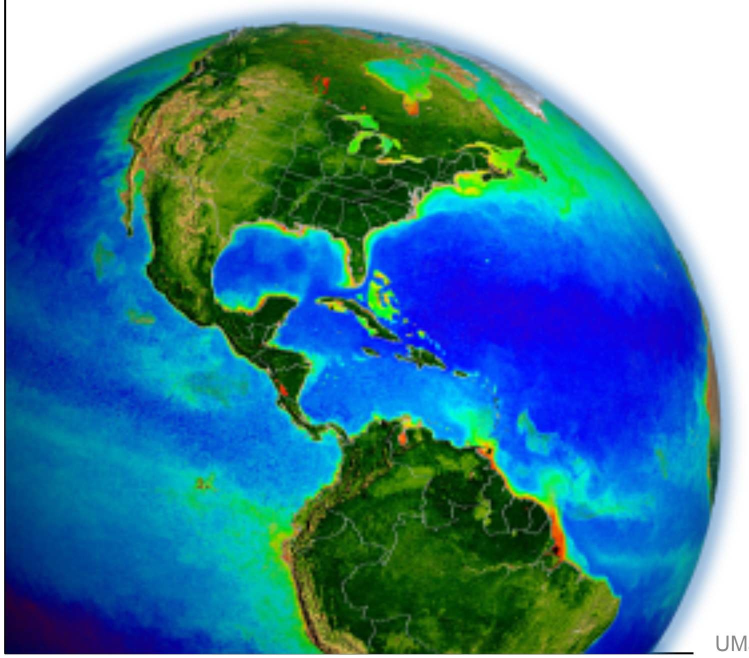
Ocean color satellite atmospheric correction



Jeremy Werdell
NASA Goddard Space Flight Center

UMaine Ocean Optics Summer Course
Jul 7 – Aug 3, 2013

Acknowledgements: Zia Ahmad, Sean Bailey,
Bryan Franz, & Wayne Robinson

satellite ocean color

we desire measurements of marine biogeochemical stocks (e.g., [ ]'s of phytoplankton, carbon) to further our understanding of marine ecosystems

satellites provide routine, synpotic views of the marine biosphere that cannot be achieved using conventional *in situ* & aircraft platforms

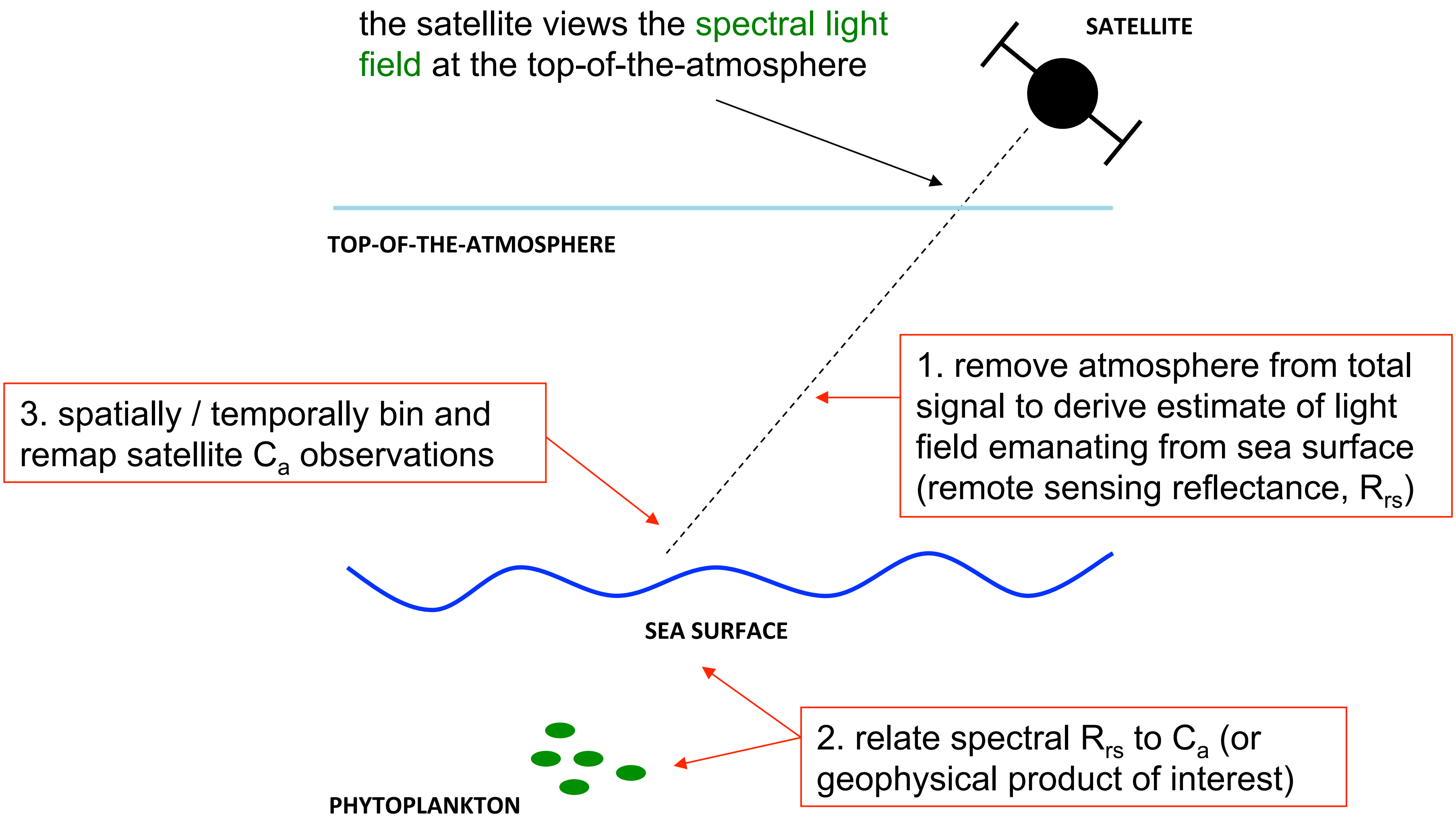
ocean color satellite instruments measure light (AOPs) – not [ ]'s

in-water constituents & their [ ]'s ➔ IOPs ➔ AOPs

in satellite ocean color, we start here
& work from right to left

(as discussed in lectures 19 & 20 last Friday)

satellite ocean color



the satellite views the spectral light field at the top-of-the-atmosphere

1. remove atmosphere from total signal to derive estimate of light field emanating from sea surface (remote sensing reflectance, R_{rs})

2. relate spectral R_{rs} to C_a (or geophysical product of interest)

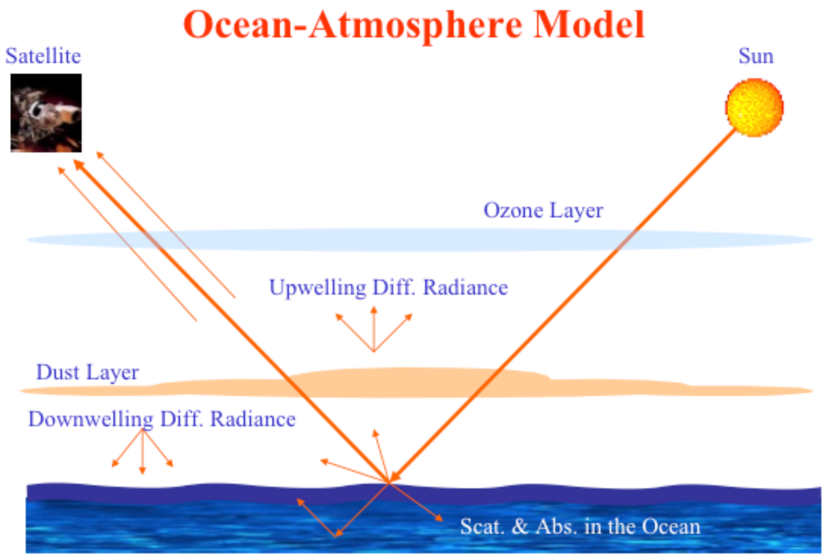
3. spatially / temporally bin and remap satellite C_a observations

satellite ocean color

ocean color satellites measure top-of-atmosphere radiances

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

terminology:
L = radiance (uW cm^{-2} nm^{-1} sr^{-1})
t = transmittance (unitless)
f = correction factor (unitless)
all terms are spectrally dependent



satellite ocean color

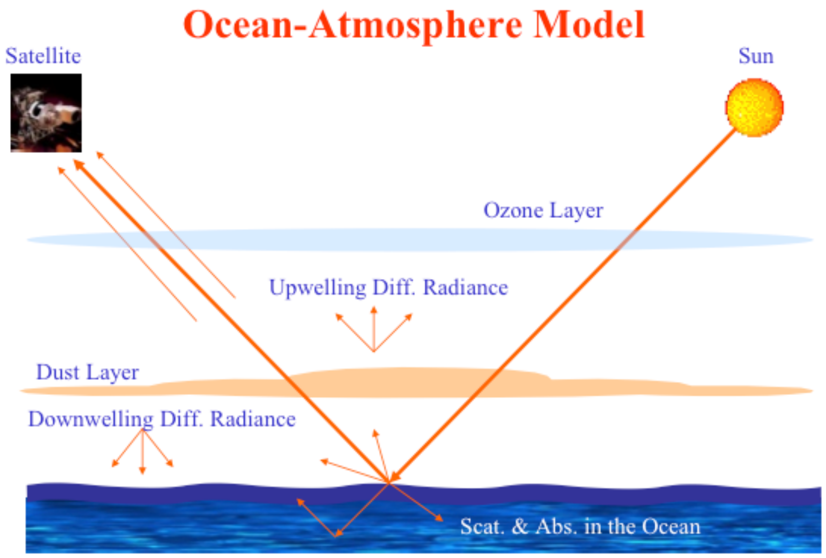
ocean color satellites measure top-of-atmosphere radiances

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

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

we desire (normalized)
remote sensing reflectances

terminology:
L = radiance (uW cm^{-2} nm^{-1} sr^{-1})
t = transmittance (unitless)
f = correction factor (unitless)
all terms are spectrally dependent



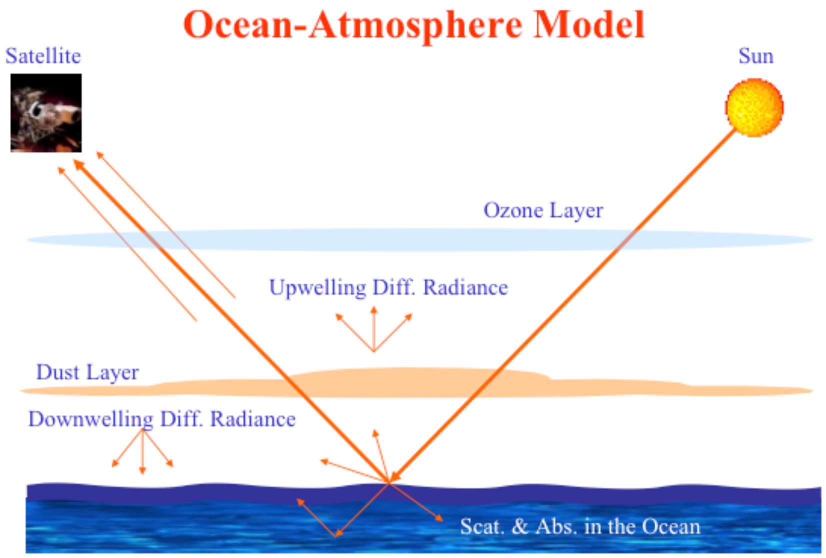
outline

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

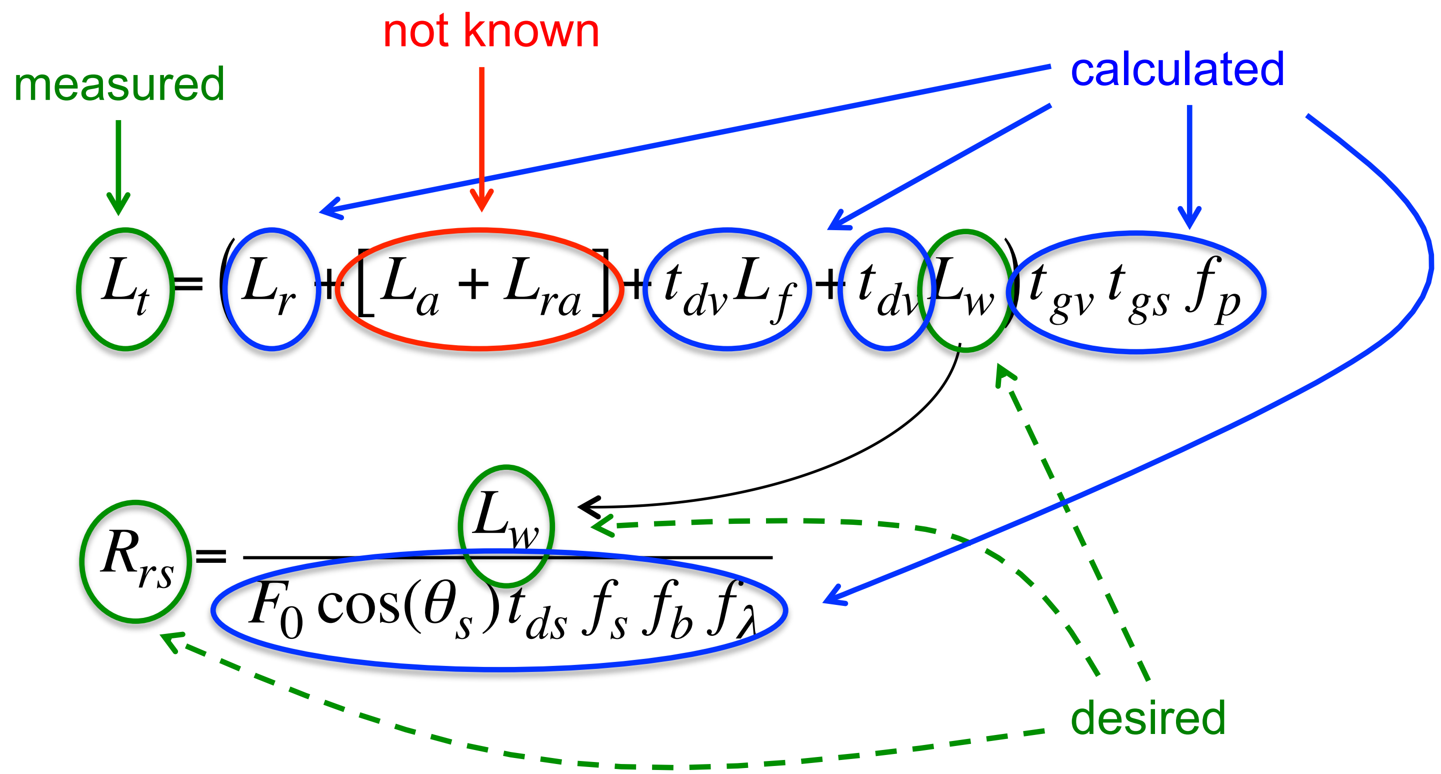
$$L_t = \left(L_r + \left[L_a + L_{ra}\right] + t_{dv} L_f + t_{dv} L_w\right) t_{gv}\, t_{gs}\, f_p$$

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

we will sequentially step through the meaning & derivation of each term in these equations



preview



measured

not known

calculated

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

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

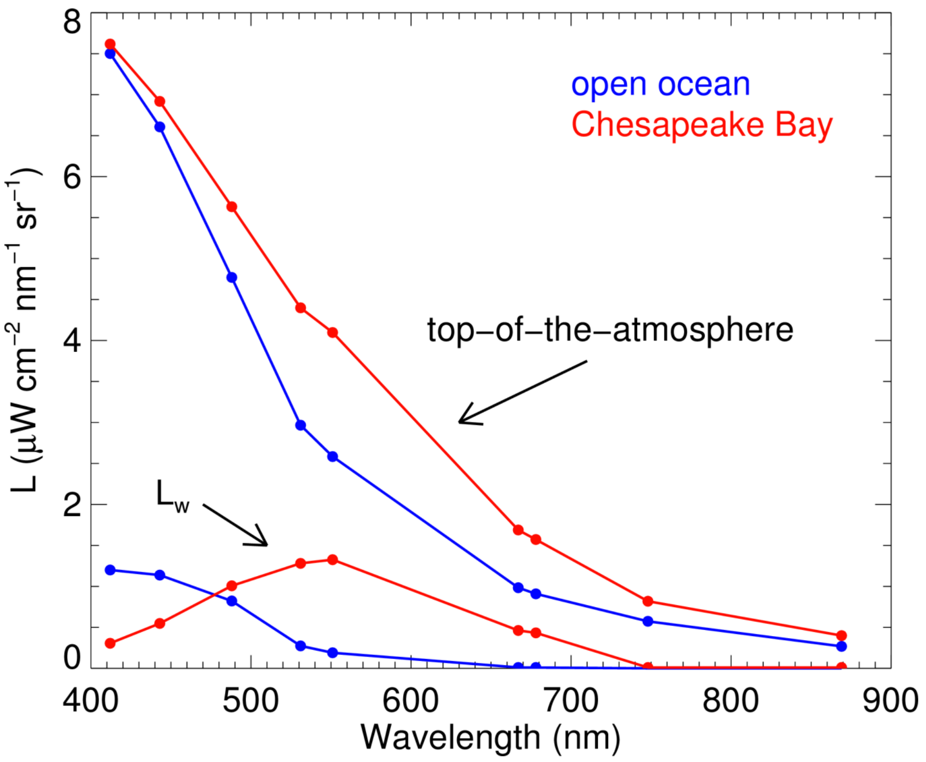
desired

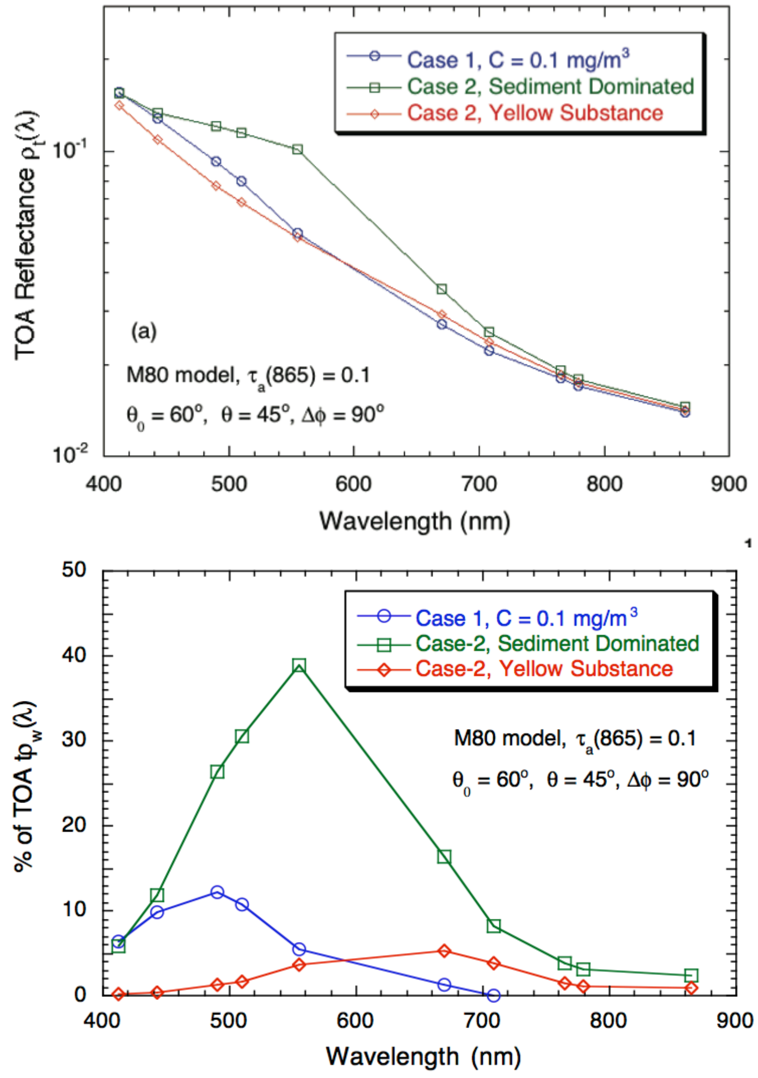
top-of-atmosphere radiance

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

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

top-of-atmosphere radiance





Menghua Wang, IOCCG Report 10

L_w is often <10% of L_t !

0.5% error in atmospheric correction or calibration corresponds to possible 5% error in L_w

known terms

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

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

known terms

instrument polarization correction factor (pre-launch measurement)

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

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

cosine of the instrument view angle

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

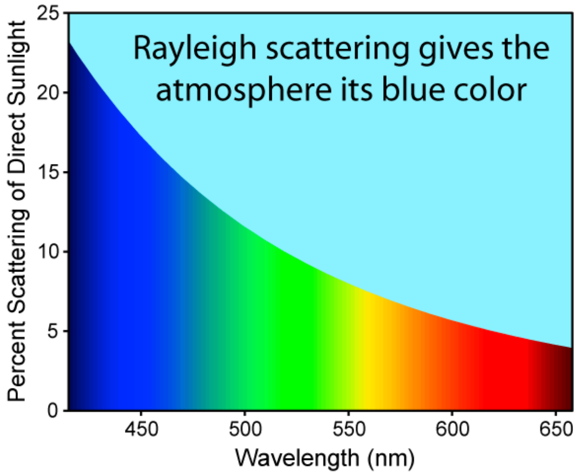
molecular (Rayleigh) scattering

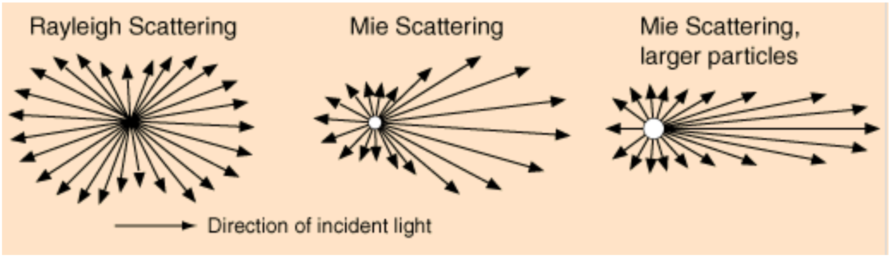
$$\overset{\checkmark}{L_t} = \left(\bigcirc\!\!\!\!\!\!L_r + \left[L_a + L_{ra} \right] + t_{dv} L_f + t_{dv} L_w \right) t_{gv}\, t_{gs}\, \overset{\checkmark}{f_p}$$

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

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

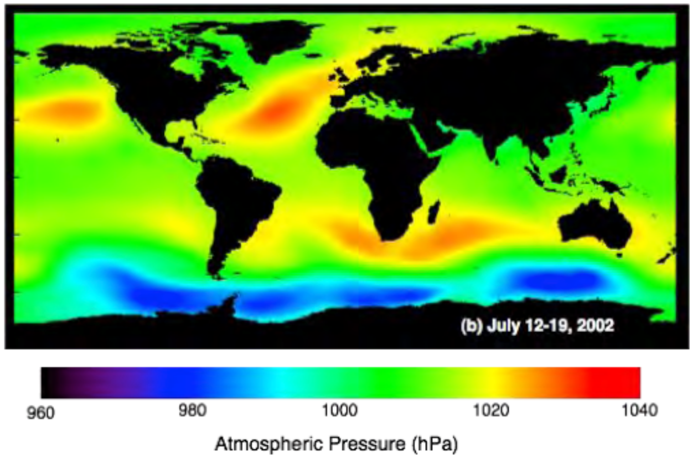
- results from electric polarizability of the particles
  - the oscillating electric field of a light wave acts on the charges within a particle, causing them to move at the same frequency
  - particle becomes a dipole whose radiation we see as scattered light
- scattering phase function is symmetrical – equal forward & backward

molecular (Rayleigh) scattering

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

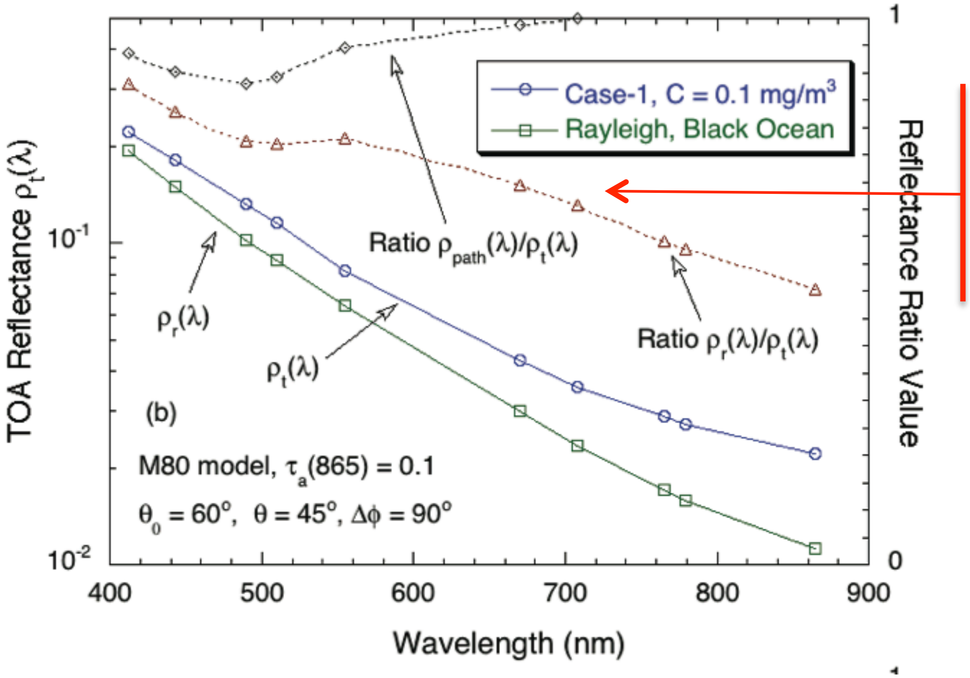
Rayleigh radiances (with polarization) are retrieved from look up tables given:

- solar & satellite viewing geometries
- wind speed (a proxy for surface roughness)
- atmospheric pressure (to adjust Rayleigh optical thickness, τ_r)



Menghua Wang, IOCCG Report 10

L_r can be 50-90% of L_t

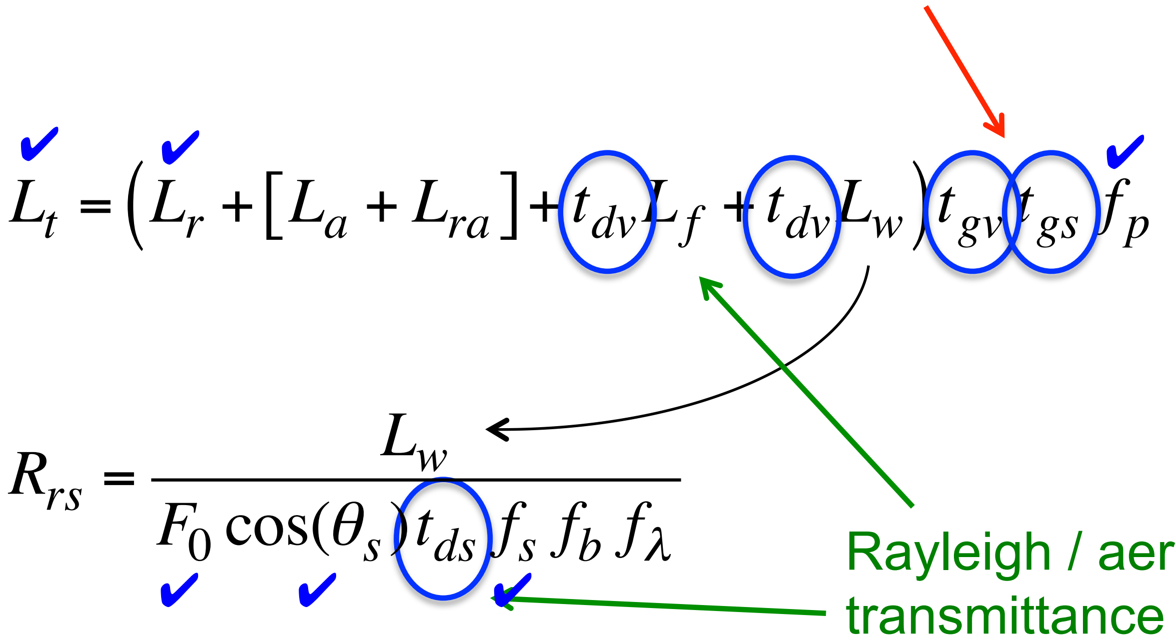


transmittances

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

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

transmittances



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

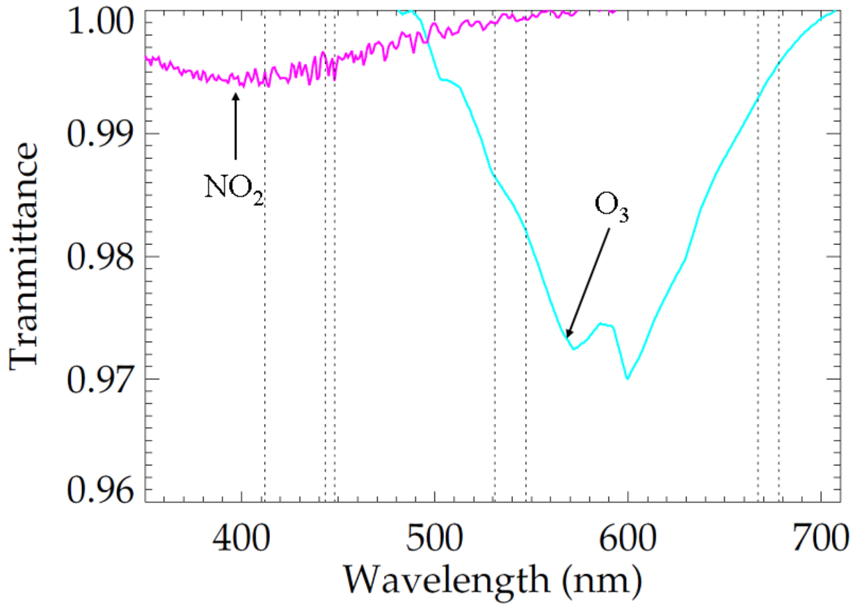
$$\overset{\checkmark}{L}_t = \left(\overset{\checkmark}{L}_r + [L_a + L_{ra}] + \boxed{t_{dv}} L_f + \boxed{t_{dv}} L_w\right) \boxed{t_{gv}} \boxed{t_{gs}} \overset{\checkmark}{f}_p$$

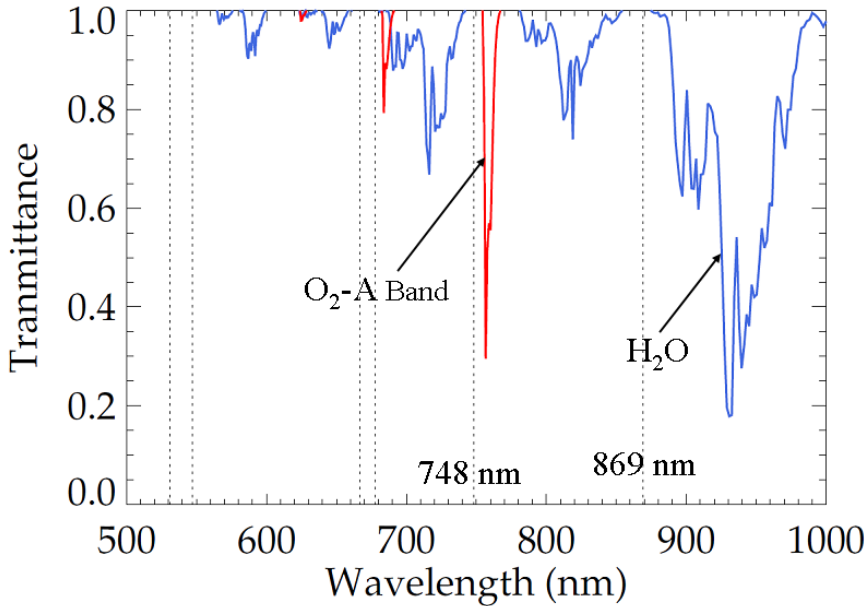
$$R_{rs} = \frac{L_w}{\underset{\checkmark}{F_0} \underset{\checkmark}{\cos(\theta_s)} \boxed{t_{ds}} \underset{\checkmark}{f_s} f_b f_\lambda}$$

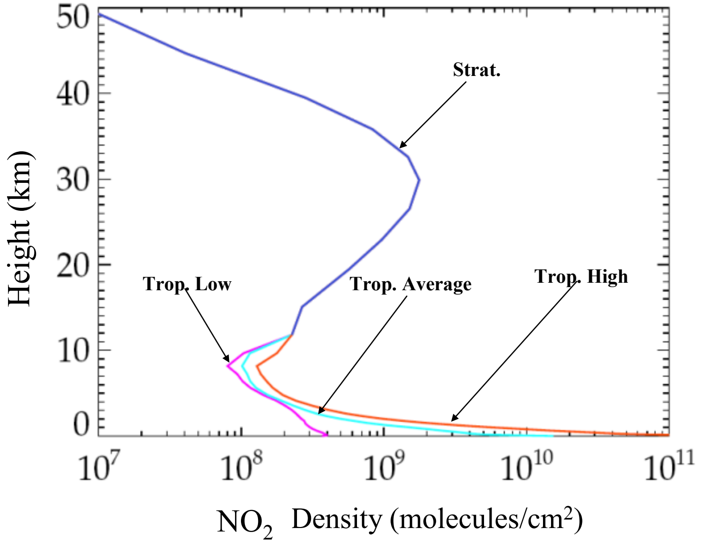
Rayleigh / aerosol diffuse
transmittance (d) in direction
of Sun (s) or satellite (v)

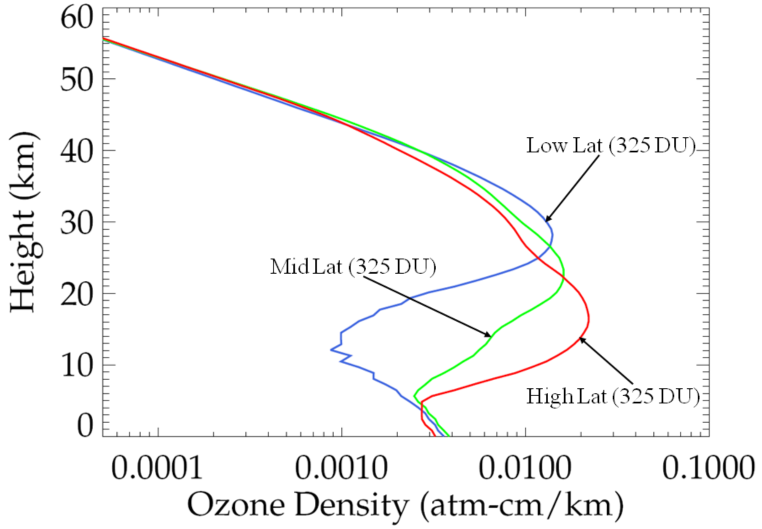
transmittances

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







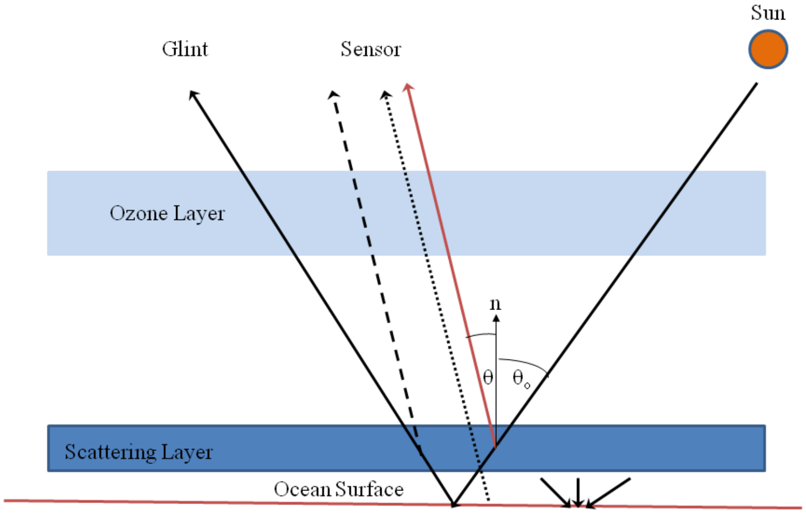


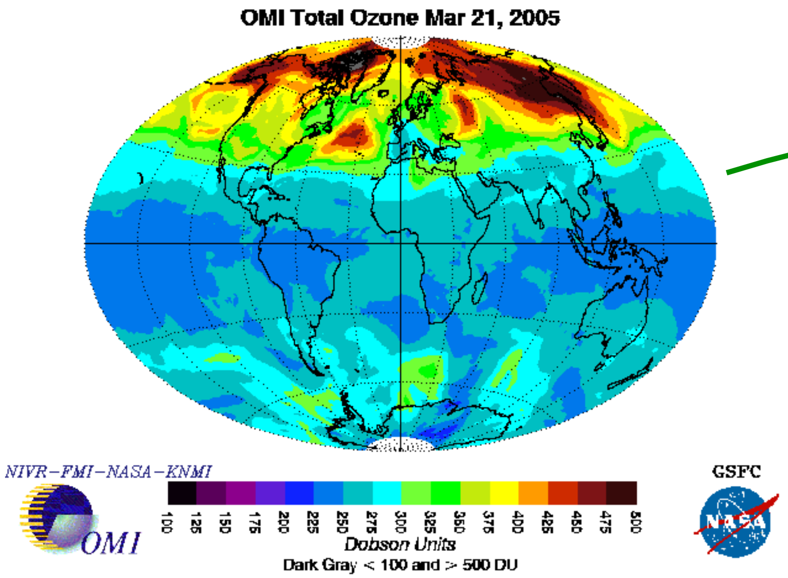
transmittances

requires ancillary data, e.g.:

- NO_2 from SCIAMACHY/GOME/OMI
- O_3 from OMI/TOMS
- water vapor from NCEP

ancillary data from varied sources for a given product often differ





example for ozone:

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

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

transmittances

$$E_d(z) = E_d(0^-)\exp(-K_d z)$$

$$E_d(z) = E_d(0^-)\exp(-\tau)$$

$$\frac{E_d(z)}{E_d(0^-)} = \exp(-\tau)$$

$$t = \exp(-\tau)$$

I often need to mentally transfer atmospheric terminology to oceanic terminology

$$\tau_{O_3} = O_3\, k_{O_3}$$

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

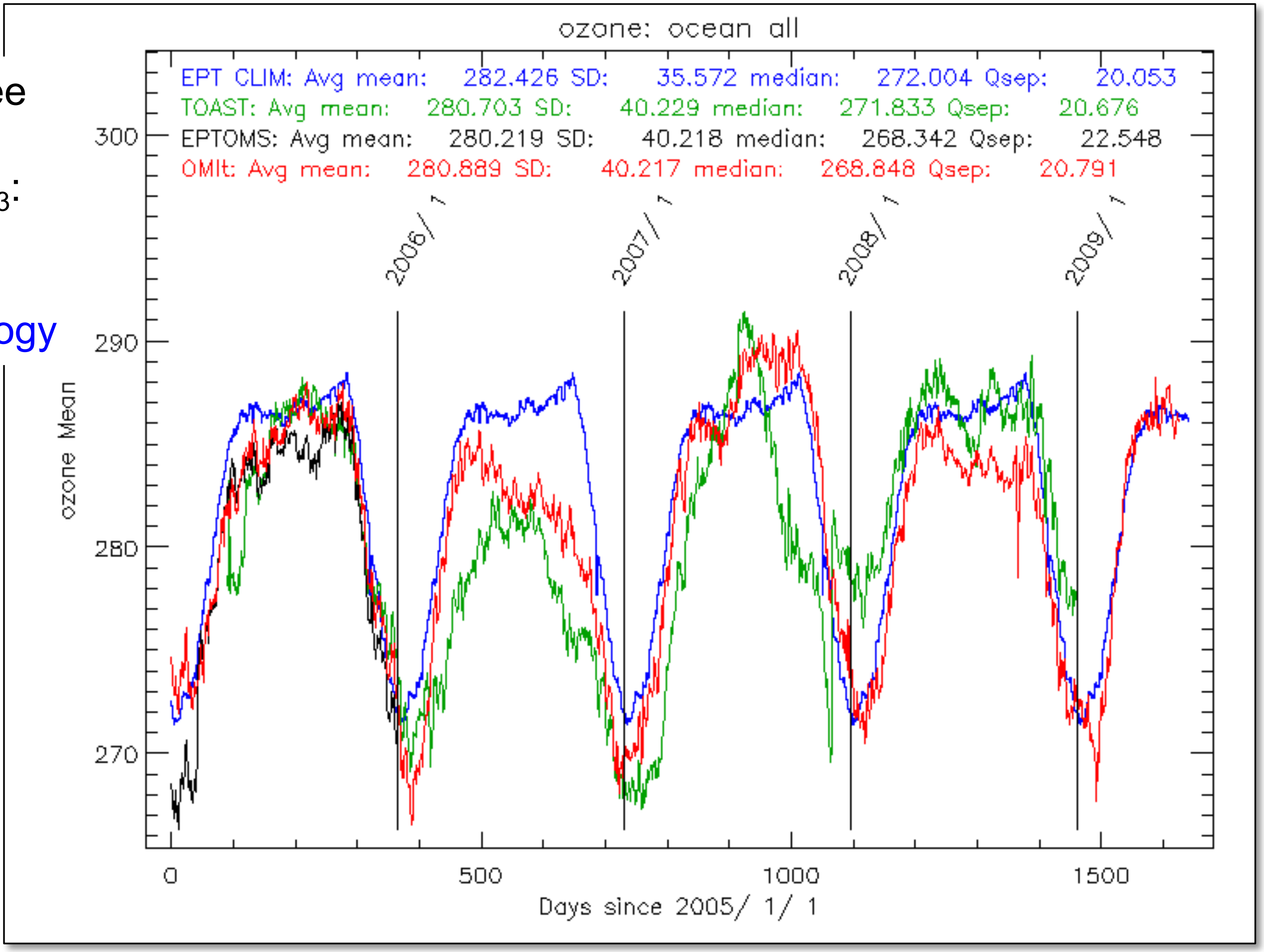
a word about ancillary data

compare three ancillary sources of O_3:

TOAST

OMI

EPT climatology

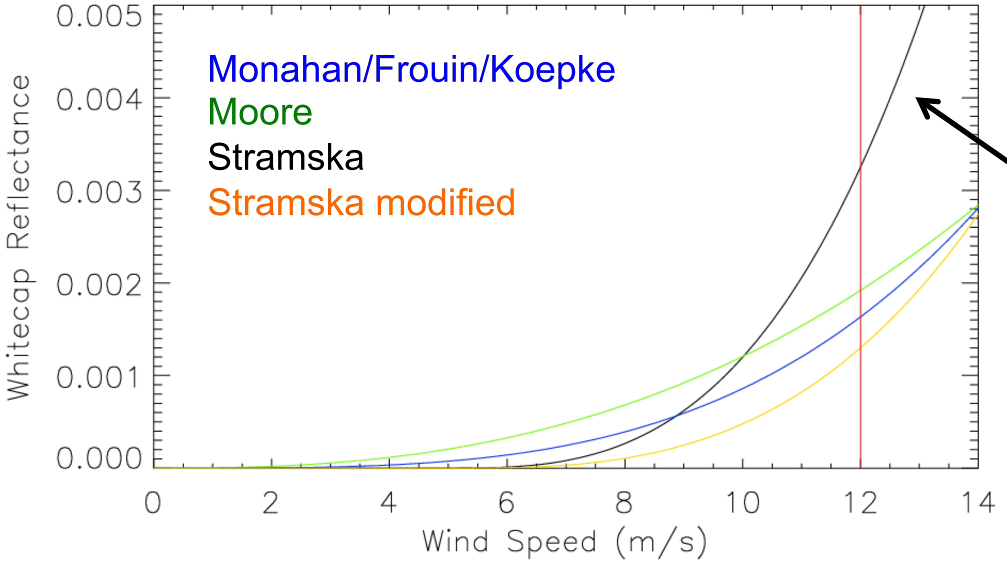


foam & whitecaps

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

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

foam & whitecaps



Stramska & Petelski, JGR, 2003

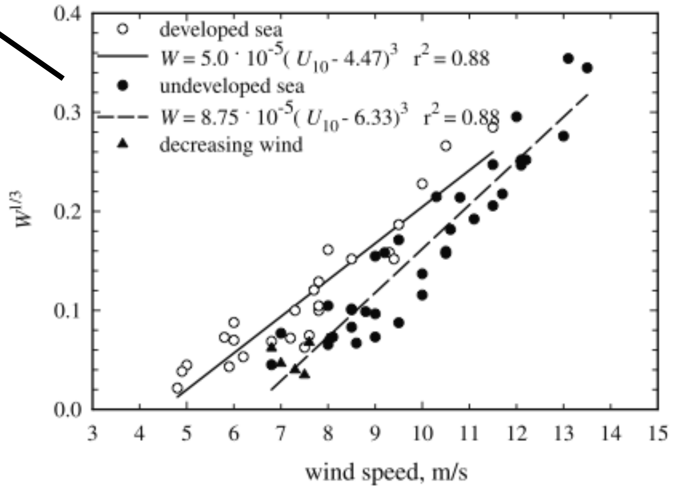
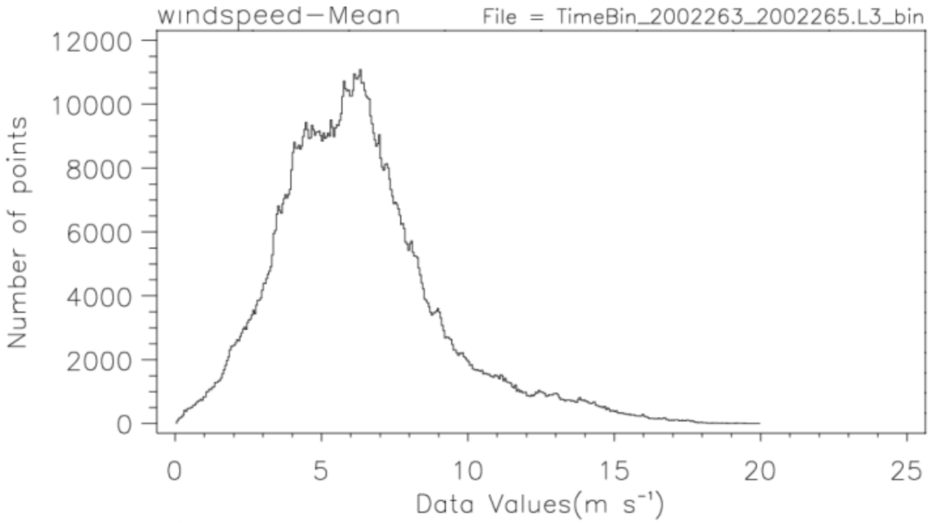


Figure 8. Oceanic whitecap coverage as a function of wind speed. Different symbols are used for the developed wave field, the undeveloped wave field, and the decreasing wind speed. See text for details.



```
Min    :      0.0155                      Mean:        6.2878
Max    :     19.9611                      STD :        2.7837
Median:       5.9863                      Mode :       6.3260

Binsize : 0.0500000,   No. of bins : 400
No. pts selected/No. pts in area : 1187244/8388608 (14.1531%)
Area : Full data
```

$$L_f \sim A\,\pi^{-1} [a (U_{10} + b)^3]$$

A = 22% (11-33%) from Koepke 1984

estimation of contribution of whitecaps & foam requires ancillary wind data (NCEP)

a quick aside about Sun glint

ideally, satellite ocean color instruments tilt away from Sun glint (e.g., SeaWiFS)

equation for top-of-atmosphere radiance can more accurately be described as:

$$L_t - \underbrace{F_0\, T_0\, T\, L_{GN}}_{\text{contribution of Sun glint}} = \left(L_r + \left[L_a + L_{ra}\right] + t_{dv} L_f + t_{dv} L_w\right) t_{gv}\, t_{gs}\, f_p$$

Sun glint

Correction of sun glint contamination on the SeaWiFS ocean and atmosphere products

Menghua Wang and Sean W. Bailey

4790 APPLIED OPTICS / Vol. 40, No. 27 / 20 September 2001

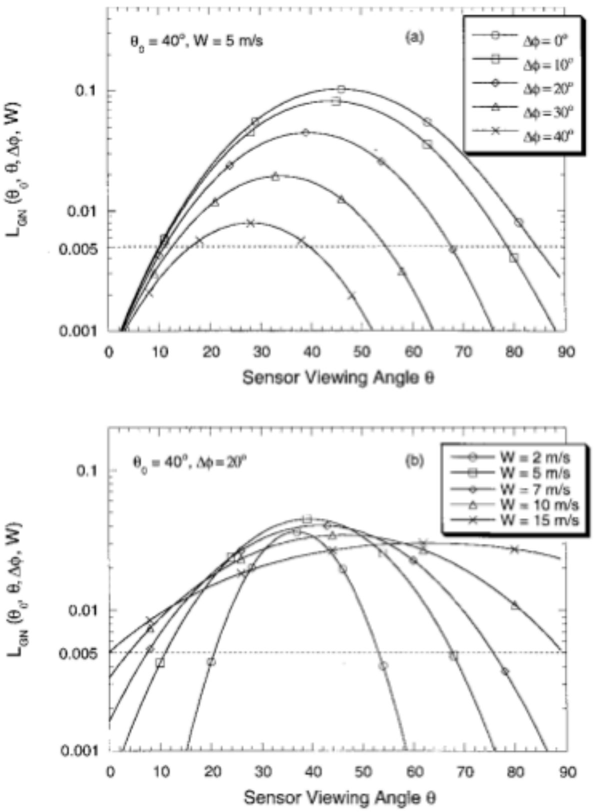


Fig. 1. Normalized sun glint radiance L_{GN} as a function of the sensor-viewing angle (solar zenith angle, 40°) and for (a) various relative azimuthal angles with surface wind speed of 5 m/s and (b) various surface wind speeds with a relative azimuthal angle of 20°.

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

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

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

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

two step iteration since we don't know τ_a:

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

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

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

aerosols

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

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

aerosols

final unknowns in top expression

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

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

additional concepts:

aerosol tables

single- vs. multi-scattering

aerosol selection

the "black pixel" assumption

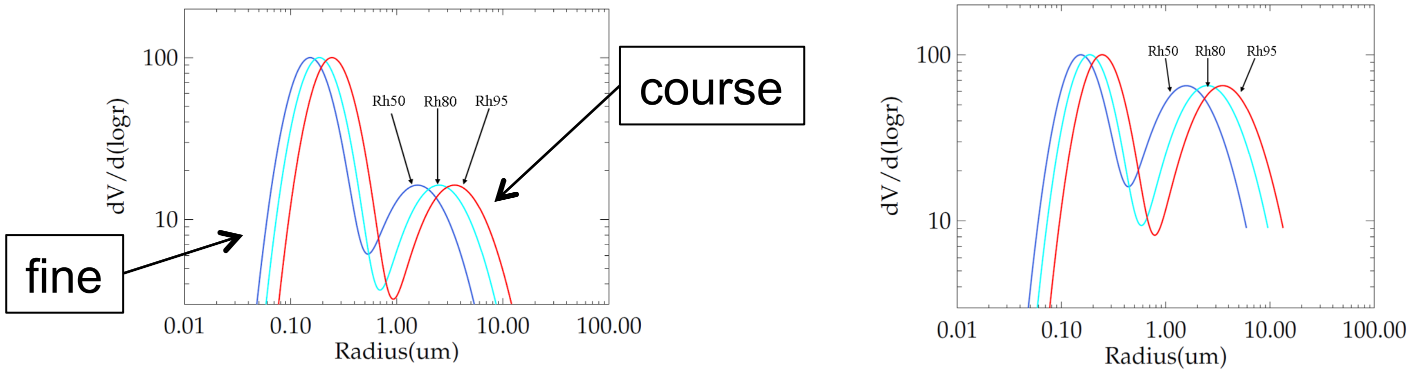
absorbing aerosols

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 (ω = 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)



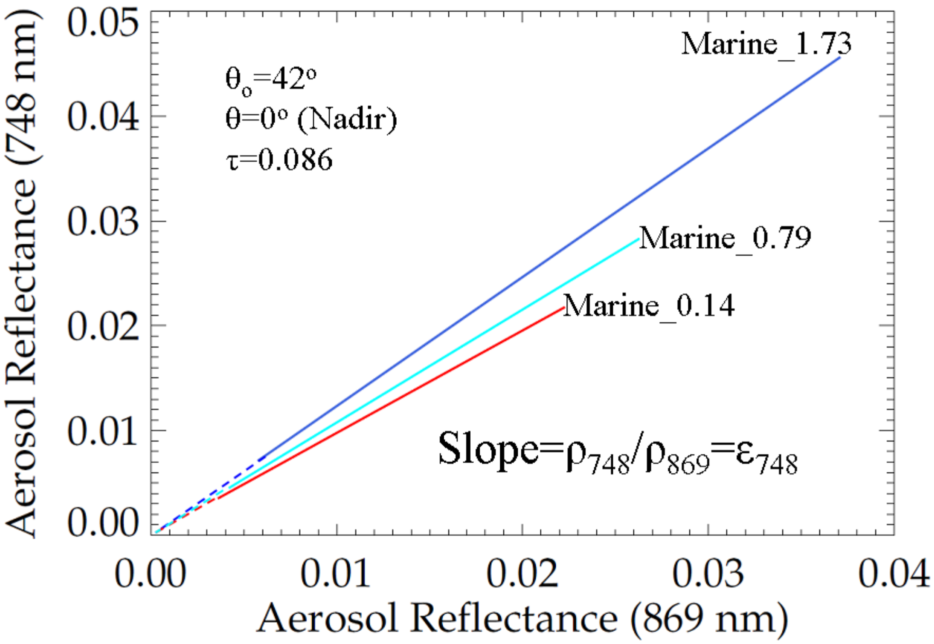
- each PSD modulated by varying relative humidity
  - humidity changes particle size
  - requires ancillary data from NCEP
- 80 aerosol tables total, built from AERONET measurements
  - 10 PSDs
  - 8 relative humidities

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 $\dfrac{\tau_a(\lambda)}{\tau_a(\lambda_0)} = \left(\dfrac{\lambda_0}{\lambda}\right)^{\alpha}$

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



black pixel assumption

final unknowns in top expression

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

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

$$L_a + L_{ra} = L_t\, t_{gv}\, t_{gs}\, f_p - L_r - t_{dv} L_f$$

aerosol selection

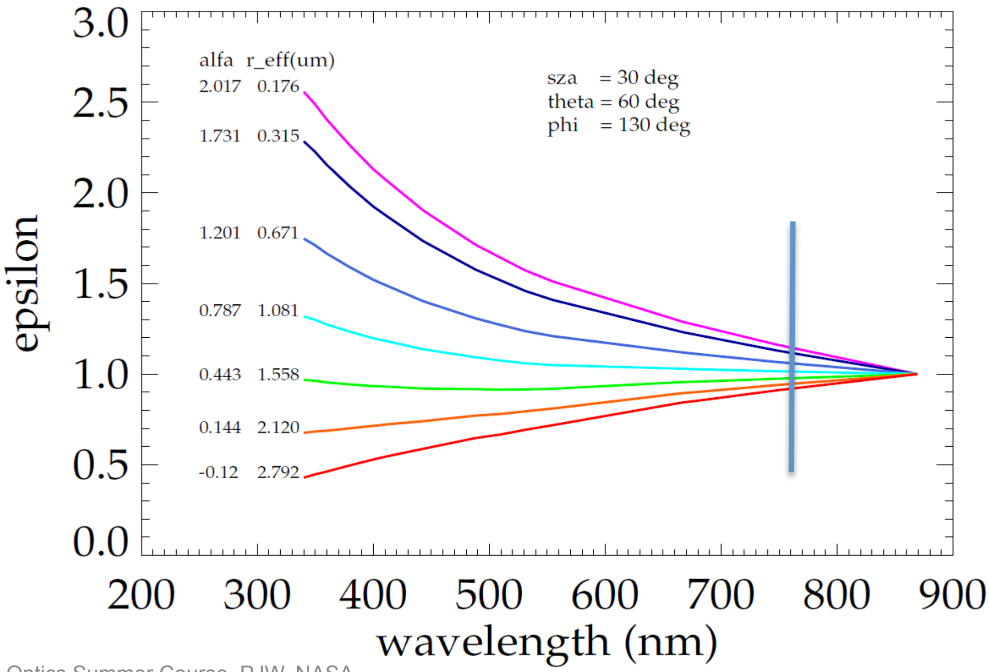
L_w(NIR) = 0, so L_a(NIR) + L_{ra}(NIR) = L_t(NIR) – (everything previously computed)

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 NCEP relative humidity
- compute epsilon values for the 10 tables [$\varepsilon(748,869) = L_a(748) / L_a(869)$]
- perform an iterative determination of the mean $\varepsilon(748,869)$ value (can be describe offline) & select a final bounding 2 aerosol models
- using 2 bounding models, calculate $\varepsilon(\lambda,869)$ from $\varepsilon(748,869)$
- calculate $L_a(\lambda) = \varepsilon(\lambda,869)\, L_a(869)$

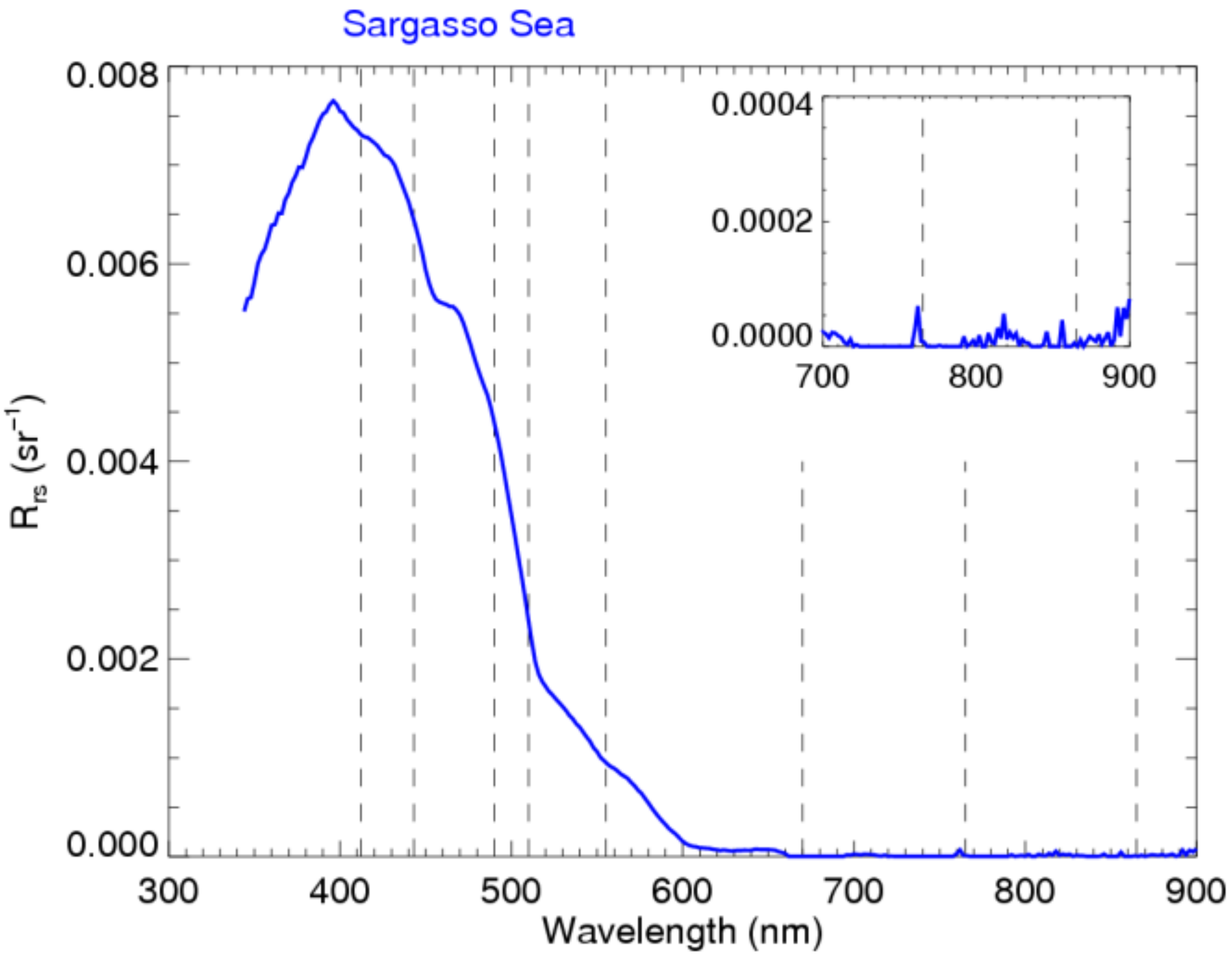
see Gordon & Wang, Applied Optics, 1994

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 (lectures 19 & 20)



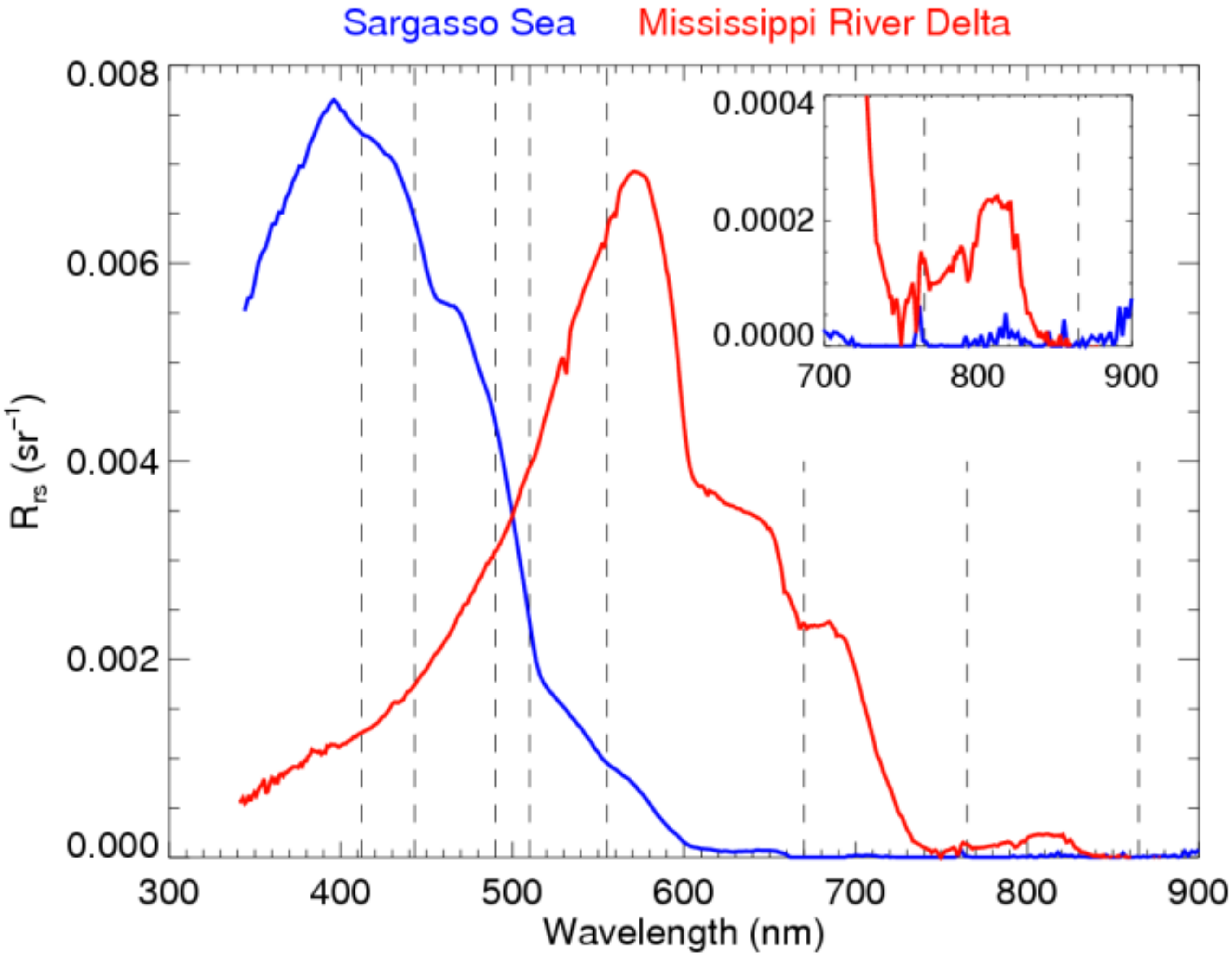
black pixel assumption

are R_{rs}(NIR) really black?



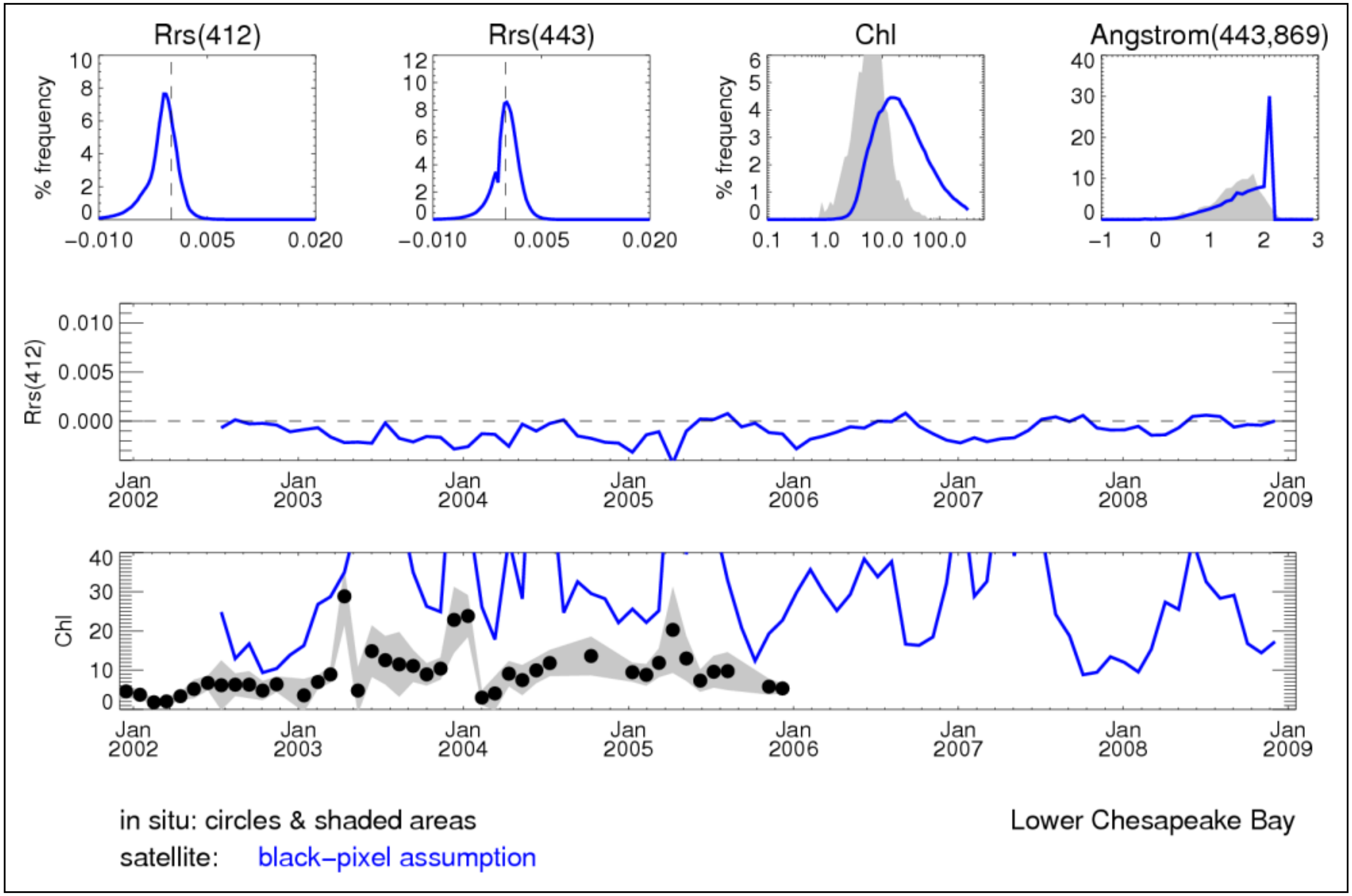
black pixel assumption

are R_{rs}(NIR) really black?



black pixel assumption

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



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

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)

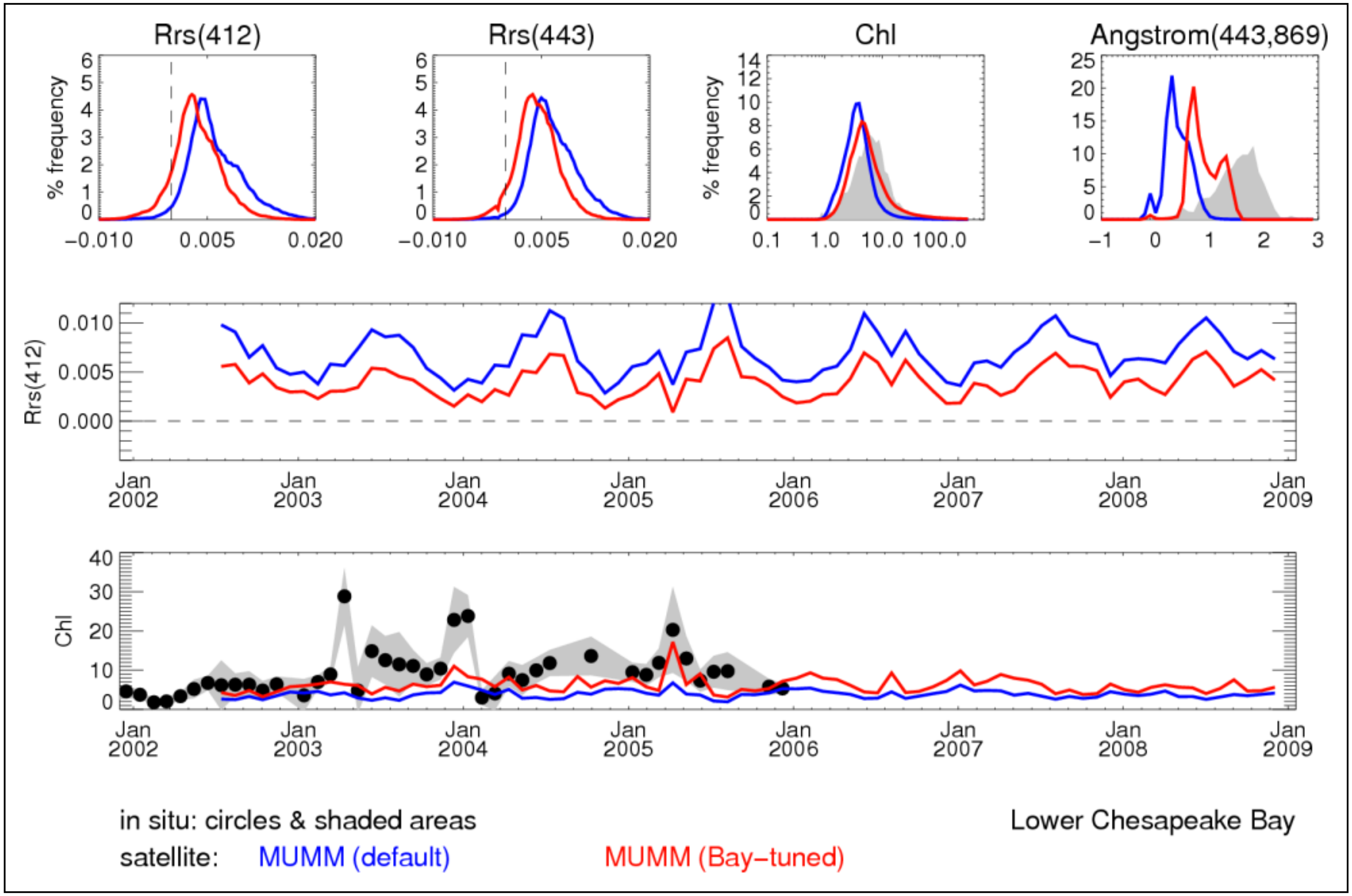
use a coupled ocean-atmosphere optimization

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

field data!

black pixel assumption

fixed aerosol & water contributions (MUMM)



in situ: circles & shaded areas

Lower Chesapeake Bay

satellite: MUMM (default) MUMM (Bay–tuned)

assign ε & ρ_w(NIR) (via fixed values, a climatology, nearby pixels)

black pixel assumption

advantages:

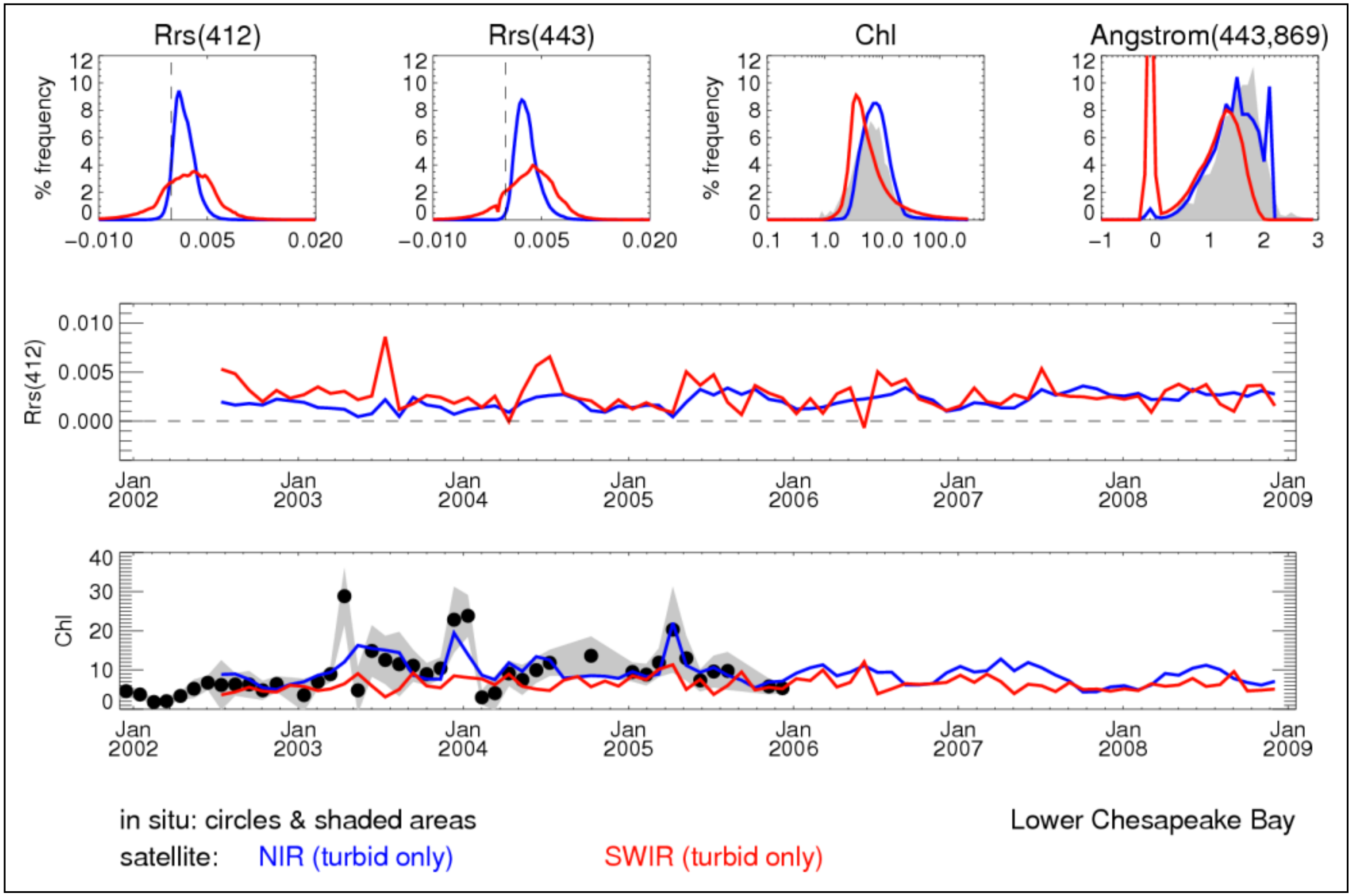
accurate configuration leads to accurate aerosol & R_{rs}(NIR) retrievals
several configuration options: fixed values, climatologies, nearby pixels
method available for all past, present, & future ocean color satellites

disadvantages:

no configuration is valid at all times for all water masses
requires local knowledge of changing aerosol & water properties
implementation can be complicated for operational processing

black pixel assumption

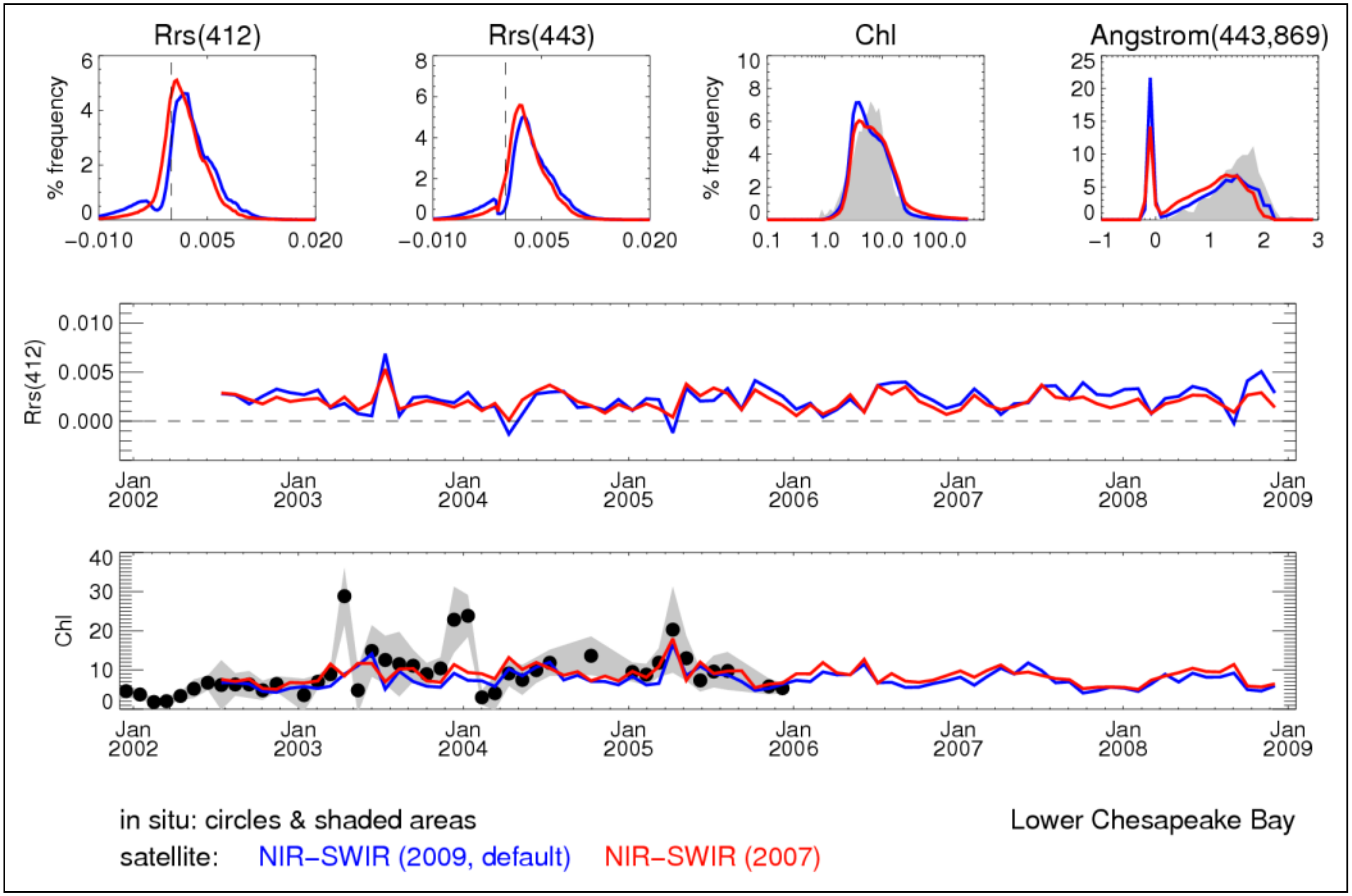
use of SWIR bands only



compare NIR & SWIR retrievals when considering only “turbid pixels”

black pixel assumption

use of NIR + SWIR bands



use SWIR bands in “turbid” water, otherwise use NIR bands

black pixel assumption

advantages:

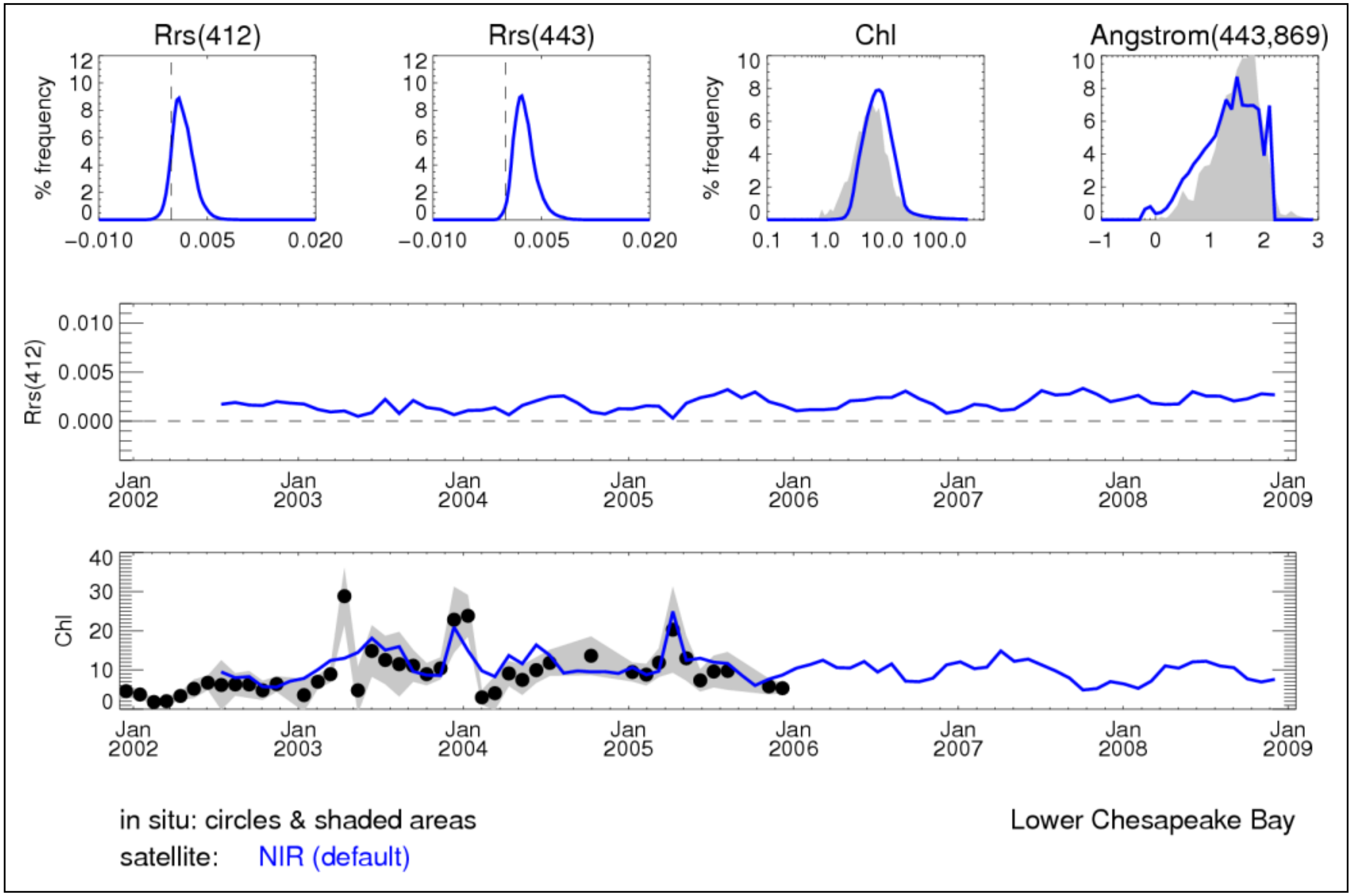
“black pixel” assumption largely satisfied in SWIR region of spectrum
straightforward implementation for operational processing

disadvantages:

only available for instruments with SWIR bands
SWIR bands on MODIS have inadequate signal-to-noise (SNR) ratios
difficult to vicariously calibrate the SWIR bands on MODIS
must define conditions for switching from NIR to SWIR

black pixel assumption

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



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

operational SeaWiFS & MODIS processing ~ 2000-present

black pixel assumption

advantages:

method available for all past, present, & future ocean color missions
straightforward implementation for operational processing

disadvantages:

bio-optical model not valid at all times for all water masses

black pixel assumption – bio-optical model

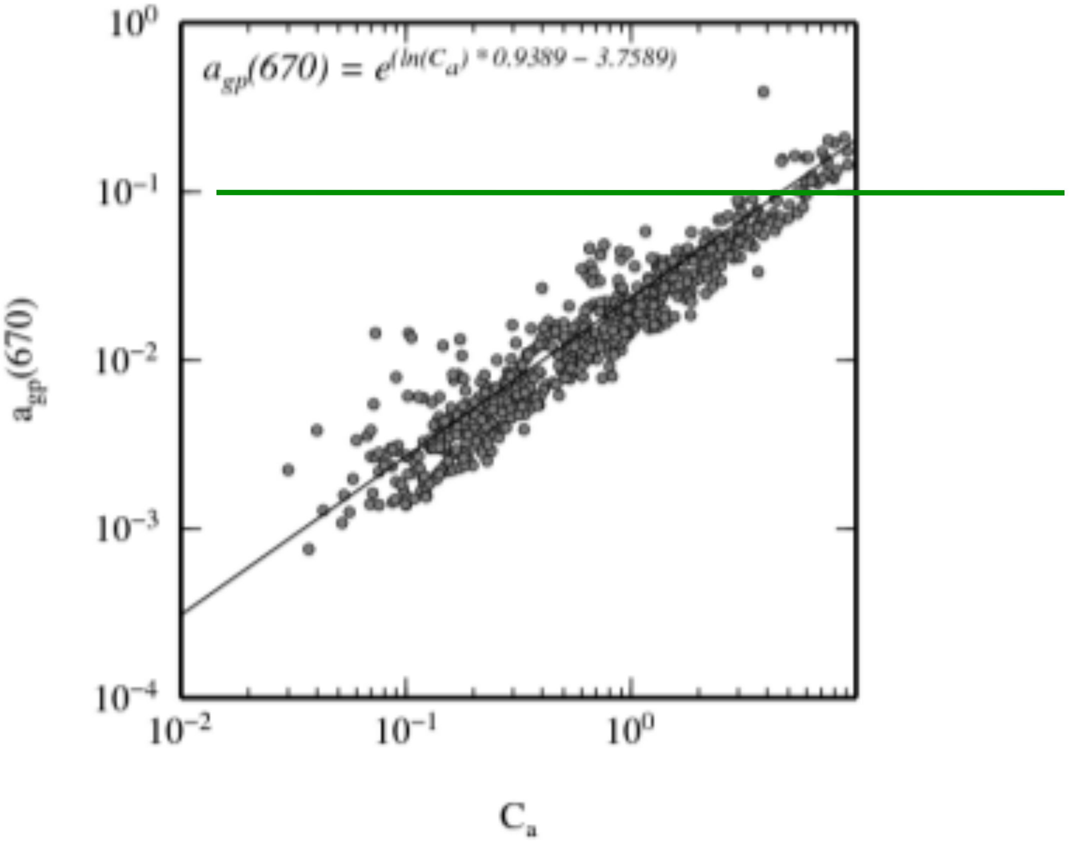
initial $R_{rs}(670)$ measured by satellite (using $R_{rs}(765) = 0$)

Bailey et al., Optics Express, 2010

black pixel assumption – 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 – 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

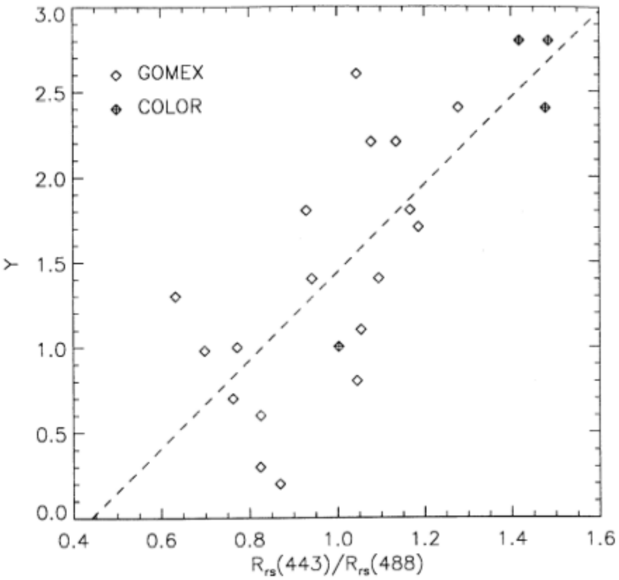
black pixel assumption – bio-optical model

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 – 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 – 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 $b_b(765)$, $a_w(765)$, & $G(765)$

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

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

Bailey et al., Optics
Express, 2010

black pixel assumption – 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

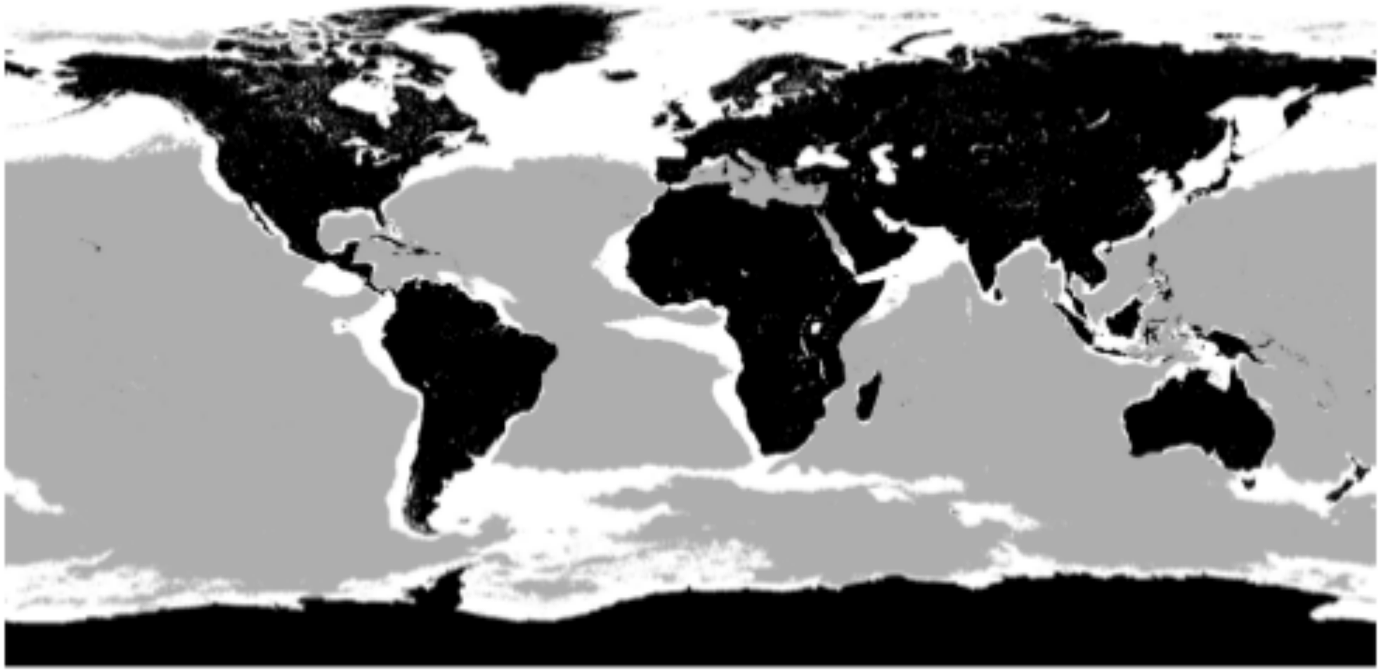
reconstruct $R_{rs}(765)$ using $b_b(765)$, $a_w(765)$, & $G(765)$

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

Bailey et al., Optics Express, 2010

black pixel assumption – 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}

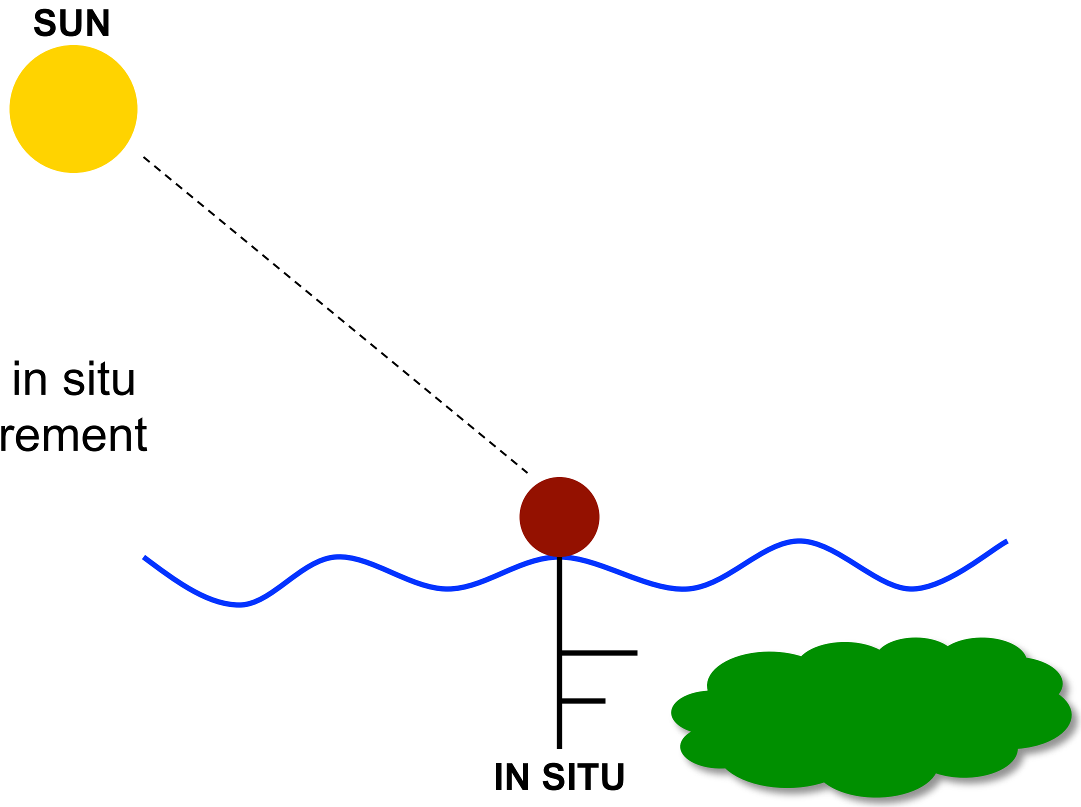
Bailey et al., Optics Express, 2010

bidirectional reflectance correction

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

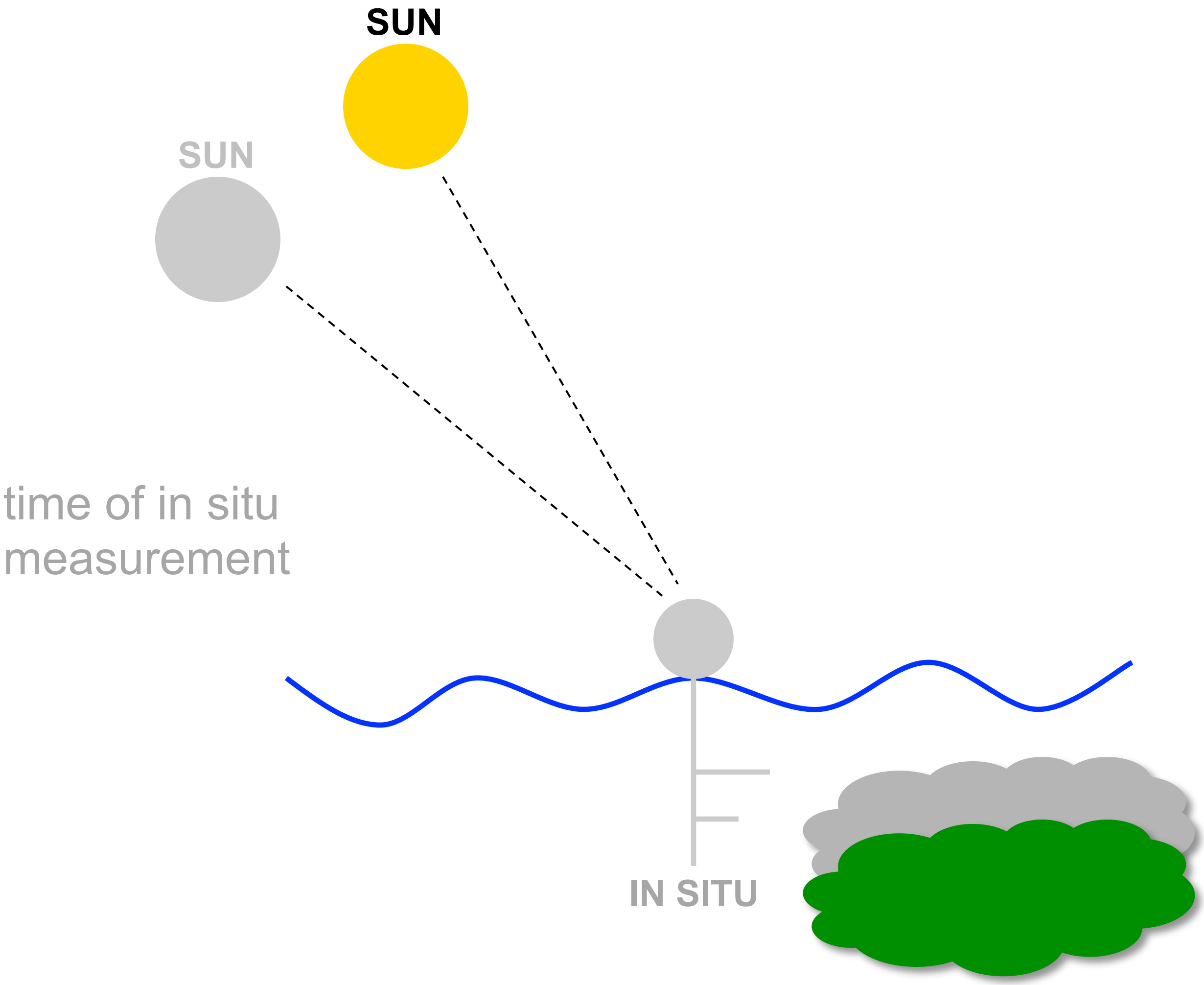
$$R_{rs} = \frac{L_w}{\underset{\checkmark}{F_0}\,\underset{\checkmark}{\cos(\theta_s)}\,\underset{\checkmark}{t_{ds}}\,\underset{\checkmark}{f_s}\,\enclose{circle}{f_b}\,f_\lambda}$$

bidirectional reflectance correction

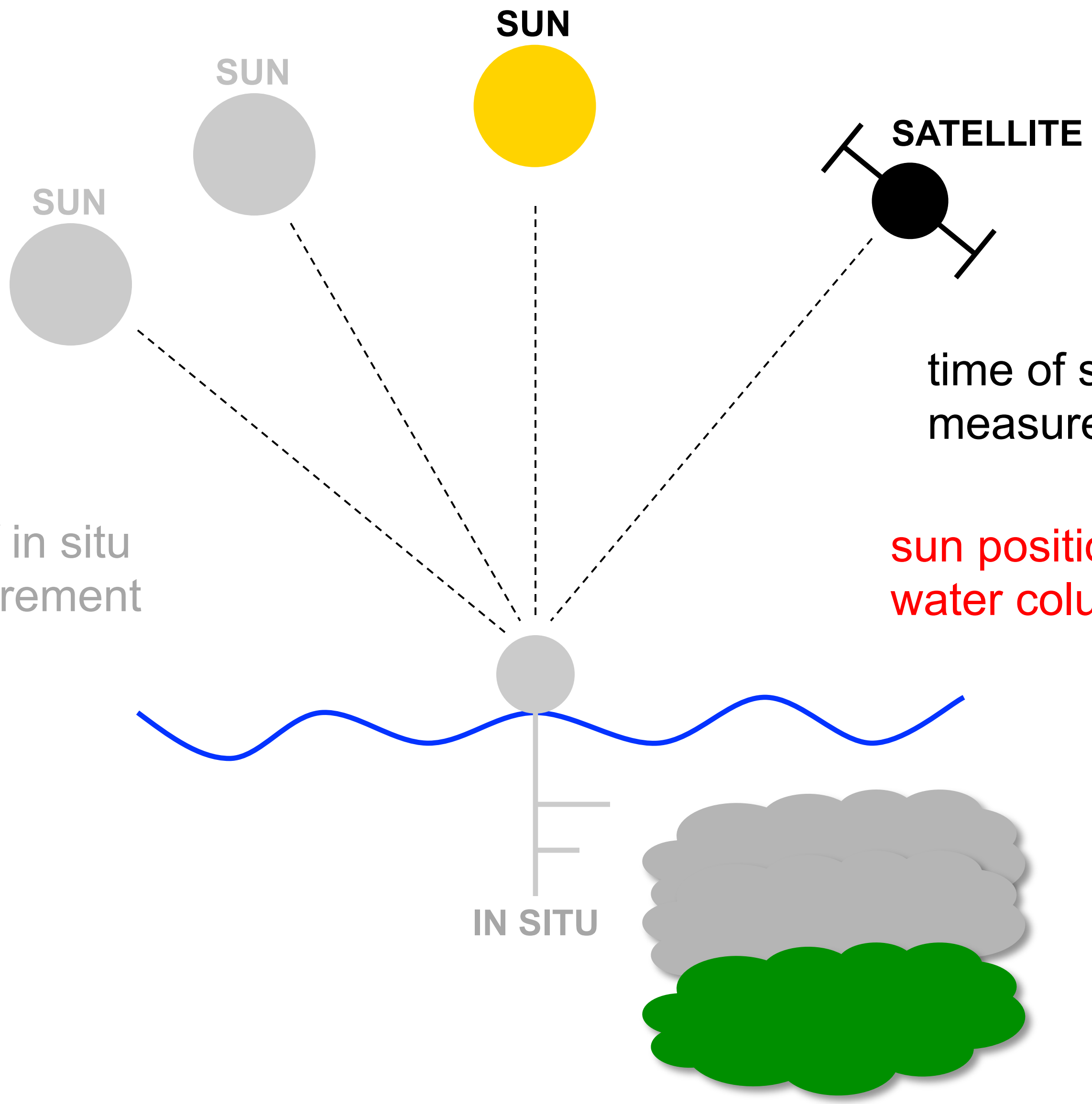


time of in situ
measurement

bidirectional reflectance correction



bidirectional reflectance correction



time of in situ
measurement

time of satellite
measurement

sun position has changed,
water column has changed

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

Morel et al., Applied Optics, 2002

normalize all measurements to condition of overhead Sun

$\Re, \Re_0, F, F_0, Q, Q_0$

from look up tables based on Chl & geometries of Sun & sensor

$$[L_w]_N^{\mathrm{ex}} = [L_w]_N \frac{\Re_0}{\Re(\theta', W)} \frac{f_0(\tau_a, W, \mathrm{IOP})}{Q_0(\tau_a, W, \mathrm{IOP})} \times \left(\frac{f(\theta_s, \tau_a, W, \mathrm{IOP})}{Q(\theta_s, \theta', \phi, \tau_a, W, \mathrm{IOP})} \right)^{-1},$$

bidirectional reflectance correction

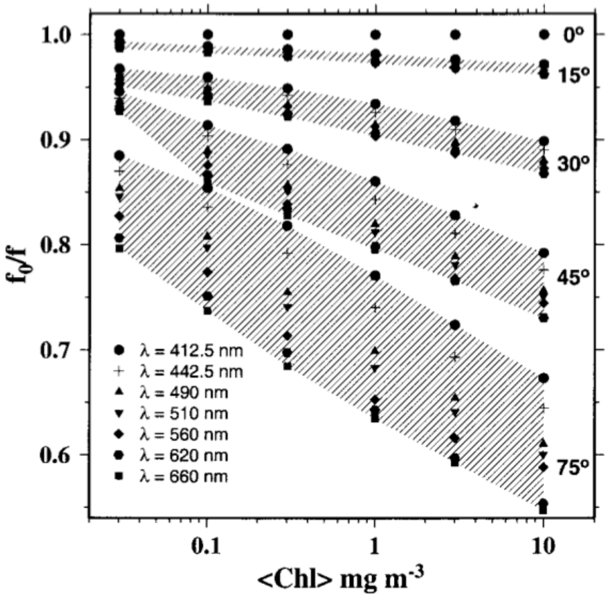


Fig. 13. Evolution of the f_0/f ratio with the Chl and for solar angles as indicated by the shaded areas (the values for $\theta_s = 60°$, which overlap those for 45° and 75°, are not displayed); the symbols are for the various wavelengths.

Morel et al., Applied Optics, 2002

normalize all measurements to condition of overhead Sun

$$\mathfrak{R}, \mathfrak{R}_0, F, F_0, Q, Q_0$$

from look up tables based on Chl & geometries of Sun & sensor

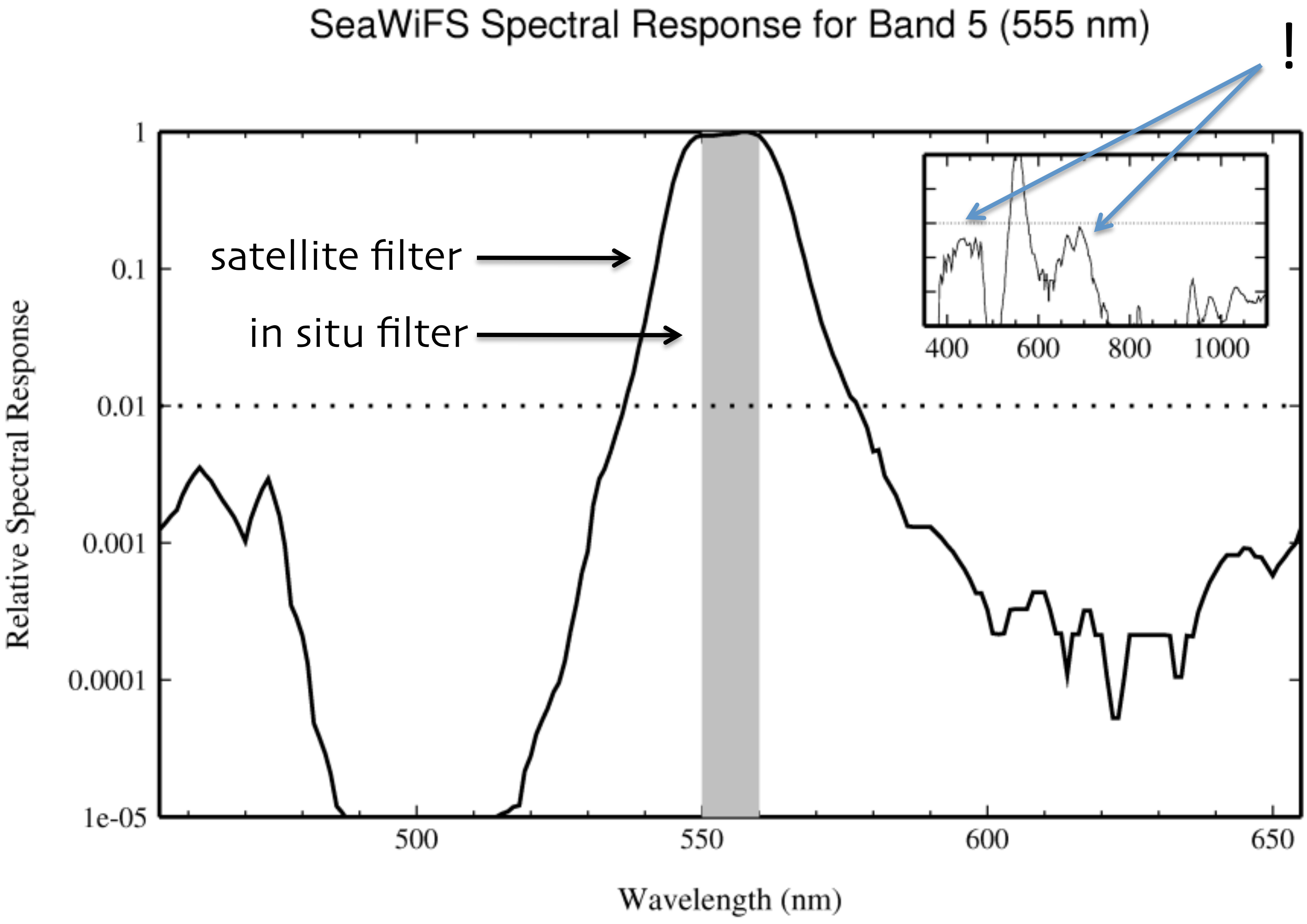
$$[L_w]_N^{\mathrm{ex}} = [L_w]_N \frac{\mathfrak{R}_0}{\mathfrak{R}(\theta', W)} \frac{f_0(\tau_a, W, \mathrm{IOP})}{Q_0(\tau_a, W, \mathrm{IOP})} \times \left(\frac{f(\theta_s, \tau_a, W, \mathrm{IOP})}{Q(\theta_s, \theta', \phi, \tau_a, W, \mathrm{IOP})} \right)^{-1},$$

spectral bandpass correction

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

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

spectral bandpass correction



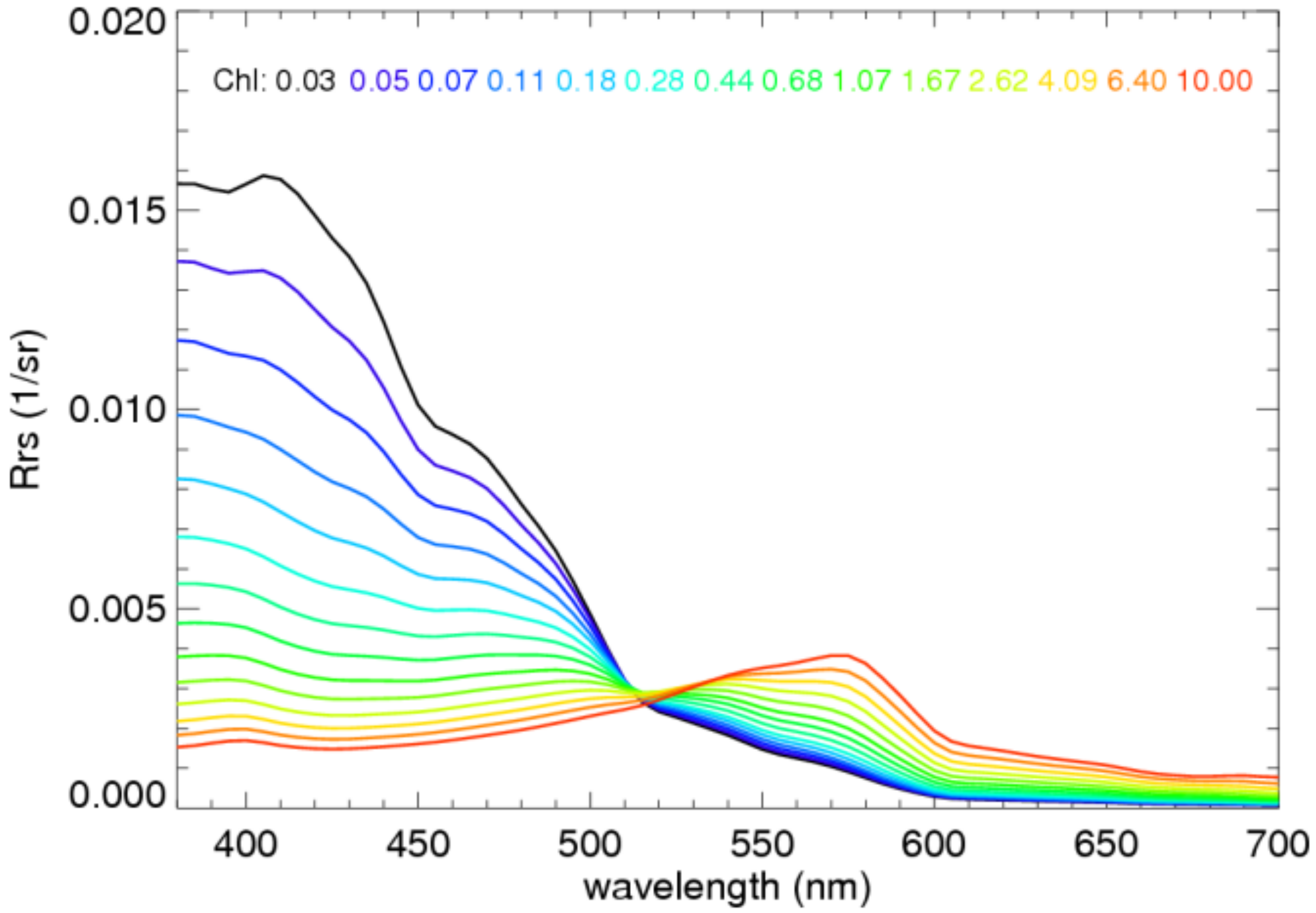
satellite filter

in situ filter

!

spectral bandpass correction

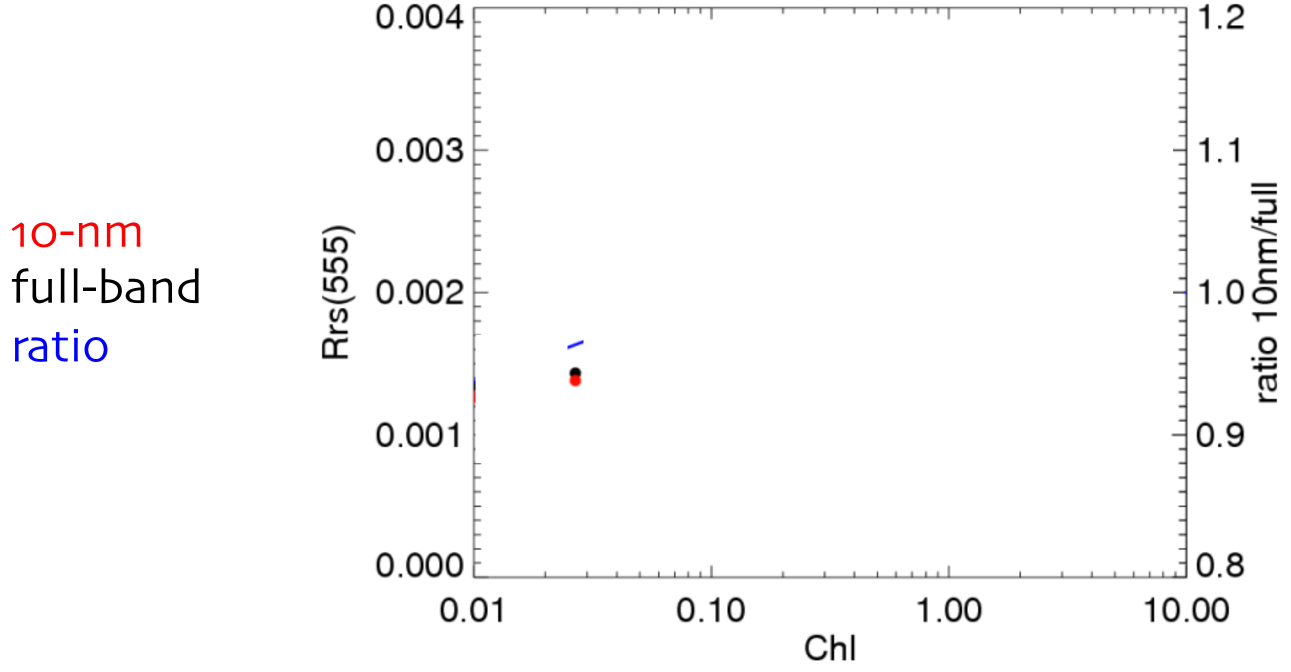
calculate $R_{rs}(\lambda)$ using Morel & Maritorena (2001) for $0.01 < Chl < 3$ mg m^{-3}



spectral bandpass correction

calculate $R_{rs}(\lambda)$ using MM01 for $0.01 < \mathrm{Chl} < 3\ \mathrm{mg\ m^{-3}}$

```
for each satellite band $\lambda_i$:
    for each $Chl_j$:
        calculate 10-nm mean $R_{rs}(\lambda_i, Chl_j)$
        calculate full-spectral-response $R_{rs}(\lambda_i, Chl_j)$
        ratio $r(\lambda_i, Chl_j)$ = 10-nm / full-band
```

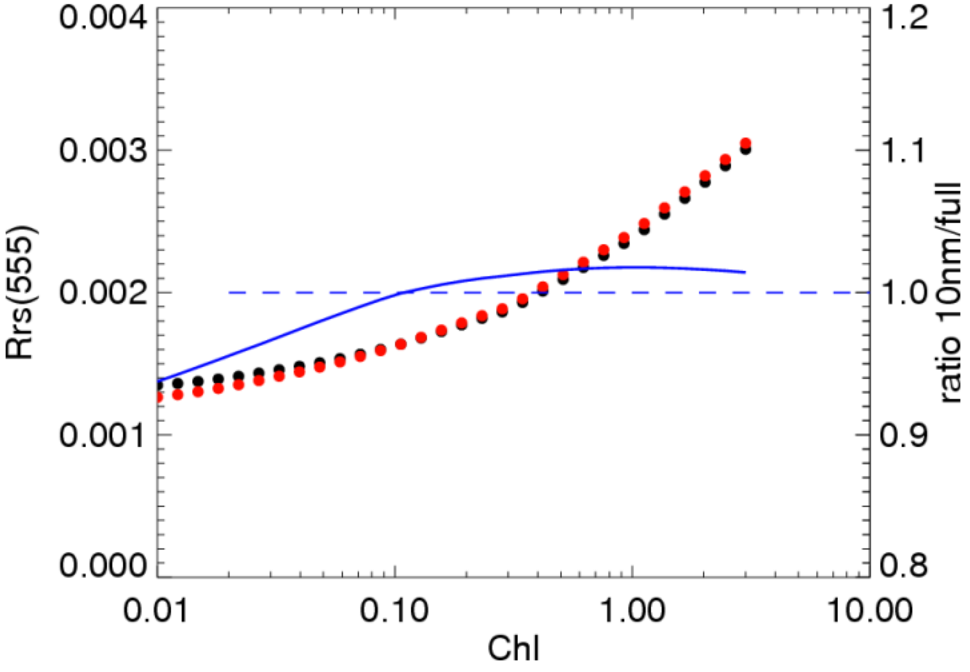


spectral bandpass correction

calculate $R_{rs}(\lambda)$ using MM01 for $0.01 < \mathrm{Chl} < 3$ mg m^{-3}

```
for each satellite band $\lambda_i$:
    for each $Chl_j$:
        calculate 10-nm mean $R_{rs}(\lambda_i, Chl_j)$
        calculate full-spectral-response $R_{rs}(\lambda_i, Chl_j)$
        ratio $r(\lambda_i, Chl_j)$ = 10-nm / full-band
```

10-nm
full-band
ratio



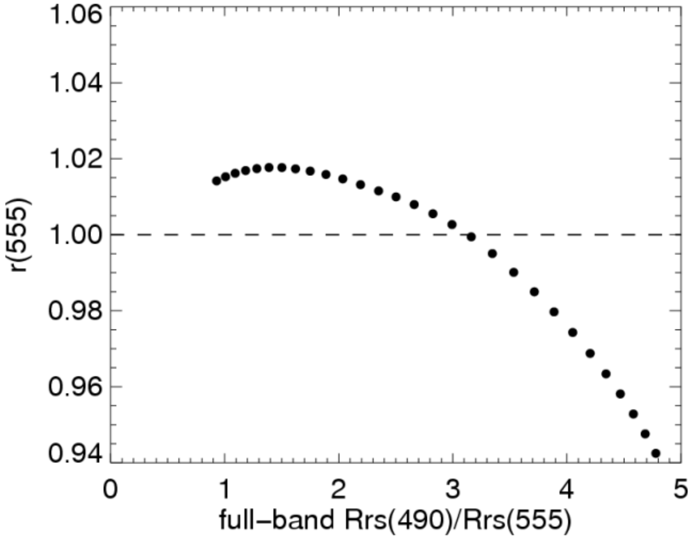
spectral bandpass correction

calculate $R_{rs}(\lambda)$ using MM01 for $0.01 < \mathrm{Chl} < 3$ mg m^{-3}

```
for each satellite band $\lambda_i$:
    for each $\mathrm{Chl}_j$:
        calculate 10-nm mean $R_{rs}(\lambda_i,\mathrm{Chl}_j)$
        calculate full-spectral-response $R_{rs}(\lambda_i,\mathrm{Chl}_j)$
        ratio $r(\lambda_i,\mathrm{Chl}_j)$ = 10-nm / full-band
```

plot / regress ratio vs. full-band $R_{rs}(490)$ / $R_{rs}(555)$

derive polynomial expression to estimate ratio from full-band ratio



spectral bandpass correction

calculate $R_{rs}(\lambda)$ using MM01 for $0.01 < \text{Chl} < 3$ mg m^{-3}

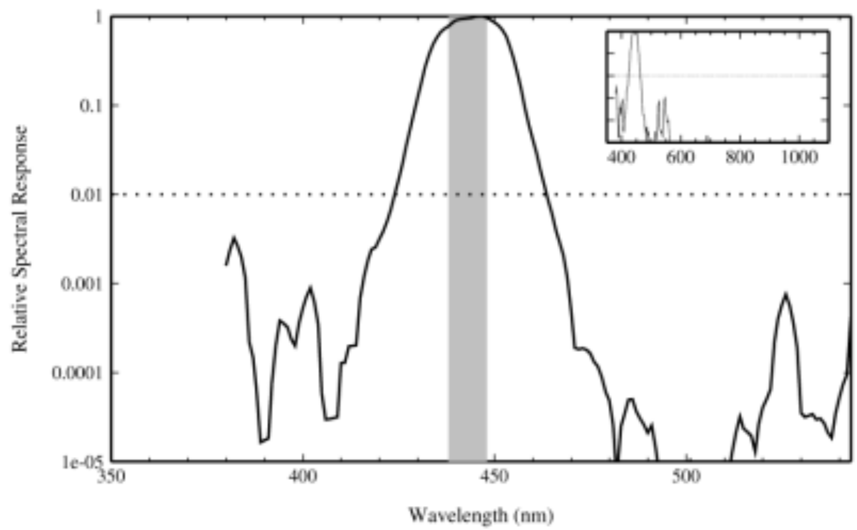
```
for each satellite band $\lambda_i$:
    for each $Chl_j$:
        calculate 10-nm mean $R_{rs}(\lambda_i, Chl_j)$
        calculate full-spectral-response $R_{rs}(\lambda_i, Chl_j)$
        ratio $r(\lambda_i, Chl_j)$ = 10-nm / full-band
```

plot / regress ratio vs. full-band $R_{rs}(490) / R_{rs}(555)$
derive polynomial expression to estimate ratio from full-band ratio

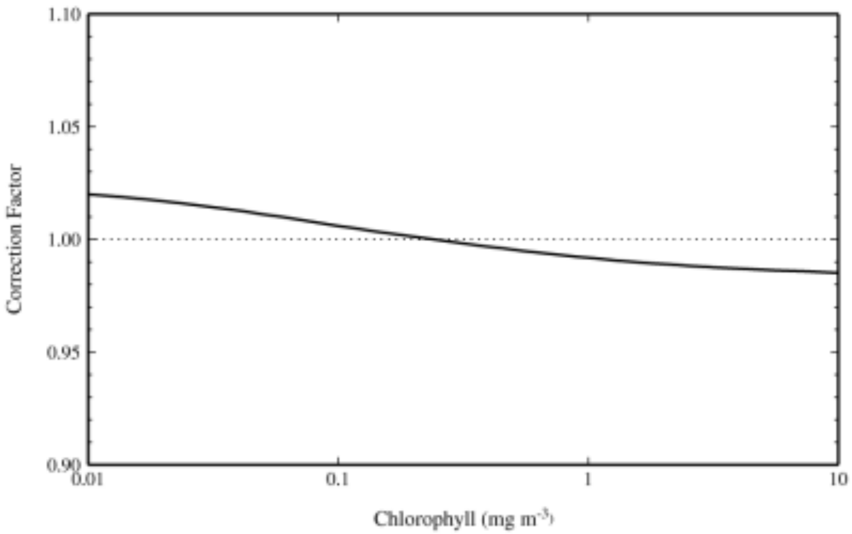
to “adjust” satellite full-band to 10-nm, apply correction factors
$Rrs(\lambda_i, 10\text{-nm}) = r(\lambda_i) * Rrs(\lambda_i, \text{full-band})$

spectral bandpass correction

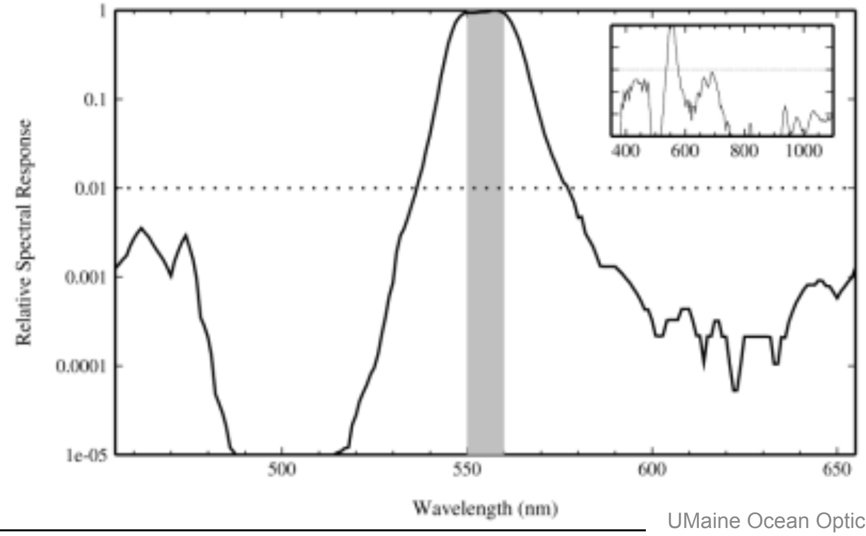
SeaWiFS Spectral Response for Band 2 (443 nm)



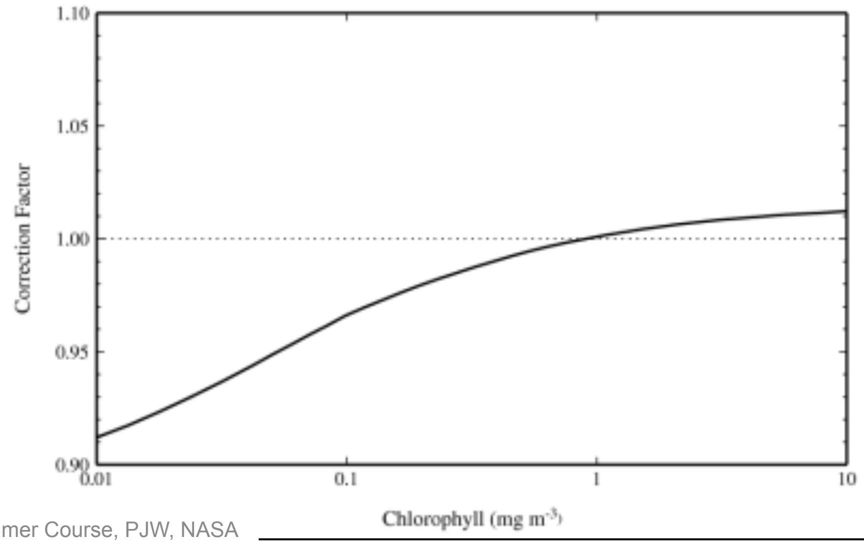
SeaWiFS Out-of-Band Correction for Band 2 (443 nm)



SeaWiFS Spectral Response for Band 5 (555 nm)



SeaWiFS Out-of-Band Correction for Band 5 (555 nm)



spectral bandpass correction

why do we care?

satellite R_{rs} adjusted using a bio-optical model

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

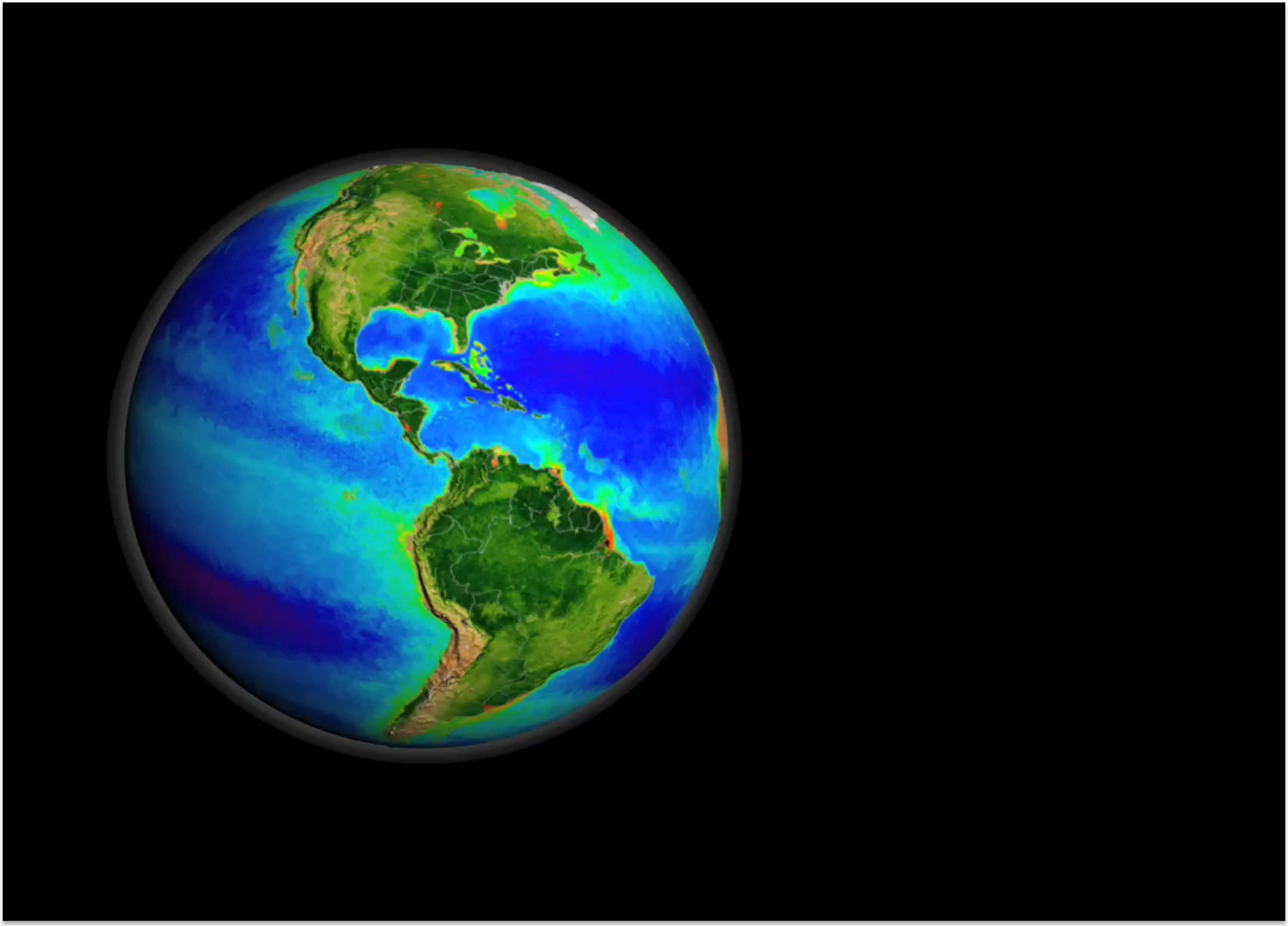
when using multispectral in situ radiometers:
enable the bandpass adjustment

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}

so there you have it – perfect R_{rs}

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

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



scorecard – ancillary data requirements

ancillary data	ancillary source	uses
atmospheric pressure	NCEP	Rayleigh
water vapor	NCEP	transmittance
relative humidity	NCEP	aerosol models
wind speed	NCEP	white caps, Sun glint, Rayleigh
ozone	OMI/TOMS	transmittance
NO_2	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 …