Atmospheric correction of ocean color images

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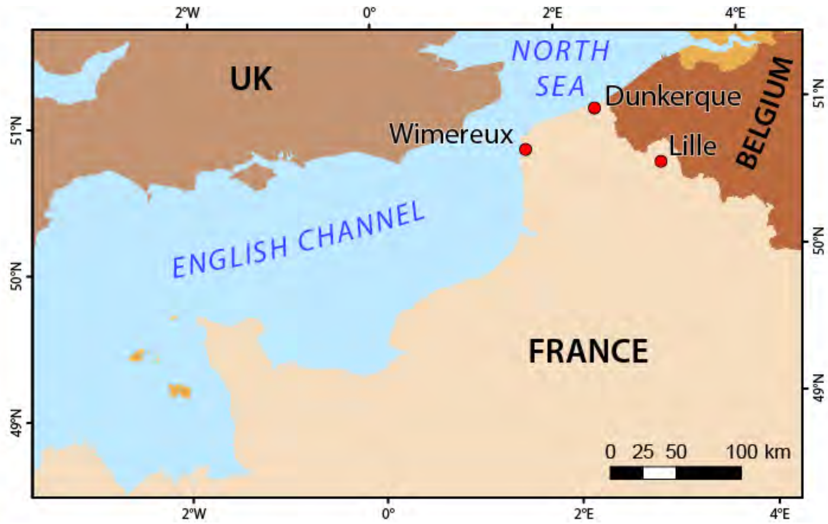
About me

- PhD « Atmospheric correction of SeaWiFS images »: jan. 2004
- Associate professor since sept. 2006 at the Université du Littoral-Côte d'Opale and the Laboratory of Oceanology and Geosciences
- Chairman of an IOCCG WG on Evaluation of atmospheric correction algorithms over optically-complex waters
- Evaluation and improvements of atmospheric correction over optically-complex waters
- Retrieval of ocean color parameters using optimization and neural networks algorithms
- Lidar for ocean color



Basic principles

How to interpret ocean color images?

The surface ocean color is regulated by the optical properties of the pure water and of those of the different particulate and dissolved matters that are in the surface layer

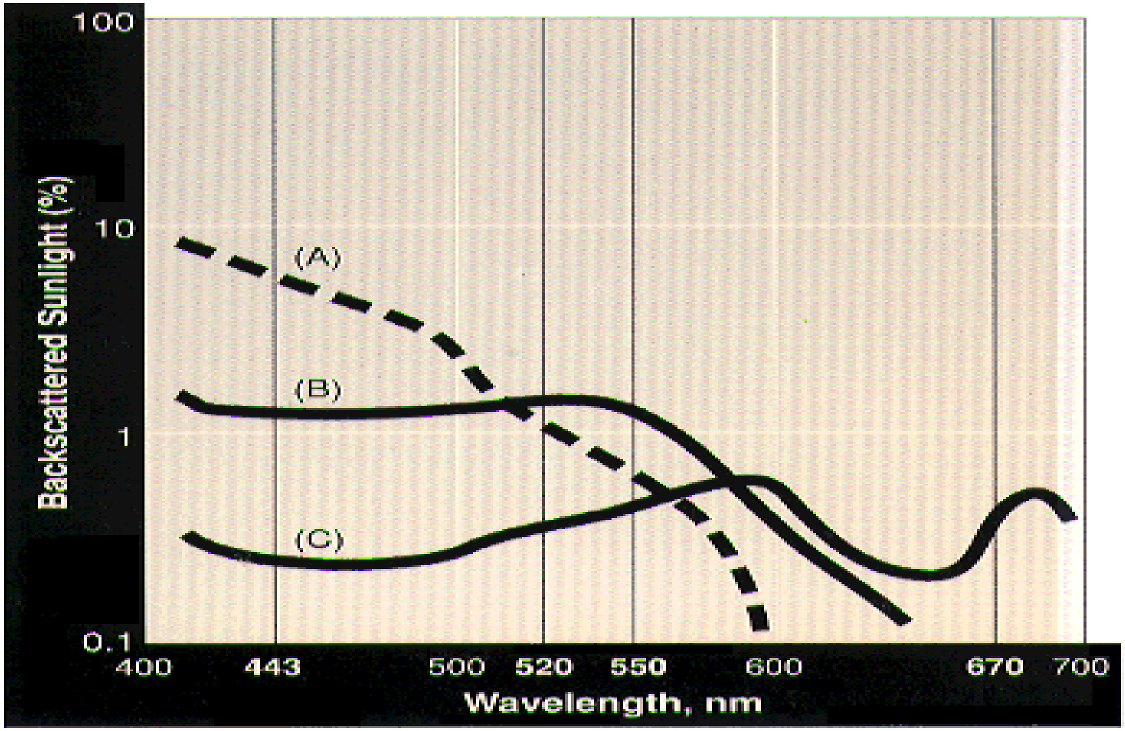
Basic principles

→ The most clearest seawaters absorb the red light and transmit and scatter the light at the shortest wavelengths (blue waters)

→ Phytoplancton contains pigments such as chlorophyll (and other accessories pigments) that absorb at other wavelengths and that contribute to the green color of the oceans

→In the coastal waters, the inorganic suspended matter backscatters the light contributing to the green, yellow and brown of the ocean color

Basic principles



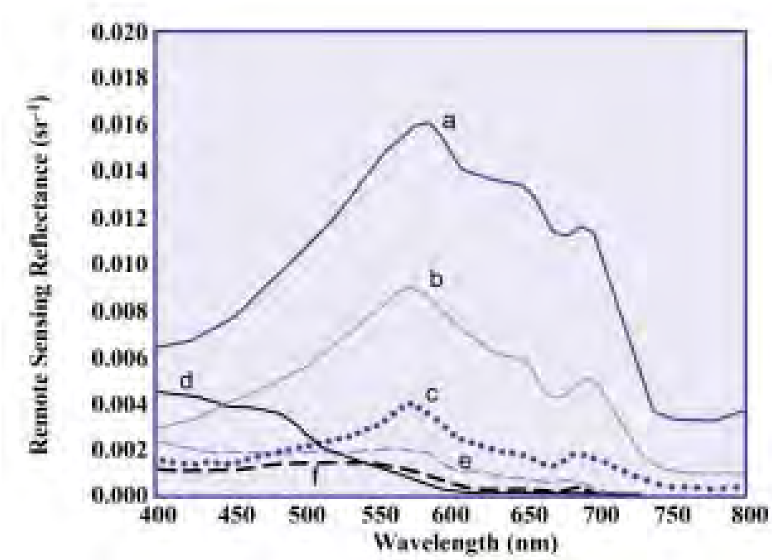
As a consequence, the color (pure water included), can be measured on the basis of the visible spectrum emitted by the ocean surface

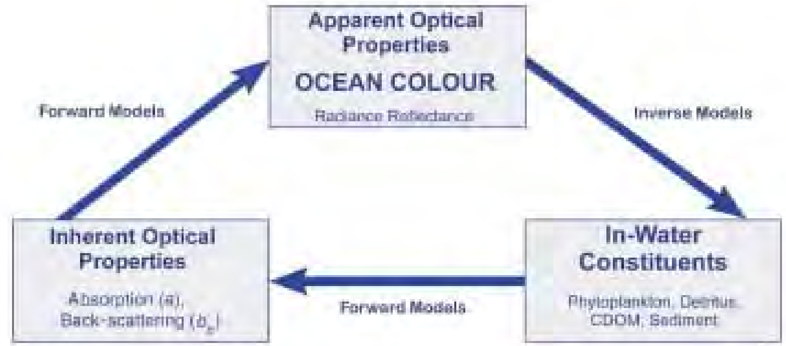
The "clear" ocean (A) has a max in blue and values close to zero in yellow and red

More phytoplankton is present in the water, more the contribution toward the green is important (B).

In the coastal waters, with high concentrations of organic detritus and inorganic particles, the maximum shifts to the red (C).

Basic principles





The surface reflectance, Rrs(λ), (called Remote-Sensing reflectance) is a function of the back-scattering and absorption coefficients of the different optically active components of seawater:

R(λ) = G • b(λ) / a(λ)

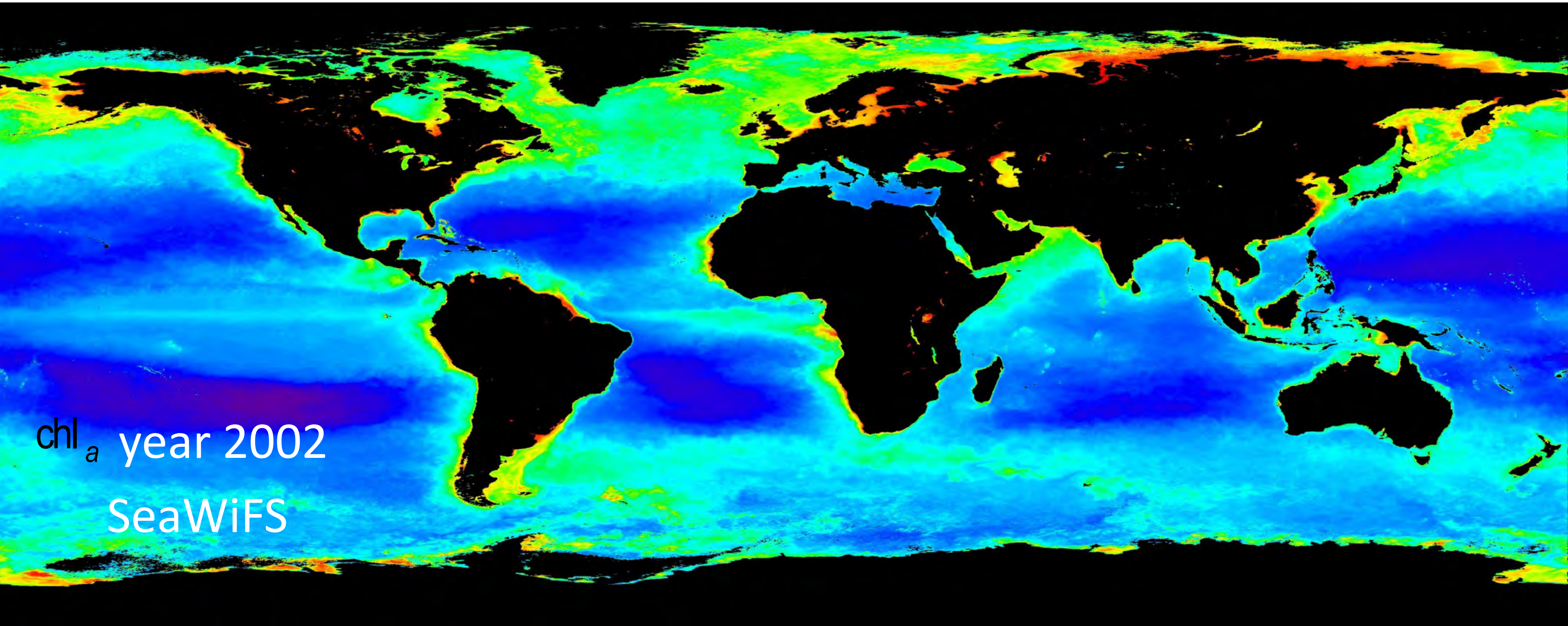
with G, a parameter that depends of the incident illumination

→ **The remote-sensing reflectance is not the final product but the accuracy of its estimation impacts the quality of the ocean color products**

→ Need for developing inversion models of $\mathbf{R_{rs}}$ for obtaining parameters of interest

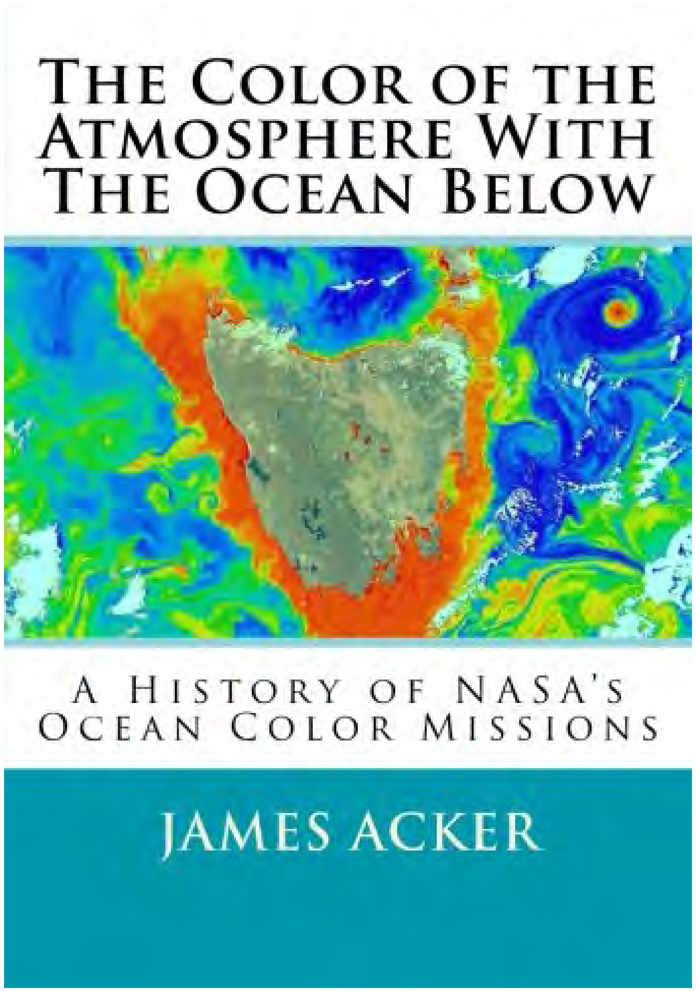
Ocean sensor remote sensors

The remote sensors on-board satellite called "ocean color" are the only tools that measure these parameters over several years and synoptically

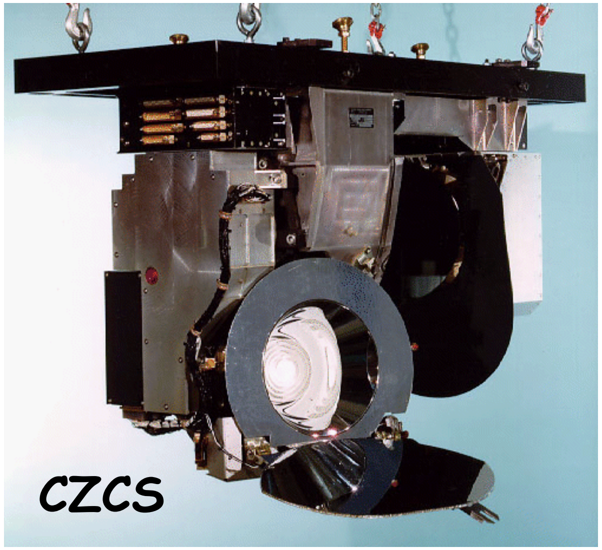


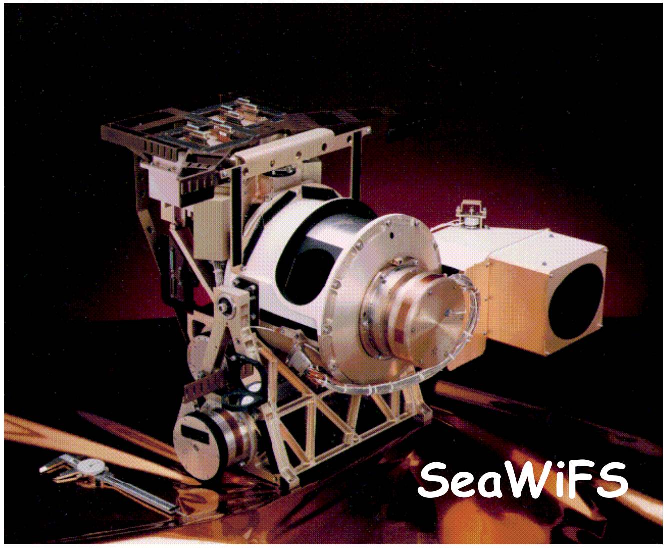
History of atmospheric correction

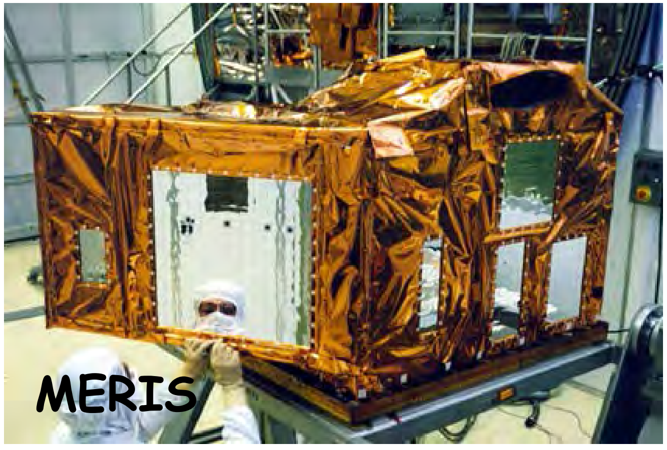
- Color photographs obtained by spacecraft
- Clarke et al. (1970): measurements of radiance spectra from aircraft → Detection of chl-a + atmos. effects
- Gordon (1978; 1980): single-scattering AC for CZCS
- Gordon and Wang (1994): mutiple-scattering AC for SeaWiFS
- Coastal waters + absorbing aerosols

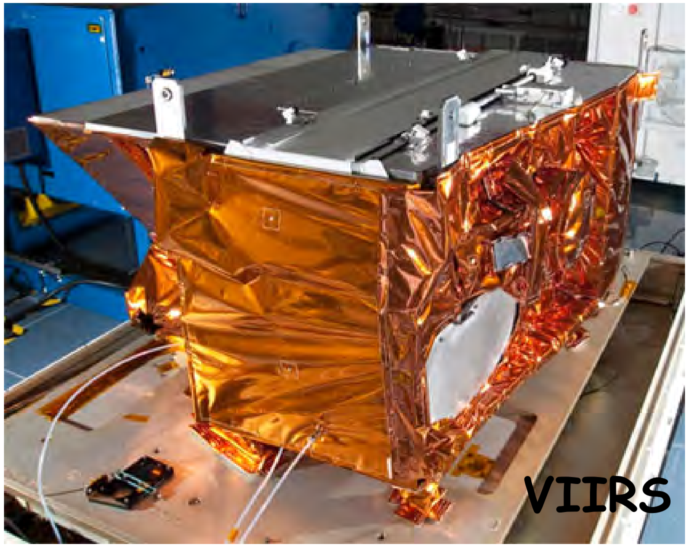


Ocean color remote sensors



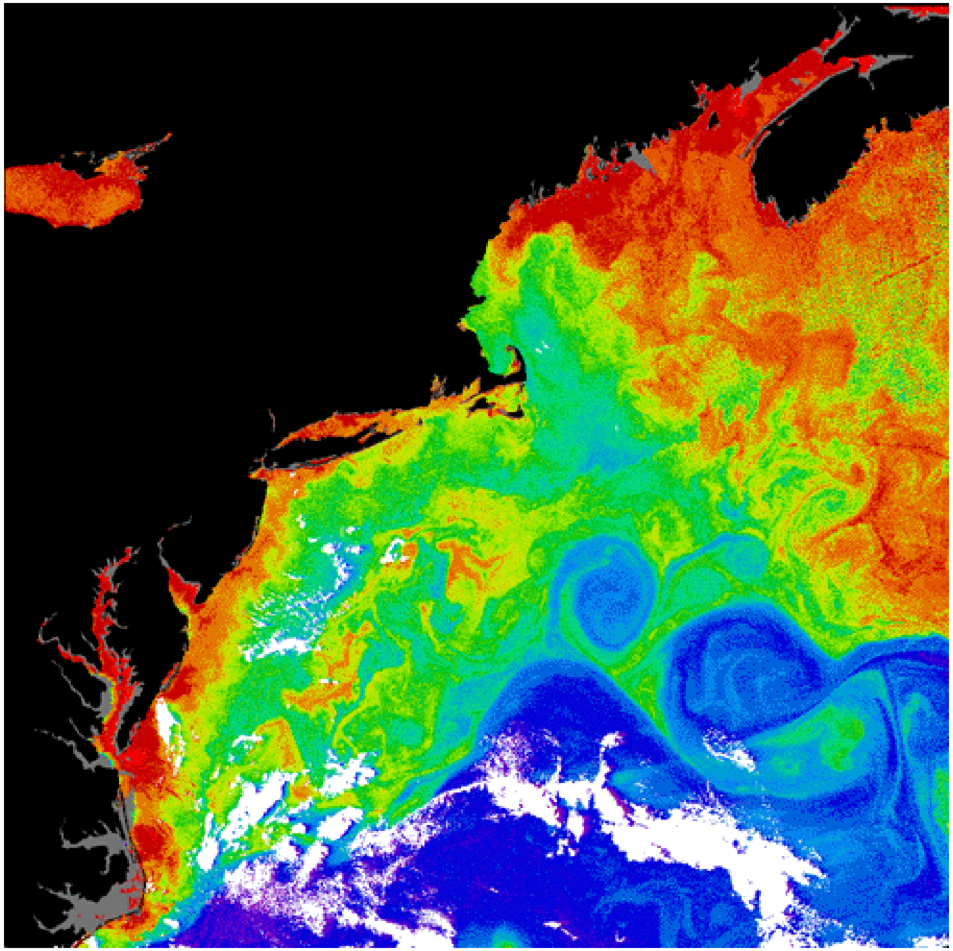




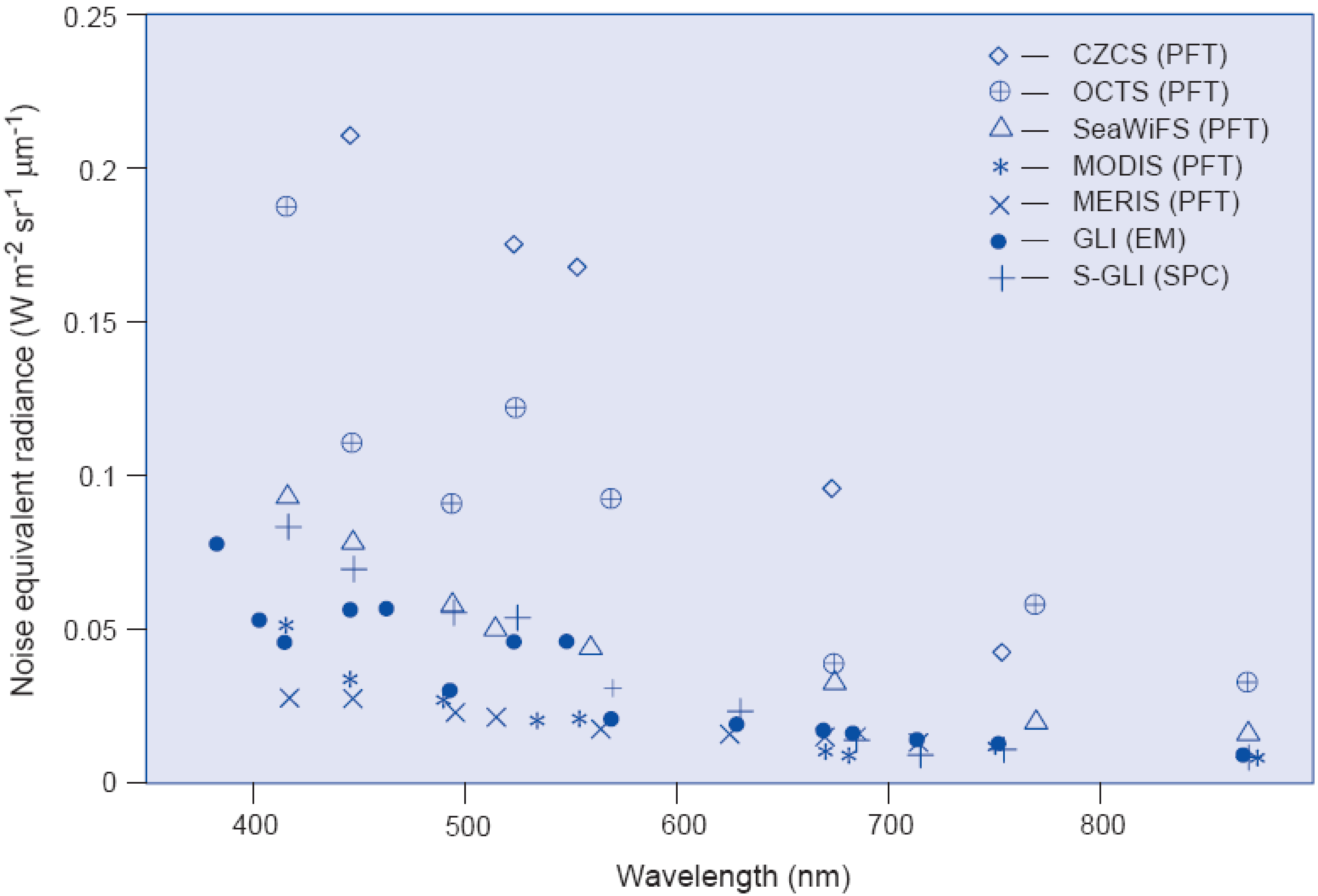


Ocean color remote sensors

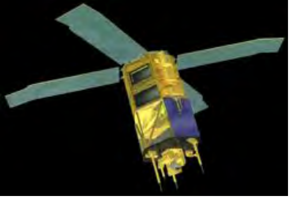
- <u>First sensor:</u>
  CZCS (1978-1986)
- <u>Successors:</u>
  PolDER 1 (1996-1997)
  PolDER 2 (2003)
  SeaWiFS (1997-2010)
- <u>Followers:</u>
  MODIS (2002-)
  MERIS (2002-2012)
- <u>New generation</u>
  GOCI (2010-)
  VIIRS (2011-)
  OLCI (2016-)



http://ioccg.org/sensors_ioccg.html



0.25
0.2
0.15
0.1
0.05
0
400
500
600
700
800
Wavelength (nm)
Noise equivalent radiance (W m^{-2} sr^{-1} μm^{-1})
CZCS (PFT)
OCTS (PFT)
SeaWiFS (PFT)
MODIS (PFT)
MERIS (PFT)
GLI (EM)
S-GLI (SPC)

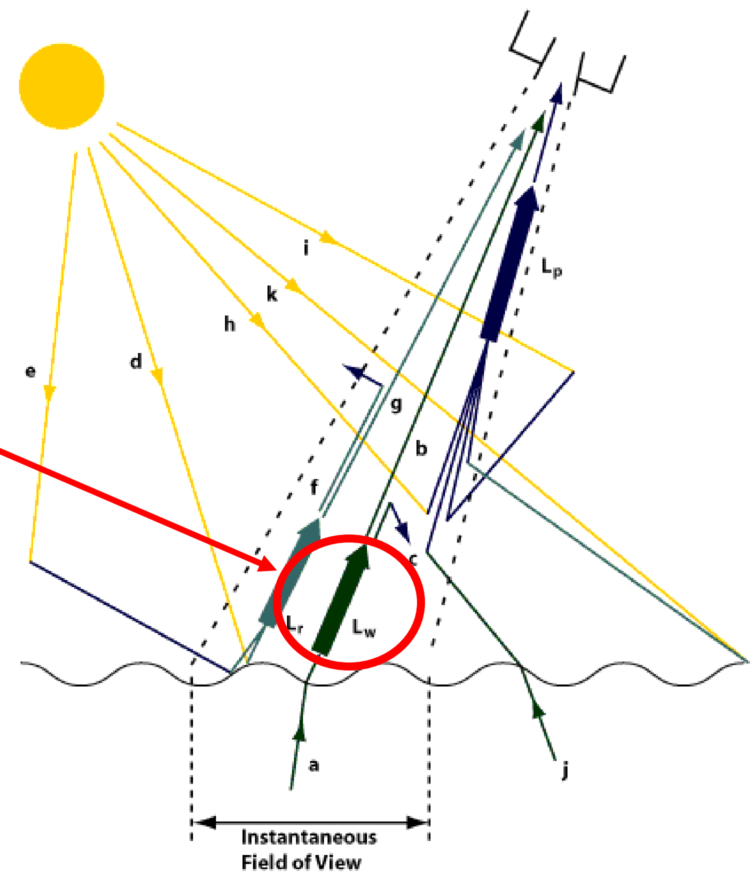


Ocean Color Radiometry (OCR)

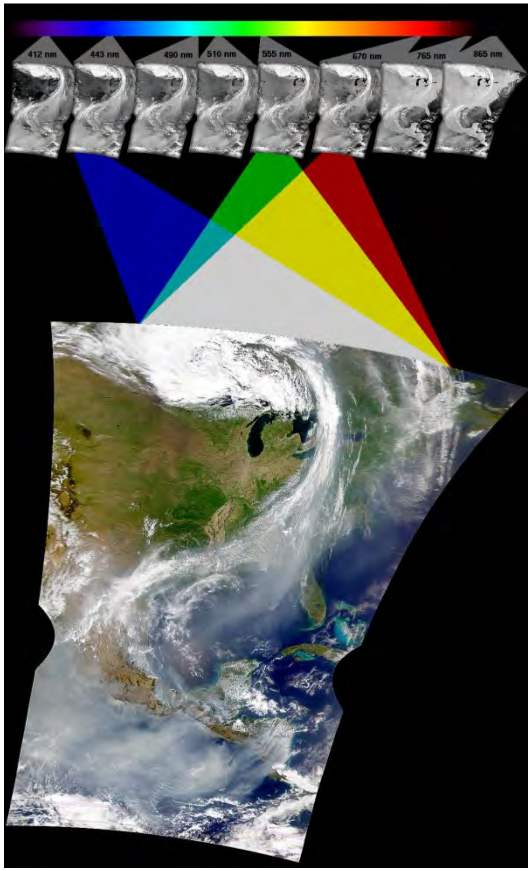
Goal: To provide quantitative data of bio-optical properties of the global ocean (IOPs, Chl, POC, CDM, species, …)

How: Remote sensing of the water leaving radiance, L_w, in the visible part of the spectrum

Main issue:
Atmospheric correction



From satellite to biogeochemical parameters… A challenging task



http://oceancolor.gsfc.nasa.gov/

$\rho_t(\lambda)$= top of atmosphere reflectance

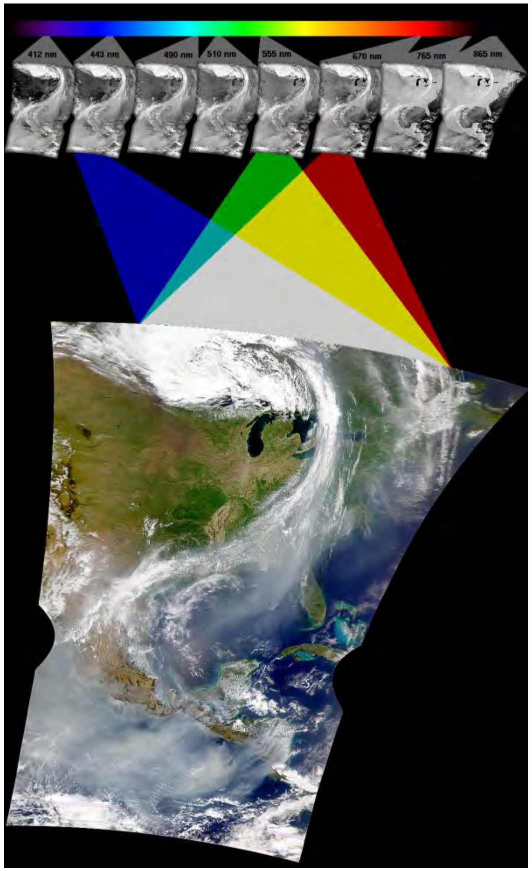
$\rho_w(\lambda)$= water-leaving reflectance (ocean color)

Biogeochemical parameters

http://kalicotier.gis-cooc.org/

From satellite to biogeochemical parameters… A challenging task

$\rho_w(\lambda)$= water-leaving reflectance (ocean color)



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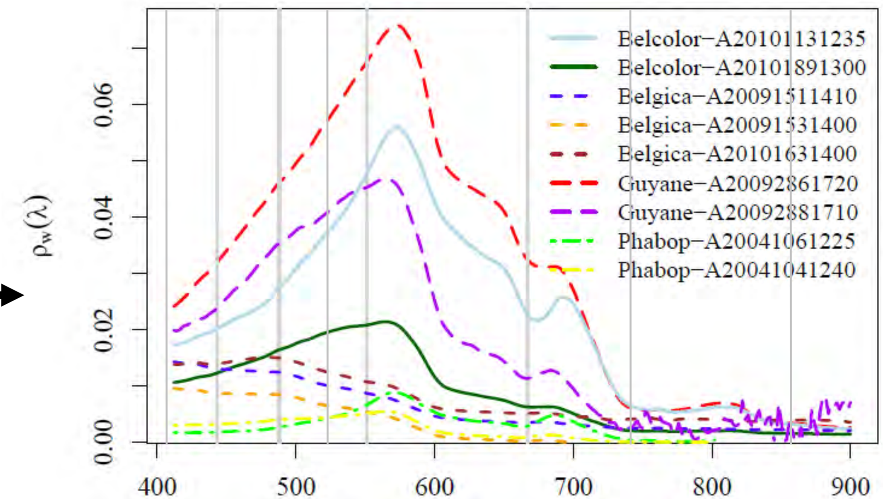

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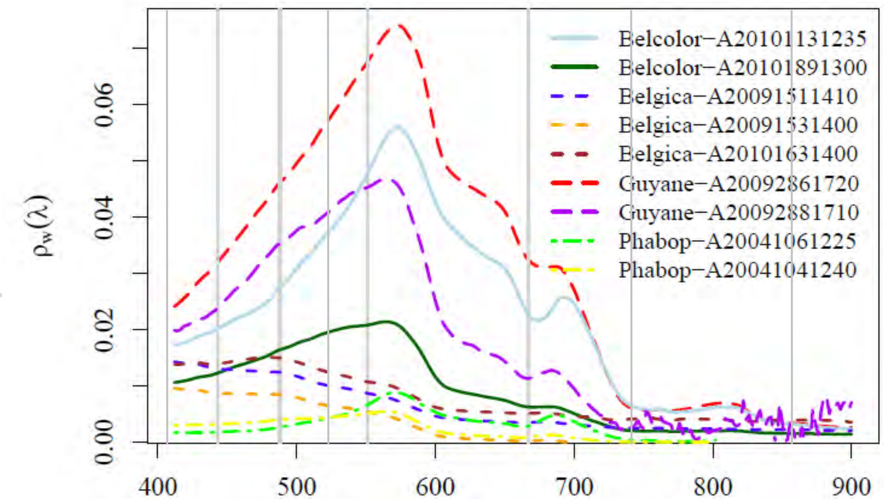
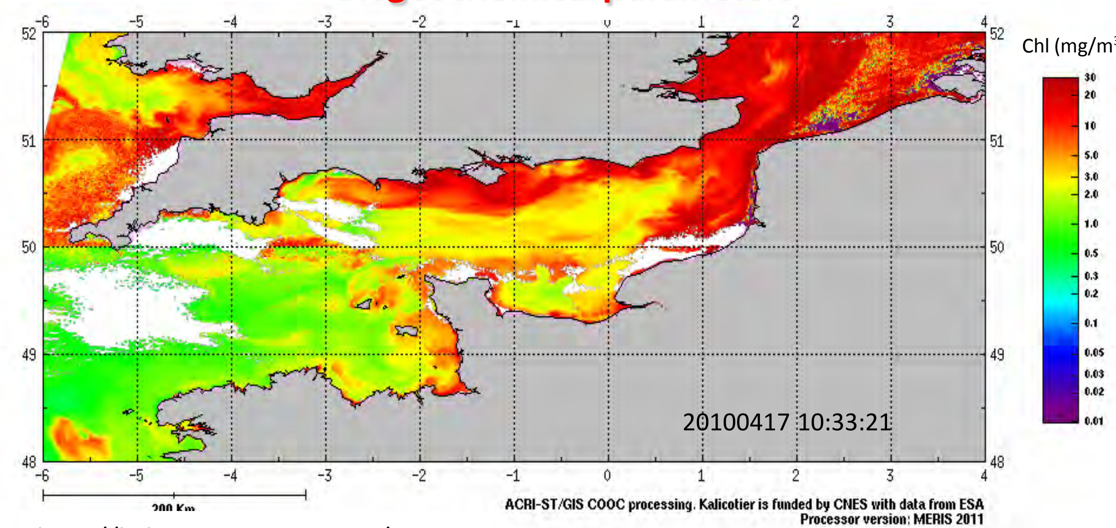


Biogeochemical parameters



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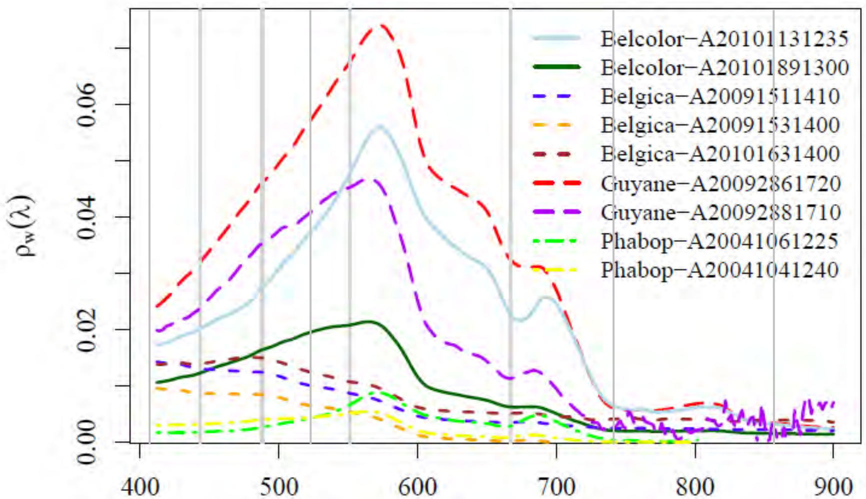
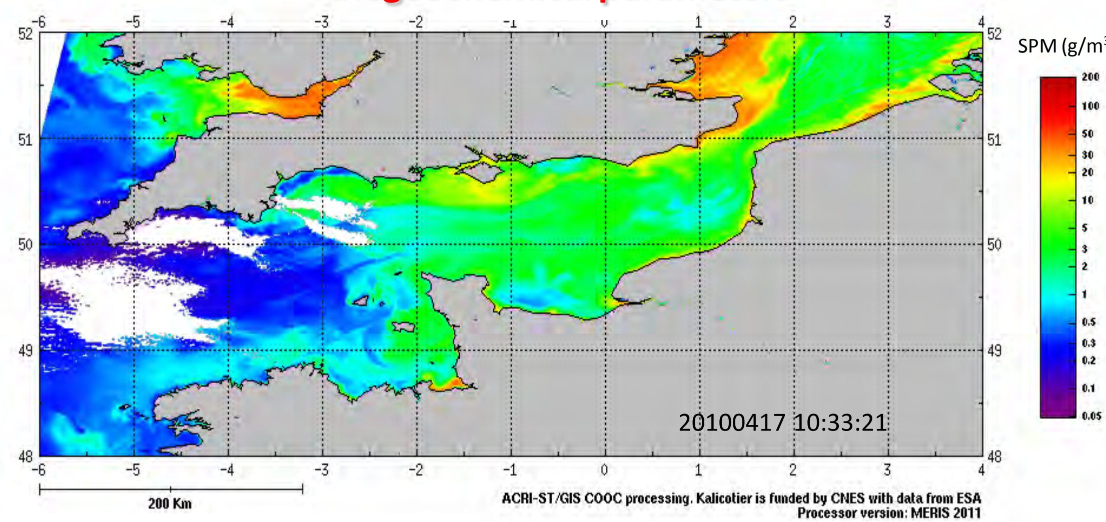


Biogeochemical parameters



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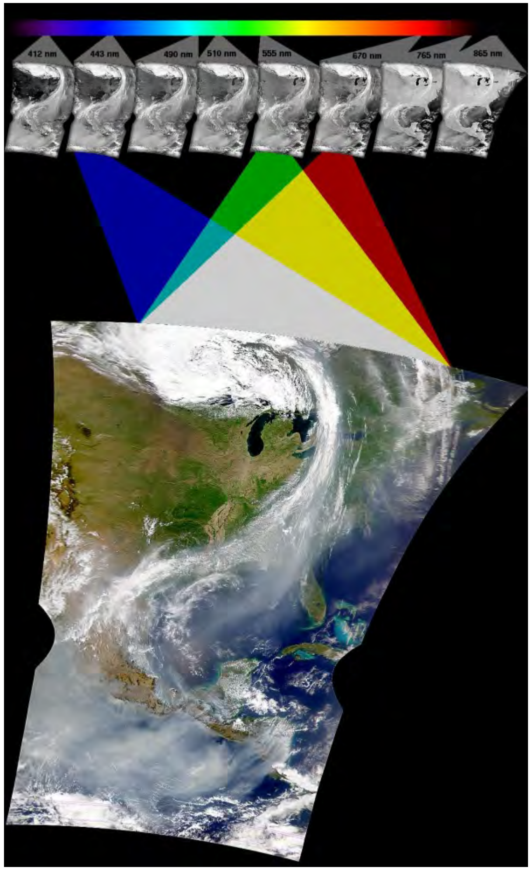

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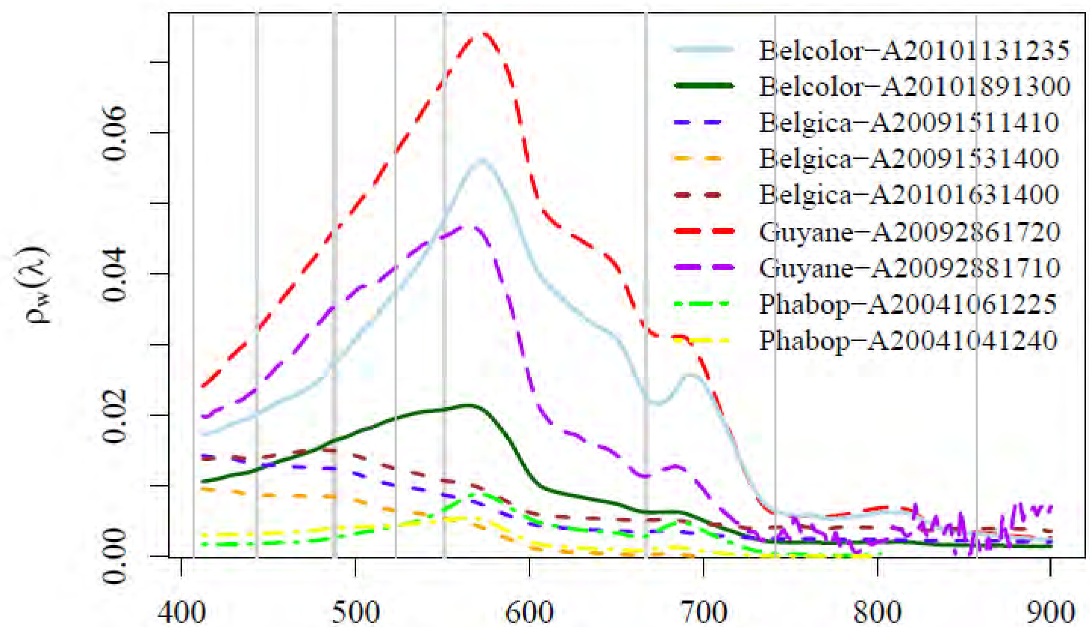

Biogeochemical parameters

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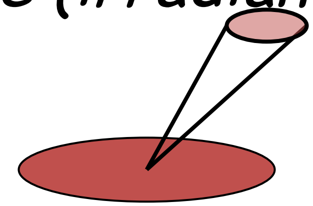
Basics of radiometry for remote sensing

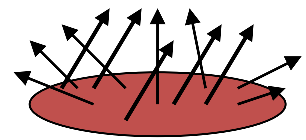
The studied target can either emitt a radiation (radiance or emittance) or be illuminated by a source (irradiance)

Radiance ($Wm^{-2}sr^{-1}$): $L(\theta,\theta_0,\Delta\phi,\lambda)$



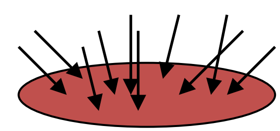
Emittance (Wm^{-2}): $M(\lambda)$

$$M=\int_{half\ space} L\cos\theta d\Omega$$



Downwelling Irradiance (Wm^{-2}): $E_d(\lambda)$

$$E_d(\theta_0,\lambda)=\int_{\Xi d} L(\theta_0,\theta,\Delta\phi)\cos\theta d\Omega$$



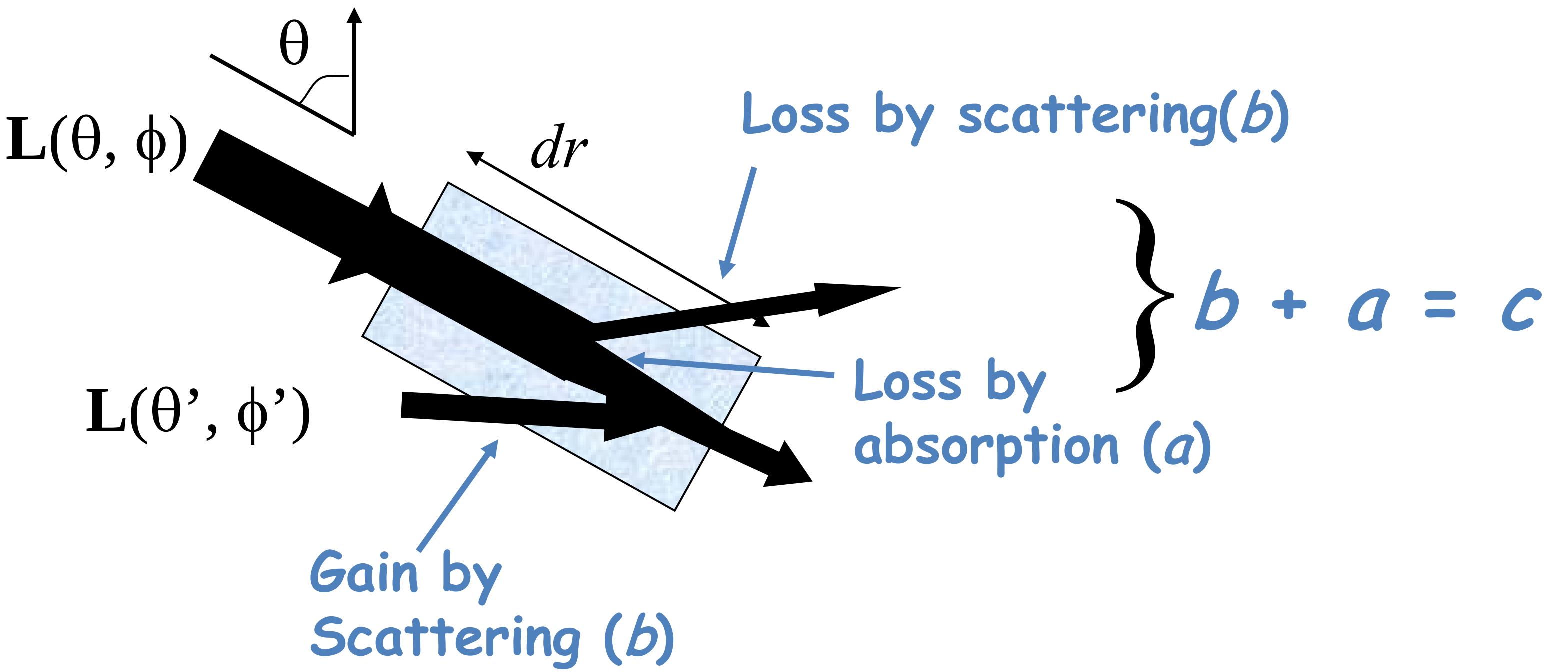
Remote sensing reflectance (sr^{-1}): $R_{rs} = L_w/E_d$ (RLw)

Radiance-to-reflectance: $\rho = \dfrac{\pi . L}{F_0 . \mu_v}$

Normalized $\rho_w = \pi . Rrs$

Radiative Transfer Equation (RTE)

$$\frac{dL(\theta,\phi)}{dr} = -cL(\theta,\phi) + 2\pi \int_0^{4\pi} \beta(\theta,\phi,\theta',\phi') L\, d\omega' + S$$



Analysis of ocean color images (1)

- Estimation of the chlorophyll-a concentration

→ estimation of the quantity of light that leaving the seawater $\rho_w (L_w, R_{rs}, nL_w n\rho_w)$

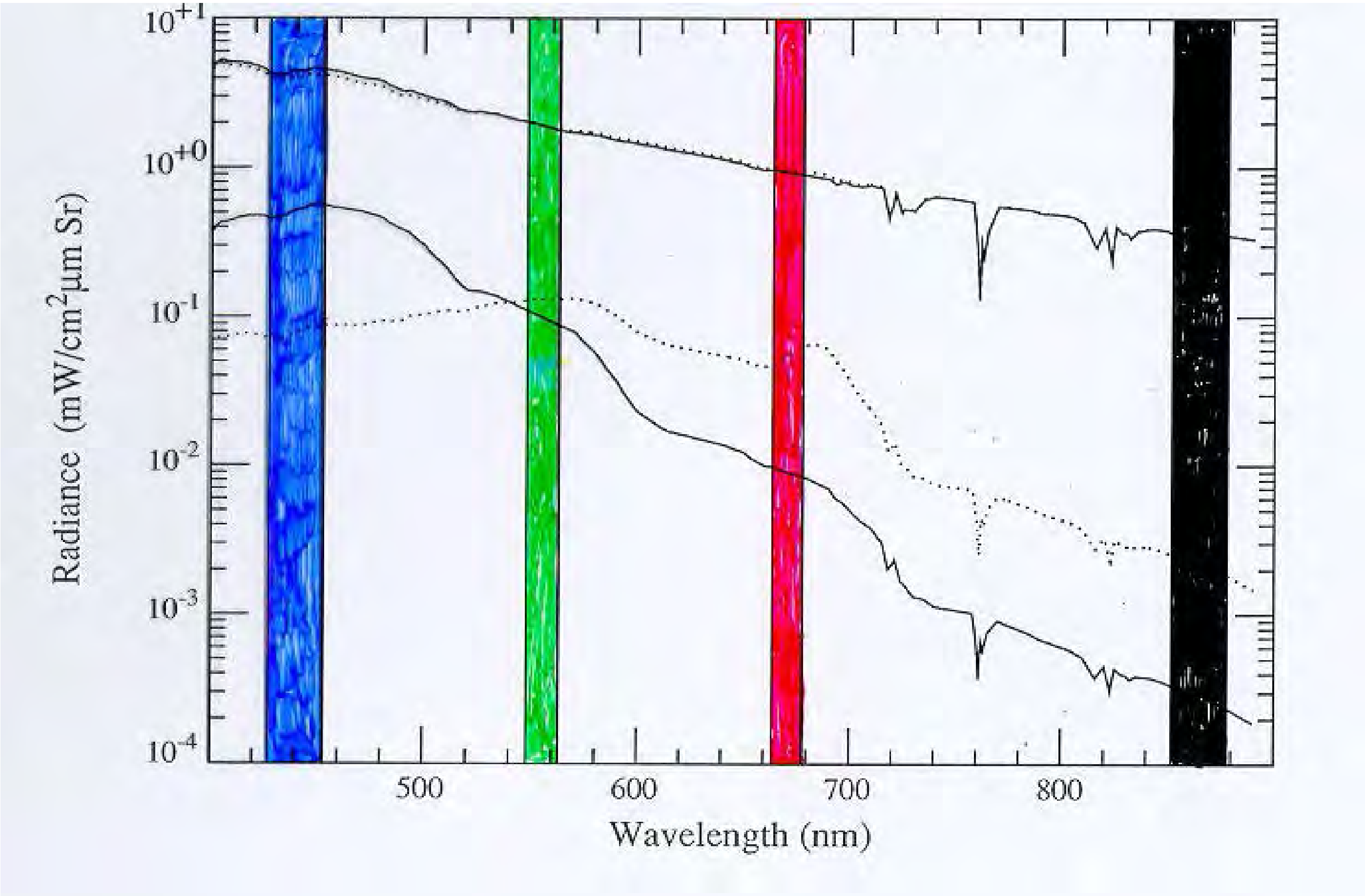
➡ ***When the chlorophyll-a concentration increases, there is less light in the blue and more in the green wavelenghts***

- Estimation of the quantity of light that leaving the seawater → Estimation of the contribution of impact of aérosols ρ_A

➡ ***It's the step called « Atmospheric Correction »***

Analysis of ocean color images(2)

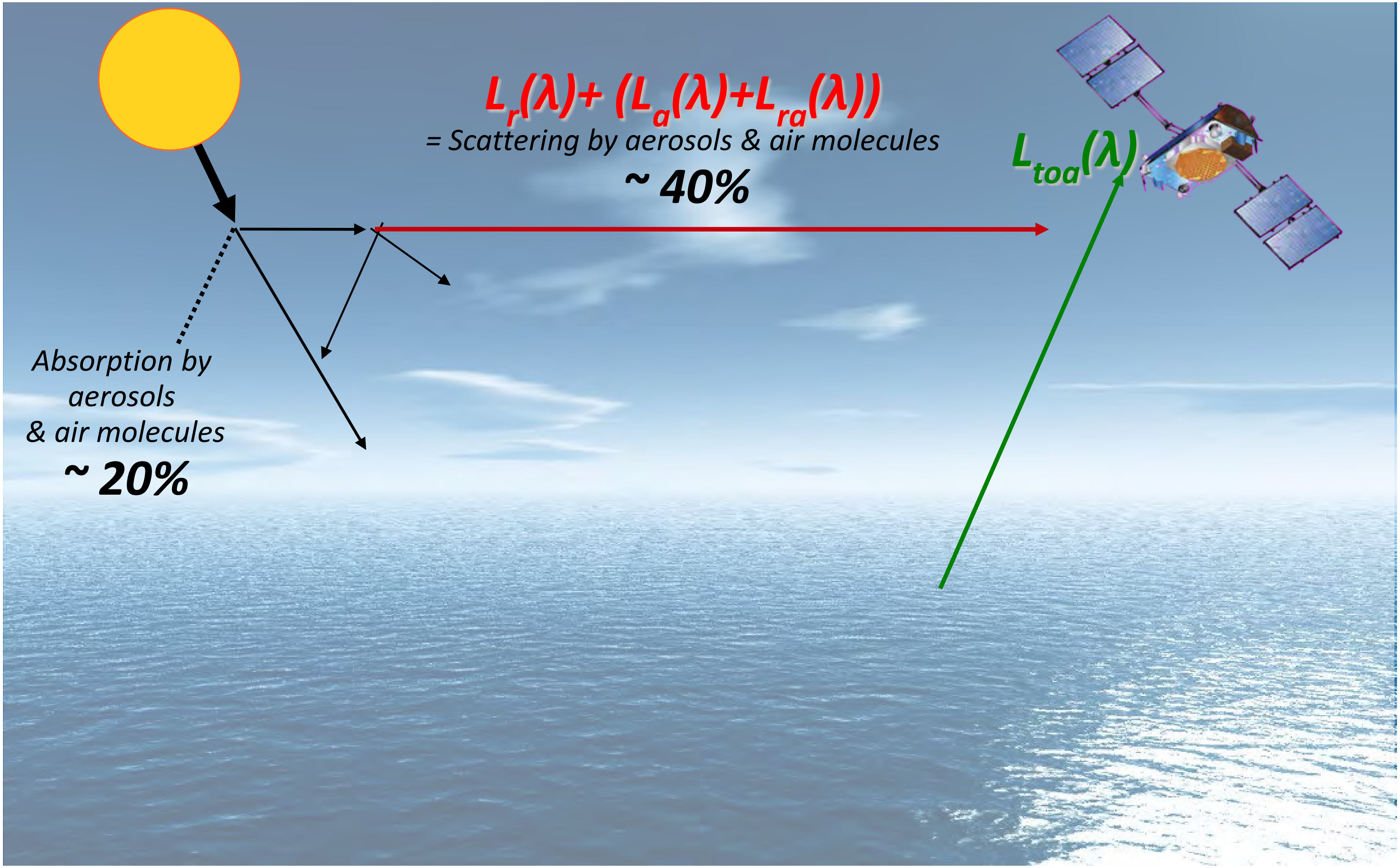
- Use of several spectral bands for the determination of each component of the TOA signal



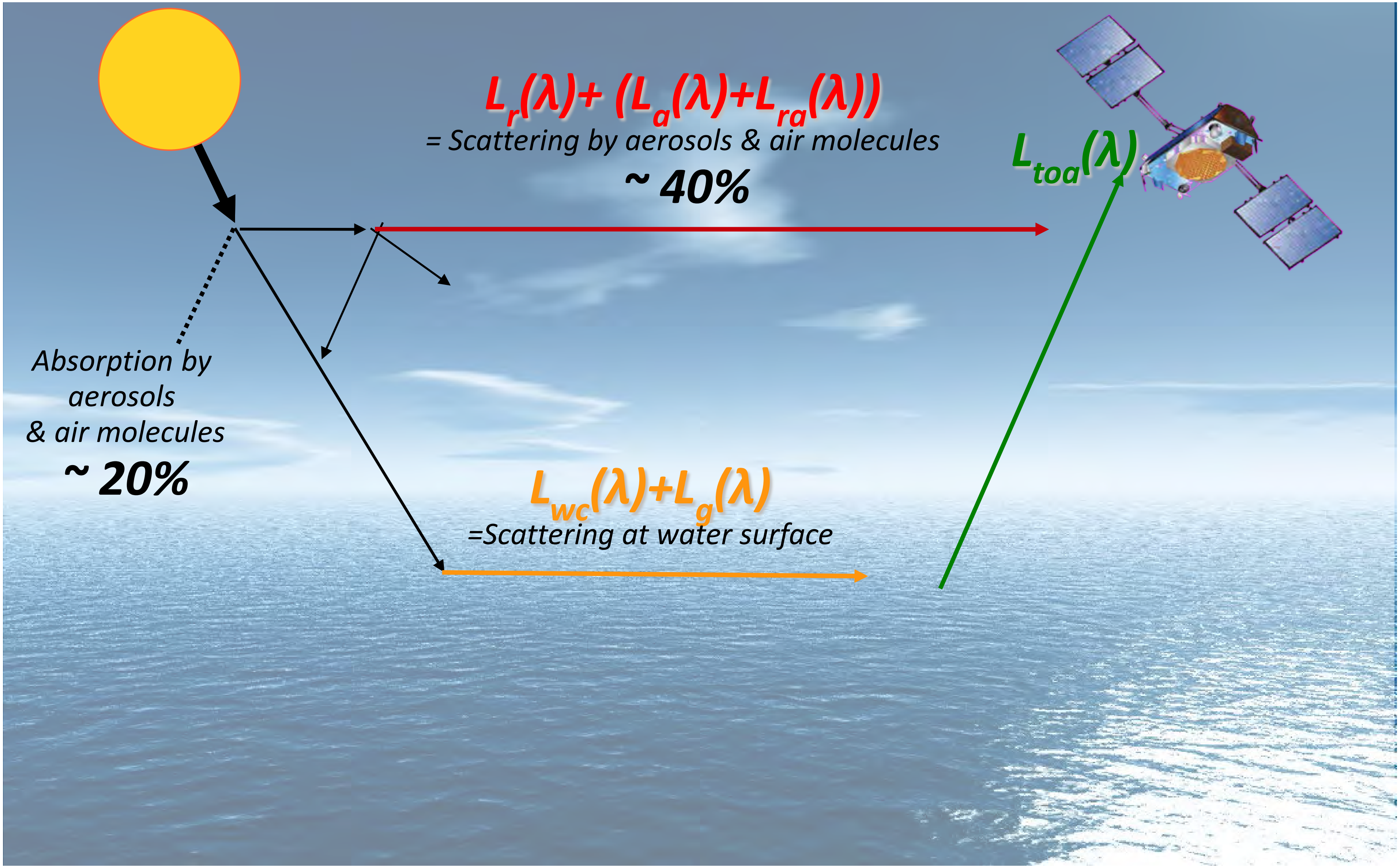
From H.R. Gordon

From $\rho_t(\lambda)$ to $\rho_W(\lambda)$
Atmospheric Correction

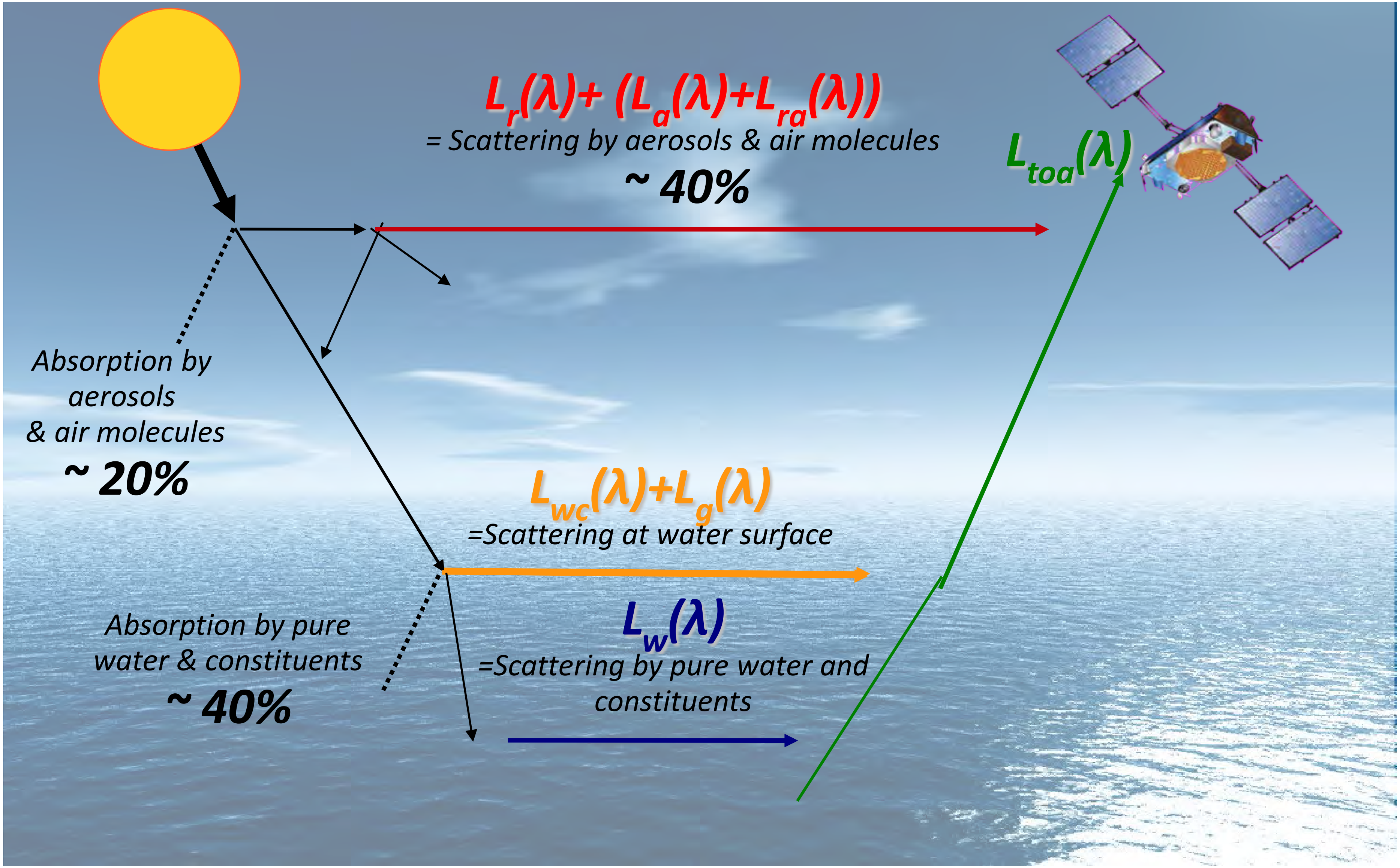
From $\rho_t(\lambda)$ to $\rho_W(\lambda)$
Atmospheric Correction



From $\rho_t(\lambda)$ to $\rho_W(\lambda)$
Atmospheric Correction



From $\rho_t(\lambda)$ to $\rho_W(\lambda)$
Atmospheric Correction



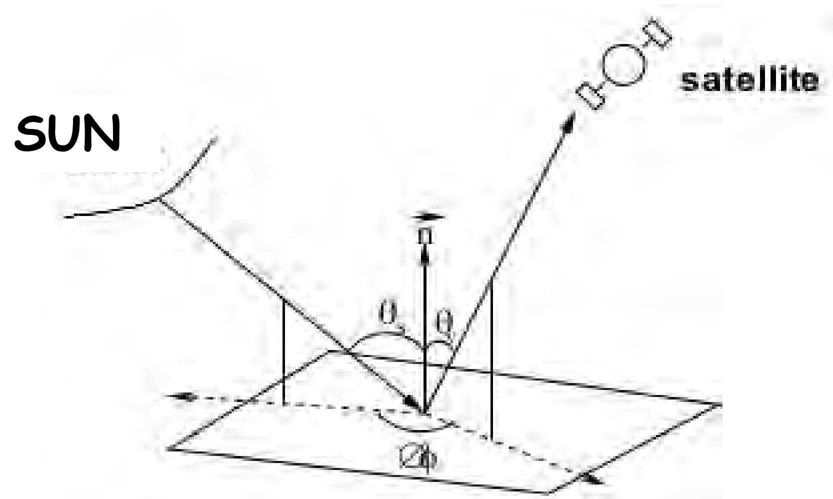
From $\rho_t(\lambda)$ to $\rho_W(\lambda)$
Atmospheric Correction

$$L_t = L_r + L_a + L_{ra} + L_g^{TOA} + L_{sky}^{TOA} + L_{wc}^{TOA} + L_w^{TOA}$$

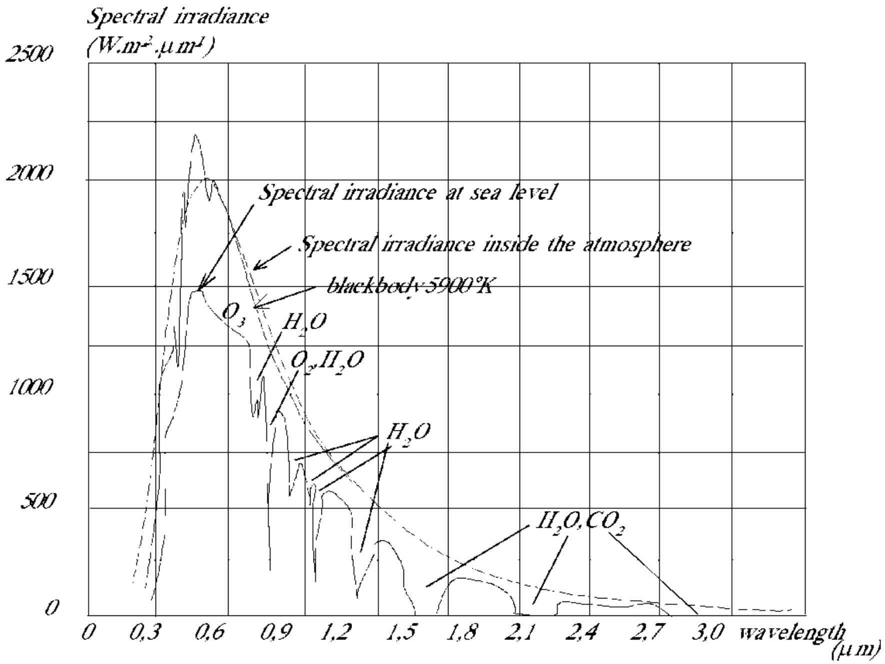
$$L_t = L_r + L_a + L_{ra} + T.L_g + t.L_{wc} + t.L_w$$

All these parameters are function of the viewing conditions:

- Sun angles θ_s
- Satellite viewing angles θ_v
- Azimuthal angles Φ

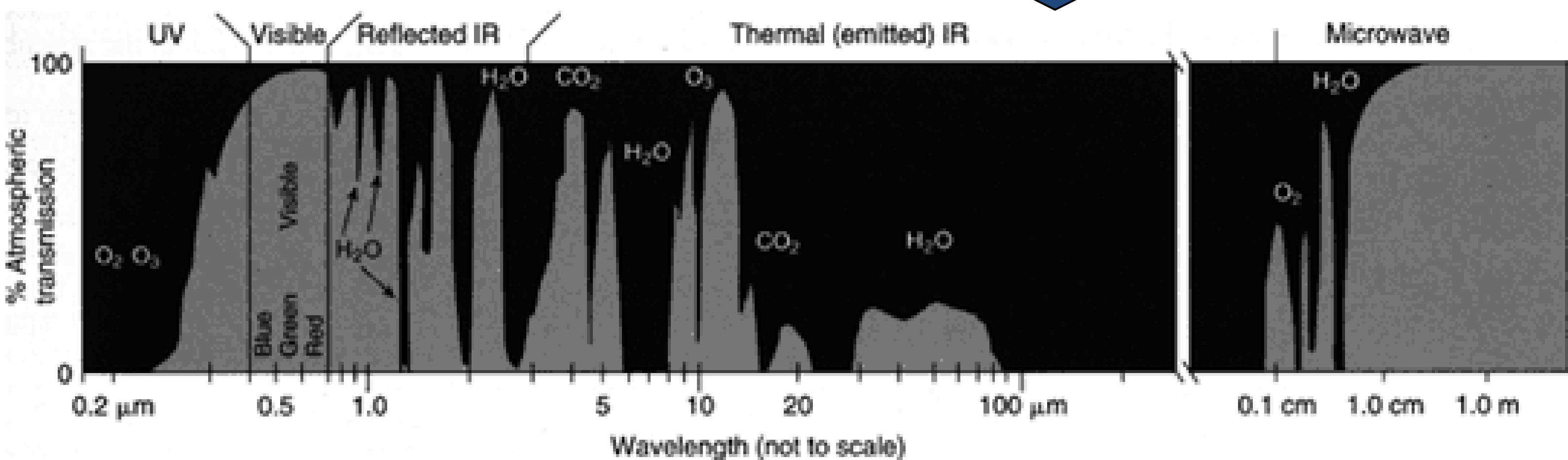


Propagation of the light through the atmosphere

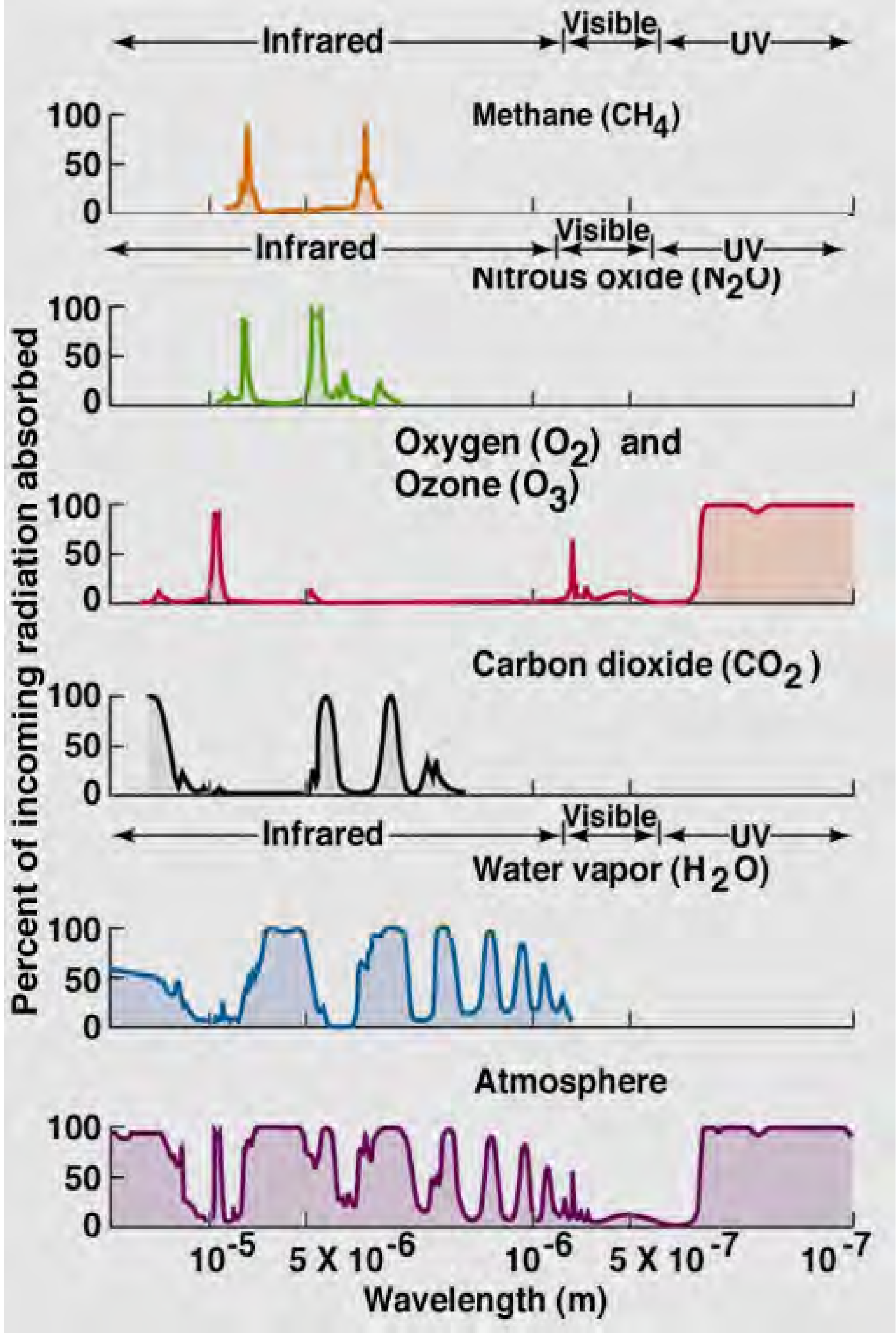


Effect of the path of the solar radiation through the atmosphere (from Valley, 1965)

Percentage of Sun light transmitted through the electro-magnetic spectrum
(http://earthobservatory.nasa.gov)



Absorption spectrum of the atmosphere.



From $\rho_t(\lambda)$ to $\rho_W(\lambda)$
Atmospheric Correction

$$L_t = L_r + L_a + L_{ra} + L_g^{TOA} + L_{sky}^{TOA} + L_{wc}^{TOA} + L_w^{TOA}$$

$$L_t = L_r + L_a + L_{ra} + T.L_g + t.L_{wc} + t.L_w$$

Effect of the atmosphere

$$L_t = (L_r + L_a + L_{ra} + T.L_g + t.L_{wc} + t.L_w).t_{gv}.t_{gs}.f_p$$

With t_{gv}: *transmittance by atmospheric gases in the viewing direction*

t_{gs}: *transmittance by atmospheric gases in the Sun's direction*

f_p: *instrument polarization-correction factor*

From $\rho_t(\lambda)$ to $\rho_W(\lambda)$ Atmospheric Correction

$$L_t(\lambda) = \boxed{L_r(\lambda)} + \underline{(L_a(\lambda)+\rho_{ra}(\lambda))} + \boxed{tL_{wc}(\lambda)+TL_g(\lambda)} + t\underline{L_W(\lambda)}$$

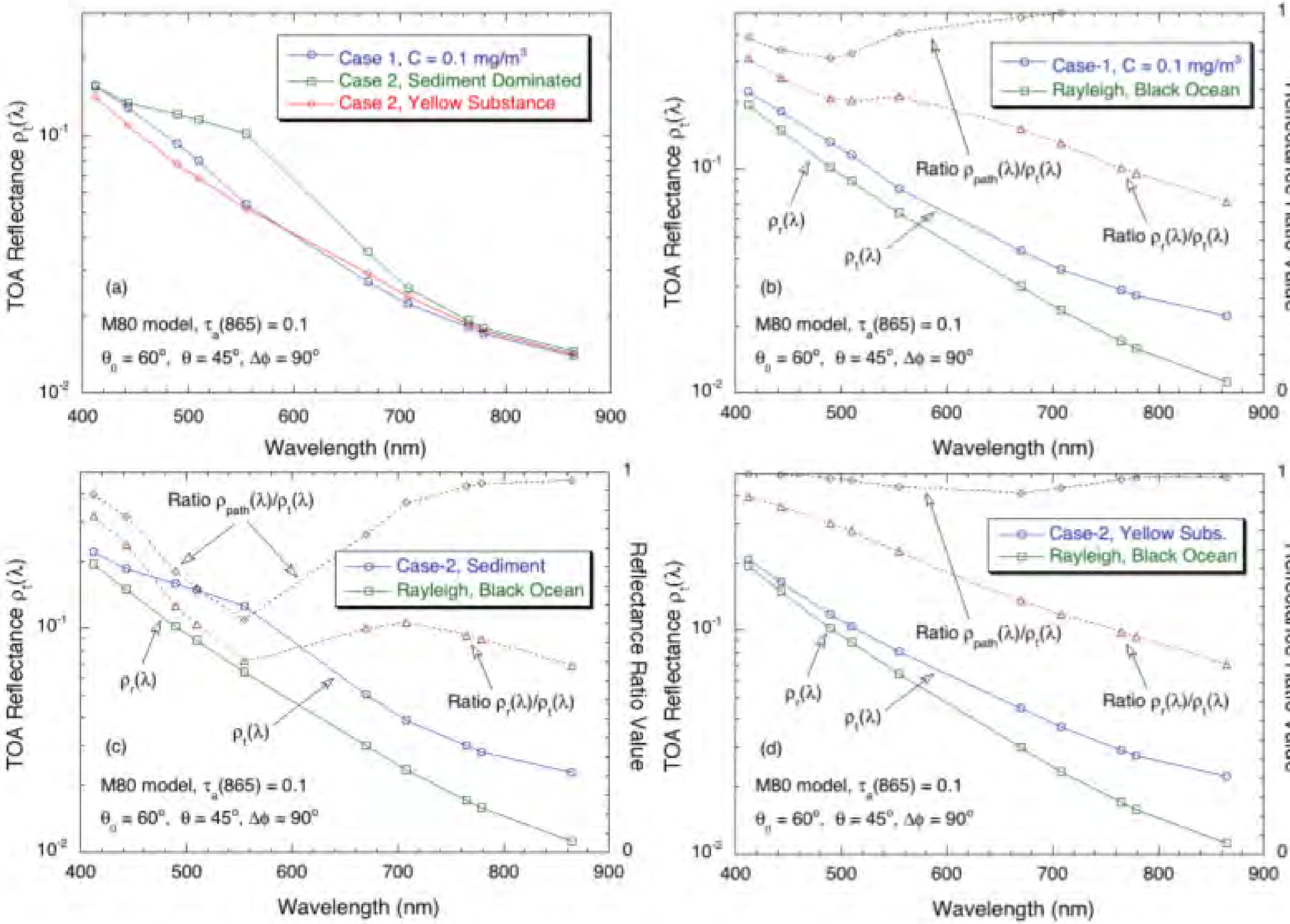
~ wind speed and atmospheric pressure
(e.g., Wang, 2002 and 2005; Ahmad and Frazer, 1982)

~ wind, sun and viewing angle
(e.g., Cox and Munk, 1954; Frouin et al., 1997; Wang and Bailey, 2001; Moore et al., 2000)

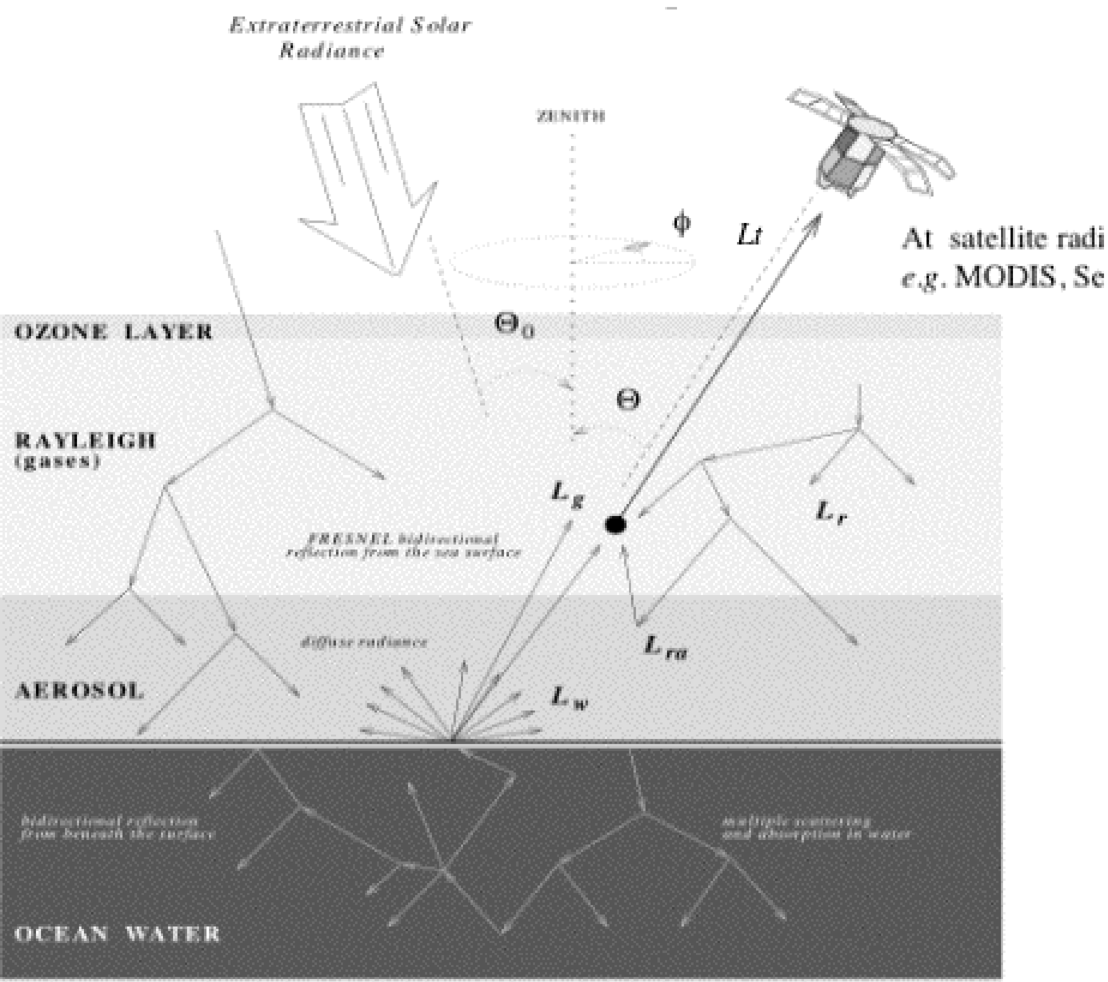
Desired quantity in ocean color remote sensing

Rayleigh-corrected reflectance:

$$\mathbf{L_{rc}(\lambda)} = L_t(\lambda) - L_r(\lambda) - tL_{wc}(\lambda) - TL_g(\lambda) = \underline{(L_a(\lambda)+L_{ra}(\lambda))} + t\underline{L_W(\lambda)}$$


Case 1, C = 0.1 mg/m³
Case 2, Sediment Dominated
Case 2, Yellow Substance
TOA Reflectance ρt(λ)
Wavelength (nm)
(a)
M80 model, τa(865) = 0.1
θ0 = 60°, θ = 45°, Δφ = 90°
Case-1, C = 0.1 mg/m³
Rayleigh, Black Ocean
Ratio ρpath(λ)/ρt(λ)
Ratio ρr(λ)/ρt(λ)
ρr(λ)
ρt(λ)
(b)
Reflectance Ratio Value
Case-2, Sediment
(c)
Case-2, Yellow Subs.
(d)

IOCCG, 2010



$$\rho_t(\lambda) = \rho_r(\lambda) + \rho_a(\lambda) + \rho_{ra}(\lambda) + t(\lambda)\,\rho_{wc}(\lambda) + t(\lambda)\,\rho_w(\lambda) + t(\lambda)\rho_g$$

L_t: total (measured)

L_r: Rayleigh (known)

L_a: aerosols (unknown)

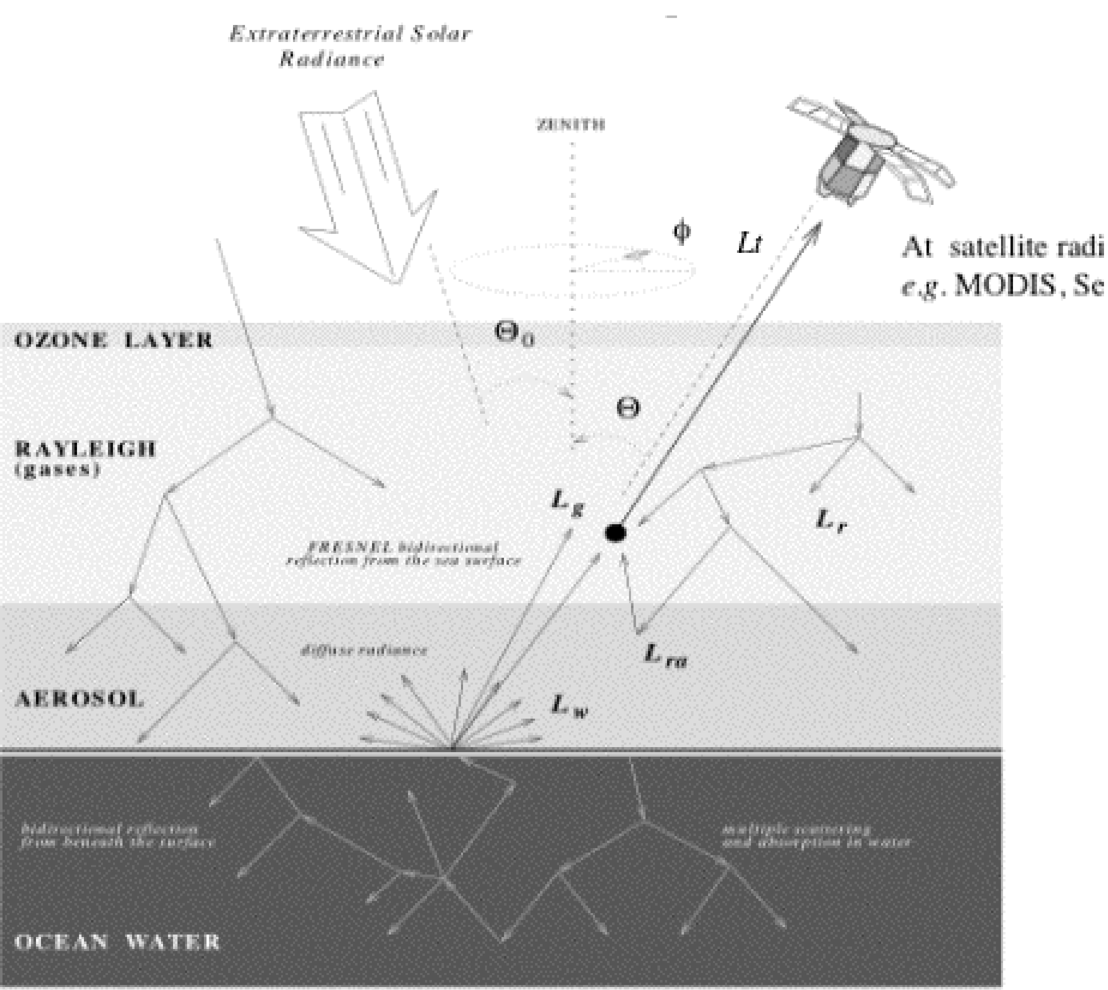
L_{ra}: Rayleigh-aerosols (unkown)

L_{wc}: foam (modelled/wind)

L_w: water (unknown, 10% of r_t)

L_g: glitter (masked or modelled)

Goal: 5% for absolute radiances and 2% for relative reflectances



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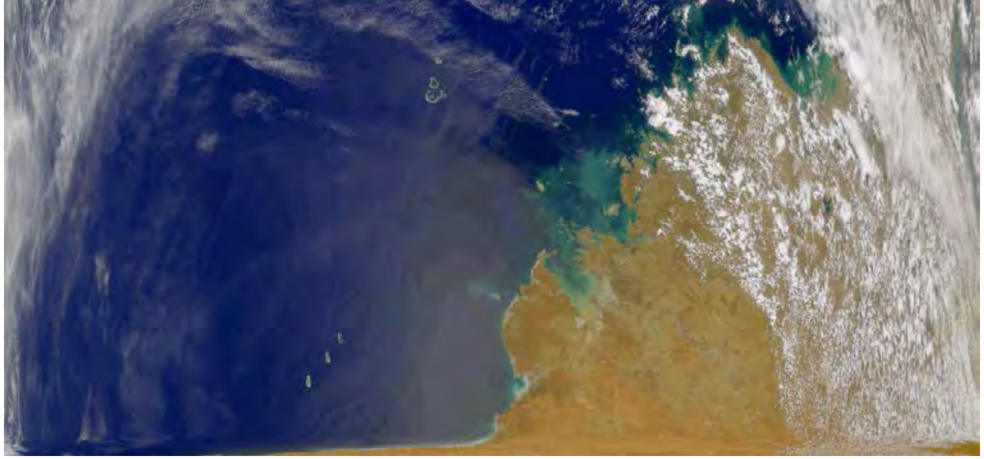
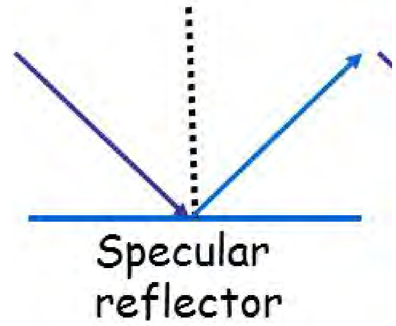
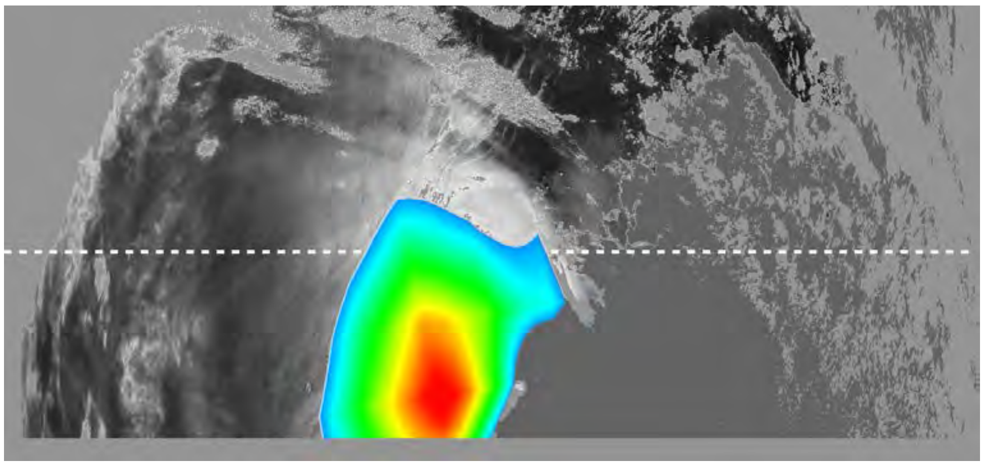
Specular reflection "Sun Glint"





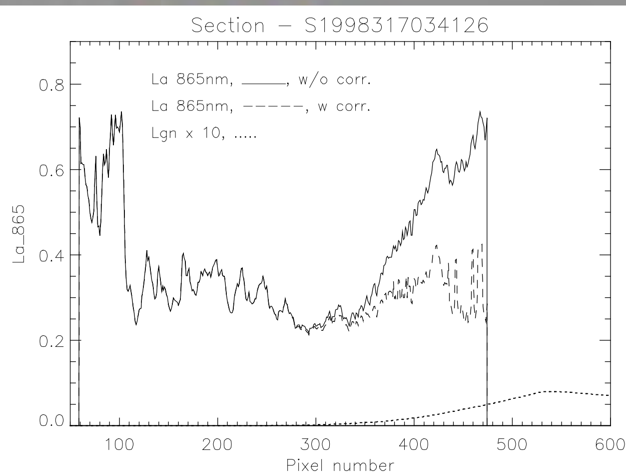


How to take into account Sun glint ?

→ Determination of the contaminated areas based on geometrical criteria

Calculation of the radiance associated to glint based on:

Probability function of the waves orientation as a function of wind + Fresnel law



Cox, C., W. Munk: Statistics of the sea surface derived from sun glitter. *J. Mar. Res.*, 13, 198-208, 1954.

redrawn from Wang, M., S. Bailey: Correction of sun glint contamination on the SeaWiFS ocean and atmosphere products. *Appl. Opt.*, 4790-4798, 2001.

$$L_g(\lambda) = F_0(\lambda)T_0(\lambda)L_{GN}$$

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

Need for ancillary data: surface wind speed and geometries of Sun & sensor

<u>In practical:</u>

-Most of sensors tilted

-

- If not, regions should be masked based on a threshold on L_{GN}

Cox and Munk model still among the best (Zhang and Wang, 2010)

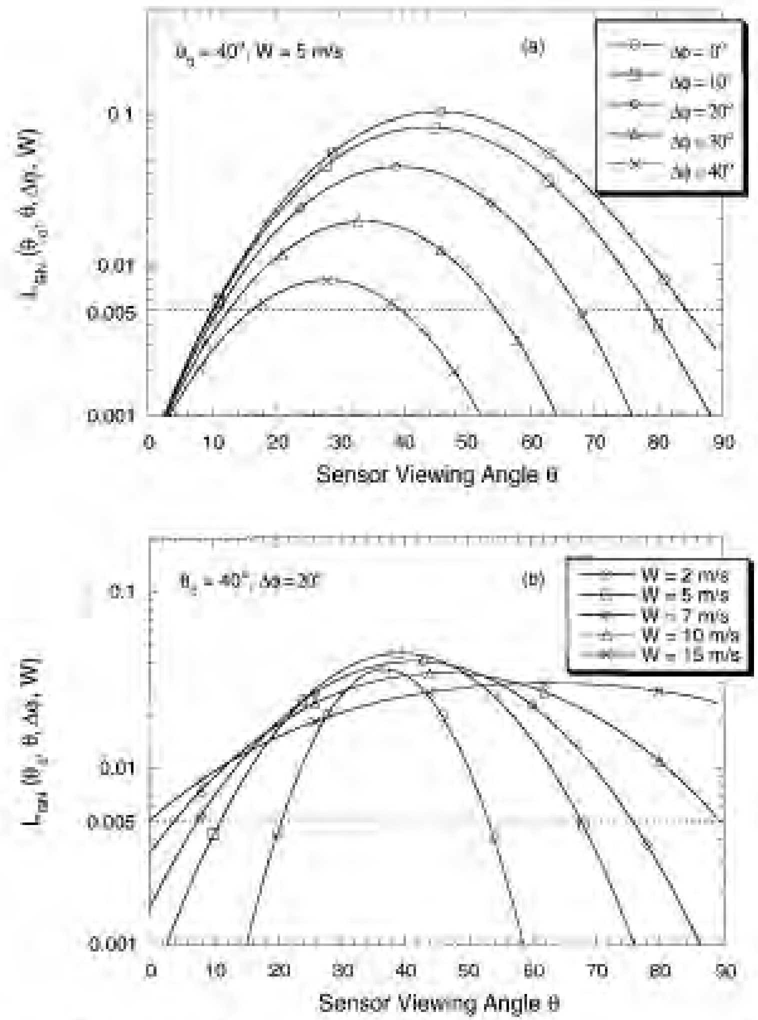
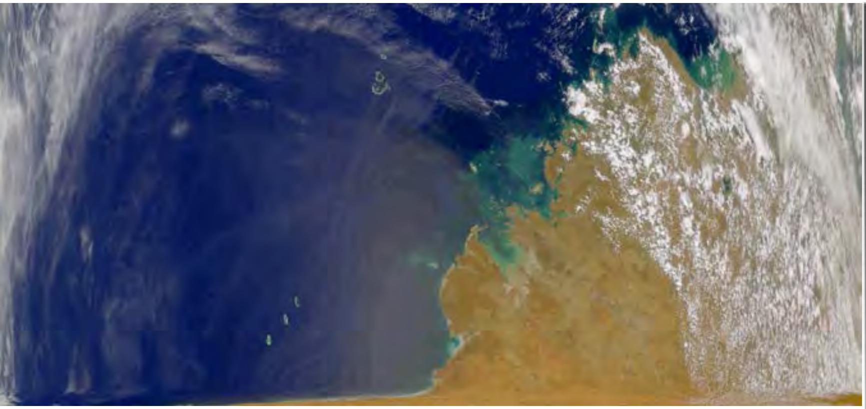
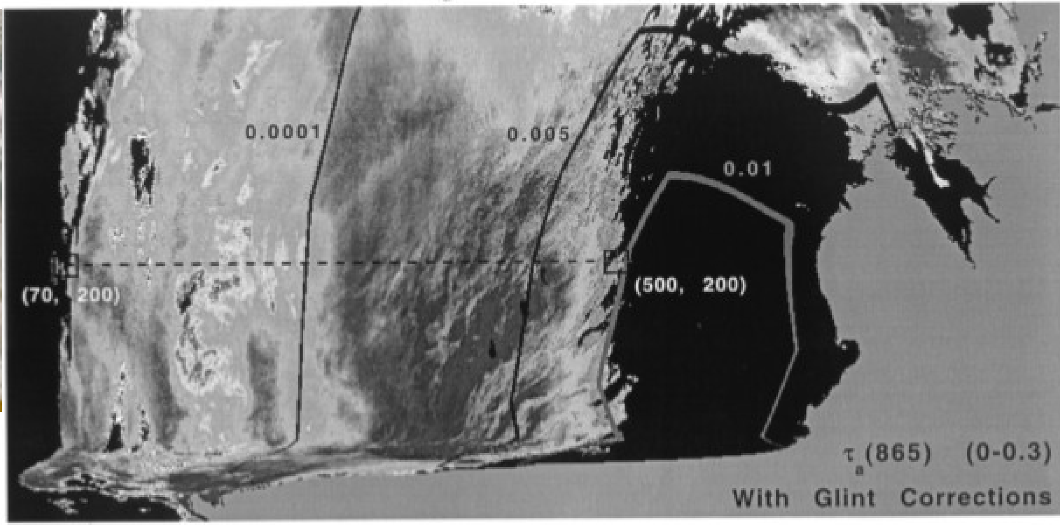


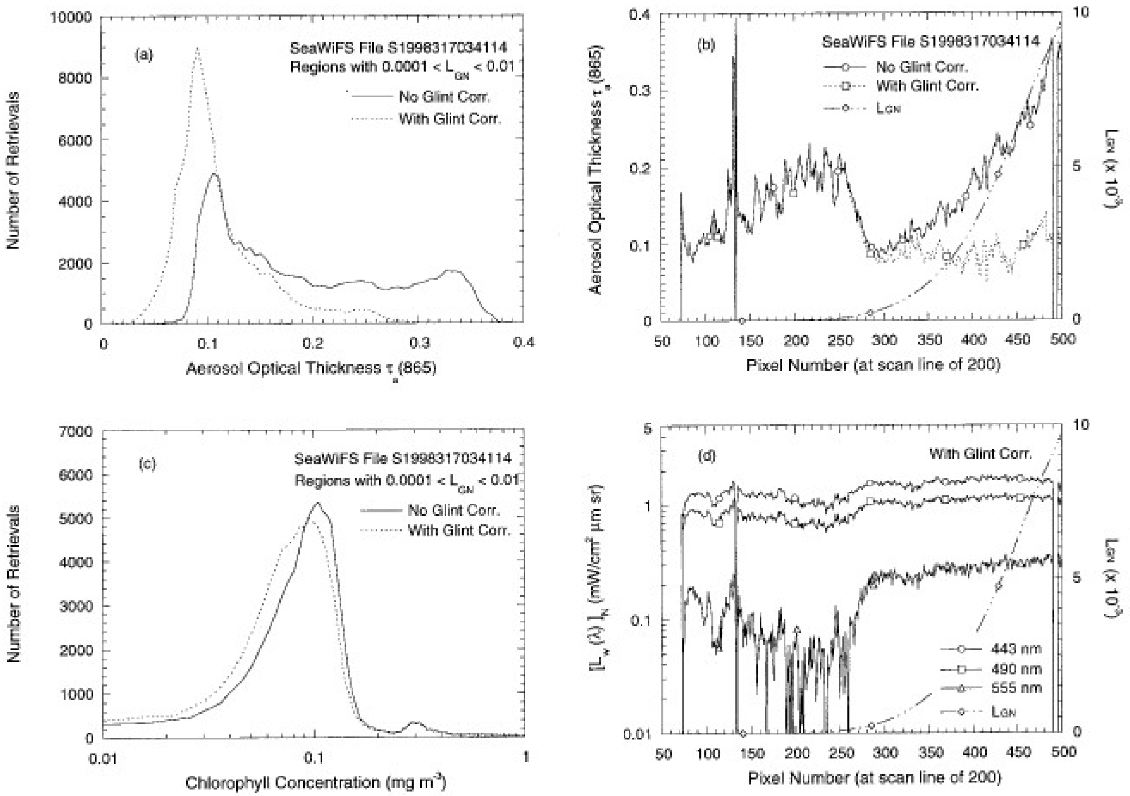
Fig. 1. Normalized sun glint radiance L_{GN} as a function of the sensor-viewing angle (solar zenith angle, 40°) and for (a) various relative azimuthal angles with surface wind speed of 5 m/s and (b) various surface wind speeds with a relative azimuthal angle of 20°.

Wang and Bailey, 2001

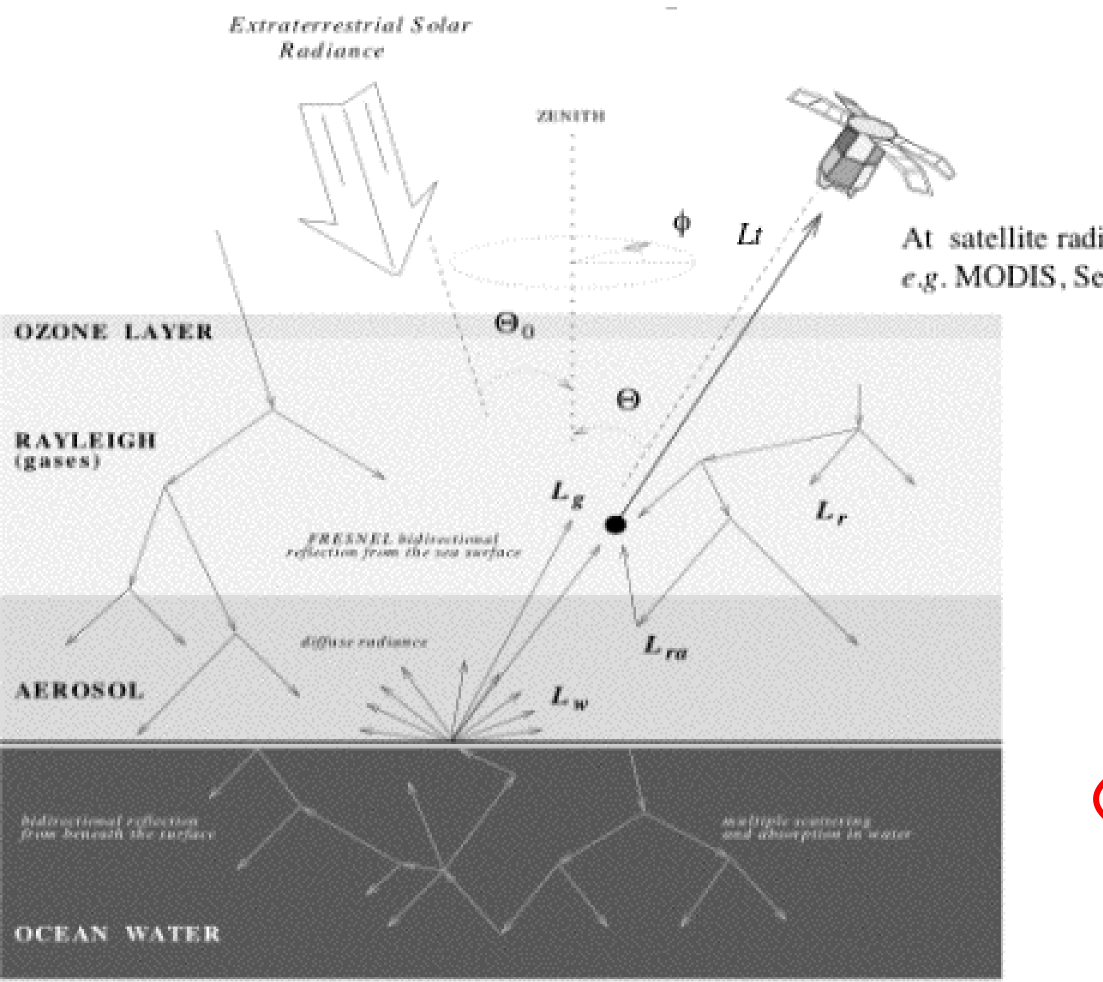




SeaWiFS aerosol optical thickness
(S1998317034114)



Wang and Bailey, 2001



$$\rho_t(\lambda) = \rho_r(\lambda) + \rho_a(\lambda) + \rho_{ra}(\lambda) + t(\lambda)\rho_{wc}(\lambda) + t(\lambda)\rho_w(\lambda) + t(\lambda)\rho_g$$

- L_t: total (measured)
- L_r: Rayleigh (known)
- L_a: aerosols (unknown)
- L_{ra}: Rayleigh-aerosols (unkown)
- L_{wc}: foam (modelled/wind)
- L_w: water (unknown, 10% of r_t)
- L_g: glitter (masked or modelled)

Goal: 5% for absolute radiances and 2% for relative reflectances

Foam "White Caps"

Stramska & Petelski, "Observations of oceanic whitecaps in the north polar waters of the Atlantic." *J. Geophys. Res.*, 108, 3086, 10.1029/2002JC001321, 2003.

Average wind speed

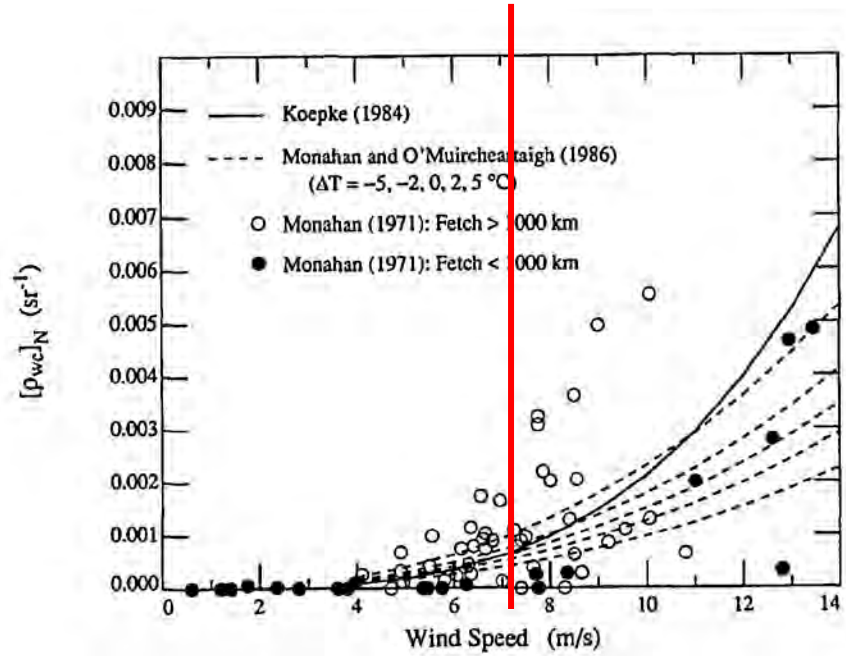


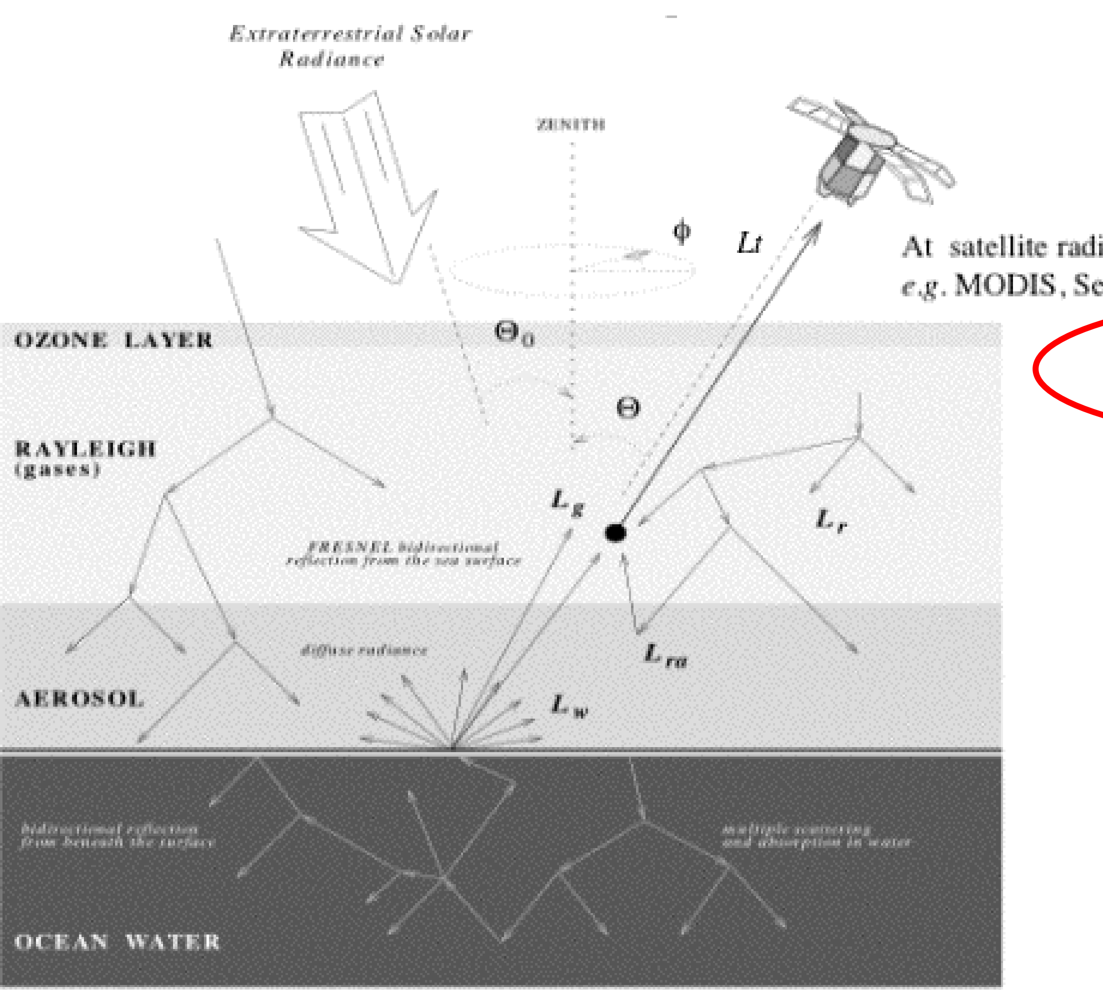
Fig. 1. $[\rho_{wc}]_N = r_{wc} f$ as a function of wind speed and atmospheric stability. For the Monahan and O'Muircheartaigh[17] relationship (dashed curves), the lower the value of $[\rho_{wc}]_N$, the greater the stability of the atmosphere. The solid curve is from Ref. 21, and the circles are from Ref. 11.

Gordon & Wang, *Appl. Opt.*, 33, 7754-7763, 1994.

Whitecaps appears when the wind speed is higher than 3 m.s^{-1} (2-3% of the oceanic surface) Their optical signature is linked to wind speed as a function of $W^{3.52}$.

The whitecaps reflectance is estimated using empirical relationships that allow to obtain reasonable estimates for wind speeds < 10-12 m.s^{-1}.

Whitecap reflectance is spectrally dependent (Frouin et al., 1996; Moore et al., 1998)



$$\rho_t(\lambda) = \rho_r(\lambda) + \rho_a(\lambda) + \rho_{ra}(\lambda) + t(\lambda)\rho_{wc}(\lambda) + t(\lambda)\rho_w(\lambda) + t(\lambda)\rho_g$$

L_t: total (measured)

L_r: Rayleigh (known)

L_a: aerosols (unknown)

L_{ra}: Rayleigh-aerosols (unkown)

L_{wc}: foam (modelled/wind)

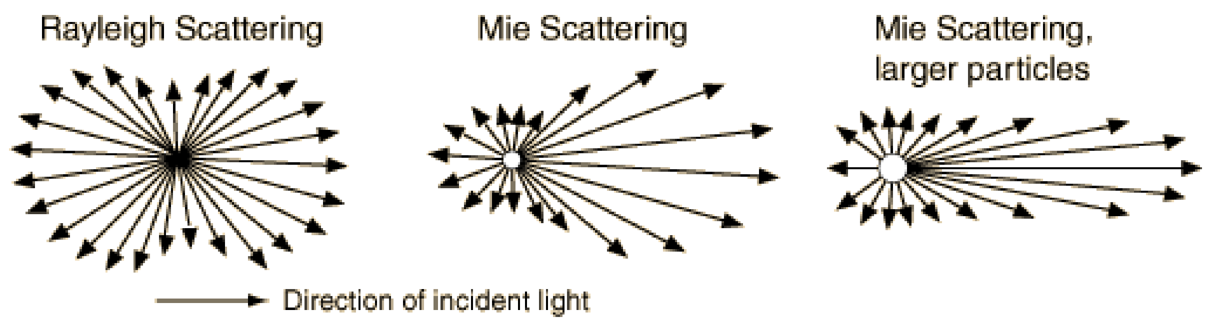
L_w: water (unknown, 10% of r_t)

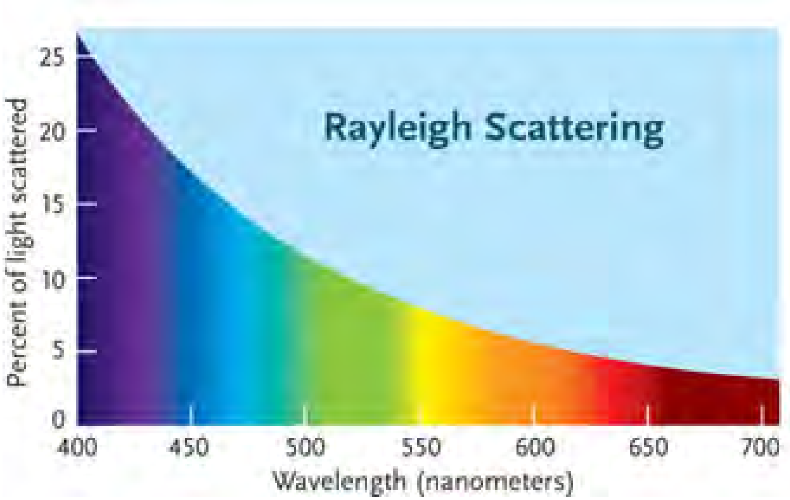
L_g: glitter (masked or modelled)

Goal: 5% for absolute radiances and 2% for relative reflectances

Rayleigh contribution

- Due to gas molecules in the atmosphere
- Dependent of size of the molecular scatterer to the incident wavelength (<< λ)

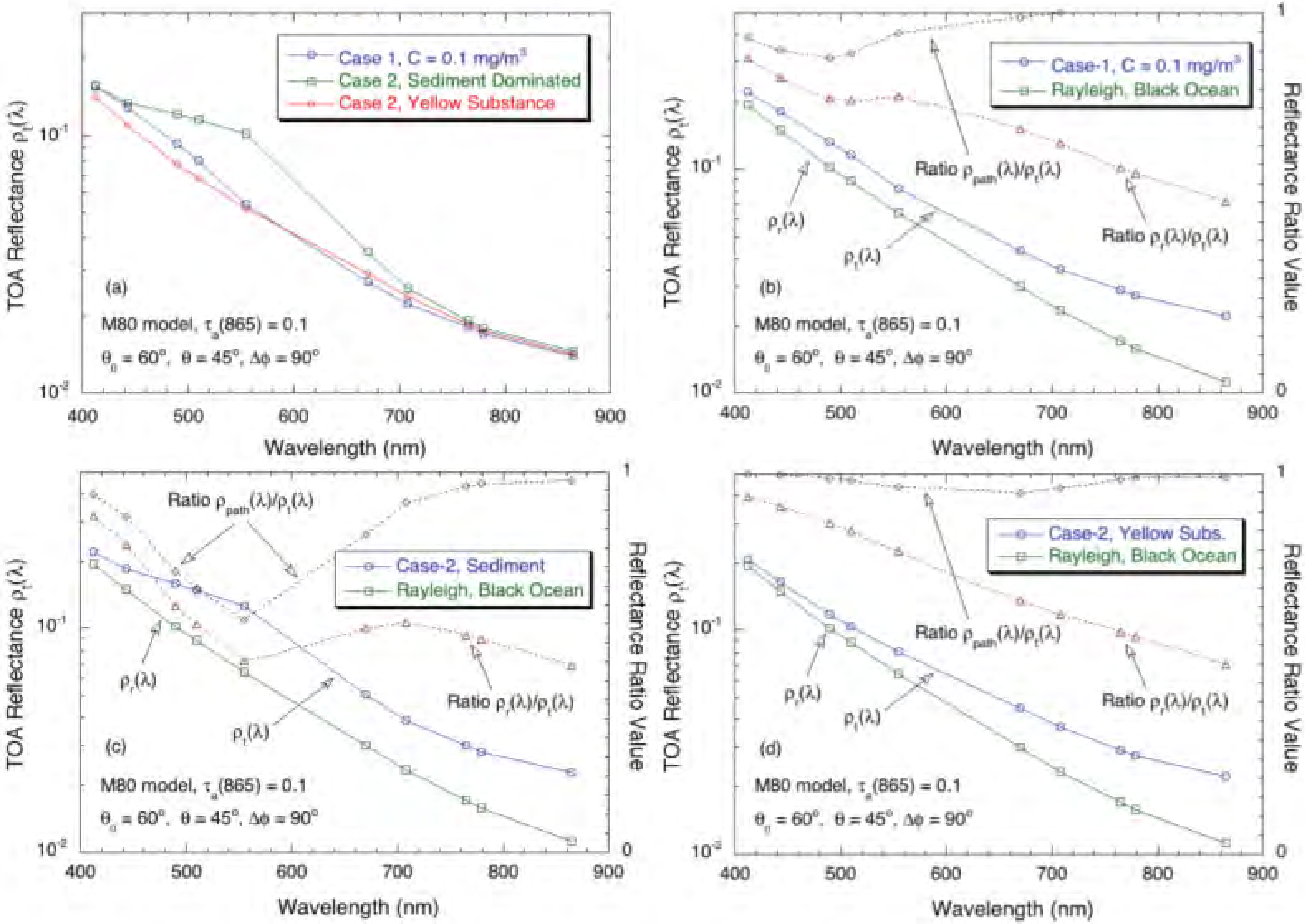




Reason why the sky is blue

Rayleigh contribution

- Lr can be 50-90% of Lt !!!!


Case 1, C = 0.1 mg/m³
Case 2, Sediment Dominated
Case 2, Yellow Substance
TOA Reflectance $\rho_t(\lambda)$
Wavelength (nm)
(a)
M80 model, $\tau_a(865) = 0.1$
$\theta_0 = 60°$, $\theta = 45°$, $\Delta\phi = 90°$
Case-1, C = 0.1 mg/m³
Rayleigh, Black Ocean
Ratio $\rho_{path}(\lambda)/\rho_t(\lambda)$
Ratio $\rho_r(\lambda)/\rho_t(\lambda)$
$\rho_r(\lambda)$
$\rho_t(\lambda)$
Reflectance Ratio Value
(b)
Case-2, Sediment
(c)
Case-2, Yellow Subs.
(d)

IOCCG, 2010

Rayleigh contribution

- Lr can be 50-90% of Lt !!!!
- Rayleigh optical thickness at 1 atmosphere of pressure:

$$\tau_{r0} = 0.0021520\left(\frac{1.0455996 - 341.29061\lambda^{-2} - 0.90230850\lambda^{2}}{1.0 + 0.0027059889\lambda^{-2} - 85.968563\lambda^{2}}\right)$$

with λ in micrometers

- <u>Pressure effects:</u>

$$\tau_r(P,\lambda) = \frac{P}{P_0}\tau_{r0}(P_0,\lambda)$$

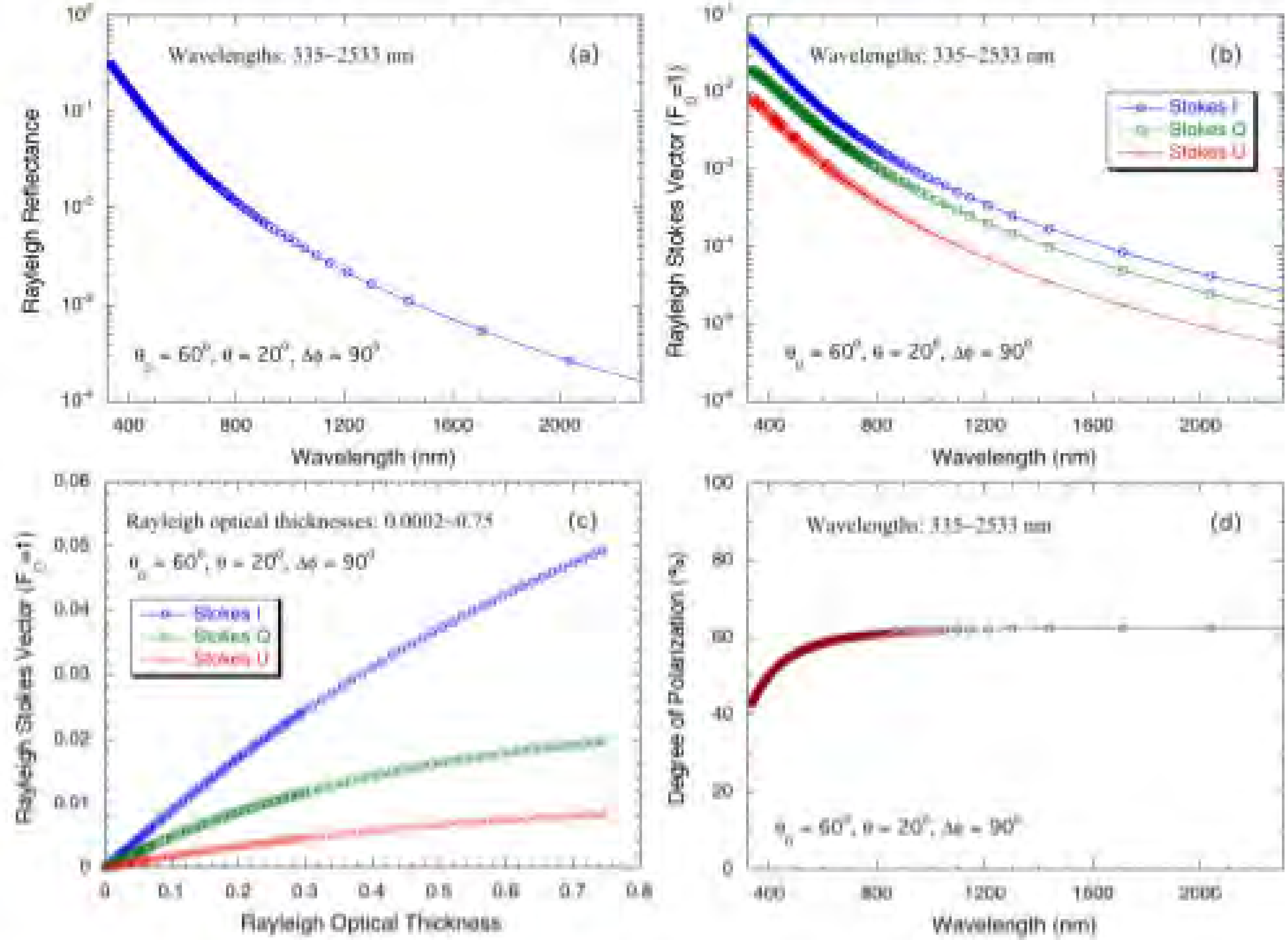


Fig. 1. Examples of the TOA Rayleigh-scattering radiances ($F_0(\lambda) = 1$) for a case with solar-zenith angle of 60°, sensor-zenith angle of 20°, and relative-azimuth angle of 90° for (a) Rayleigh radiance as a function of the wavelength, (b) Rayleigh Stokes components as a function of the wavelength, (c) Rayleigh Stokes components as a function of Rayleigh optical thickness, and (d) the degree of linear polarization (%) as a function of the wavelength.

Wang, 2016

Rayleigh contribution

- Rayleigh radiance:

$$L_r(P) = L_r(P_0)\frac{1-\exp\left[-C.\tau_r/\cos\theta_v\right]}{1-\exp\left[-C.\tau_{r0}/\cos\theta_v\right]}$$

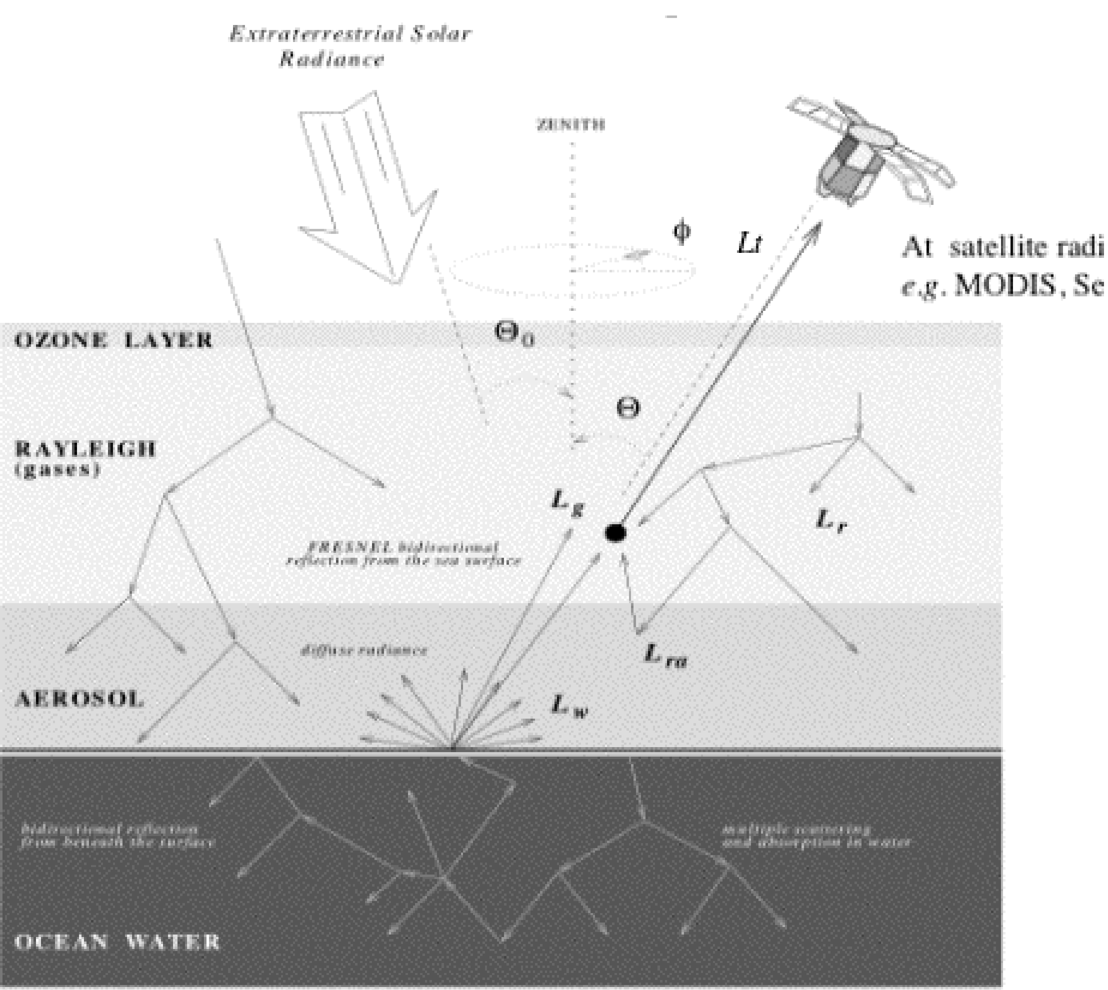
with C a function of τ_r

- Rayleigh scattering radiance can be computed accurately
- Need for wind speed (surface roughness) and atmospheric pressure

→ **Ancillary data**

→ Atmospheric pressure: NCEP

→ Wind speed: NCEP



$$\rho_t(\lambda) = \rho_r(\lambda) + \rho_a(\lambda) + \rho_{ra}(\lambda) + t(\lambda)\rho_{wc}(\lambda) + t(\lambda)\rho_w(\lambda) + t(\lambda)\rho_g$$

L_t: total (measured)

L_r: Rayleigh (known)

L_a: aerosols (unknown)

L_{ra}: Rayleigh-aerosols (unkown)

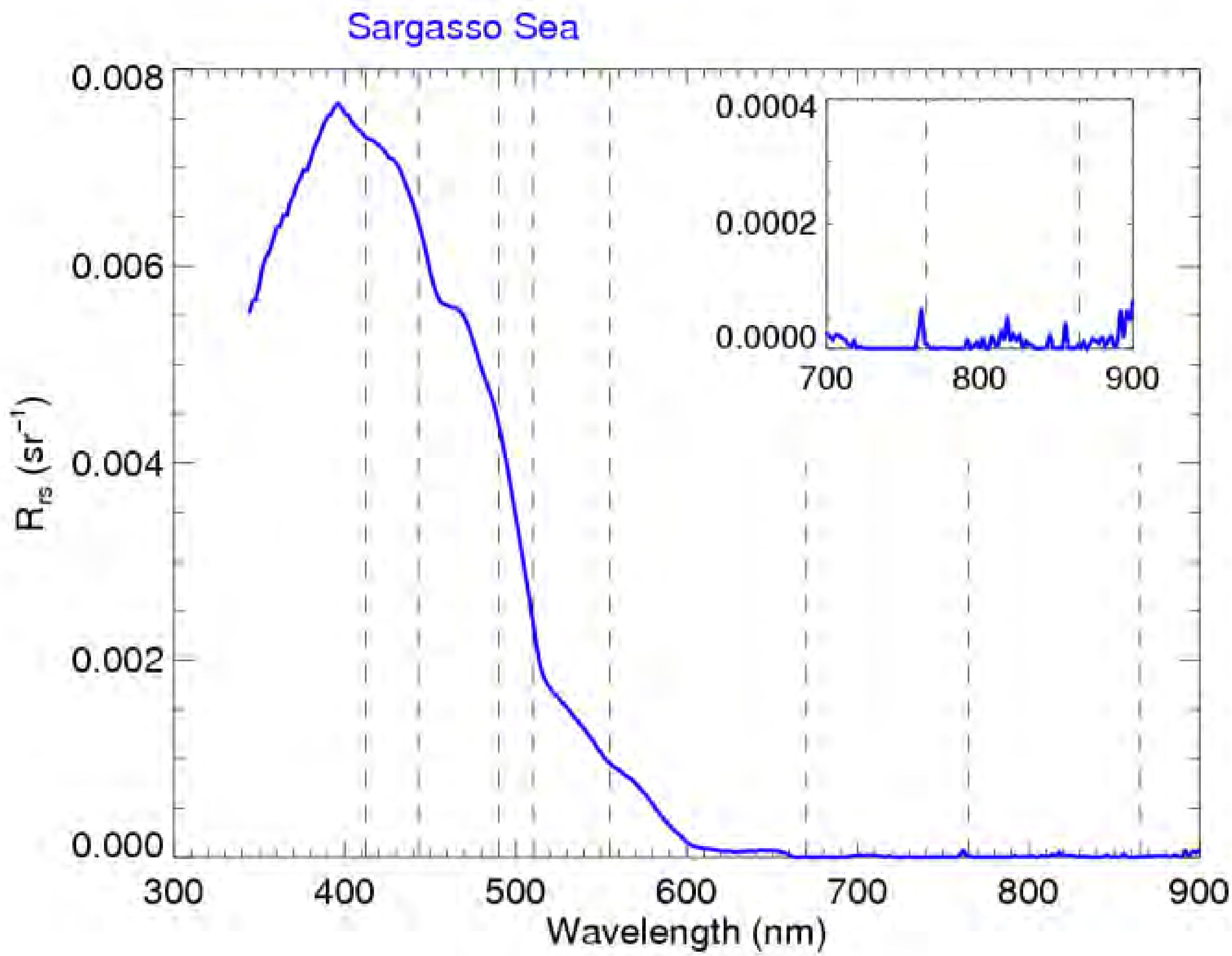
L_{wc}: foam (modelled/wind)

L_w: water (unknown, 10% of r_t)

L_g: glitter (masked or modelled)

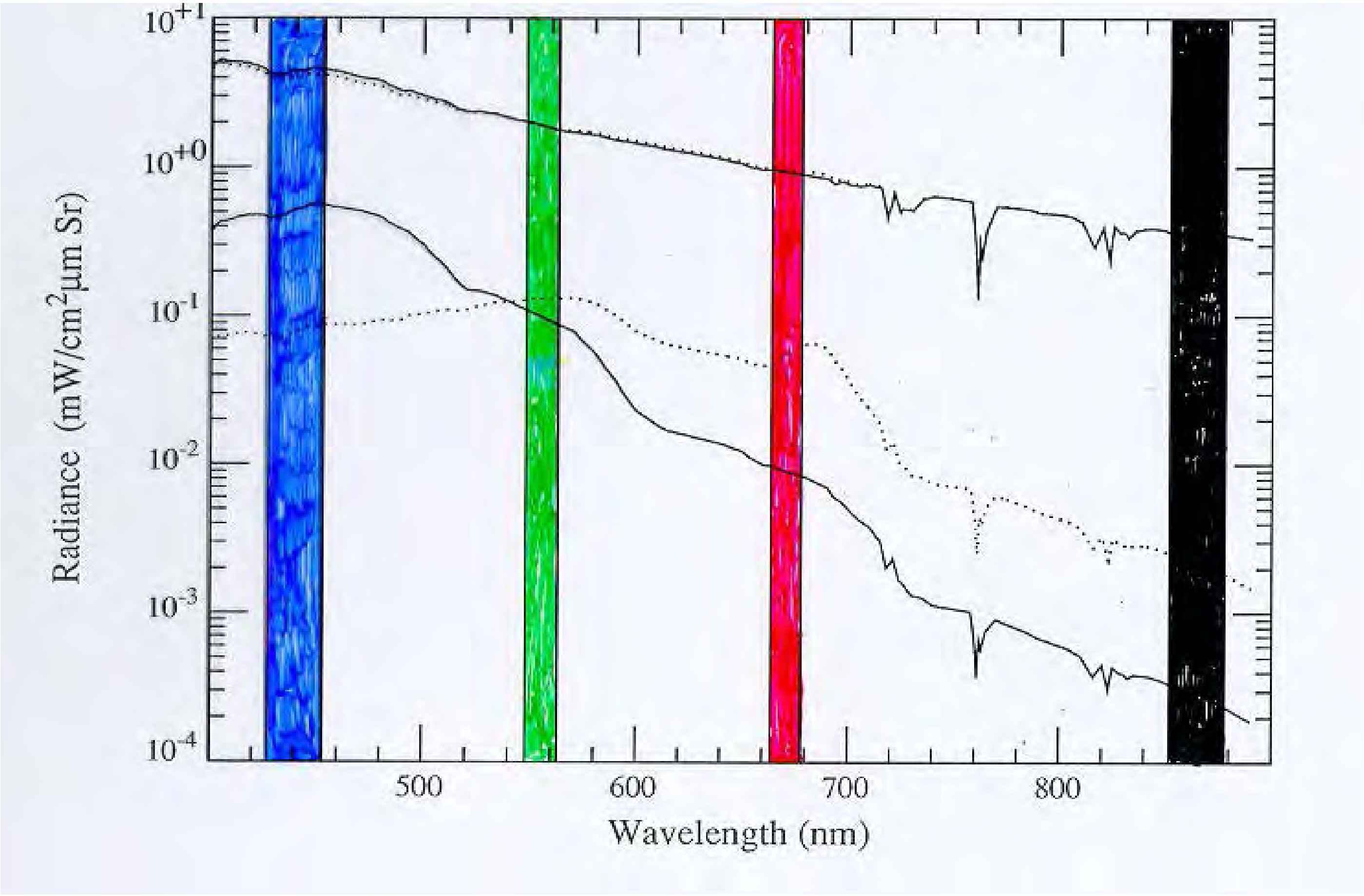
Goal: 5% for absolute radiances and 2% for relative reflectances

no one uses the “black pixel assumption” anymore



Analysis of ocean color images(2)

- Use of several spectral bands for the determination of each component of the TOA signal



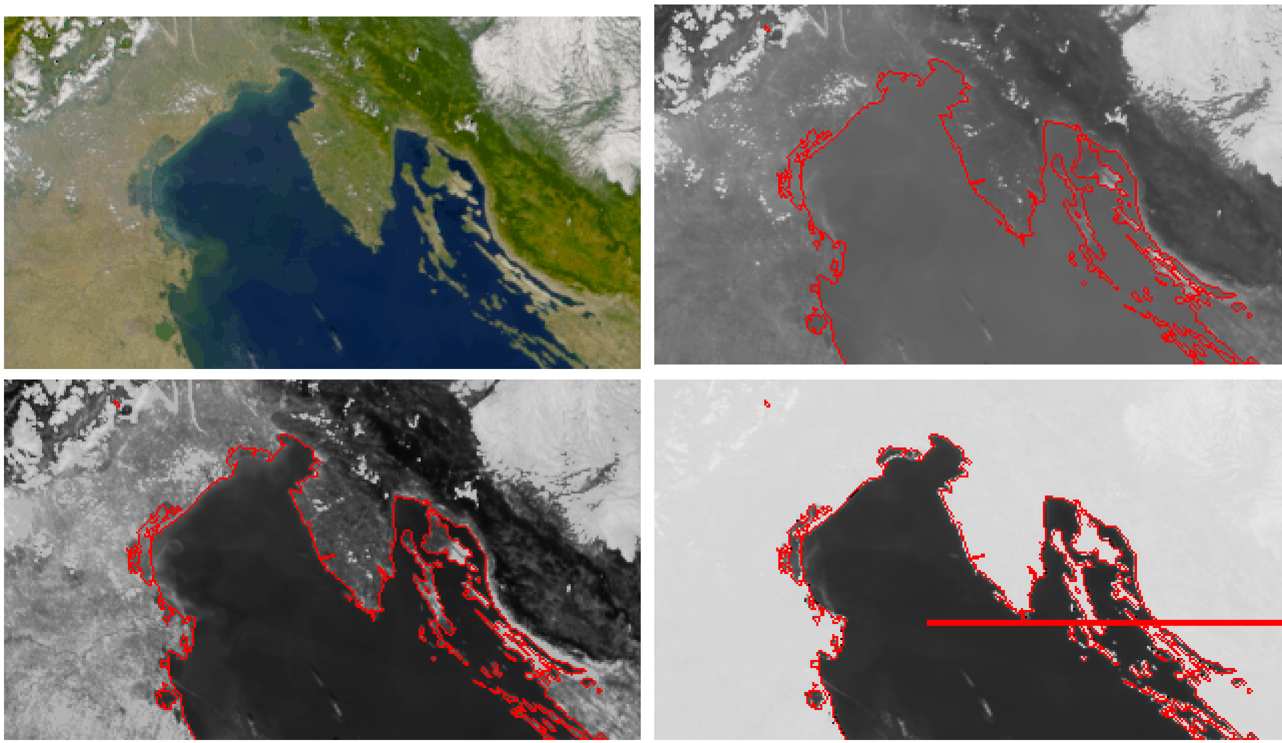
From H.R. Gordon

"Standard approach" (Gordon 1997)

SeaWiFS, Level-1, 10 Sep. 1998, N. Adriatic

'true-color'

L_{toa}, 412 nm



L_{toa}, 555 nm

L_{toa}, 865 nm

Extrapolation of aerosol Models to the visible

Estimation of the aerosol model

Estimation of aerosol In the NIR

At 765 and 865 nm, Seawater is considered Totally black (black pixel assumption)

There are other possibilities !!!

The classical approach:

- The black pixel assumption: $\rho_w=0$ in the NIR (due the high Pure sea water absorption) (gordon et al., 1997).

- ρ_a is then estimated at two NIR wavelengths which allows to retrieve the type of aerosols, and the concentration using look-up tables established from radiative transfer computations.

- This information is extrapolated towards the visible domain to retrieve $\rho_w(\lambda)$ in the visible.

The main problems:

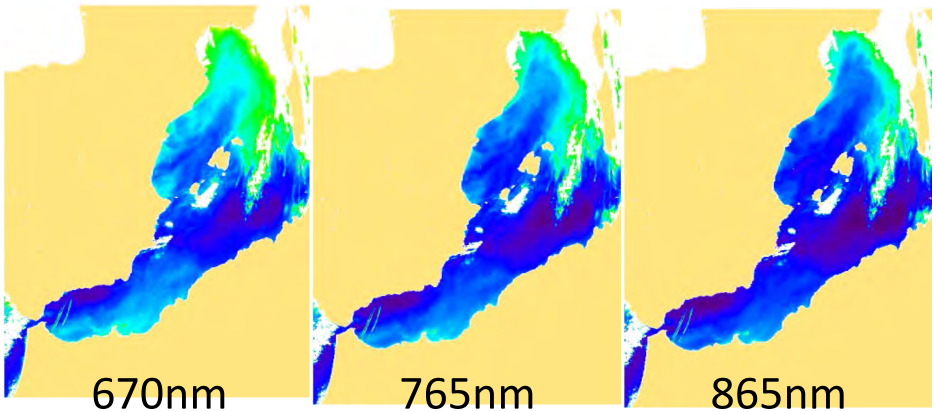
- Presence of absorbing aerosols (Antoine et al., 2006)
- Bottom albedo in clear shallow waters
- Presence of sediment in coastal areas ($\rho_w \neq 0$ in NIR)
- $\rho_w \neq 0$ in NIR for eutrophic waters (Siegel et al., 2001)

Solutions

Solving simultaneously the atmospheric and oceanic radiative system (Iterative procedures (Siegel et al., 2001), neuronal network approaches (Jamet et al., 2005), NIR similarity spectrum (Ruddick et al., 2000))

Standard processing (1/2)

In the infra-red, $\rho_t(\lambda)-\rho_r(\lambda)=\rho_A(\lambda)$



Hypothesis: ocean totally absorbing

$\rho_w(\lambda)$ negligeable

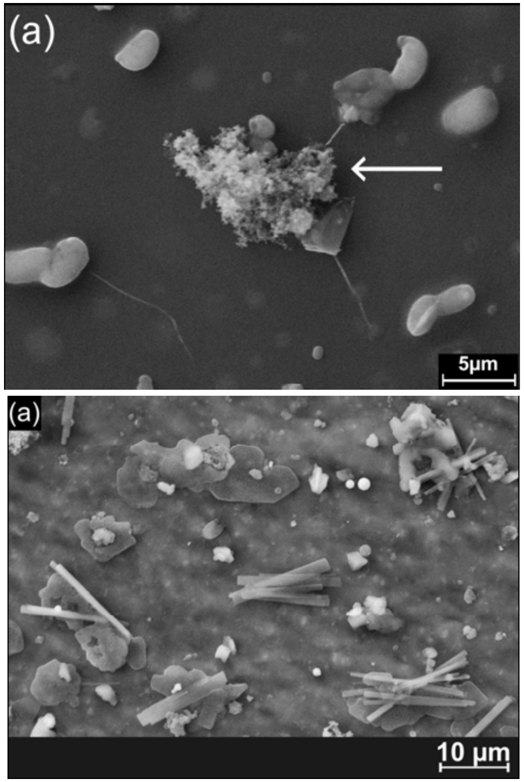
Estimation of aerosol optical properties and model:

τ, α

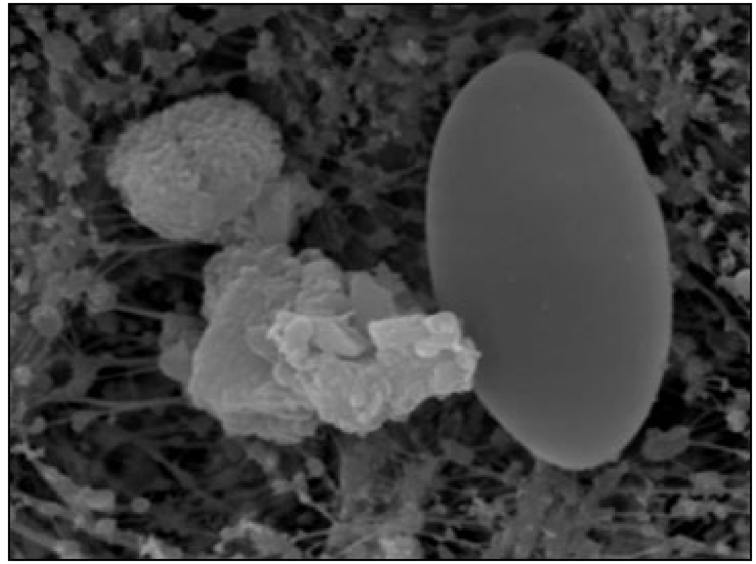
Estimation of ρ_A and t

Aerosols

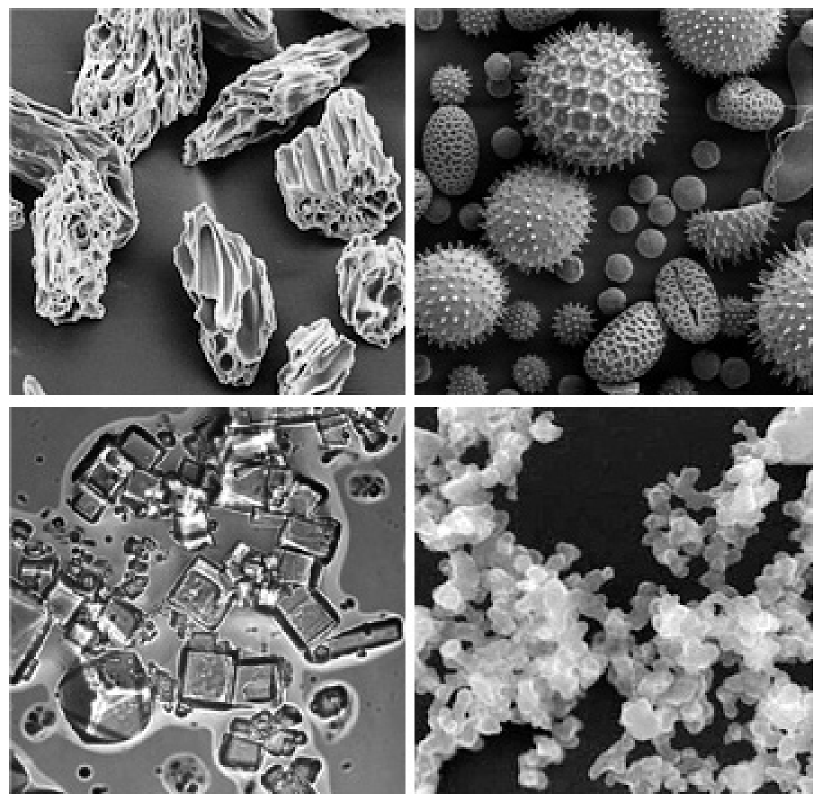
- Small particles (solid or liquid) in suspension in the atmosphere larger than gas molecules

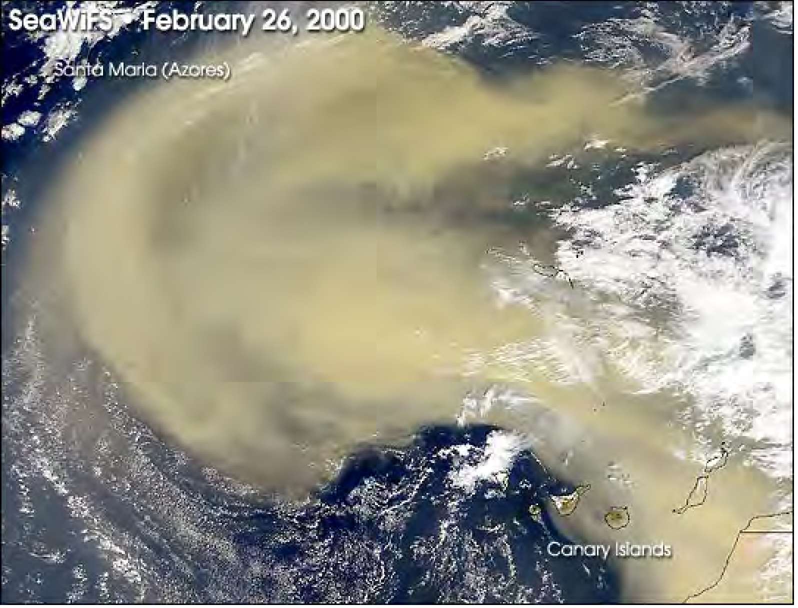


From M. Choel, 2005



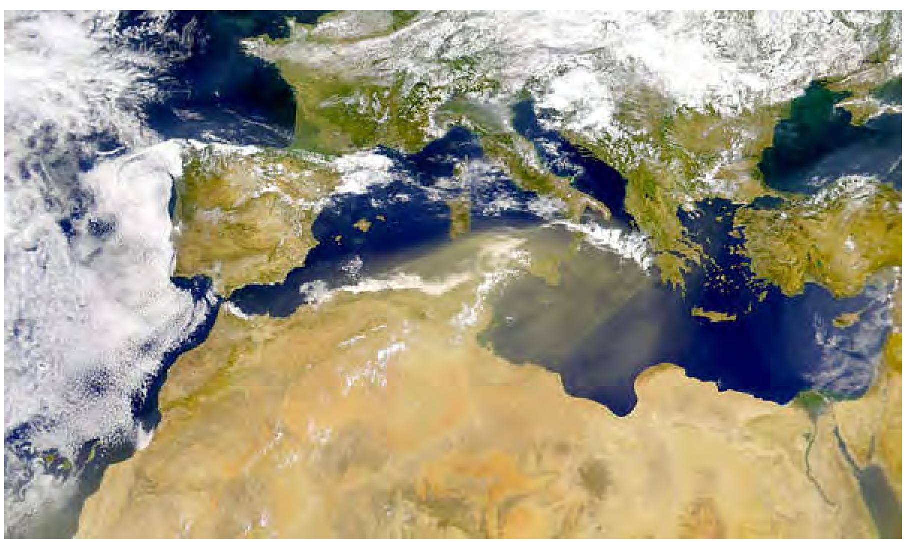
From www.chile.ird.fr/





Desert dust in the eastern part of the Atlantic Ocean (26 February 2000

Haze aerosol in the North Atlantic (4 May 2001)



Desert dust in the Mediterranean Sea

Aerosols

- Small particles (solid or liquid) in suspension in the atmosphere larger than gas molecules
- **Defined by three parameters:**

  – **Optical thickness** τ : proxy of aerosol concentration in the air column

$$\tau_a(\lambda) = \int_z^\infty \sigma_{ext}(\lambda) dz$$

with $\sigma_{ext}(\lambda)$ the extinction coefficient:

$$dL(\lambda) = -L(\lambda).\sigma_{ext}(\lambda) dz$$

Aerosols

- Small particles (solid or liquid) in suspension in the atmosphere larger than gas molecules
- **Defined by three parameters:**
  - **Optical thickness** τ: proxy of aerosol concentration in the air column
  - **Angström coefficient** α : proxy of aerosol size

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

Aerosols

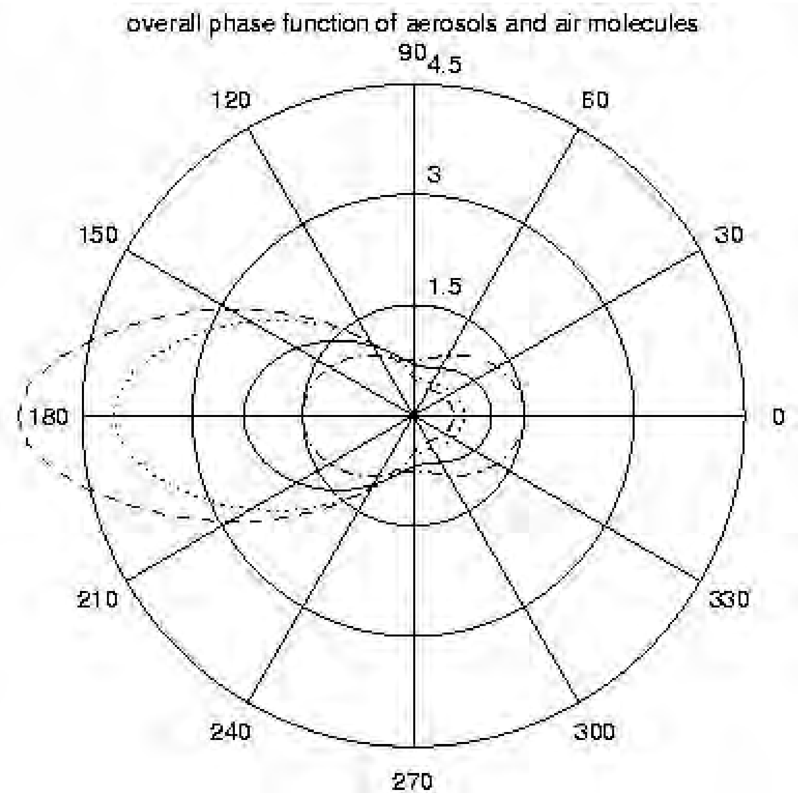
- Small particles (solid or liquid) in suspension in the atmosphere larger than gas molecules
- **Defined by three parameters:**
  - **Optical thickness** τ : proxy of aerosol concentration in the air column
  - **Angström coefficient** α: proxy of aerosol size
  - **Single-scattering albedo** ω: proxy of absorption properties (ratio of scattering coefficient to the extinction coefficient)

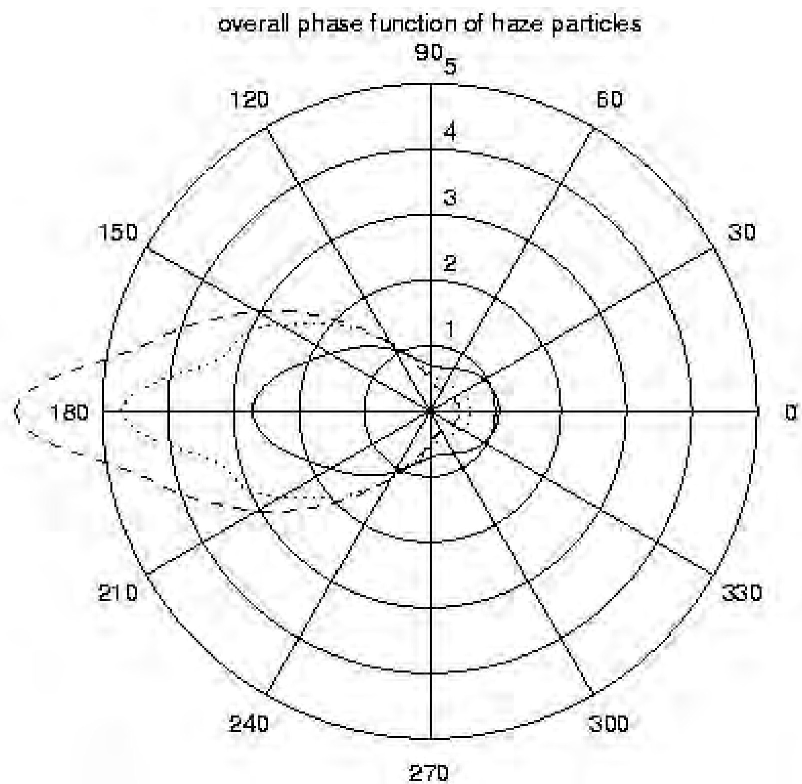
Aerosols

- Small particles (solid or liquid) in suspension in the atmosphere larger than gas molecules
- **<u>Defined by three parameters:</u>**
  - **Optical thickness** τ : proxy of aerosol concentration in the air column
  - **Angström coefficient** α: proxy of aerosol size
  - **Single-scattering albedo** ω: proxy of absorption properties (ratio of scattering coefficient to the extinction coefficient)
  - **Refractive index m_r-i.m_i:** m_i related to particle absorption

Aerosols

- Small particles (solid or liquid) in suspension in the atmosphere larger than gas molecules
- **Other important parameters:**
  - **Scattering phase function**





http://www.atm.damtp.cam.ac.uk/people/mgb/aniso.html

Aerosol Size Distributions

Number distribution →
$n_n(D_p)=dN/dD_p$

Surface area distribution →
$n_s(D_p)= dS/dD_p$
$S=\pi D_p^2$

Volume distribution →
$n_v(D_p)=dV/dD_p$
$V=(\pi/6)*D_p^3$

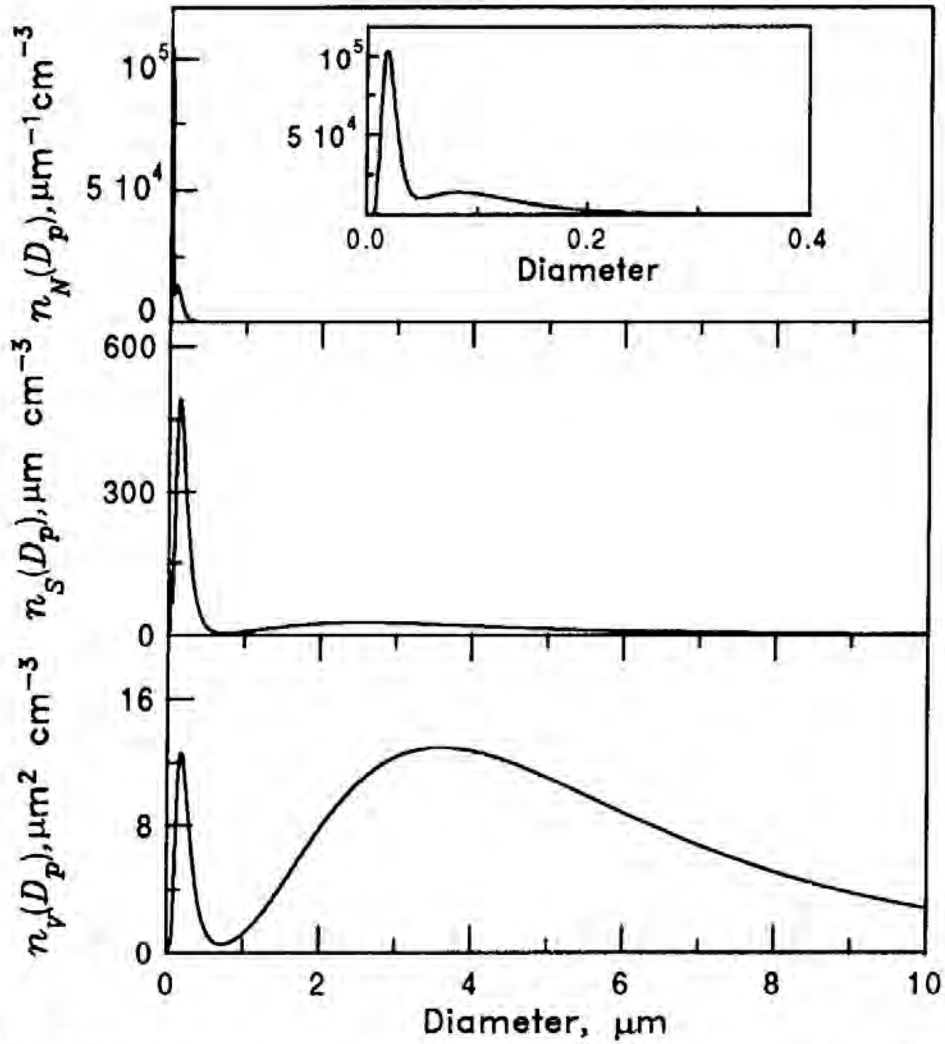


FIGURE 7.4 Atmospheric aerosol number, surface, and volume continuous distributions versus particle size. The diameter range 0 to 0.5 μm for the number distribution is shown as an inset.

Log-normal distributions

Number distribution →
$n_n(\log D_p) = dN/d \log D_p$

Surface area distribution →
$n_s(\log D_p) = dS/d \log D_p$

Volume distribution →
$n_v(\log D_p) = dV/d \log D_p$

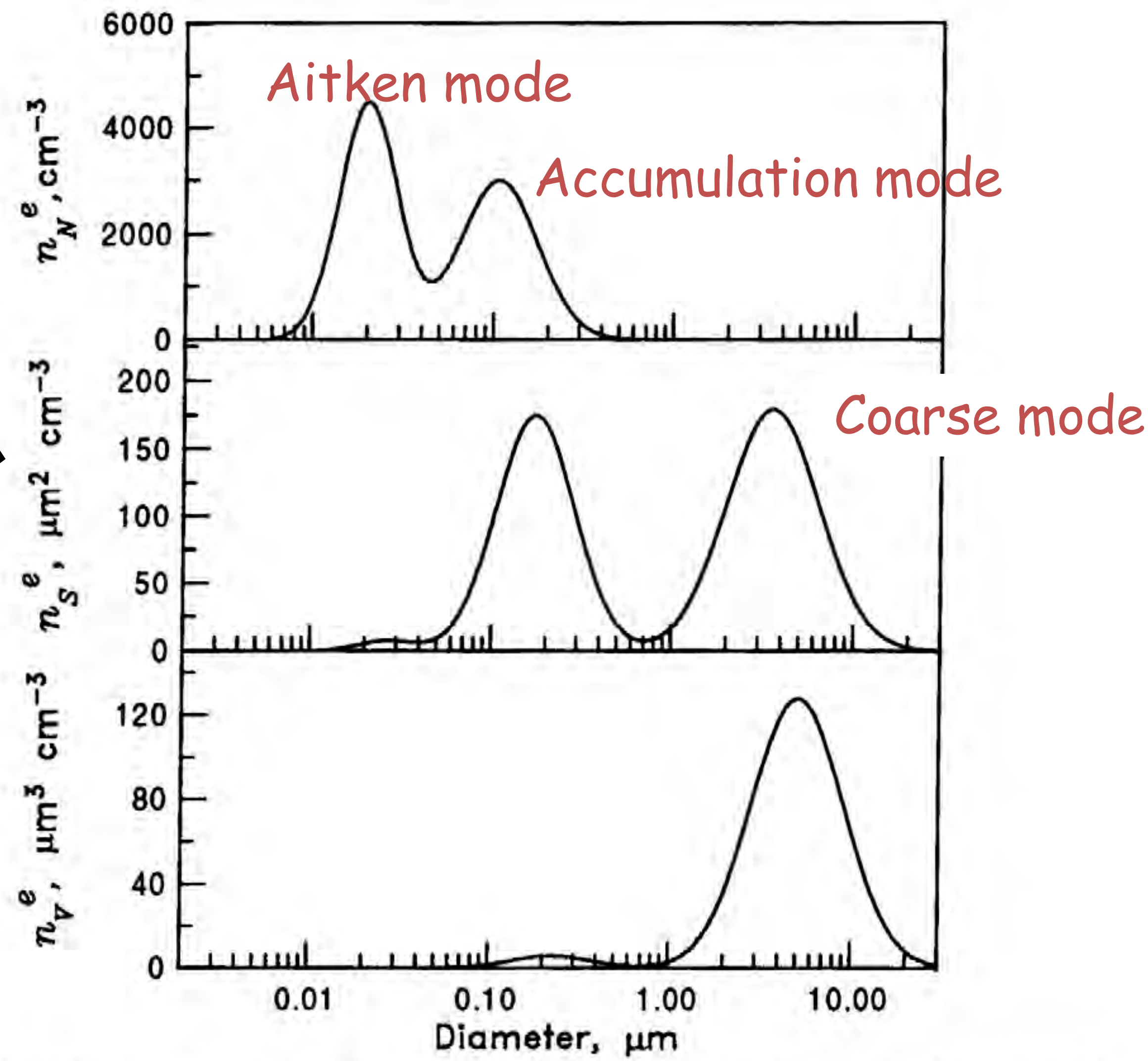


FIGURE 7.6 The same aerosol distribution as in Figures 7.4 and 7.5 expressed as a function of log D_p and plotted versus log D_p. Also shown are the surface and volume distributions. The areas below the three curves correspond to the total aerosol number, surface, and volume, respectively.

NASA Aerosol models

- **Shettle and Fenn (1979)**
  - Lognormal distribution of tropospheric and maritime aerosols

$$n(D) = \sum_{i=1}^{2} n_i(D)$$

$$\begin{aligned} n_i(D) &= \frac{dN_i(D)}{dD} \\ &= \frac{N_i}{D.\log_e(10).\sqrt{2\pi}\sigma_i} \exp\left[-\frac{1}{2}\left(\frac{\log_{10}(D/D_i)}{\sigma_i}\right)^2\right] \end{aligned}$$

NASA Aerosol models

- **<u>Shettle and Fenn (1979)</u>**
  - Lognormal distribution of tropospheric and maritime aerosols
  - Representative of tropospheric, coastal, maritime and oceanic aerosols

Aerosol model	Relative humidity (%)	Symbol
Oceanic	99	099
Maritime	50, 70, 90, 99	M50-M99
Coastal	50, 70,,90, 99	C50-C99
Tropospheric	50, 90, 99	T50-T99

New NASA Aerosol models

- **<u>Ahmad et al. (2010):</u>**
  - Based on AERONET models
  - Bimodal lognormal distributions (narrower than previous models)

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

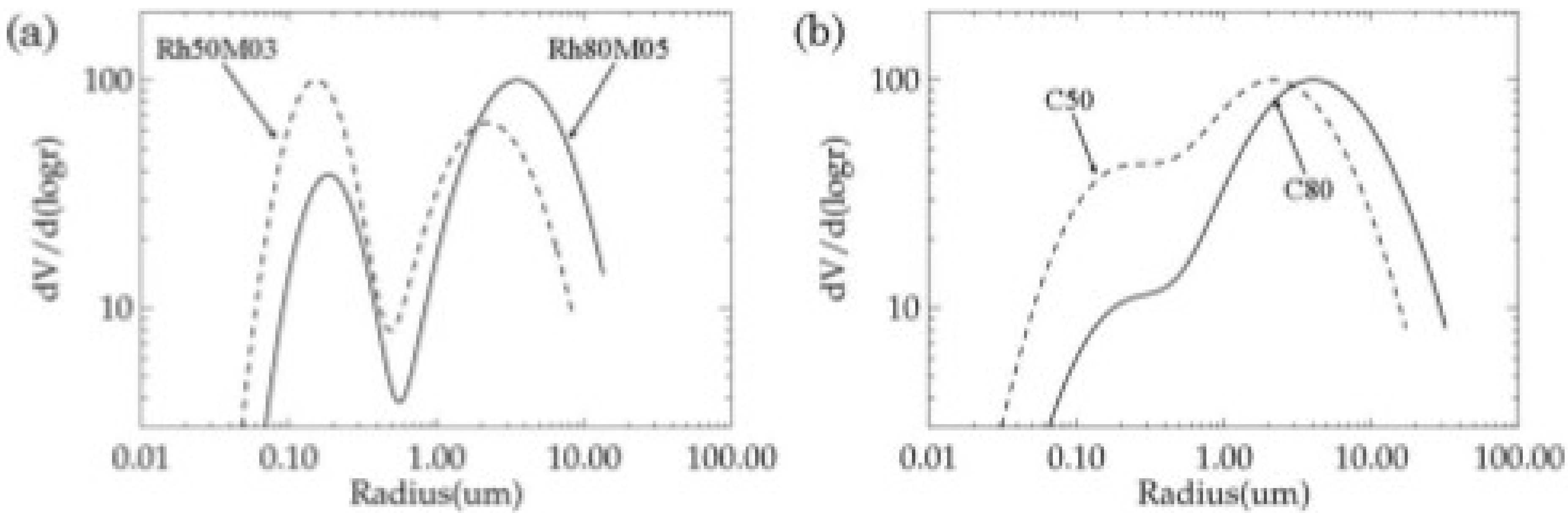
with Voi: volume of particles

r_{voi}: volume geometric mean radius

σ_i: geometric standard deviation

New NASA Aerosol models

- **<u>Ahmad et al. (2010):</u>**
  - Based on AERONET models
  - Bimodal lognormal distributions (narrower than previous models)



New NASA Aerosol models

- **<u>Ahmad et al. (2010):</u>**
  - Based on AERONET models
  - Bimodal lognormal distributions (narrower than previous models)
  - Modal radii and refractive indices as a function of relative humidity
  - Eight relative humidity values: 30, 50, 70, 75, 80, 85, 90 and 95%
  - For each RH: 10 distributions

  → 80 aerosol models

atmospheric correction & the “black pixel” assumption

$$\rho_t(\lambda) = \rho_w(\lambda) + \rho_g(\lambda) + \rho_f(\lambda) + \rho_r(\lambda) + \rho_a(\lambda)$$

TOA water glint foam air aerosols

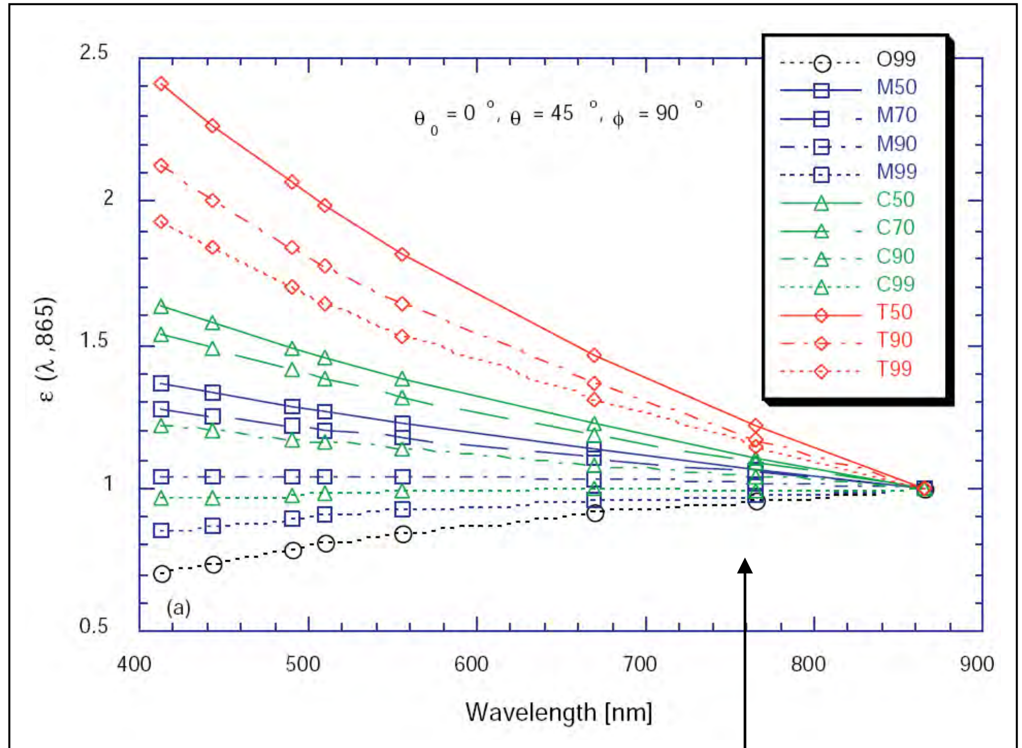
need $\rho_a(\lambda)$ to get $\rho_w(\lambda)$ and vice-versa

the “black pixel” assumption (pre-2000):

calculate aerosol ratios, ε :

$$\varepsilon(748,869) \approx \frac{\rho_a(748)}{\rho_a(869)}$$

$$\varepsilon(\lambda,869) \approx \frac{\rho_a(\lambda)}{\rho_a(869)}$$



$\varepsilon(748,869)$

Courtesy of J. Werdell

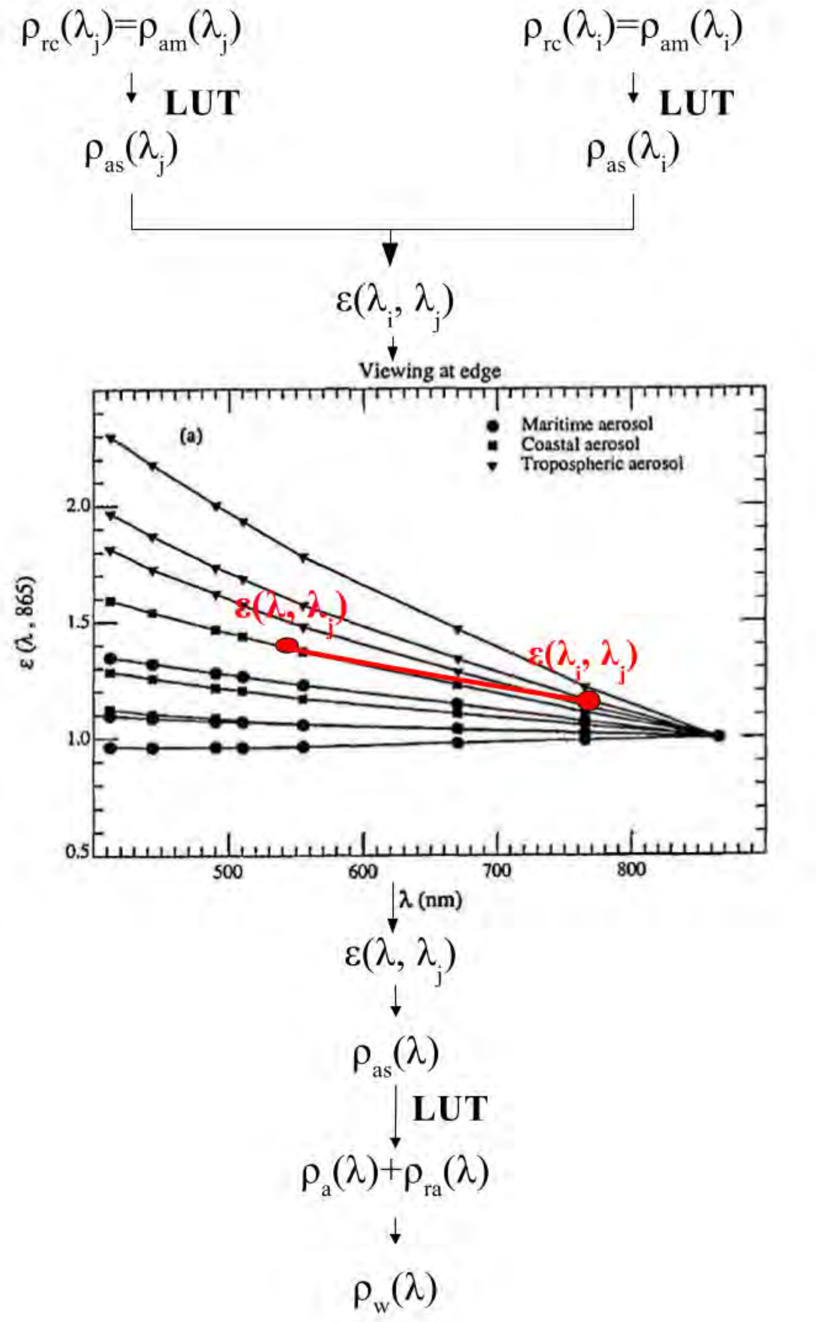
Black pixel assumption (Gordon and Wang, 1994)

<u>Based on hypothesis:</u>

Ocean is totally absorbant in NIR

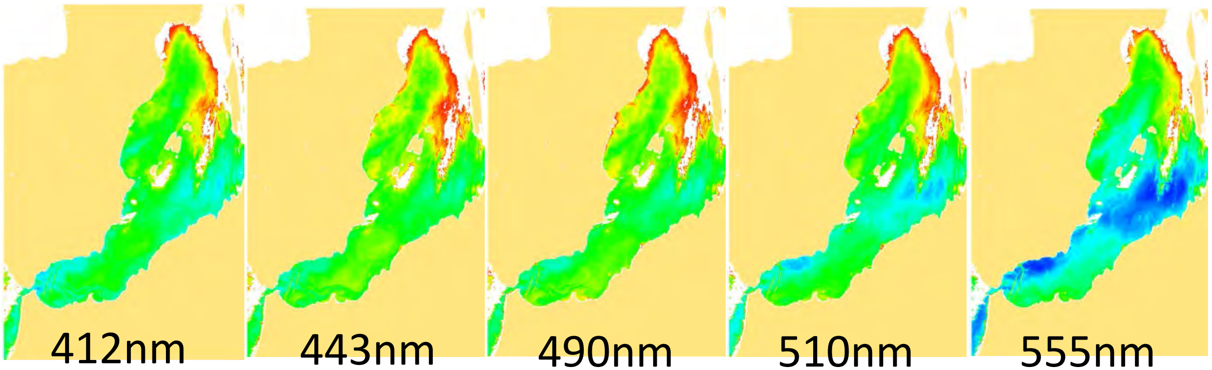
MERIS/OLCI AC based on same principle (Antoine and Morel, 1999):

- SF aerosol models + Dust model



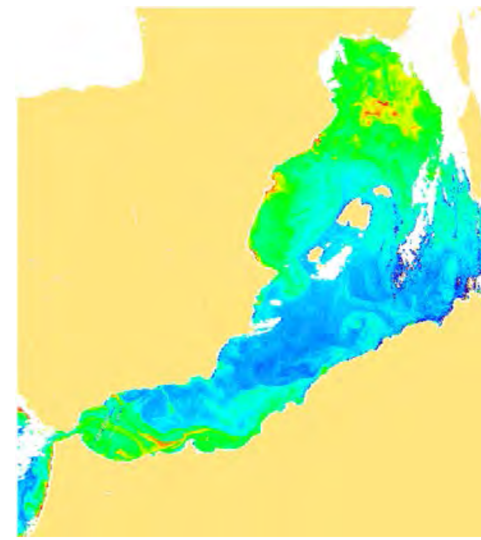
Standard processing (2/2)

In the visible, $(\rho_t(\lambda)-\rho_r(\lambda)-\rho_A(\lambda))/t(\lambda)= \rho_w(\lambda)$



Bio-optical algorithm

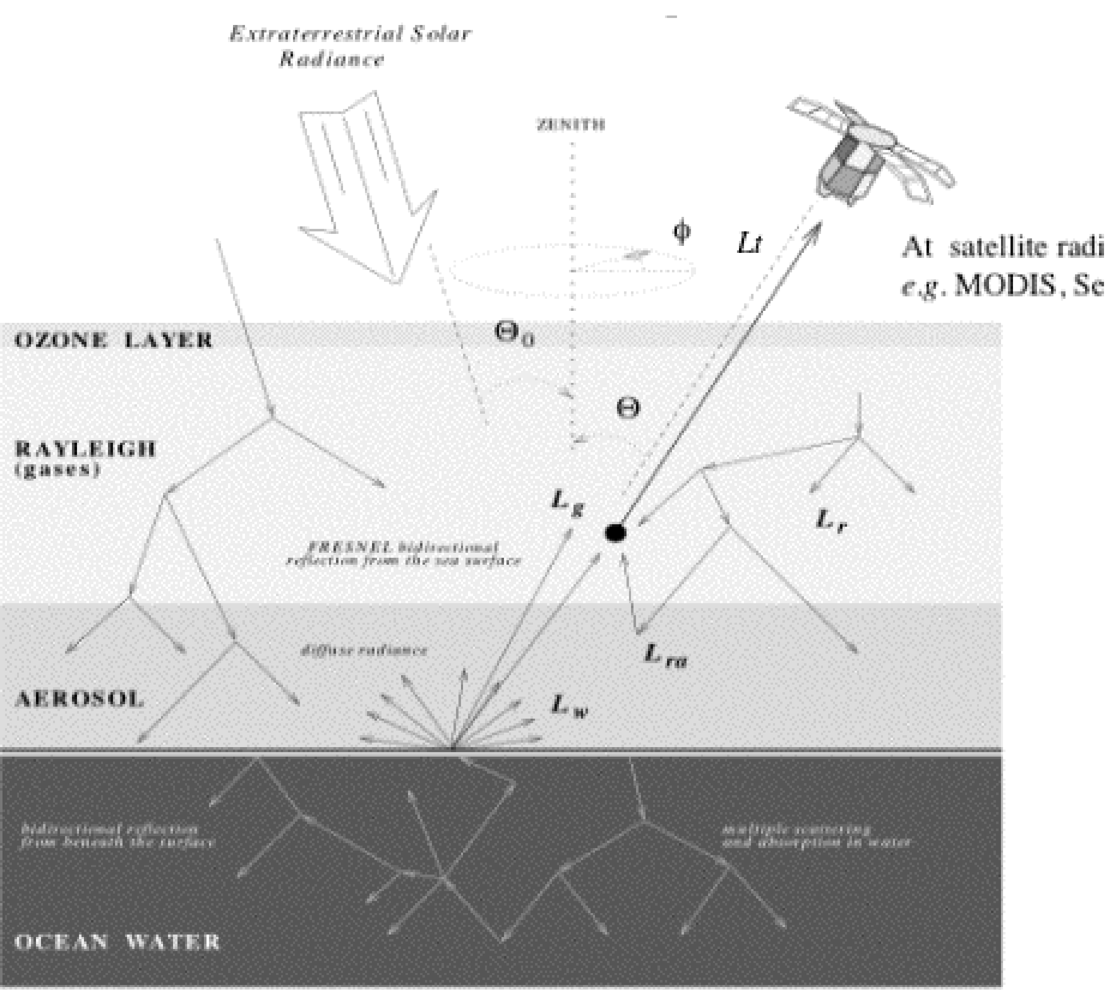
chl-a = $f(\rho_w(\lambda))$



Hypothesis: 1. Open Ocean

2. Non or weakly absorbing aerosols

atmosphere and ocean not coupled



$$\rho_t(\lambda) = \rho_r(\lambda) + \rho_a(\lambda) + \rho_{ra}(\lambda) + t(\lambda)\rho_{wc}(\lambda) + t(\lambda)\rho_w(\lambda) + t(\lambda)\rho_g$$

ρ_t: total (measured)

ρ_r: Rayleigh (known)

ρ_a: aerosols (unknown)

ρ_{ra}: Rayleigh-aerosols (unkown)

ρ_{wc}: foam (modelled/wind)

ρ_w: water (unknown, 10% of r_t)

ρ_g: glitter (masked or modelled)

Goal: 5% for absolute radiances and 2% for relative reflectances

Direct and diffuse transmittance

- **Direct transmittance:**

$$T(\theta_v,\lambda)=\exp[-(\tau_r(\lambda)+\tau_{oz}(\lambda)\tau_a(\lambda))/\cos(\theta_v)]$$

- **Diffuse transmittance:**

$$t(\theta_v,\phi_v)=\frac{\rho_w(\theta_v,\phi_v)_{TOA}}{\rho_w(\theta_v,\phi_v)}$$

Direct and diffuse transmittance

- **Diffuse transmittance:**

$$t(\theta_v, \phi_v, \lambda) = \exp\left[-\left(\frac{\tau_r(\lambda)}{2} + \tau_{oz}(\lambda)\right)\left(\frac{1}{\mu_v}\right)\right] t_a(\theta_v, \lambda)$$

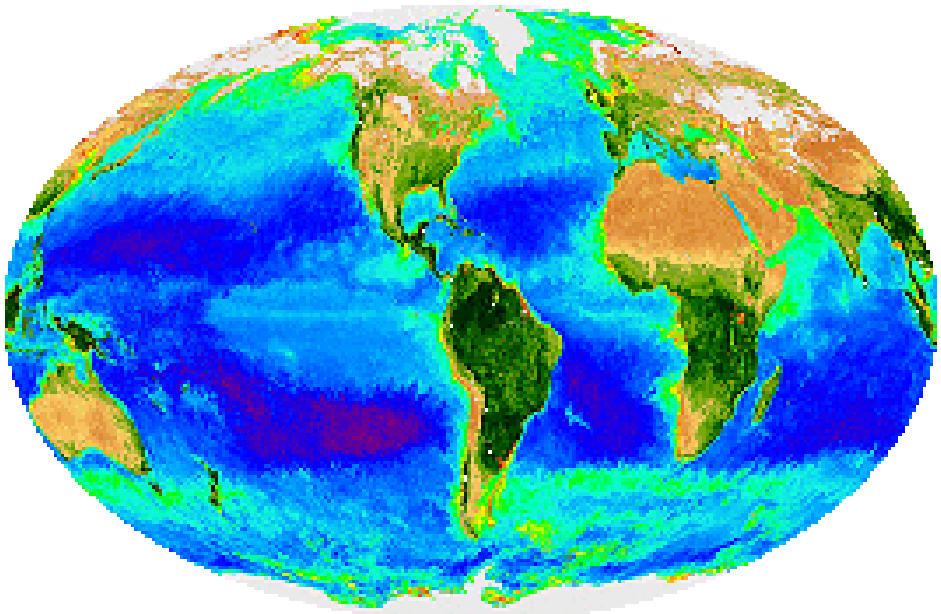
with

$$t_a(\theta_v, \lambda) = \exp\left[-\frac{\left[1 - \omega_a(\lambda) F_a(\mu_v, \lambda)\right]\tau_a(\lambda)}{\mu_v}\right]$$

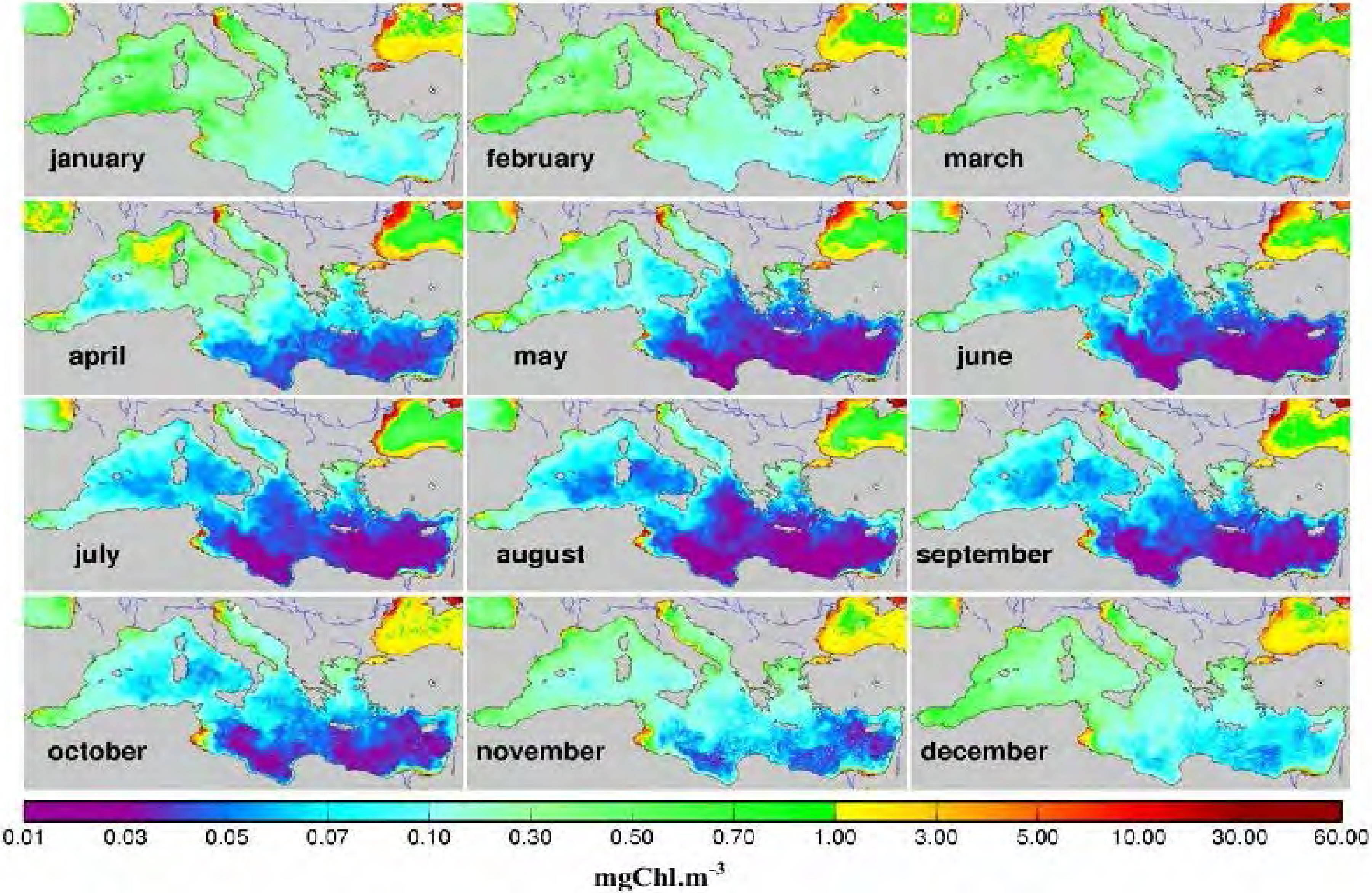
where

$F_a(\mu_v, \lambda)$ is related to the scattering phase function of the aerosol

Chlorophyll-a concentration: Historical product of remote sensing of ocean color

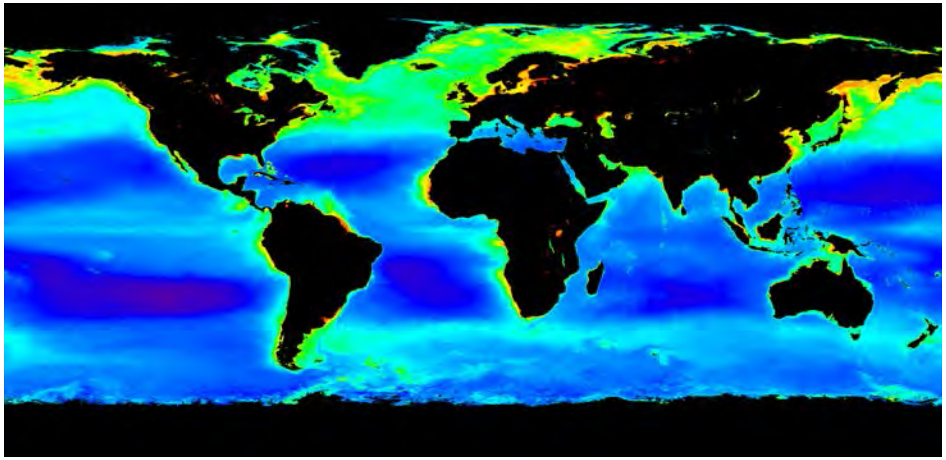


Source :http://oceancolor.gsfc.nasa.gov/

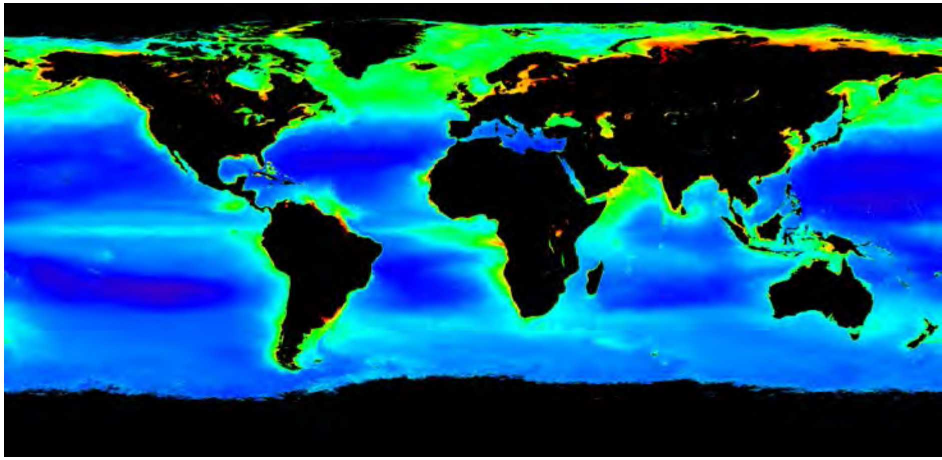


Monthly variability of the chlorophyll-a concentration in the Mediterranean Sea for 1999

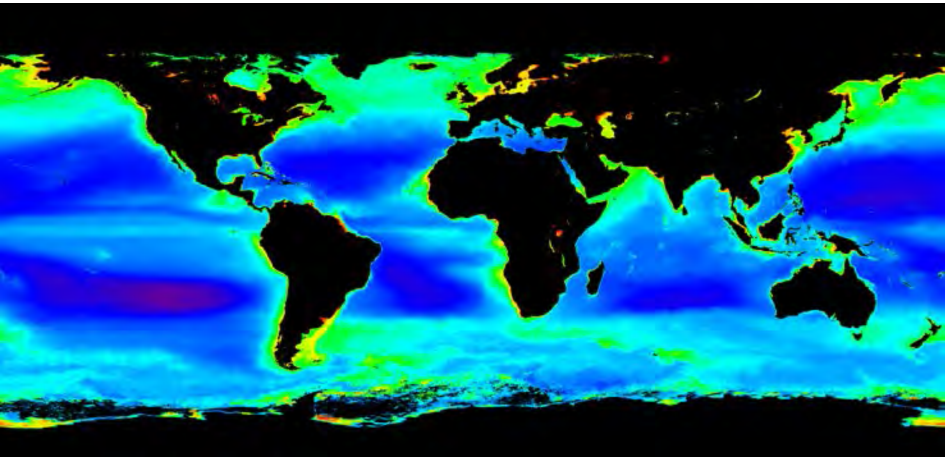
Bosc, 2004



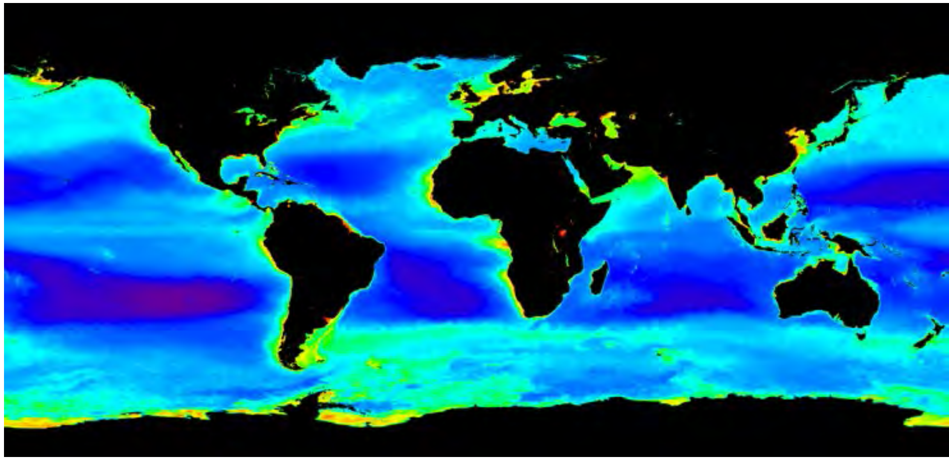
Spring



Summer



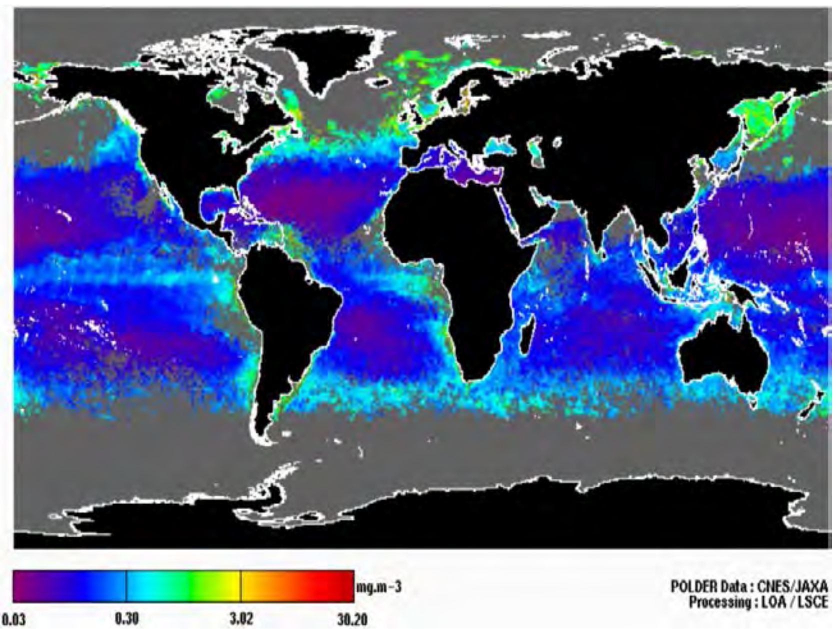
Fall



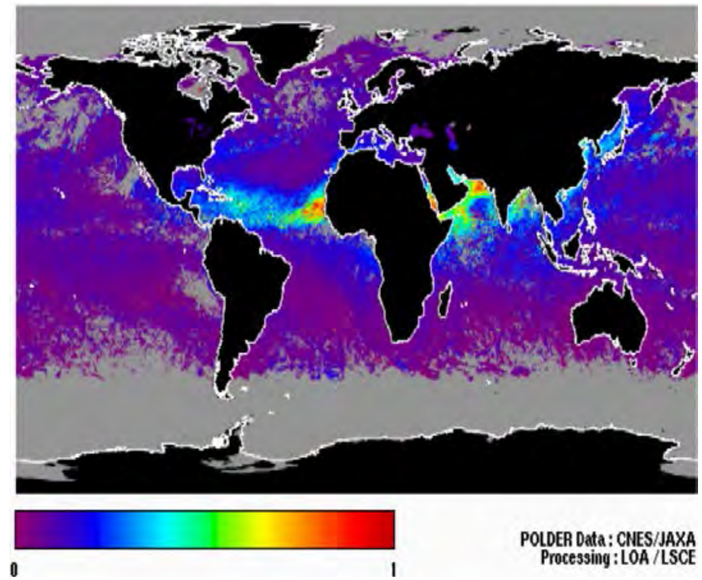
Winter

Seasonal mean of the chlorophyll-a concentraiton between 1997 and 2006 from SeaWiFS

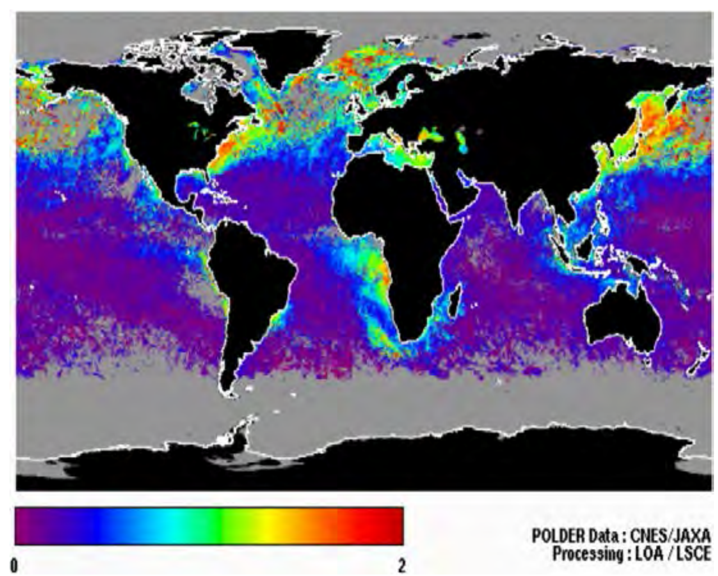
Secondary products: Aerosol optical properties



chl-a (POLDER 2)



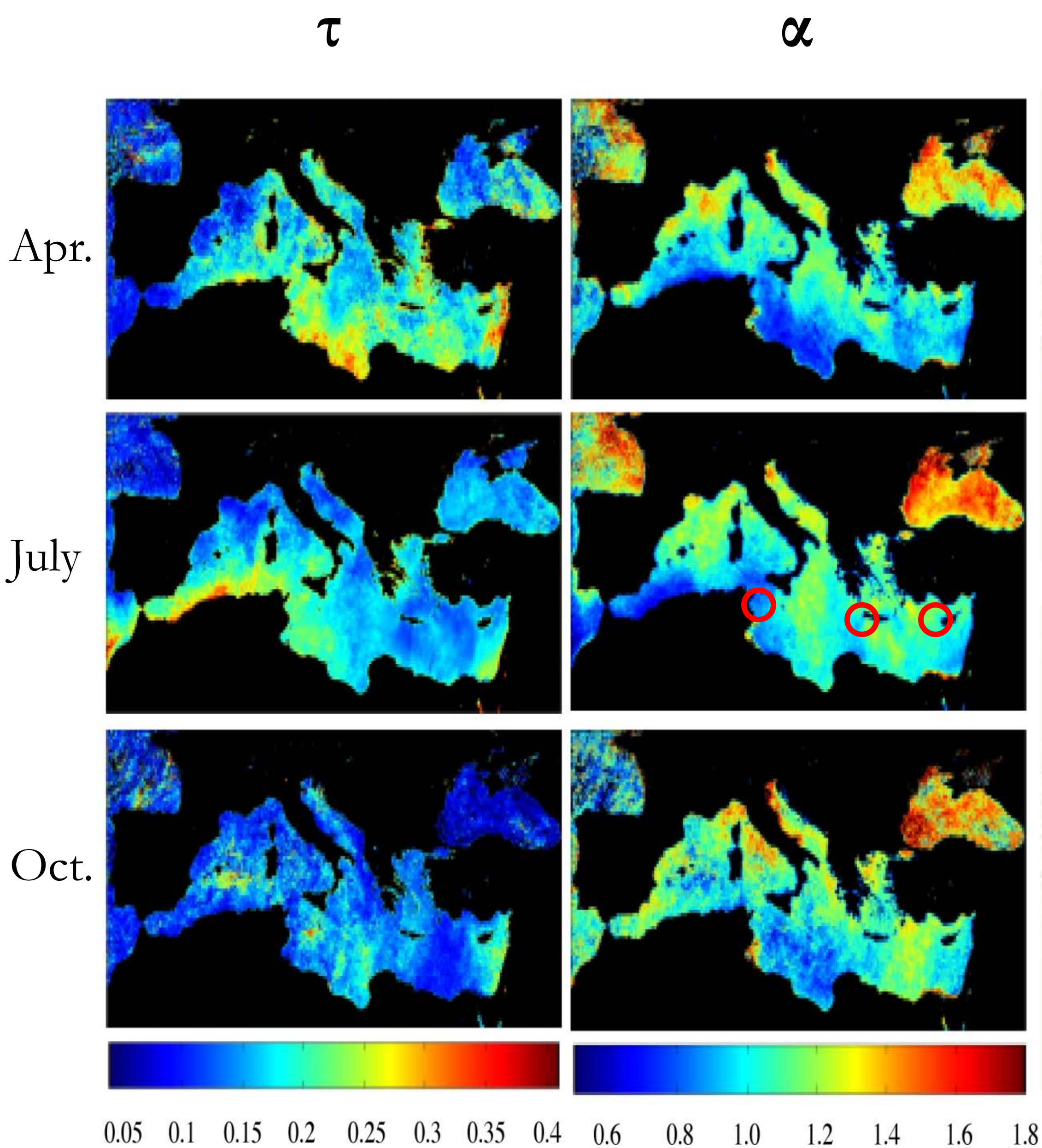
τ

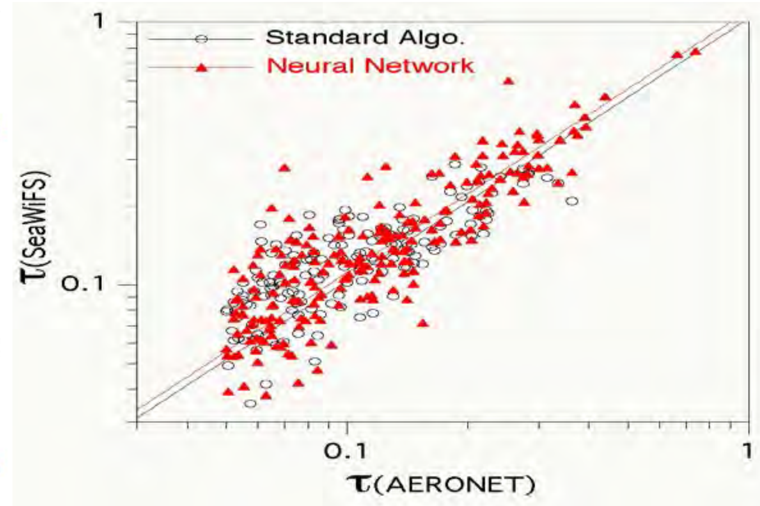


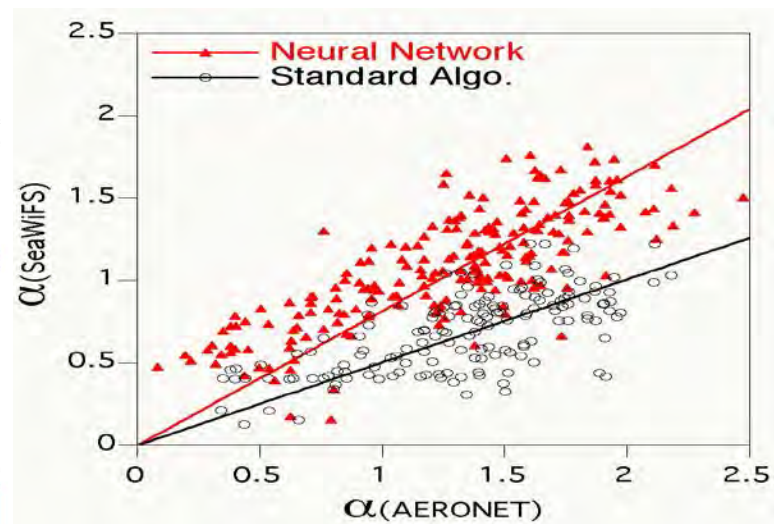
α

June 2003

Seasonal variability of aerosols in the Mediterranean Sea in 2000







Jamet et al., 2004

remote sensing of turbid, coastal waters is difficult

temporal & spatial variability

- satellite sensor resolution
- satellite repeat frequency
- validity of ancillary data (SST, wind)
- resolution requirements & binning options

straylight contamination (adjacency effects)

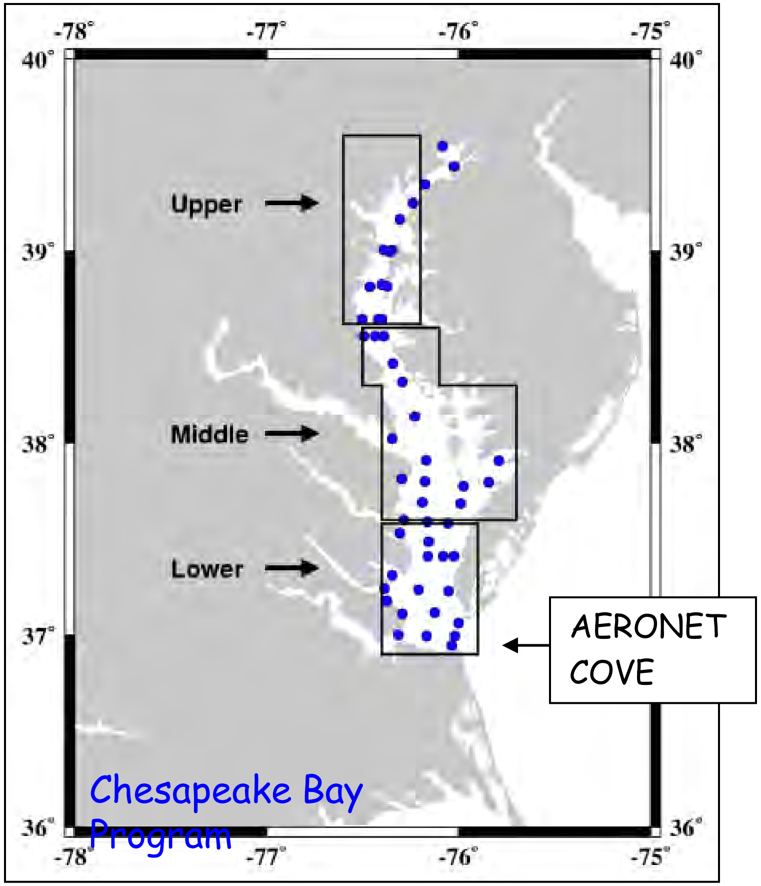
non-maritime aerosols (dust, pollution)

- region-specific models required?
- absorbing aerosols

suspended sediments & CDOM

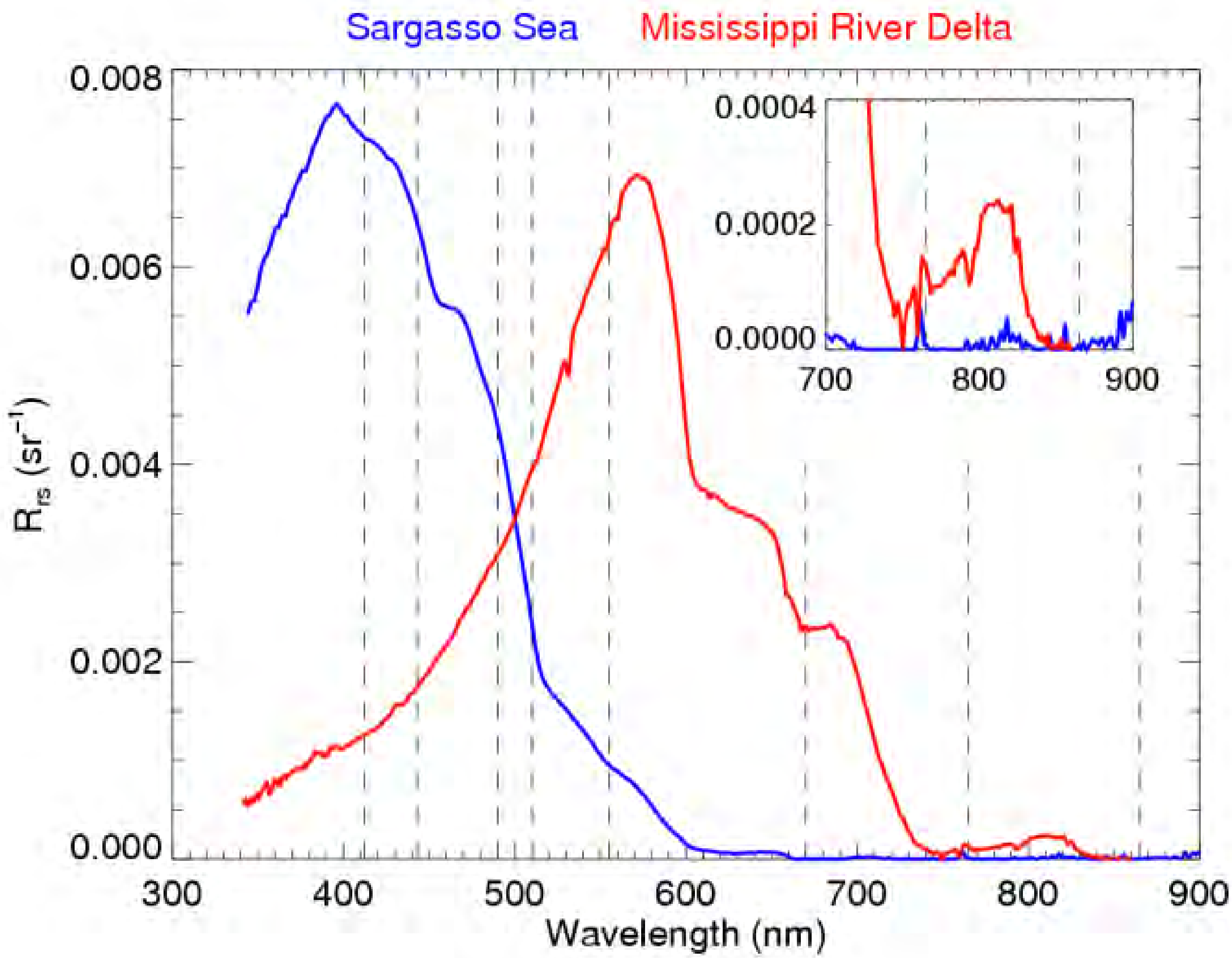
- complicates estimation of R_{rs}(NIR)
- complicates BRDF (f/Q) corrections
- saturation of observed radiances

anthropogenic emissions (NO_2 absorption)



From J. Werdell

no one uses the “black pixel assumption” anymore



From J. Werdell

approaches to account for R_{rs}(NIR) > 0 sr^{-1} overlap

many approaches exist, here are a few examples:

- assign aerosols (ε) and/or water contributions (Rrs(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)

Aiken et al. 1999	MERIS/OLCI
Bailey et al. 2010	NASA
Jiang and Wang 2014	MODIS
Shanmugam, 2012	any sensor
Wang et al. 2012	GOCI

- use a coupled ocean-atmosphere optimization

  e.g., Moore et al., 1999; Chomko & Gordon 2001, Stamnes et al. 2003, Jamet et al., 2005, Brajard et al., 2006a, b, 2008, 2012; Ahn and Shanmugam, 2007; Kuchinke et al. 2009; Steinmetz et al., 2010;
- Other

  e.g., Chen et al., 2014; Doerrfer et al., 2007; He et al., 2013; Mao et al., 2013, 2014; Schroeder et al., 2007; Singh and Shanmugam, 2014

approaches to account for $R_{rs}(NIR) > 0\ sr^{-1}$ overlap

many approaches exist, here are a few examples:

- assign aerosols (ε) and/or water contributions (Rrs(NIR))

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

- use shortwave infrared bands

  e.g., **Wang & Shi 2007 (similar than GW94 but using SWIR bands to determine aerosols)**

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

  Aiken et al. 1999 MERIS/OLCI

  Bailey et al. 2010 NASA

  Jiang and Wang 2014 MODIS

  Shanmugam, 2012 any sensor

  Wang et al. 2012 GOCI

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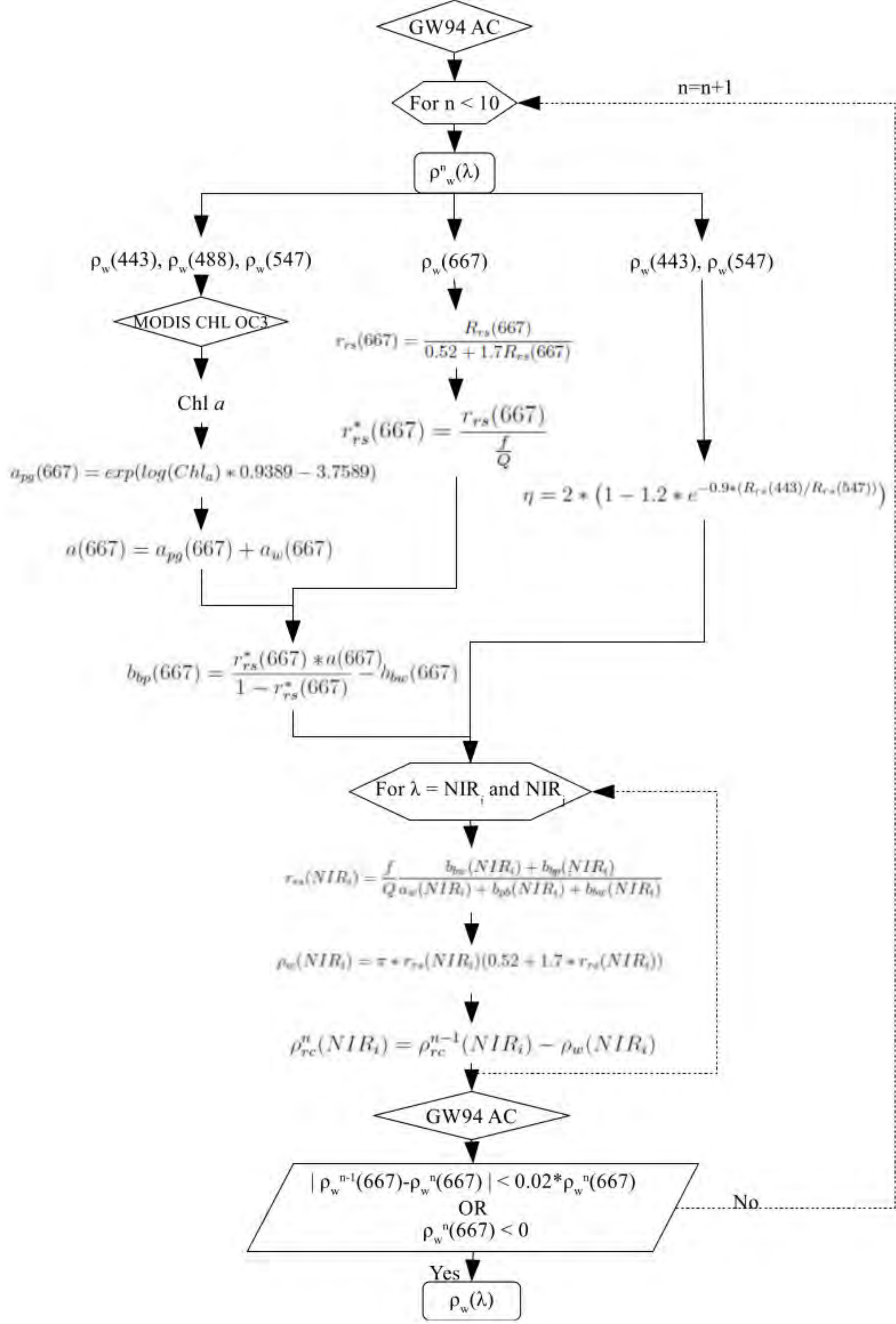
- Other

  e.g., Chen et al., 2014; Doerrfer et al., 2007; He et al., 2013; Mao et

NASA algorithm (GW94; Bailey et al., 2010)

<u>Based on hypothesis:</u>

- Iterative process
- NIR bio-optical model
- non-zero Lw(NIR) can be reconstructed from Lw(λ) in the red bands (667 nm) assuming a power-law function → Spectral dependence of $b_{bp}(\lambda)$
- Use GW94 as first guess



MUMM algorithm (Ruddick et al., 2000; 2006

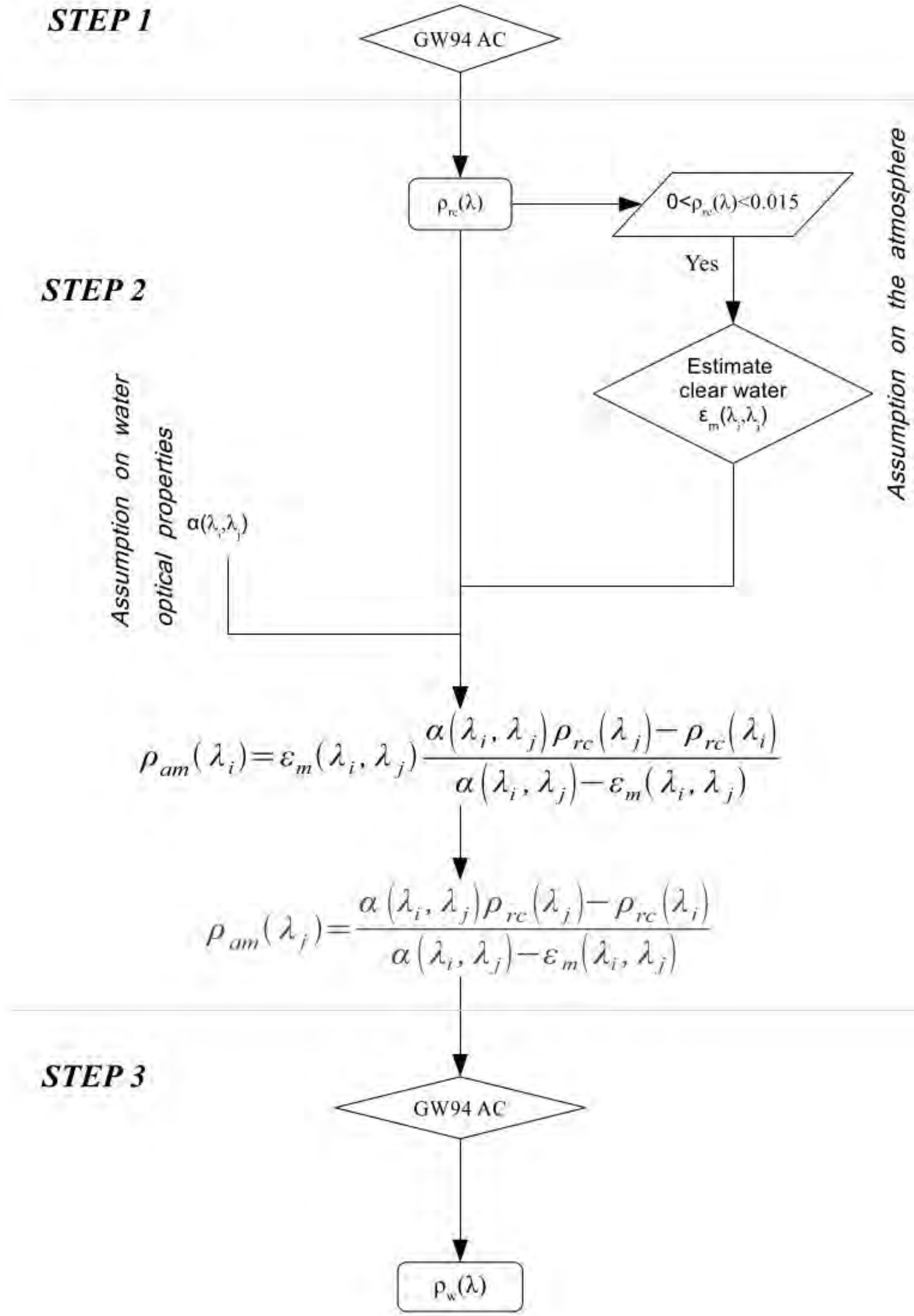
<u>Based on hypothesis:</u>

Spatial homogeneity of aerosol and water-leaving reflectances ratio in the NIR

→**<u>Definition of two parameters</u>**

→α (ocean): constant (sensor dependent)
→ε (aerosol): constant over region of interest → needs to be calculated for each image

Three steps AC



Polymer algorithm (Steinmetz et al., 2011)

1. Correction for gaseous absorption and Rayleigh scattering

2. Spectral matching using a model for atmosphere and glint + ocean reflectance:

$$\rho'_{\mathrm{TOA}}(\lambda) = \underbrace{T(\lambda)c_0 + c_1\lambda^{-1} + c_2\lambda^{-4}}_{\substack{\text{Atmosphere} \\ \text{+Sun glint model}}} + \underbrace{t(\lambda)\rho^{+}_{w,\mathrm{mod}}(\lambda,\mathrm{chl}, b_{bs})}_{\substack{\text{Ocean water} \\ \text{reflectance model}}}$$

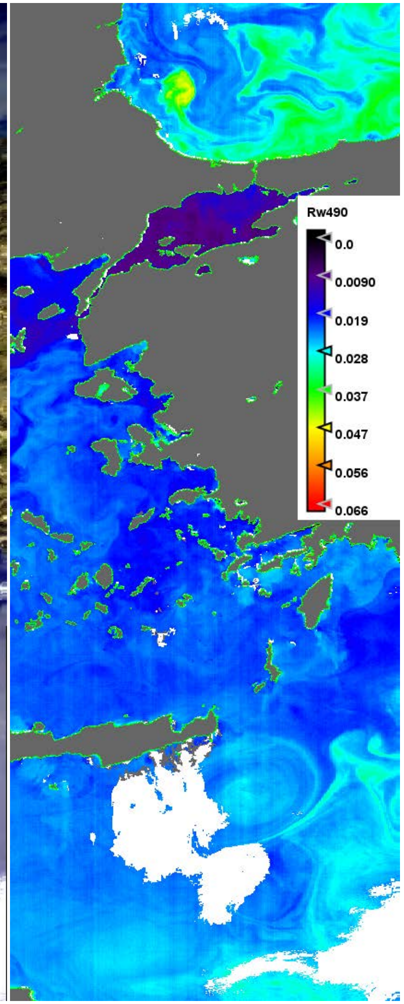
- Simultaneous optimization of 5 parameters
- Using the whole sensor spectrum (from 412 to 865 nm)

3. Iterative optimization using Nelder-Mead simplex method

Example of sun glint correction

Comparison of 2 scenes taken one day apart

With sun glint

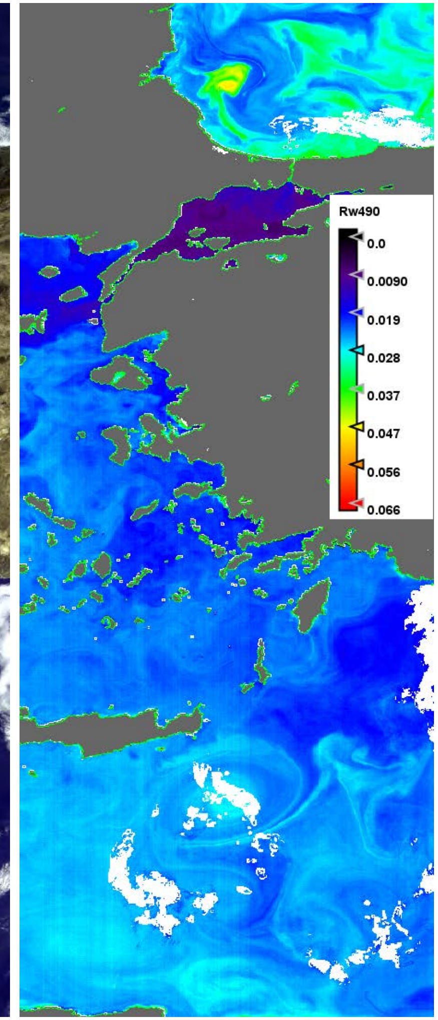


RGB composite

$\rho_w^+(490)$

May 14, 2007

Without sun glint

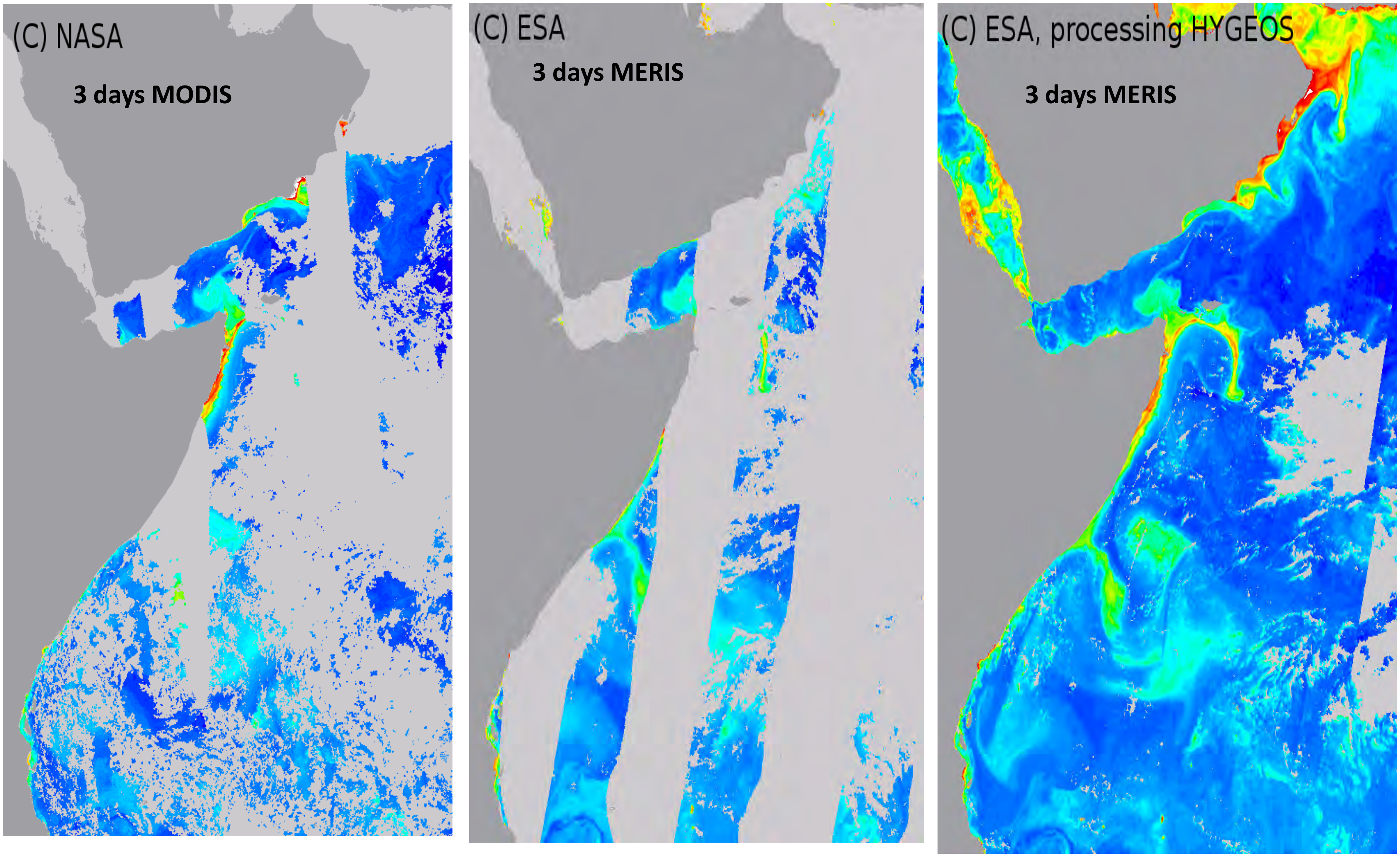


RGB composite

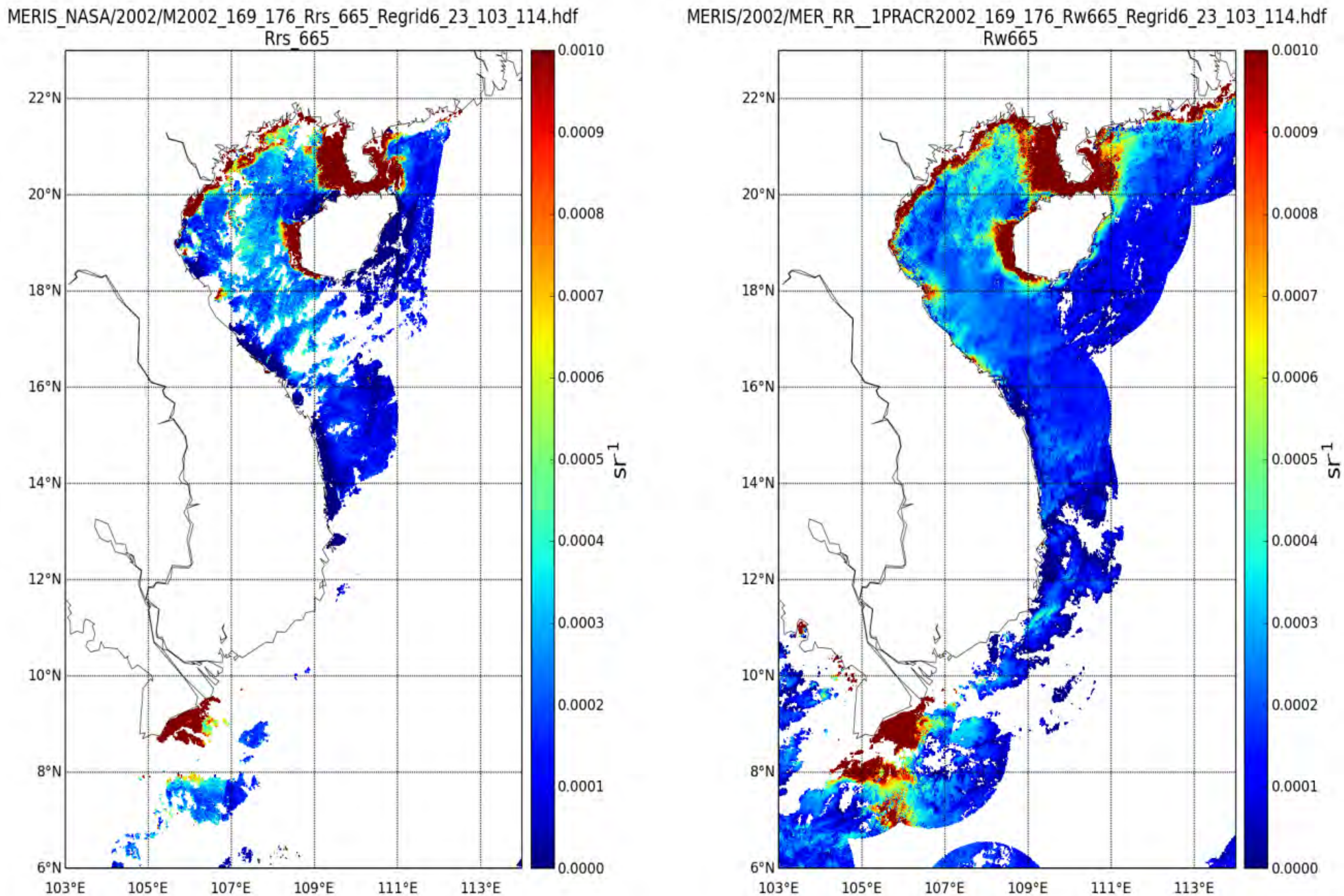
$\rho_w^+(490)$

May 15, 2007

Polymer algorithm



Adaptation of the optimization technique used in the POLYMER algorithm (Steinmetz et al., 2010) for coastal regions (ANR GlobCoast)



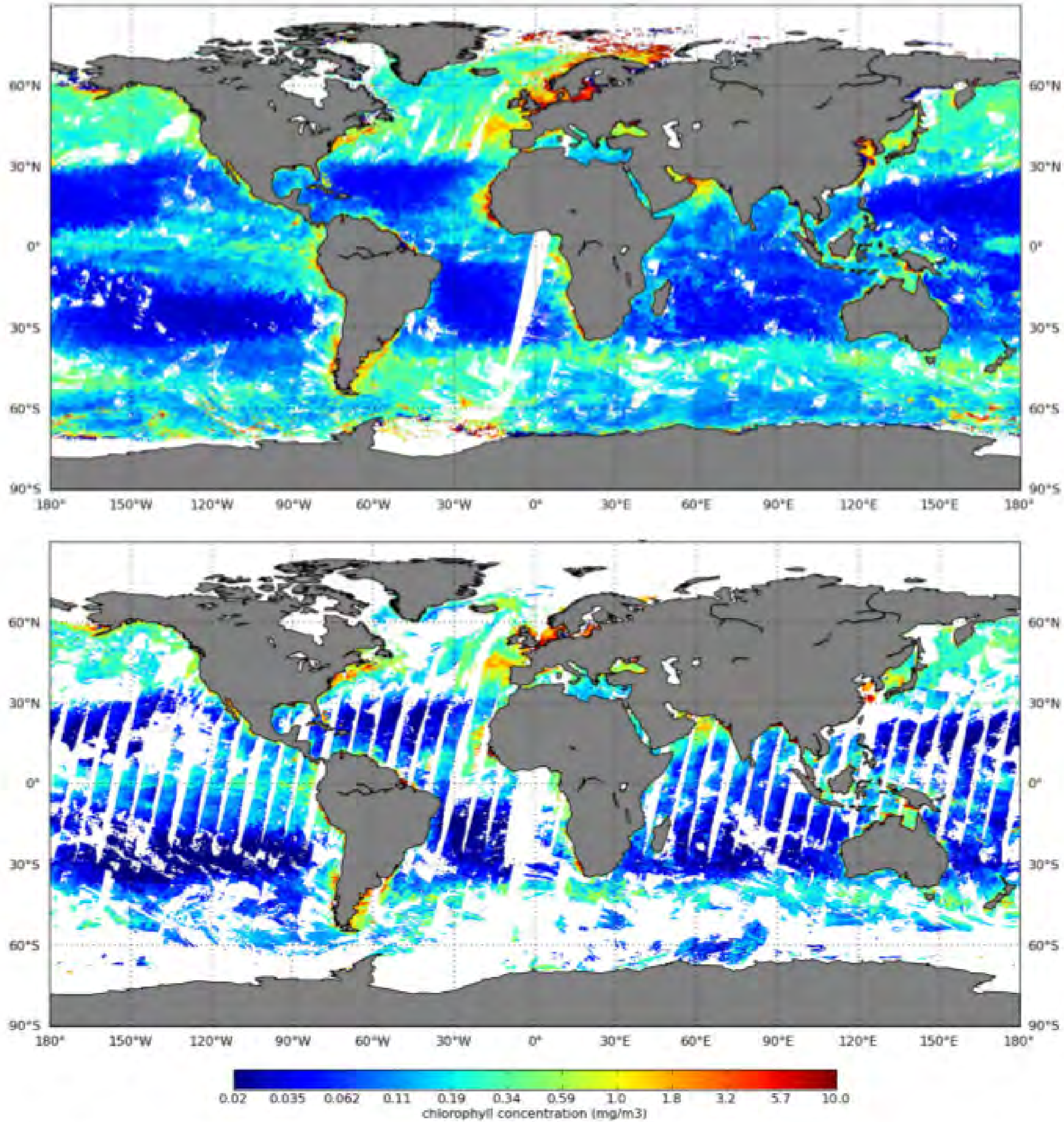
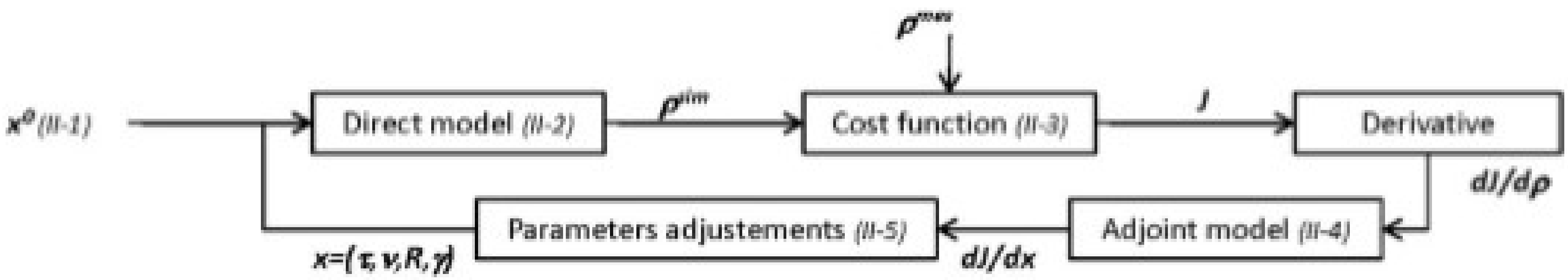


Fig. 1. MERIS 3-day composite chlorophyll retrieval (March 20th to 22nd 2003) processed with POLYMER (top) and with the standard MEGS processor (bottom). The coverage for POLYMER is doubled (73% compared to 35.5%) mainly due to retrieval under sun glint conditions.

Müller et al. (2014)

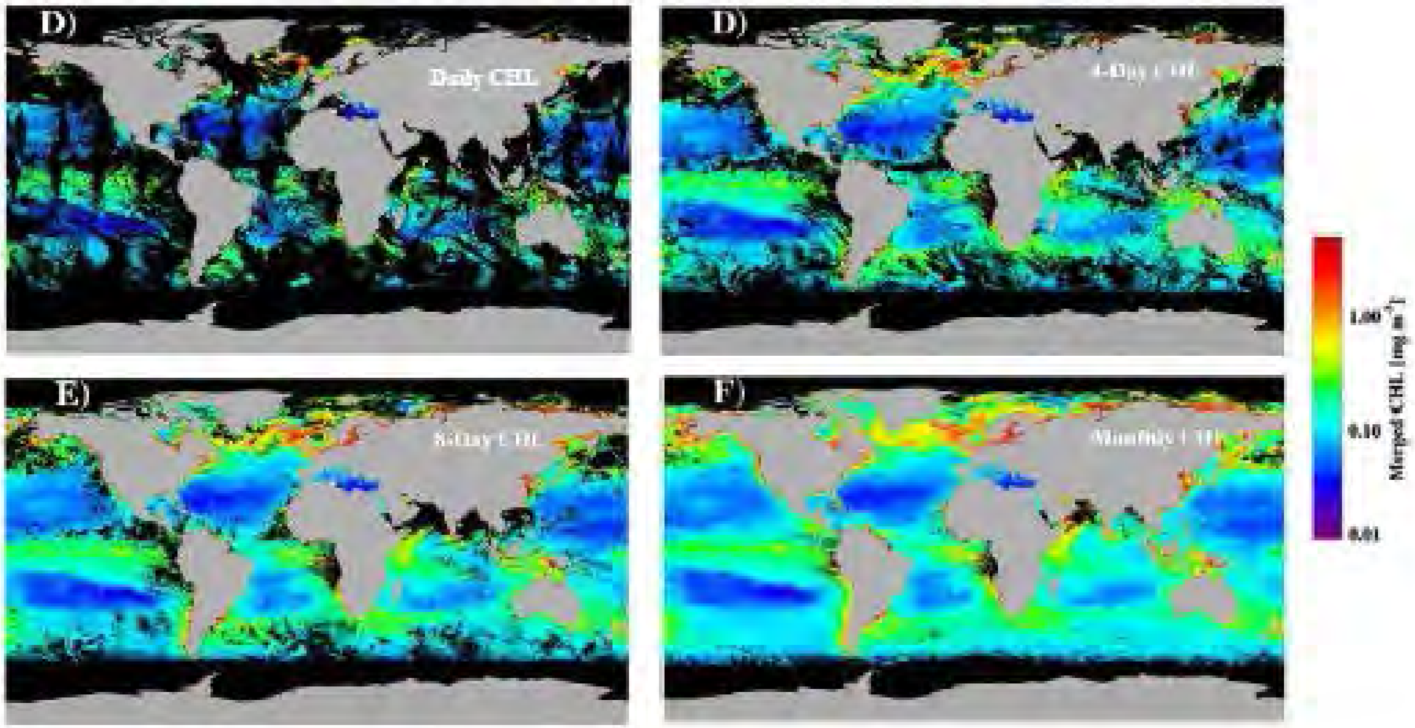
Spectral matching/optimization algorithm

- Chomko et al. (1998); Kuchinke et al. (2009)
- Jamet et al. (2004); Brajard et al. (2010)
- Li et al. (2003); Stamnes et al. (2005)



- Ocean and atmosphere are coupled
- Use of LUT or NN or … for simulating (La+Lra, t, Lw)
- Allow to deal with absorbing aerosols/coastal waters

Which coverage?



	Average percentage cover of the ocean (standard deviation)			
	SeaWiFS	MODIS-AQUA	MERIS	MERGED
Daily	14.58 (1.03)	11.81 (1.03)	7.77 (1.05)	25.22 (1.88)
4-Day	41.62 (4.67)	33.91 (2.97)	25.18 (4.97)	56.98 (6.24)
8-Day	59.06 (6.72)	51.31 (4.52)	40.23 (6.90)	72.50 (7.59)
Monthly	82.95 (9.79)	79.43 (4.75)	73.34 (9.47)	87.69 (8.87)

Validation of atmospheric correction (1/10)

- **Match-ups definition:**

  - Co-location of in-situ dataset and satellite images
  - Time difference criteria: open of coastal waters? +/- 1h or +/- 3h?
  - Extraction of satellite data over a box of several pixels: 3x3 or 5x5 or ...?
  - Calculation of satellite mean values only for valid pixels:

Bailey and Werdell, 2006

Different types of satellite data

Level 0

Level 0 data are unprocessed instrument/payload data at full resolution. Any artifacts of the communication (e.g. synchronization frames, communication headers) of these data from the spacecraft to the ground station have been removed. These data are the most raw format available, and are only provided for a few of the missions that we support.

Level 1A

Level 1A data are reconstructed, unprocessed instrument data at full resolution, time-referenced and annotated with ancillary information including radiometric and geometric calibration coefficients and georeferencing parameters (e.g. platform ephemeris data) computed and appended but *not* applied to the Level 0 data. **It is this last point that makes Level 1A the preferred archival data level. If the sensor calibration changes, the data *do not need to be reacquired* — no mean feat where large data sets are concerned. The same is not true for Level 1B data (described below) which must be replaced every time the sensor calibration changes.**

Level 1B

Level 1B data are Level 1A data that have had instrument/radiometric calibrations applied.

Level 2

Level 2 data consist of derived geophysical variables at the same resolution as the source Level 1 data. These variables are grouped into a few product suites

Level 3

Level 3 data are derived geophysical variables that have been aggregated/projected onto a well-defined spatial grid over a well-defined time period.

Different types of satellite data

Level 0

Level 0 data are unprocessed instrument/payload data at full resolution. Any artifacts of the communication (e.g. synchronization frames, communication headers) of these data from the spacecraft to the ground station have been removed. These data are the most raw format available, and are only provided for a few of the missions that we support.

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Level 3

Level 3 data are derived geophysical variables that have been aggregated/projected onto a well-defined spatial grid over a well-defined time period.

Flags system

Examples of flags when processing SeaWiFS, MODIS and VIIRS data With the NASA SeaDAS software

In red:
Flags for L2/L3 products

→ To assure the radiometric quality of the data

→ To remove the « noisy » pixels

Bit	Name	Description
01	**ATMFAIL**	Atmospheric correction failure
02	**LAND**	Pixel is over land
03	BADANC	Reduced quality of ancillary data
04	**HIGLINT**	High sun glint
05	**HILT**	Observed radiance very high or saturated
06	**HISATZEN**	High sensor view zenith angle
07	COASTZ	Pixel is in shallow water
08	NEGLW	Negative water-leaving radiance retrieved
09	**STRAYLIGHT**	Straylight contamination is likely
10	**CLDICE**	Probable cloud or ice contamination
11	**COCCOLITH**	Coccolithofores detected
12	TURBIDW	Turbid water detected
13	**HISOLZEN**	High solar zenith
14	HITAU	High aerosol optical thickness
15	**LOWLW**	Very low water-leaving radiance (cloud shadow)
16	**CHLFAIL**	Derived product algorithm failure
17	**NAVWARN**	Navigation quality is reduced
18	ABSAER	possible absorbing aerosol (disabled)
19	TRICHO	Possible trichodesmium contamination
20	**MAXAERITER**	Aerosol iterations exceeded max
21	MODGLINT	Moderate sun glint contamination
22	**CHLWARN**	Derived product quality is reduced
23	**ATMWARN**	Atmospheric correction is suspect
24	DARKPIXEL	Rayleigh-subtraced radiances is negative
25	SEAICE	Possible sea ice contamination
26	**NAVFAIL**	Bad navigation
27	**FILTER**	Pixel rejected by user-defined filter
28	SSTWARN	SST quality is reduced
29	SSTFAIL	SST quality is bad
30	HIPOL	High degree of polarization
31	spare	spare
32	OCEAN	not cloud or land

Flags system

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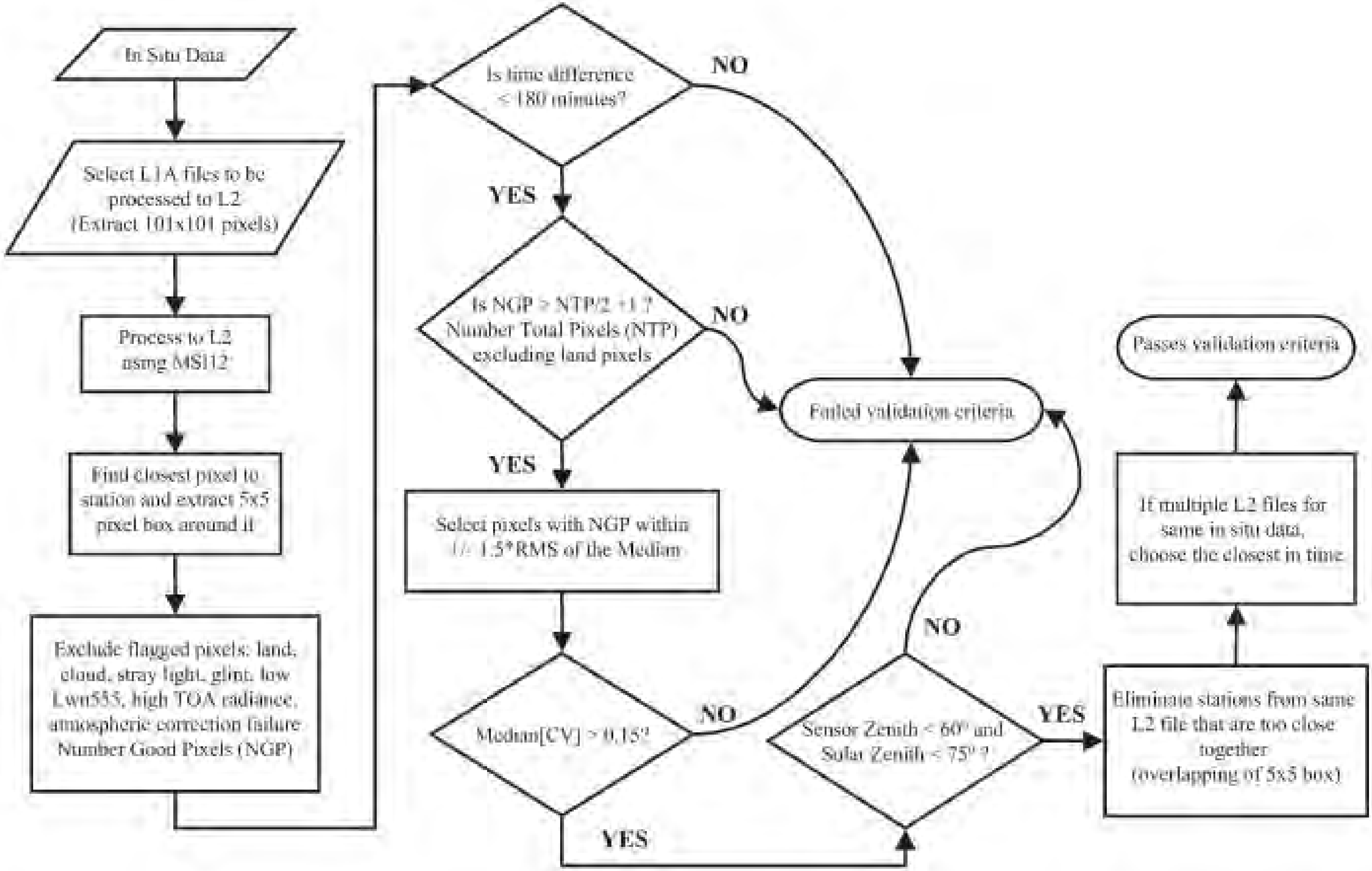
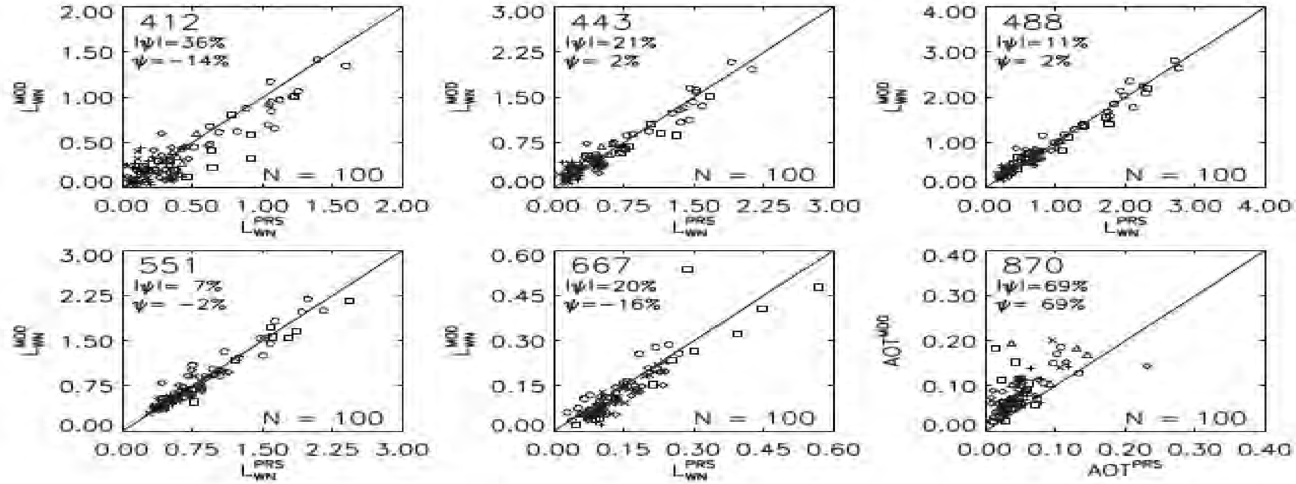
  - Time difference criteria: open of coastal waters? +/- 1h or +/- 3h?
  - Extraction of satellite data over a box of several pixels: 3x3 or 5x5 or …?
  - Calculation of satellite mean values over the box only for valid pixels: how many pixels? At least 50% or 100% or X%?
  - Calculation of variability coefficient $\sigma/\langle x\rangle$: only values <0.2 or <…? On which parameters?

Bailey and Werdell, 2006



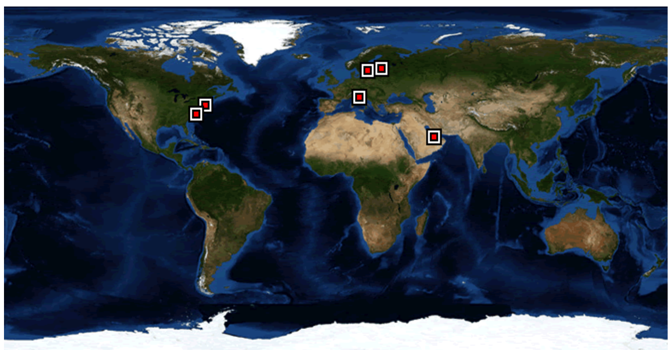
Bailey and Werdell, 2006

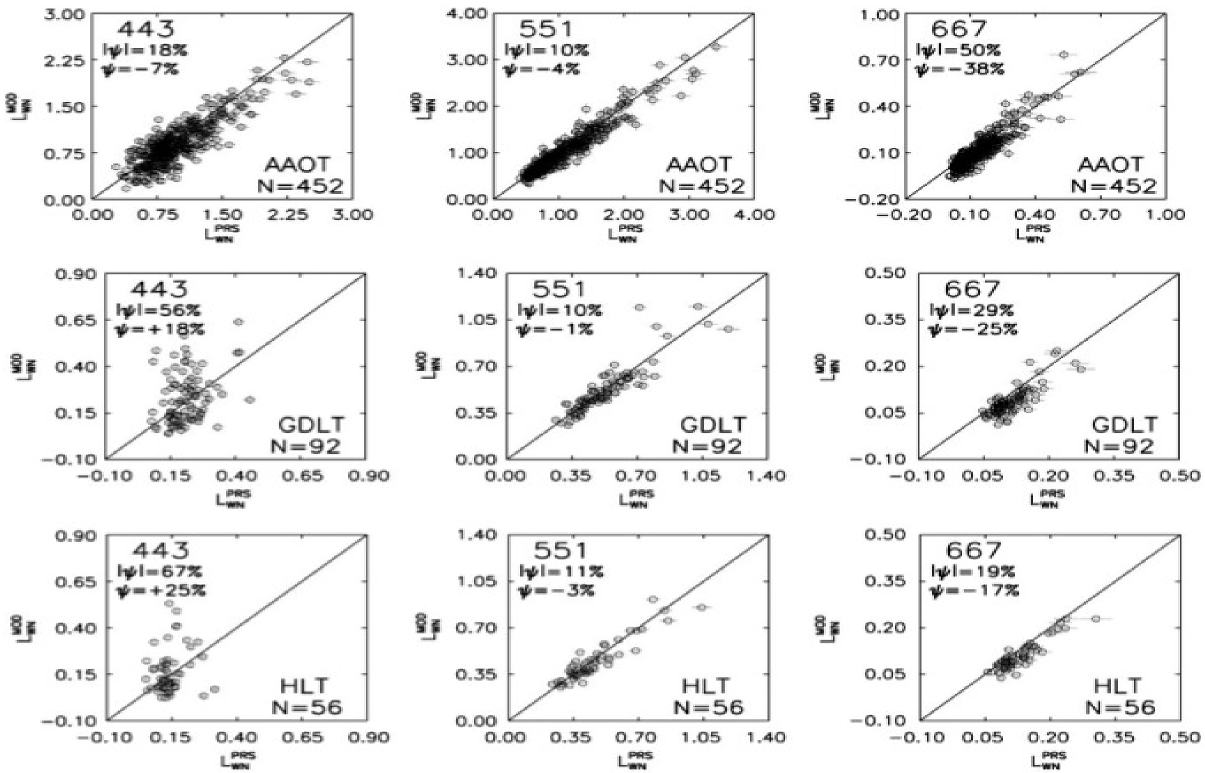


Zbibordi et al. (2009)

AERONET-OC sites:

- Mainly open ocean
- Absorbing oceans





Zibordi et al. (2010)

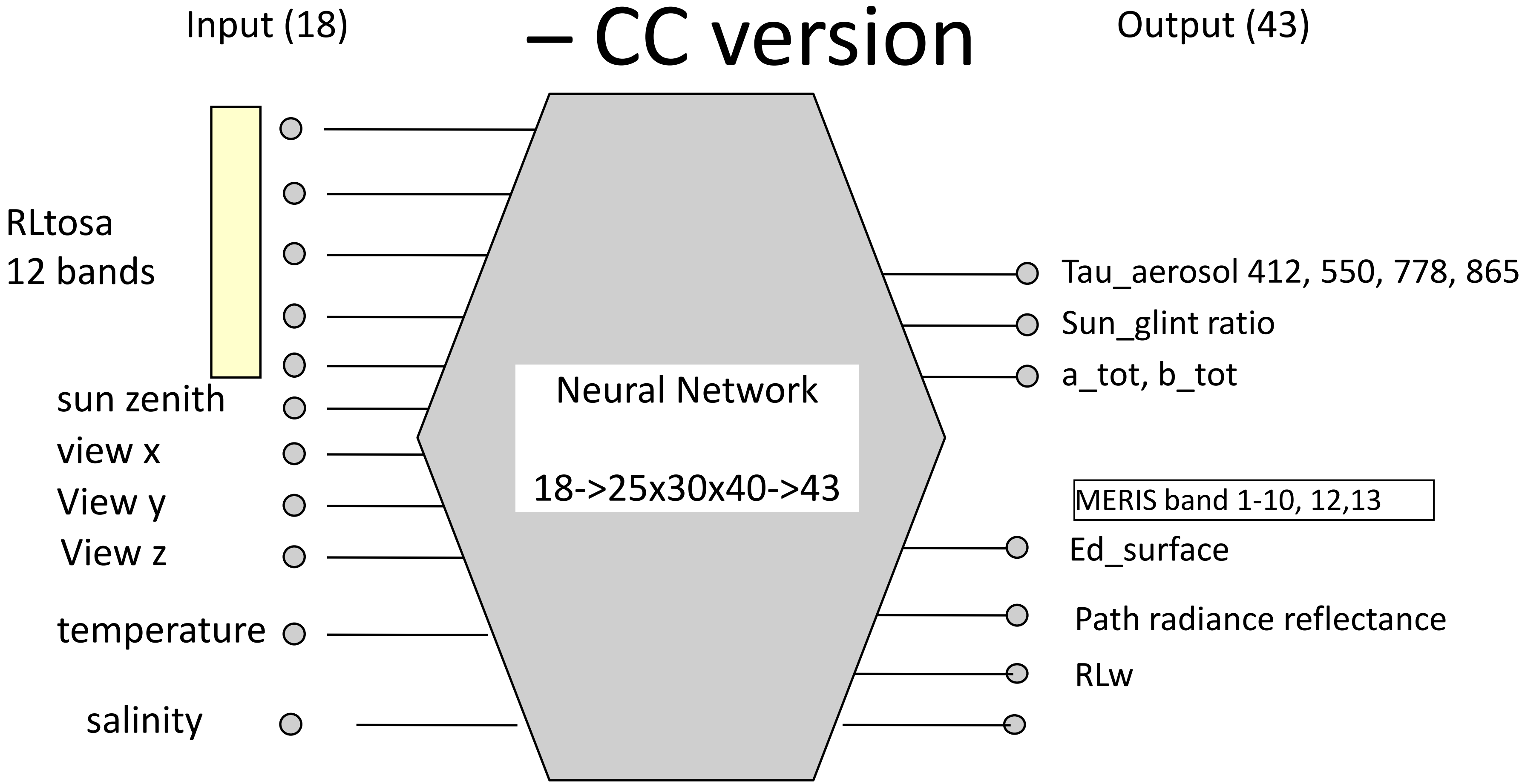
MERIS AC (CCI-OC) round –robin comparison in open ocean

Dataset: Mermaid dataset (http://mermaid.acri.fr/home/home.php)

Four AC:

- NASA standard
- MERIS standard (Antoine and Morel (1999), MEGS)
- C2R (NN, Doerffer et al., 2007)

Inverse NN for atmospheric correction – CC version



$RLw(\theta,\phi) = Lw(\theta,\phi) / Ed$

For each water type

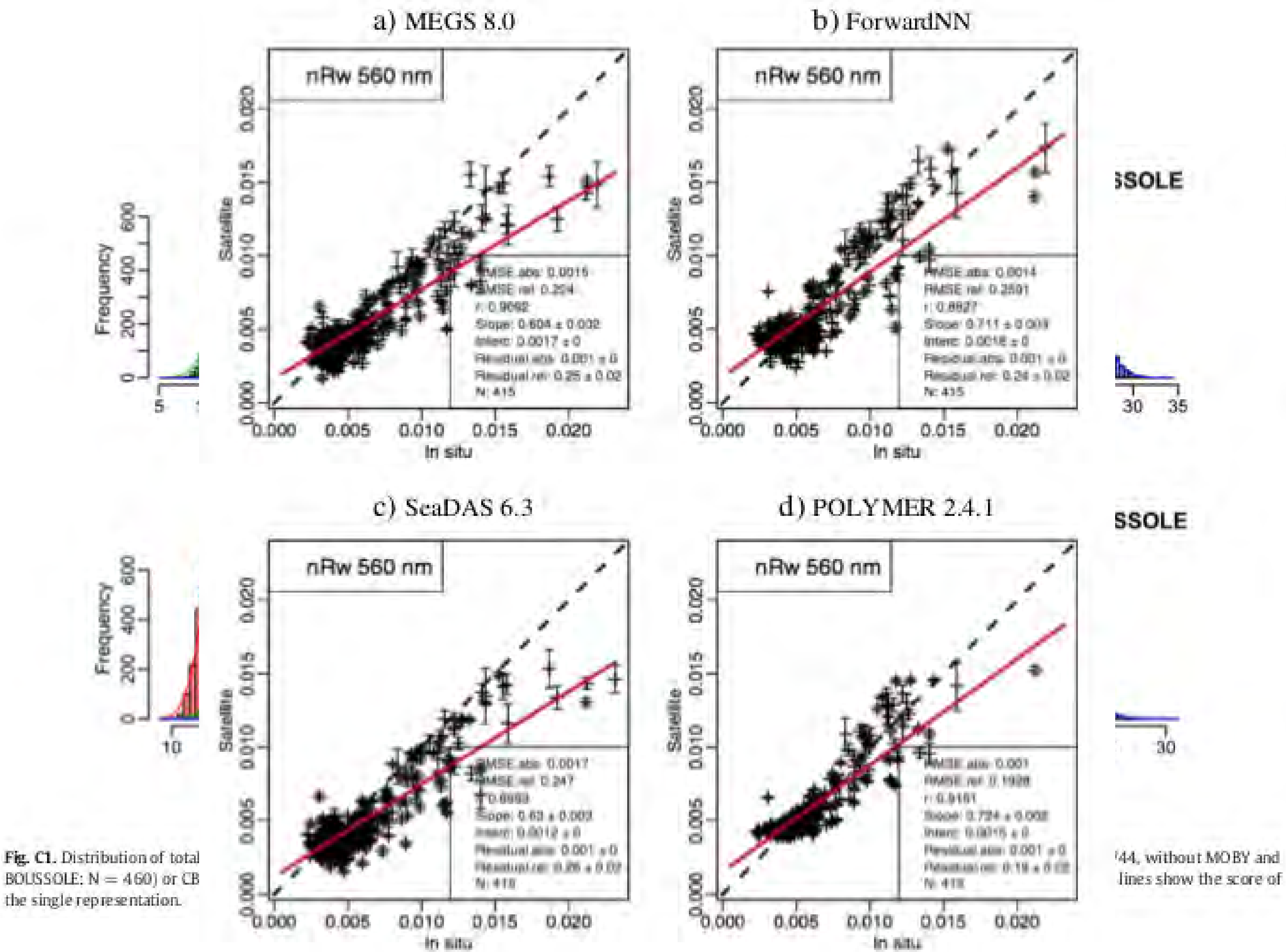
MERIS AC (CCI-OC) round –robin comparison in open ocean

Dataset: Mermaid dataset (http://mermaid.acri.fr/home/home.php)

Four AC:

- NASA standard
- MERIS standard (Antoine and Morel (1999), MEGS)
- C2R (NN, Doerffer et al., 2007)
- POLYMER (Steinmetz et al., 2010)

MERIS AC (CCI-OC) round –robin comparison in open ocean



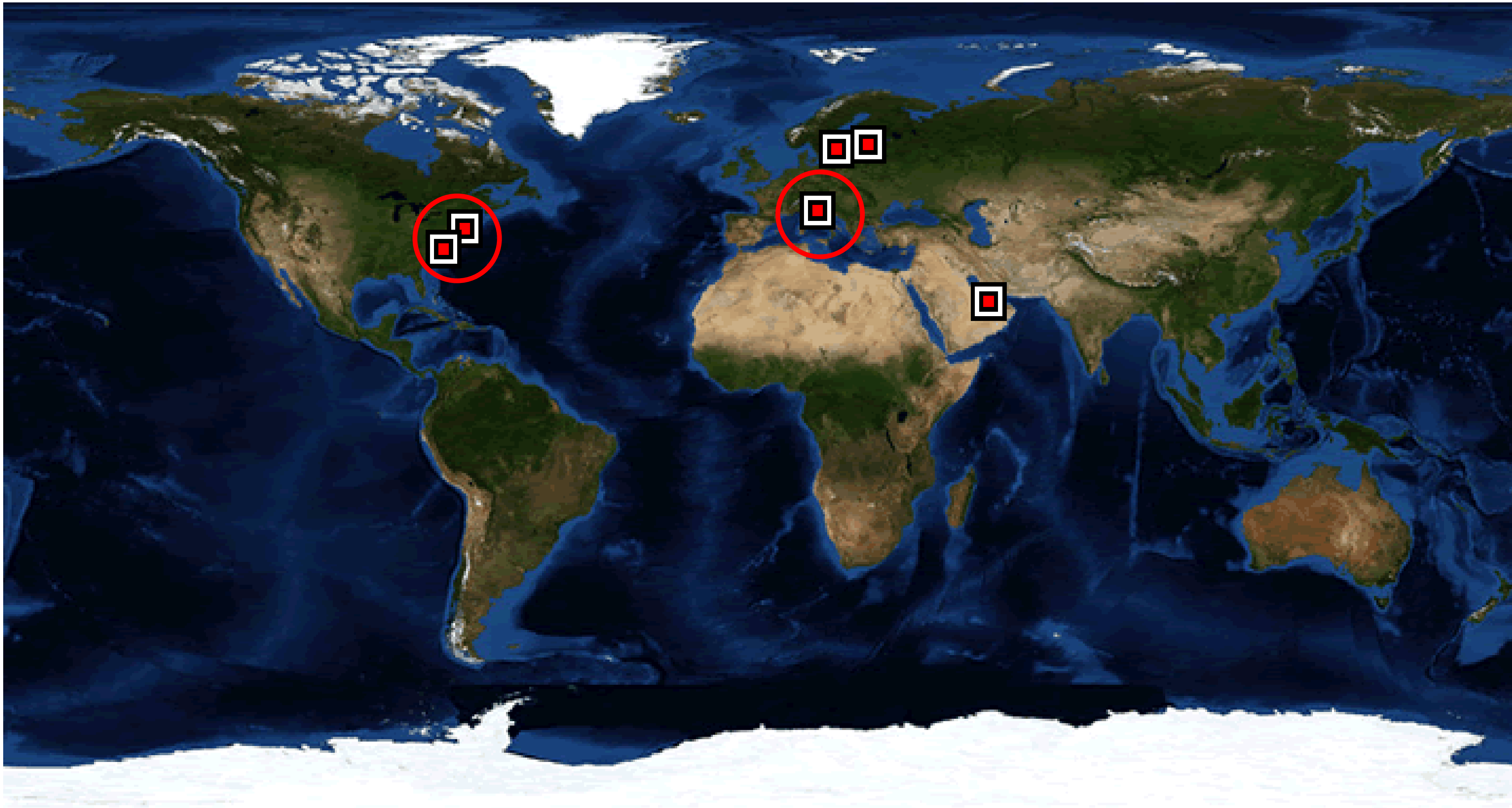
Müller et al. (2014a)

Atmospheric Correction Algorithms over turbid waters

- Three NIR ocean contribution removing/AC algorithms (Jamet et al., RSE, 2011)
  - Stumpf et al. (2003)/ Bailey et al., (2010) S03:
    - Based on Gordon and Wang atmospheric correction (GW94)
    - SeaWiFS/MODIS standard algorithm
    - Iterative process
    - Bio-optical model used to determine $b_b(670)$
  - Ruddick et al. (2000) R00:
    - Based on Gordon and Wang atmospheric correction (GW94)
    - Spatial homogeneity of the L_w(NIR) and L_A(NIR) ratios over the subscene of interest
    - α: Ratio of L_w(NIR) cst = 1.72
    - ε: Ratio of L_A(NIR) determined for each subscene
  - Kuchinke et al. (2009) K09:
    - Spectral optimization algorithm
    - Junge aerosol models
    - GSM bio-optical model (Garver, 2002)
    - Atmosphere and ocean coupled

DATA

- Satellite data:
  - (M)LAC SeaWiFS 1km at nadir → Processed with SeaDAS 6.1 (R2009) (Fu et al., 1998)
  - nLw(412→865), τ(865), α(510,865)
- *In situ* data: *AERONET-OC* network (Zibordi et al., 2006, 2009)
  - Three sites
  - 7 λ centered at 412, 443, 531, 551, 667, 870 and 1020 nm

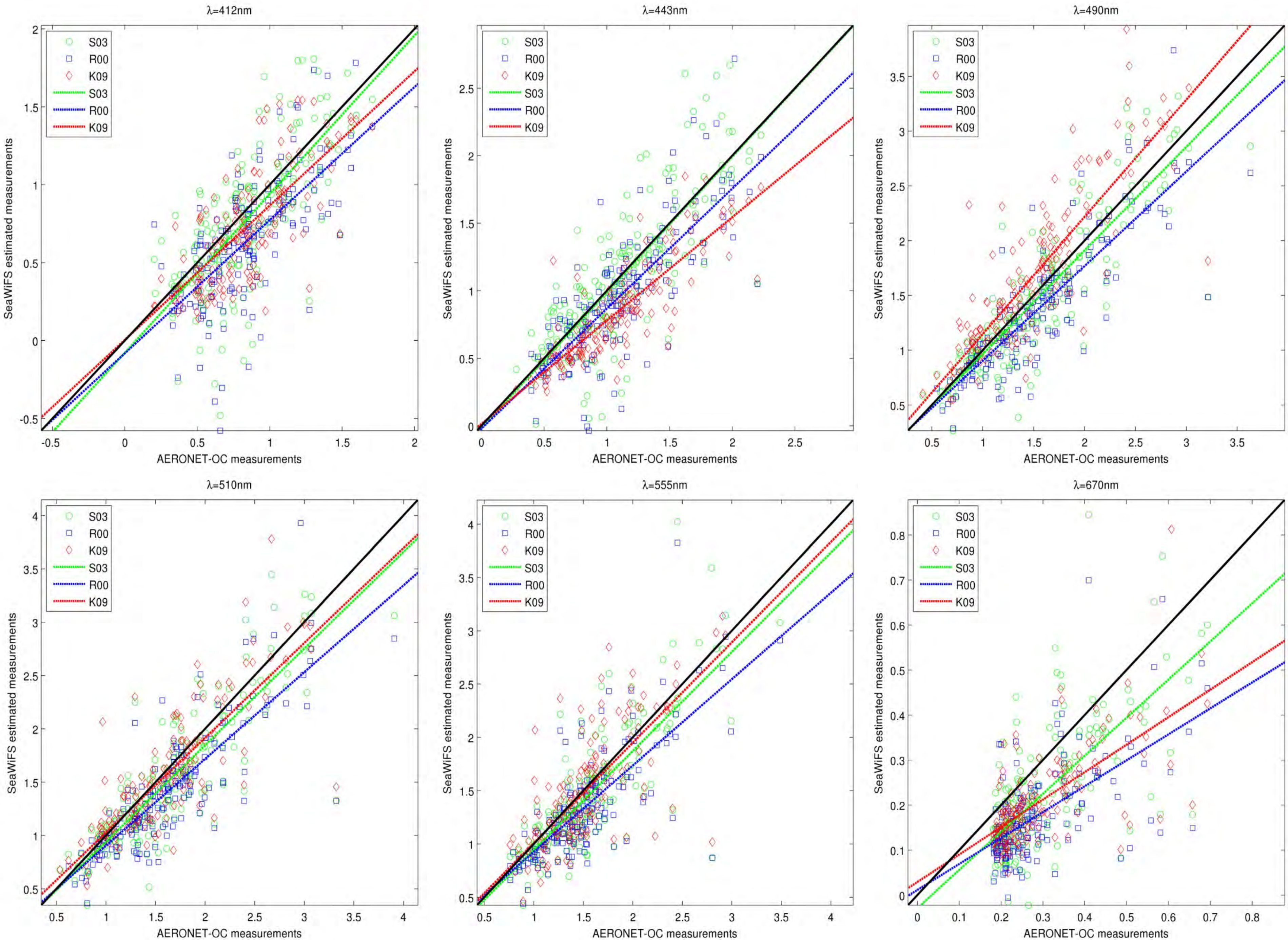


Results

- Only **turbid** waters (Robinson et al., 2003): nLw(670)>0.186
- Comparison of the normalized water-leaving radiances nL_w between 412 and 670 nm and of the aerosol optical properties (the Ångström coefficient $\alpha(510,865)$ and the optical thickness $\tau(865)$)

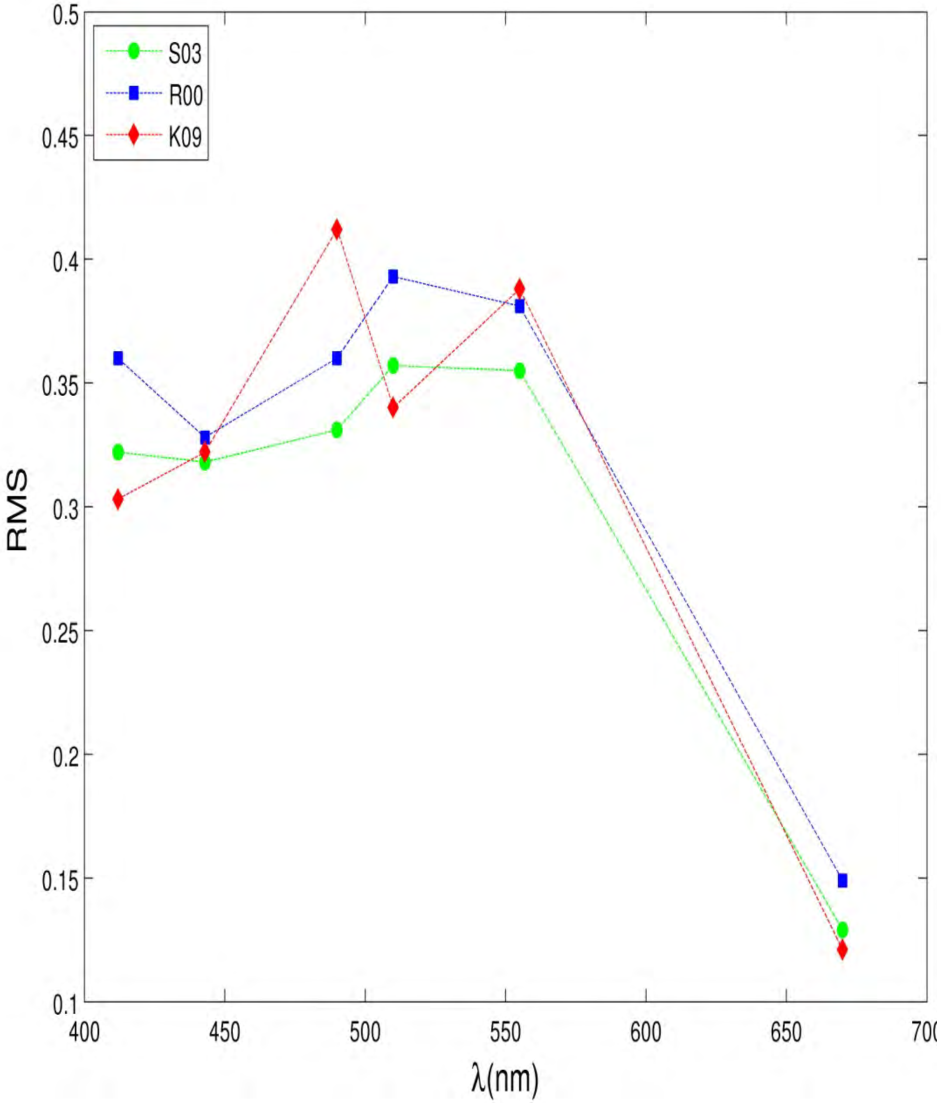
	MVCO	AAOT	COVE	TOTAL	$nL_w(412) < 0$
S03	20	163	18	**201**	7
R00	19	129	17	165	6
Kuchinke	13	134	13	160	**0**

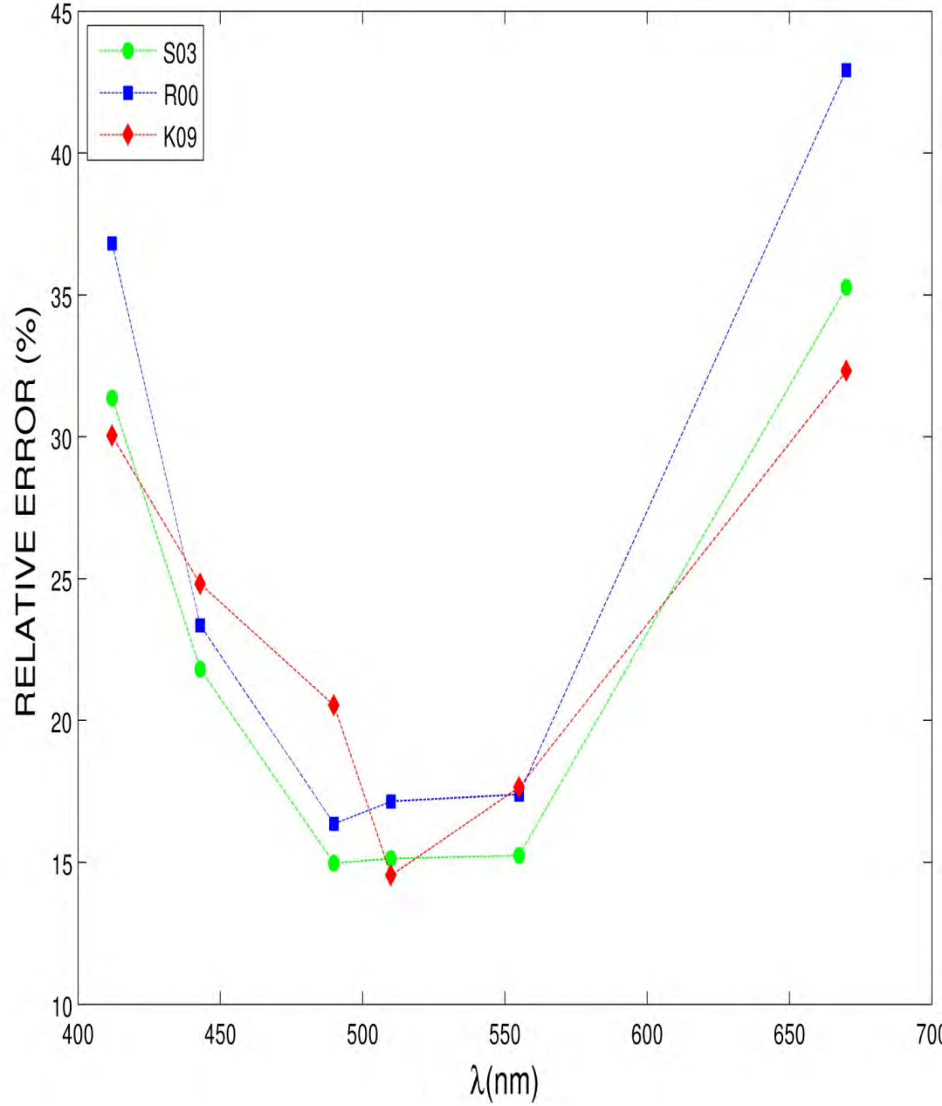
# of matchups for each algorithm and each AERONET-OC site

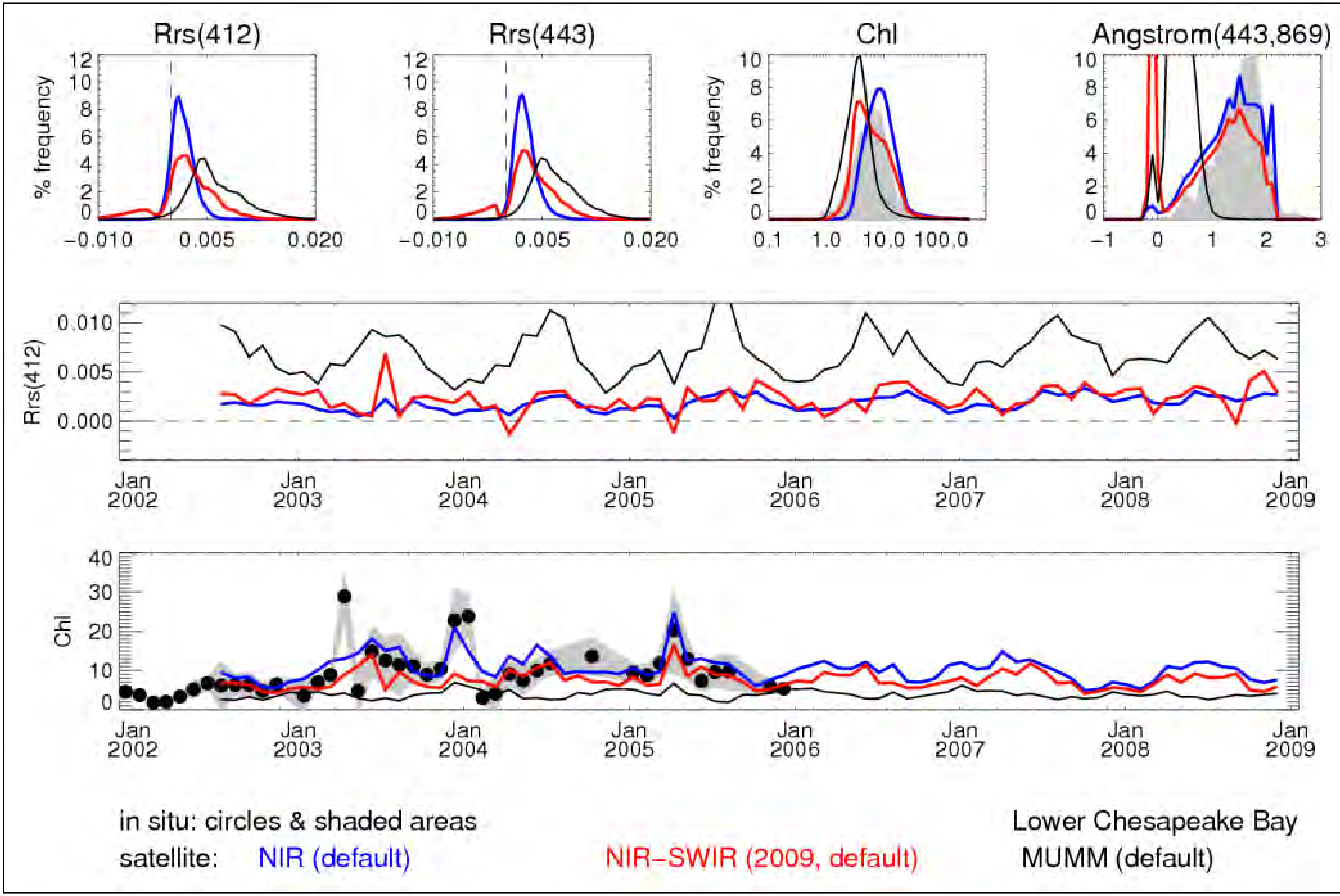


Jamet et al., 2011

Jamet et al., 2011







Courtesy of Jeremy Werdell

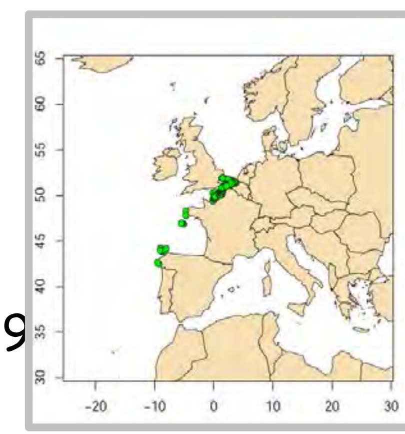
In-Situ data

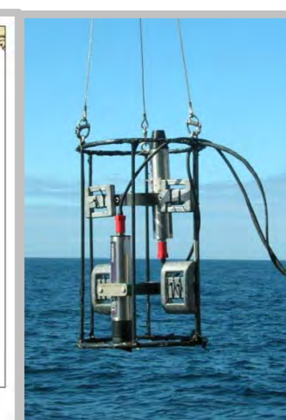
1. AERONET-OC data:

= global network of above-water autonomous radiometers located in coastal regions

- AAOT: 2002-2007
- COVE: 2006-2009
- MVCO: 2004-2005
- Gustav Dalen: 2005-2009
- Helsinki: 2006-2009

2. Cruise data from LOG:





= in-water measurements with TriOS - Optical Sensors

- North Sea and English Channel 2009/05-2009/09
- French Guiana 2009/10-2009/10

Matchup pairs

<u>Matching satellite images with in-situ data:</u>

- 3 by 3 pixel window around the station
- Median of at least 6 « valid » pixels within the window
- Spatial homogeneity within the window
- Focus on turbid waters only

(in-situ nL_w (667) > 0.183 mW. cm^{-2} um^{-1} sr^{-1})

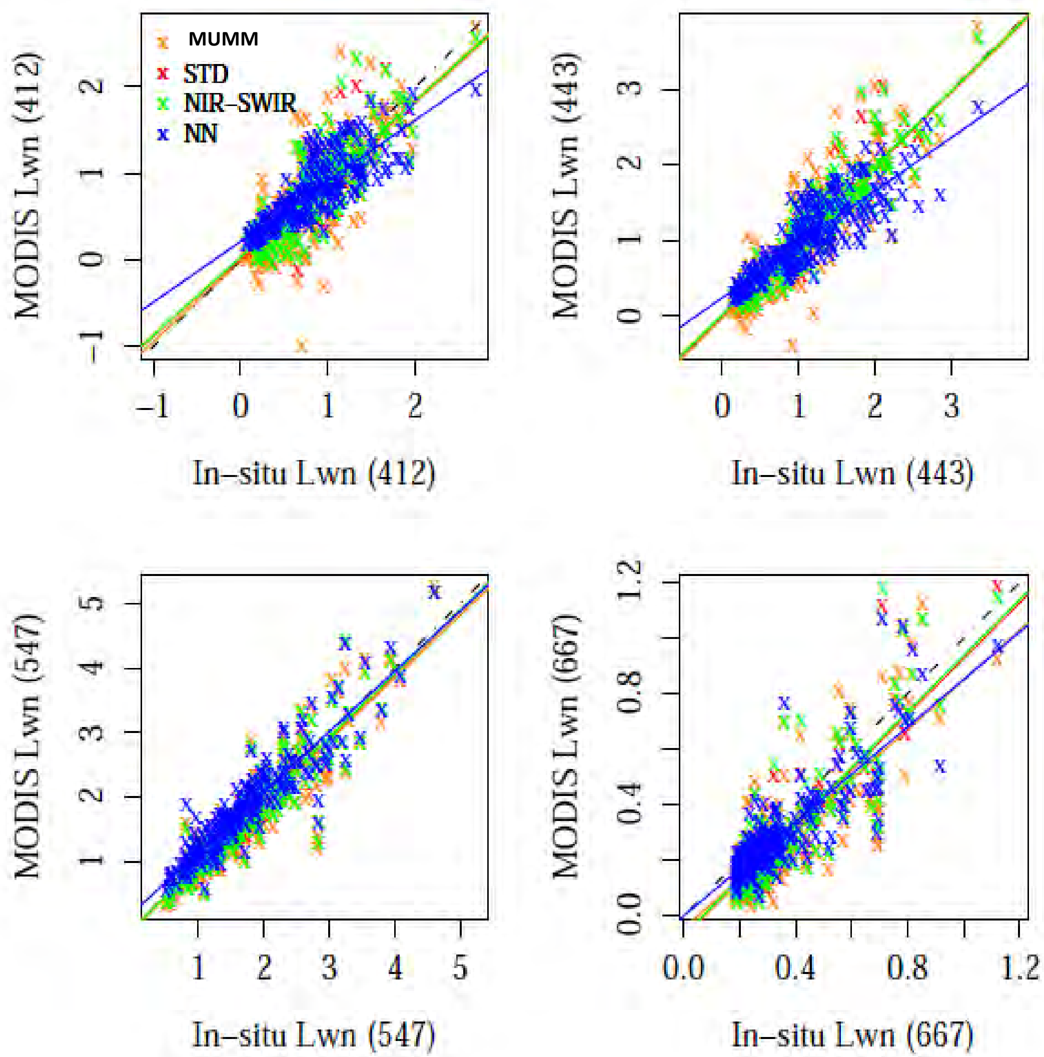
Excluded matchups:

	STD	SIMIL	NN	SWIR
< 6 pixels	738	740	798	762
non-uniform (nLw(547))	139	106	98	286
non-turbid	1000	1000	1000	1000
flagged NN	-	-	769	-
total	313	328	238	284

→ ***Reduced to 187 for inter-comparison (matchup has an estimation for each algorithm)***

Global Evaluation

- 211 match-ups AERONET-OC & LOG)
- Overall the STD AC method performs the best
- ↑ spatial coverage but ↑ neg. $L_{wn}(\lambda)$ values with the MUMM AC method
- STD, MUMM and NIR-SWIR tend to underestimate $L_{wn}(\lambda)$ (bias between -26 and 3%)
- STD, MUMM and NIR-SWIR perform better in the green (< 20% RE), not as well in the blue & red (> 30% RE)
- **NN performs better in the blue (30% RE) and red (22% RE) and not as well in the green (up to 27% RE)**



Goyens et al., (2013) [a]

Global evaluation of the algorithms

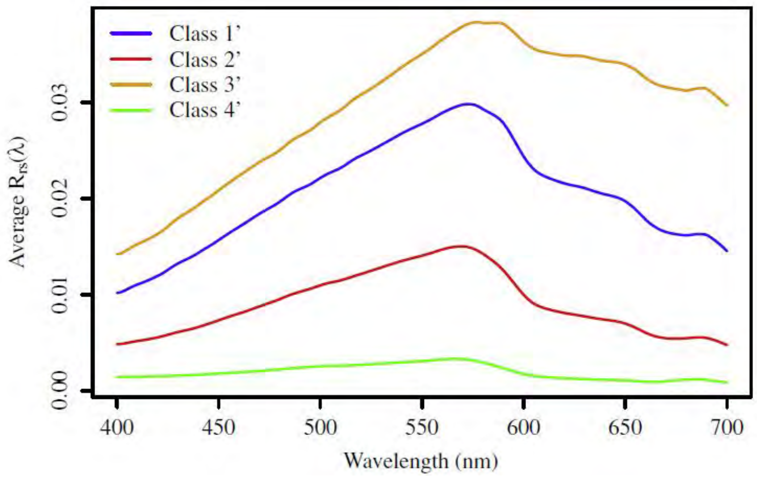
Table 4: Statistical comparison of algorithms

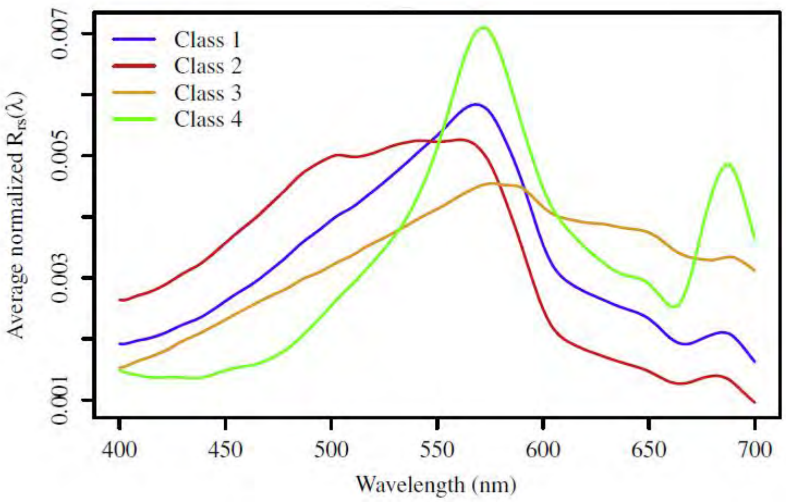
	R	Intercept	Slope	RE	RMSE	Biais
nLw(412)						
SIMIL	0.785	0.006	0.926	41.398	0.339	-6.182
STD	0.87	0.01	0.921	34.254	0.246	-1.407
SWIR	0.857	0.025	0.925	35.719	0.258	1.904
NN	0.919	0.159	0.74	21.716	0.192	5.421
nLw(443)						
SIMIL	0.873	-0.022	1.007	29.982	0.338	-3.089
STD	0.931	-0.008	1.001	21.506	0.234	0.698
SWIR	0.923	0.006	1.004	22.162	0.251	2.777
NN	0.936	0.182	0.742	18.397	0.245	-0.133
nLw(488)						
SIMIL	0.923	-0.078	1.046	19.993	0.346	-2.878
STD	0.952	-0.061	1.04	13.351	0.266	-0.534
SWIR	0.949	-0.048	1.044	13.664	0.278	0.757
NN	0.938	0.276	0.923	23.145	0.319	17.967
nLw(531)						
SIMIL	0.912	0.011	0.955	14.807	0.332	-3.758
STD	0.933	0	0.966	11.662	0.289	-2.933
SWIR	0.93	0.008	0.97	11.783	0.294	-2.016
NN	0.91	0.3	0.932	20.106	0.376	15.366
nLw(547)						
SIMIL	0.896	0.042	0.93	14.514	0.347	-4.152
STD	0.916	0.015	0.952	12.201	0.312	-3.514
SWIR	0.914	0.023	0.956	12.158	0.315	-2.655
NN	0.889	0.323	0.872	16.755	0.358	10.082
nLw(667)						
SIMIL	0.78	-0.024	0.833	33.263	0.141	-24.808
STD	0.842	-0.06	0.956	30.194	0.127	-24.499
SWIR	0.83	-0.055	0.963	29.729	0.128	-22.249
NN	0.829	0.071	0.637	17.79	0.108	-11.472

Evaluation of the algorithms as a function of the water types

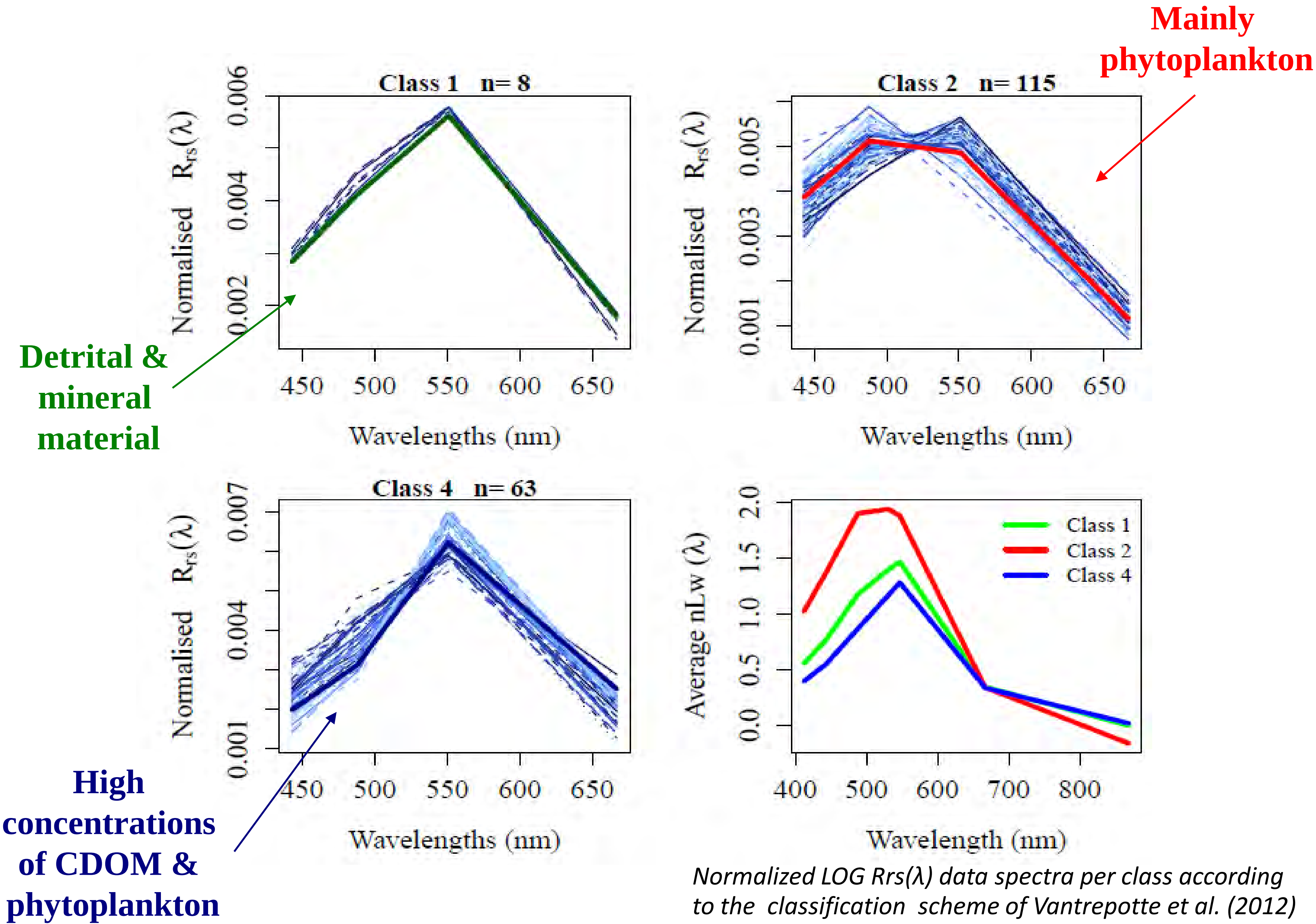
Classification of in-situ Lw spectra in 4 water type classes defined by Vantrepotte et al. (2012)

Focus on turbid waters only ! → ***Distinguish classes based on normalized reflectance spectra***

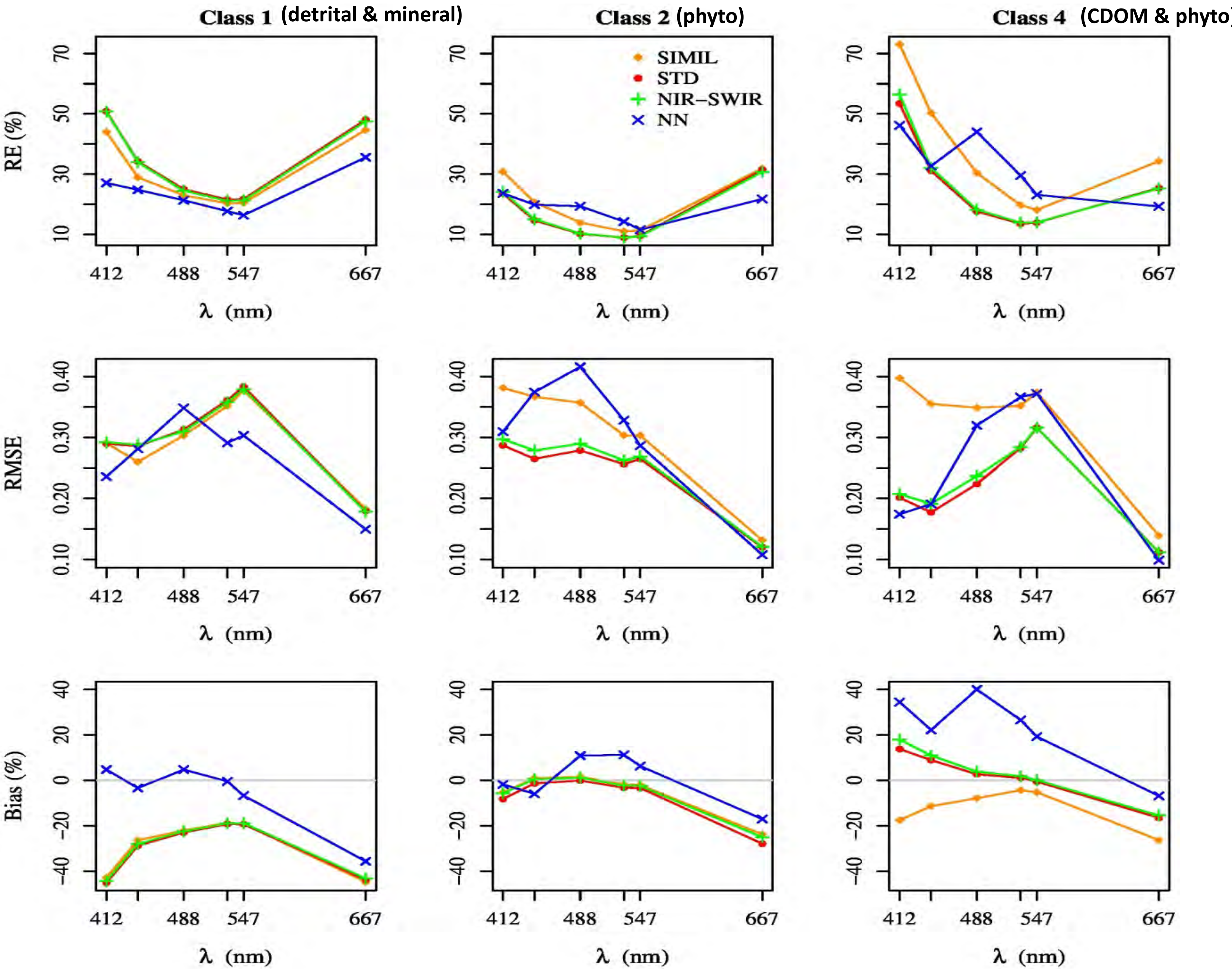




Evaluation of the algorithms as a function of the water types



Normalized LOG Rrs(λ) data spectra per class according to the classification scheme of Vantrepotte et al. (2012)



Goyens et al., 2013; Vantrepotte et al., 2012

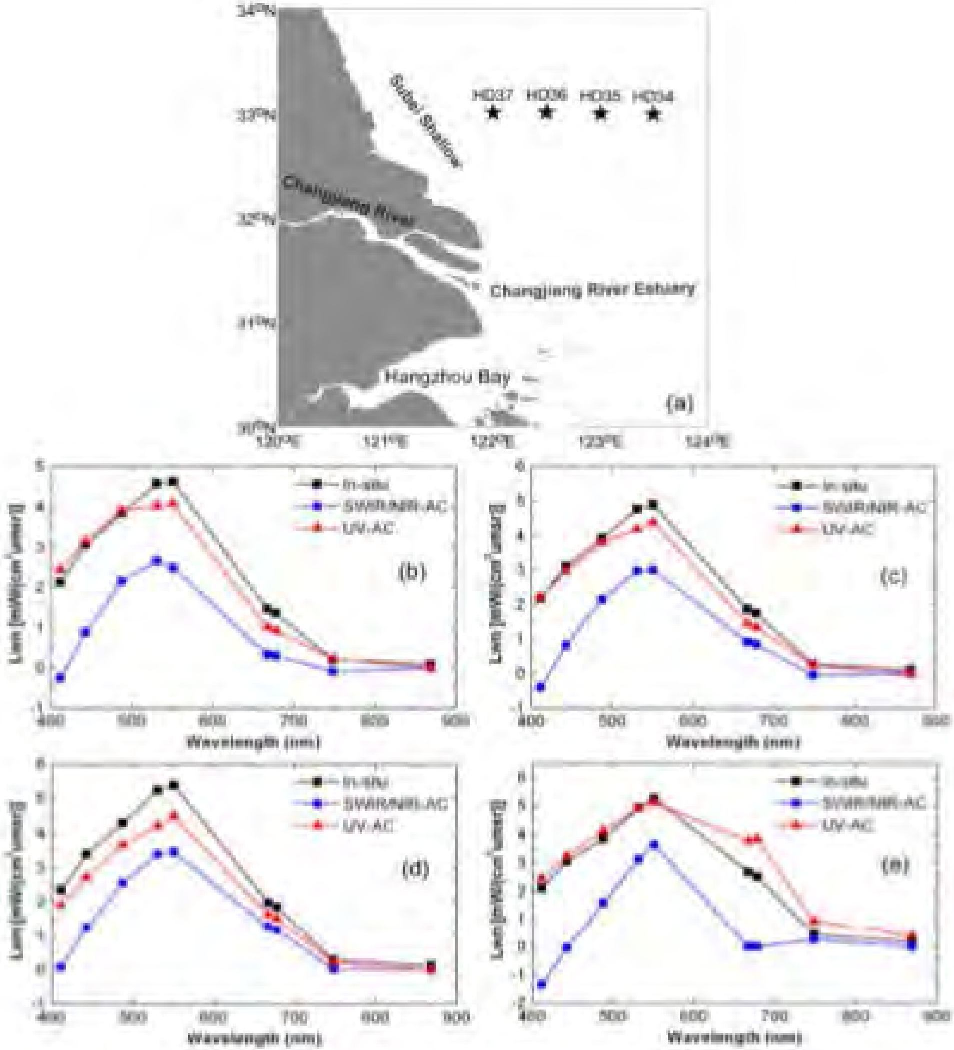


Fig. 6. Comparisons between satellite retrieved and in situ measured normalized water-leavi
radiances. (a) Locations of the in situ measurement of normalized water-leaving radiances or
April 2003 (marked as stars); (b) comparison at station HD34; (c) comparison at station HD3
(d) comparison at station HD36; (e) comparison at station HD37.

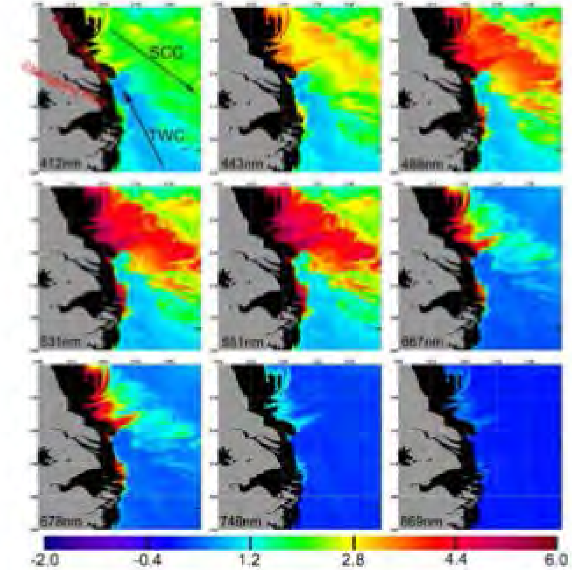


Fig. 4. The L_{wn} retrieved by Aqua/MODIS on 5 April 2003 using the UV-AC(412nm) algorithm (unit: mW/(cm^2·μm·sr)). Arrows in the sub-image of 412nm indicate the Subei Coastal Current (SCC) and the Taiwan Warm Current (TWC).

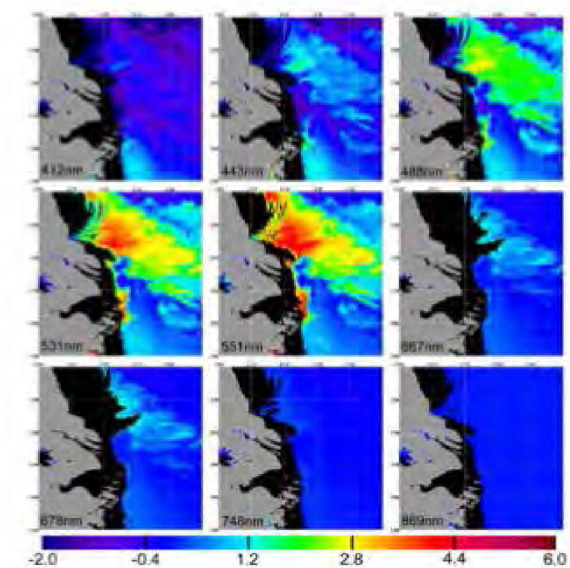
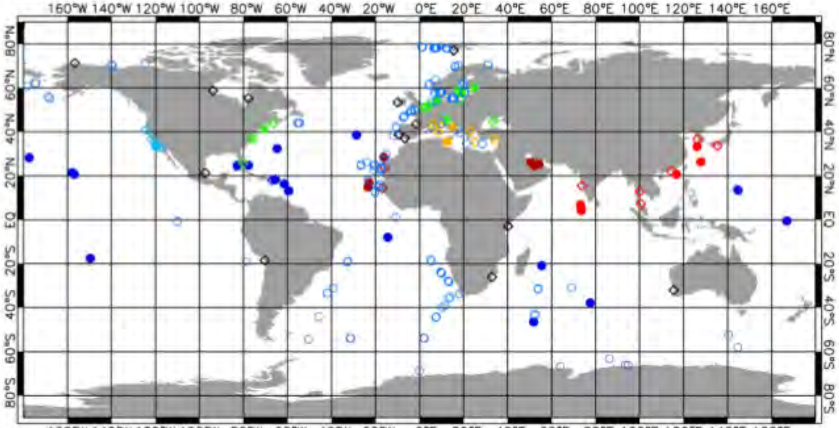


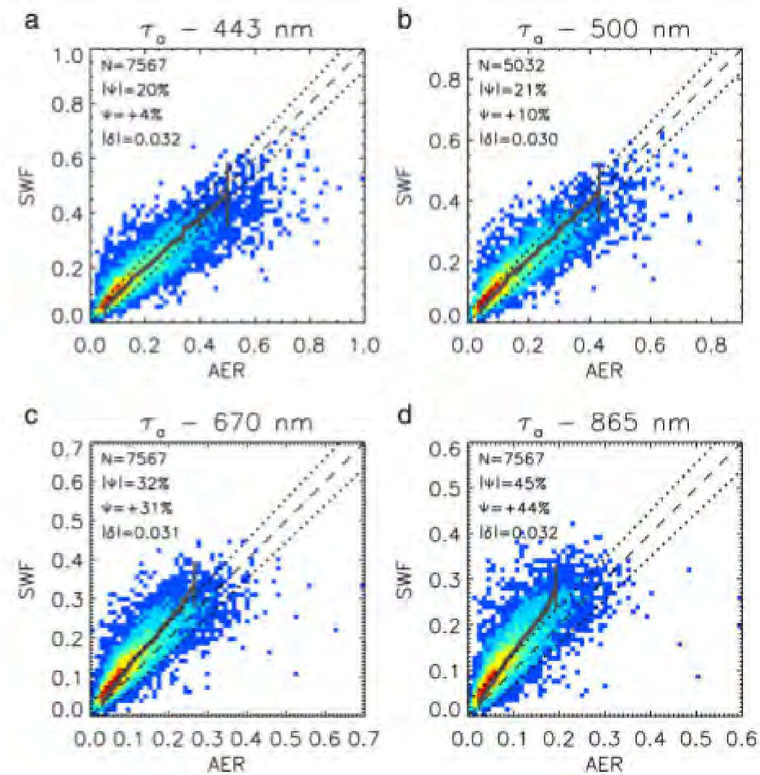
Fig. 5. The L_{wn} retrieved by Aqua/MODIS on 5 April 2003 using the SeaDAS 6.3 based on the SWIR/NIR-AC algorithm (unit: mW/(cm^2·μm·sr)).

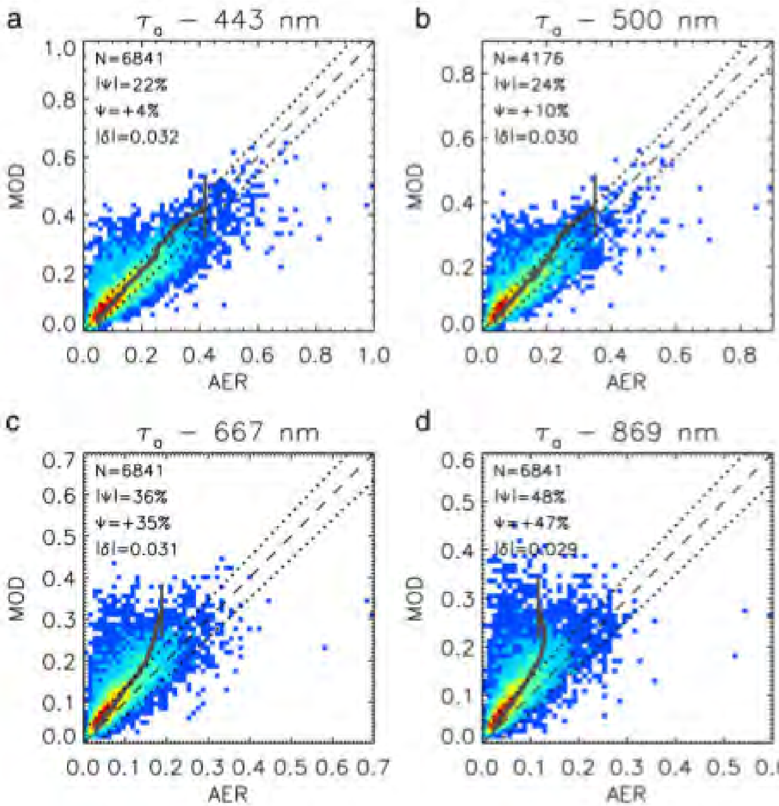
USE OF UV BANDS

He et al., 2012

Validation of aerosol optical properties

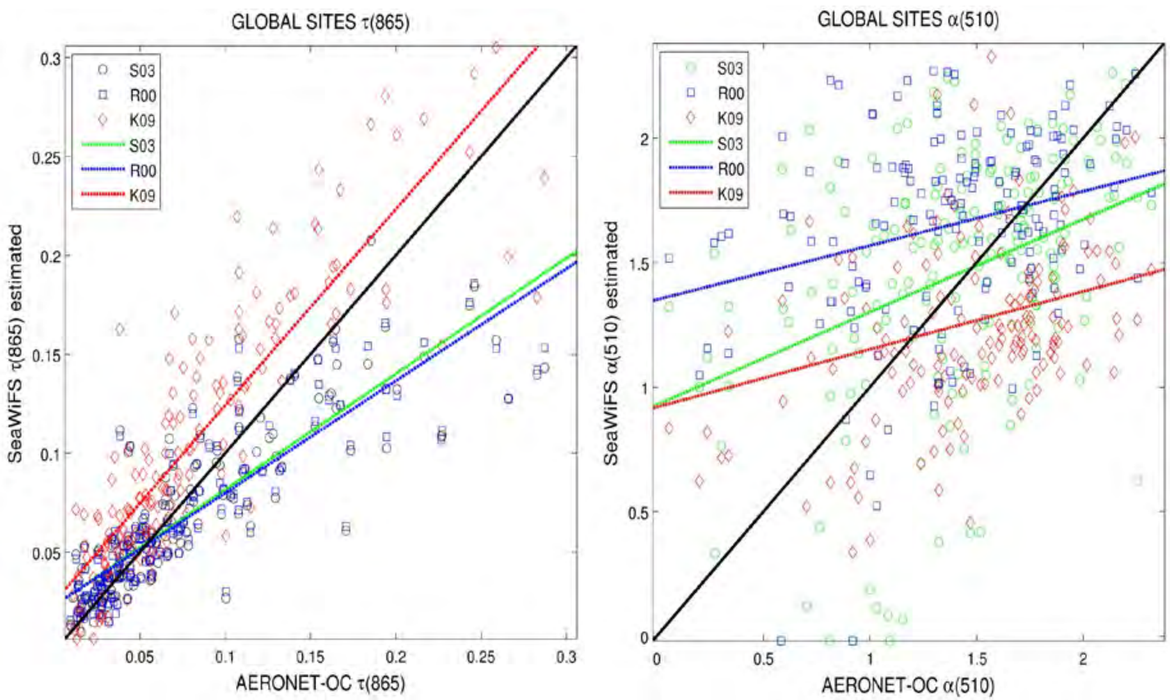




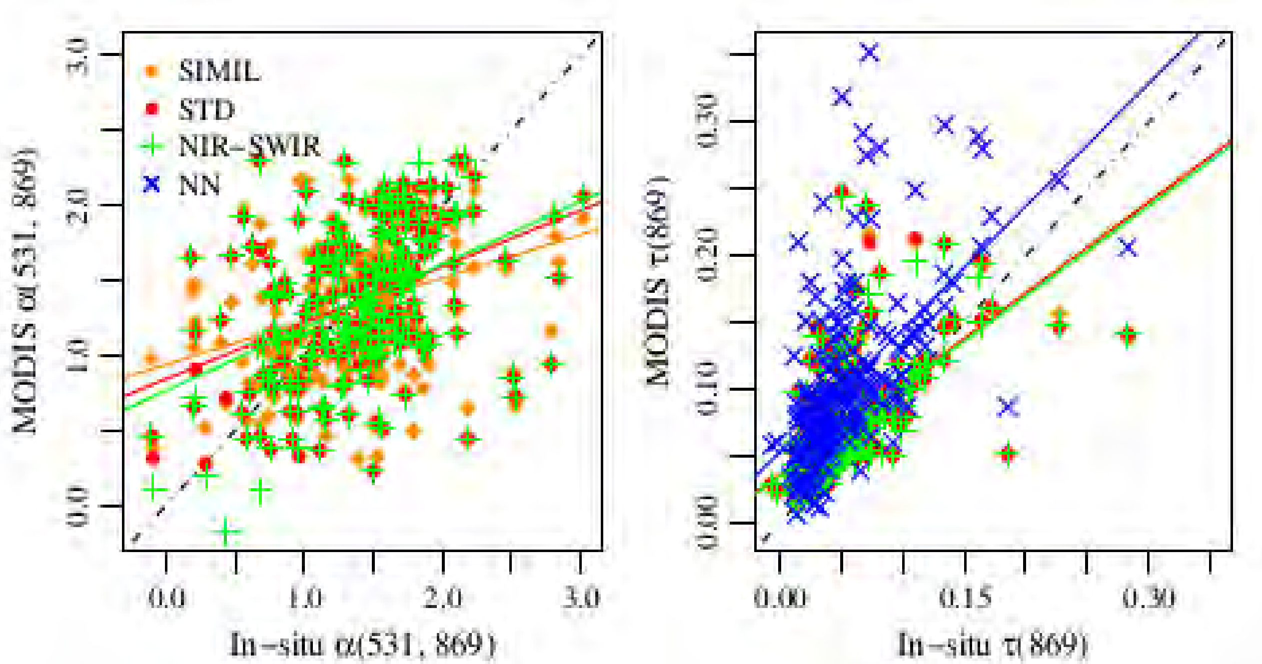


	N	|ψ|			ψ			|δ|				δ
		443	667	869	443	667	869	443	667	869	α	α
All	6841	22	36	48	+4	+35	+47	0.032	0.031	0.029	0.52	−0.52
All islands	773	39	45	51	+28	+43	+49	0.041	0.036	0.034	0.27	−0.27
Pacific	233	44	56	58	+39	+52	+57	0.041	0.036	0.034	0.32	−0.32
N. Atlantic	52	33	37	36	+11	+28	+34	0.032	0.028	0.025	0.33	−0.31
S. Hemisphere	186	36	38	42	+10	+29	+38	0.048	0.038	0.038	0.28	−0.26
Caribbean	302	37	47	57	+32	+47	+57	0.039	0.037	0.036	0.25	−0.23
Continental	2675	19	44	58	+6	+44	+58	0.028	0.034	0.031	0.60	−0.60
N.E. America	419	18	51	61	−2	+50	+61	0.026	0.033	0.028	0.72	−0.72
Continental Europe	1524	18	46	58	+8	+45	+58	0.030	0.040	0.035	0.59	−0.59
Atlantic Europe	732	20	36	54	+7	+35	+54	0.024	0.025	0.026	0.57	−0.57
Mediterranean	1578	20	26	40	−5	+24	+40	0.033	0.027	0.028	0.60	−0.60
Desert dust	486	21	22	26	−3	+13	+22	0.037	0.031	0.031	0.33	−0.33
Arabo-Persian Gulf	190	16	18	24	−6	+13	+18	0.037	0.030	0.030	0.36	−0.36
N.W. Africa	296	25	26	30	+2	+14	+26	0.039	0.034	0.033	0.31	−0.30
Asia	326	24	30	42	−2	+24	+41	0.050	0.036	0.038	0.55	−0.54
N.E. Asia	283	24	31	44	0	+24	+42	0.050	0.037	0.038	0.55	−0.55
S.E. Asia	31	25	20	41	−16	+19	+41	0.054	0.026	0.038	0.64	−0.57
Indian	12	14	24	16	−11	−1	+15	0.036	0.039	0.024	0.51	−0.49
US Pacific	639	24	42	59	+12	+40	+58	0.022	0.024	0.025	0.52	−0.51
Arctic	158	40	91	73	+38	+91	+71	0.036	0.035	0.022	0.34	−0.30

Melin et al., 2010



Jamet et al., 2011



Goyens et al., 2013

Other issues

- Adjacency effects
- Absorbing aerosols

Adjacency effects

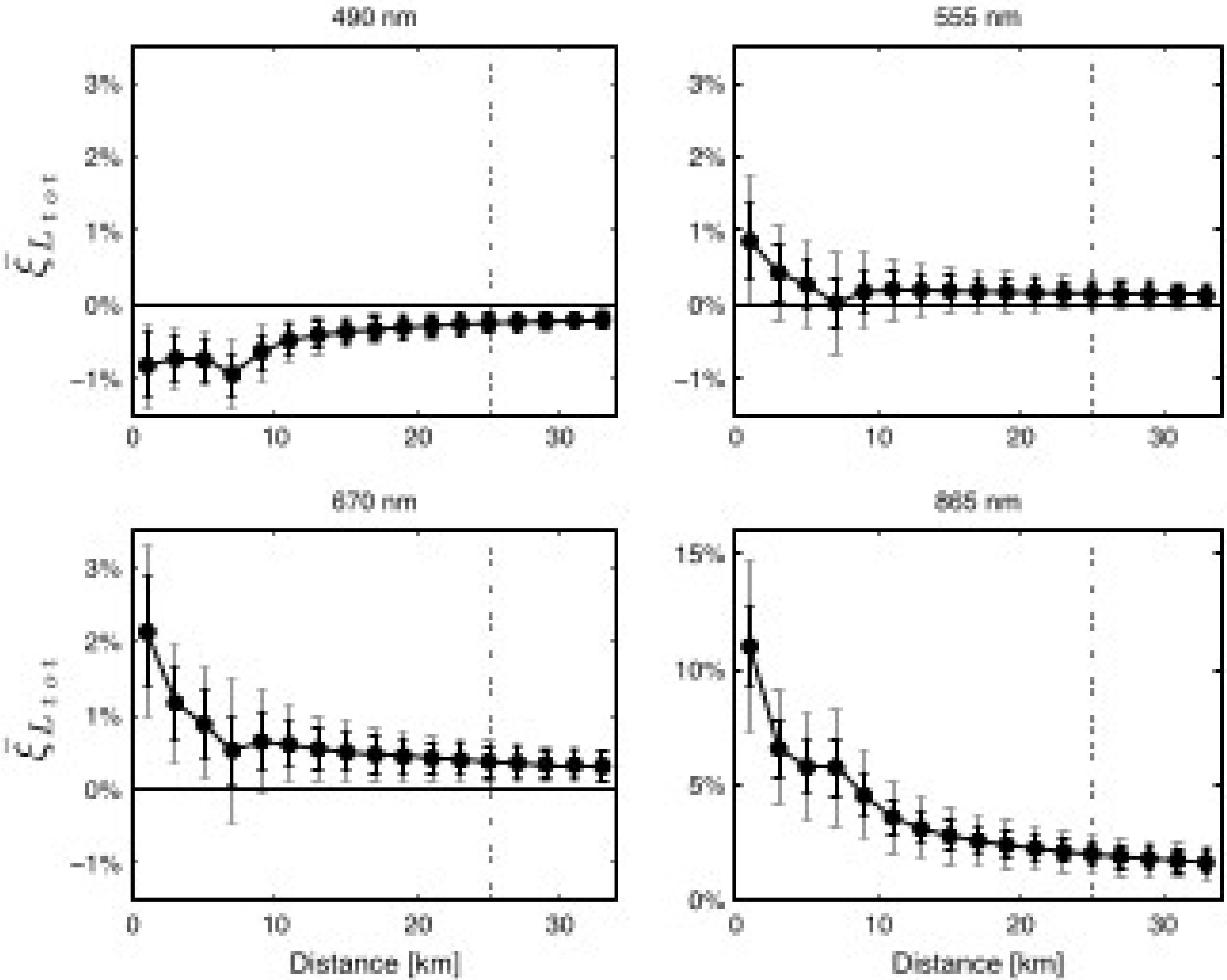
- Adjacency effects are associated with the change in digital number of a pixel caused by atmospheric scattering of radiance that originates outside of the sensor element’s

- They are important in coastal zone or in the vicinoty of clouds and sea icea or even in the open ocean (e.g., upwelling systems), i.e. when the spatial contrast between the target and its environment is relatively large

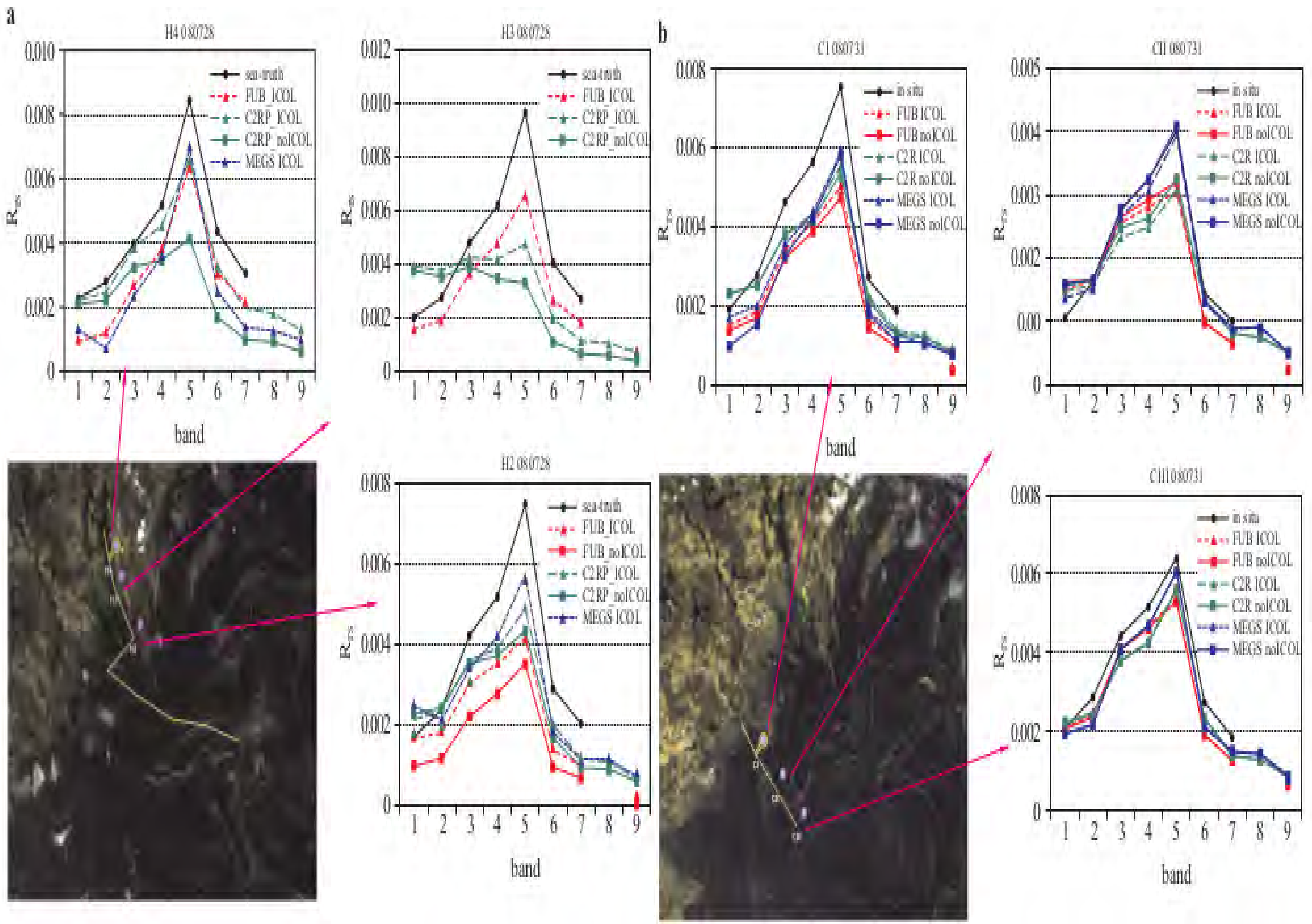
- They may affect significantly the retrieval of marine reflectance and chlorophyll-a concentration, all the more as pixel size is small. Scale of influence is larger for moleculare scattering that aerosol scattering and when aerosols are located at a higher latitude

- Adjacency effects are generally ignored in standard atmospheric correction schemes and operational processing of satellite ocean-color imagery

Adjacency effects



Bulgarelli et al., 2014



Kratzer et al., 2010

<u>SIMEC method:</u>

sensor-generic adjacency pre-processing method

Estimation of contribution of the background radiance based on the correspondence with the NIR similarity spectrum

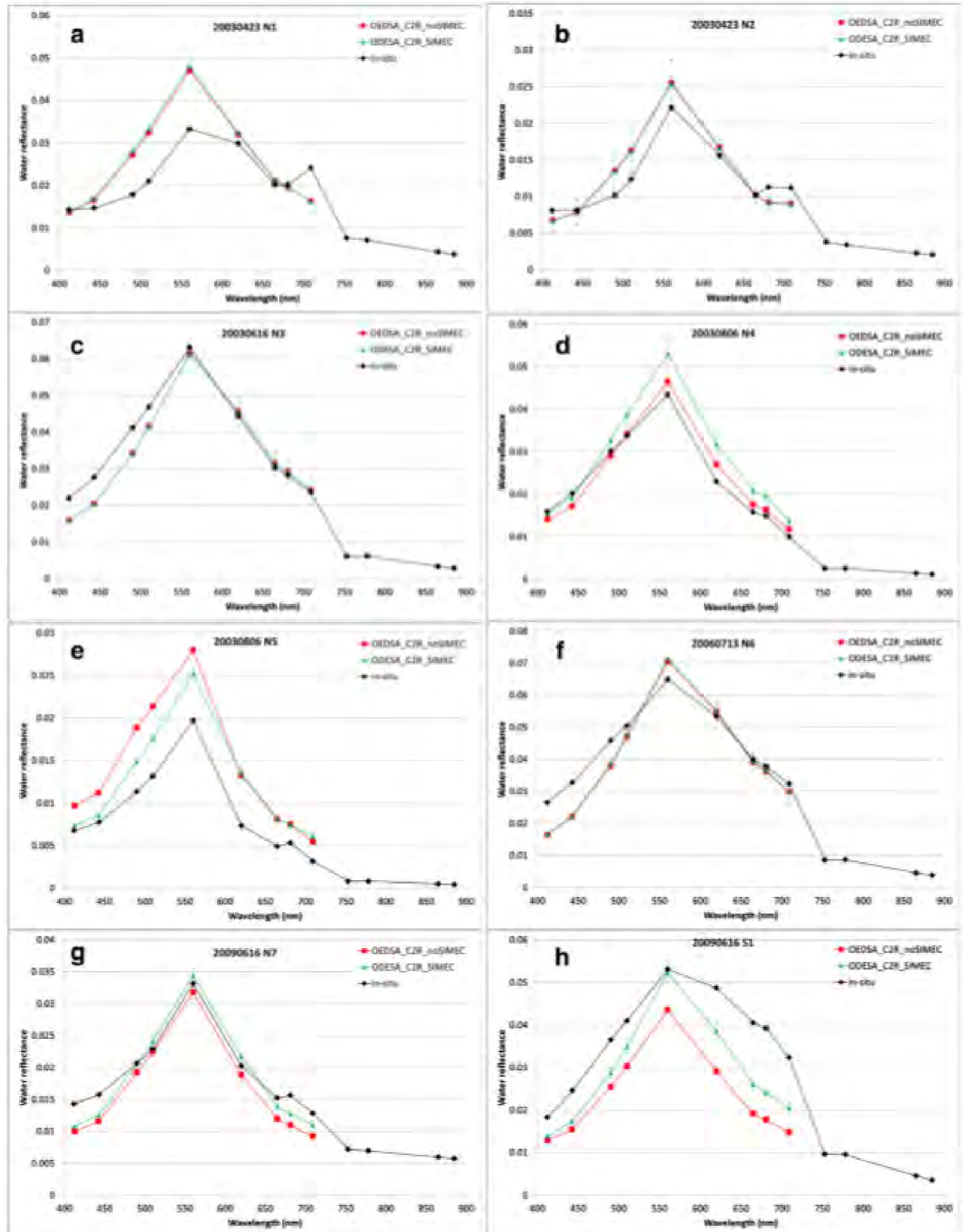
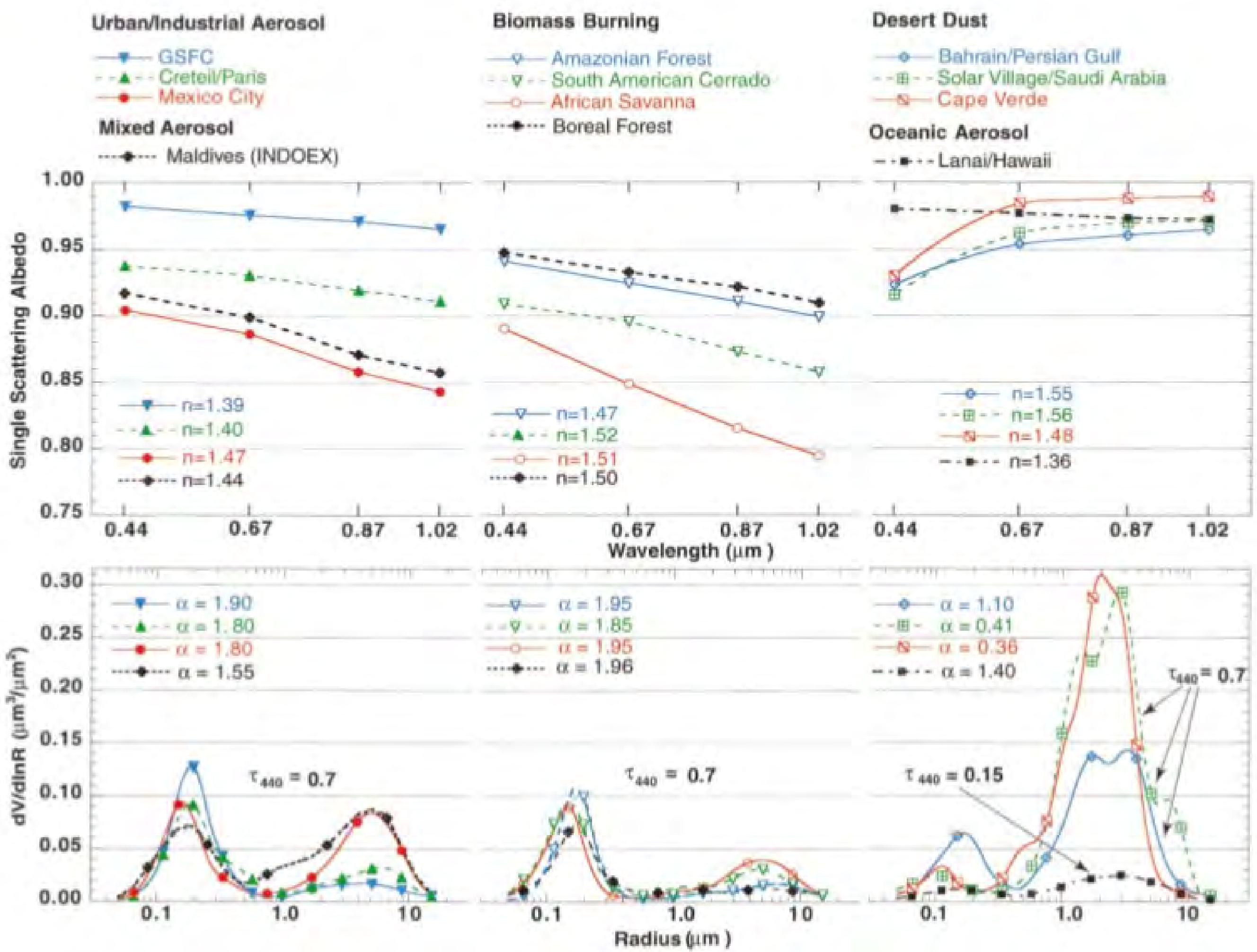


Fig. 8. Comparison between normalized water reflectance measured in situ (black diamonds) and the normalized water reflectance extracted from MERIS FR within a 3 × 3 pixel window around the in situ station derived from the ODESA-C2R processor with (green triangles) and without (red squares) SIMEC pre-processing for North Sea (N) and Scheldt river (S) sampling points. The date of acquisition and sample station is given in the title of each plot. Error bars refer to the standard deviation calculated from the retrieved MERIS water reflectance for a 3 × 3 pixel window. Please note that Y-axis are scaled differently in the figures. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

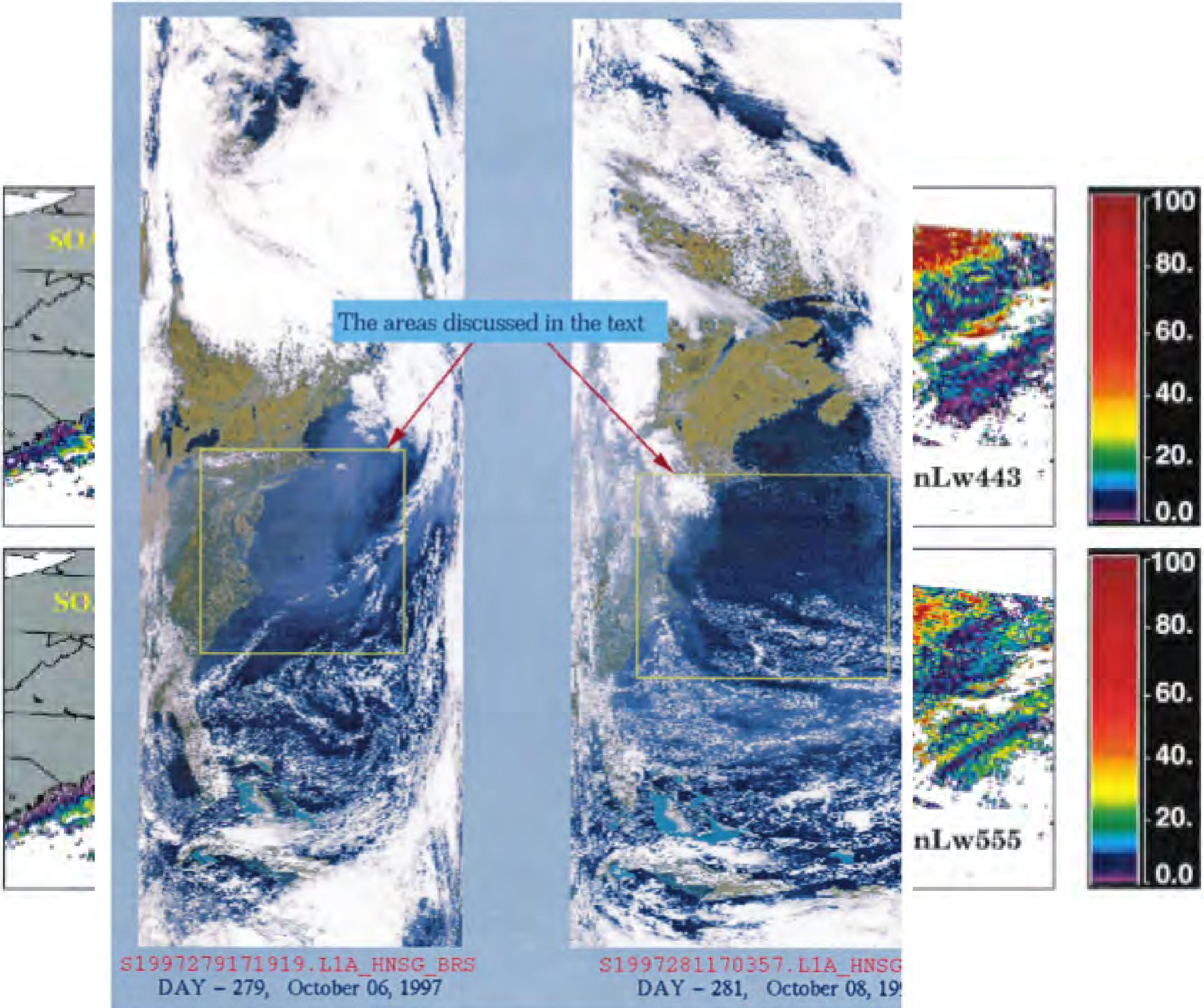
Knaeps et al., 2014

Absorbing aerosols

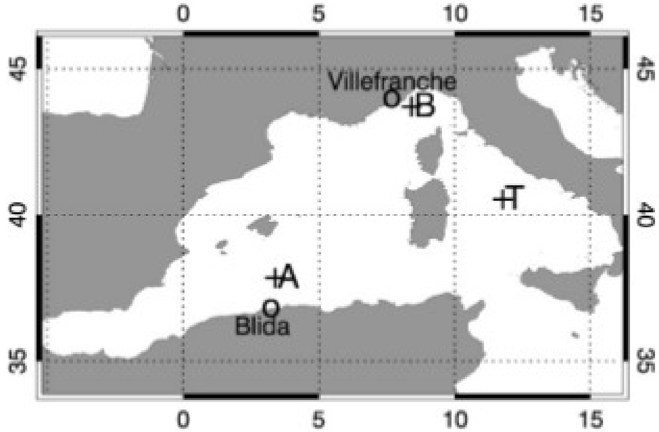
- Not detectable with only NIR bands
- Spectral dependency

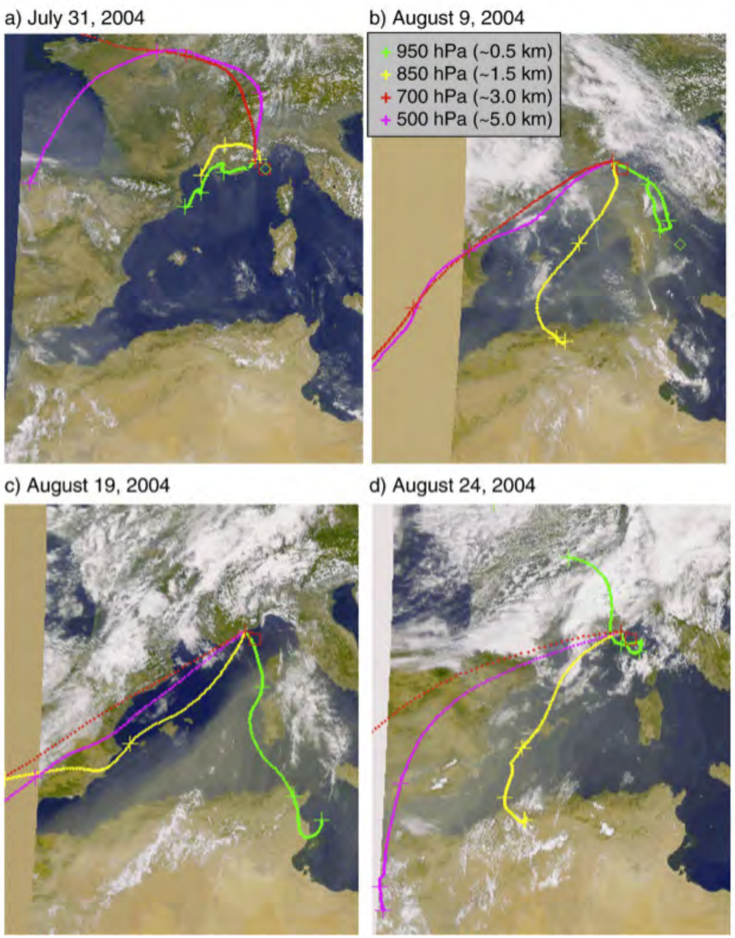


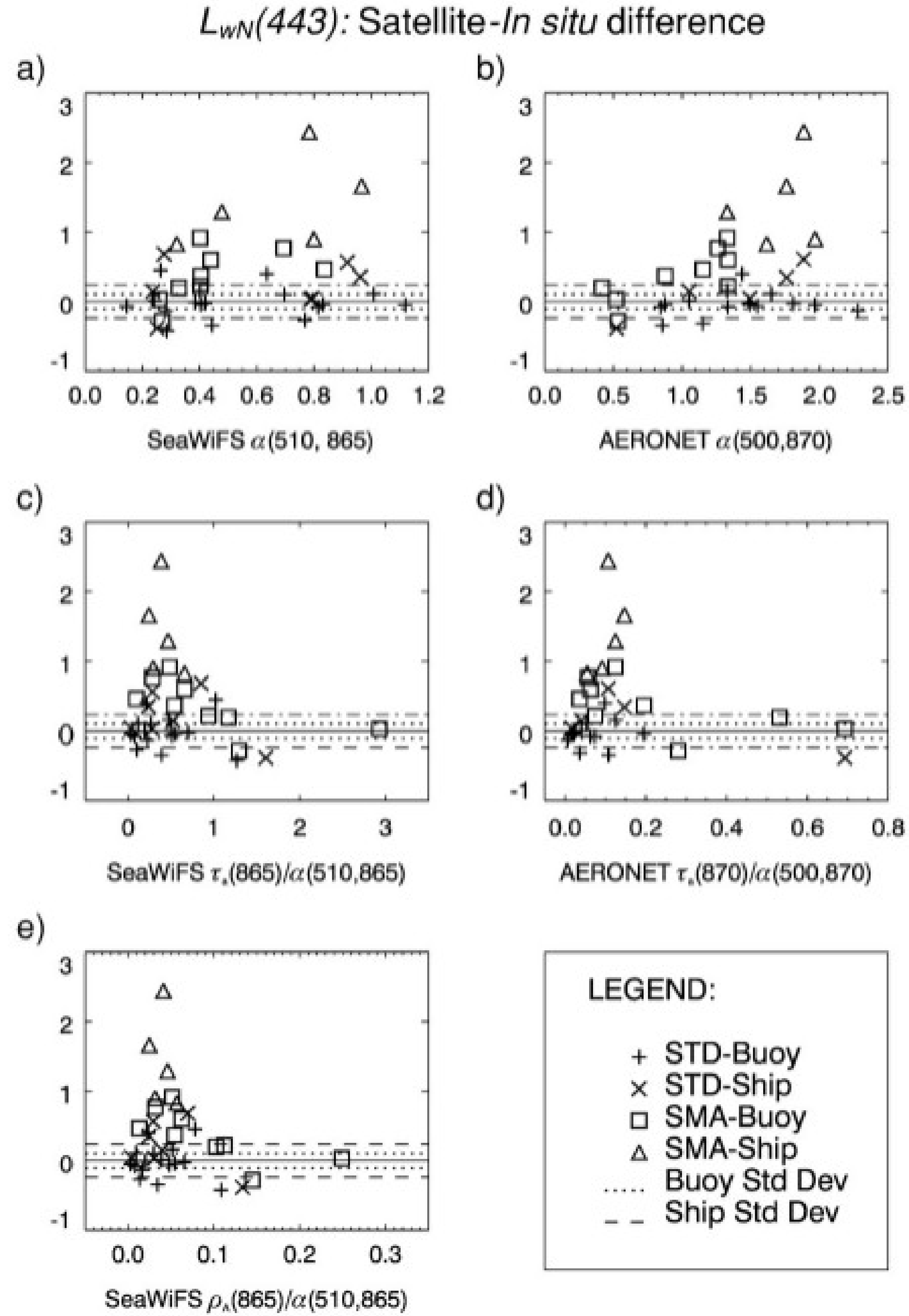
Dubovik et al., 2002



Chomko and Gordon, 2001





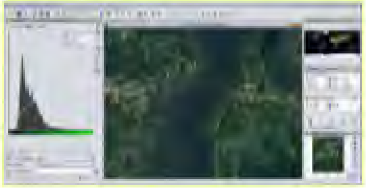


Banzon et al., 2009

Sofwares to process ocean color images

- SeaDAS: http://seadas.gsfc.nasa.gov/

General Description



SeaDAS is a comprehensive image analysis package for the processing, display, analysis, and quality control of ocean color data. While originally developed to support the SeaWiFS mission, it now supports most US and international ocean color missions. The primary focus of SeaDAS is ocean color data, but it is applicable to many satellite-based earth science data analyses

The latest version (SeaDAS 7.3.1) is the result of a collaboration with the developers of ESA's BEAM software package. The core visualization package for SeaDAS 7 is based on the BEAM framework, with extensions that provide the functionality provided by previous versions of SeaDAS..

Features
Requirements
License
Download

Supported Missions

- MODIS
- SeaWiFS
- CZCS
- VIIRS
- HICO
- Aquarius
- Landsat8/OLI
- MERIS
- OCTS
- OCM
- OCM-2
- OSMI
- MOS
- GOCI

User Support

- SeaDAS Video Tutorials and Demos
- SeaDAS FAQ
- SeaDAS Help Pages
- Other SeaDAS Tutorial Material
- Ocean Color Web
- Ocean Color Forum
- SeaDAS Mailing List

Other

- SeaDAS Visualization Source Code
- Processing Binaries and Source Code
- SeaDAS version 6.4
- MODISL1DB 1.8

Sofwares to process ocean color images

- SeaDAS: http://seadas.gsfc.nasa.gov/
- BEAM/VISAT: http://www.brockmann-consult.de/cms/web/beam/

The European Space Agency is making BEAM available free of charge to the user community

Maintenance Phase

Please note that BEAM is not further developed. It will remain under maintenance until at least mid of 2016. During this maintenance phase we will continue our user support. We encourage all BEAM users to use SNAP from now on. SNAP is the successor and evolution of BEAM. When installing SNAP along with the Sentinel-3 Toolbox you will have the same great user experience as with BEAM. You can even extend the number of features by installing other toolboxes like those for Sentinel-1 or Sentinel-2.

Thanks to all our dear and loyal BEAM users.
We hope that you now turn into SNAP users.

BEAM is an **open-source** toolbox and development platform for viewing, analysing and processing of remote sensing raster data. Originally developed to facilitate the utilisation of image data from **Envisat**'s optical instruments, BEAM now supports a growing number of other raster data formats such as **GeoTIFF** and **NetCDF** as well as data formats of other EO sensors such as **MODIS**, **AVHRR**, **AVNIR**, **PRISM** and **CHRIS/Proba**. Various data and algorithms are supported by dedicated extension **plug-ins**.

Software Components

- VISAT - An intuitive desktop application to be used for visualization, analyzing and processing of remote sensing raster data. To get an impression of how VISAT looks and feels like, please take a look at the related screenshots page.
- A set of scientific tools running either from the command line or invoked by VISAT, also entirely written in Java.
- A rich Java API for the development of new remote sensing applications and BEAM extension plug-ins.

Supported Instruments

This following table lists the data product formats which are supported by BEAM using the reader modules provided in the standard installation. Information about the access to these products is given on the data sources page.

Instrument	Platform	Formats
MERIS L1b/L2	Envisat	Envisat N1
MERIS L3	Envisat	NetCDF
AATSR L1b/L2	Envisat	Envisat N1
ASAR	Envisat	Envisat N1
ATSR L1b/L2	ERS	Envisat N1, ERS
SAR	ERS	Envisat N1
OLCI [1)]	Sentinel-3	NetCDF/SAFE
SLSTR [1)]	Sentinel-3	NetCDF/SAFE
MSI [1)]	Sentinel-2	JPEG2000/SAFE
CHRIS L1	Proba	HDF4
AVNIR-2 L1/L2	ALOS	CEOS
PRISM L1/L2	ALOS	CEOS
MODIS L2	Aqua, Terra	HDF4
AVHRR/3 L1b	NOAA-KLM	NOAA, METOP
MSS	Landsat 1-5	GeoTIFF
TM	Landsat 4	GeoTIFF
TM	Landsat 5	GeoTIFF, FAST
ETM+	Landsat 7	GeoTIFF
OLI, TIRS	Landsat 8	GeoTIFF
SPOT VEGETATION	SPOT	HDF

[1)] In development - available in 2014

Generic EO Data Formats

BEAM supports the following generic raster formats:

Format	Support	Description
BEAM-DIMAP	read + write	The standard BEAM I/O format. It comprises an XML header based on the SpotImage/CNES DIMAP schema and ENVI images for the raster data.

- **SNAP 2.0 released**
  17. Nov 2015, 11:28
- **BEAM-Python also for Python 2.7 available**
  02. Jul 2014, 15:48
- **BEAM 5.0 released**
  08. May 2014, 08:34
- **Reader for Landsat 8 available**
  02. Sep 2013, 09:05
- **SMOS-Box 2.3 released**
  06. Jun 2013, 15:59

more...

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Colour Manipulation Maximum Values
By Augusto Nunes Vundo

resample the data
By Amber ling

MODIS MOD13A1, MOD13Q1 mosaiking problem
By Genadi Archil Tvauri

more...

Sofwares to process ocean color images

- SeaDAS: http://seadas.gsfc.nasa.gov/
- BEAM/VISAT: http://www.brockmann-consult.de/cms/web/beam/
- SNAP: https://sentinel.esa.int/web/sentinel/toolboxes/sentinel-3

The Sentinel-3 Toolbox

The Sentinel-3 Toolbox consists of a rich set of visualisation, analysis and processing tools for the exploitation of OLCI and SLSTR data from the upcoming Sentinel-3 mission. As a multi-mission remote sensing toolbox, it also supports the ESA missions Envisat (MERIS & AATSR), ERS (ATSR), SMOS as well as third party data from MODIS (Aqua and Terra), Landsat (TM), ALOS (AVNIR & PRISM) and others. The various tools can be run from an intuitive desktop application or via a command-line interface. A rich application programming interface allows for development of plugins using Java or Python.

The Sentinel-3 Toolbox is being developed for ESA by Brockmann Consult in partnership with the University of Reading, C-S France, ACRI-ST and Array.

This first release of the Sentinel-3 Toolbox is a stand-alone toolbox intended for exploitation of medium resolution optical and SMOS data. It provides all tools known from the ESA BEAM and SMOS toolboxes, plus a Sentinel-3 data reader, an uncertainty data visualisation tool and a context search feature. The next release will consist of a common Sentinel Application Platform (SNAP) for Sentinel-1, Sentinel-2 and Sentinel-3 with a single installer and application interface.

Downloads

The Sentinel-3 Toolbox can be downloaded from the Science Toolbox Exploitation Platform (STEP).

Resources

NEWS: Sample Beta products available (June 2016)

The SENTINEL-3 sample products beta version are released to users.

The Commissioning Phase is still on-going and therefore evolutions and improvements are expected in the short term before official core data product release.

Users are invited to read the Product Note before using them.

Sample products are available on the Scientific HUB at "scihub.copernicus.eu". Auto-registration is required for accessing the server.

Sentinel-3 Test Data (July 2015)

New Sentinel-3 Test Data Sets have been produced using MERIS and AATSR data. These data provide realistic features (land, sea, cloud) but they also contain some limitations due to the input data (AATSR and MERIS swath, missing spectral channels copied or interpolated from existing channels).

Before using them one must read the Optical Test Data Set description, which provides more information and details the limitations with the data.

These Test Data Sets provide a good overview of what the future Sentinel-3 optical missions products will be like.

Disclaimer

Access to the Sentinel-3 OLCI/SLSTR Test Data Set (TDS) constitutes acceptance of the following general terms and conditions:

The data are released as preliminary data set on an "as is" basis to be used only with appropriate caution as the Sentinel-3 products format and content are under finalisation. The data have not been subjected to the ESA quality control or quality assurance procedures and do not meet the criteria and standards of official ESA data. ESA reserves the right to revise the data format and content at any time pursuant to further analysis and review. Neither ESA nor any other party involved in creating, producing or delivering the data shall be held liable for any consequences arising from the use of this data.

FTP access to some Test Data Sets are provided below:

- Sentinel-3 OLCI Test Data Set
- Sentinel-3 SLSTR Test Data Set
- Sentinel-3 SYNERGY Test Data Set

FTP access to the Full Test Data Sets:

Download

Here you can download the latest installers for SNAP and the Sentinel Toolboxes.

Data provision is available to all users via the **Sentinel Data Hub**.

Current Version

The current version is **4.0.0** (08.07.2016 **12:40**).

For detailed information about changes made for this release please have a look at the release notes of the different projects: SNAP, S1TBX, S2TBX, S3TBX, SMOS Box

We offer three different installers for your convenience. Choose the one from the following table which suits your needs. During the installation process each toolbox can be excluded from the installation. Toolboxes which are not initially installed via the installer can be later downloaded and installed using the plugin manager. Please note that SNAP and the individual Sentinel Toolboxes also support numerous sensors other than Sentinel.

	Windows 64-Bit	Windows 32-Bit	Mac OS X	Unix 64-bit
Sentinel Toolboxes	These installers contain the **Sentinel-1**, **Sentinel-2**, **Sentinel-3** Toolboxes			
	Download	Download	Download	Download
SMOS Toolbox	These installer contains only the **SMOS Toobox**. Download also the Format Conversion Tool (Earth Explorer to NetCDF) and the user manual.			
	Download	Download	Download	Download
All Toolboxes	These installers contain the **Sentinel-1**, **Sentinel-2**, **Sentinel-3** Toolboxes and **SMOS Toolbox**			
	Download	Download	Download	Download

If you later decide to install an additional toolbox to your installation you can follow this step-by-step guide.

We are happy to **get your feedback** on the software installation procedure, functionalities, encountered issues, etc on the **Forum**. You may also watch the **Blog** to be informed about SNAP news such as new software releases or interesting events.

Release Notes

SNAP, S1TBX, S2TBX, S3TBX, SMOS

Previous Versions

Former releases can be downloaded from the **Previous Versions** page.

Sources

All software is published under the GPL-3 license and its sources are available on **GitHub**.

Sofwares to process ocean color images

- SeaDAS: http://seadas.gsfc.nasa.gov/
- BEAM/VISAT: http://www.brockmann-consult.de/cms/web/beam/
- SNAP: https://sentinel.esa.int/web/sentinel/toolboxes/sentinel-3
- ODESA: http://earth.eo.esa.int/odesa/

Optical Data processor ODESA European Space Agency

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Optical Data processor of the European Space Agency

The ODESA system intends to provide the users a complete level 2 processing environment for the MERIS instrument as well as for the future ESA optical sensors on board Sentinel 3.

ODESA supplies the user community with the MERIS Ground Segment development platform MEGS®, including source code, embedded in an efficient framework for testing and for validation activities.

Validation facilities include match-up processing & analysis, data set selection & analysis, level 3 products generation & analysis and the possibility to perform remote processing, e.g. for testing purpose and for validation activities requiring large amounts of data.

MERIS on-line processing	Access MERIS data from remote processing facility available to qualified processors.
Software distribution	Download the MERIS level 2 processor (MEGS®) and its operation environment
Analysis tools	Download and install the ODESA analysis tools, including the BEAM toolbox
Validation & qualification	Validate your algorithm and get him qualified to access the MERIS on-line processing
Forum	All you want to discuss about ODESA and MERIS

Related Links

MERIS demonstration level 3
MERIS marine L3 QC
MERMAID in-situ database
Access to Ocean Colour data

What I didn't talk about

- Shallow waters
- BRDF
- Sensor spectral response
- Vicarious calibration
- Radiative tranfer model/code for generating Look-Up Tables
- Exact nLw
- Single vs mutiple scattering

Thank you