The anisotropy of the aquatic reflectance “BRDF”

Jaime Pitarch, Vittorio Ernesto Brando, Marco Talone, Constant Mazeran, Davide D'Alimonte, Tamito Kajiyama, Ewa Kwiatkowska, David Dessailly and Juan Ignacio Gossn

BRDF correction of S3 OLCI water reflectance products

PO: Juan I. Gossn
PL: Davide D’Alimonte

What is the BRDF?

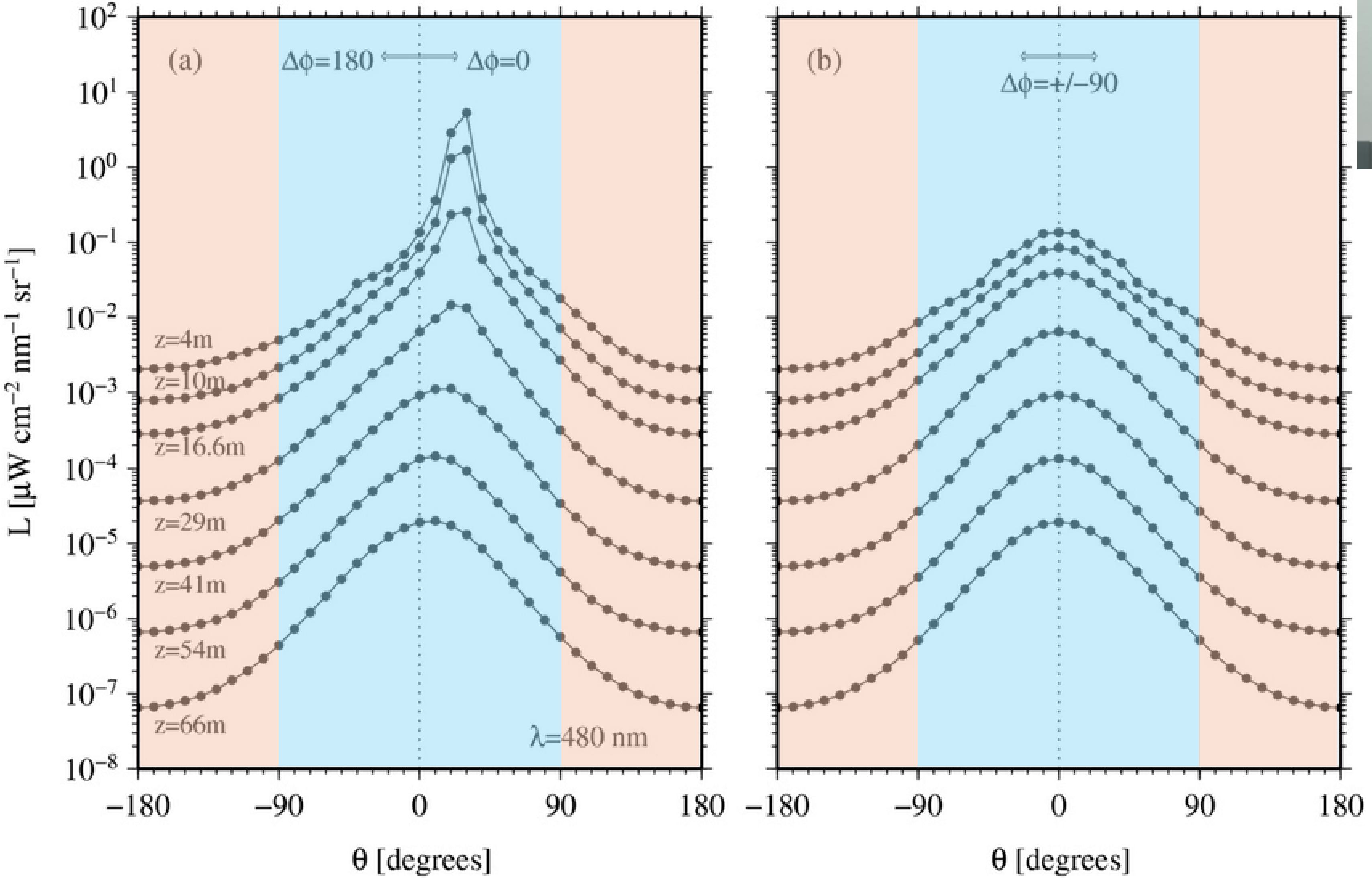
- Do you think the color of the grass is different because the grass is different?
- The *apparent* color is different, but the *inherent* color is the same

The lake Pend Oreille experiment, 1957

https://apps.dtic.mil/sti/tr/pdf/AD0268283.pdf

Downwelling

Upwelling

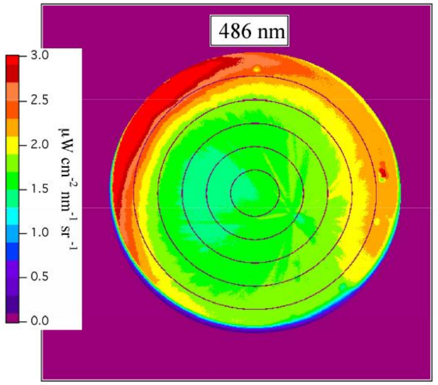


Redrawn by Antoine et al. (2013)

Downwelling

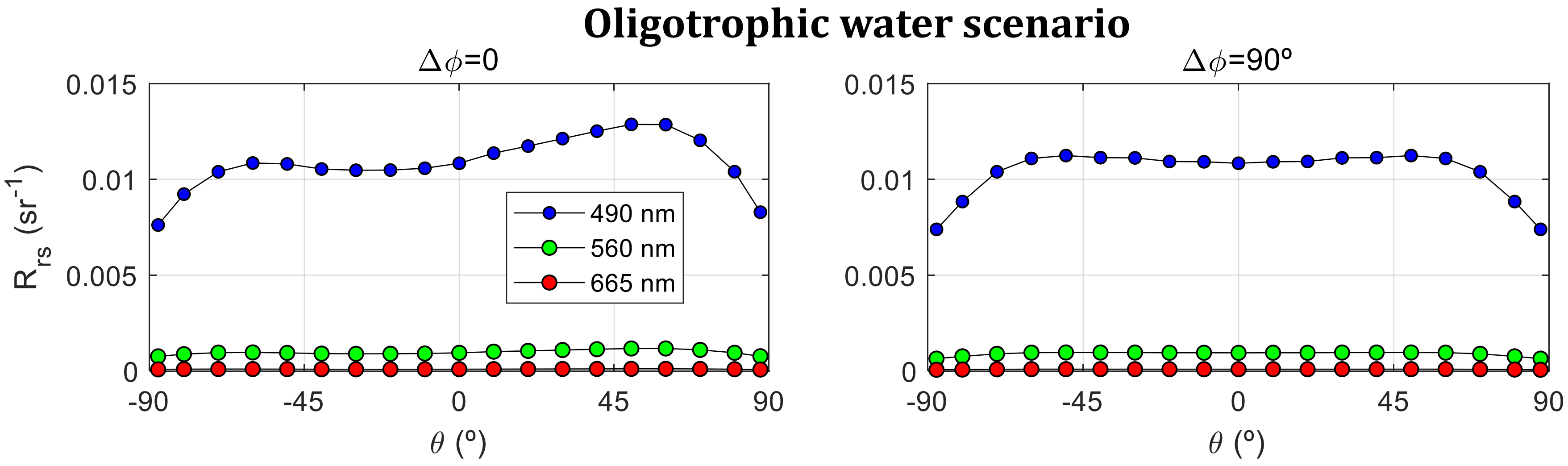
Free stock image

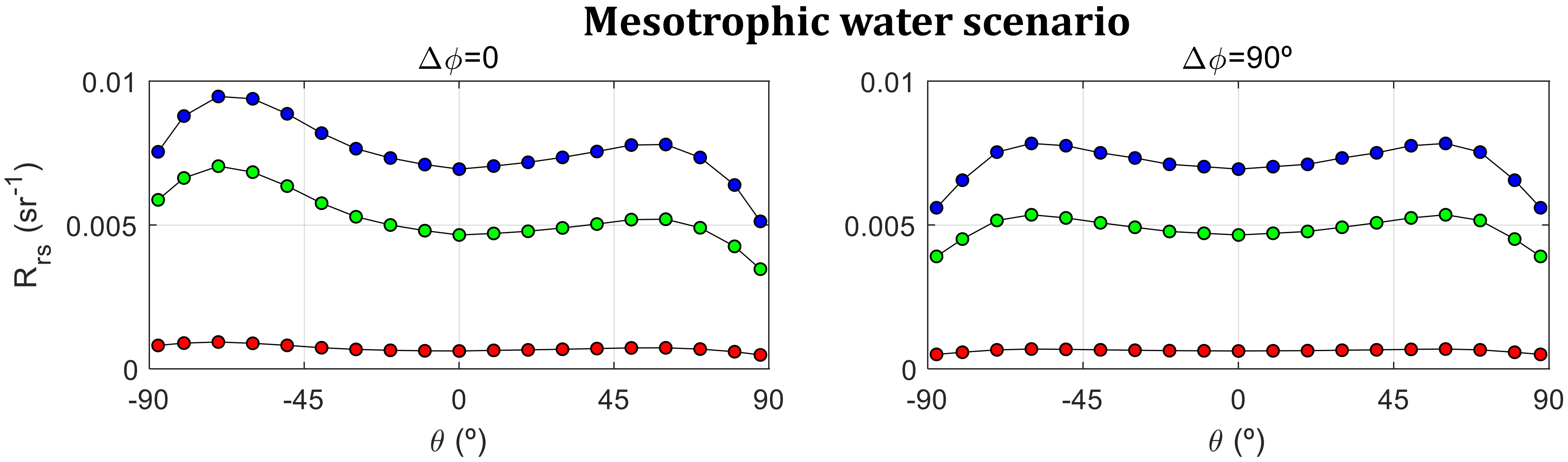
Upwelling



Voss and Chapin (2005)

- Radiance varies with the observing angles → so does R_{rs}
- But… is the angular shape invariant?





- …I am afraid it is not invariant
- It depends on the IOPs

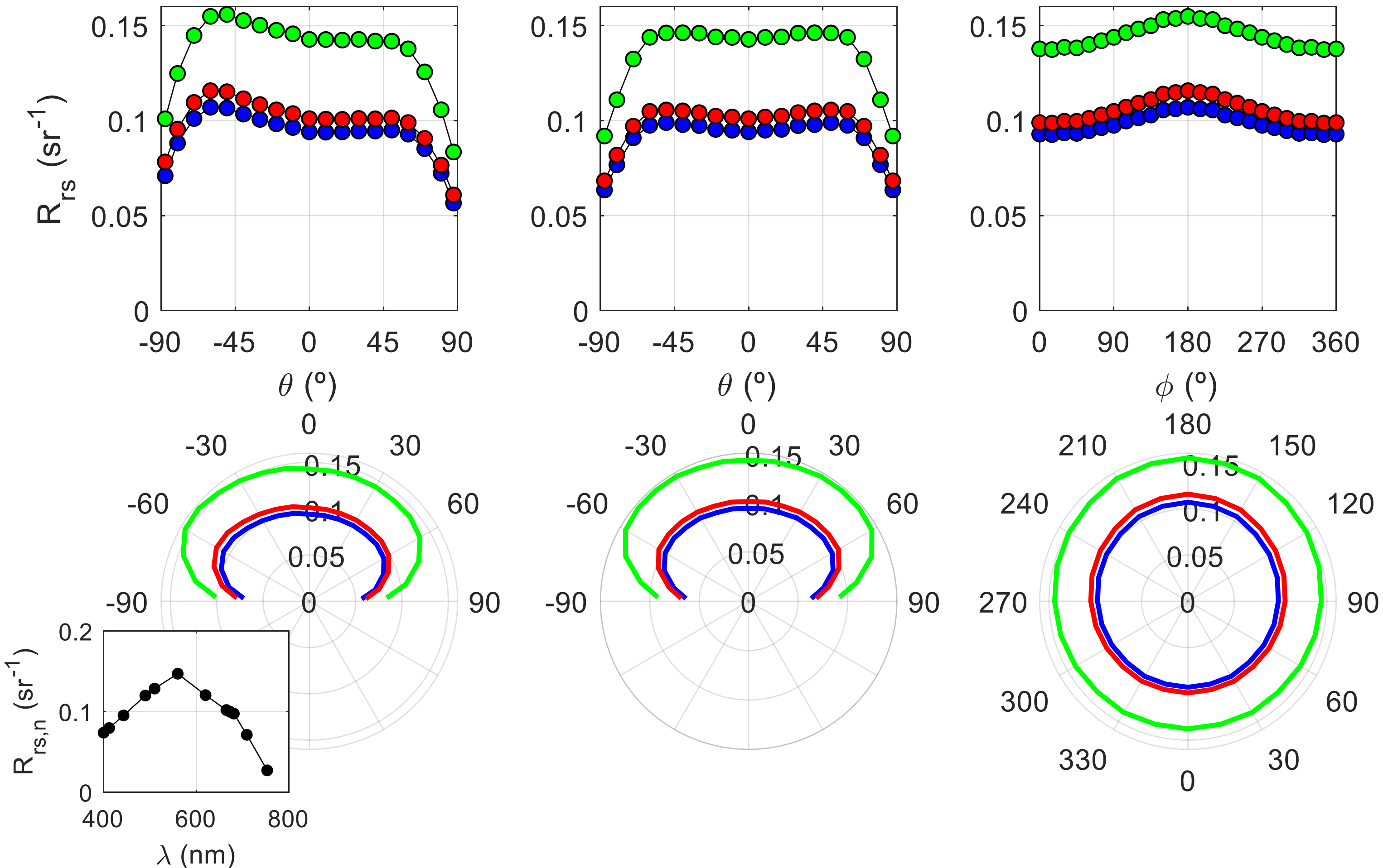
- ALL waters in the world have bidirectional effects
- Extremely turbid water does NOT lead to isotropy of R_{rs}

INT. J. REMOTE SENSING, 2001, VOL. 22, NO. 2 & 3, 275–295

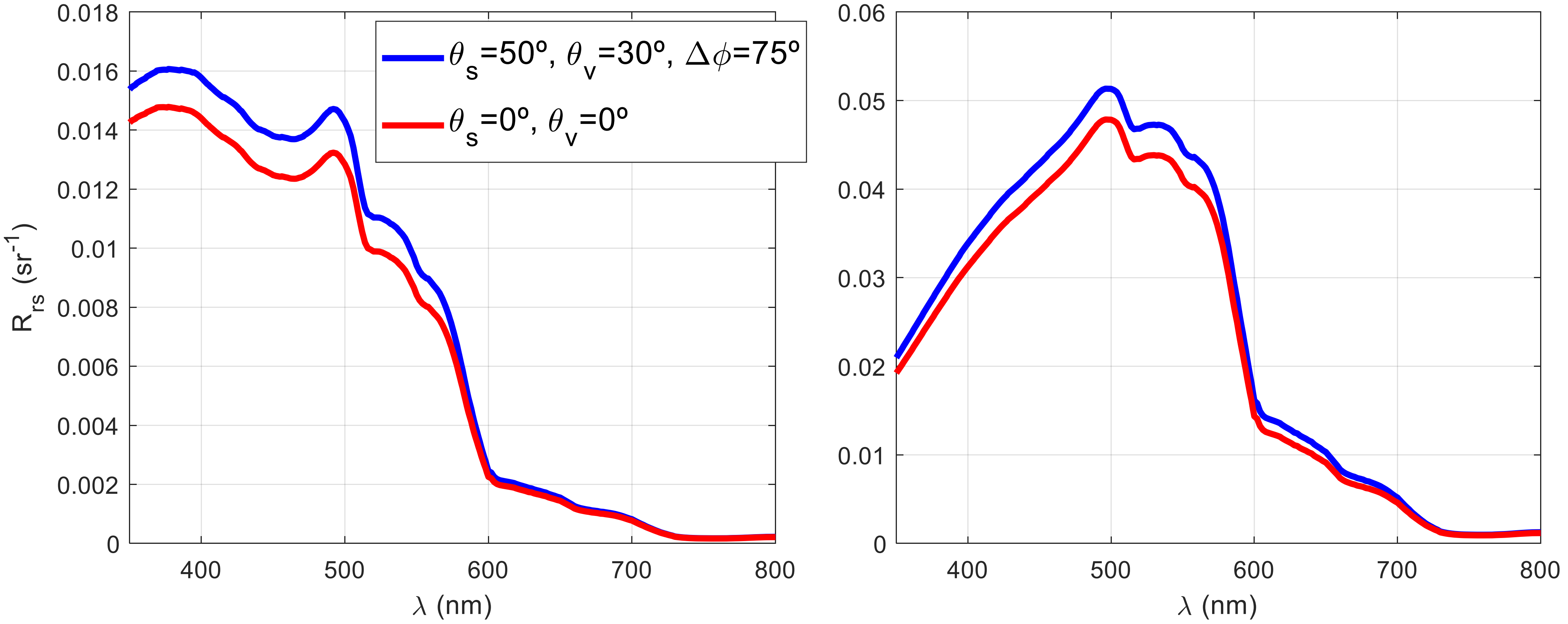
Non-isotropy of the upward radiance field in typical coastal (Case 2) waters

H. LOISEL and A. MOREL

10.1080/014311601449934



- The goal is to convert ***R_{rs}*** into ***R_{rs}***
- But… how?

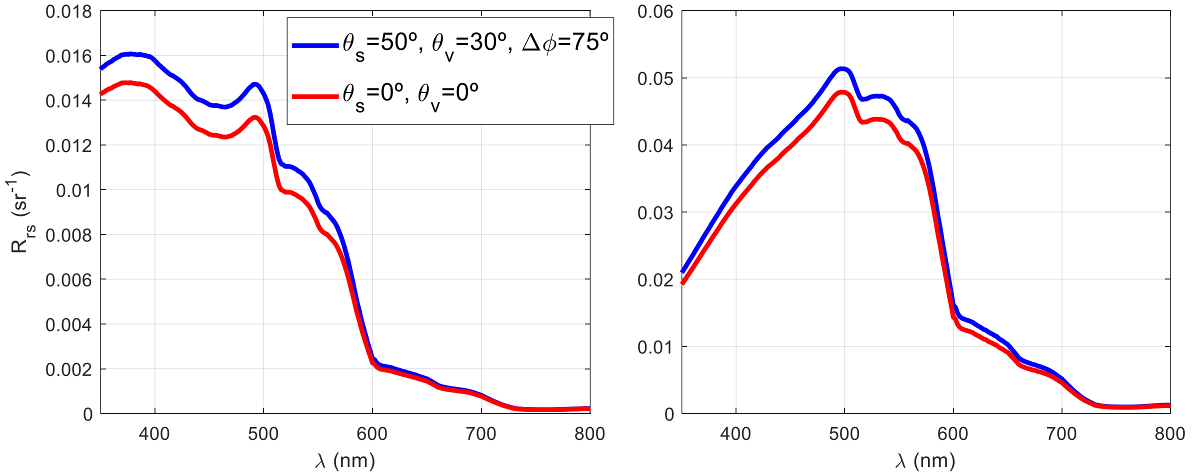


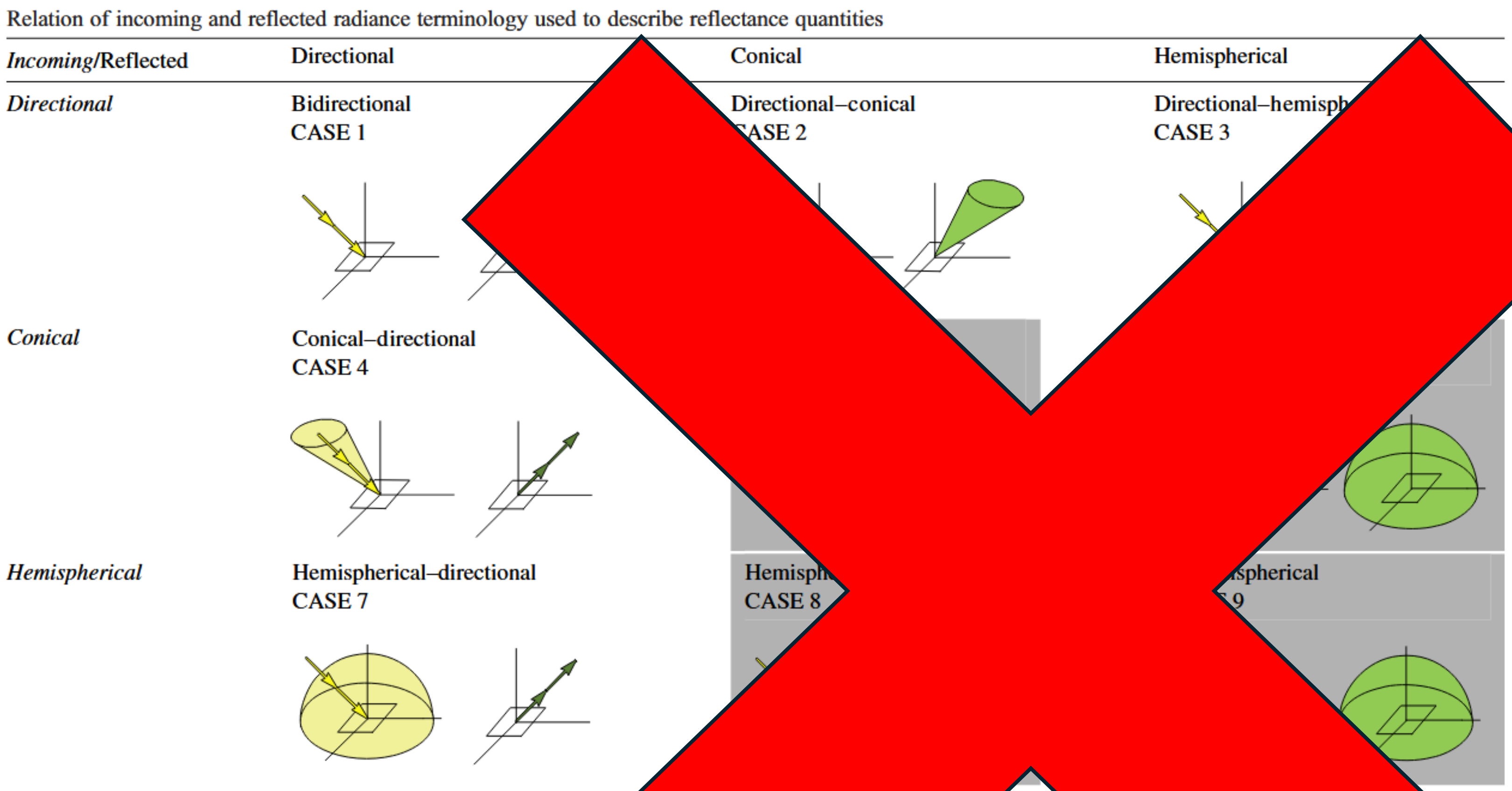
- To convert $\boldsymbol{R_{rs}}$ into $\boldsymbol{R_{rs}}$, we need to know the IOPs

- So, the BRDF is nothing more than the remote sensing problem

- We don't need the "BRDF" notion

- We better talk about anisotropy or bidirectionality





$$\mathrm{RDF}_\lambda = f_\mathrm{r}(\theta_\mathrm{i}, \phi_\mathrm{i}; \theta_\mathrm{r}, \phi_\mathrm{r}; \lambda) = \frac{\mathrm{d}L_\mathrm{r}(\theta_\mathrm{i}, \phi_\mathrm{i}; \theta_\mathrm{r}, \phi_\mathrm{r}; \lambda)}{\mathrm{d}E_\mathrm{i}(\theta_\mathrm{i}, \phi_\mathrm{i}; \lambda)} \quad [\mathrm{sr}^{-1}]$$

Schaepman-Strub et al. (2006)

10.1016/j.rse.2006.03.002

- Tilstone et al. (2 … neous defini…
  - ➢ How would yo … is definition to anoth … us such as Lee 2011 … You can’t

$$BRDF(\theta, \theta_0, \Delta\phi, \lambda, chl) = \mathfrak{R}_0(U_{10}) \frac{f_0(\lambda, U_{10}, chl)}{Q_0(\lambda, U_{10}, chl)} \left[\mathfrak{R}(\theta, U_{10}) \frac{f(\theta_0, \lambda, U_{10}, chl)}{Q(\theta, \theta_0, \Delta\phi, \lambda, U_{10}, chl)} \right]^{-1}$$

10.1364/OE.551042

- Definitions in Morel and Gentili (1996) are very confusing too…

$$(L_w)_N^{\mathrm{ex}} = \cdots\frac{\cdots, \theta_0, \Delta\phi)}{Q_0}\,(L_w)_N^{s}$$

$$(L_w)_N^{s} = \frac{L_w(\cdots}{\varepsilon t(\theta_0)\cdots}$$

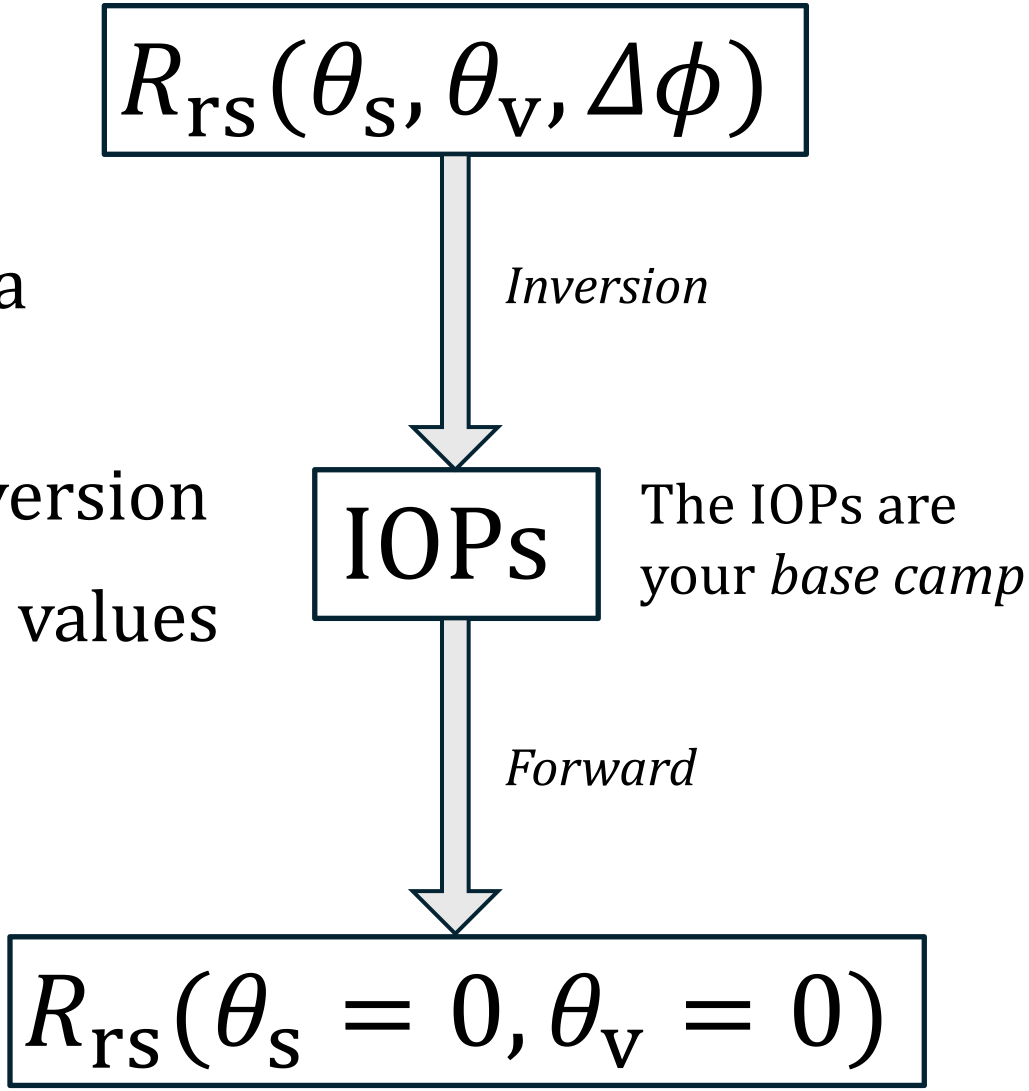
$$\cdots\theta_0)\;\frac{Q_n(\theta_0)}{Q_0}\,(L_w)_N^{f}.$$

- … and R_{rs} is defined … wing (not todays's definition)

$$R_{\mathrm{R}\cdots} \cdots \frac{\cdots_w(\theta = 0, \cdots}{E_d(0^+, \theta_0)}$$

You need an **analytical model of $\boldsymbol{R_{\mathrm{rs}}}$** as a function of the IOPs and of Ω, that:

- ➢Is simple enough to allow algebraic inversion
- ➢Is complex enough to provide accurate values



- You start model development by solving for R_{rs} from the scalar radiative transfer equation
    - ➢ That is our *truth*
    - ➢ what tells you the amount of radiance in the water as a consequence of:
        - ✓ Absorption
        - ✓ Scattering
    - ➢ You need to impose boundary conditions: top and bottom

$$\cos\theta \frac{dL}{dz} =$$

$$-cL + \int_0^{2\pi} \int_0^{\pi} L(\theta', \phi') \beta(\theta', \phi' \rightarrow \theta', \phi') \sin\theta \, \mathrm{d}\theta' \, \mathrm{d}\phi'$$

- Zaneveld's model and implementations based on it have numerous issues

$$\frac{L_u(\theta_s,\theta_v,\phi)}{E_{od}} = \frac{\beta(\psi)}{-\cos(\theta_v)K_{Lu}(\theta_s,\theta_v,\phi) + c - f_L(\theta_s,\theta_v,\phi)b_f}$$

10.1029/95JC00453

$$r_{rs} \cong \frac{1}{\overline{\mu}_d}\frac{\beta(\psi)}{b_b} / \left[\frac{a}{b_b}\left(1-\cos(\theta_v)\Psi_{K_{Lu}}\overline{\mu}_\infty{}^{-1}\right) + f_L\left(1-\widetilde{b}_b{}^{-1}\right) + \widetilde{b}_b{}^{-1}\right]$$

10.3390/app8122684

Morel: a series of fundamental papers

Morel 1991 10.1364/AO.30.004427

$$R = f' \frac{b_b}{a + b_b}$$

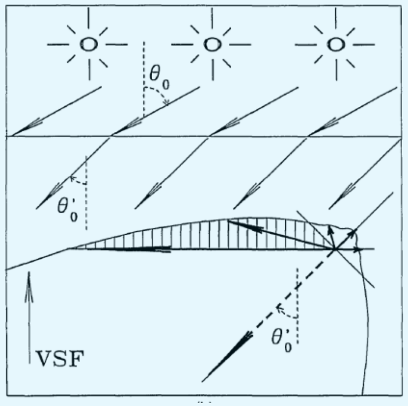
ing the upward stream. In the classical Eq. (13), b_b is by approximation used to replace a variable and unknown portion of the VSF where the backward lobe, after various convolutions, often has a major, albeit not exclusive, role. This approximation results in a nonconstant f factor in this equation. For exam-

Morel 1993 10.1364/AO.32.006864

The L_u field is also controlled by the optical properties of the water itself, which are summarized by the set of parameters $\overline{\omega}$ and η. Instead of η, a more adequate parameter is η_b, a similar dimensionless quantity, except that only backscattering is concerned, so that

$$\eta_b = b_{bw}/(b_{bw} + b_{bp}), \qquad (11)$$

$$\frac{L_u(\theta_0, \theta', \Delta\varphi)}{E_d(0^-)} = \frac{f}{Q}\frac{b_b}{a}$$



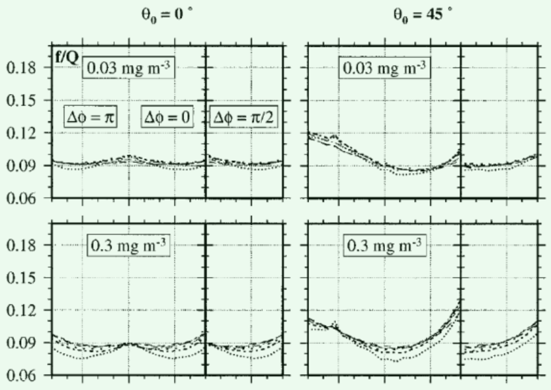
Morel 1996 10.1364/AO.35.004850

C. Bidirectional Properties

To get a complete picture of the anisotropic upward radiant field, all the observation angles must be considered. Some examples of the variations in the ratio

$$f(\theta_0, \lambda, \mathrm{Chl})/Q(\theta', \theta_0, \Delta\phi, \lambda, \mathrm{Chl})$$

and desirable. Stokes vector computation of the upward radiance[30] could be envisaged; it is likely premature, considering the inaccuracies that remain in the current bio-optical models. In this study, the



Morel 2002 10.1364/AO.41.006289

The determination of the two other quantities, f and Q, requires that the in-water radiance field (particularly the upward field) be computed for all geometries, environmental conditions, and water types.

The quantities $f(\lambda, \theta_s, \mathrm{Chl})$ and the ratios $f(\lambda, \theta_s, \mathrm{Chl})/Q(\lambda, \theta_s, \theta', \phi, \mathrm{Chl})$ are tabulated as functions of the five following parameters:

- Wavelength (λ), seven values;
- Zenith-sun angle (θ_s), six values;
- Chlorophyll concentration (Chl), six values;

Morel: how are models developed?

$$\cos\theta \frac{dL}{dz} = -cL + \int_0^{2\pi}\int_0^{\pi} L(\theta', \phi')\beta(\theta', \phi' \rightarrow \theta', \phi')\sin\theta \, \mathrm{d}\theta' \, \mathrm{d}\phi'$$

You get the *true* R_{rs} from here

$$R_{\mathrm{rs}} \approx \Re \frac{f}{Q}\frac{b_{\mathrm{b}}}{a}$$

- You know a and b_{b} in advance
- You know R_{rs} because you solved the RTE
- You know $\Re$ because a smart person calculated it for you with his Monte-Carlo code

You calculate $\frac{f}{Q}$ by fitting the model to the data

Morel: bio-optical modelling for the RTE simulations

- A three-component model: water (w), phytoplankton (chl) and CDOM (y)
- Phytoplankton:
  - Its absorption ALWAYS has the same spectral shape
  - Chl varies between 0.1 and 10 mg m^{-3}
- CDOM:
  - is related to phytoplankton with a fully deterministic equation
  - Its spectral slope is constant at 0.014

$$b_{bp}/b_p = \tilde{b}_{bp} = 0.002 + \{0.01[0.5 - 0.25 \log_{10}(\text{Chl})]\}$$

$$b_p(\lambda, \text{Chl})/b_p(550, \text{Chl}) = (\lambda/550)^v,$$

where the varying exponent v is expressed as

$$v = (1/2)[\log_{10}(\text{Chl}) - 0.3],$$

when $0.02 < \text{Chl} < 2$ mg m^{-3},

$$v = 0,$$

when $\text{Chl} > 2$ mg m^{-3}.

$$a(\lambda) = a_w(\lambda) + 0.06 A_{chl}(\lambda)(\text{Chl})^{0.65} + a_y(\lambda),$$

where

$$a_y(\lambda) = a_y(440) \exp[-0.014(\lambda - 440)]$$

$$a_y(440) = 0.2[a_w(440) + 0.06 A_{chl}(440)(\text{Chl})^{0.65}],$$

The phase function

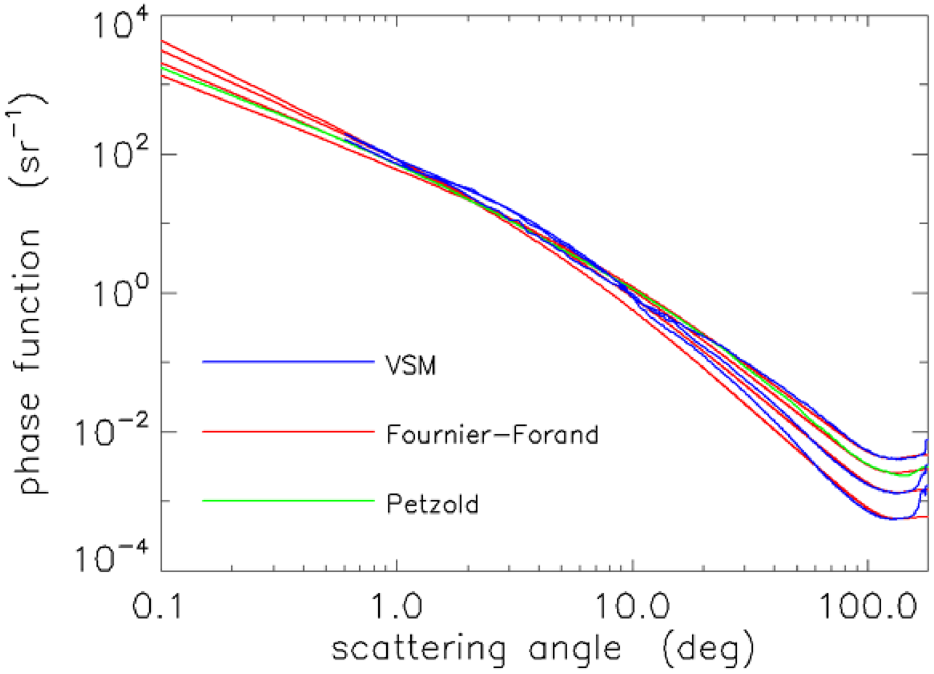
VSF → β

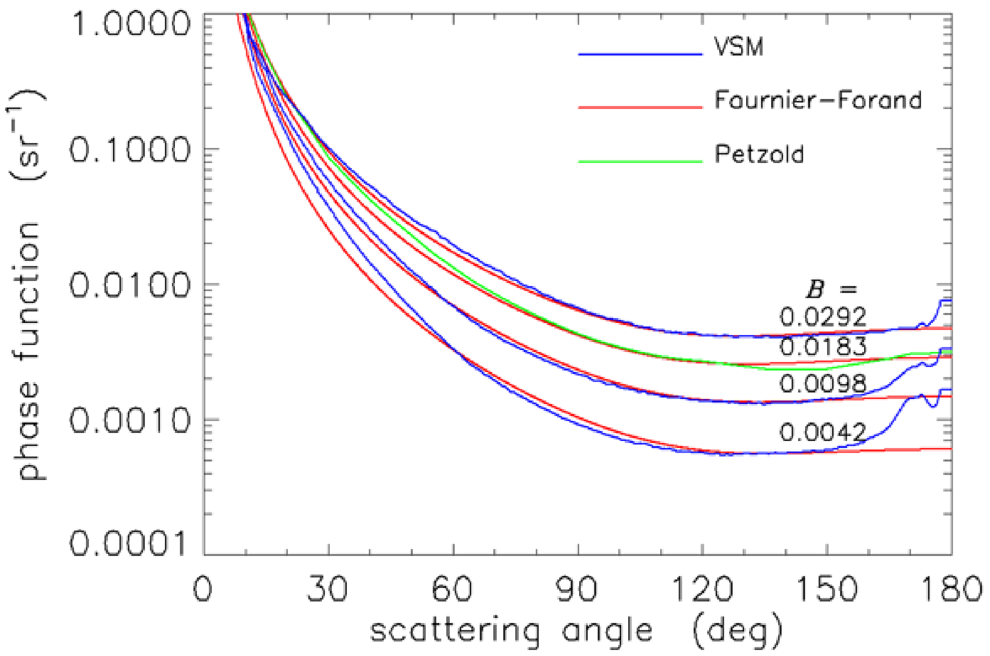
$$= \beta_{\mathrm{w}} + \beta_{\mathrm{p}}$$
$$= \beta_{\mathrm{w}} + \beta_{\mathrm{ph}} + \beta_{\mathrm{NAP}}$$
$$= \beta_{\mathrm{w}} + \beta_{\mathrm{ph}} + \beta_{\mathrm{det}} + \beta_{\mathrm{min}}$$
=…

- These are the VSFs of every water constituent
- The split is justified on:
  - The ability to quantify each one of them
  - The differences in their angular patterns
- They increase ~ proportionally to their respective concentrations

$$\tilde{\beta}_{\mathrm{x}} = \frac{\beta_{\mathrm{x}}}{b_{\mathrm{x}}}$$

$$b_{\mathrm{x}} = 2\pi \int_0^{\pi} \beta_{\mathrm{x}}(\Psi) \sin\Psi \mathrm{d}\Psi$$





Mobley, Ocean Optics Web Book
www.oceanopticsbook.info/

The phase function

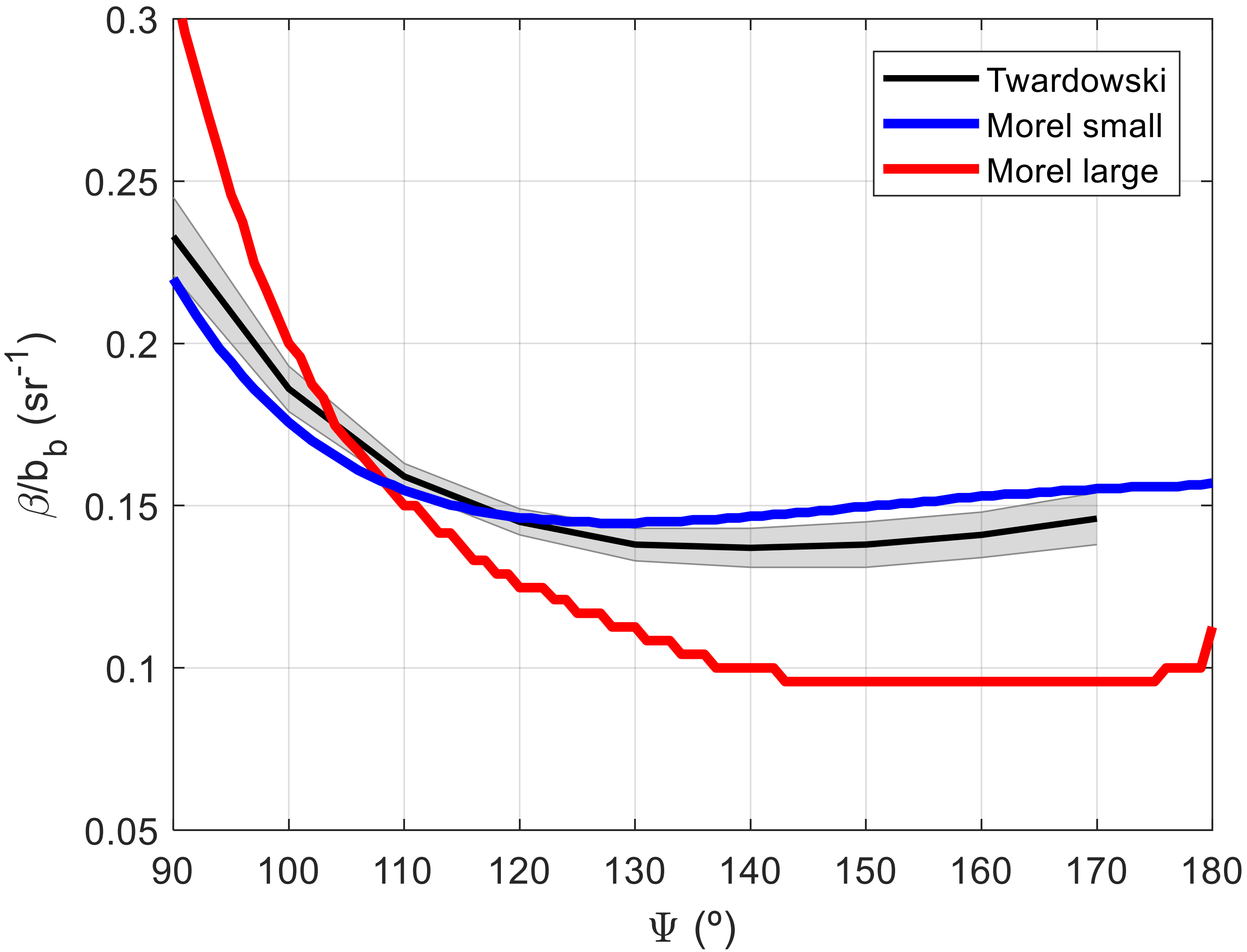
- Hydrolight needs the phase function, $\tilde{\beta}_{\mathrm{x}} = \frac{\beta_{\mathrm{x}}}{b_{\mathrm{x}}}$
- BUT Twardowski showed that a parameter that is more related to remote sensing is $P_{\mathrm{x}} = \frac{\beta_{\mathrm{x}}}{b_{\mathrm{b,x}}}$ 10.1364/AO.48.006811
- Twardowski's $\frac{\beta_{\mathrm{x}}}{b_{\mathrm{b,x}}}$ is inversely related to Zhang's χ factor with: $\chi_{\mathrm{x}} = \frac{\mathrm{b}_{b,x}}{2\pi\beta_{\mathrm{x}}}$
- Twardowski showed that $\frac{\beta_{\mathrm{x}}}{b_{\mathrm{b,x}}}$'s variability is quite restricted between 90 and 180 degrees, for all kinds of marine particles (Zhang disagrees) 10.1364/AO.414695
- This can help you decide whether or not a phase function is realistic

Morel’s phase functions

10.1364/AO.41.006289

$$\tilde{\beta}_p(\psi,\ \mathrm{Chl}) = \alpha_s(\mathrm{Chl})\tilde{\beta}_{p,s}(\psi) + \alpha_l(\mathrm{Chl})\tilde{\beta}_{p,l}(\psi)$$

- $\tilde{\beta}_{p,s}$ and $\tilde{\beta}_{p,l}$ were calculated using Mishchenko’s T-matrix Fortran code, assuming a Junge PSD distribution of ellipsoidal, randomly oriented homogeneous particles



- $\tilde{\beta}_{p,s}$ for Chl=0.1 mg m^{-3}
- $\tilde{\beta}_{p,l}$ for Chl=10 mg m^{-3}
- A weighted average in between

The QAA

10.1364/AO.41.005755

ioccg.org/groups/Software_OCA/QAA_v5.pdf

$$\omega_{\mathrm{b}} = \frac{\mathrm{b_b}}{\mathrm{a+b_b}} \qquad r_{\mathrm{rs}} = g_0\omega_{\mathrm{b}} + g_1\omega_{\mathrm{b}}^2 \qquad R_{\mathrm{rs}} = \Re r_{\mathrm{rs}}$$

- Widely used, even outside the QAA (e.g., GIOP, etc…)
- $g_0, \; g_1$ → single values, calculated from data for various sun zeniths and only for nadir-view
- $\Re$ → technically inconsistent with Hydrolight

Lee 2011

10.1364/AO.50.003155

$$\omega_{\mathrm{w}} = \frac{\mathrm{b_{bw}}}{\mathrm{a+b_b}}$$

$$\omega_{\mathrm{p}} = \frac{\mathrm{b_{bp}}}{\mathrm{a+b_b}}$$

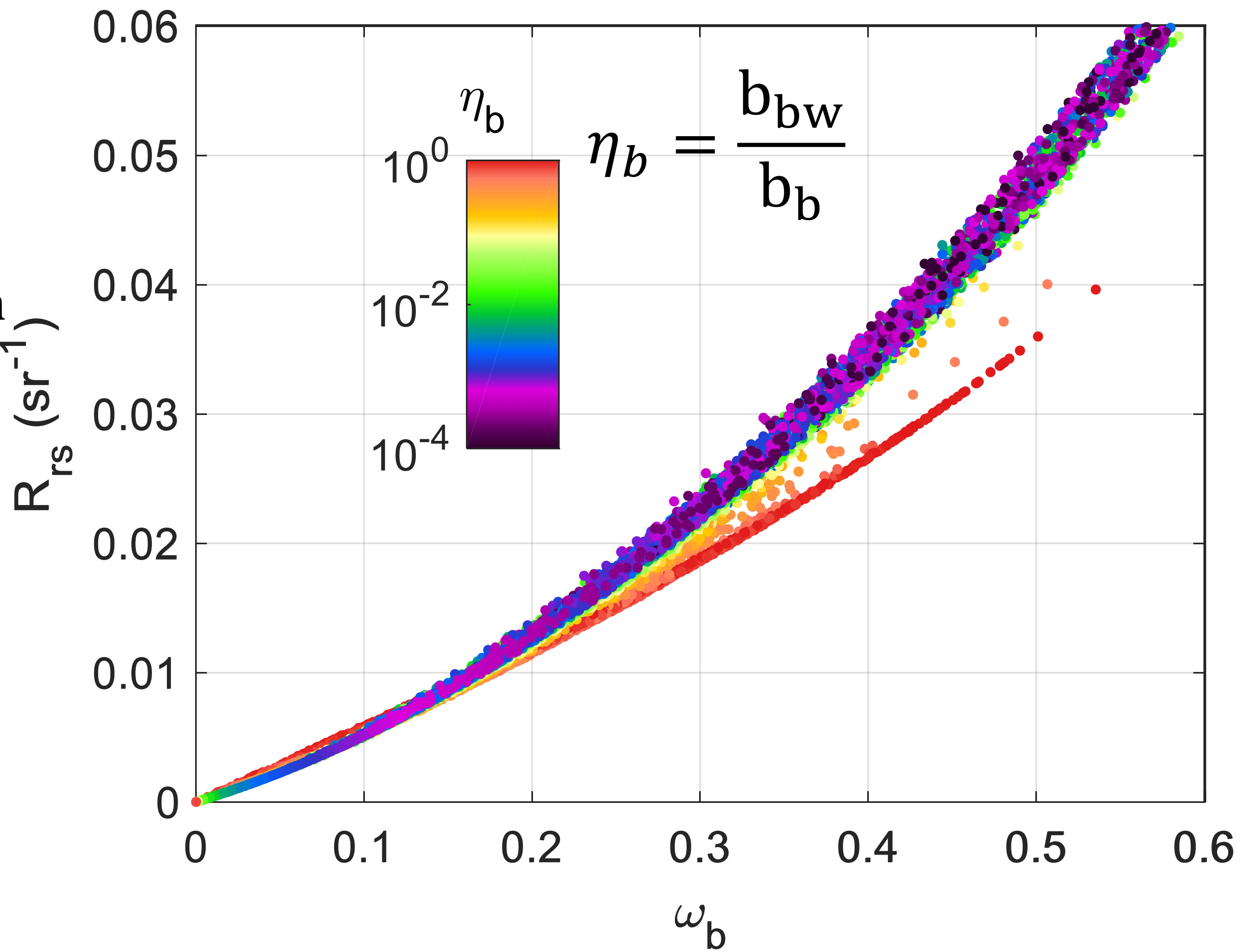
$$R_{\mathrm{rs}} = G_0^w\omega_{\mathrm{w}} + G_1^w\omega_{\mathrm{w}}^2 + G_0^p\omega_{\mathrm{p}} + G_1^p\omega_{\mathrm{p}}^2$$

$$G_0^w, G_1^w, G_0^p, G_1^p = f(\theta_{\mathrm{s}}, \theta_{\mathrm{v}}, \Delta\phi)$$

- R_{rs} is directly calculated (no $\Re$)
- *G*'s are *wavelength agnostic*

- Why consider $\omega_w = \frac{b_{bw}}{a+b_b}$ and $\omega_p = \frac{b_{bp}}{a+b_b}$ separately?

- Does not $\omega_b = \frac{b_b}{a+b_b}$ alone encapsulate enough information to predict R_{rs} with accuracy?



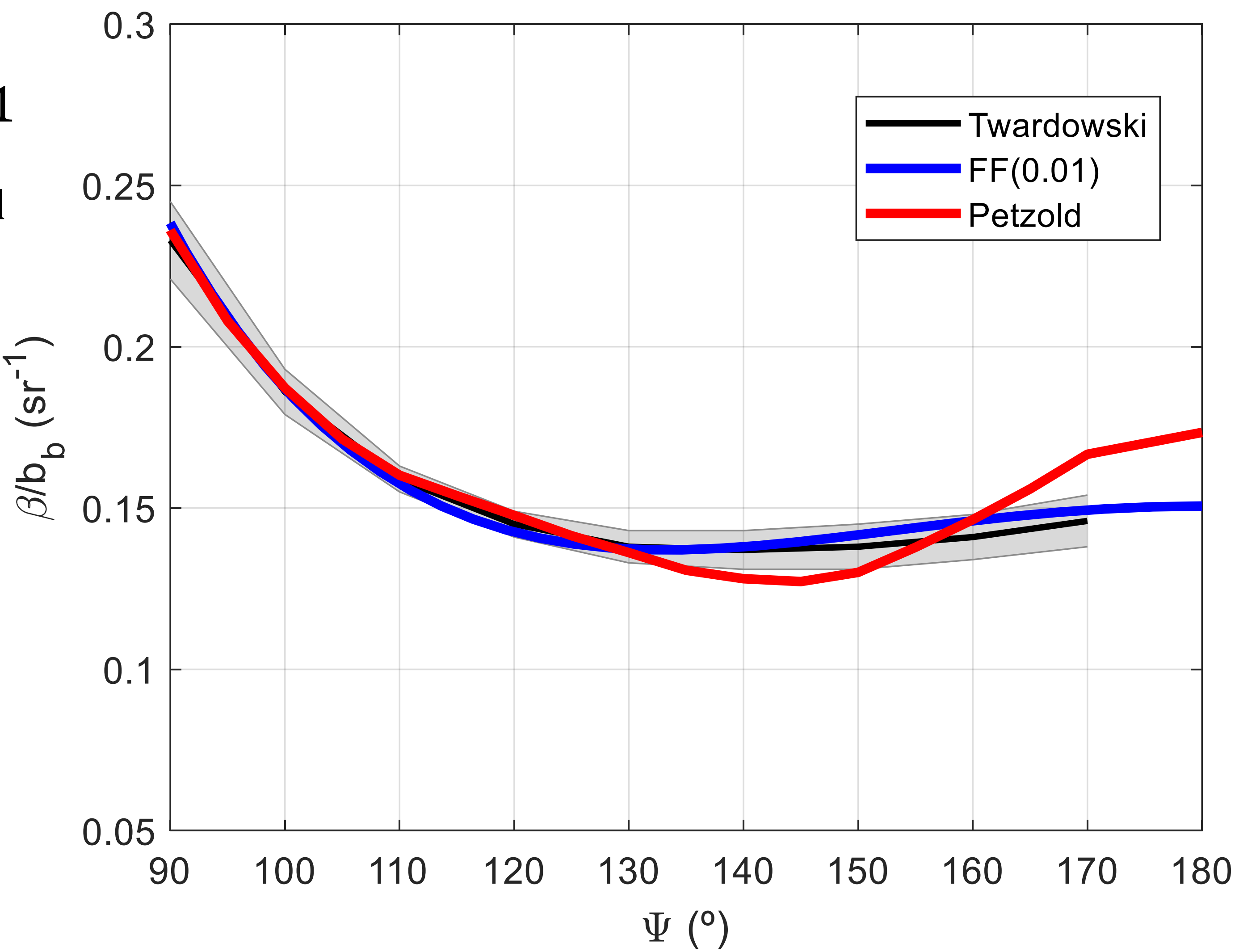
Lee: bio-optical modelling for the RTE simulations

- A four-component model: water (w) , phytoplankton (chl) , non-algal particles (NAP) and CDOM (y)
- Replicating the IOCCG dataset's modelling
- Pseudo-case 1 assumption: everything is a function of chl, but with a random part
- Phytoplankton:
  - Chl varies between 0.03 and 30 mg m^{-3}
  - Real absorption spectra, adjusted to be consistent with chl
- Non-algal particles:
  - Assumes an exponential shape for absorption and a power law for scattering, randomly linked to chl
- CDOM:
  - is related to chl with a random coefficient
  - Its spectral slope varies
- We can say this modelling is a good starting point

Lee's phase functions

$$\beta = \beta_{\mathrm{w}} + \beta_{\mathrm{ph}} + \beta_{\mathrm{NAP}} = \beta_{\mathrm{w}} + b_{\mathrm{ph}}(chl)\tilde{\beta}_{\mathrm{ph}} + b_{\mathrm{NAP}}(chl)\tilde{\beta}_{\mathrm{NAP}}$$

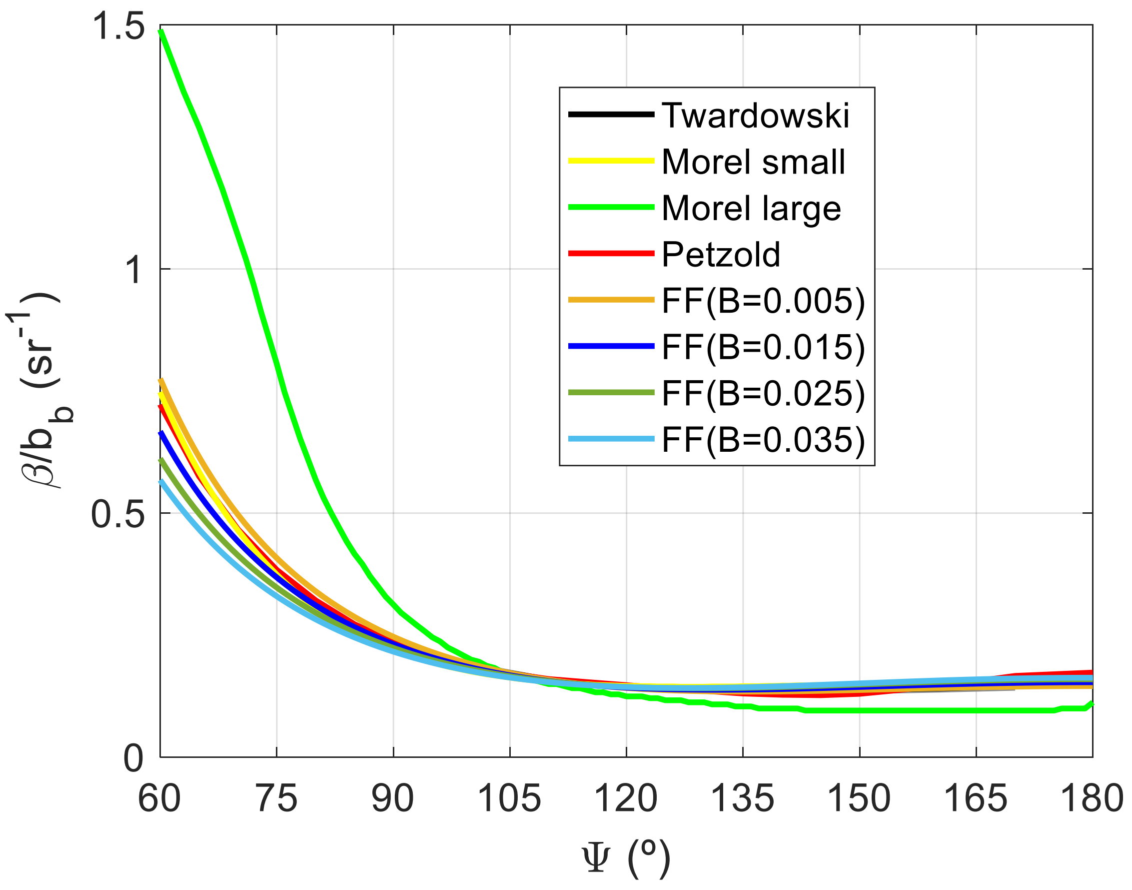
- $\tilde{\beta}_{\mathrm{ph}}$: Fournier-Forand, with a backscattering ratio $B_{\mathrm{ph}} = \frac{b_{\mathrm{b,ph}}}{b_{\mathrm{ph}}} = 0.01$
  - Backward shape consistent with empirical evidence
  - Fixed backscattering ratio is a minor shortcoming
- $\tilde{\beta}_{\mathrm{NAP}}$: Petzold average: B_{NAP}=0.0183
  - Totally not ok with empirical evidence

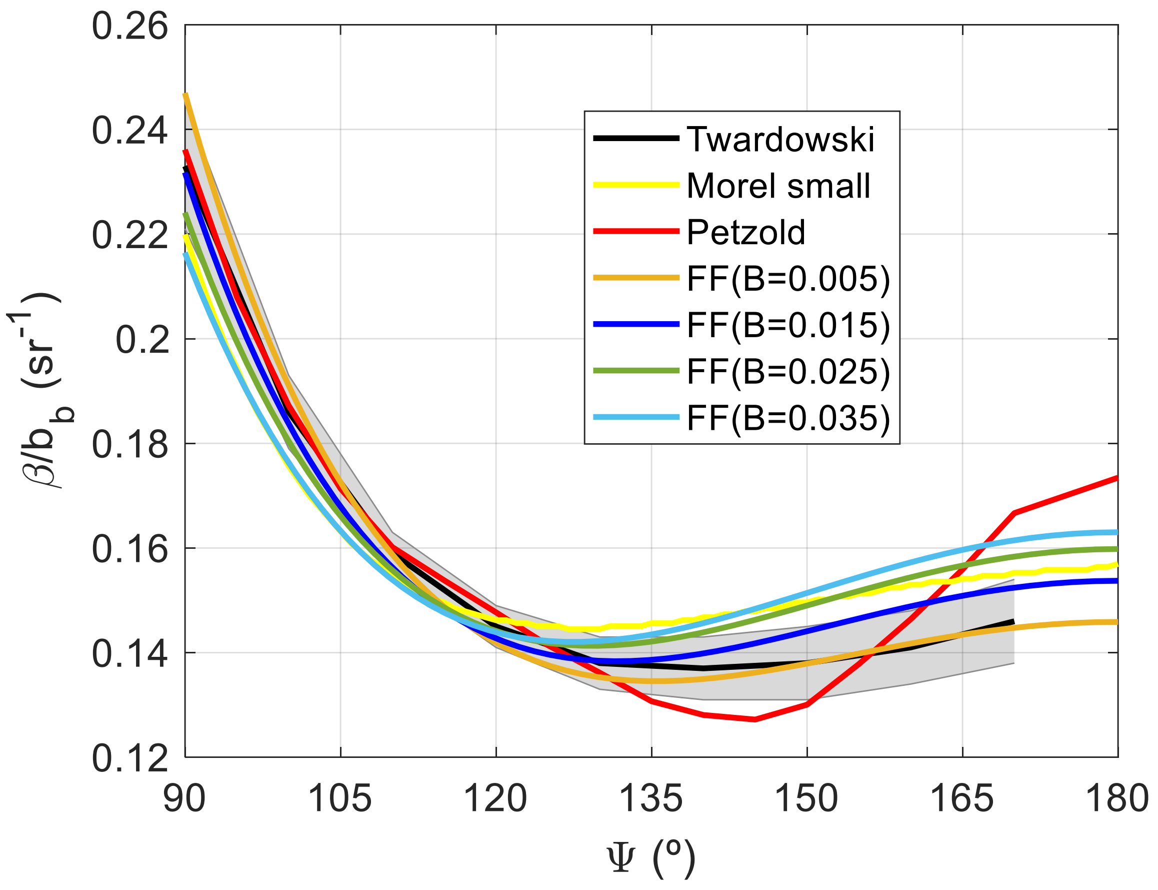


misclab.umeoce.maine.edu/ftp/classes/OO2017/readings/Fournier_SPIE3761_1999.pdf

www.oceanopticsbook.info/packages/iws_l2h/conversion/files/Petzold_VSF_SIO72-78.pdf

Phase functions: summary





A new method based on Lee 2011

- Lee 2011 is the right starting point for a number of technical reasons
  - ➢ It has a proper R_{rs} modelling, separating water and particles
  - ➢ It is a modular method, allowing to target specific weaknesses
  - ➢ It is based on the QAA for IOP inversion
- But we need a dataset to build a new method
  - ✓ A wide range of realistic IOPs
  - ✓ A wide range of angular combinations
  - ✓ Such dataset did not exist before

Earth Syst. Sci. Data, 17, 435–460, 2025
https://doi.org/10.5194/essd-17-435-2025

Open Access Earth System Science Data

A hyperspectral and multi-angular synthetic dataset for algorithm development in waters of varying trophic levels and optical complexity

Jaime Pitarch[1] **and Vittorio Ernesto Brando**[1,2]

[1]Consiglio Nazionale delle Ricerche (CNR), Istituto di Scienze Marine (ISMAR), Via del Fosso del Cavaliere 100, 00133 Rome, Italy
[2]CSIRO Environment, Aquatic Remote Sensing Team, 16 Clunies Ross Street, GPO Box 1700, Canberra ACT 2601, Australia

Correspondence: Jaime Pitarch (jaime.pitarch@cnr.it)

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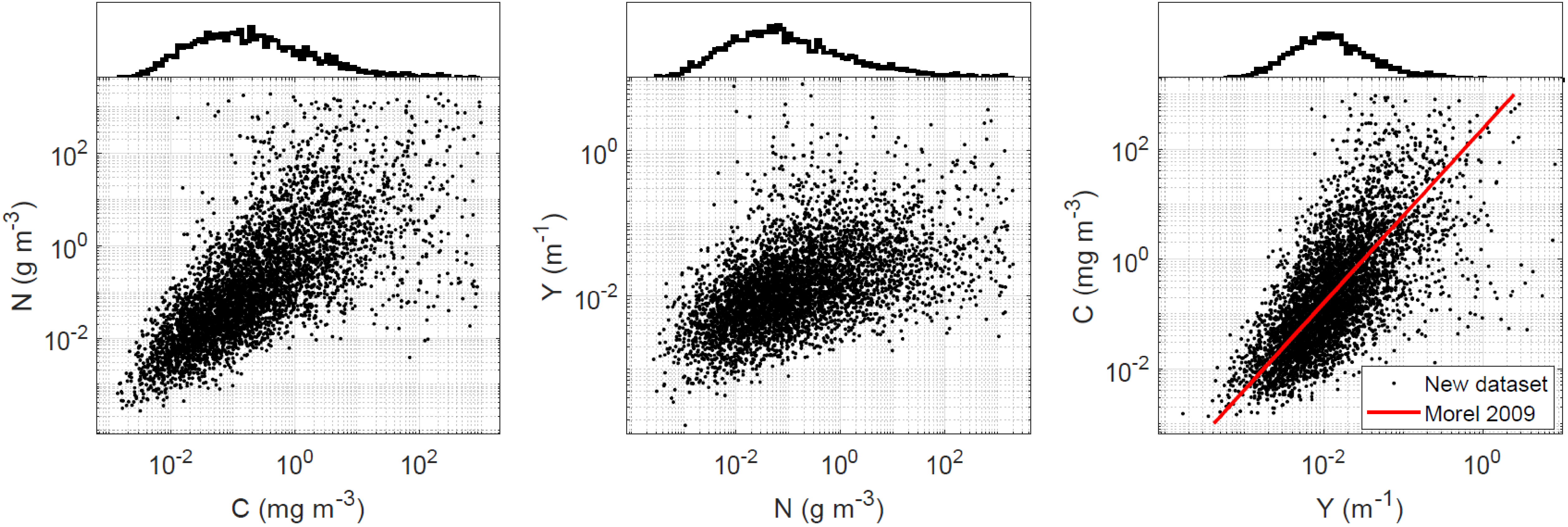
Pitarch and Brando (2024), or PB24 dataset

- Resolved at the full range of geometries (1300 angular combinations in total)
  - $\theta_{\mathrm{s}} = [0{:}\,10°{:}\,80°, 87.5°]$
  - $\theta_{\mathrm{v}} = [0{:}\,10°{:}\,80°, 87.5°]$
  - $\Delta\phi = [0{:}\,15°{:}\,180°]$
- 5000 IOP cases, covering an extensive range of water types
- Phase functions chosen from the Fournier-Forand family (FF), with varying backscattering ratio
- Bio-optical modeling introducing covariances between IOPs to mimic natural variability

PB24 dataset

- Driven by the concentrations of chlorophyll (C), non-algal particles (N) and CDOM (Y)

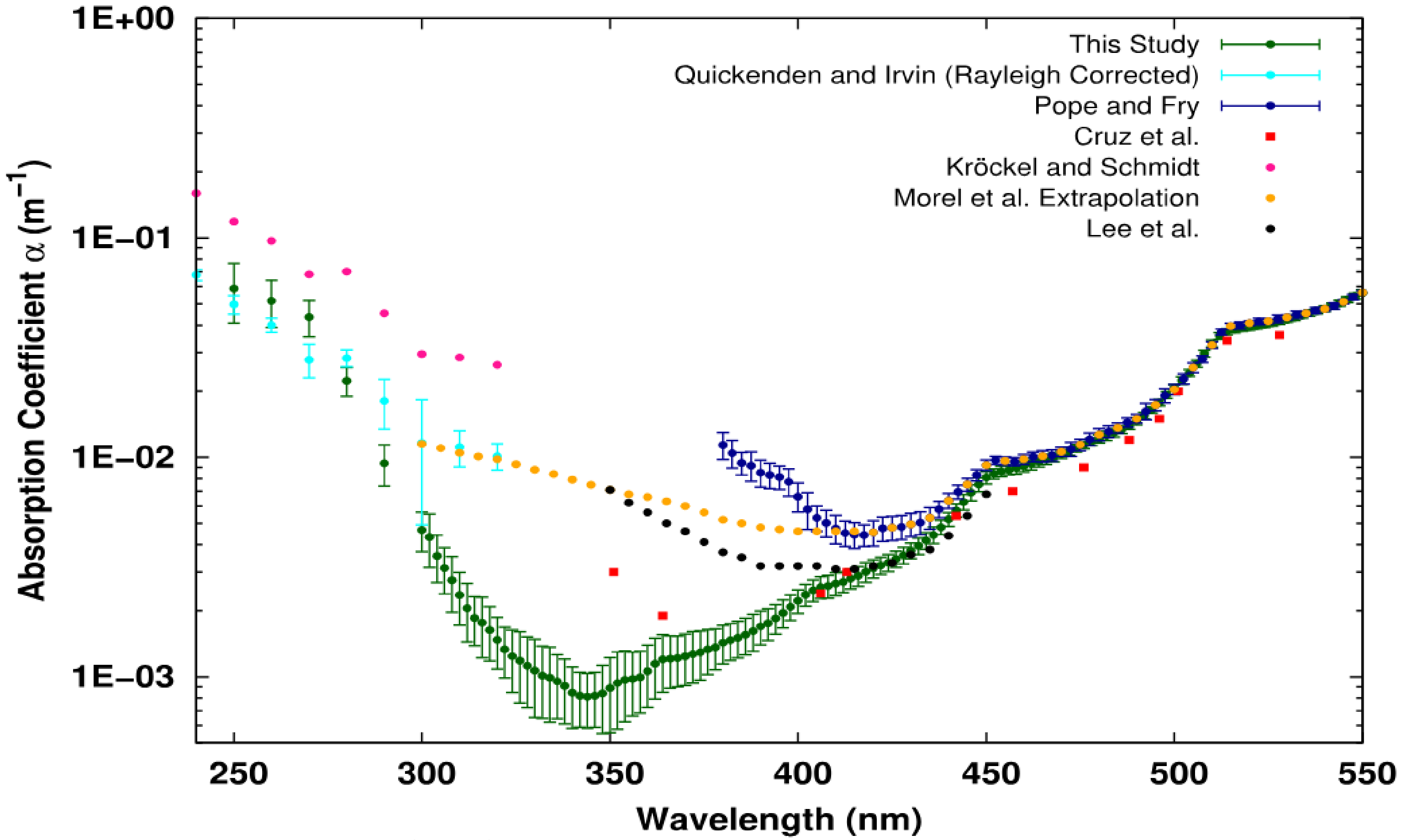


$$a(\lambda) = a_{\mathrm{w}}(\lambda) + a_{\mathrm{ph}}(\lambda) + a_{\mathrm{NAP}}(\lambda) + a_{\mathrm{g}}(\lambda)$$

$$\beta(\Psi,\lambda) = \beta_{\mathrm{w}}(\Psi,\lambda) + \beta_{\mathrm{ph}}(\Psi,\lambda) + \beta_{\mathrm{NAP}}(\Psi,\lambda)$$

Pure water absorption and scattering

- Scattering: Zhang et al. (2009) for T=20°C and S=35 PSU 10.1364/OE.17.005698
- Absorption, WOPP merged dataset by Roettgers calvalportal.ceos.org/documents/10136/64871/WOPP.zip

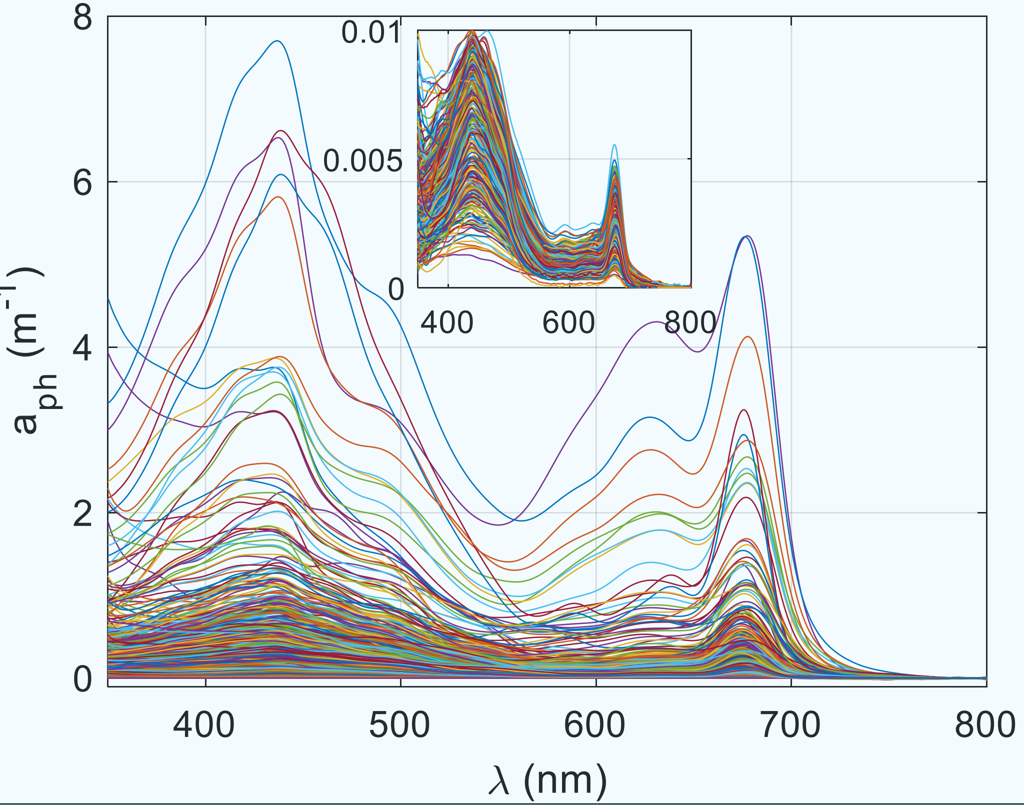


Mason and Fry (2016)
10.1364/AO.55.007163

PB24 dataset: phytoplankton absorption and scattering

Absorption

- Pool of real absorption spectra
  - ✓ 3025 QC'd spectra
  - ✓ 4 orders of magnitude
  - ✓ Down to 350 nm
- Given C, a random spectrum is chosen and scaled, to verify $a_{ph}(670) = A(670)C^{E(670)}$



Scattering

$$c_{\mathrm{ph}}(\lambda) = c_{\mathrm{ph}}(660)\left(\frac{660}{\lambda}\right)^{n_1}$$

$$c_{\mathrm{ph}}(660) = p_3 C^{0.795} \quad \text{where} \quad p_3 \leftarrow \mathcal{U}(0.06, 0.6)$$

$$n_1 = -0.4 + \frac{1.6 + 1.2\Re}{1 + C^{0.5}} \quad \text{where} \quad \Re \leftarrow \mathcal{U}(0,1)$$

$$B_{\mathrm{ph}} \leftarrow \mathcal{N}(\mu, \sigma) \quad \text{where}$$

$$\mu = 0.002 + (0.01 - 0.002) \cdot \exp[-0.56 \log_{10}(C)]$$

$$\sigma = 0.001(3 - \log_{10}(C)) + 0.001$$

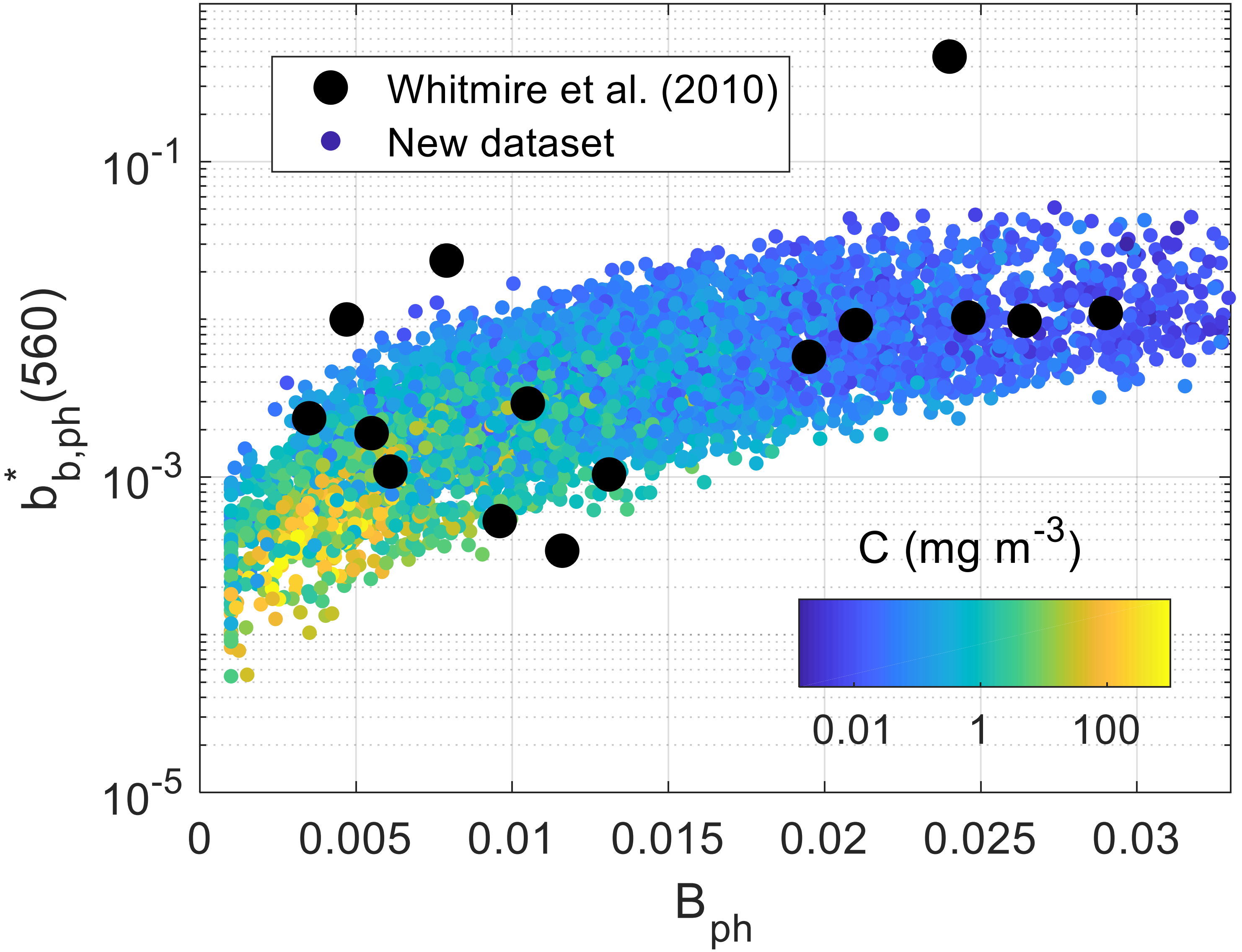
$$\tilde{\beta}_{\mathrm{ph}} \sim FF(B_{\mathrm{ph}})$$

$$b_{\mathrm{ph}} = c_{\mathrm{ph}} - a_{\mathrm{ph}}$$

$$\beta_{\mathrm{ph}} = b_{\mathrm{ph}} \tilde{\beta}_{\mathrm{ph}}$$

Phytoplankton absorption and scattering

- I will never stress enough how proud I am of this result



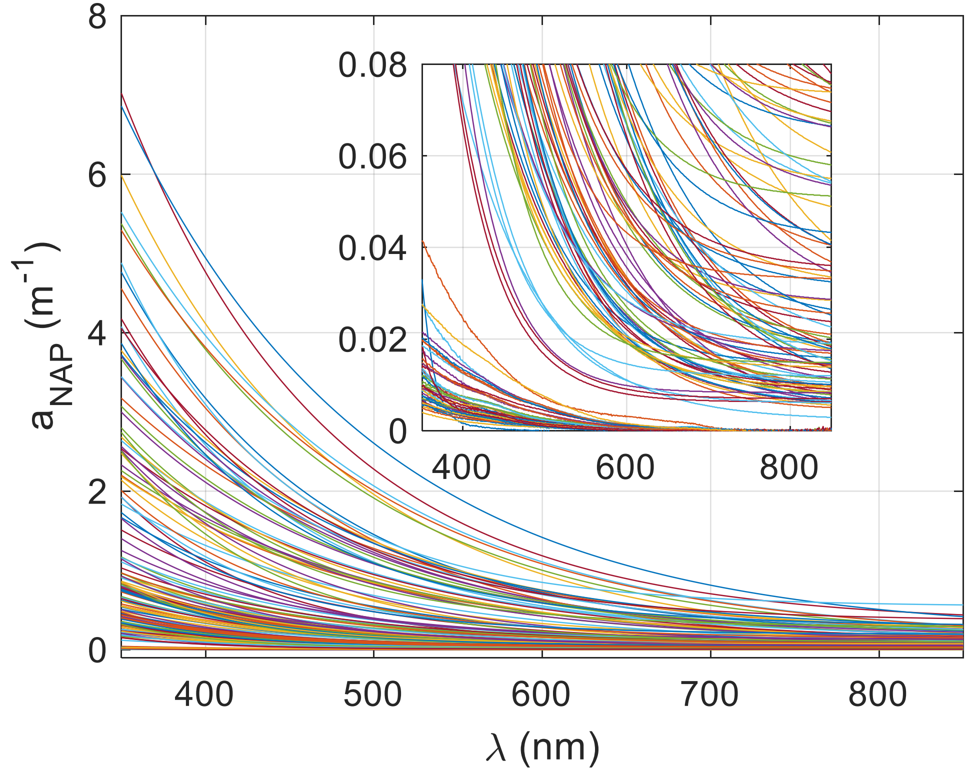
10.1364/OE.18.015073

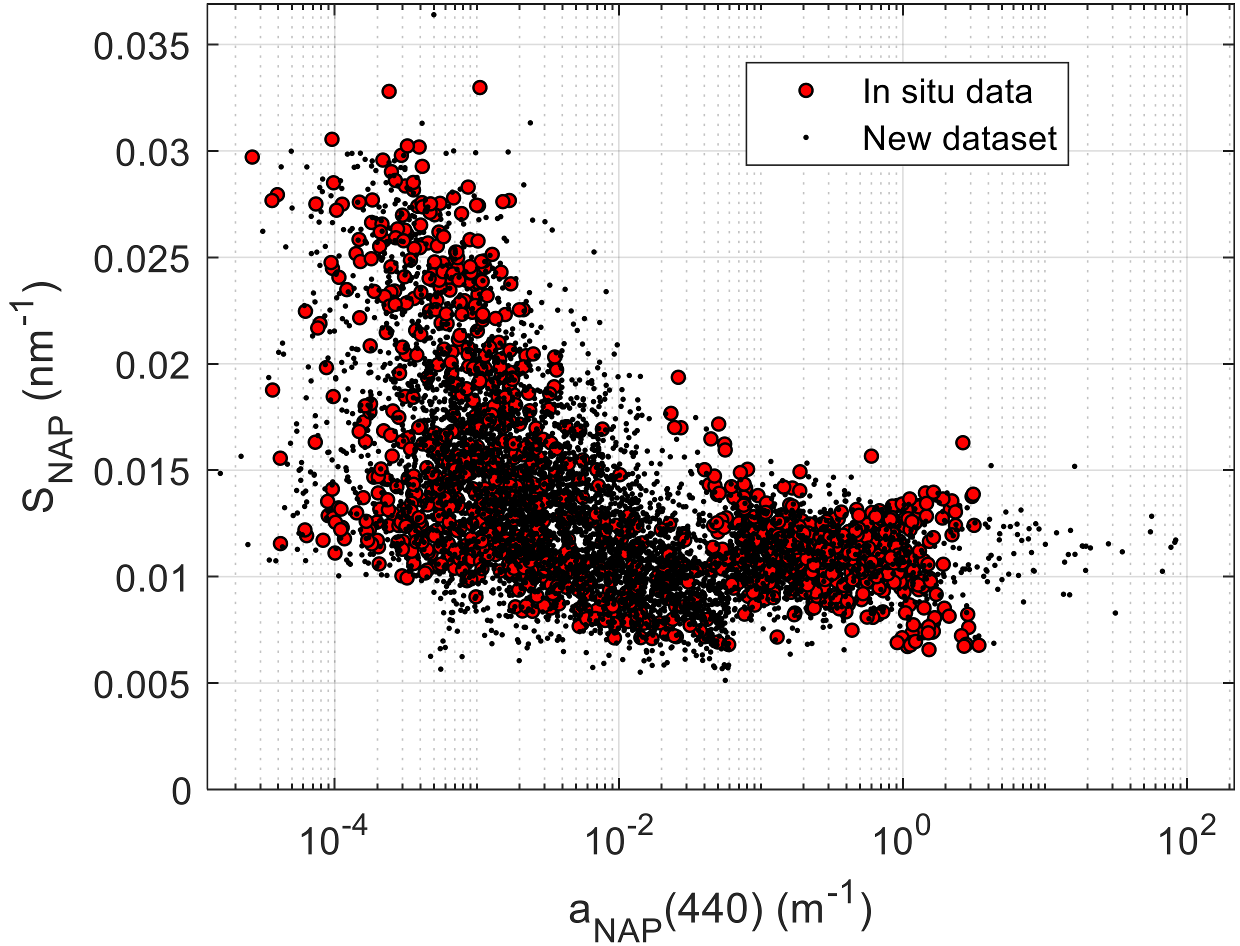
NAP absorption and scattering

- Analytical modelling, strongly data-driven

$$\hat{a}_{\mathrm{NAP,mod}}(\lambda) = a_{\mathrm{NAP}}(\lambda_0)e^{-S_{\mathrm{NAP}}(\lambda-\lambda_0)} + a_{\mathrm{NAP,off}}$$
$$\rightarrow a_{\mathrm{NAP,mod}}(\lambda) = \hat{a}_{\mathrm{NAP,mod}}(\lambda) - a_{\mathrm{NAP,off}}$$

Fit→$\lambda \in [350,750]$ nm

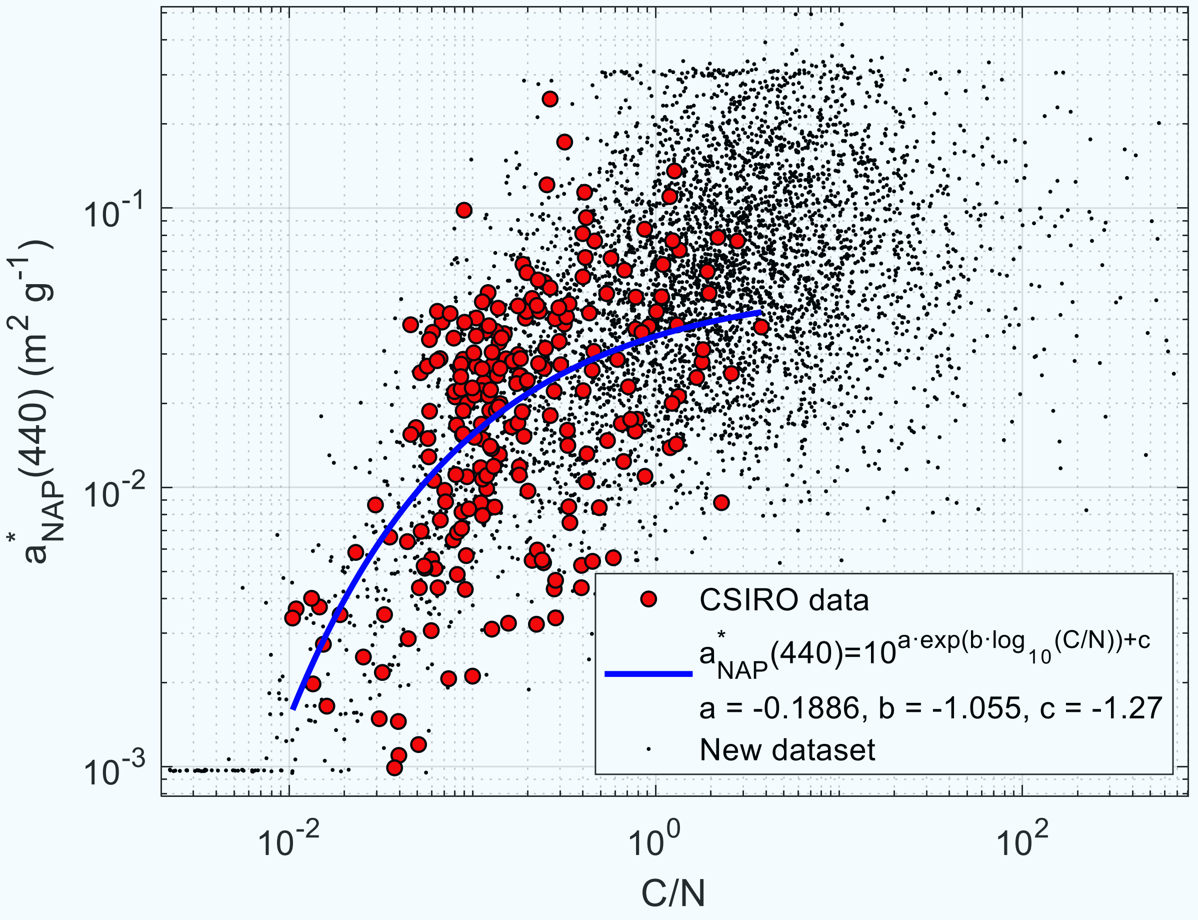




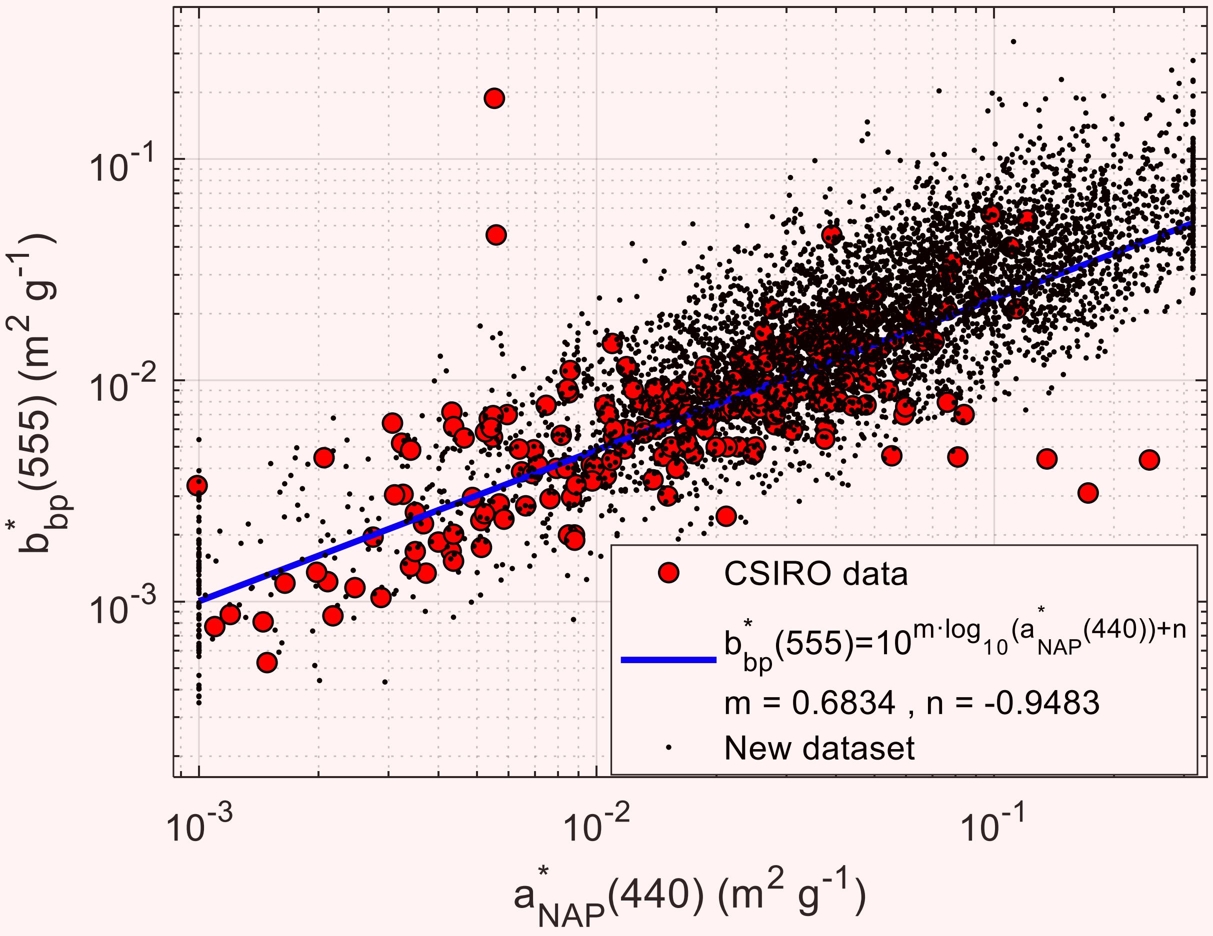
NAP absorption and scattering

10.1029/2008JC005039
10.3389/fmars.2017.00114
10.1016/j.seares.2016.01.008
10.3390/rs15030652
10.1364/AO.51.002808

Can we predict $a^*_{\mathrm{NAP}}(440)$ as a function of something else?



Are a^*_{NAP} and b^*_{bp} related?



NAP absorption and scattering

$$c_{\mathrm{NAP}}(\lambda) = c_{\mathrm{NAP}}(440)\left(\frac{\lambda}{440}\right)^{-\gamma_{\mathrm{NAP}}}$$

$$\gamma_{\mathrm{NAP}} \leftarrow \mathcal{N}(\mu, \sigma) \text{ where } \mu = 0.7, \sigma = 0.3$$

$$c_{\mathrm{NAP}}(440) = a_{\mathrm{NAP}}(440) + b_{\mathrm{NAP}}(440)$$

$$b_{\mathrm{NAP}}(440) = \frac{b_{\mathrm{b,NAP}}(440)}{B_{\mathrm{NAP}}} \text{ where } B_{\mathrm{NAP}} \leftarrow \mathcal{U}(0.01, 0.02)$$

$$b_{\mathrm{b,NAP}}(440) = T b^{*}_{\mathrm{bp}}(440) - b_{\mathrm{ph}}(440) \text{ where } T = N + 0.07C$$

$$\tilde{\beta}_{\mathrm{NAP}} \sim FF(B_{\mathrm{NAP}})$$

$$b_{\mathrm{NAP}} = c_{\mathrm{NAP}} - a_{\mathrm{NAP}}$$

$$\beta_{\mathrm{ph}} = b_{\mathrm{ph}} \tilde{\beta}_{\mathrm{ph}}$$

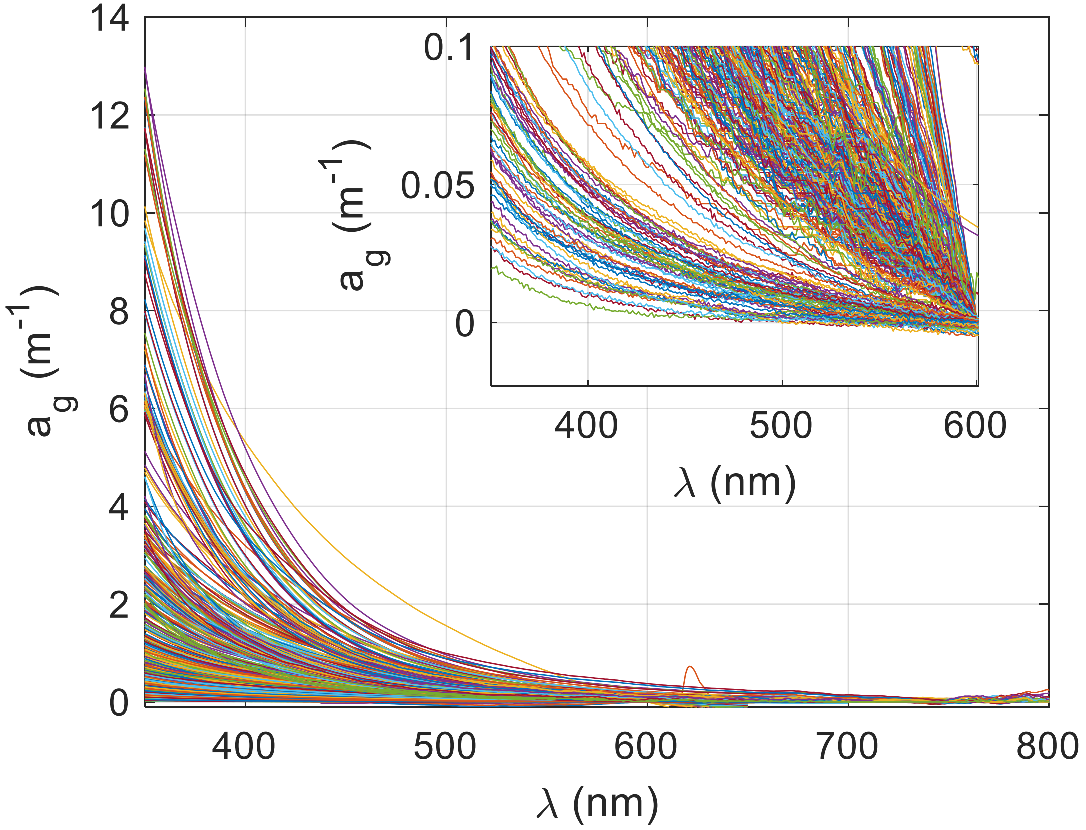
CDOM absorption

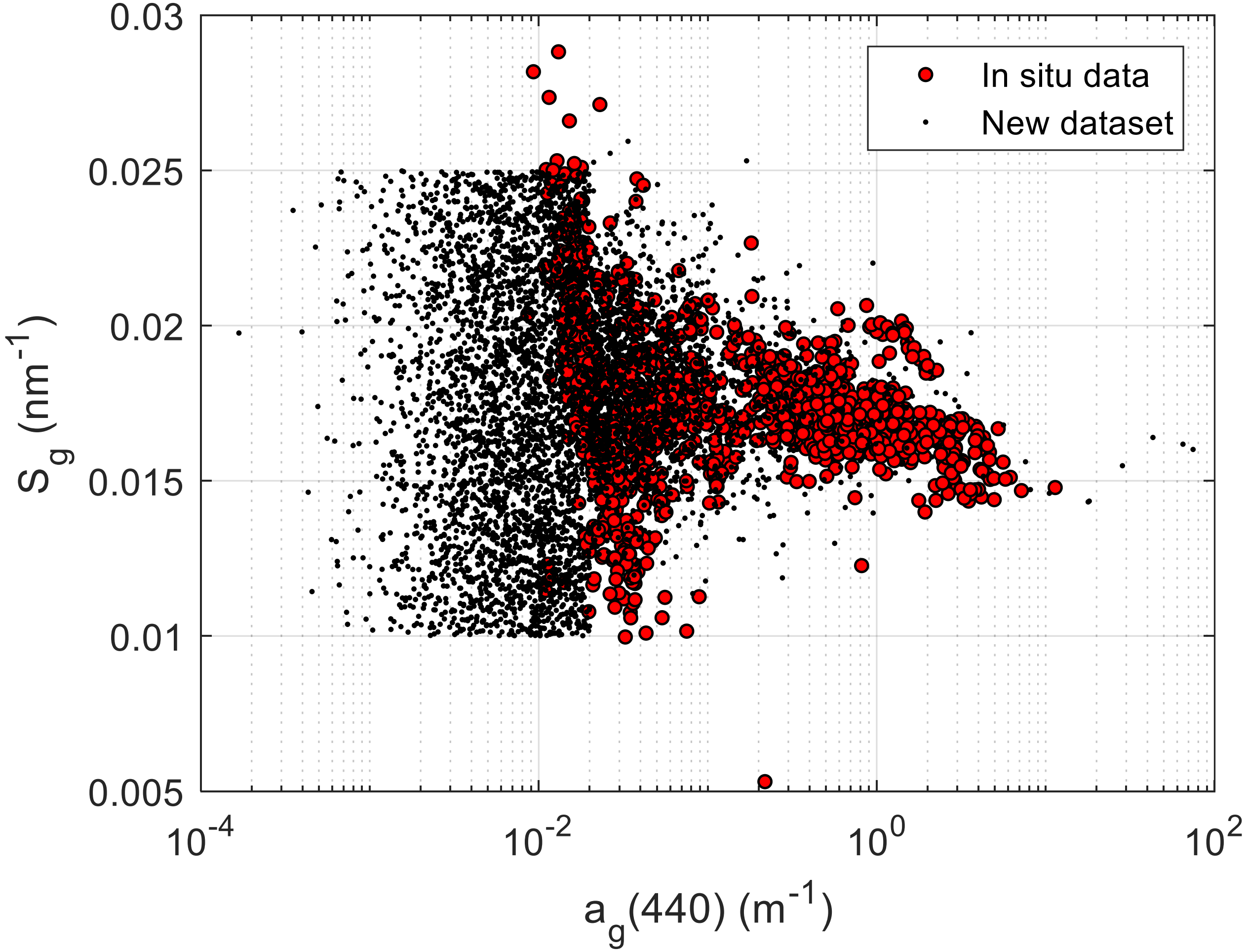
- Analytical modelling, strongly data-driven

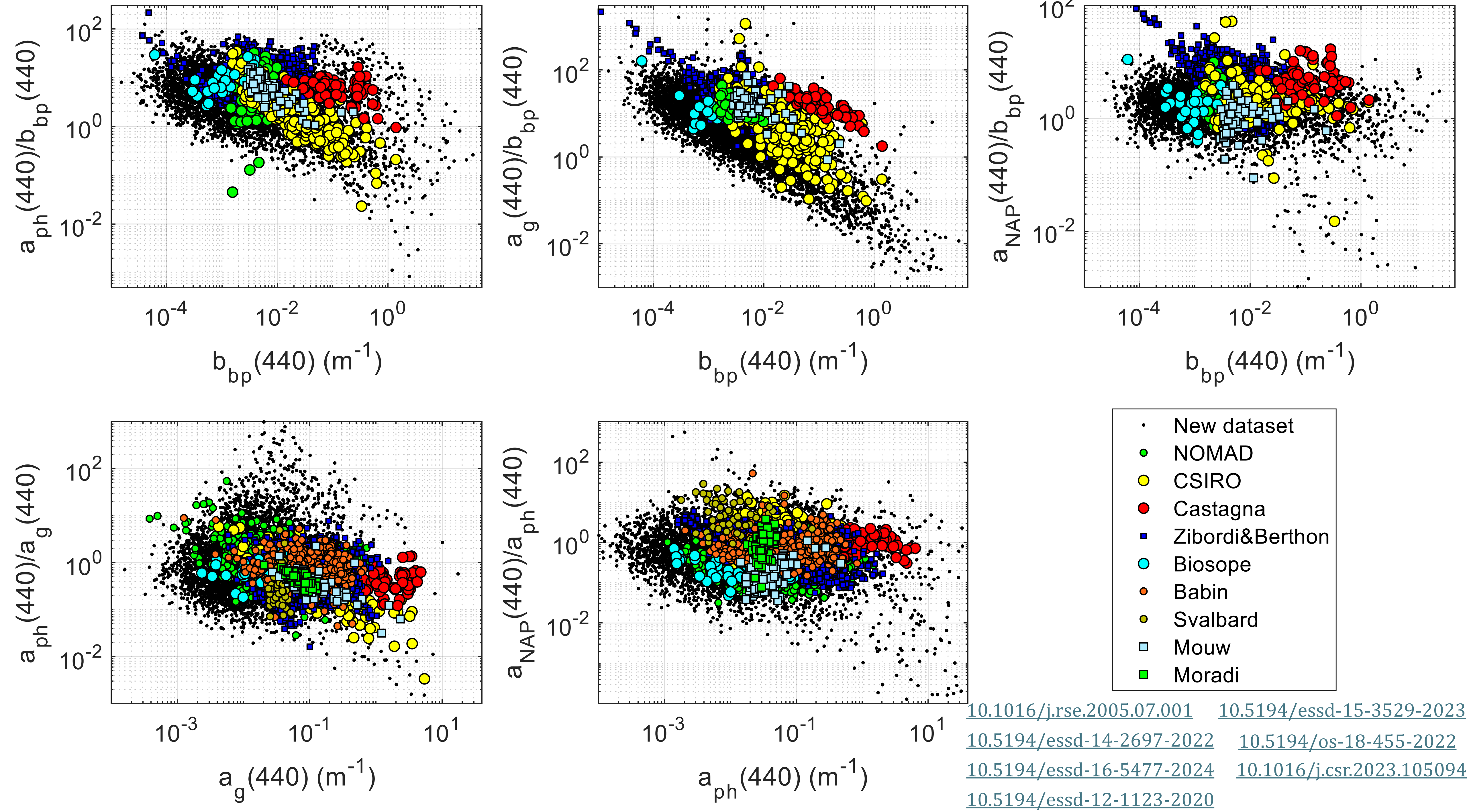
$$\hat{a}_{g,mod}(\lambda) = a_g(\lambda_0)e^{-S_g(\lambda-\lambda_0)} + a_{g,off}$$

$$\rightarrow a_{g,mod}(\lambda) = \hat{a}_{g,mod}(\lambda) - a_{g,off}$$

Fit $\rightarrow \lambda \in [350,750]$ nm





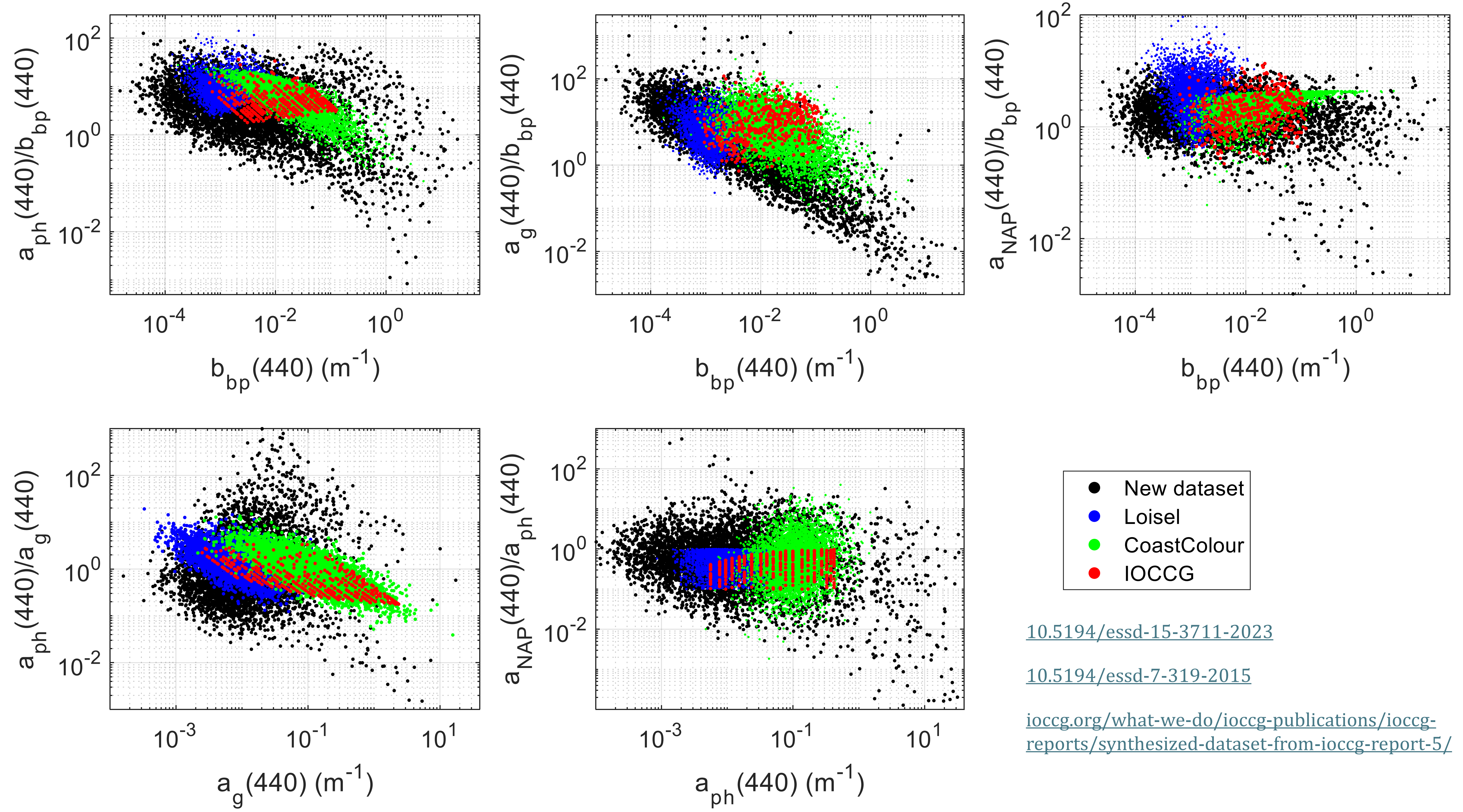


10.1016/j.rse.2005.07.001 10.5194/essd-15-3529-2023

10.5194/essd-14-2697-2022 10.5194/os-18-455-2022

10.5194/essd-16-5477-2024 10.1016/j.csr.2023.105094

10.5194/essd-12-1123-2020



10.5194/essd-15-3711-2023

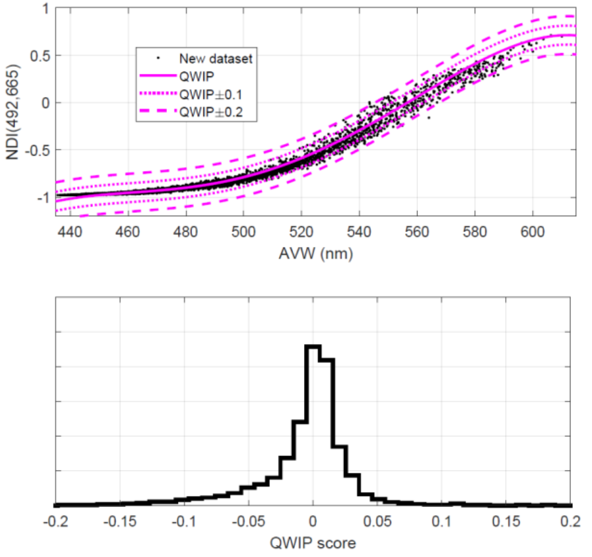
10.5194/essd-7-319-2015

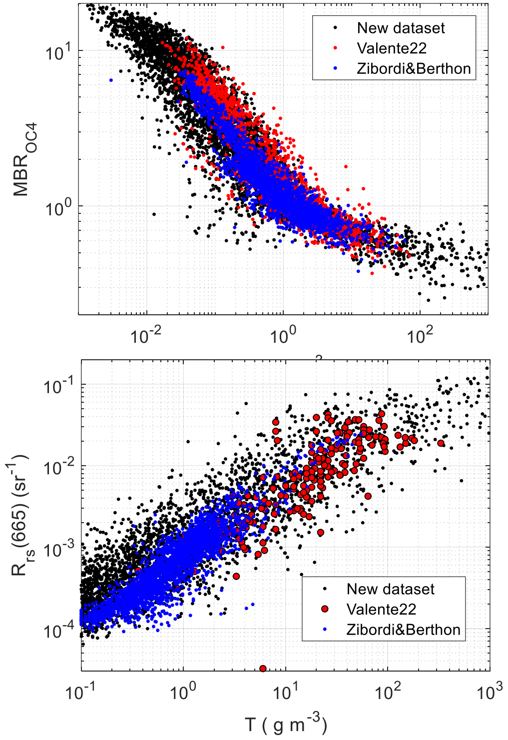
ioccg.org/what-we-do/ioccg-publications/ioccg-reports/synthesized-dataset-from-ioccg-report-5/

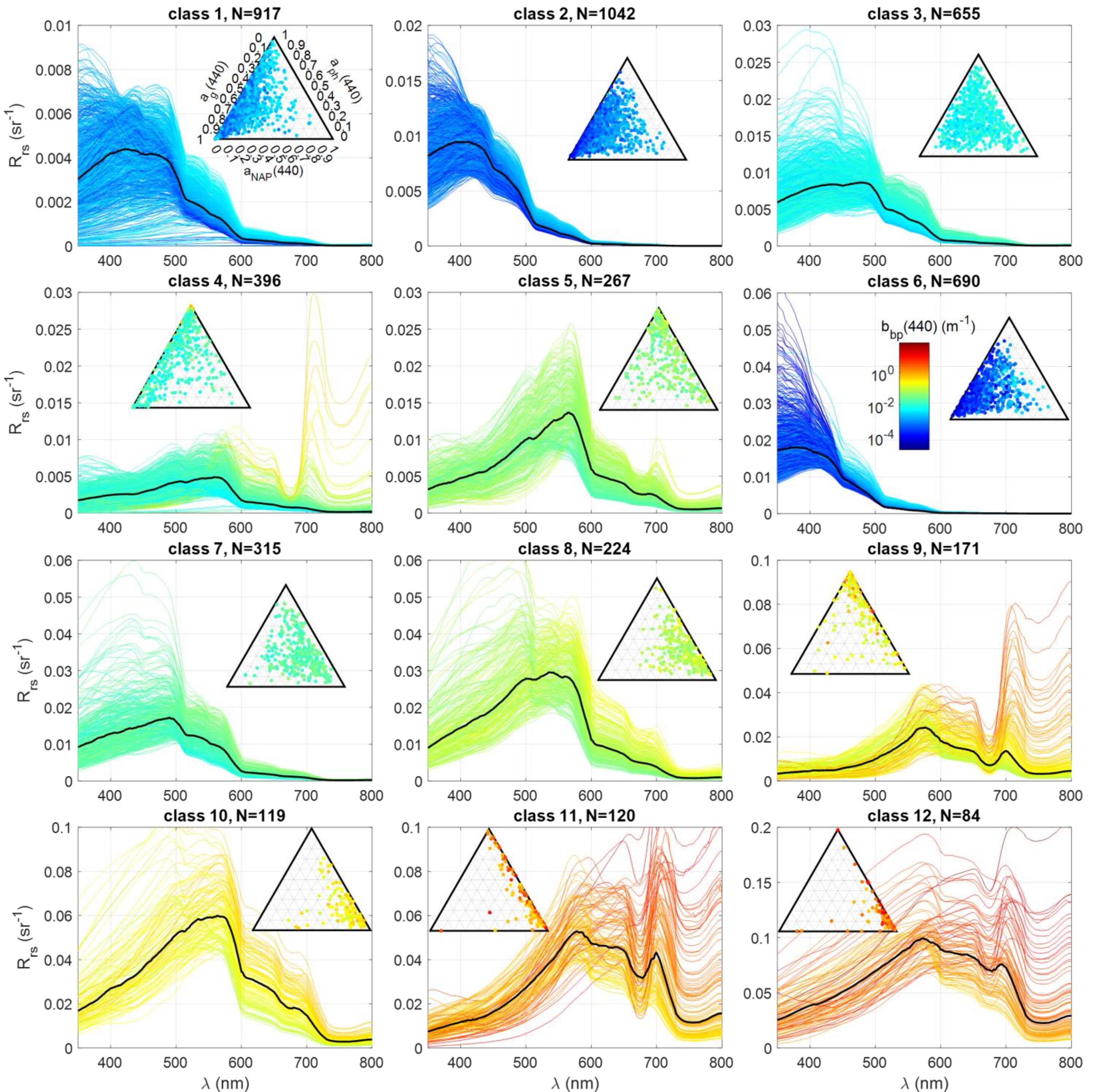
- TIME TO RUN HYDROLIGHT

Results: R_{rs}

- Spectra are classified in optical water types
- Inset, the absorption budget
- Color is b_{bp}
- Watch out the different vertical scales
- QWIP scores satisfactory
- OC4 curve and R_{rs} link to TSM are within empirical evidence

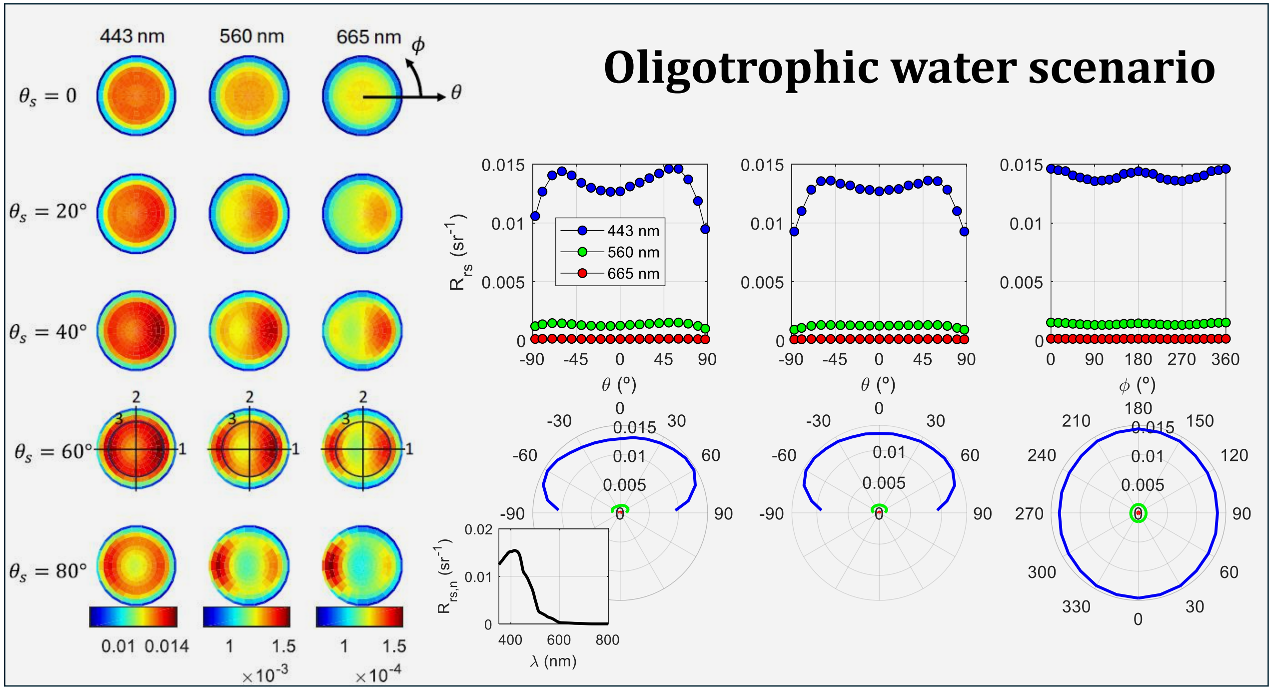


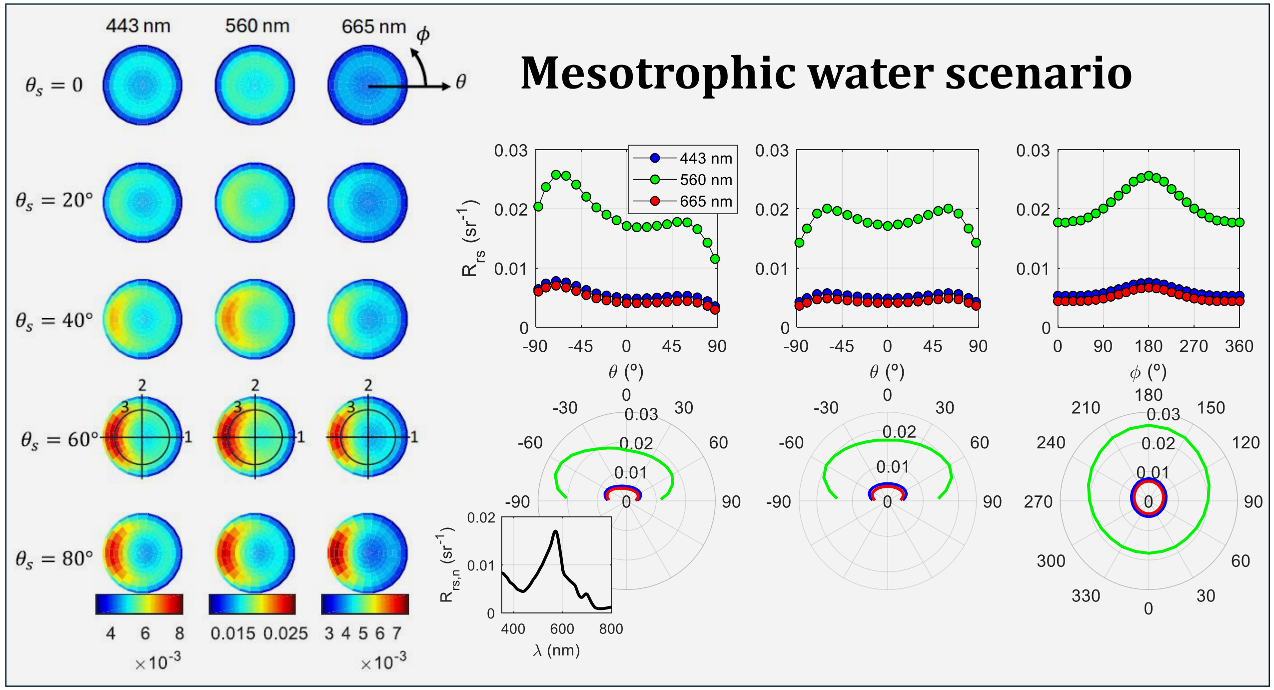




Results: bidirectionality

- Notice shifting maxima depending on the water type
- For a given water type, notice patterns variations with the wavelength, caused by the related IOP variation





Development of a new bidirectional reflectance model

- Now, we have a dataset to work with
- We will replace the more questionable parts of Lee 2011 with new relationships

THE BIRTH OF O25

O25: Calculating new "G" coefficients

Wild and crazy bio-optical modelling → Hydrolight

$$\omega_{\mathrm{w}} = \frac{\mathrm{b_{bw}}}{\mathrm{a+b_b}}$$

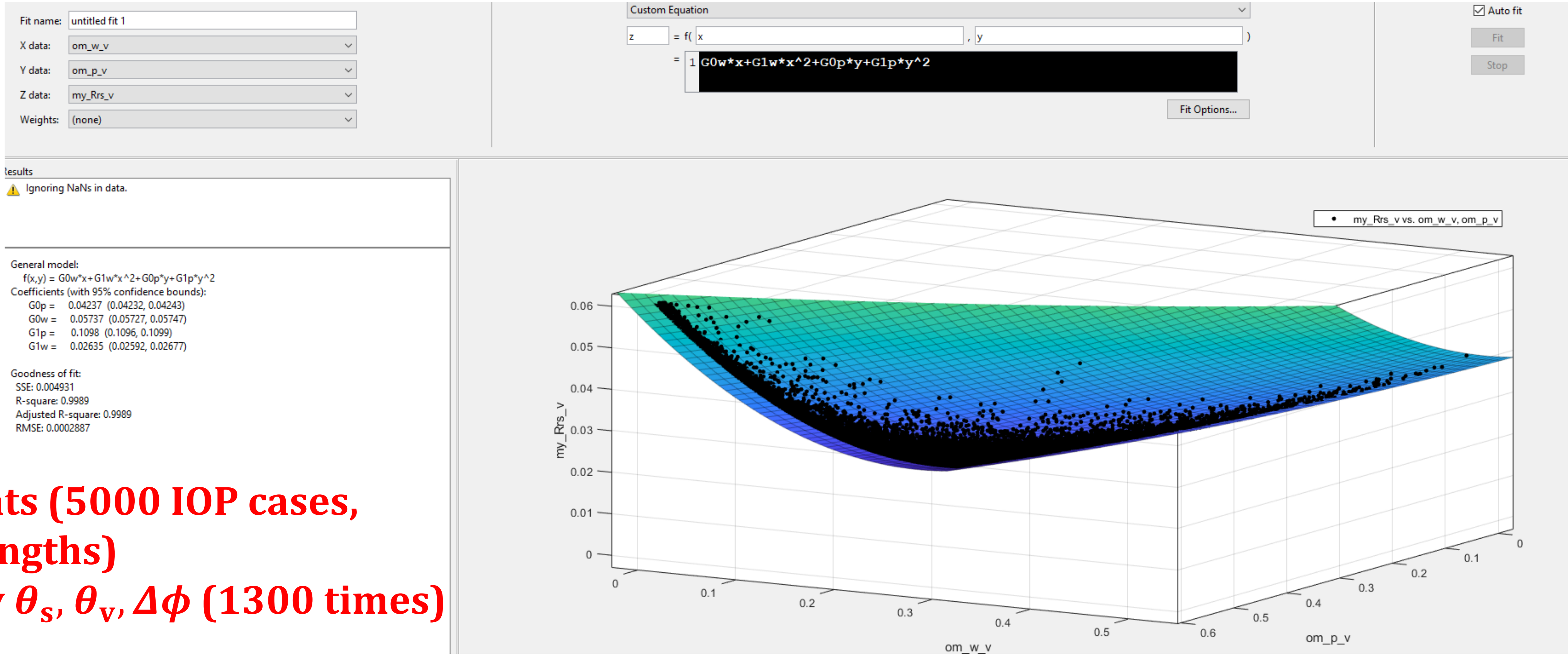
$$\omega_{\mathrm{p}} = \frac{\mathrm{b_{bp}}}{\mathrm{a+b_b}}$$

Hydrolight → R_{rs}

- Impose an analytical relationship
- Bi-variate fit for every $\theta_{\mathrm{s}}, \theta_{\mathrm{v}}, \Delta\phi$

$$R_{\mathrm{rs}} = G_0^w \omega_{\mathrm{w}} + G_1^w \omega_{\mathrm{w}}^2 + G_0^p \omega_{\mathrm{p}} + G_1^p \omega_{\mathrm{p}}^2$$

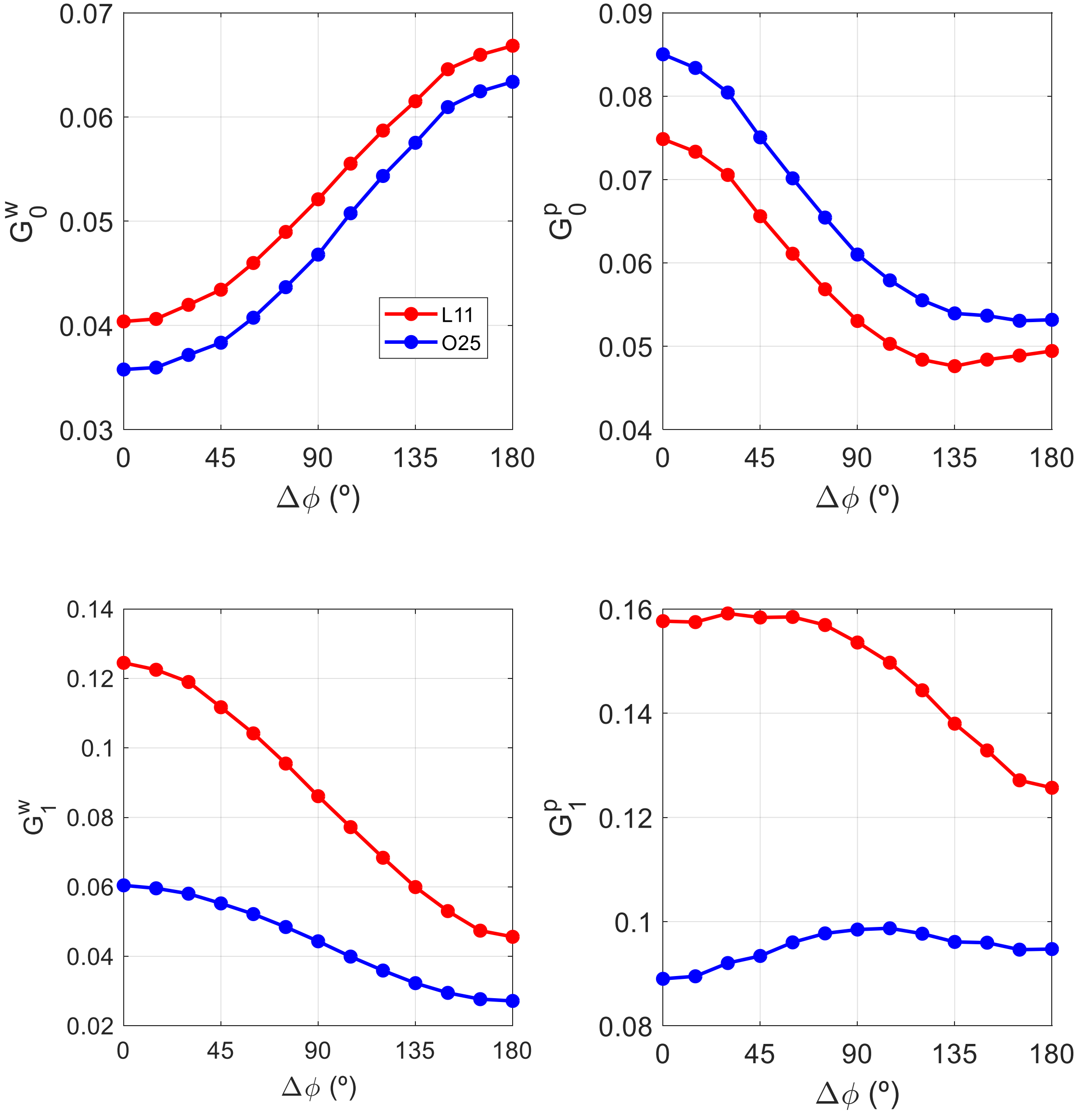
$$G_0^w, G_1^w, G_0^p, G_1^p = f(\theta_{\mathrm{s}}, \theta_{\mathrm{v}}, \Delta\phi)$$



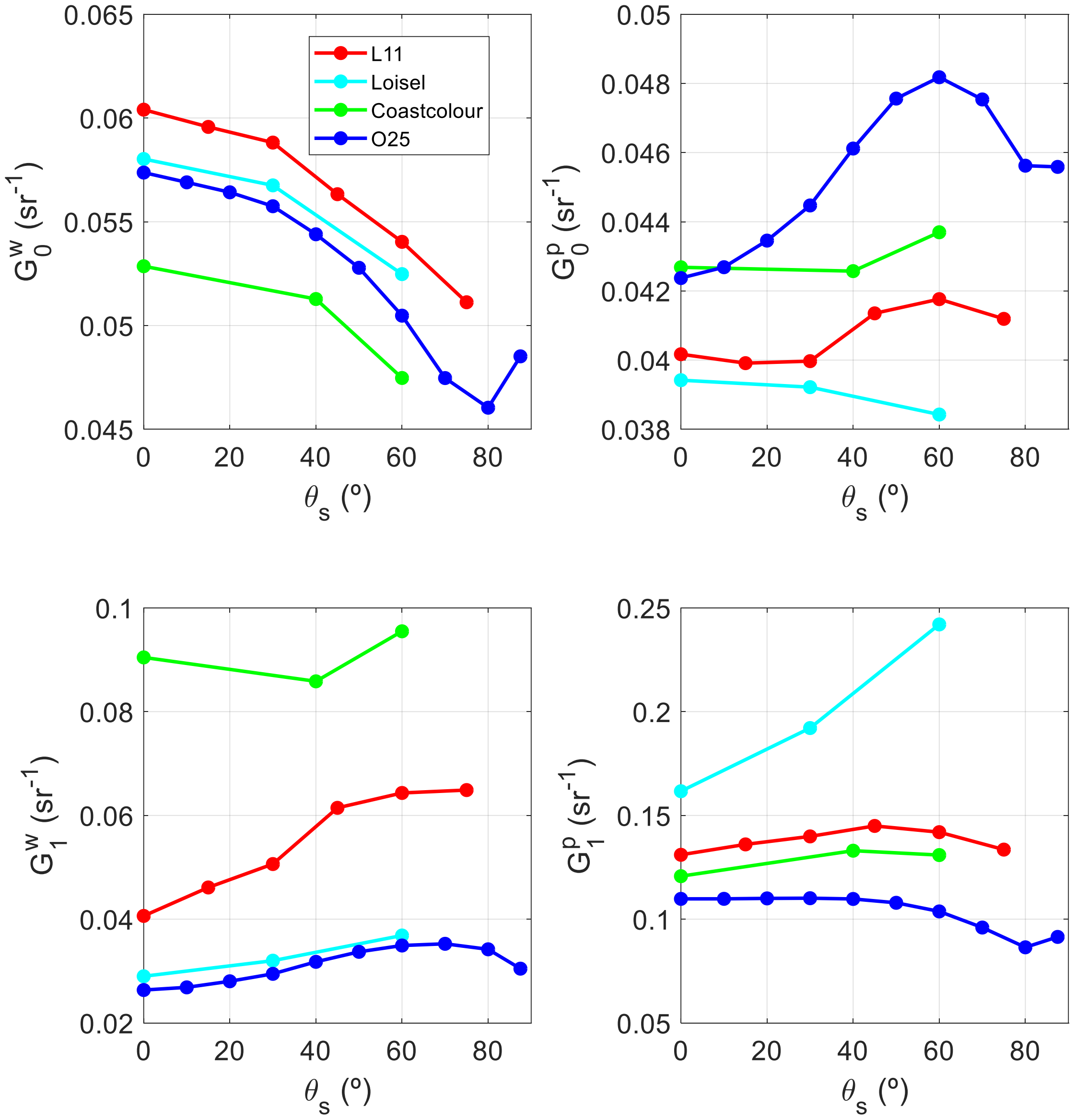
- **60000 data points (5000 IOP cases, times 12 wavelengths)**
- **Repeat for every $\theta_{\mathrm{s}}, \theta_{\mathrm{v}}, \Delta\phi$ (1300 times)**

O25: calculating new “G” coefficients

$\theta_s = 60°, \theta_v = 60°$



$\theta_v = 0°$



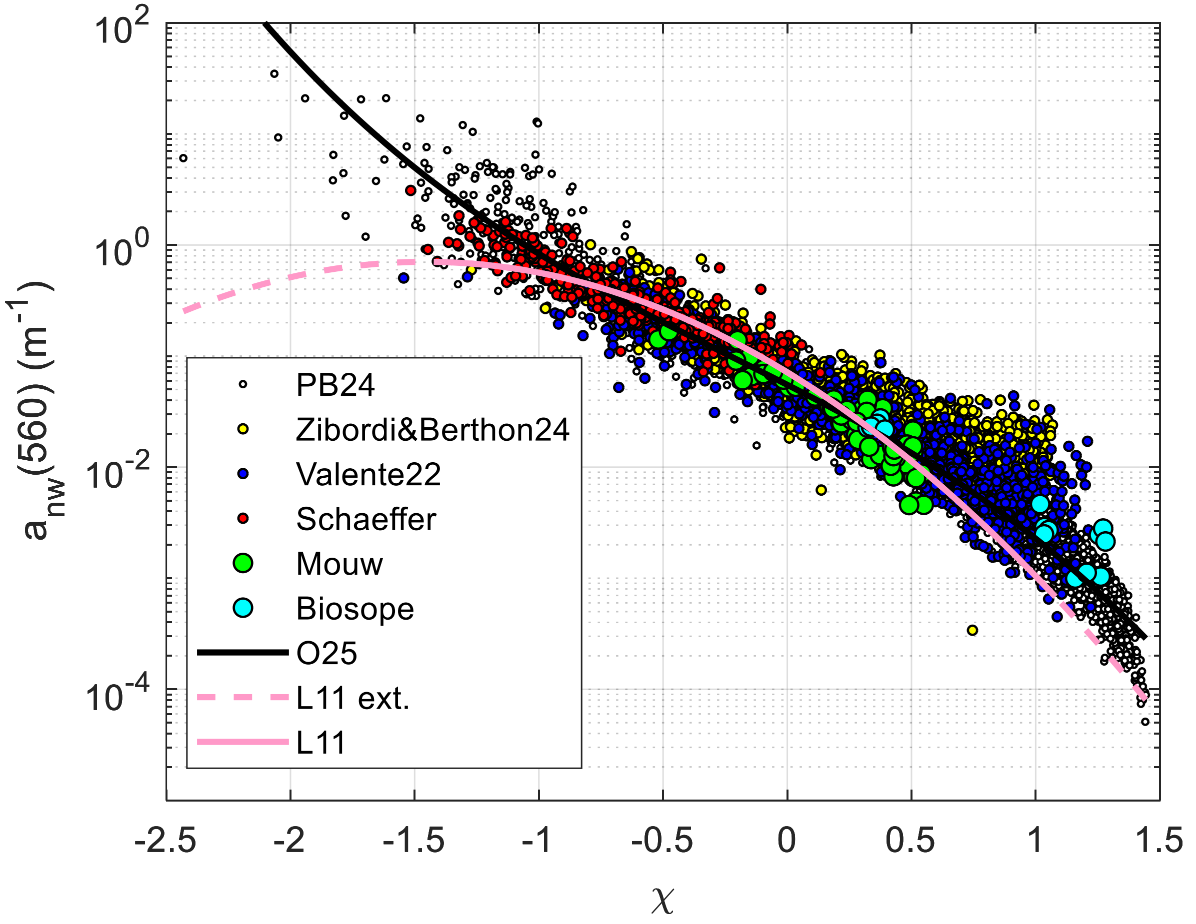
O25: calculating a new absorption prior

$$R_{rs} = G_0^w \omega_w + G_1^w \omega_w^2 + G_0^p \omega_p + G_1^p \omega_p^2$$

$$\omega_w = \frac{b_{bw}}{a+b_b} \qquad \omega_p = \frac{b_{bp}}{a+b_b}$$

- Remote sensing is an ill-posed problem
- We need to insert additional information in our algorithm in order to solve for absorption and scattering spectra
- We independently estimate non-water absorption at one band using a scalar predictor χ

$$\chi = \log_{10}\left(\frac{R_{rs}(443) + R_{rs}(490)}{R_{rs}(560) + 5\,\frac{R_{rs}^2(665)}{R_{rs}(490)}}\right)$$



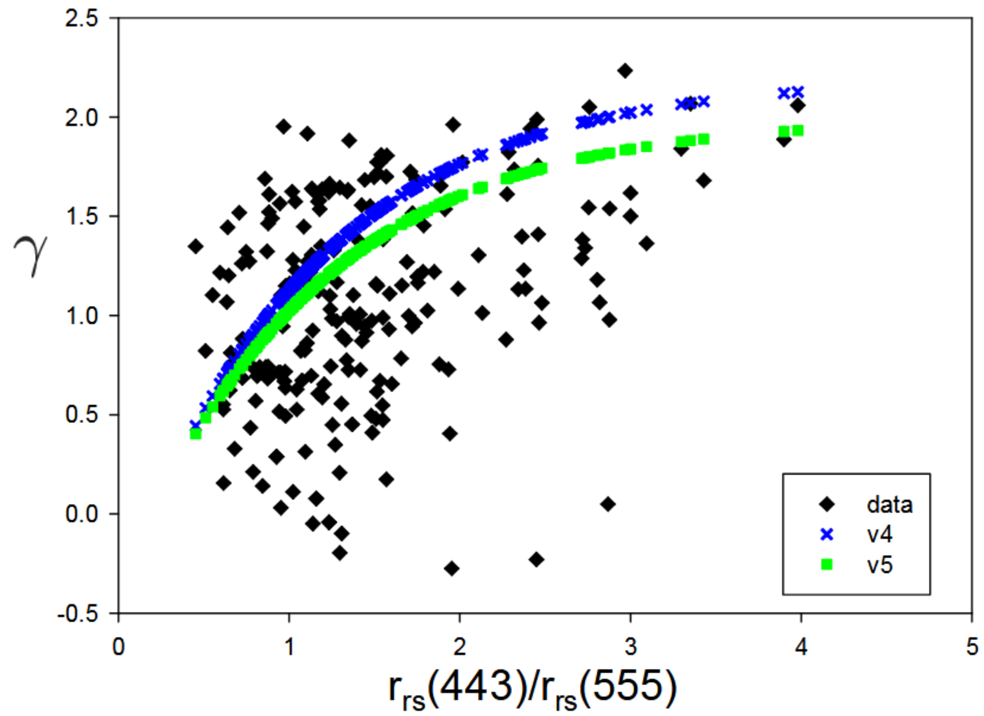
O25: new backscattering slope

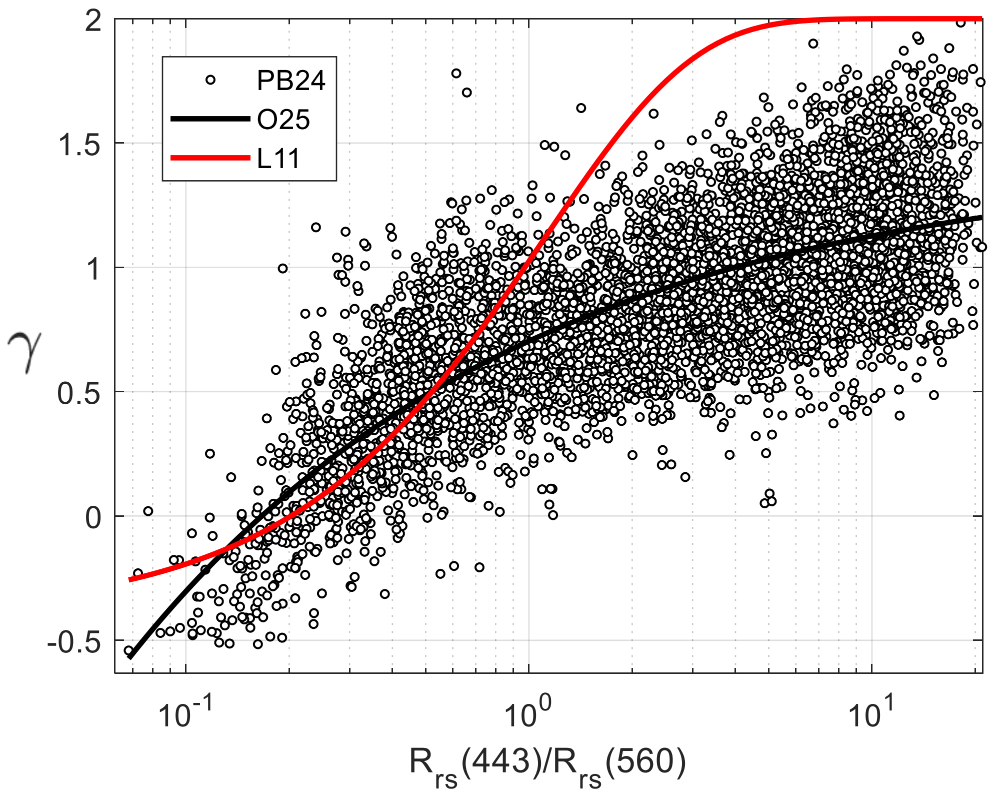
- QAA/L11/O25 work by:
- First, retrieving IOPs at one band (previous slide)
- Then, by extending IOPs at all bands

$$b_{\mathrm{bp}}(\lambda) = b_{\mathrm{bp}}(\lambda)\left(\frac{\lambda}{\lambda_0}\right)^{-\gamma}$$

- This functional form is not assumed in the synthetic dataset!!
- Only for IOP retrieval!!

QAA/L11





O25: validation

- O25 has been built on very solid physical principles and supported by empirical evidence
- But how does O25 perform with independent data, compared to previous methods?

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Check for updates

Comparison of correction methods for bidirectional effects in ocean colour remote sensing

Davide D'Alimonte [a,*], Tamito Kajiyama [a], Jaime Pitarch [b], Vittorio Ernesto Brando [b], Marco Talone [c], Constant Mazeran [d], Michael Twardowski [e], Srinivas Kolluru [e], Alberto Tonizzo [f], Ewa Kwiatkowska [g], David Dessailly [g], Juan Ignacio Gossn [g]

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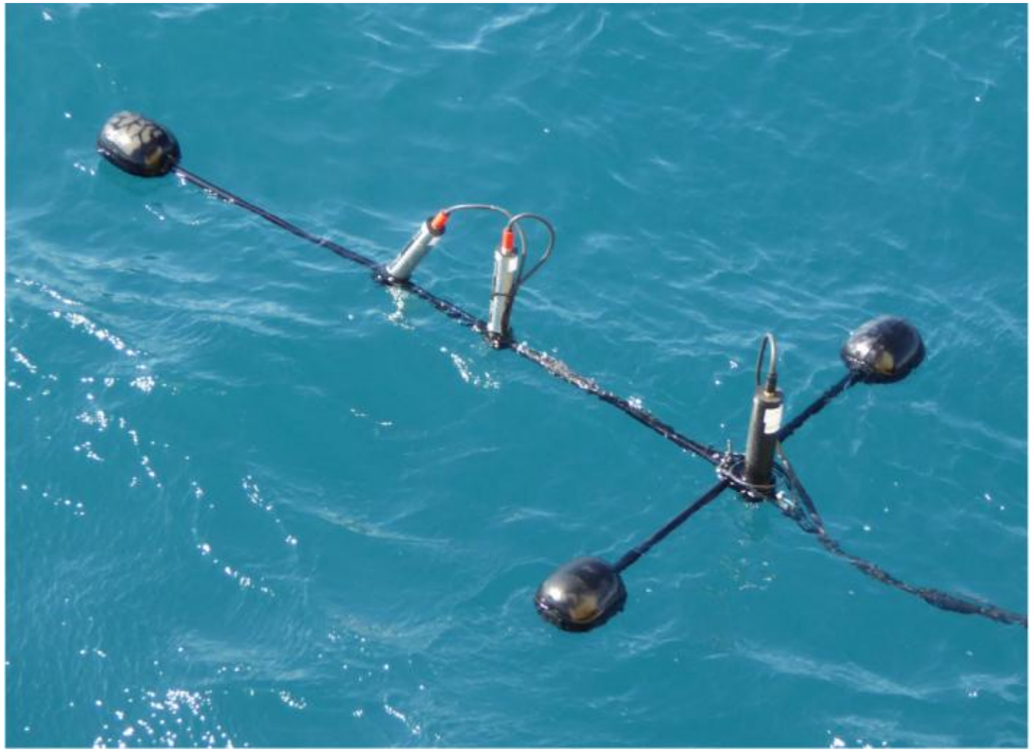
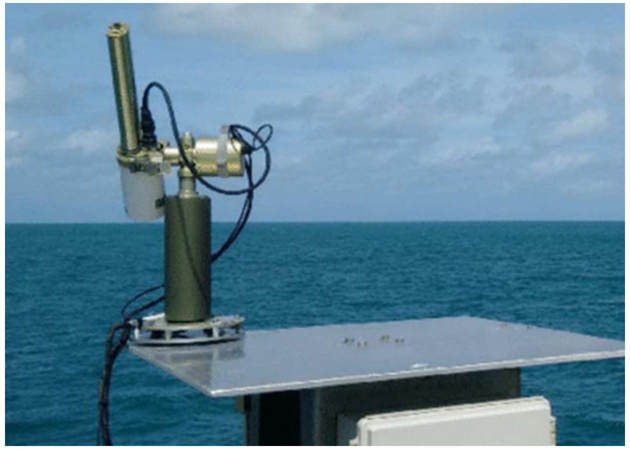
Pitarch et al. (in review)

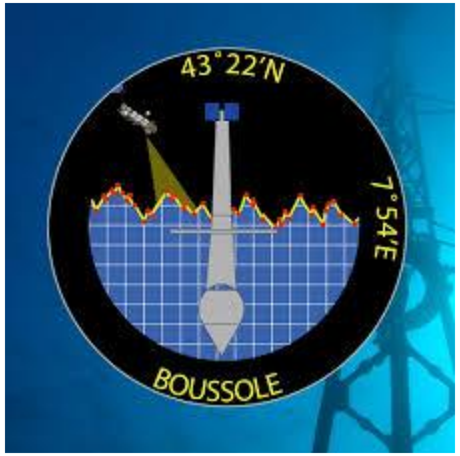
The article status has been idle for weeks. The associate editor must be enjoying holidays.

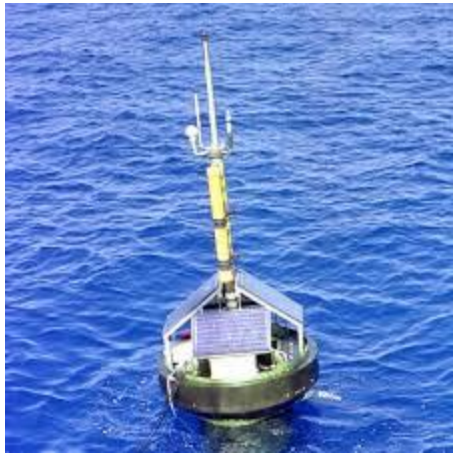
Validation datasets

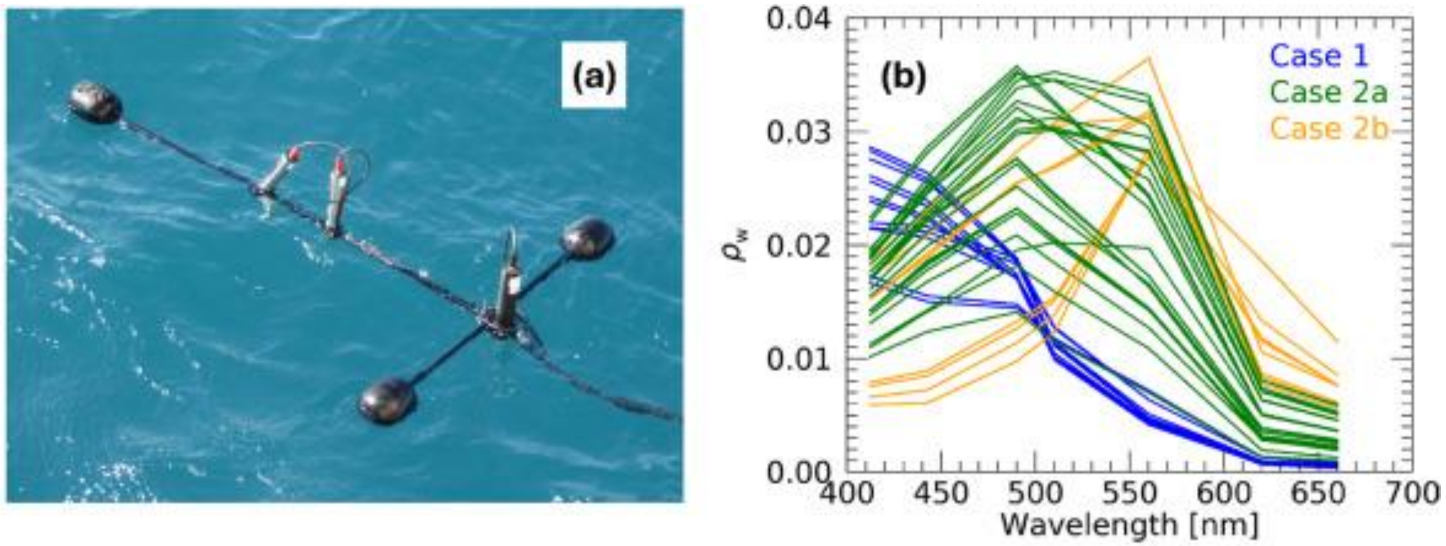
- O25 has been built on very solid physical principles and supported by empirical evidence
- But how does O25 perform with independent data, compared to previous methods?

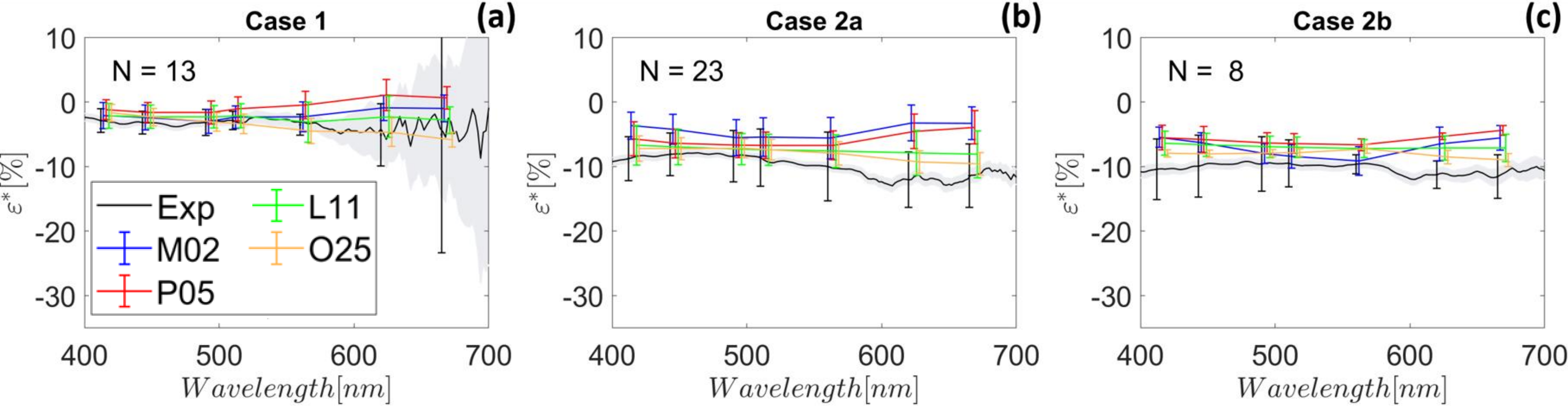









(a)
(b)
Case 1
Case 2a
Case 2b
ρ_w
Wavelength [nm]


Case 1
(a)
N = 13
Exp
L11
M02
O25
P05
Case 2a
(b)
N = 23
Case 2b
(c)
N = 8
$\varepsilon^*[\%]$
$Wavelength[nm]$

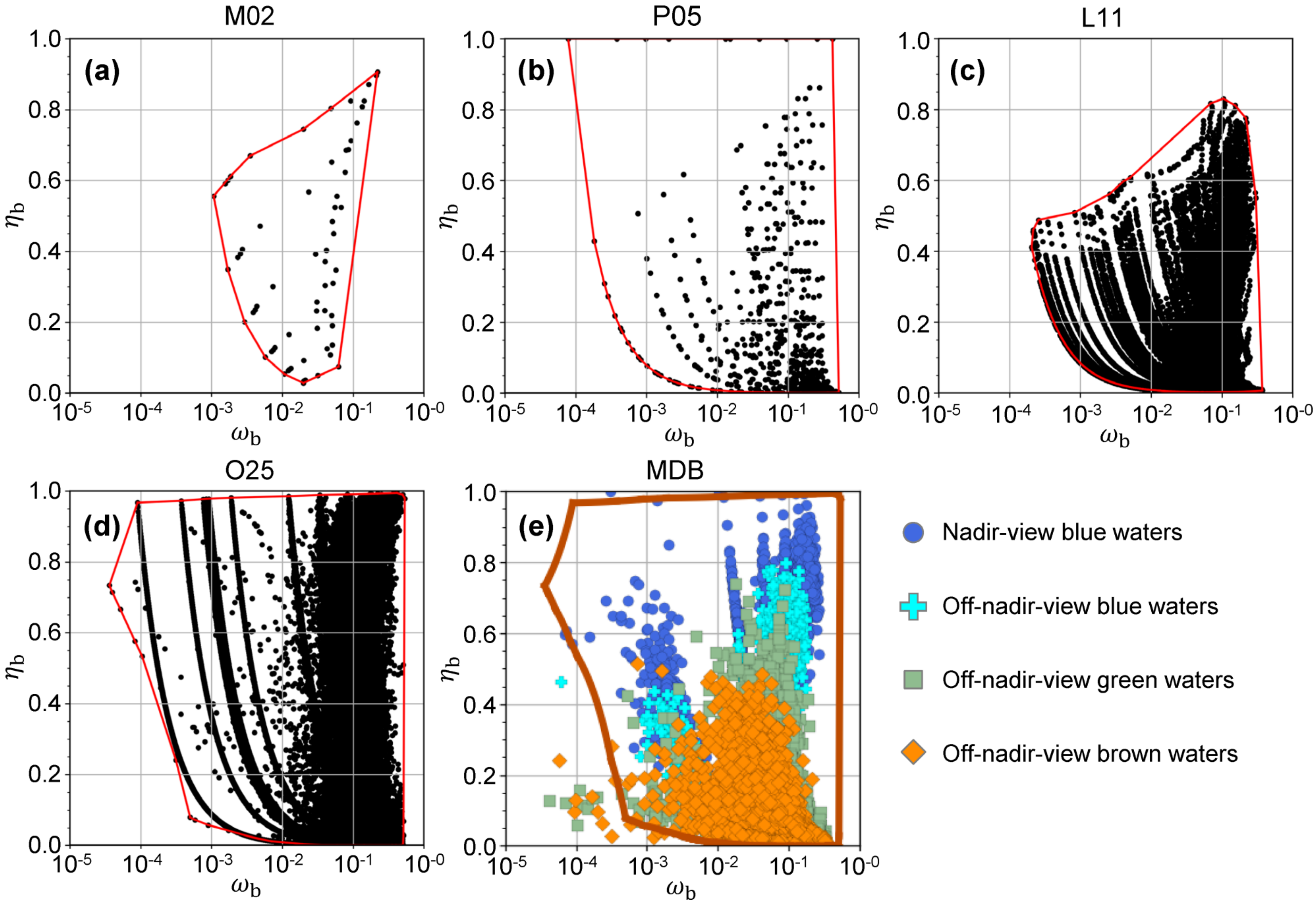
- Agreement between matched satellite and in situ data increases if both are corrected for bidirectionality
- Not doing it will lead to worse statistics

I COULD SHOW THE RESULTS WITH MOBY, BOUSSOLE AND AERONET-OC BUT I WILL NOT BECAUSE YOU ARE TIRED

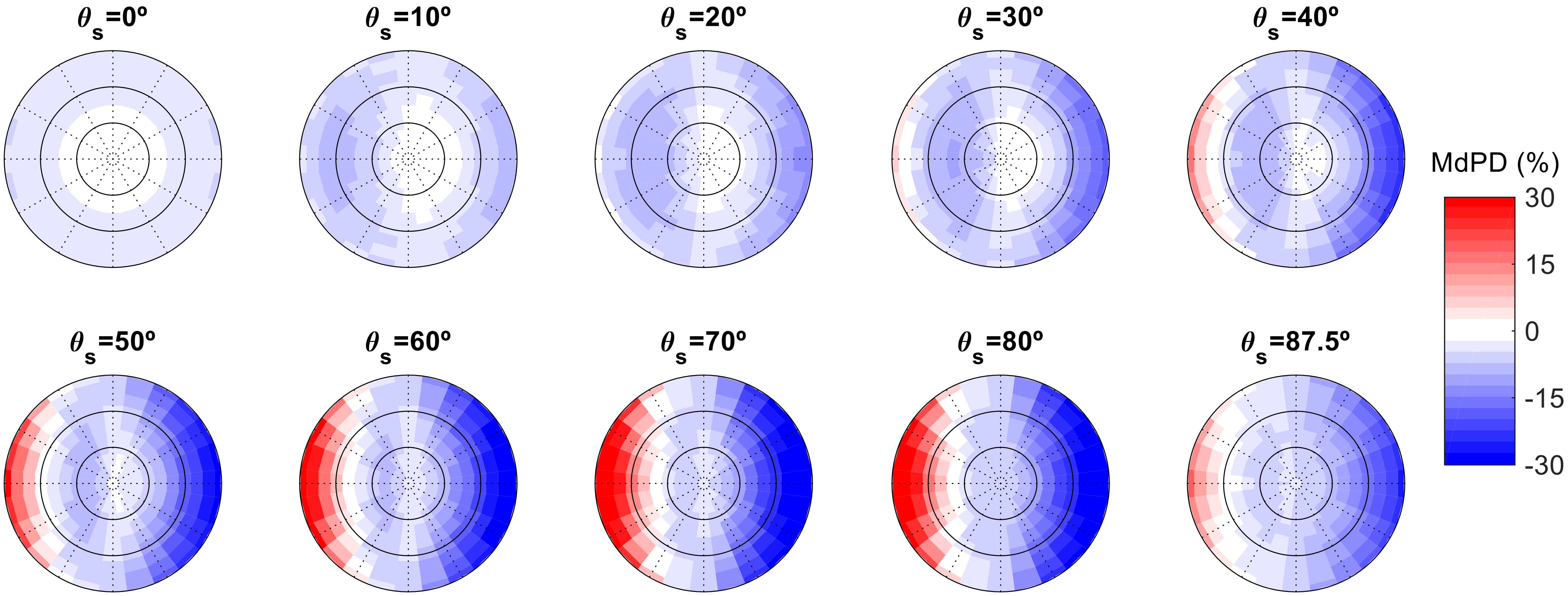
RESULTS CONFIRM THE GENERAL BETTER PERFORMANCE OF O25

JUST TRUST ME FOR NOW AND READ THE PAPERS IF YOU ARE INTERESTED

O25 new features: applicability range



O25 new features: uncertainty estimates



O25: summary

- O25 outperforms ALL pre-existing methods in ALL water types
- O25 has the broadest applicability range
- O25 is reversible with ~0% error
- O25 has fully characterized uncertainties
- O25 will be used to deliver Sentinel-3 L2 data from 4th reprocessing
- O25 is readily applicable to multispectral and hyperspectral data, in situ and satellite-borne
- O25 can also be your IOP retrieval algorithm
- Extension of O25 to Sentinel-2 and Landsat is straight-forward
- Get it for free from my GitHub github.com/jaipipor/O25
- Install the latest version of O25 from PyPI: `pip install o25`

O25: evolution

O25 performs greatly but it is not the definitive method

- It is fit for the validation datasets but evidence suggests that some parts could be improved
- I have recently come up with a strategy to reduce its uncertainties to virtually zero
- Extensive collection of multi-directional in situ radiances would be highly desirable for further validation

Only after very generous funding

I thank everyone who contributed in any way to the success of this project

It has been a lot of fun

Thank you