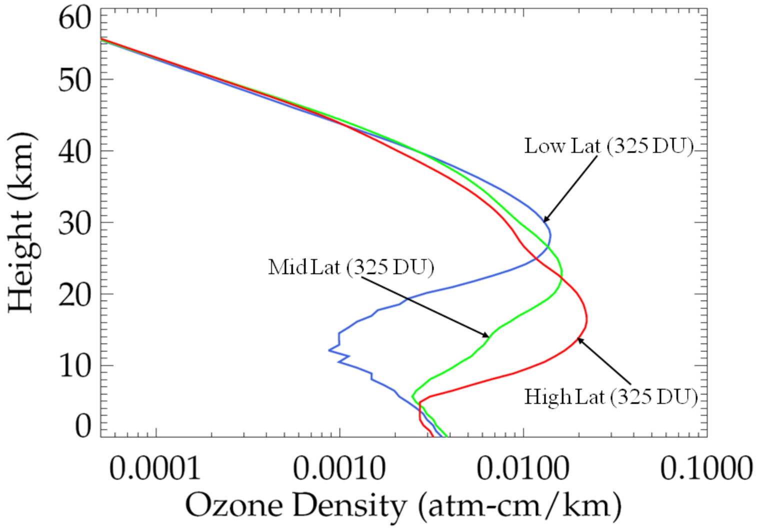
nitrogen dioxide, ozone, oxygen, & water vapor all attenuate sunlight

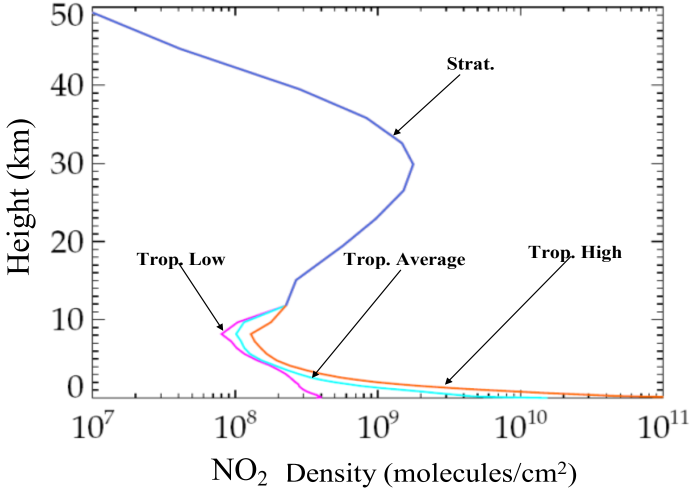




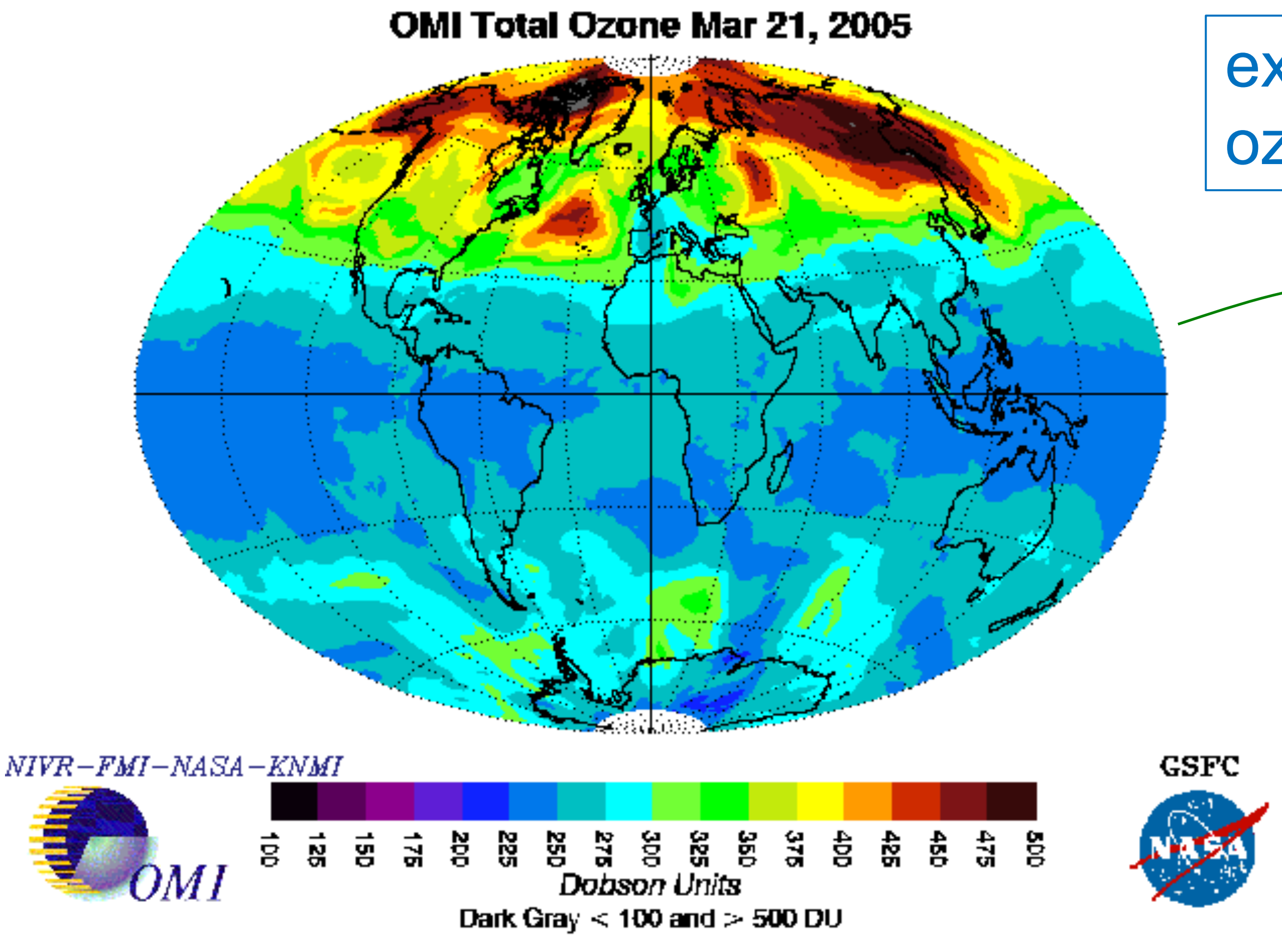


O_3 optically thin & high in atmosphere, but NO_2 dense & near the surface





calculating gaseous transmittance requires ancillary data



example using OMI ozone measurements

$$\tau_{O_3} = O_3 \, k_{O_3} \leftarrow \text{from LUT}$$

$$t_{O_3} = \exp\left[-\tau_{O_3}\left(\frac{1}{\cos(\theta_0)} + \frac{1}{\cos(\theta)}\right)\right]$$

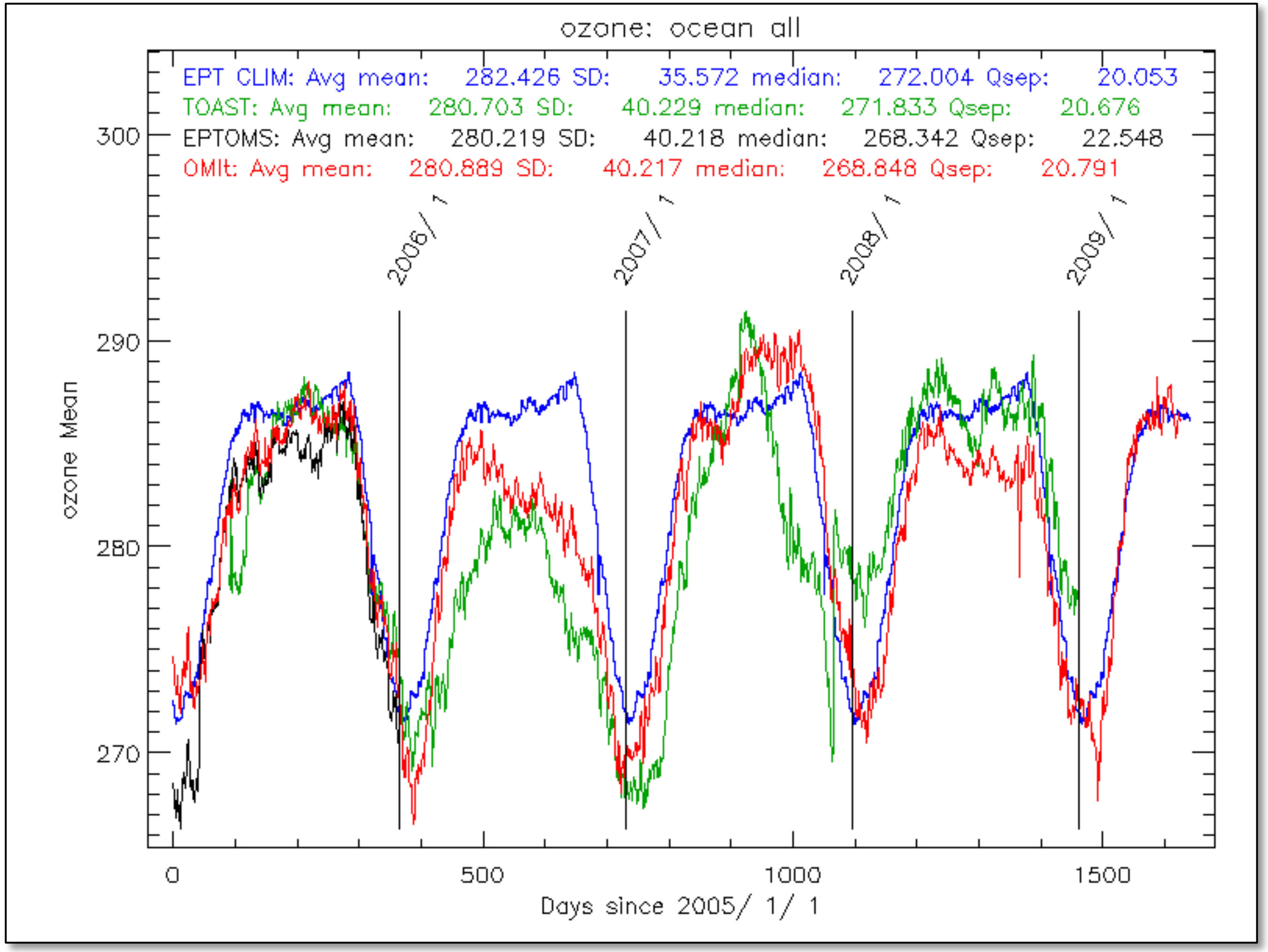
most transmittances are calculated in this manner

all ancillary data are not created equal

compare three ancillary sources of O_3:

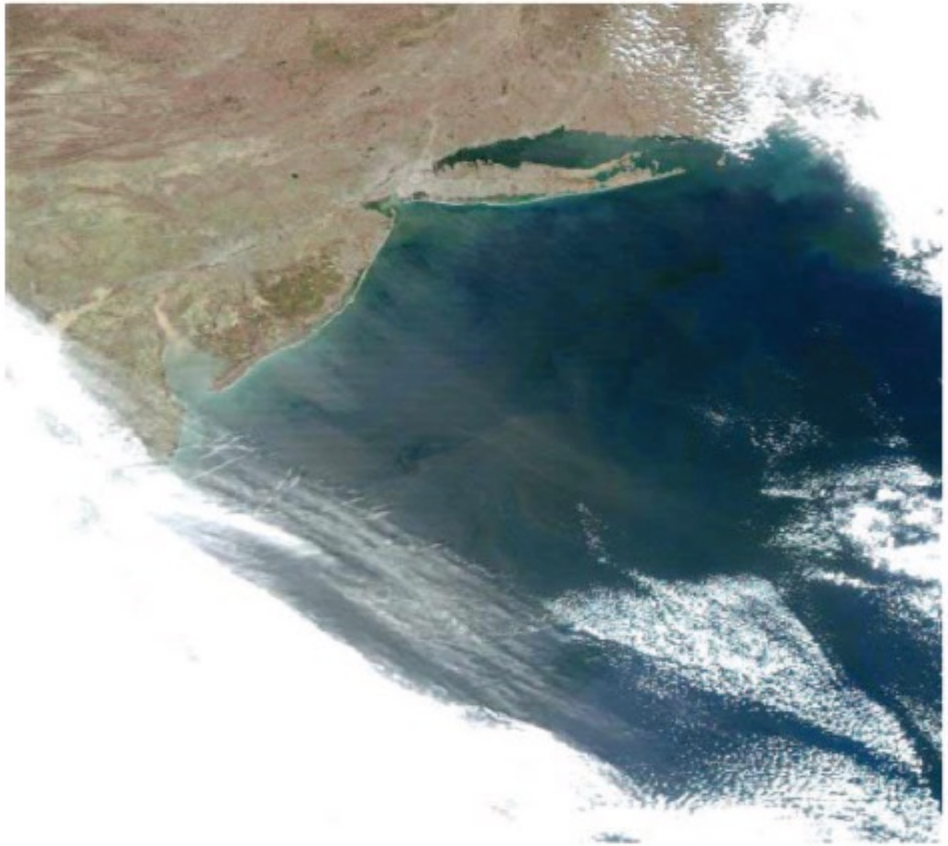
TOAST
OMI
EPT climatology

small differences in ancillary data can lead to big differences in geophysical products

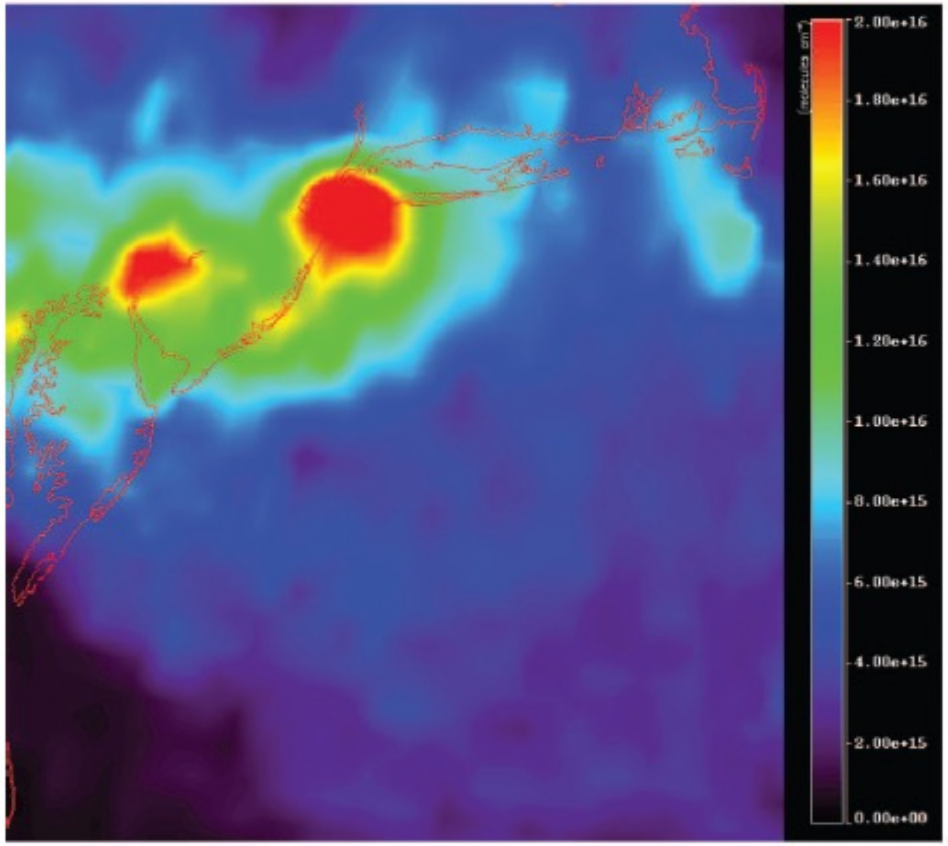


TOAST: Total Ozone from Analysis of Stratospheric and Tropospheric components
OMI: Ozone Mapping Instrument
EPTOMS: Earth-Probe Total Ozone Monitoring Spectrometer
...and there are others

no surprise: Lots of NO_2 near NY City and Philadelphia



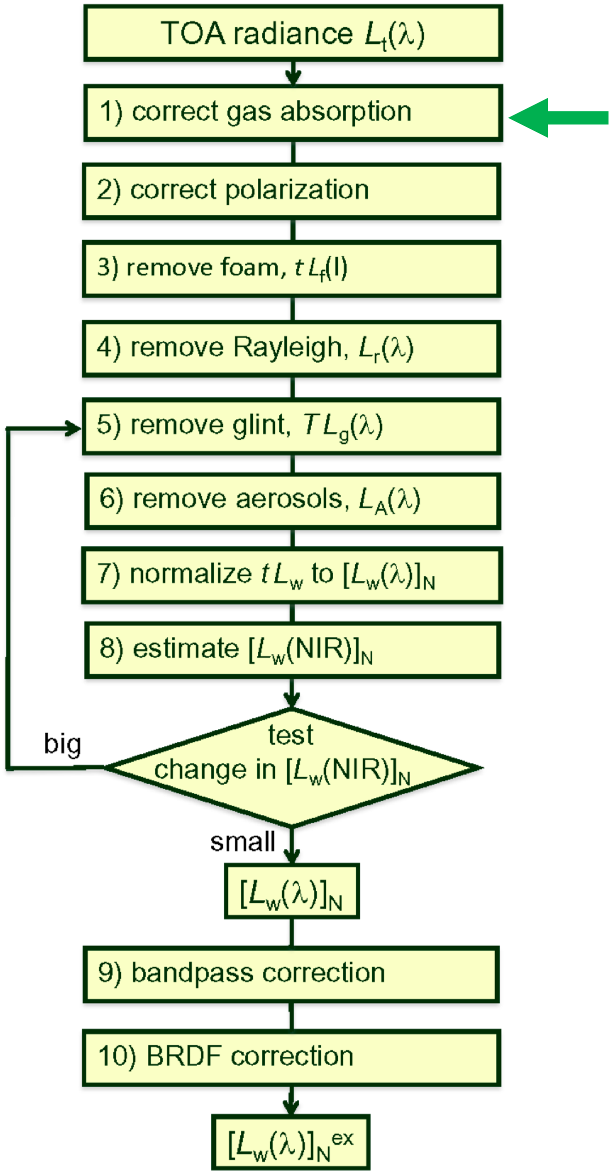
RGB image of a MODIS-Aqua scene from 11 April 2005

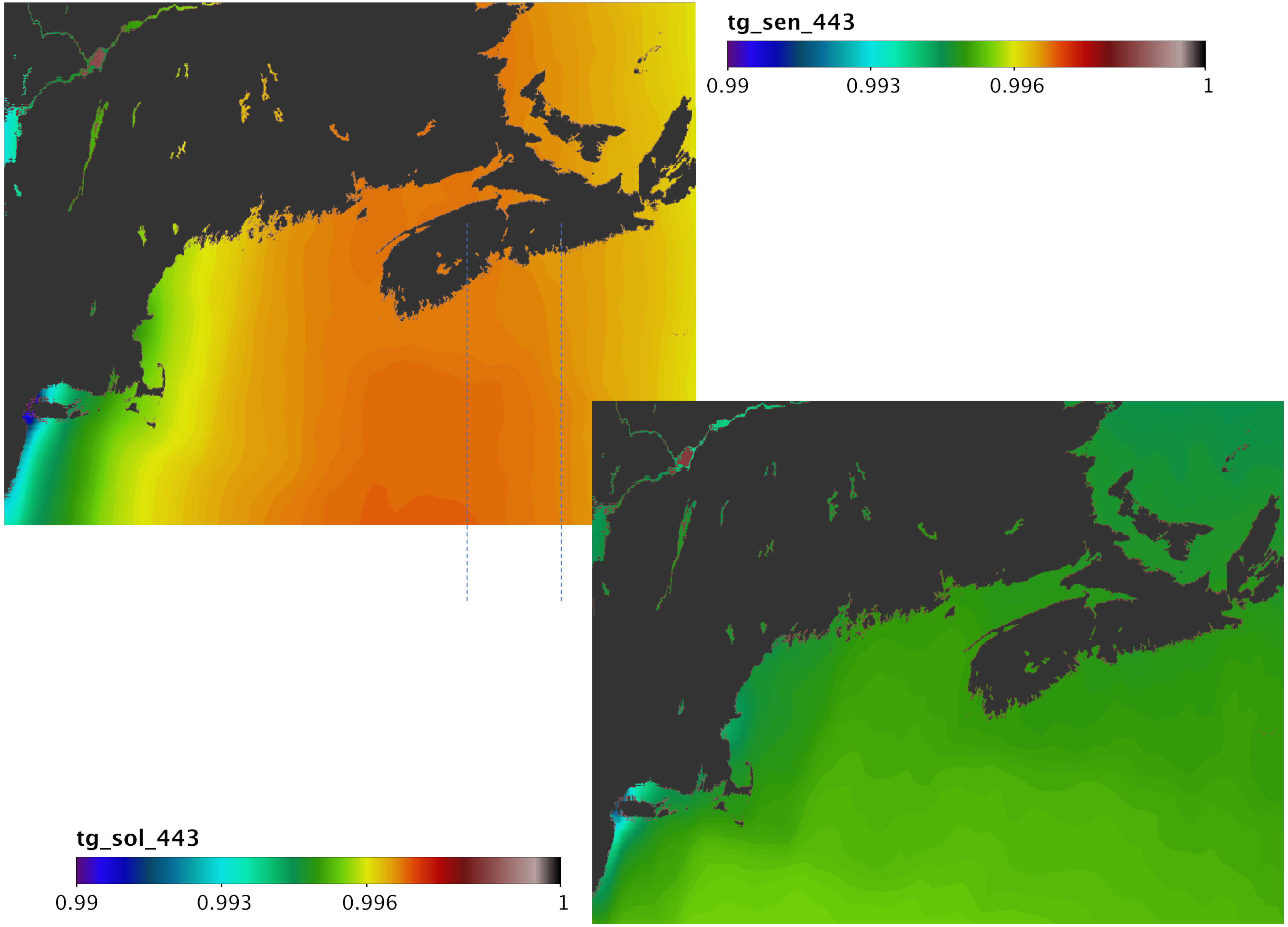


OMI tropospheric NO2 amount on 11 April 2005

From Ahmad et al. (2007)

processing cadence: L_t / t_{gv} / t_{gs}





instrument polarization sensitivity

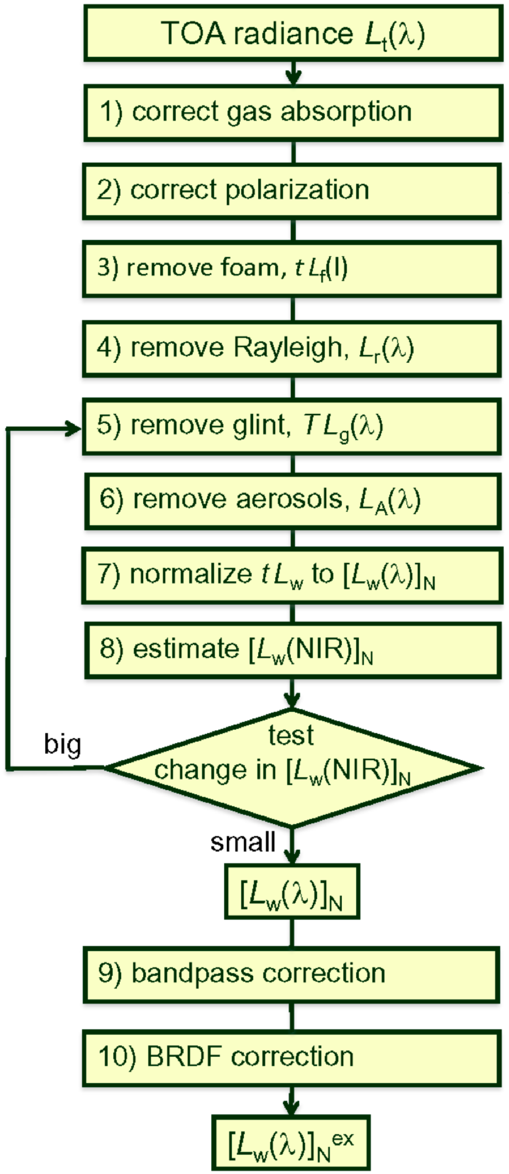
instrument polarization correction factor (pre-launch measurement)

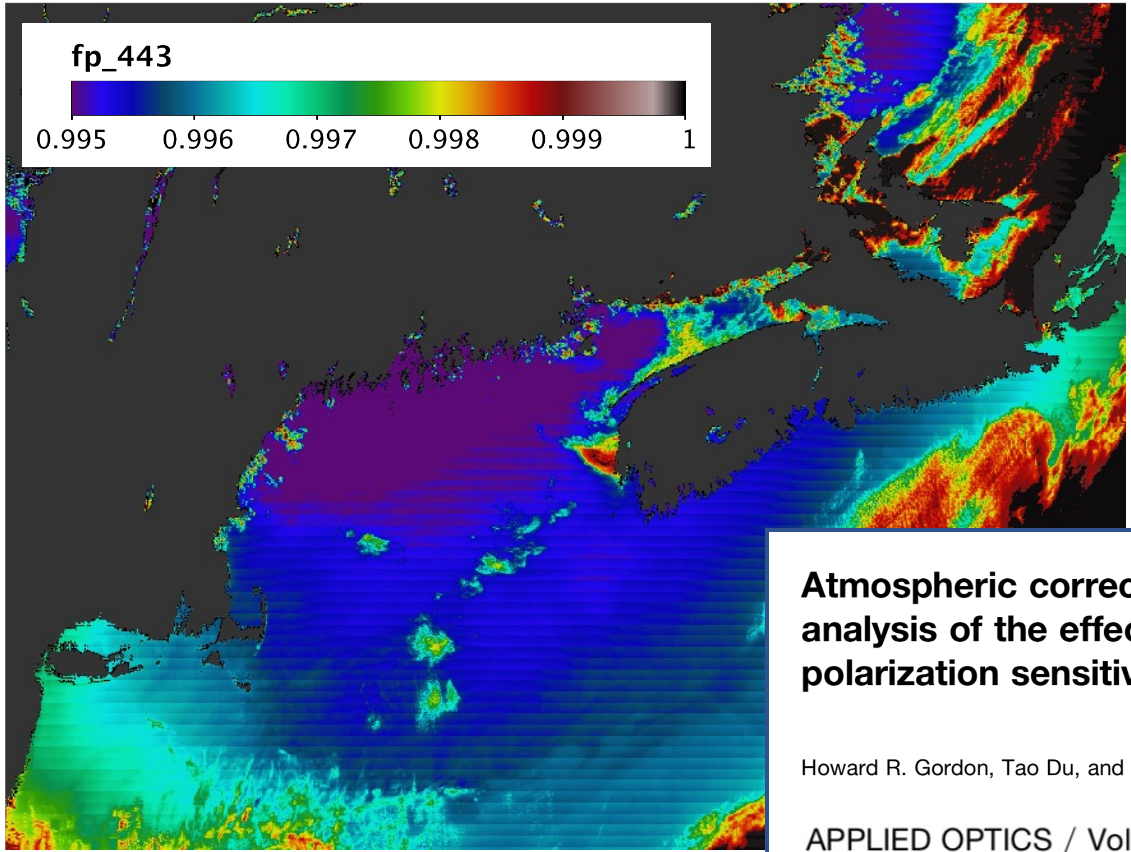
$$L_t = \left(L_r + [L_a + L_{ra}] + t_{dv} L_f + t_{dv} L_w\right) t_{gv}\, t_{gs}\, f_p + T L_g$$

MODIS requires an additional correction

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

processing cadence: L_t / t_{gv} / t_{gs} / f_p





some satellite instruments include depolarizers in their fore optics, which mitigates instrument polarization sensitivity

Atmospheric correction of ocean color sensors: analysis of the effects of residual instrument polarization sensitivity

Howard R. Gordon, Tao Du, and Tianming Zhang

APPLIED OPTICS / Vol. 36, No. 27 / 20 September 1997

Moderate-Resolution Imaging Spectroradiometer ocean color polarization correction

Gerhard Meister, Ewa J. Kwiatkowska, Bryan A. Franz, Frederick S. Patt, Gene C. Feldman, and Charles R. McClain

APPLIED OPTICS / Vol. 44, No. 26 / 10 September 2005

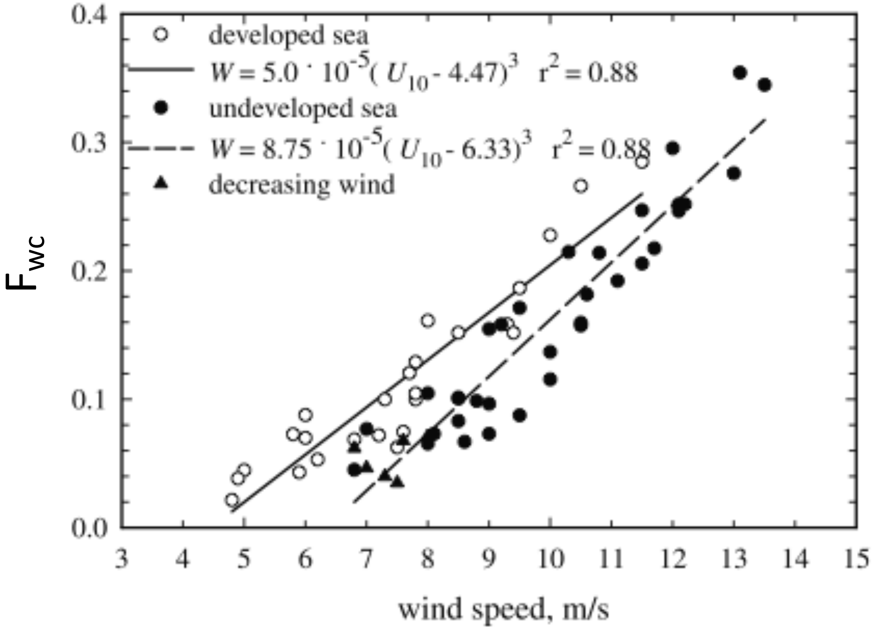
foam & whitecaps

$$L_t = \left(L_r + \left[L_a + L_{ra}\right] + t_{dv} L_f + t_{dv} L_w\right) t_{gv}\, t_{gs}\, f_p + T\, L_g$$

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

foam & whitecaps

Stramska & Petelski, JGR, 2003



$\rho_f = \pi\ L_f = A\ F_{wc}$

A = 22% (11-33%) from Koepke 1984
+ a correction for decreasing reflectance in red & NIR

$\rho_f(412) = \pi\ L_f(412) = 1.925 \times 10^{-5}\ (U_{10} - 6.33)^3$

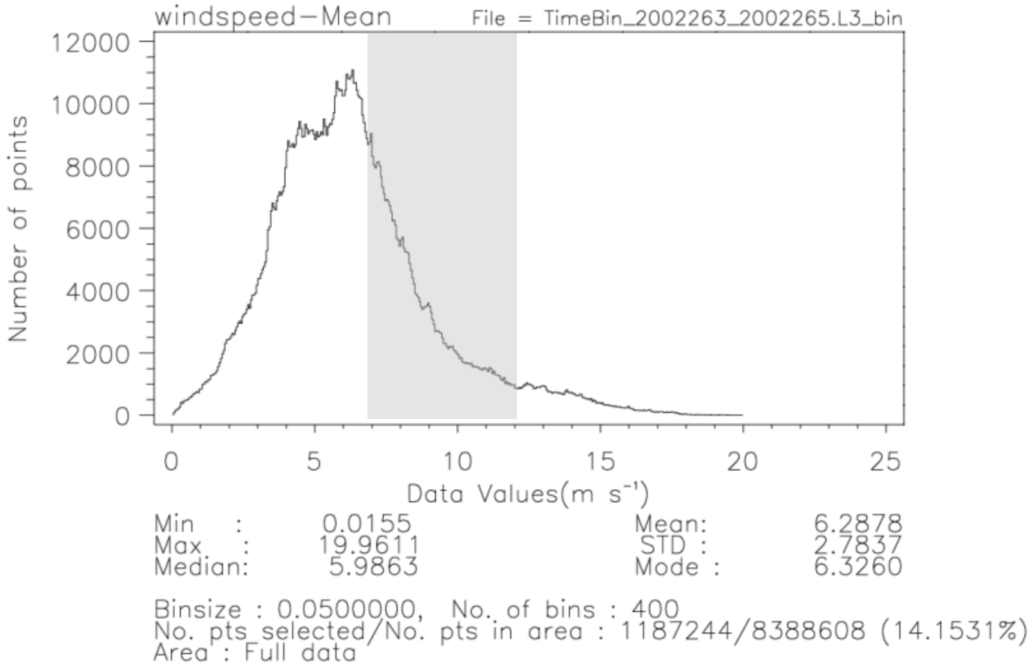
estimation of contribution of whitecaps & foam requires ancillary wind data (e.g., NCEP)

ORIGINAL RESEARCH ARTICLE
Front. Earth Sci., 26 February 2019 | https://doi.org/10.3389/feart.2019.00014

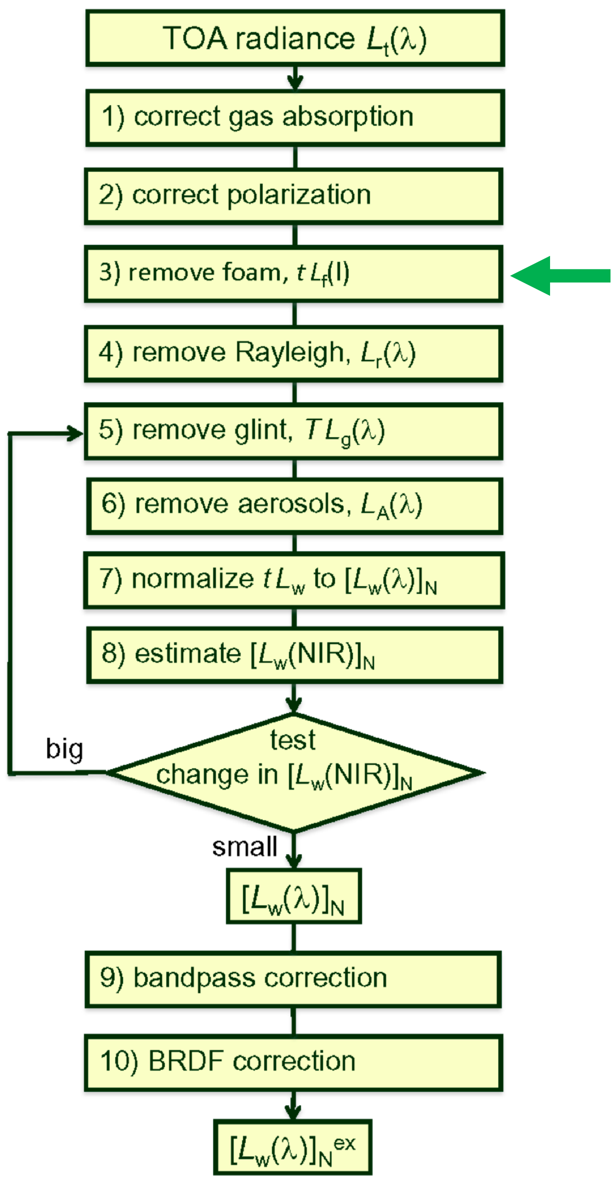
Check for updates

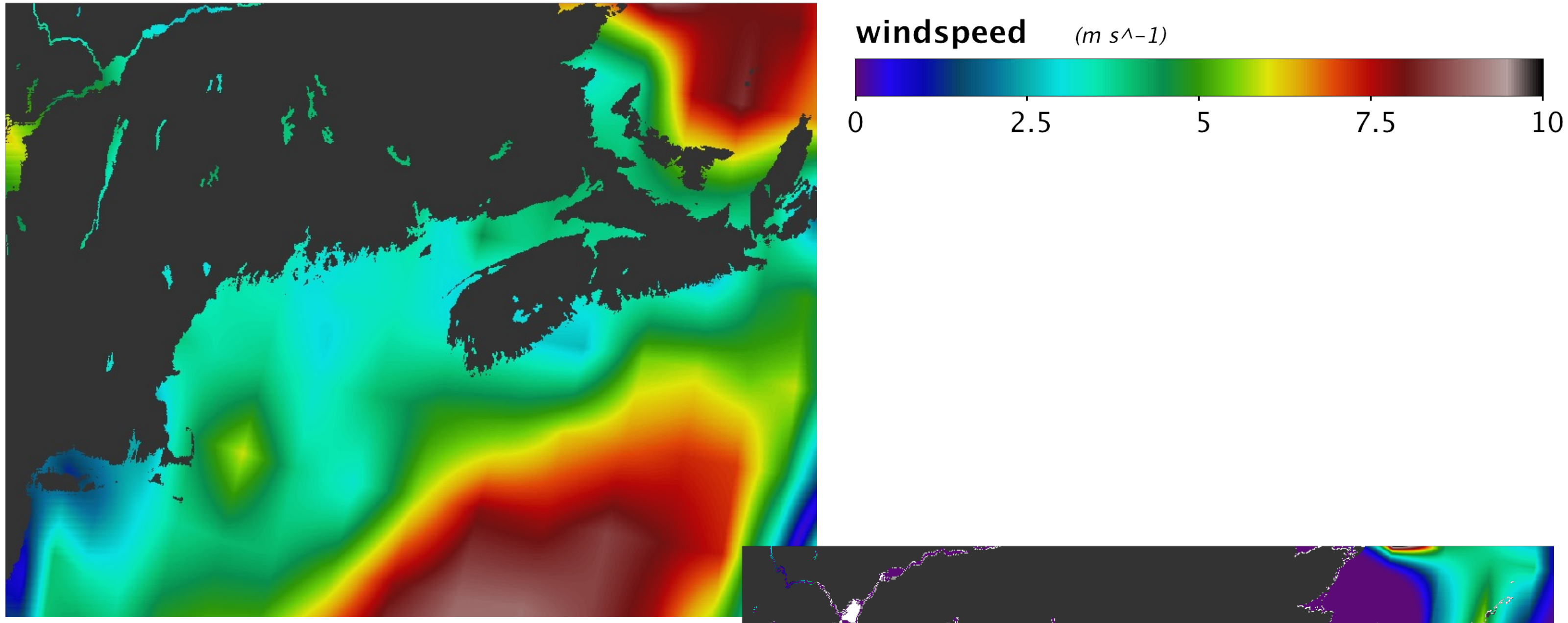
Hyperspectral Measurements, Parameterizations, and Atmospheric Correction of Whitecaps and Foam From Visible to Shortwave Infrared for Ocean Color Remote Sensing

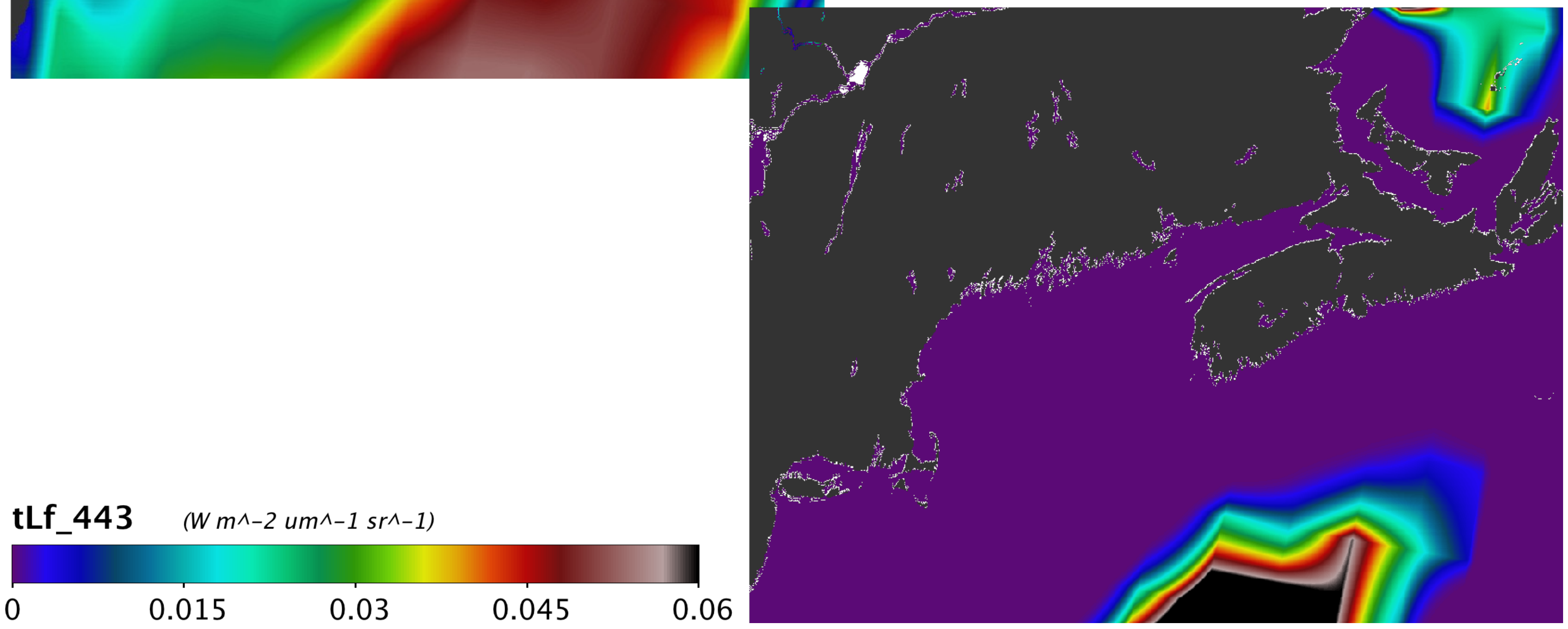
Heidi M. Dierssen*
Department of Marine Sciences, University of Connecticut, Groton, CT, United States



processing cadence: L_t / t_{gv} / t_{gs} / f_p - tL_f







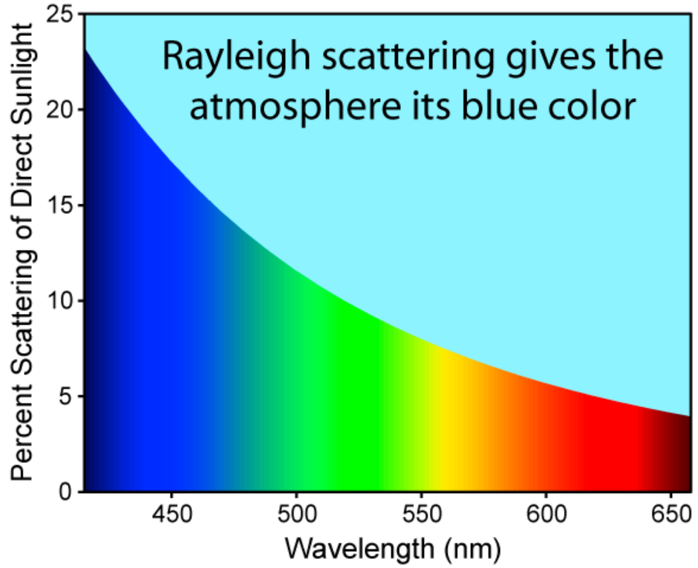
molecular (Rayleigh) scattering

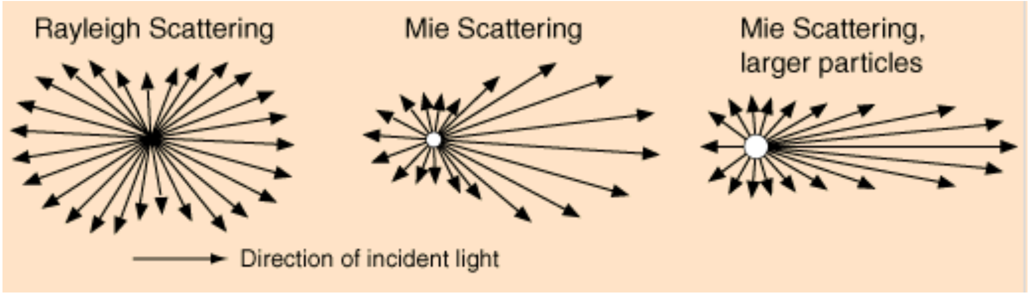
$$L_t = \left(L_r + [L_a + L_{ra}] + t_{dv} L_f + t_{dv} L_w\right) t_{gv}\, t_{gs}\, f_p + T L_g$$

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

molecular (Rayleigh) scattering

- elastic scattering of electromagnetic radiation by particles much smaller than the wavelength of light (atoms or molecules)
- Rayleigh scattering of sunlight in atmosphere causes diffuse sky radiation – why the sky is blue and the Sun is yellow





http://hyperphysics.phy-astr.gsu.edu/hbase/atmos/blusky.html

- scattering phase function is symmetrical – equal forward & backward

a quick aside on computational efficiency

$$L_{\mathrm{R}} = L_{\mathrm{r}} t_{\mathrm{gv}} t_{\mathrm{gs}} f_{\mathrm{p}}$$

- Rayleigh TOA contribution (L_R) is factored into the product of a Rayleigh term (L_r), diffuse transmittances, & a polarization correction factor
- develop & maintain one **look-up table** (LUT) for L_r, computed using a standard atmosphere & the non-absorbing gases N_2 and O_2 for various Sun & viewing geometries
- transmittances calculated separately
- **computational efficiency**: without doing this, the Rayleigh LUT would become a function of other gases affecting transmission (ozone, NO_2, & water vapor), making it too large for efficient operational use

molecular (Rayleigh) scattering

Rayleigh optical properties are calculable (to ~0.2%) – made challenging by a rough, reflective ocean (versus a flat, black ocean)

Rayleigh radiances (with polarization) are retrieved from look up tables given:

- solar & satellite viewing geometries
- wind speed (a proxy for surface roughness (influences L_{sky}))
- atmospheric pressure (∝ # gas molecules, adjusts Rayleigh optical thickness, τ_r)

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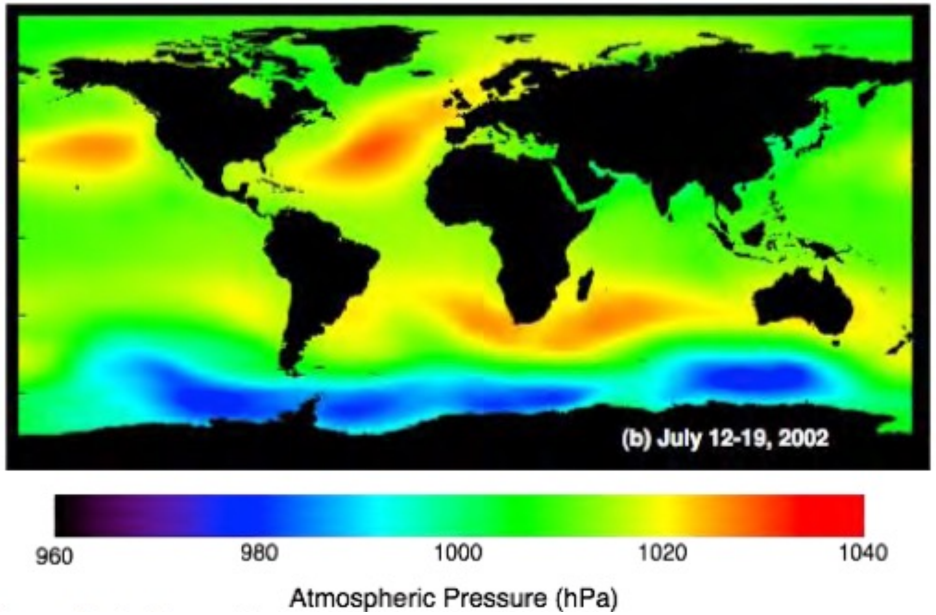
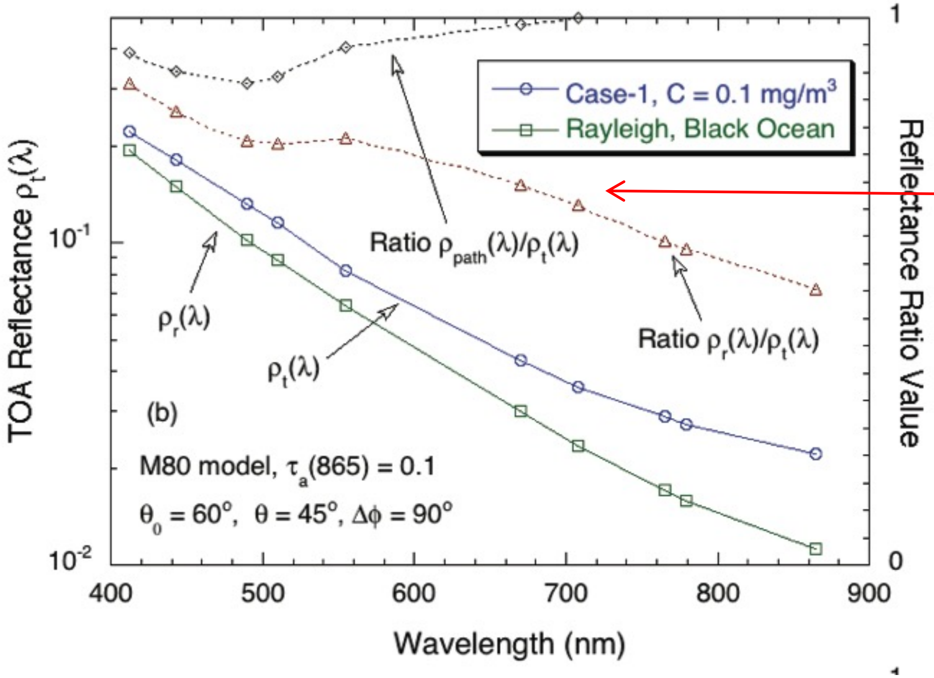
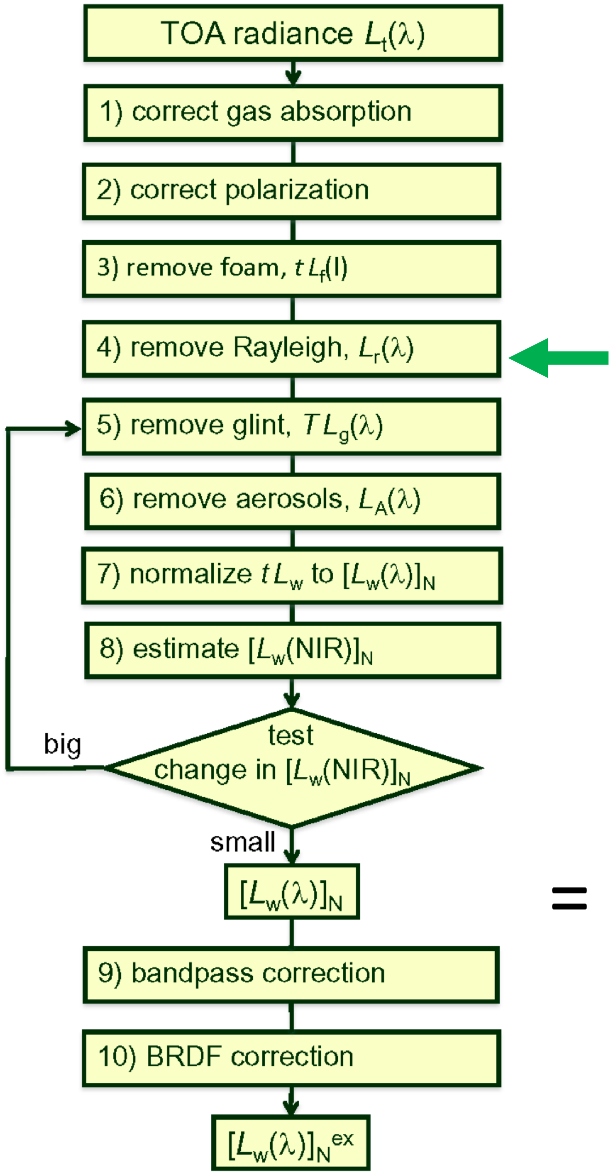
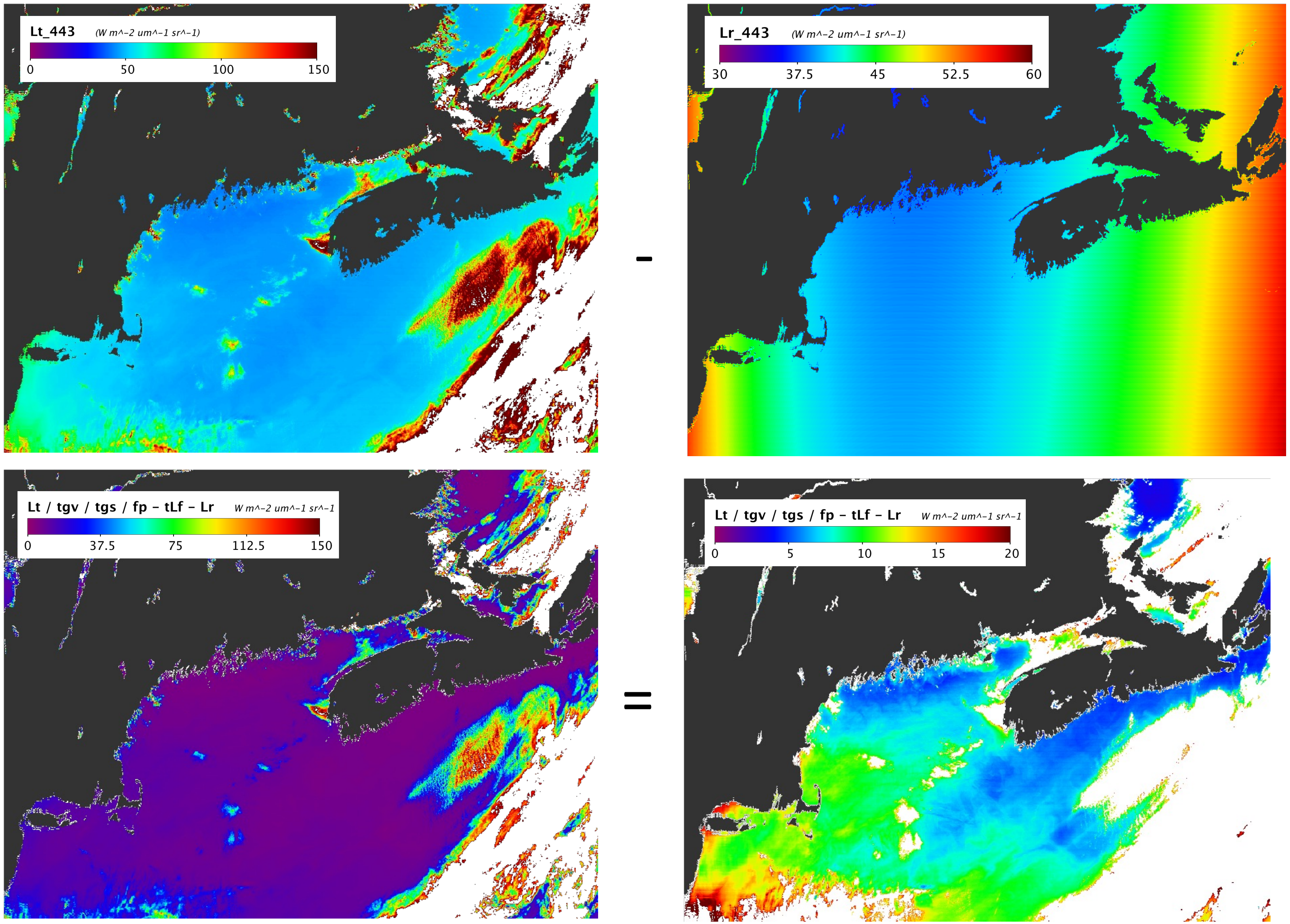




L_r can be 50-90% of L_t

processing cadence: L_t / t_{gv} / t_{gs} / f_p – tL_f - L_r



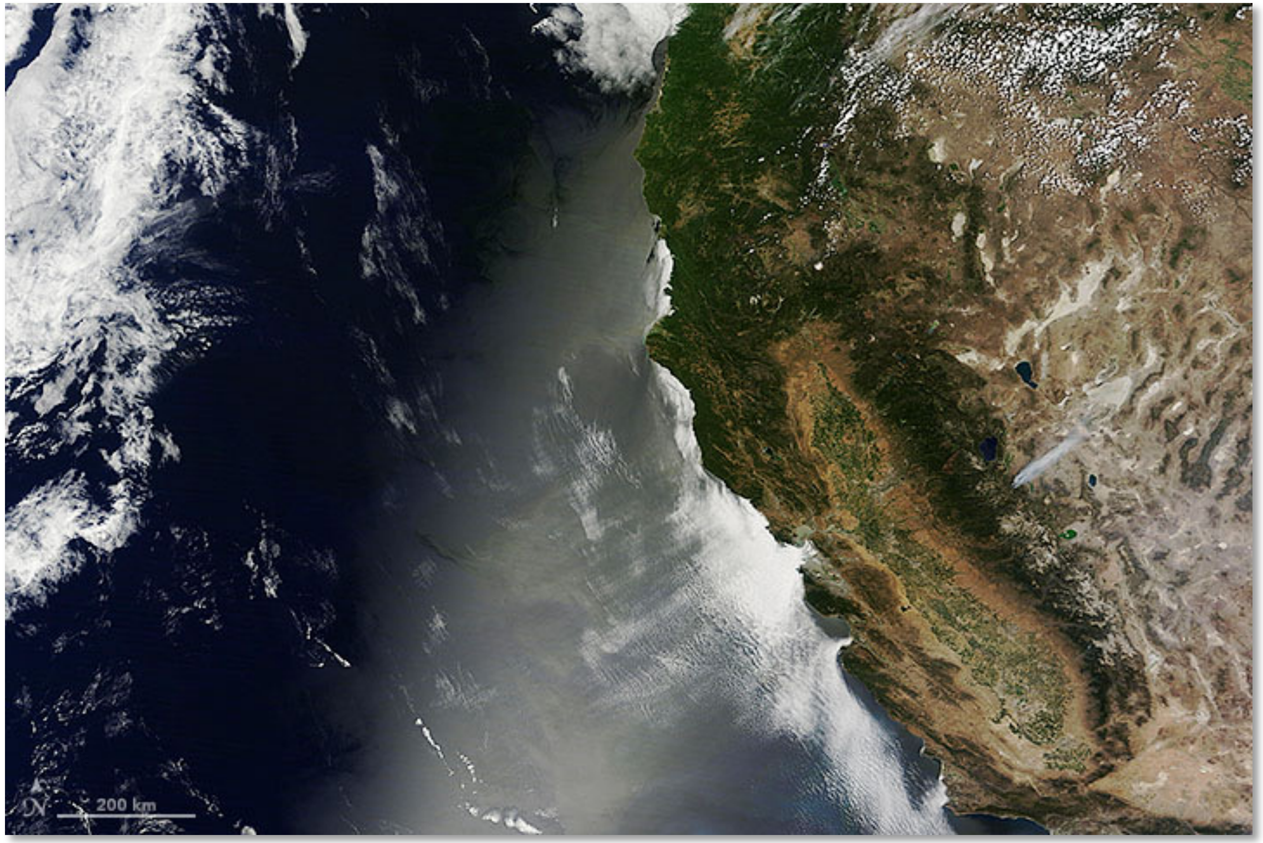


Sun glint

$$L_t = \left(L_r + [L_a + L_{ra}] + t_{dv} L_f + t_{dv} L_w\right) t_{gv}\, t_{gs}\, f_p + T L_g$$

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

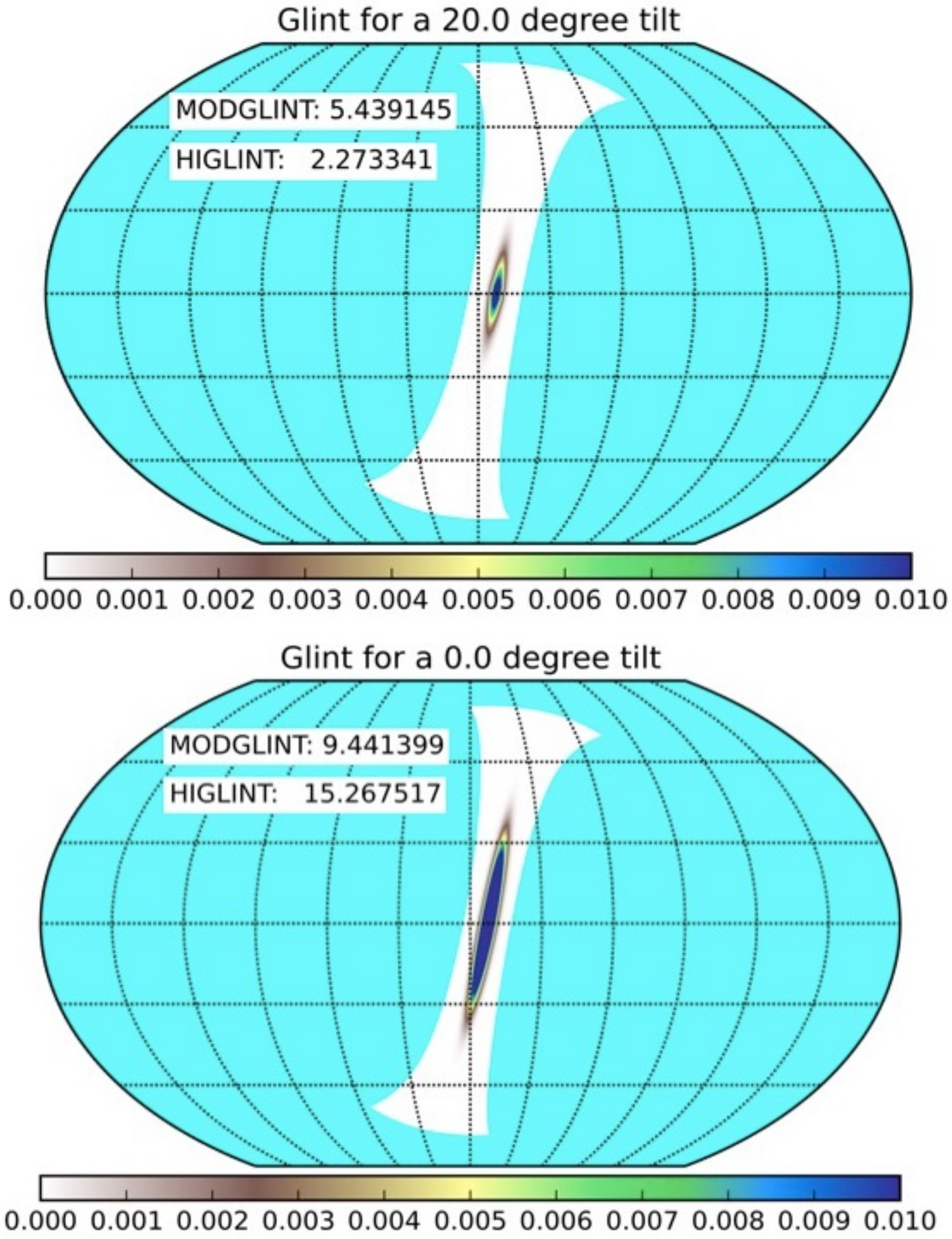
we cannot see “ocean color” through Sun glint

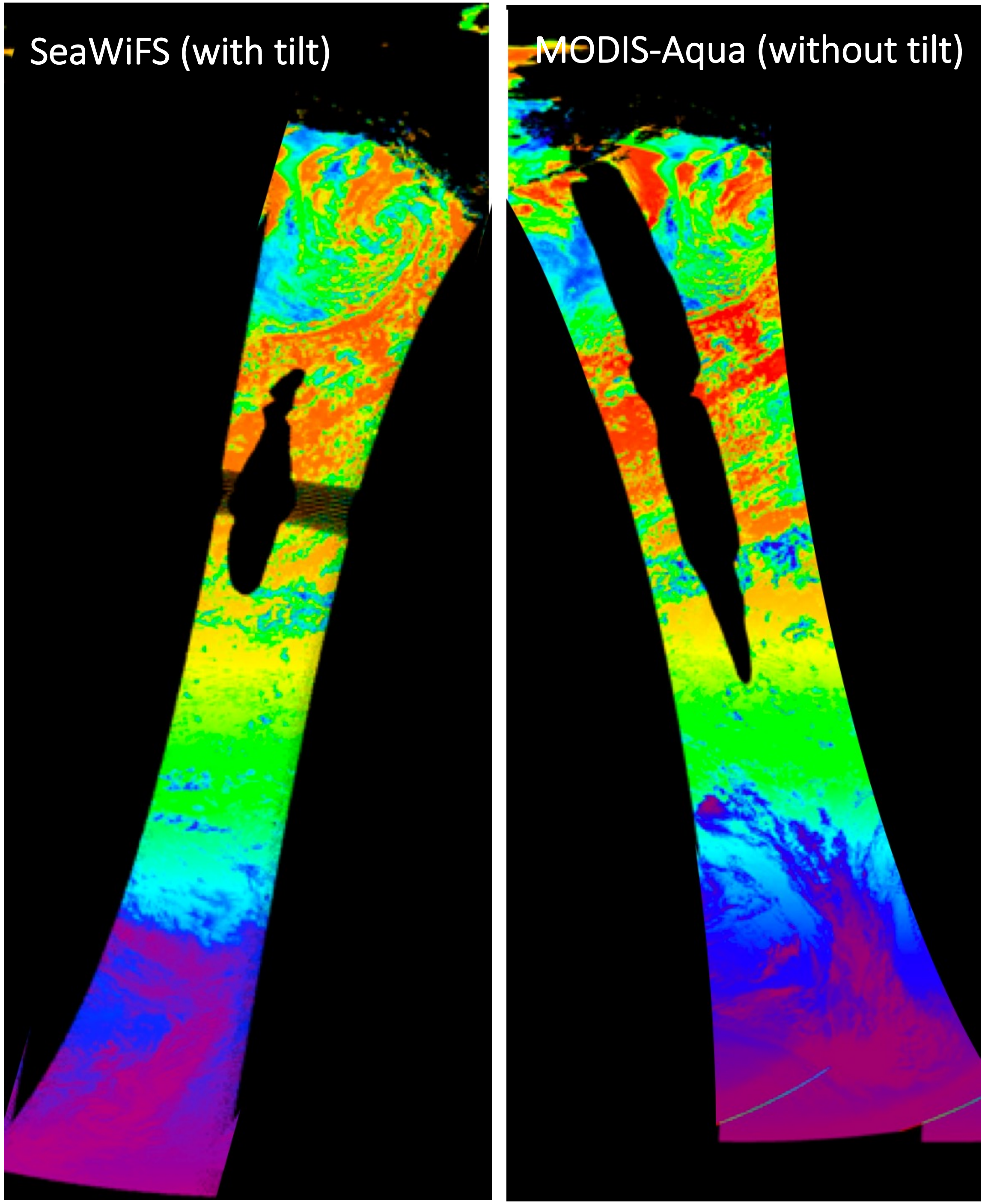


Courtesy NASA Earth Observatory

Ground to Space: A Glittering Path of San Francisco Sunglint

https://earthobservatory.nasa.gov/blogs/earthmatters/2016/11/09/ground-to-space-a-glittering-path-of-san-francisco-sunglint/


Glint for a 20.0 degree tilt
MODGLINT: 5.439145
HIGLINT: 2.273341
0.000 0.001 0.002 0.003 0.004 0.005 0.006 0.007 0.008 0.009 0.010
Glint for a 0.0 degree tilt
MODGLINT: 9.441399
HIGLINT: 15.267517
0.000 0.001 0.002 0.003 0.004 0.005 0.006 0.007 0.008 0.009 0.010

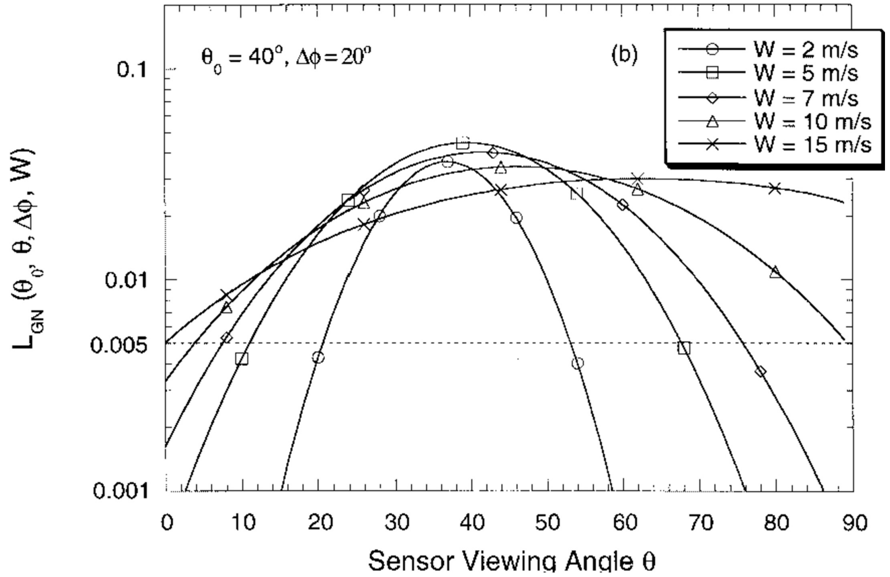

SeaWiFS (with tilt)
MODIS-Aqua (without tilt)
PAR = Photosynthetically Available Radiation (Einstein m-2 d-1)

Sun glint

Sun glint can be further expressed as:

$$T\, L_g = F_0\, T_0\, T\, L_{GN}$$

L_{GN} is glint radiance normalized to no atmosphere & $F_0 = 1$



L_{GN} from Cox and Munk (1954) requires ancillary wind speed & geometries of Sun & sensor

$$T_0 T = \exp\left[-(\tau_r + \tau_a)\left(\frac{1}{\cos(\theta_0)} + \frac{1}{\cos(\theta)}\right)\right]$$

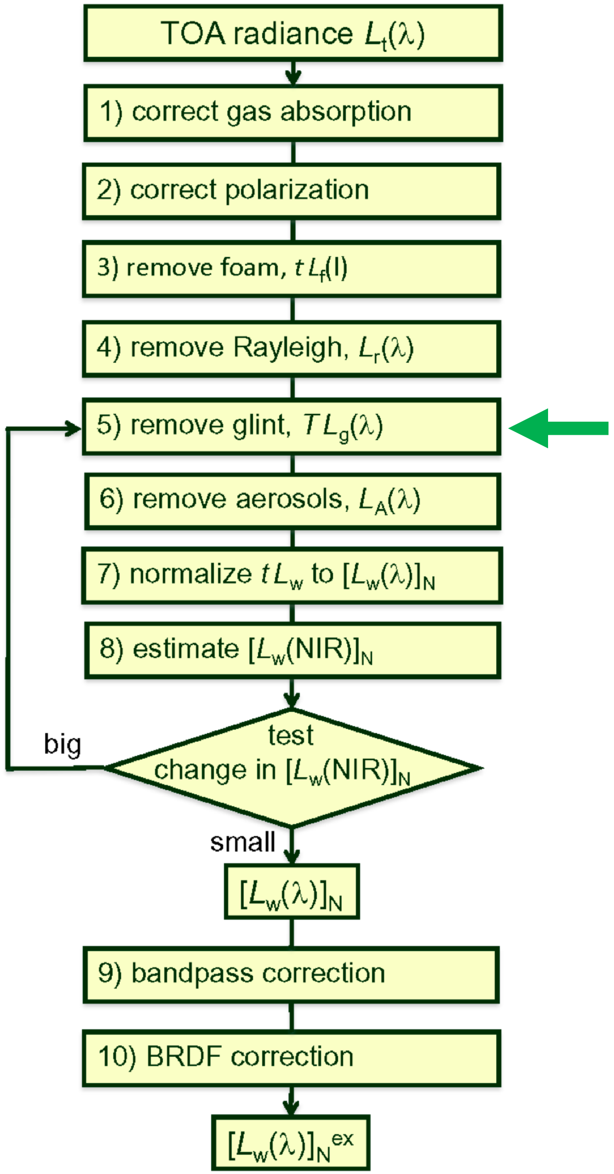
two step iteration since we don't know τ_a:

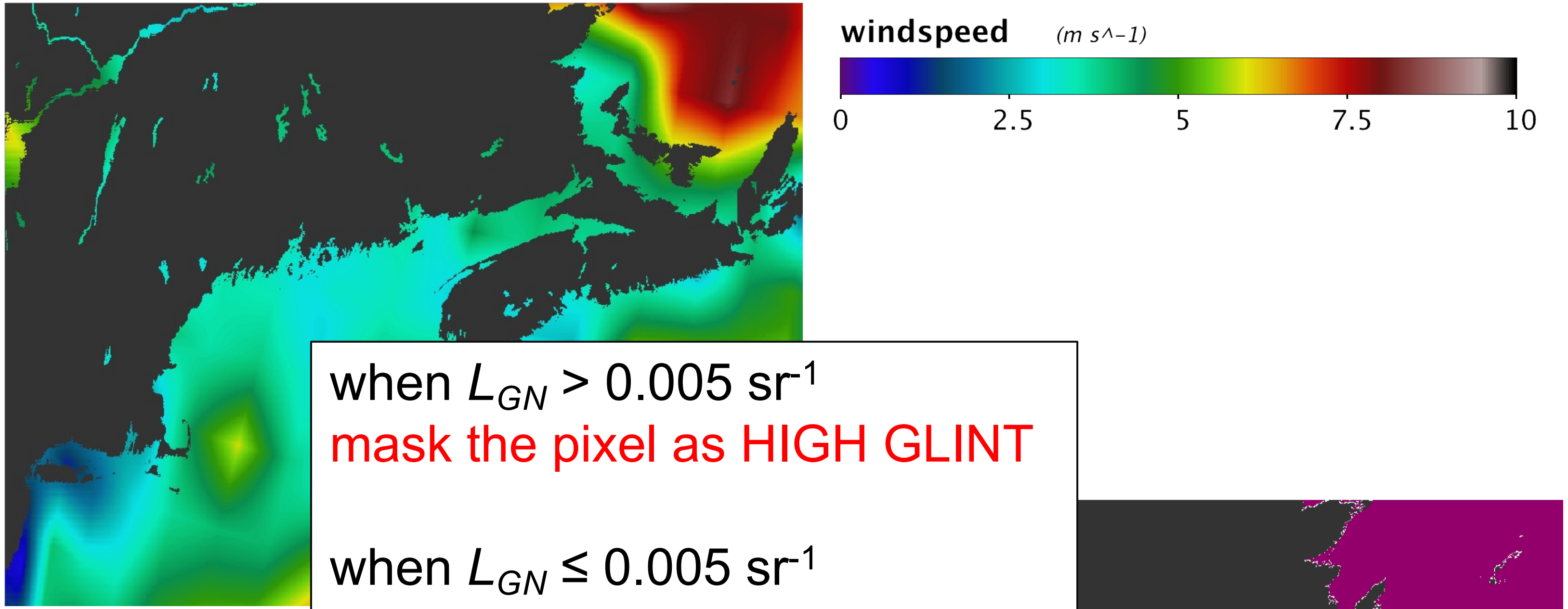
(1) $[L_t, \tau_a', W]$ ➔ $L_t^{(1)}=L_t-L_g$ ➔ $\tau_a^{(1)}$

(2) $[L_t^{(1)}, \tau_a^{(1)}, W]$ ➔ $L_t^{(2)}=L_t^{(1)}-L_g$ ➔ $\tau_a^{(2)}$

with initial guess of $\tau_a' \sim 0.1$ (additional logic included to prevent overcorrection)

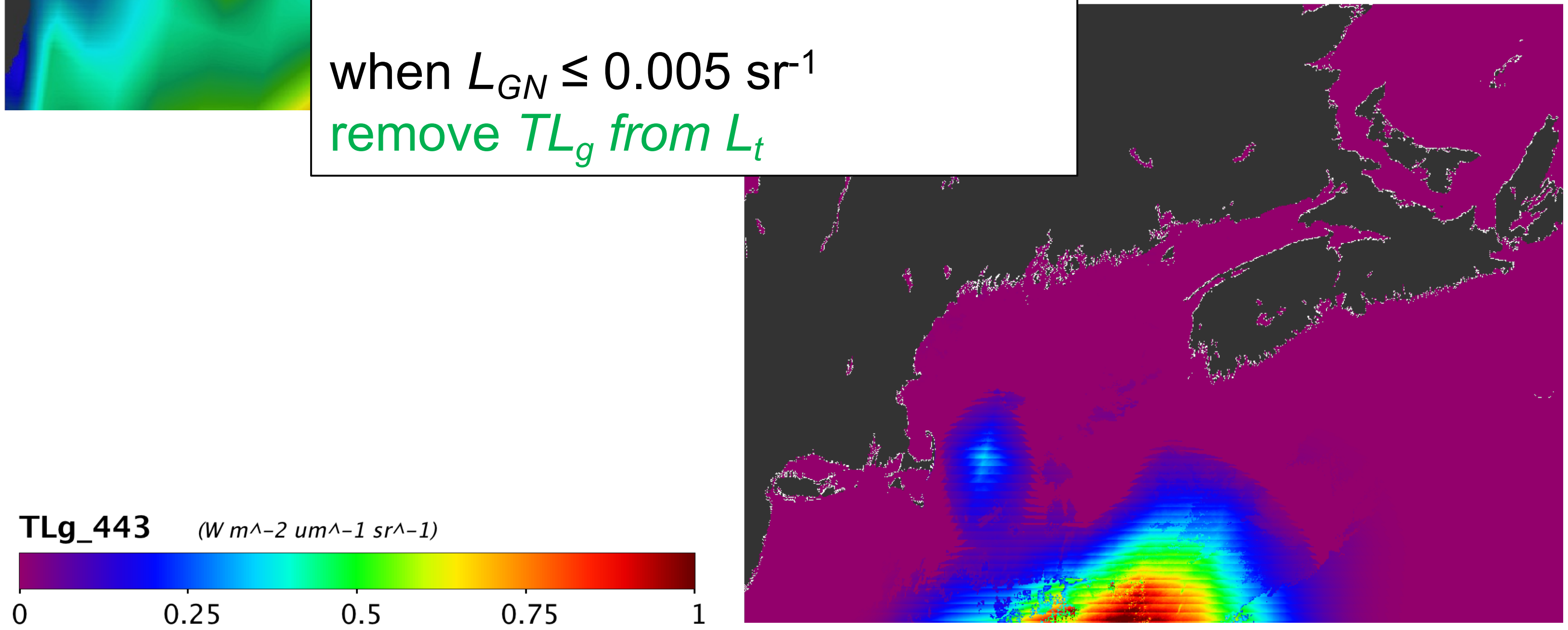
processing cadence: L_t / t_{gv} / t_{gs} / f_p – tL_f - L_r - TL_g





when L_{GN} > 0.005 sr^{-1}
mask the pixel as HIGH GLINT

when $L_{GN} \leq$ 0.005 sr^{-1}
remove TL_g *from* L_t



aerosols: **the hard part**

$$L_t = \left(L_r + \left[L_a + L_{ra}\right] + t_{dv} L_f + t_{dv} L_w\right) t_{gv}\, t_{gs}\, f_p + T\, L_g$$

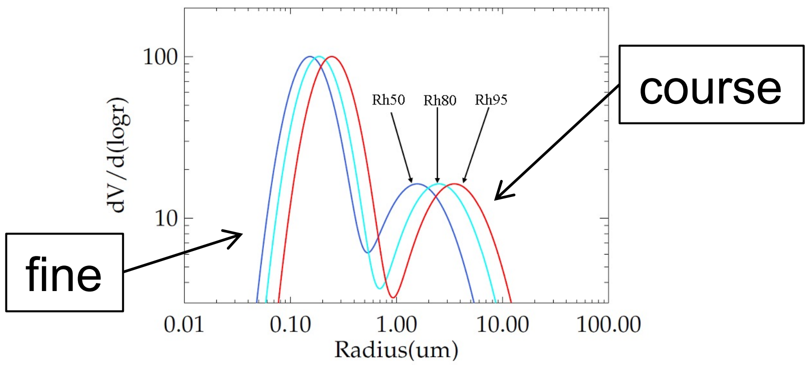
$$R_{rs} = \frac{L_w}{F_0 \cos(\theta_s)\, t_{ds}\, f_s\, f_b\, f_\lambda}$$

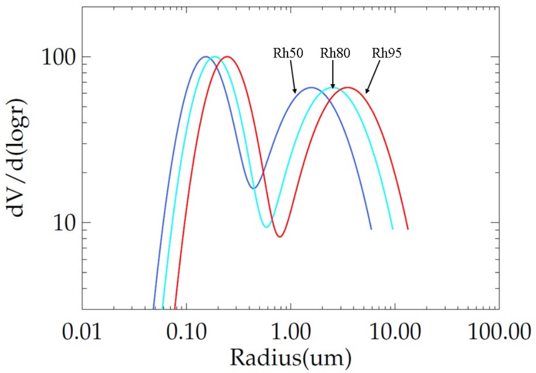
aerosol tables

- aerosol properties can be characterized by their particle size distribution (PSD) & their complex index of refraction (m)
- given a PSD & m (& assuming sphericity), aerosol optical properties can be computed using Mie theory:
  - scattering phase function ($\tilde{\beta}$)
  - single scattering albedo ($\omega = b / c$)
  - extinction coefficient ($c = a + b$)
- aerosol optical thickness relates to extinction coefficient
  - $\tau_a = \int_0^z c(z)\, dz$
- aerosol tables are generated for various PSDs (& m's) & are
  - defined by $\tilde{\beta}$, ω, τ_a (& other variables)
  - navigated using solar & satellite viewing geometries

aerosol tables

- we assume each PSD to be represented by 2 lognormal distributions
  - fine particles (continental & sometimes absorbing)
  - coarse particles (oceanic / sea salt & non-absorbing)





- each PSD modulated by varying relative humidity
  - humidity changes particle size
  - requires ancillary data from GMAO
- 80 aerosol tables total, built from AERONET measurements
  - 10 PSDs
  - 8 relative humidities

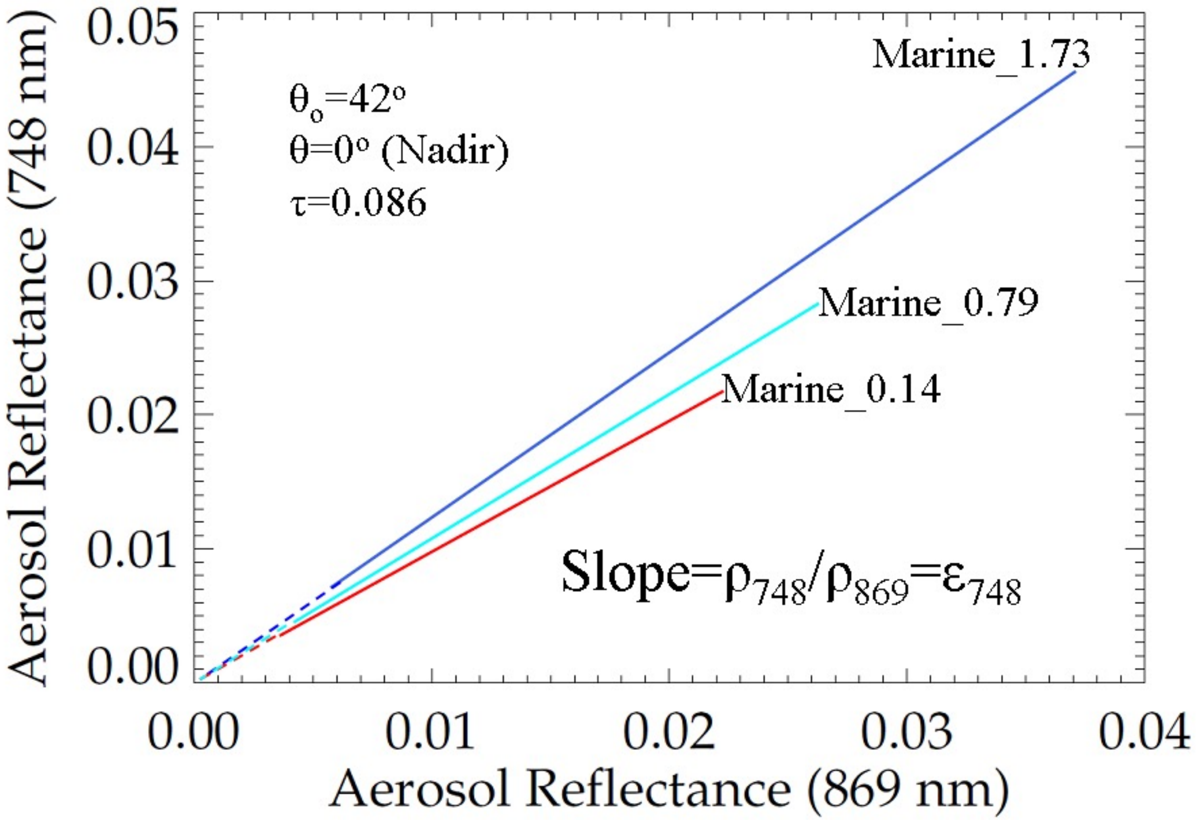
see Ahmad et al., Applied Optics, 2010

aerosol tables

- the Angstrom exponent (α) provides an estimator of particle size
  - high α = small particles
  - low α = large particles
  - defined via $\frac{\tau_a(\lambda)}{\tau_a(\lambda_0)} = \left(\frac{\lambda_0}{\lambda}\right)^{\alpha}$

- aerosol models often defined by epsilon (ε)
  - $\varepsilon(748,869) = \frac{L_a(748)}{L_a(869)}$

do we know these values yet???



black pixel assumption

final unknowns in top expression

$$L_t = \left(L_r + \left[L_a + L_{ra}\right] + t_{dv} L_f + t_{dv} L_w\right) t_{gv}\, t_{gs}\, f_p + T\, L_g$$

in the open ocean, we can assume (???) that L_w in the near-infrared (NIR) is = 0 (rather, is *black*)

thus, in the NIR (e.g., 748 and 869 nm):
L_a(NIR) + L_{ra}(NIR) = L_t(NIR) – the terms we computed

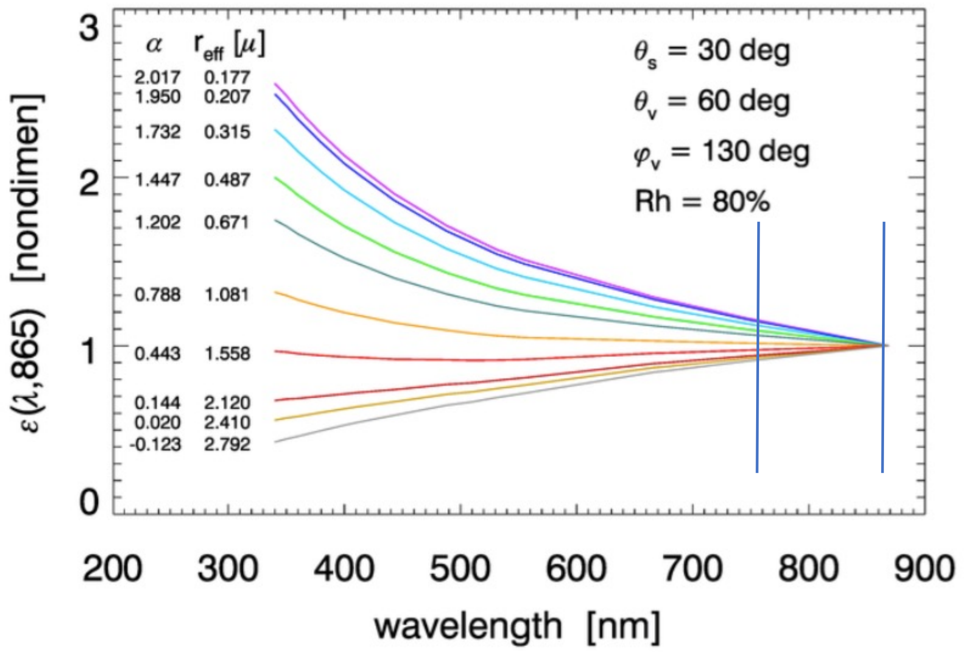
aerosol selection

L_w(NIR) = 0, so L_a(NIR) + L_{ra}(NIR) = L_t(NIR) – (everything previously computed)
how do we estimate L_a(visible) + L_{ra}(visible)?

- let's refer to [L_a + L_{ra}] simply as L_a & ignore single- vs. multi-scattering issues
- select the 10 aerosol tables that match the observed GMAO relative humidity
- compute epsilon values for the 10 tables [ε(748,869) = L_a(748) / L_a(869)]
- perform an iterative determination of the mean ε(748,869) value & select a final bounding 2 aerosol models
- using 2 bounding models, calculate $\varepsilon(\lambda,869)$ from ε(748,869)
- calculate $L_a(\lambda) = \varepsilon(\lambda,869)\, L_a(869)$

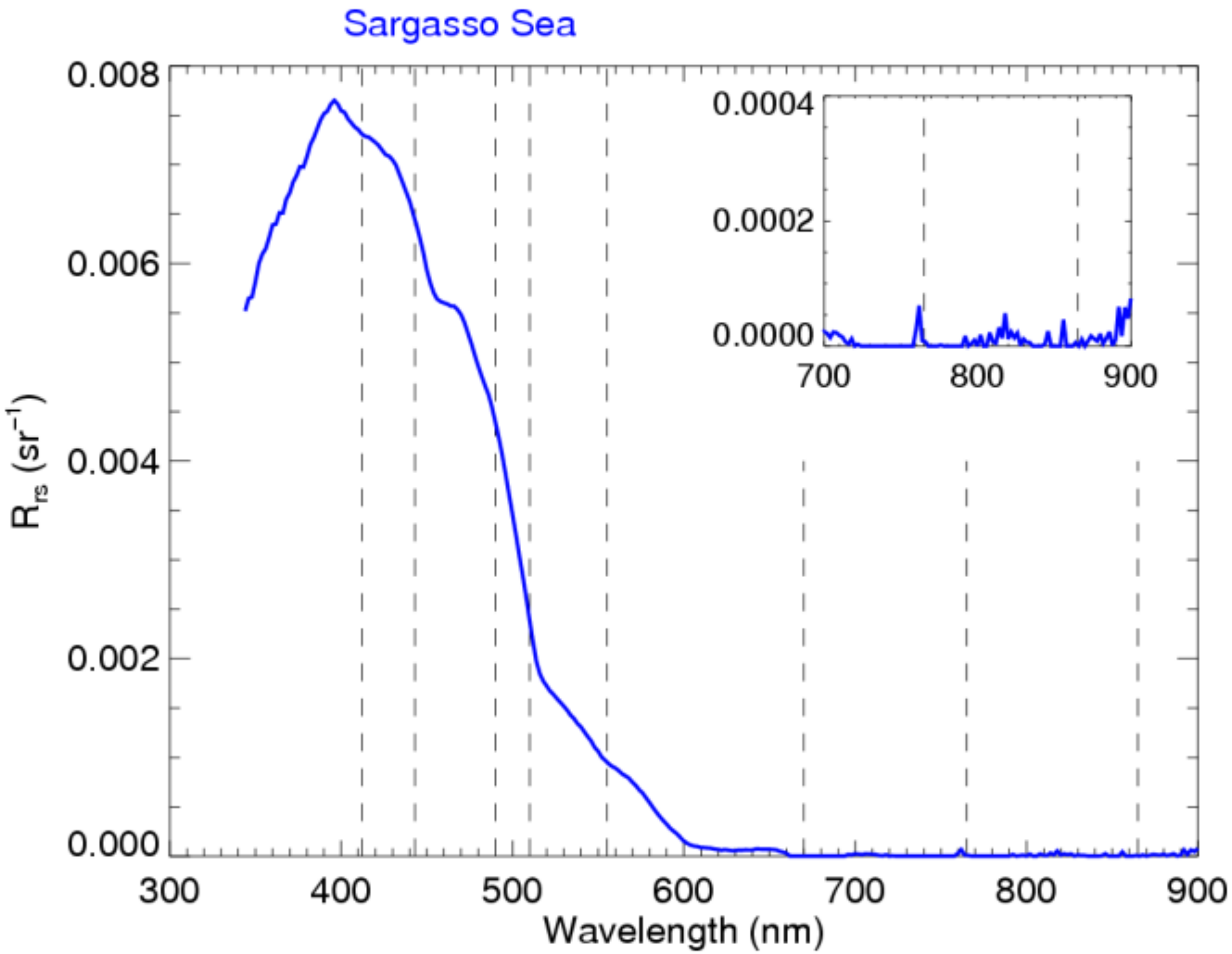
see Gordon & Wang, Applied Optics, 1994

final retrieval of $L_a(\lambda)$ is more accurate than that of τ_a and α; not unlike retrievals of $a(\lambda)$ being more accurate than $a_{dg}(\lambda)$ &$a_{ph}(\lambda)$ in inversion models



is the black pixel assumption valid?

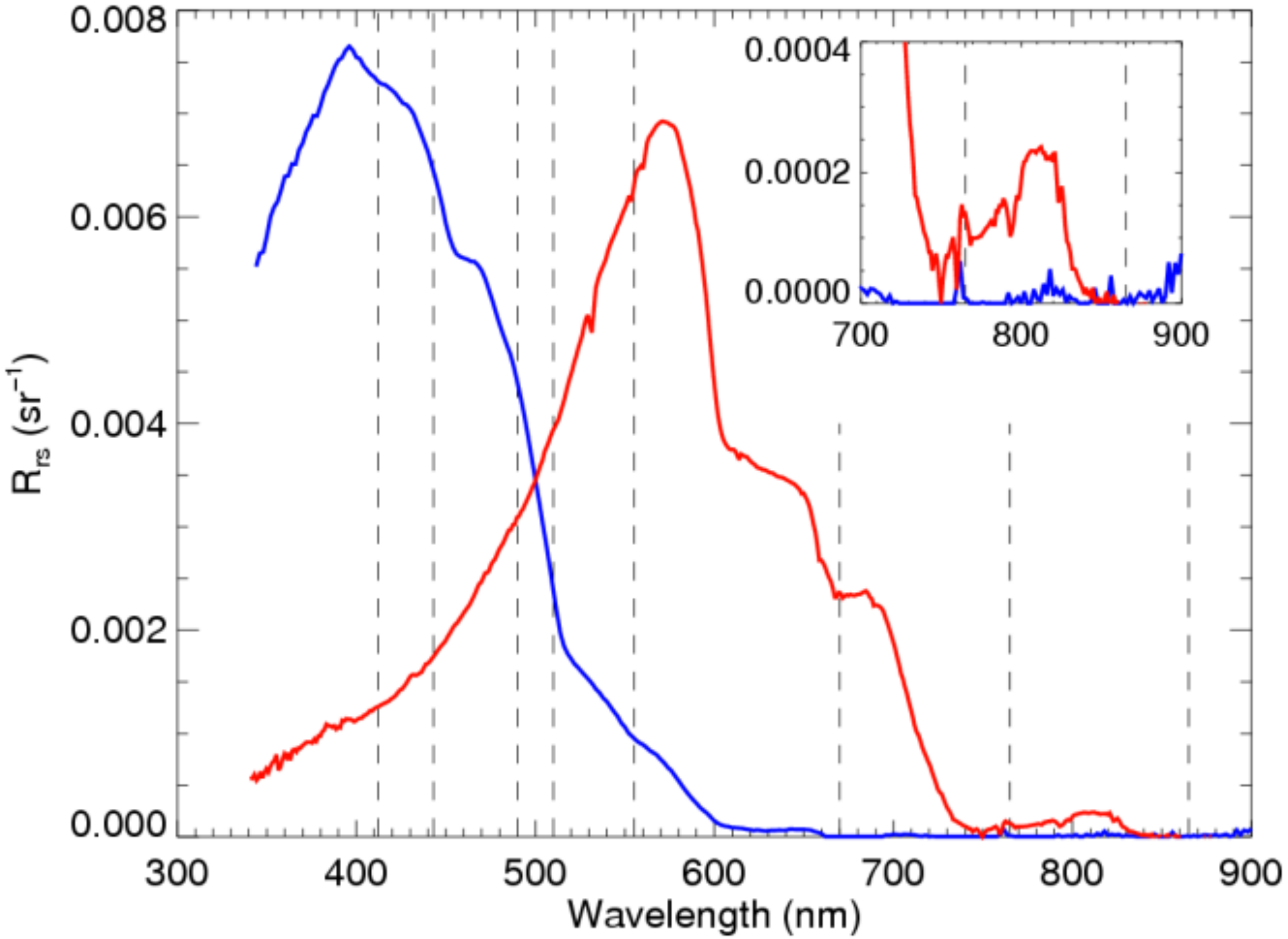
are R_{rs}(NIR) really black?

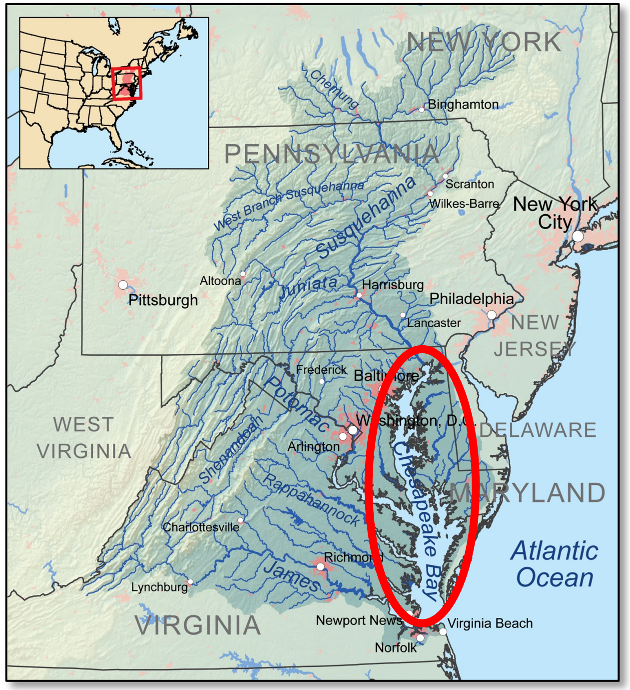


is the black pixel assumption valid?

are R_{rs}(NIR) really black?

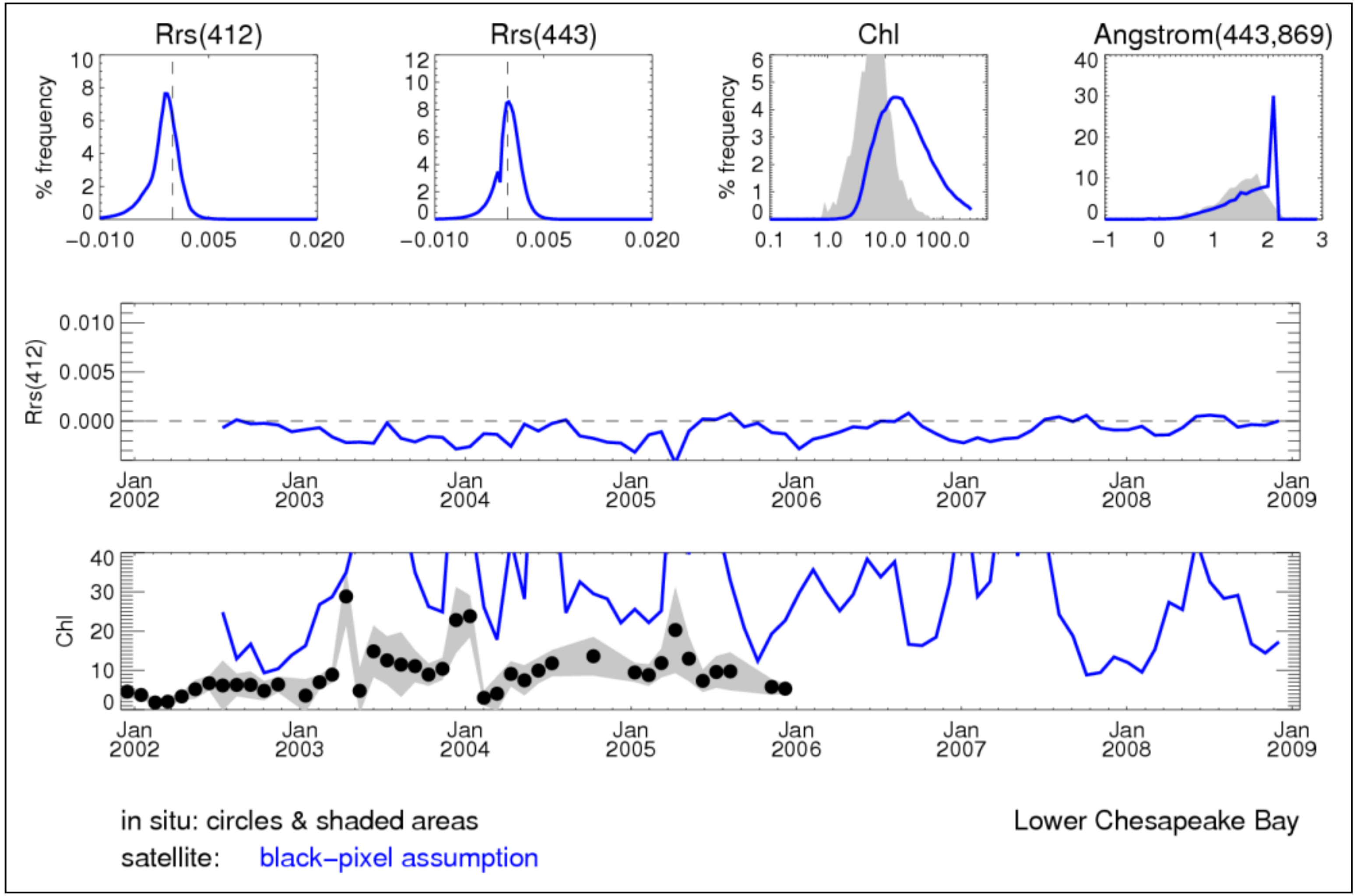
Sargasso Sea Chesapeake Bay





is the black pixel assumption valid?

what happens when we don't account for $R_{rs}(NIR) > 0$?



use the "black pixel" assumption (e.g., SeaWiFS 1997-2000)

how to proceed with the black pixel assumption?

what to do when R_{rs}(NIR) > 0?

many approaches exist, here are a few examples:

assign aerosols (ε) and/or water contributions (R_{rs}(NIR))

e.g., Hu et al. 2000, Ruddick et al. 2000

use shortwave infrared bands

e.g., Wang & Shi 2007

correct/model the non-negligible R_{rs}(NIR)

Siegel et al. 2000	used in SeaWiFS Reprocessing 3 (2000)
Stumpf et al. 2003	used in SeaWiFS Reprocessing 4 (2002)
Lavender et al. 2005	MERIS
Bailey et al. 2010	used in SeaWiFS Reprocessing 6 (2009)

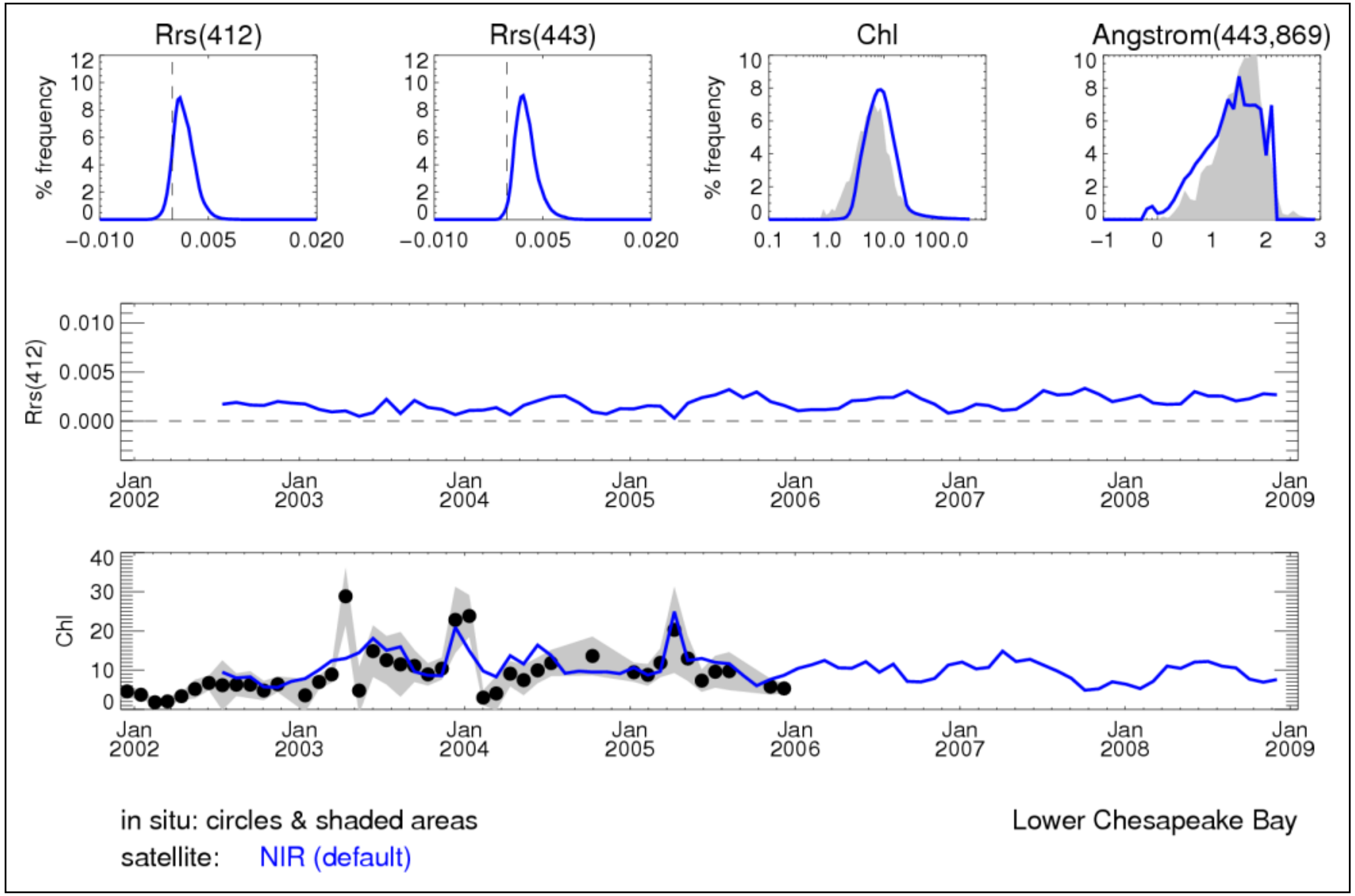
use a coupled ocean-atmosphere optimization

e.g., Chomko & Gordon 2001, Stamnes et al. 2003, Kuchinke et al. 2009

field data!

black pixel assumption – a bio-optical model

correction of non-negligible R_{rs}(NIR)



estimate R_{rs}(NIR) using a bio-optical model

operational VIIRS & MODIS processing ~ 2000-present

black pixel assumption – a bio-optical model

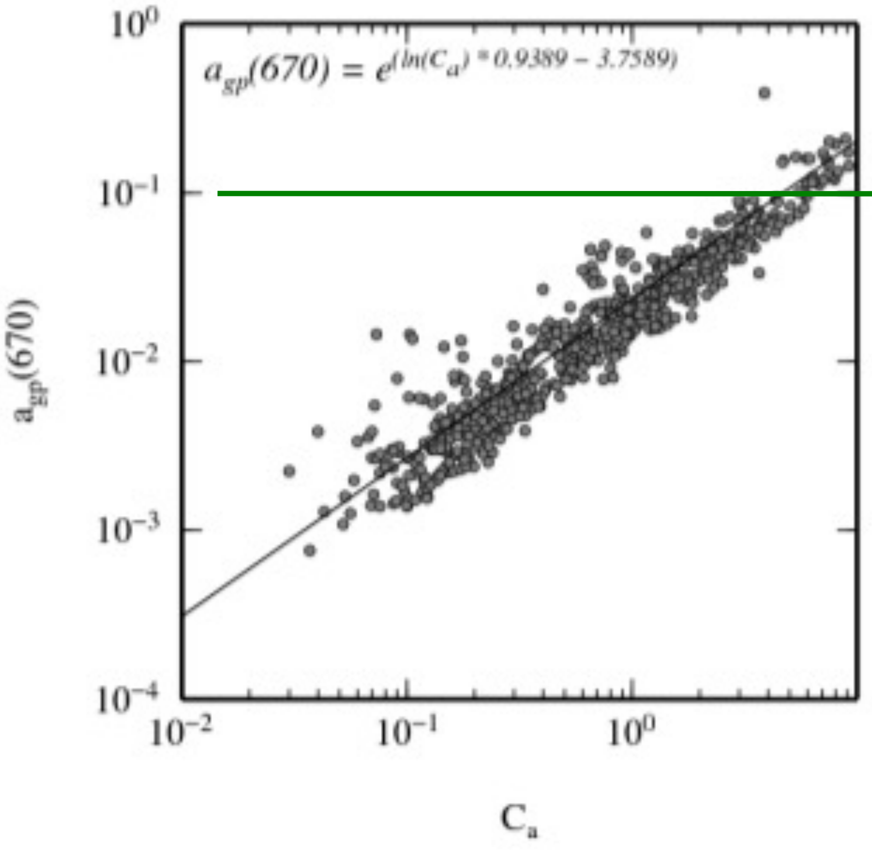
initial $R_{rs}(670)$ measured by satellite (using $R_{rs}(765) = 0$)

Bailey et al., Optics Express, 2010

black pixel assumption – a bio-optical model

initial $R_{rs}(670)$ measured by satellite (using $R_{rs}(765) = 0$)

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



$= 0.1\ m^{-1}$

$a_w(670) = 0.44\ m^{-1}$

Bailey et al., Optics Express, 2010

black pixel assumption – a bio-optical model

initial $R_{rs}(670)$ measured by satellite (using $R_{rs}(765) = 0$)

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

estimate $b_b(670)$ using $R_{rs}(670)$, $a(670)$, & $G(670)$ [Morel et al. 2002]

$$R_{rs}(670) = G(670)\frac{b_b(670)}{a(670) + b_b(670)}$$

Bailey et al., Optics Express, 2010

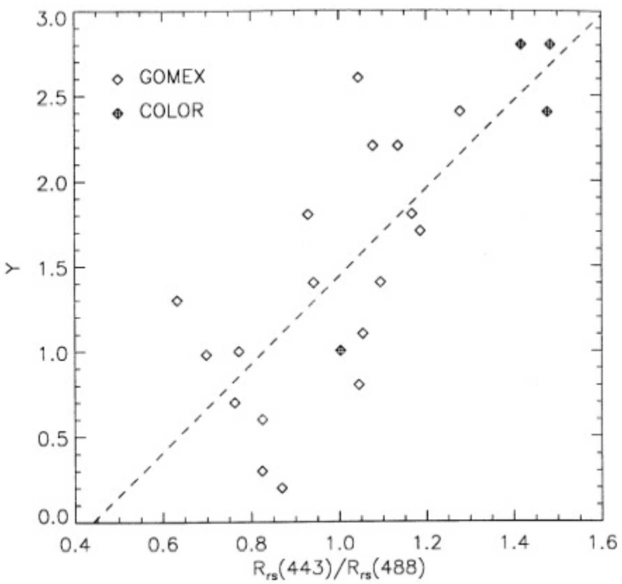
black pixel assumption – a bio-optical model

initial $R_{rs}(670)$ measured by satellite (using $R_{rs}(765) = 0$)

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

estimate $b_b(670)$ using $R_{rs}(670)$, $a(670)$, & $G(670)$ [Morel et al. 2002]

model η using $R_{rs}(443)$ & $R_{rs}(555)$ [Lee et al. 2002]



$$\eta = 2.0\left[1 - 1.2\exp\left(-0.9\,\frac{R_{rs}(443)}{R_{rs}(555)}\right)\right]$$

from Carder et al. 1999

Bailey et al., Optics Express, 2010

black pixel assumption – a bio-optical model

initial $R_{rs}(670)$ measured by satellite (using $R_{rs}(765) = 0$)

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

estimate $b_b(670)$ using $R_{rs}(670)$, $a(670)$, & $G(670)$ [Morel et al. 2002]

model η using $R_{rs}(443)$ & $R_{rs}(555)$ [Lee et al. 2002]

estimate $b_b(765)$ using $b_b(670)$ & η

$$b_b(765) = b_{bw}(765) + b_{bp}(670)\left(\frac{670}{765}\right)^{\eta}$$

Bailey et al., Optics Express, 2010

black pixel assumption – a bio-optical model

initial $R_{rs}(670)$ measured by satellite (using $R_{rs}(765) = 0$)

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

estimate $b_b(670)$ using $R_{rs}(670)$, $a(670)$, & $G(670)$ [Morel et al. 2002]

model η using $R_{rs}(443)$ & $R_{rs}(555)$ [Lee et al. 2002]

estimate $b_b(765)$ using $b_b(670)$ & η

reconstruct $R_{rs}(765)$ using $b_b(765)$, $a_w(765)$, & $G(765)$

$$R_{rs}(765) = G(765)\frac{b_b(765)}{a_w(765) + b_b(765)}$$

$a_w(765) = 2.85\ m^{-1}$

Bailey et al., Optics Express, 2010

black pixel assumption – a bio-optical model

initial $R_{rs}(670)$ measured by satellite (using $R_{rs}(765) = 0$)

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

estimate $b_b(670)$ using $R_{rs}(670)$, $a(670)$, & $G(670)$ [Morel et al. 2002]

model η using $R_{rs}(443)$ & $R_{rs}(555)$ [Lee et al. 2002]

estimate $b_b(765)$ using $b_b(670)$ & η

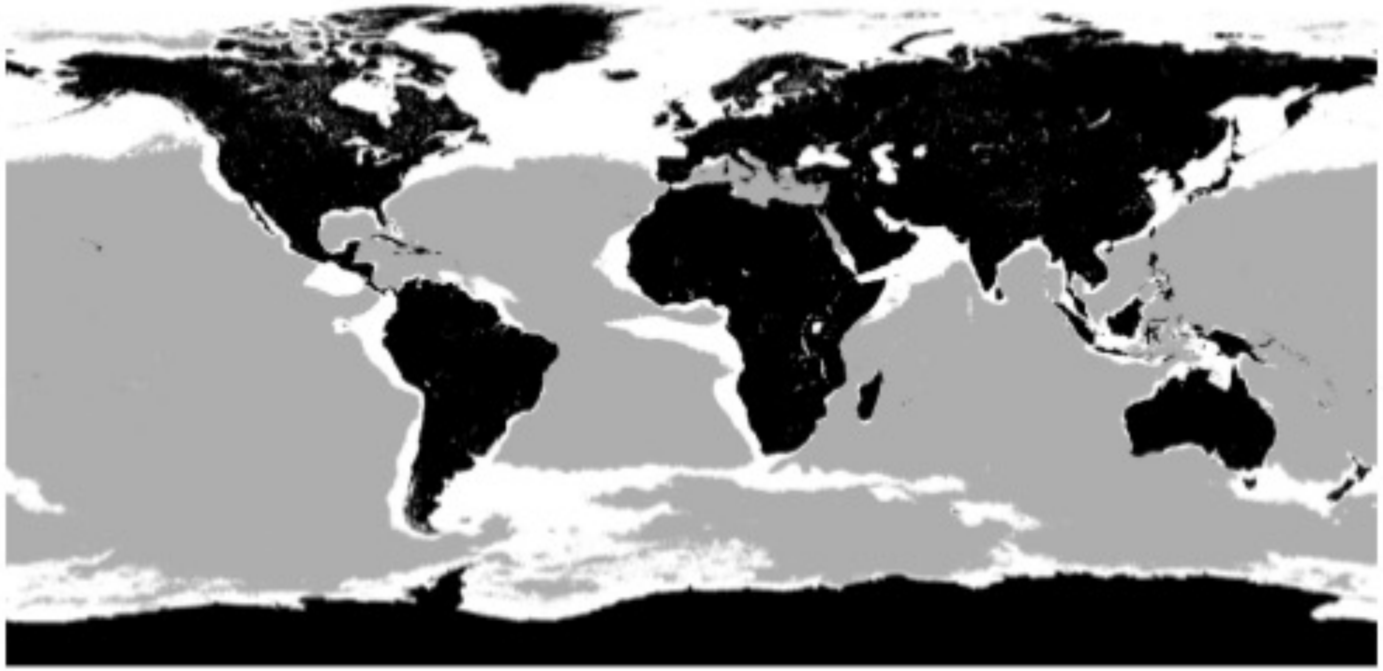
reconstruct $R_{rs}(765)$ using $b_b(765)$, $a_w(765)$, & $G(765)$

iterate until Rrs(765) changes by <2% (typically 3-4 iterations)

Bailey et al., Optics Express, 2010

black pixel assumption – a bio-optical model

locations of application of bio-optical model



black = land; grey = Chl < 0.3 mg m^{-3}; white Chl > 0.3 mg m^{-3}

not applied when Chl < 0.3 mg m^{-3}
weighted application when 0.3 < Chl < 0.7 mg m^{-3}
fully applied when Chl > 0.7 mg m^{-3}

Bailey et al., Optics Express, 2010

example alternative aerosol selection schemes

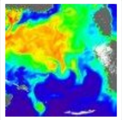
ORIGINAL RESEARCH ARTICLE
Front. Earth Sci., 31 May 2019 | https://doi.org/10.3389/feart.2019.00116

Check for updates

Multiband Atmospheric Correction Algorithm for Ocean Color Retrievals

Amir Ibrahim[1,2]*, Bryan A. Franz[1], Ziauddin Ahmad[1,3] and Sean W. Bailey[1]

- "MBAC"
- uses multiple NIR/SWIR bands instead of 2
- GW94, but no assumption of single-scattering



Atmospheric correction in presence of sun glint: application to MERIS

François Steinmetz, Pierre-Yves Deschamps, and Didier Ramon

Author Information ▾ Find other works by these authors ▾

Optics Express Vol. 19, Issue 10, pp. 9783-9800 (2011) • https://doi.org/10.1364/OE.19.009783

- "POLYMER"
- spectral matching approach
- https://www.hygeos.com/polymer

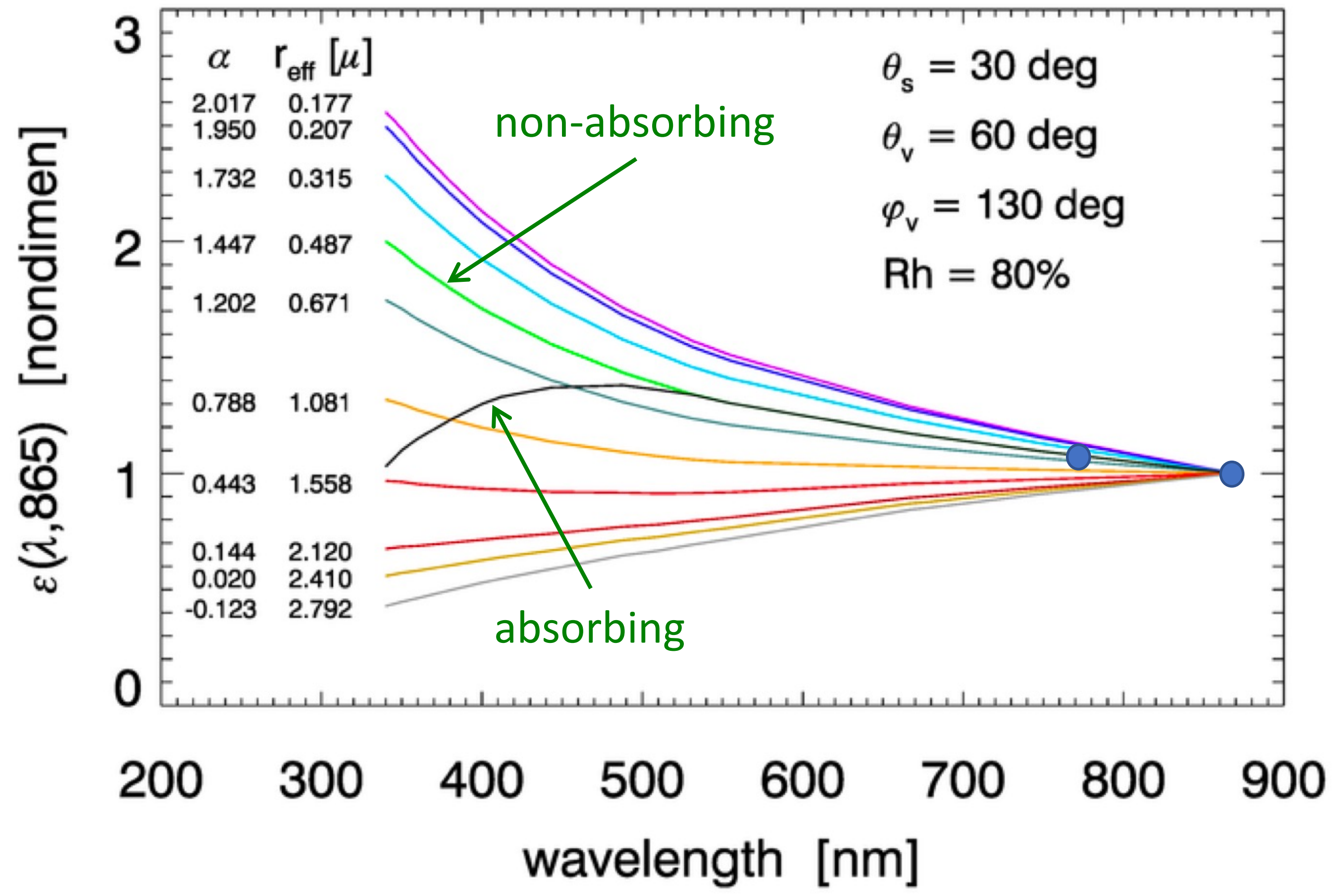
ORIGINAL RESEARCH ARTICLE Provisionally accepted The full-text will be published soon. Notify me
Front. Earth Sci. | doi: 10.3389/feart.2019.00100

Modeling atmosphere-ocean radiative transfer: A PACE mission perspective.

Jacek Chowdhary[1]*, Pengwang Zhai[2], Emmanuel Boss[3], Heidi M. Dierssen[4], Robert J. Frouin[5], Amir I. Ibrahim[6], Zhongping Lee[7], Lorraine A. Remer[6], Michael Twardowski[8], Feng Xu[9], Xiaodong Zhang[10], Matteo Ottaviani[11], William R. Espinosa[6] and Didier Ramon[12]

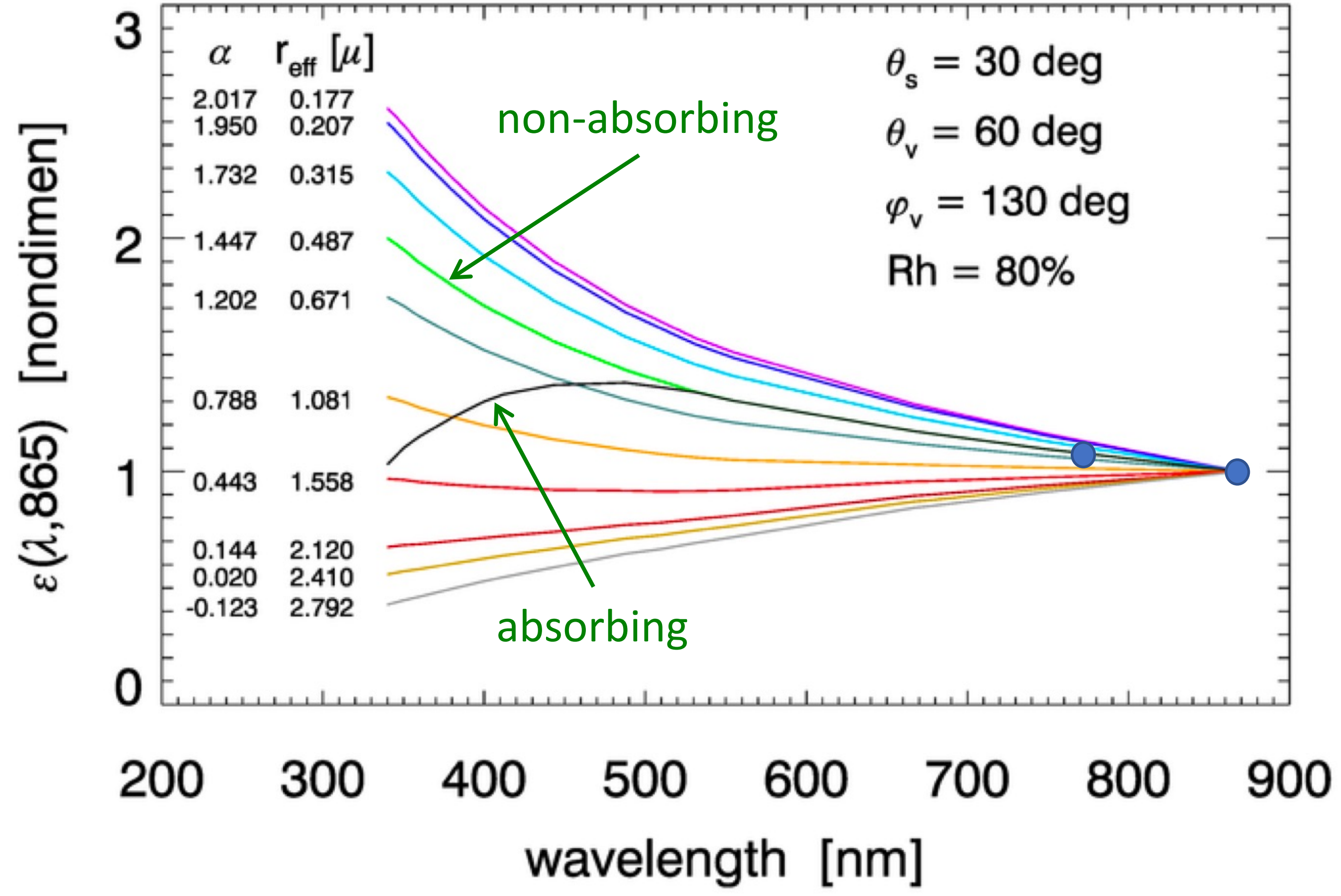
- radiative transfer for coupled ocean-atmosphere systems

atmospheric correction (currently) assumes no absorbing aerosols



Q: Why not use a wavelength near 350 or 400 nm, which could distinguish between absorbing and nonabsorbing aerosols?

atmospheric correction (currently) assumes no absorbing aerosols

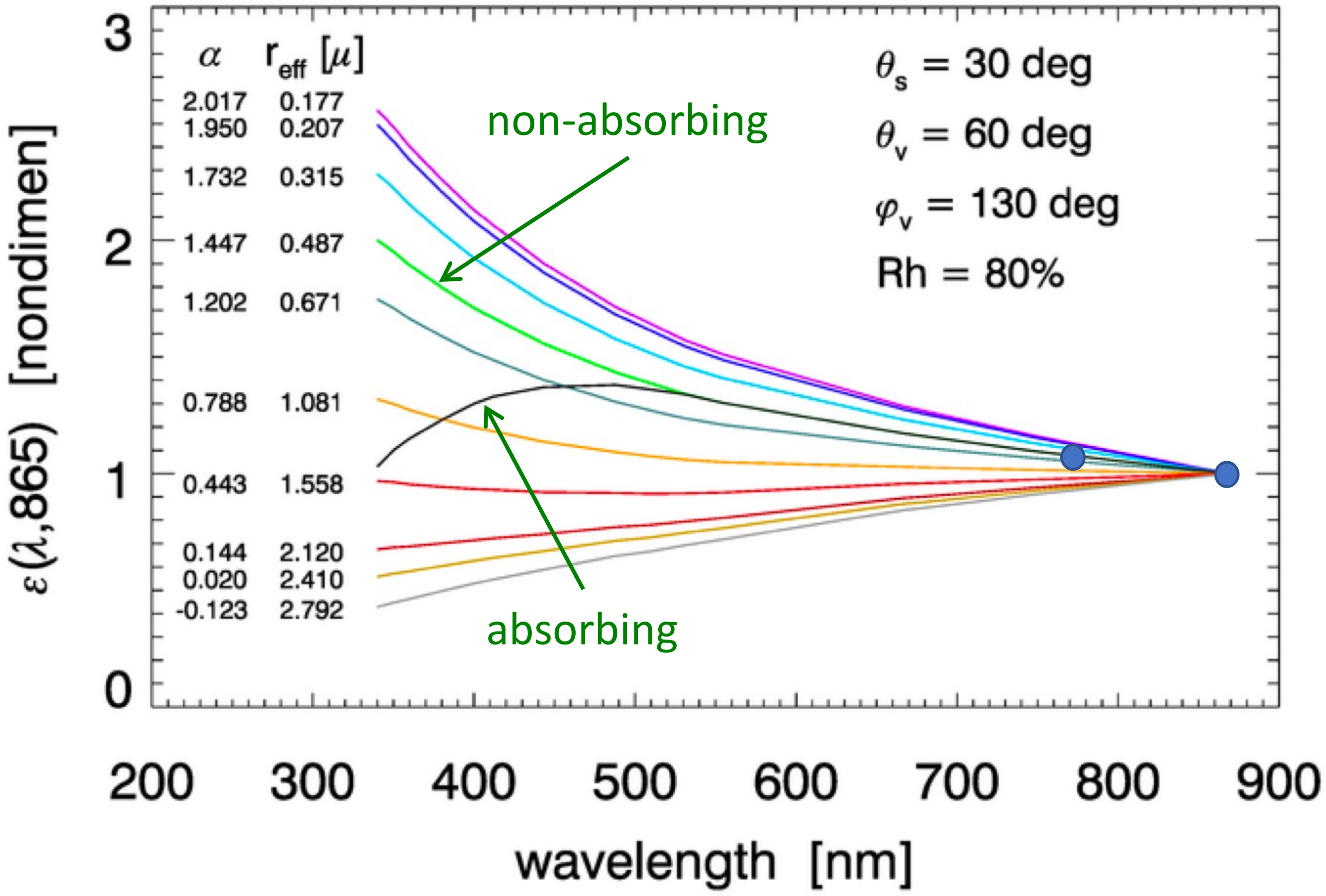


Q: Why not use a wavelength near 350 or 400 nm, which could distinguish between absorbing and nonabsorbing aerosols?

A: the water isn't black

Q: Why not use a wavelength < 300 nm, where the ocean is again black due to high CDOM and water absorption?

atmospheric correction (currently) assumes no absorbing aerosols

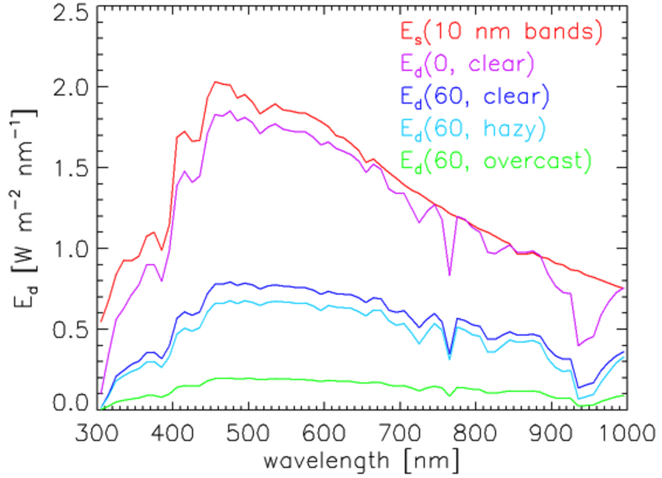


Q: Why not use a wavelength near 350 or 400 nm, which could distinguish between absorbing and nonabsorbing aerosols?

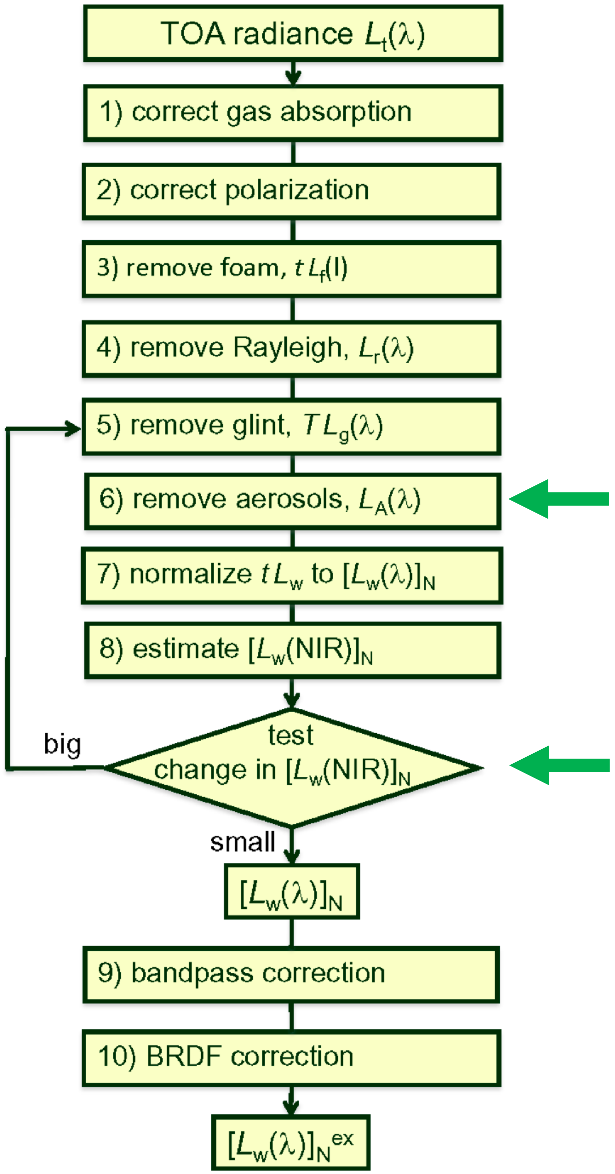
A: The water isn't black

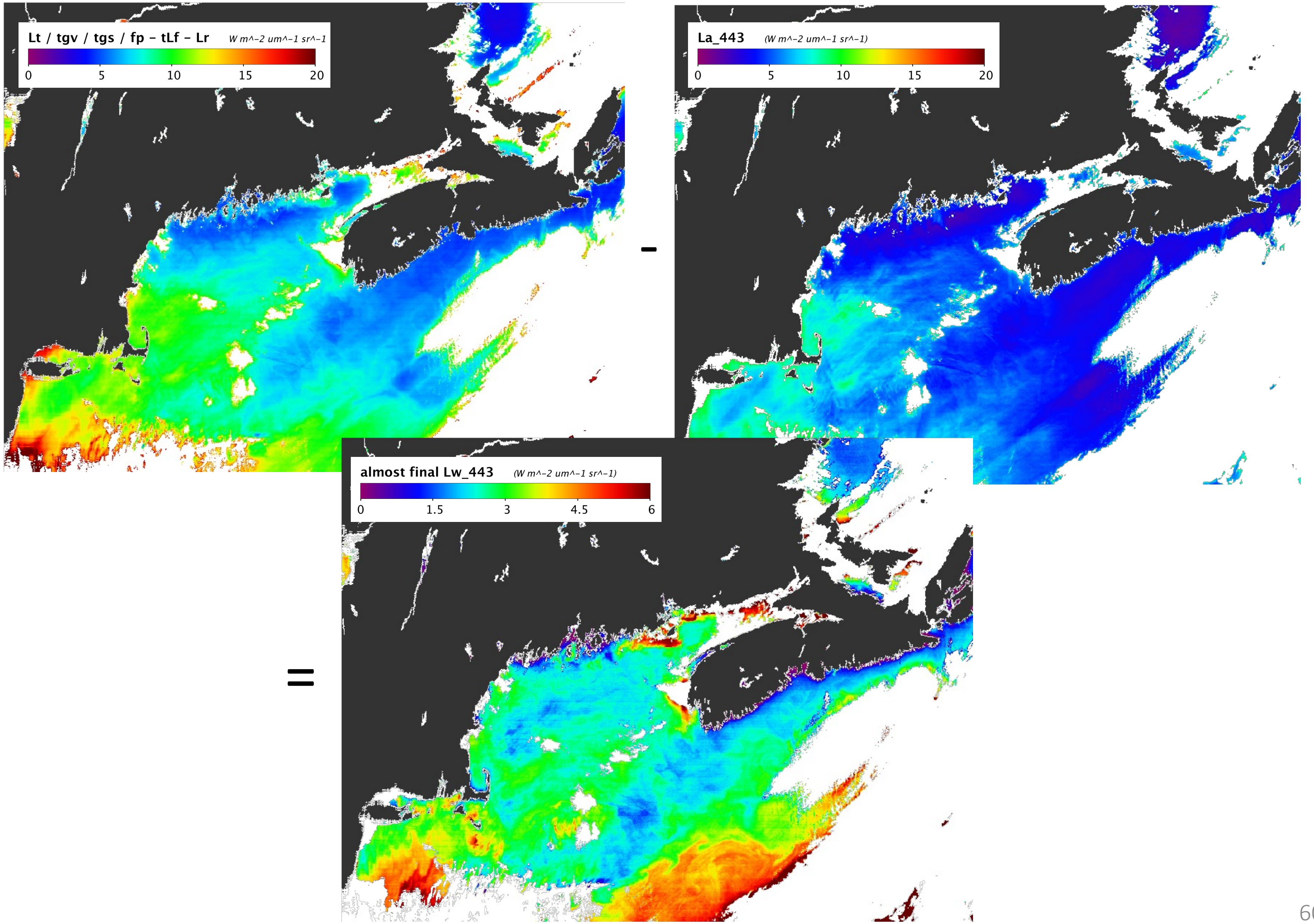
Q: Why not use a wavelength < 300 nm, where the ocean is again black due to high CDOM and water absorption?

A: There ain't no sunlight



processing cadence: L_t / t_{gv} / t_{gs} / f_p – tL_f - L_r – TL_g - L_a



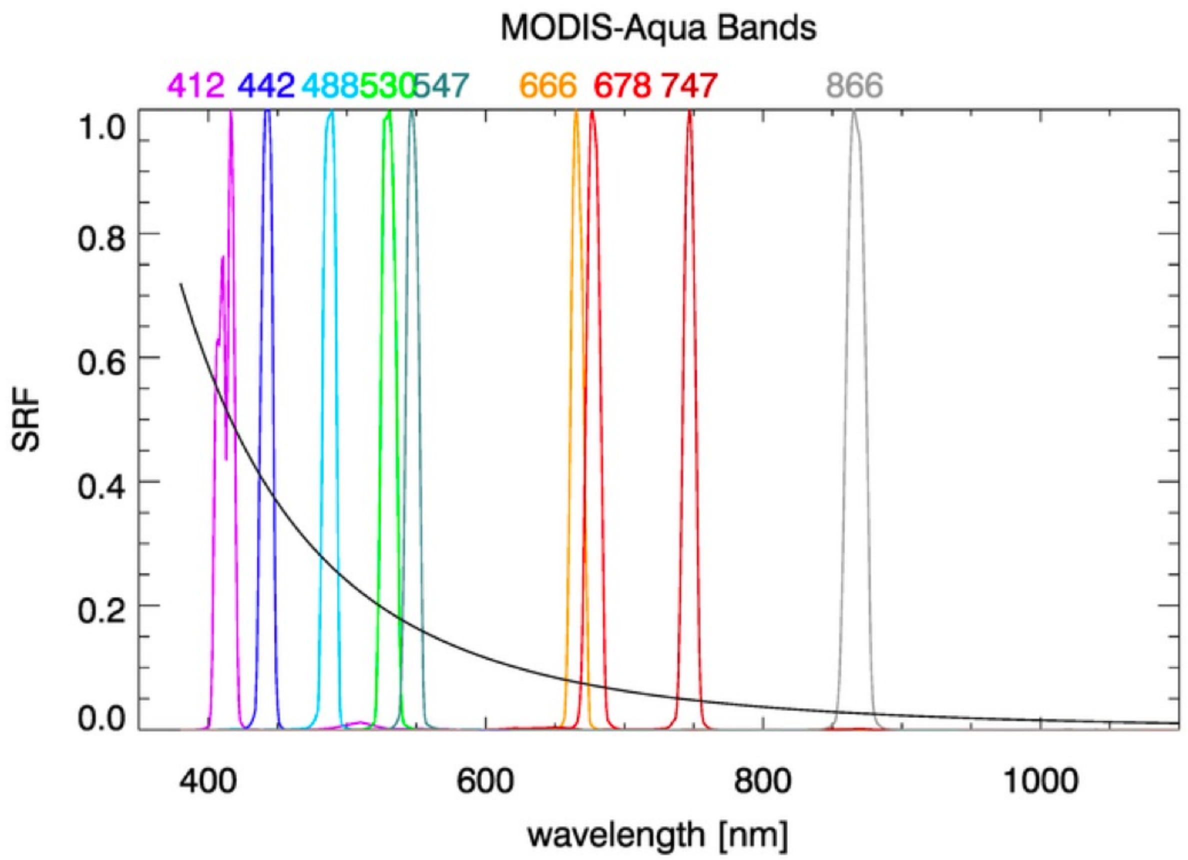


spectral bandpass correction

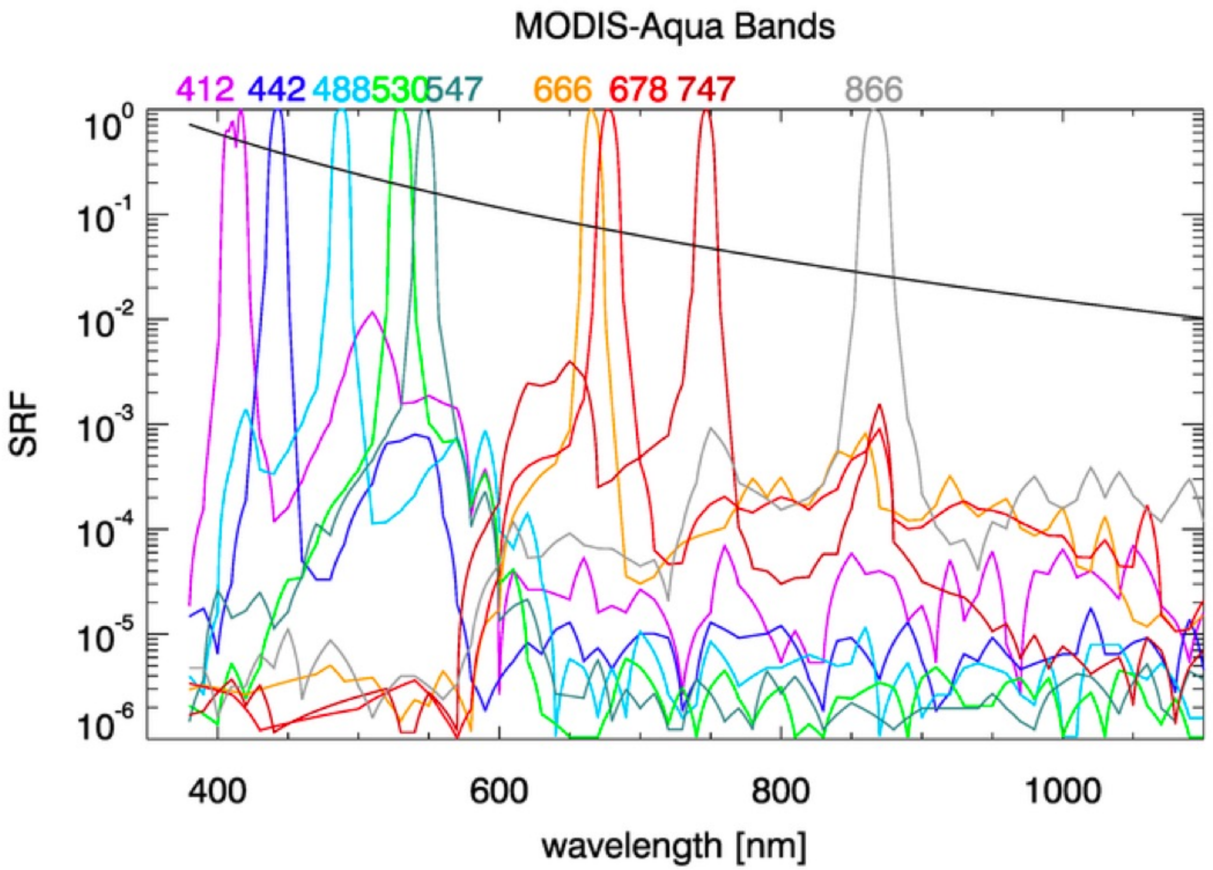
$$L_t = \left(L_r + [L_a + L_{ra}] + t_{dv} L_f + t_{dv} L_w\right) t_{gv}\, t_{gs}\, f_p + T\, L_g$$

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

instrument spectral bandpasses



sensor bands appear well separated on a linear axis

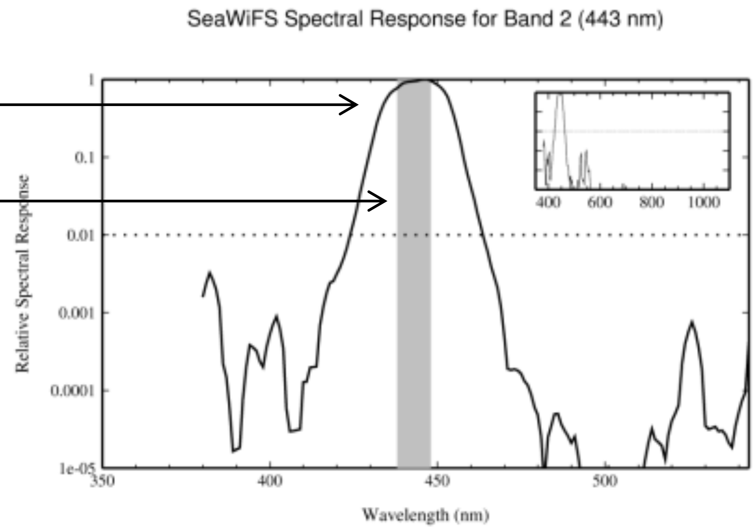


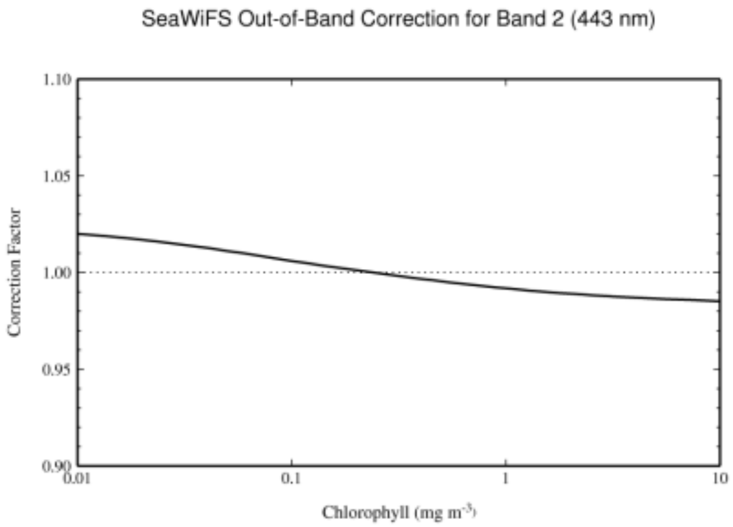
however, sensor band response overlaps enough to cause problems

correction for light that comes from outside the nominal wavelength band

satellite filter

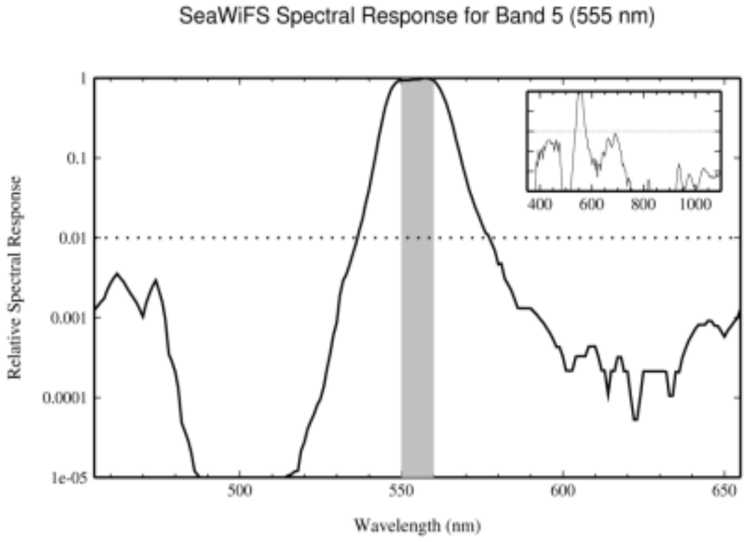
in situ filter

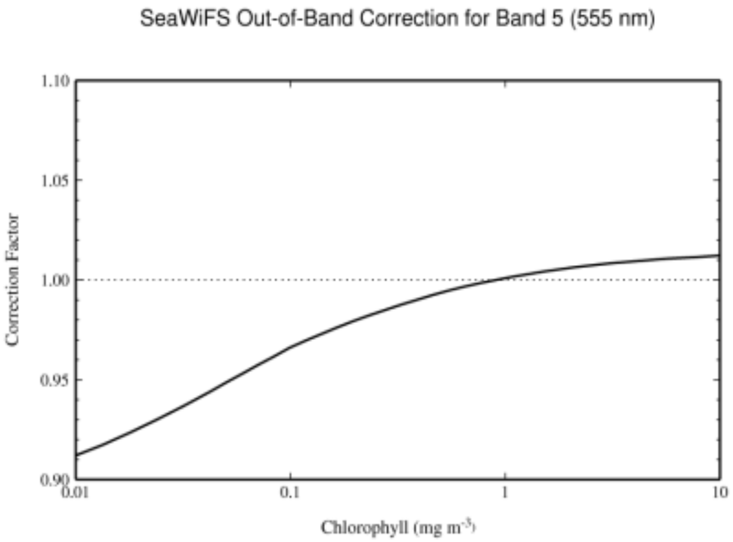




different for each band of each sensor

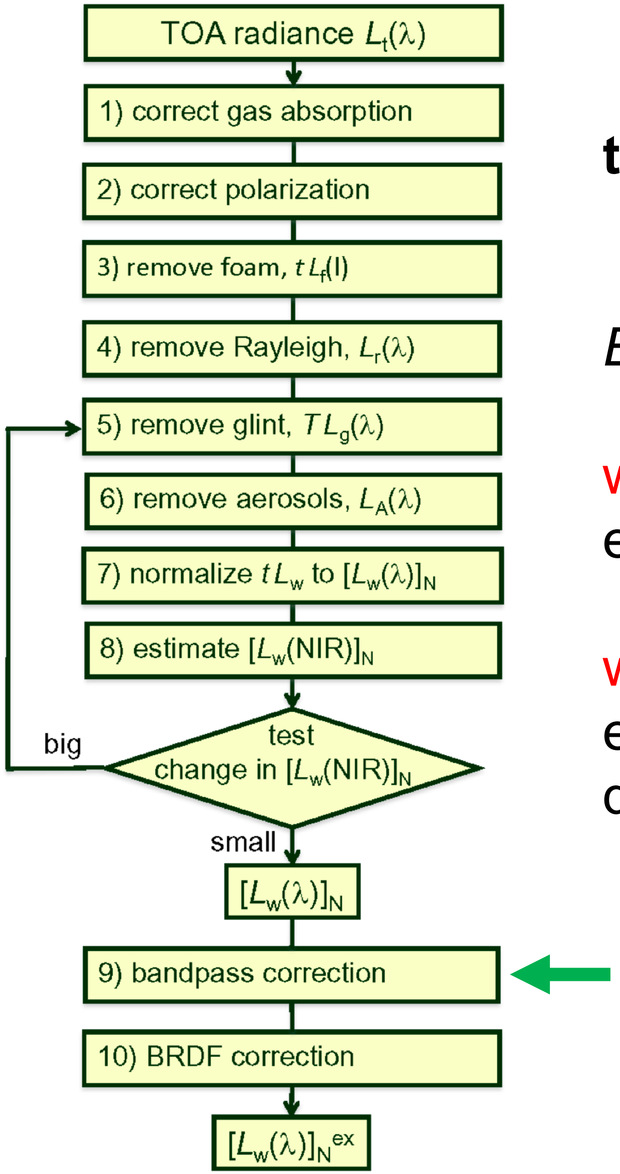
correction uses a clear-water (Morel) reflectance model





see SeaWiFS post-launch TM vol. 22

processing cadence: spectral bandpass correction



take care when executing satellite-to-in situ match-ups

Example for heritage multi-spectral satellite instruments:

when using multispectral in situ radiometers:
enable the bandpass adjustment

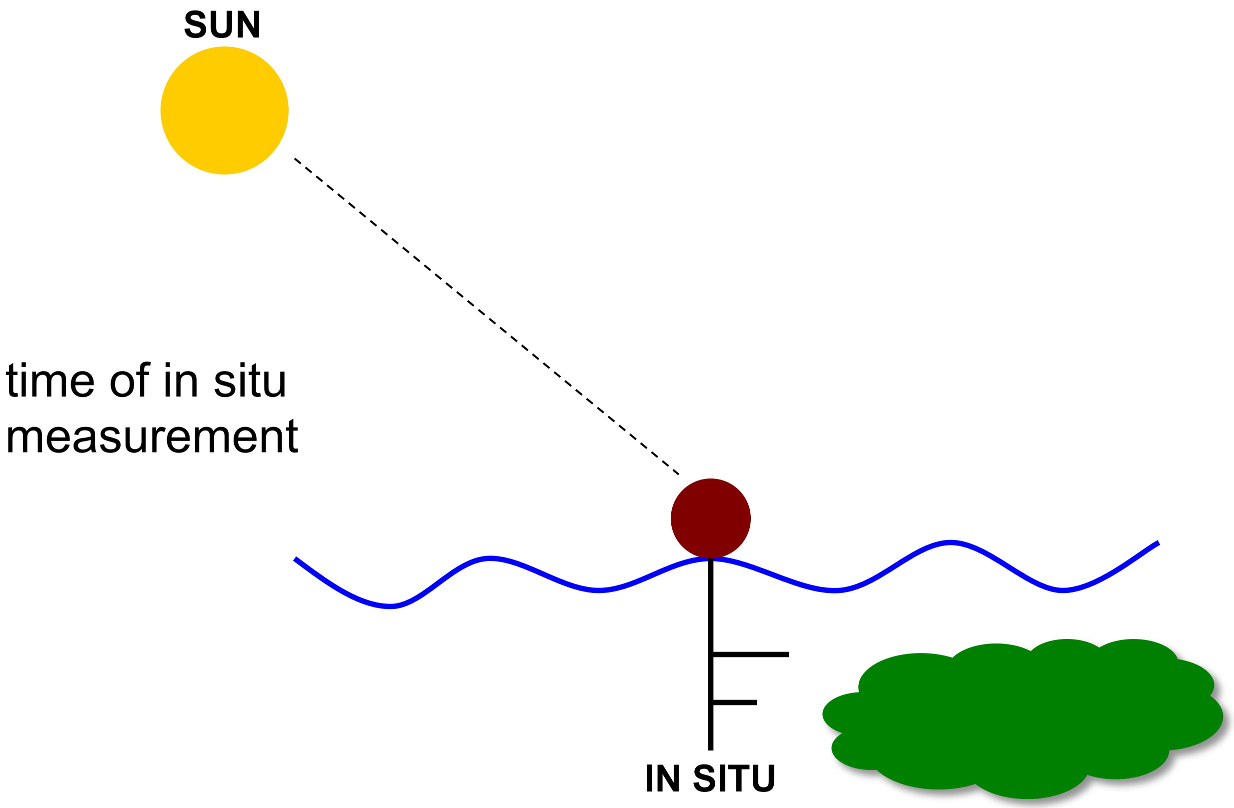
when using hyperspectral in situ radiometers:
enable the adjustment when applying 10-nm filter to in situ R_{rs}
disable the adjustment when applying full-spectral-response to in situ R_{rs}

bidirectional reflectance correction

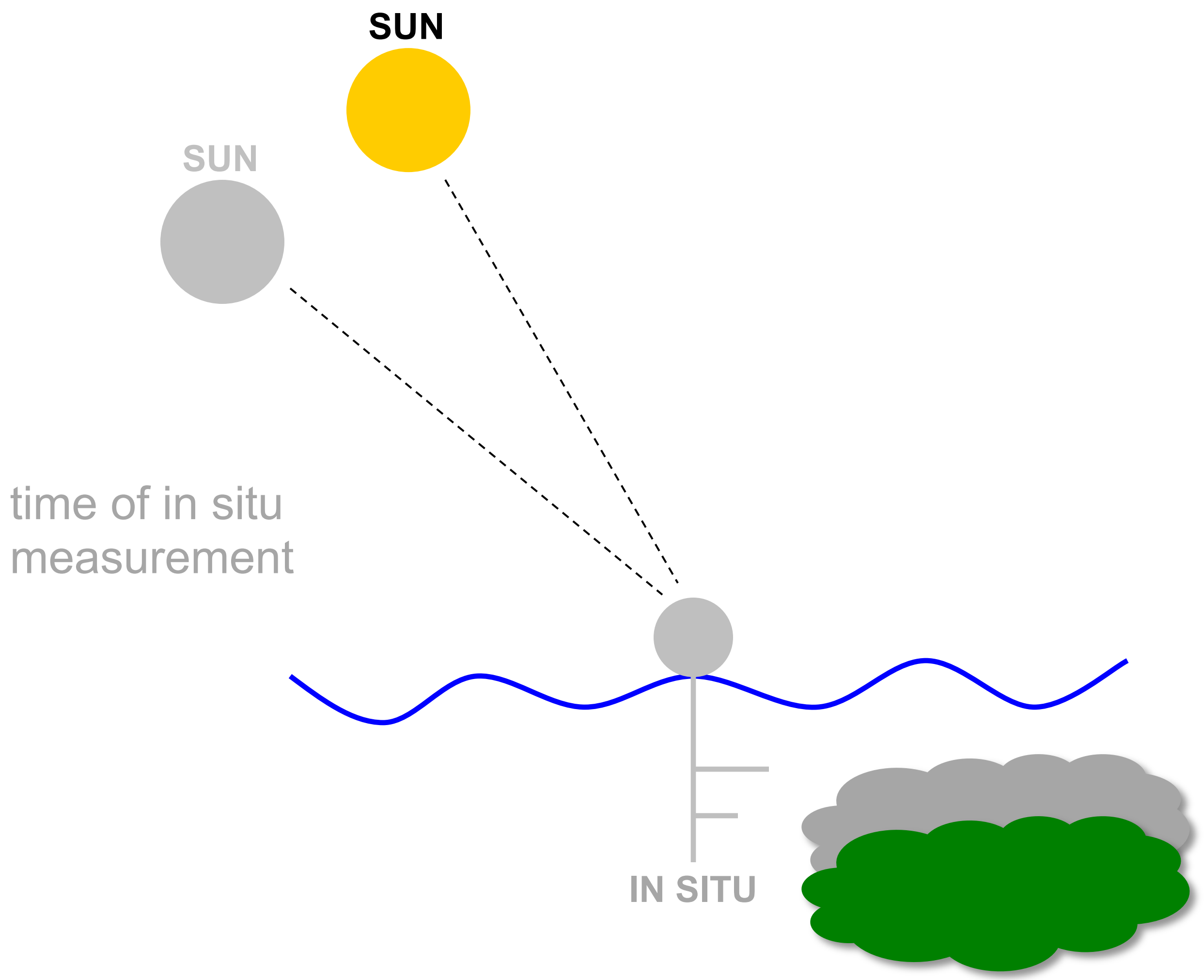
$$L_t = \left(L_r + [L_a + L_{ra}] + t_{dv} L_f + t_{dv} L_w\right) t_{gv}\, t_{gs}\, f_p + T\, L_g$$

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

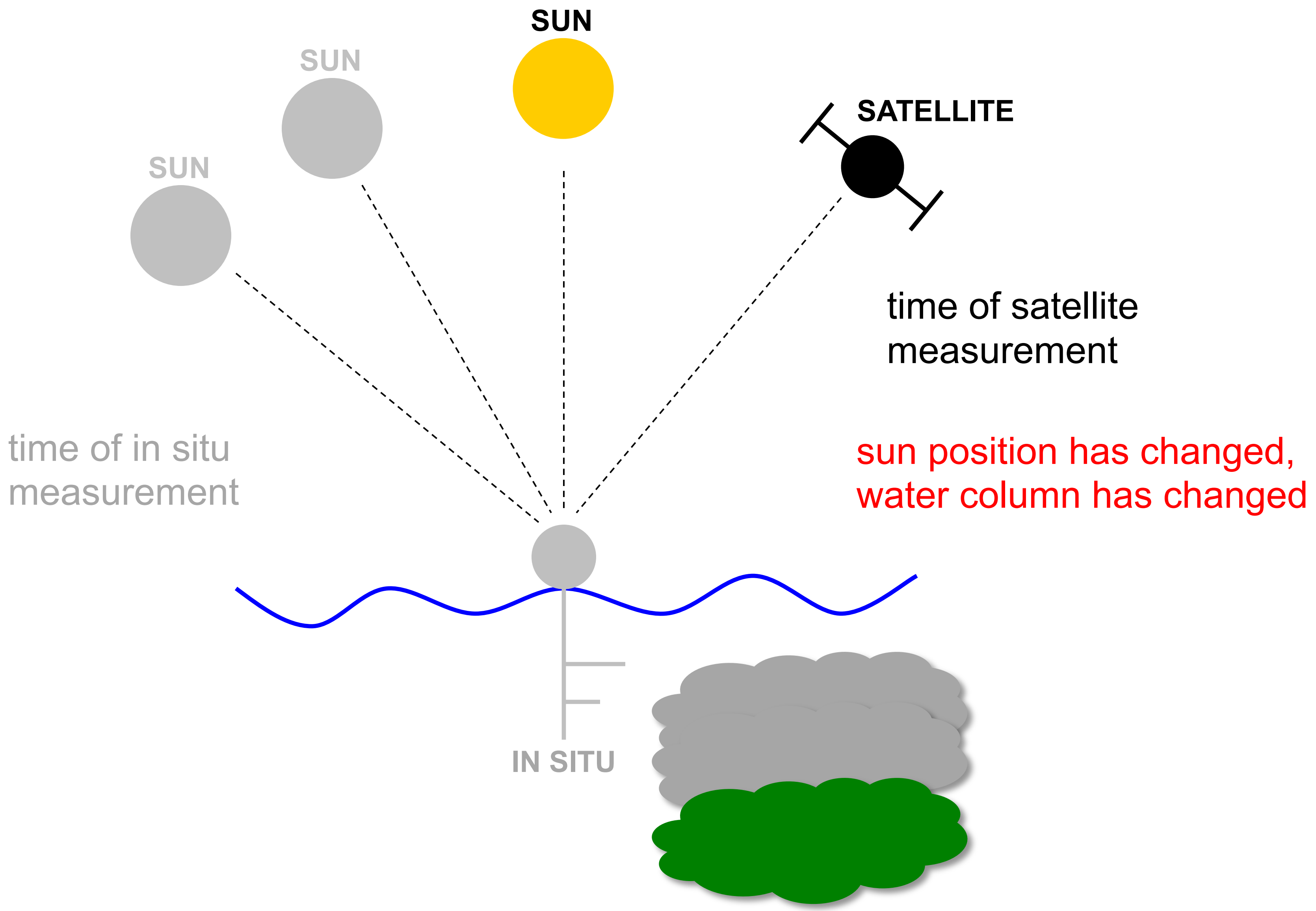
bidirectional reflectance correction



bidirectional reflectance correction



bidirectional reflectance correction



bidirectional reflectance correction

we normalize R_{rs} to account for Sun's changing position in the sky:

- pathlengths through atmosphere
- transmission of light through air-sea & sea-air interfaces
- angular features of in-water volume scattering functions

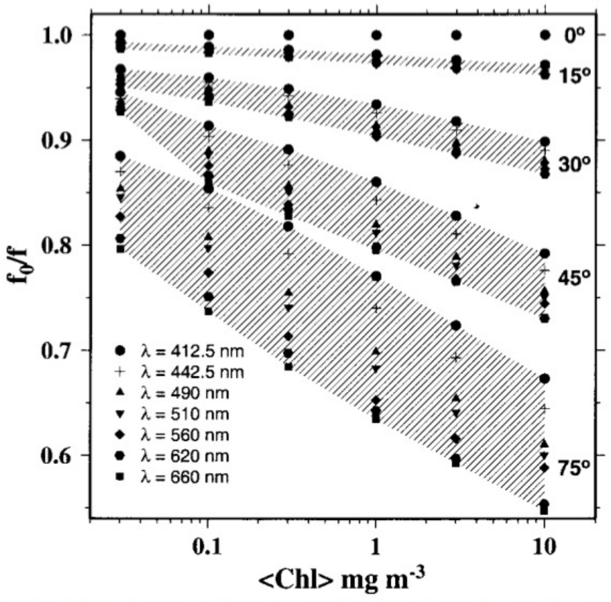
$$[L_w]_N^{ex} \equiv [L_w(\theta_v, \phi)]_N \frac{\mathfrak{R}_o(W)}{\mathfrak{R}(\theta_v', W)} \frac{f_o(\mathrm{ATM}, W, \mathrm{IOP})}{Q_o(\mathrm{ATM}, W, \mathrm{IOP})} \left[\frac{f(\theta_s, \mathrm{ATM}, W, \mathrm{IOP})}{Q(\theta_s, \theta_v', \phi, \mathrm{ATM}, W, \mathrm{IOP})}\right]^{-1}$$

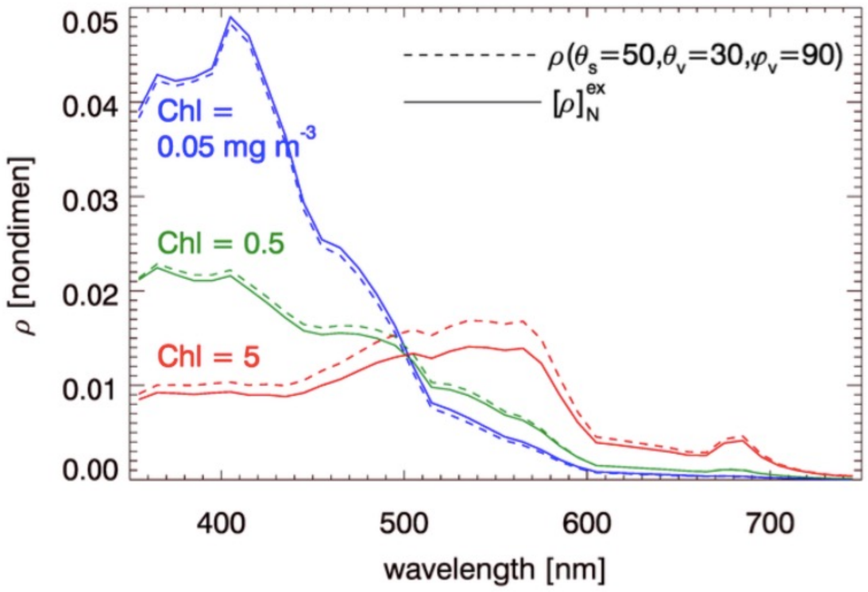
Morel et al., Applied Optics, 2002

$\mathfrak{R}, \mathfrak{R}_0, f, f_0, Q, Q_0$ from look-up-tables based on Chl & geometries of Sun & sensor

to normalize all measurements (no subscript) to condition of overhead Sun (subscript $_0$)

bidirectional reflectance correction





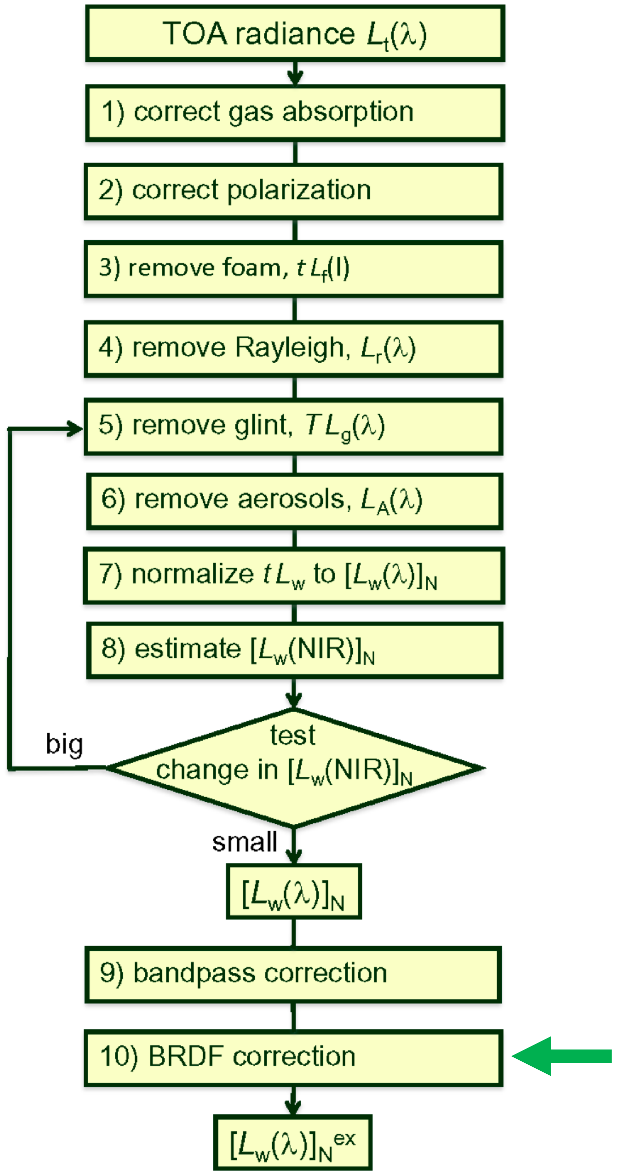
$$[L_w]_N^{ex} \equiv [L_w(\theta_v, \phi)]_N \frac{\Re_o(W)}{\Re(\theta'_v, W)} \frac{f_o(\mathrm{ATM}, W, \mathrm{IOP})}{Q_o(\mathrm{ATM}, W, \mathrm{IOP})} \left[\frac{f(\theta_s, \mathrm{ATM}, W, \mathrm{IOP})}{Q(\theta_s, \theta'_v, \phi, \mathrm{ATM}, W, \mathrm{IOP})}\right]^{-1}$$

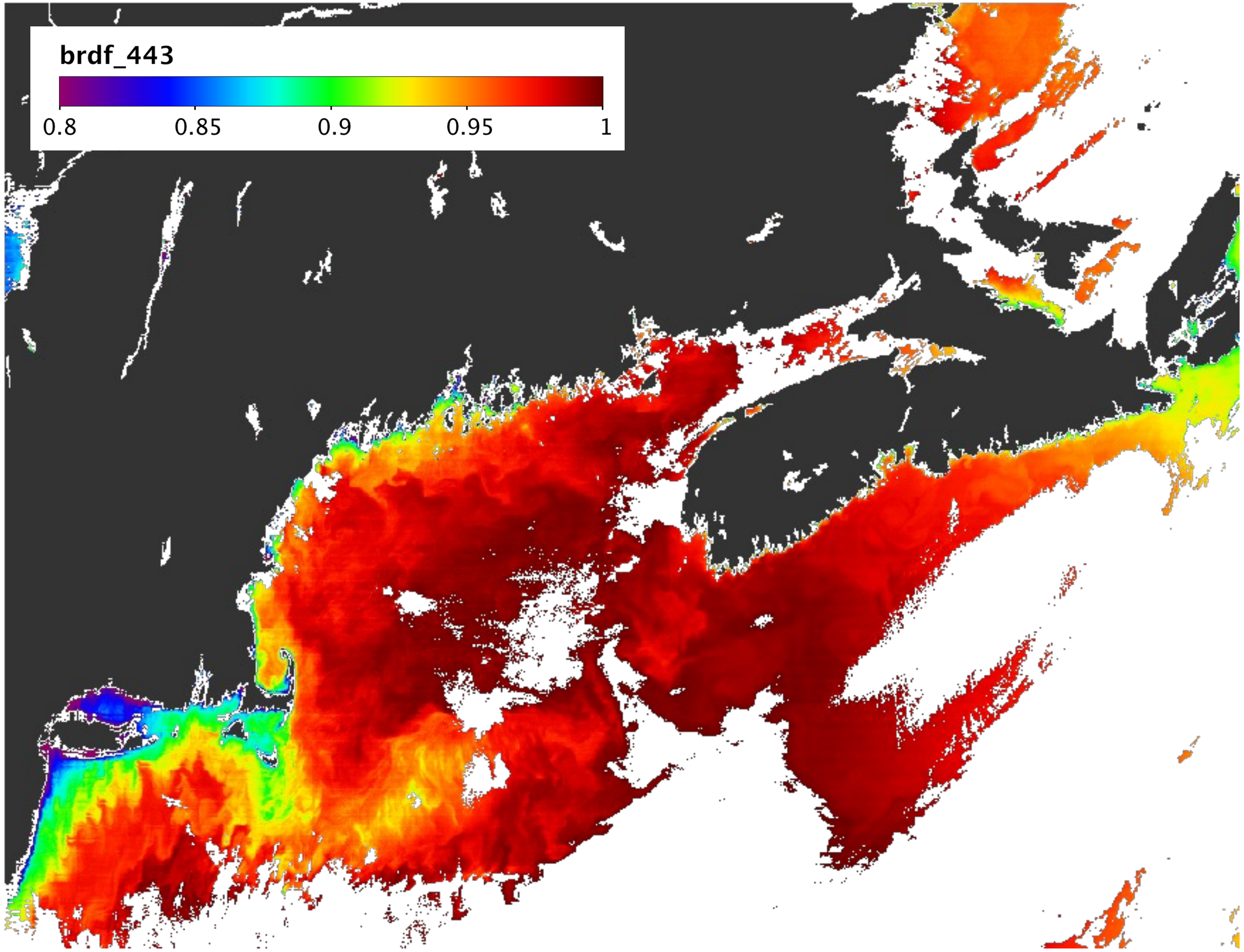
Morel et al., Applied Optics, 2002

$\Re, \Re_0, f, f_0, Q, Q_0$ from look-up-tables based on Chl & geometries of Sun & sensor

to normalize all measurements (no subscript) to condition of overhead Sun (subscript $_0$)

processing cadence: BRDF correction





so there you have it – perfect R_{rs}

$$\checkmark \quad \checkmark \quad \checkmark \quad \checkmark \ \checkmark \quad \checkmark \ \checkmark \quad \checkmark \quad \checkmark \quad \checkmark \quad \checkmark$$

$$L_t = \left(L_r + \left[L_a + L_{ra}\right] + t_{dv} L_f + t_{dv} L_w\right) t_{gv}\, t_{gs}\, f_p + T\, L_g$$

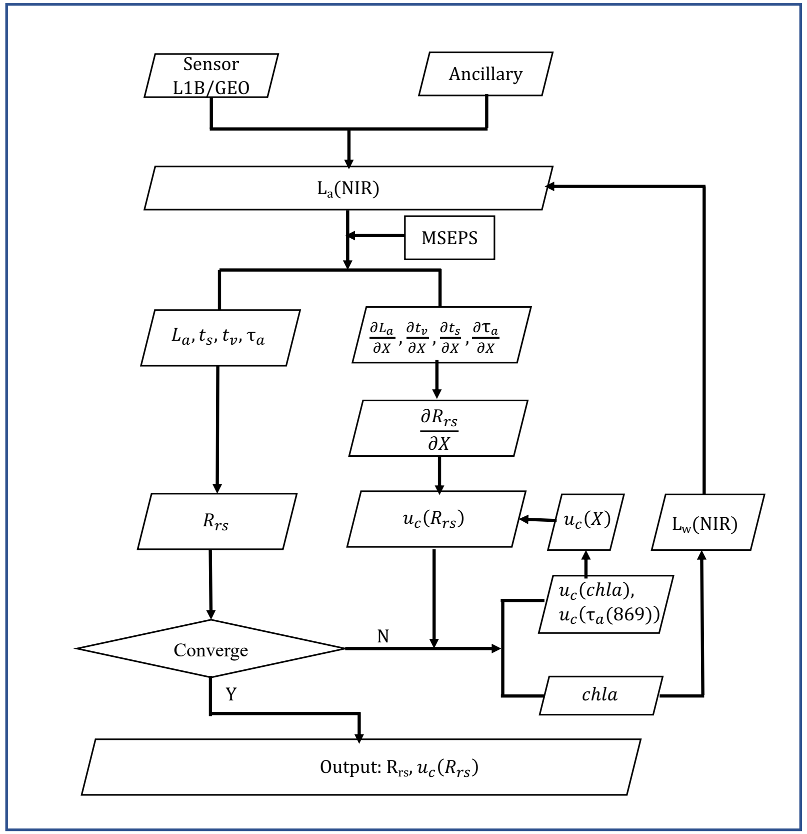
$$R_{rs} = \frac{L_w}{F_0 \cos(\theta_s)\, t_{ds}\, f_s\, f_b\, f_\lambda}$$

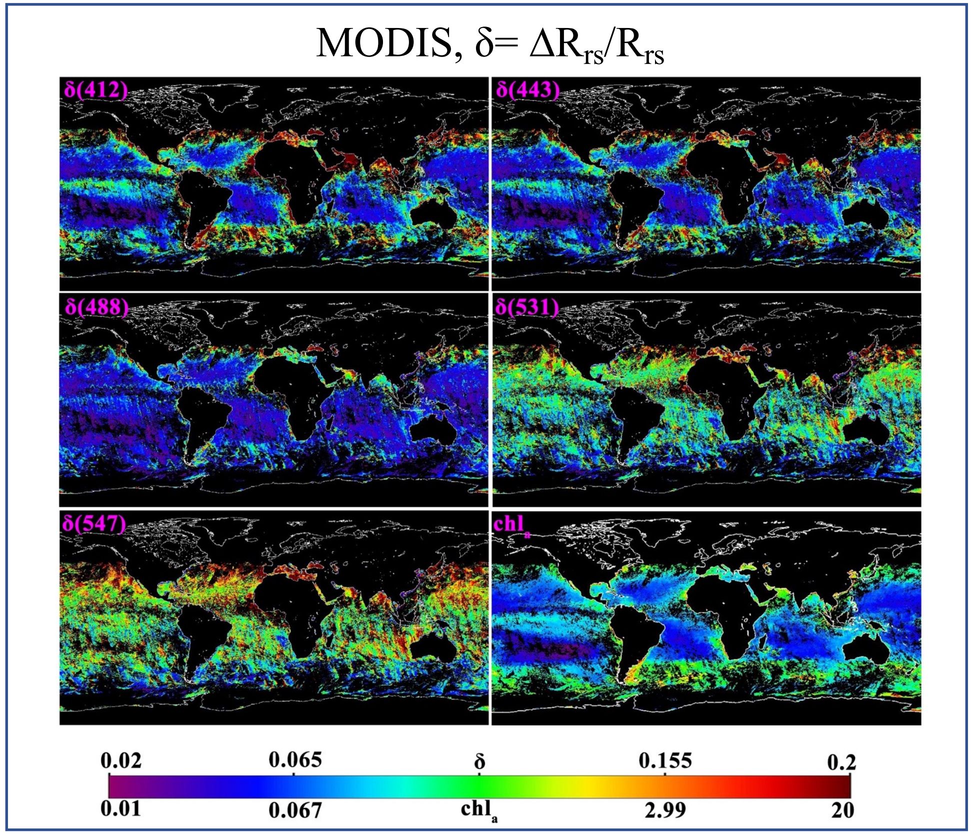
$$\checkmark \quad \checkmark \quad \checkmark \ \checkmark \ \checkmark \ \checkmark$$

$R_{rs}(\lambda)$ Uncertainties

- framework for analytical propagation of instrument noise, systematic error, and AC model error to $R_{rs}(\lambda)$ uncertainty, $\Delta R_{rs}(\lambda)$, has been developed/implemented for MSEPS and MBAC.

- M. Zhang, A. Ibrahim, B.A. Franz, Z. Ahmad, and A.M. Sayer, "Estimating pixel-level uncertainty in ocean color retrievals from MODIS," Opt. Express 30, 31415-31438 (2022).



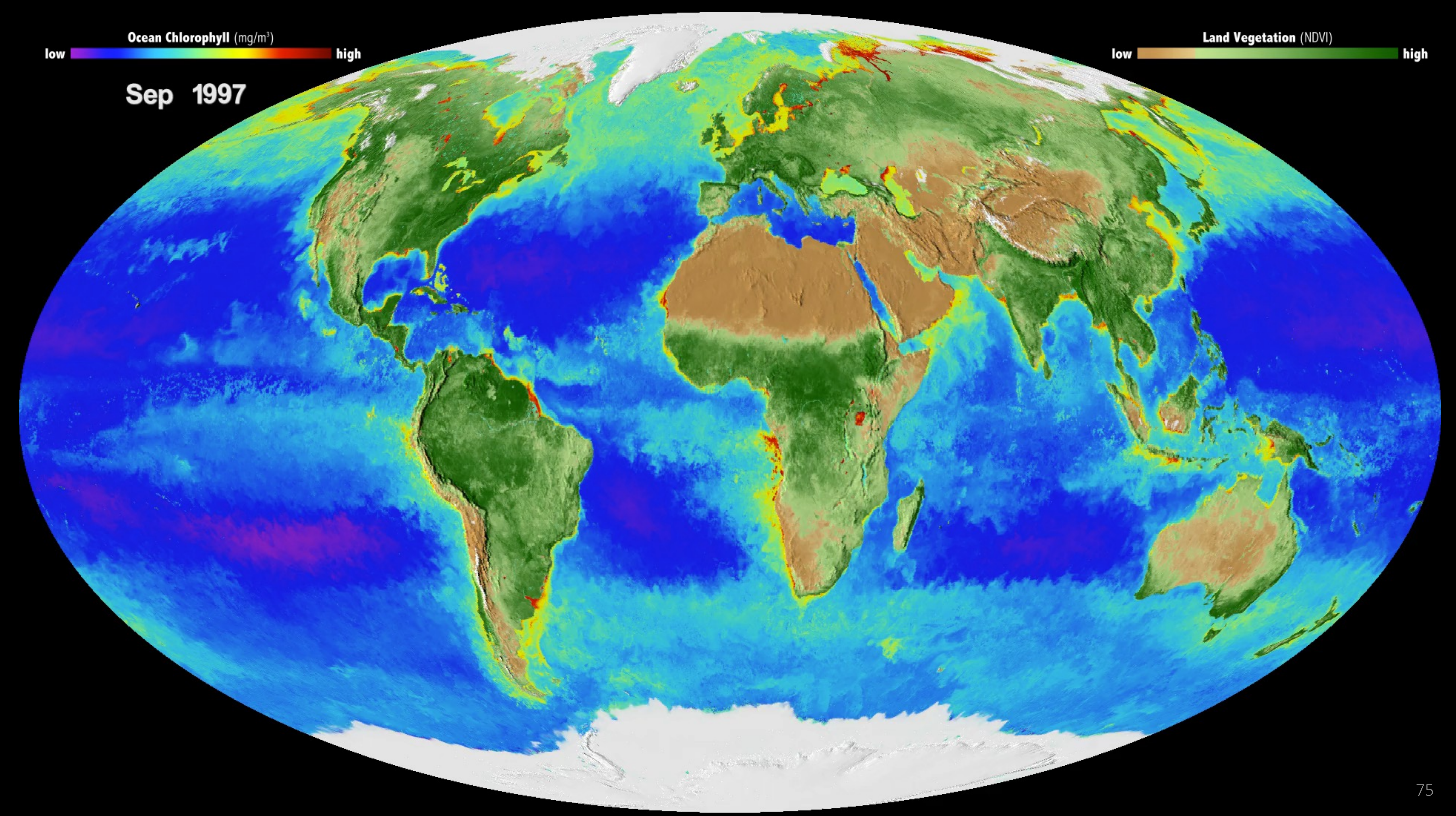


scorecard – ancillary data requirements

ancillary data	ancillary source	uses
atmospheric pressure	GMAO (formerly NCEP)	Rayleigh
water vapor	GMAO (“ NCEP)	transmittance
relative humidity	GMAO (“ NCEP)	aerosol models
wind speed	GMAO (“ NCEP)	white caps, Sun glint, Rayleigh
ozone	GMAO (“ OMI/TOMS)	transmittance
NO_2	GMAO (“ Sciamachy/OMI/GOME)	transmittance
sea surface temperature	Reynolds	bio-optical algorithms
sea ice	NSIDC	masking

look-up tables, coefficients

aerosol models
Rayleigh
Rayleigh optical thickness
ozone absorption
NO_2 absorption
pure seawater absorption, scattering, index of refraction (temp/sal dependent)
f/Q (bidirectional reflectance distributions)
others …


Ocean Chlorophyll (mg/m³)
low
high
Sep 1997
Land Vegetation (NDVI)
low
high

Thank you! Questions?