Ocean Optics Summer Class

Calibration and Validation for Ocean Color Remote Sensing

Closure

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What is Closure?

Closure refers to obtaining the same quantity in at least two different ways.

If the agreement is good (within the uncertainties of the methods used) we say that closure has been achieved.

Performing closure in papers is a great way to convince reviewers to accept your paper—i.e., that you have good data and good modeling.

Data-data closure shows agreement between disparate data sets, e.g. using two different instruments and/or different calibration methodologies, AOP and IOP, in-situ vs. remote.

Model-model closure indicates that model assumptions (e.g. plane-parallel vs 3D; with and without inelastic scattering) do not introduce significant error.

Scale closure: are measurements made on small spatial scales (cm^3 water samples; a mooring) consistent with large-scale measurements (K_d, R_{rs}; a satellite)

Model-data closure ties it all together

Overview

- Show two examples of output from advanced HydroLight simulations to show what is necessary to achieve model-data closure, i.e., getting all of your inputs to H and outputs from H to agree with your measurements

Measurements Necessary for Model-Data Closure

HydroLight inputs

• absorption coef $a(z,\lambda)$ (e.g., from ac-9 or spectrophotometer)
• scattering coef $b(z,\lambda)$ (e.g., from ac-9)
• scattering phase function $\beta(z,\lambda,\psi)$ (almost never measured, but may have backscatter fraction $B = b_b/b$ from b_b (e.g,, HydroScat or EcoVSF) and b (ac-9)
• boundary conditions: sea state (wind speed); sun location and sky conditions (usually model), bottom reflectance (in shallow water)

HydroLight outputs

• radiometric variables (radiances and irradiances; usually measure $L_u(z,\lambda)$ and $E_d(z,\lambda)$ at a minimum)
• apparent optical properties (K_d, R, R_{rs} etc obtained from radiometric measurements). The most common for remote sensing is remote sensing reflectance R_{rs} (often measure E_d(air) and $L_u(z)$ and extrapolate upward from underwater L_u , or estimate R_{rs} using above-surface techniques)

Comprehensive Data Sets Are Extremely Scarce

Everyone wants comprehensive data sets, but no one wants to pay for them, and scientists don’t want to be forced to take data they themselves aren’t going to use.

See my notes on comprehensive data sets in the Papers directory (ComprehensiveDataSets.pdf) for an overview of what should be measured in a field experiment, but never is (cost, lack of interest, ignorance, politics, …)

When you go home and design your grand field experiment, at least look at these notes and do the best you can with the available resources.

The HyCODE Data Set

Data set from ONR HyCODE (Hyperspectral Coastal Ocean Dynamics Experiment) 2000 off the coast of New Jersey (LEO-15 site)

measurements taken near local noon on 24 July 2000 at
39^o 24.91' N, 74^o, 11.78' W (station 19); cloudy sky, wind = 6 m/s

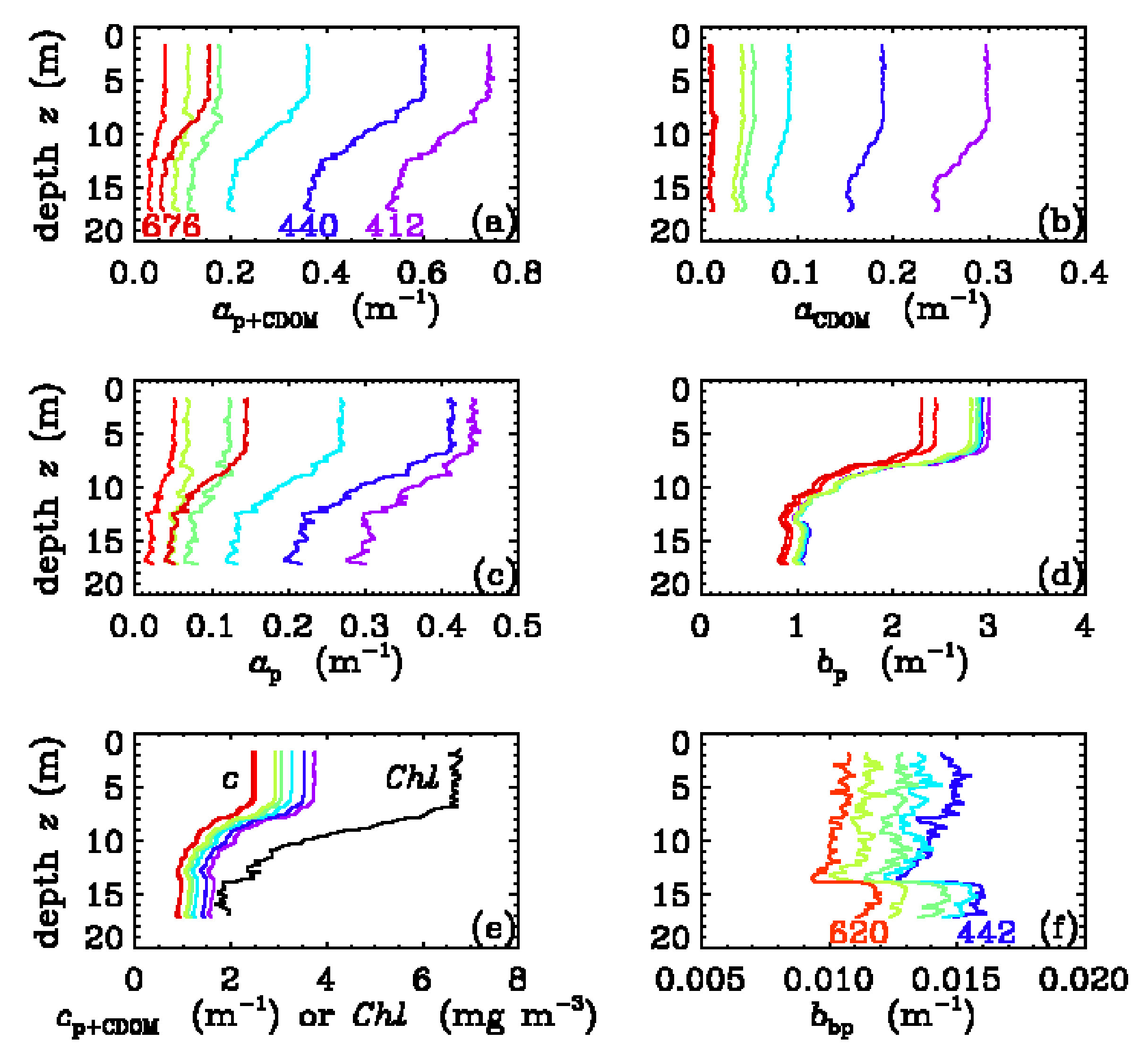
See Mobley et al, 2002, *Applied Optics* 41(6), 1035-1050 for details

Table 4. Data Taken at the LEO-15 Site as Used to Model the In-Water Light Field[a]

Quantity Measured	Instrument	Nominal Wavelength (nm)
Total $a(z, \lambda)$, total $c(z, \lambda)$	Unfiltered ac-9	412, 440, 488, 532, 555, 650, 676, 715
Dissolved $a(z, \lambda)$	Filtered ac-9	412, 440, 488, 532, 555, 650, 676, 715
Backscatter $b(z, \lambda)$ derived from VSF at $\psi = 140$ deg	HydroScat-6	442, 488, 532, 555, 620
Backscatter $b(z, \lambda)$ derived from VSF at $\psi = 100$, 125, and 150 deg	ECO-VSF	530
VSF ($\psi = 0.6$–179.6 deg)	VSM	530
$E_d(z, \lambda)$ and $L_u(z, \lambda)$	OCP	412, 443, 489, 533, 555, 591, 683
Sky $E_d(\lambda)$	Multichannel visible detector system	412, 443, 489, 533, 555, 591, 683
Sky $E_d(\lambda)$ and $L_u(z = 0.6\ \text{m}, \lambda)$	Hyper-TSRB	123 wavelengths between 396 and 798

[a]Most instruments have a nominal 10-nm bandwidth centered on the listed wavelengths.

HyCODE Data



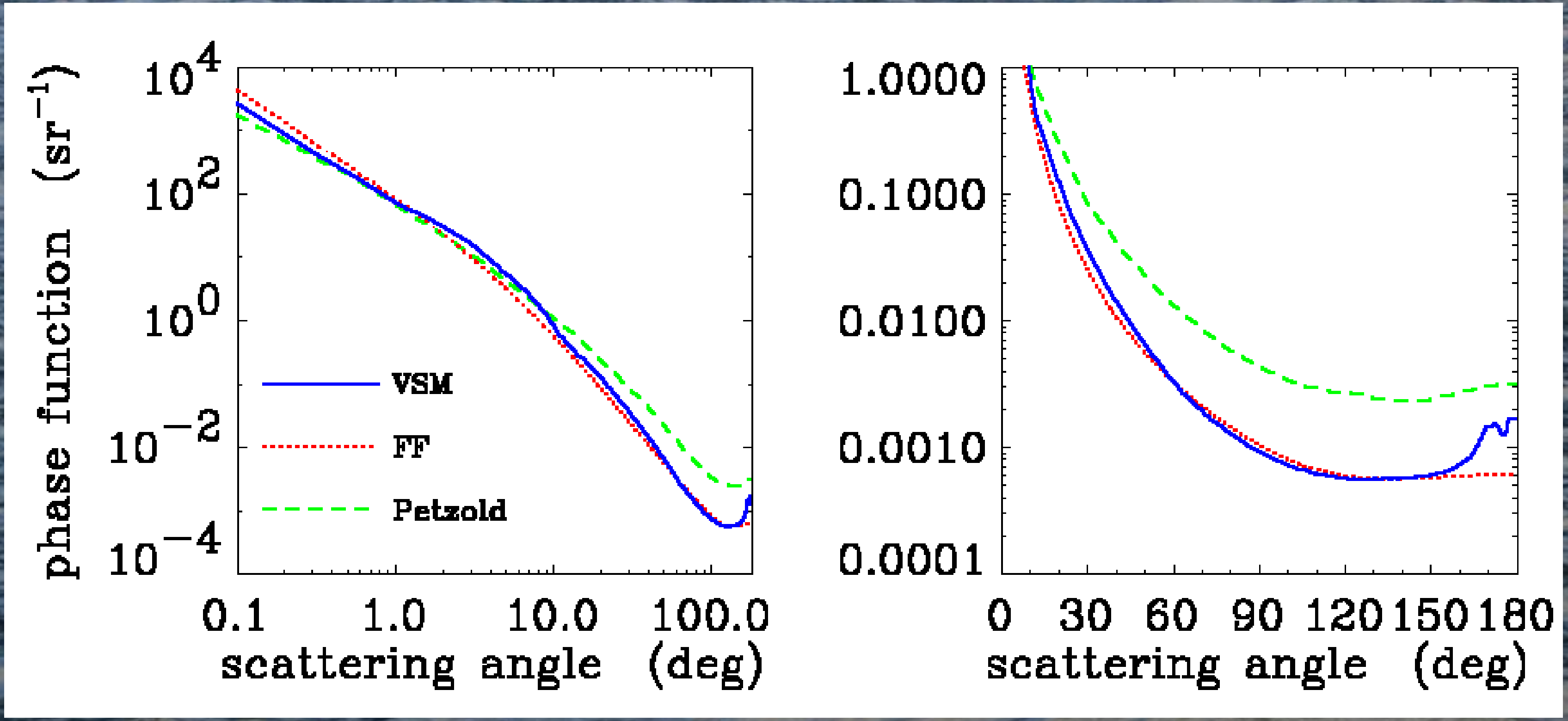
ac-9, both filtered (CDOM absorption) and unfiltered (total *a* and *b*)

HydroScat-6 (b_b)

can get B_p from measured b_{bp}/b_p

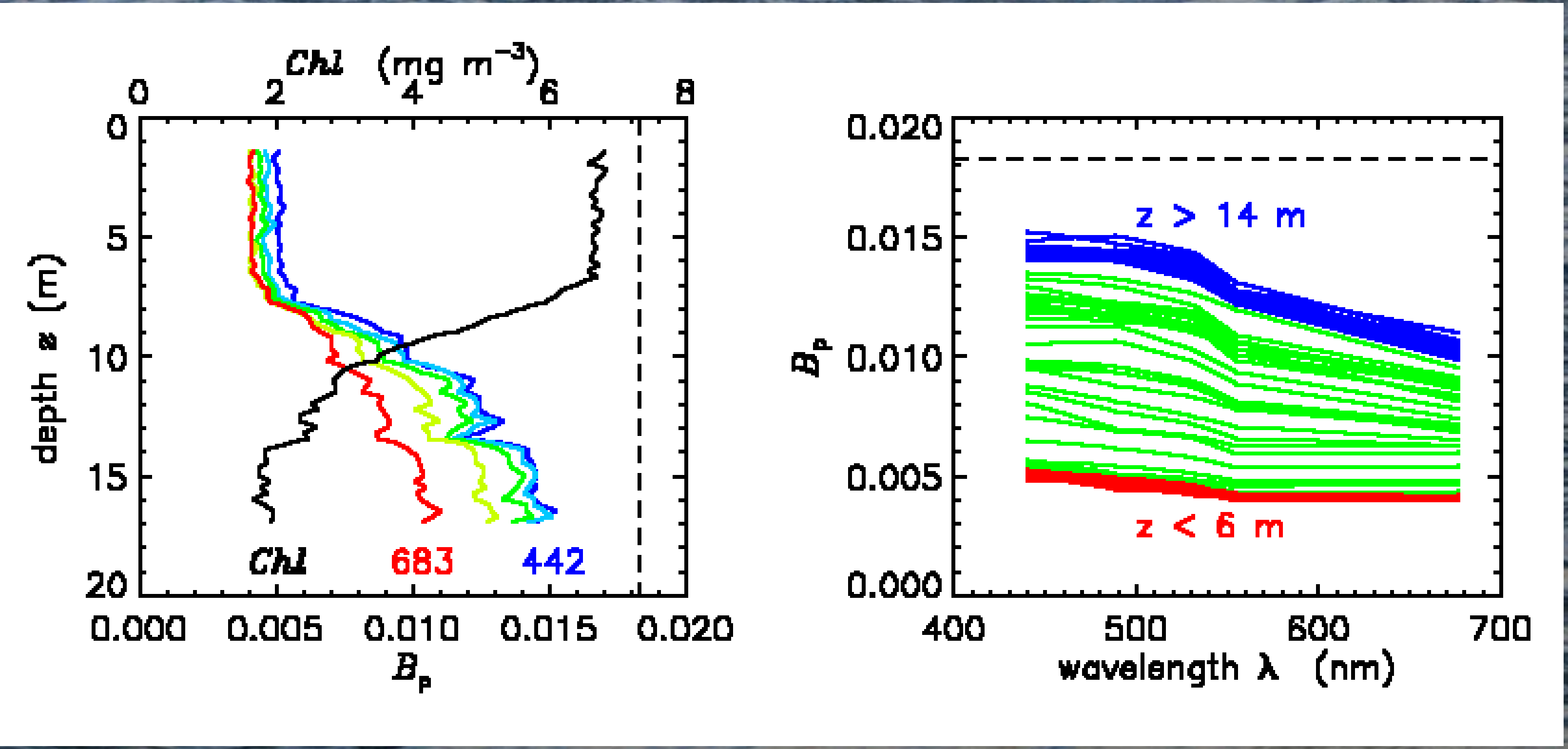
can then use B_p to define a Fournier-Forand phase function with the same backscatter fraction (Mobley, 2002. *AO* 41(6), 1035-1050)

HyCODE Data



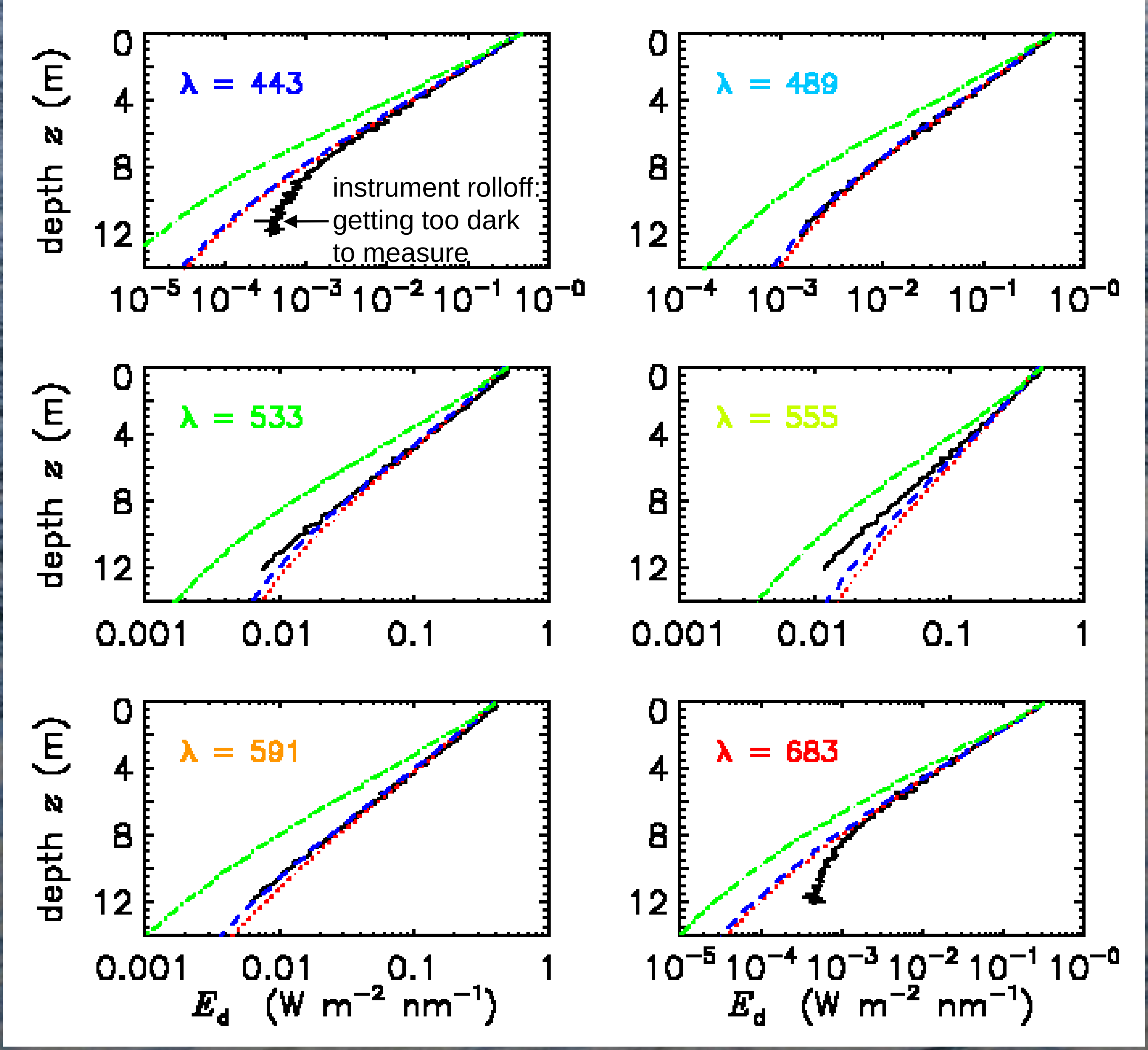
Also have VSF measurements (extremely rare) at 2 m depth at 530 nm from a novel Ukrainian instrument (Lee and Lewis, 2003. *J Atmos Ocean Tech* 20(4), 563-571)

HyCODE Data



Note that the measured B_p is much less than for the commonly used Petzold "average particle" phase function (0.0183), and B_p varies with depth and wavelength; value depends on type of particles: predominately phytoplankton near surface vs resuspended sediments near the bottom (18 m depth)

HyCODE Data: HydroLight vs E_d Measurements



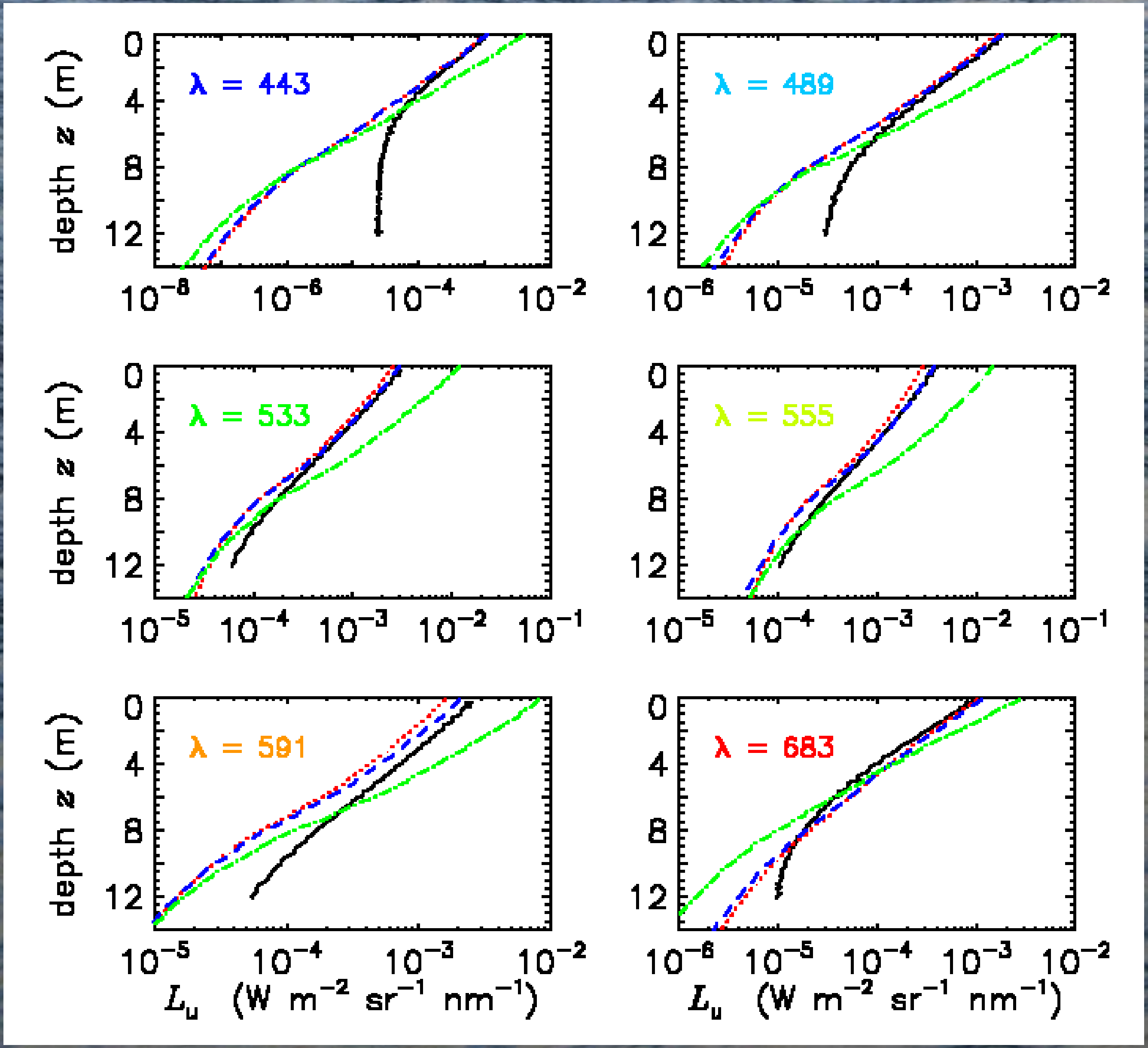
black: measurements

green: H with Petzold phase function

red: H with FF phase function determined from measured b_b/b

blue: H with measured pf

HyCODE Data: HydroLight vs L_u Measurements



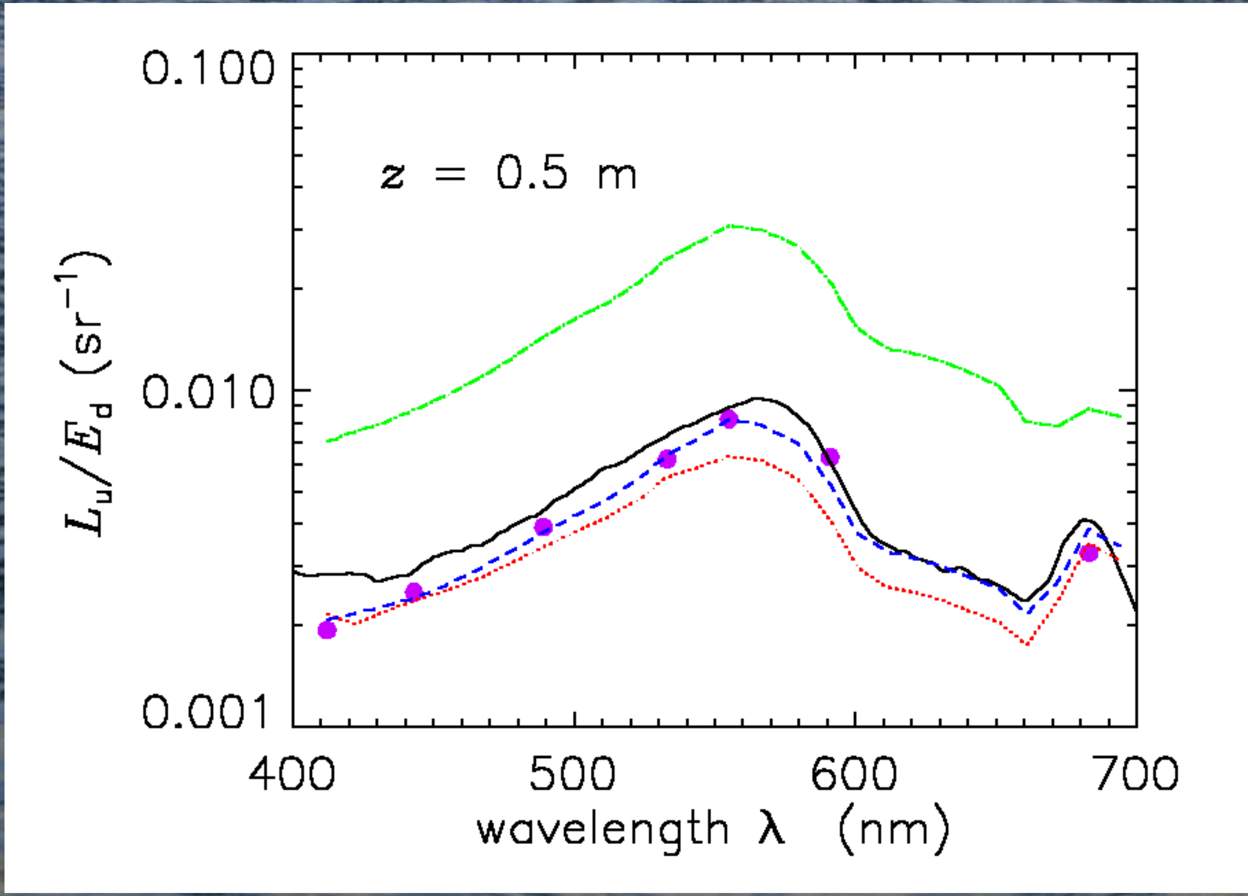
black: measurements

green: H with Petzold phase function

red: H with FF phase function determined from measured b_b/b

blue: H with measured pf

HyCODE Data: HydroLight vs L_u/E_d Measurements



black: measured by Hyper-TSRB (Satlantic)

purple dots: measured by OCP (Ocean Color Profiler; Satlantic)

green: H with Petzold phase func.

red: H with FF pf determined from measured b_b/b

blue: H with measured pf

HyCODE Data: HydroLight vs K_{Lu} Measurements

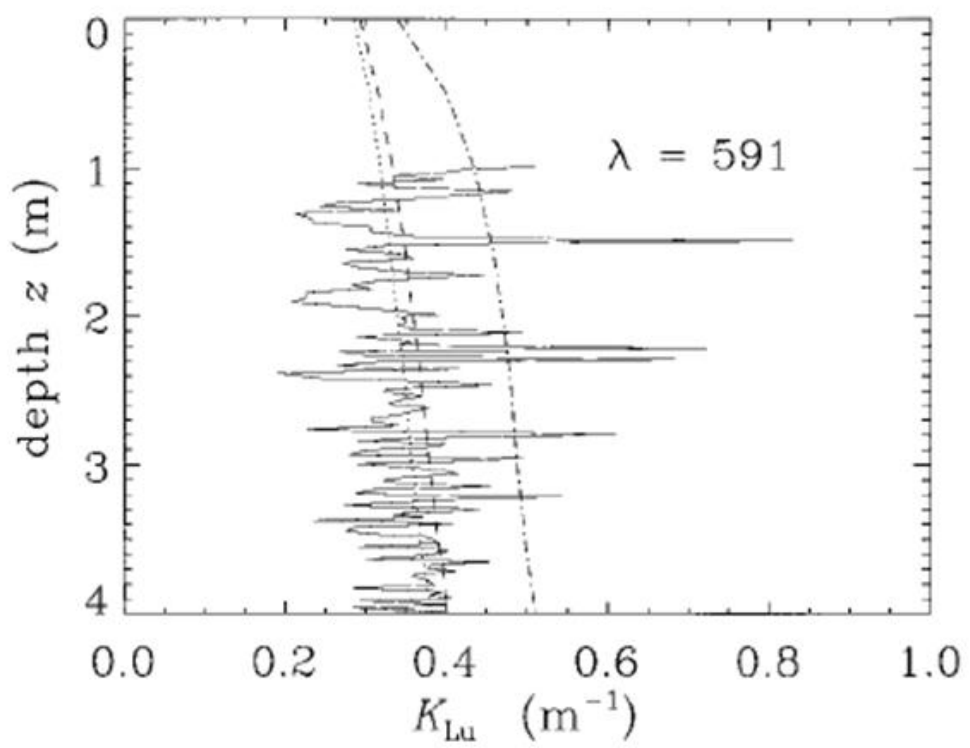


Fig. 16. Comparison of measured and HYDROLIGHT-predicted diffuse attenuation for upwelling radiance at 591 nm. Solid curve, measured values; dotted curve, predicted values with the FF phase function; dashed curve, predicted values with the measured phase function; dashed–dotted curve, predicted values with the Petzold phase function.

The Mobley et al. 2002 paper showed that the exact shape of the phase function makes only a few per cent difference in E_d, L_u, R_{rs}, etc, so long as the backscatter fraction $B_p = b_{bp}/b_p$ is correct

Measured vs HydroLight for Chesapeake Bay

Tzortziou et al, “Bio-optics of the Chesapeake Bay from measurements and radiative transfer closure.” *Estuarine, Coastal and Shelf Science* (2006).

She shows how to “do it right” in taking and processing data, and modeling it with HydroLight.

Complex case 2 water

Read this paper!

Measured vs HydroLight for Chesapeake Bay

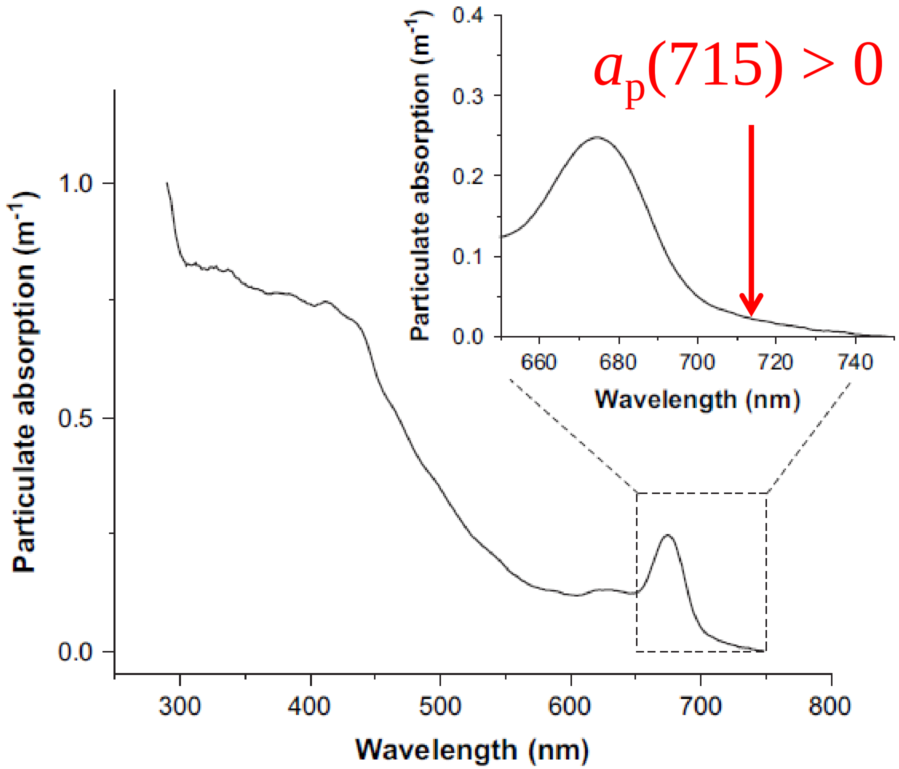
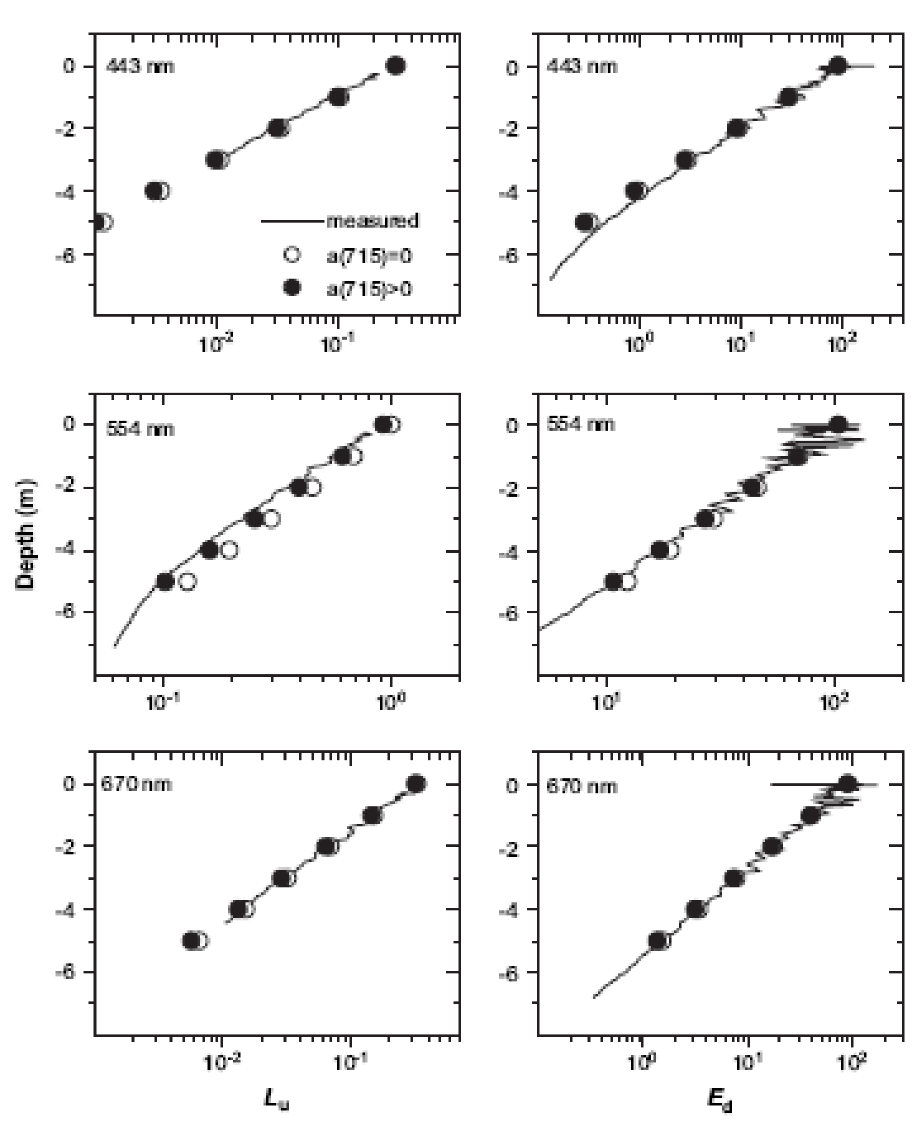


Fig. 4. Particulate absorption (sum of absorption by phytoplankton and non-algal particles) in the 290–750 nm wavelength region, measured spectrophotometrically for station PI, on 28 September 2001. The residual non-zero particulate absorption at 715 nm is shown more clearly in the inset figure.

Can't use the simple ac-9 scattering correction that assumes $a_p(715) = 0$

Measured vs HydroLight for Chesapeake Bay



Improved ac-9 scattering correction ($a_p(715) \neq 0$) gives better L_u and E_d

Measured vs HydroLight for Chesapeake Bay

Improved ac-9 scattering correction and phase function via b_b/b and fluorescence gives better L_w

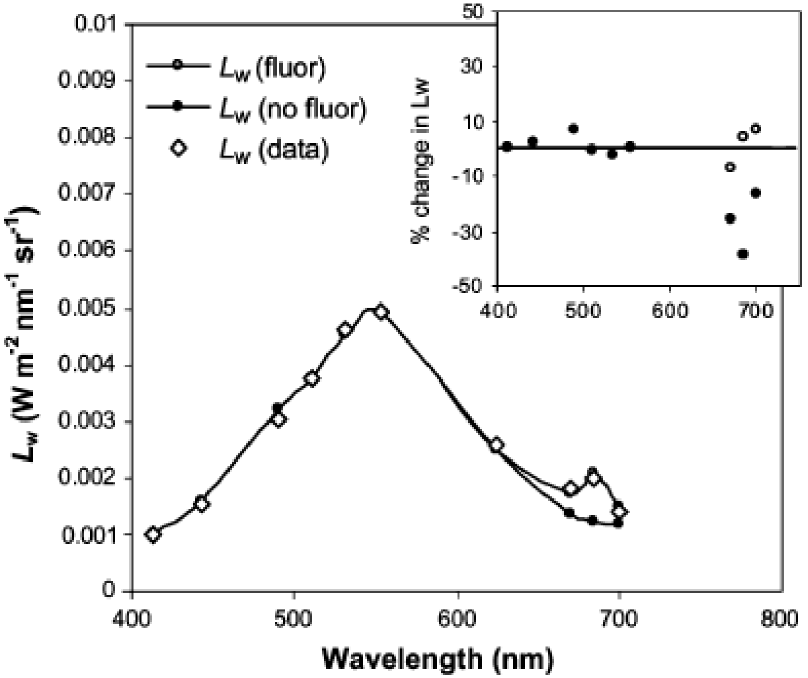


Table 2

Improvement of agreement between measured and model-estimated L_w as information on the specific IOPs measured at station PI (28 September 2001) is successively incorporated into the model. The final agreement between data and model demonstrates the good optical closure obtained at this study site after applying the results from our detailed measurements to properly account in the radiative transfer modeling for the observed optical characteristics

Radiative transfer modeling	Absolute % difference between model and data
1. $a_{t-w}(715) = 0$, fluorescence included, Petzold VSF	for $L_w(554)$: 50%
2. FF VSF with $b_b/b = 0.015$ (otherwise 1)	for $L_w(554)$: 20%
3. FF VSF with $b_b/b(\lambda, z)$ (otherwise 1)	for $L_w(554)$: 9%
4. $a_{t-w}(715) = a_{CARY}(715)$ (otherwise 3)	for $L_w(554)$: 0.6% for $L_w(685)$: 4%
5. Chl-*a* fluorescence not included (otherwise 4)	for $L_w(685)$: 40%

Measured vs HydroLight for Chesapeake Bay

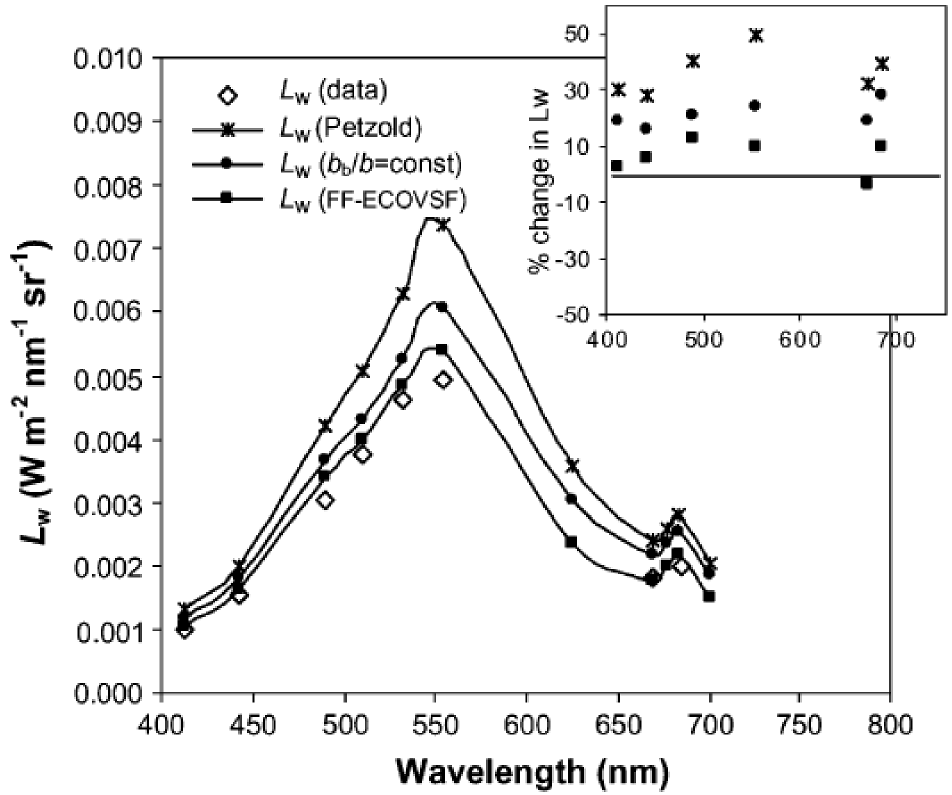
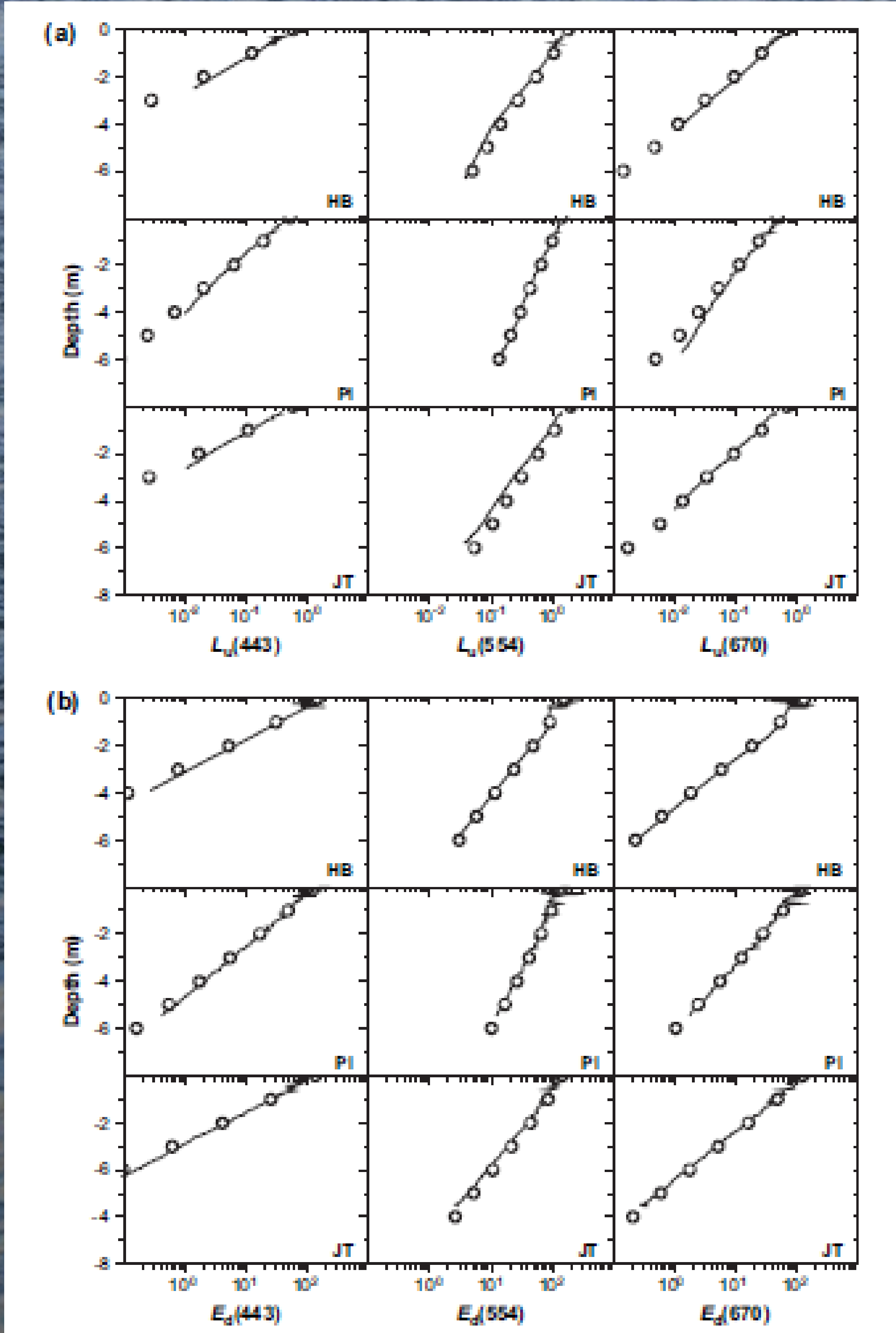


Fig. 3. L_w spectra estimated using: (1) a Petzold "average particle" scattering phase function (stars), (2) an FF scattering phase function with a constant backscattering ratio, $b_b/b = 0.015$ (filled circles); and (2) an FF scattering phase function as determined by measured wavelength- and depth-dependent b_b/b (filled squares). Measured L_w are shown as open diamonds. Percent differences in L_w between measurements and model estimations are shown in the inset figure (percent differences estimated as $(L_{w(model)} - L_{w(data)})/L_{w(data)}$).

Phase function effects on L_w



Measured vs HydroLight for Chesapeake Bay

L_u and E_d comparisons for 3 stations and 3 wavelengths

Table 3

Percent differences in measured and model-estimated L_u and E_d (443, 554, 670 nm) at 1 m depth. Comparisons are shown for measurements representative of the most turbid waters we observed in the Bay (22 May 2002). Percent differences were estimated as:

$$\frac{L_{u(\text{model})} - L_{u(\text{data})}}{\frac{1}{2}\left(L_{u(\text{model})} + L_{u(\text{data})}\right)} 100 \text{ (and similarly for } E_d\text{)}$$

Station	L_u (wavelength in nm)			E_d (wavelength in nm)		
	443	554	670	443	554	670
HB	−4.1	11.6	5.6	8.9	0.4	0.8
PI	17.4	7.4	0.6	3.5	6.4	5.5
JT	−15.5	16.4	6.7	−2.9	9	5.8

Measured vs HydroLight for Chesapeake Bay

Comparison of all L_u and E_d measurements

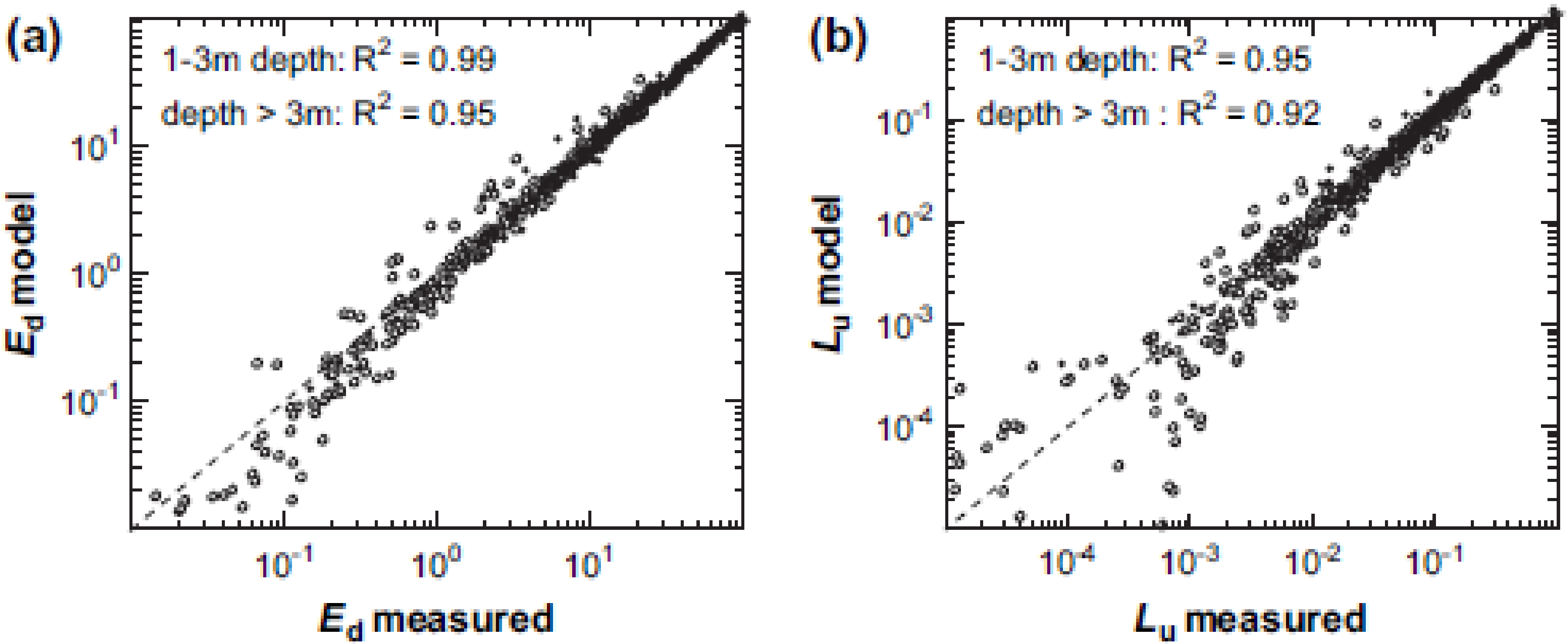
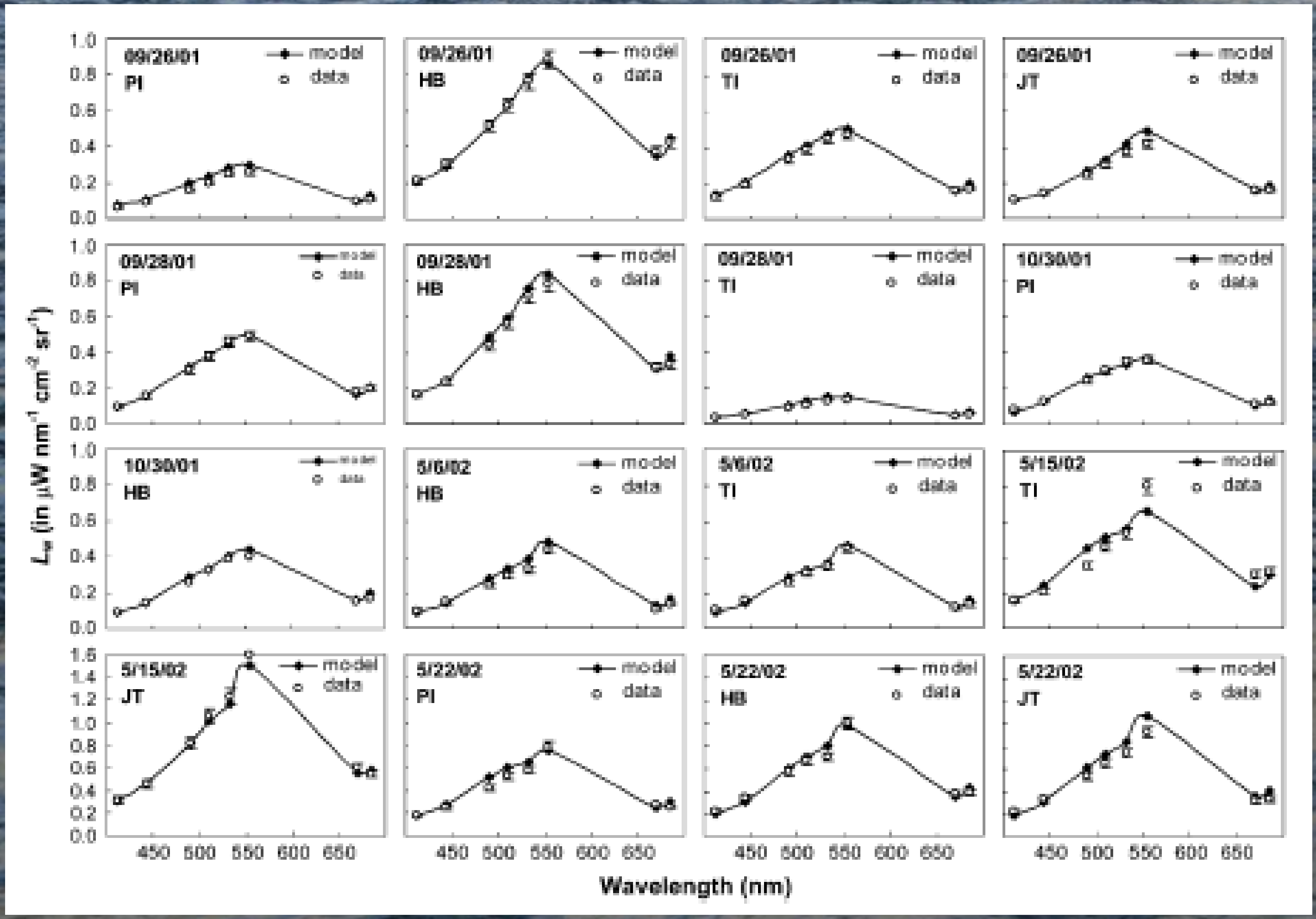


Fig. 8. Comparison between model-estimated and in-situ measured (a) $E_d(z)$ (in μW nm^{-1} cm^{-2}) and (b) $L_u(z)$ values (in μW nm^{-1} cm^{-2} sr^{-1}) at depths 0–6 m, for all cruises-stations that comparisons with the radiative transfer model were performed. Comparisons within the first 3 m are shown as dark circles ($R^2 = 0.99$ for E_d, $R^2 = 0.95$ for L_u), while comparisons for depths below 3 m are shown as open circles ($R^2 = 0.95$ for E_d, $R^2 = 0.92$ for L_u) (the 1:1 line is also shown for comparison).

Measured vs HydroLight for Chesapeake Bay

L_w and HydroLight comparisons at various stations
Note: errors bars are std dev from 3 measurments

L_w (μW cm^{-2} sr^{-1} nm^{-1})



wavelength (nm)

Measured vs HydroLight for Chesapeake Bay

L_w and HydroLight comparisons at various stations

Table 4

Percent differences in estimated L_w values (412–685 nm) using in-situ measurements and model simulations. Percent differences were estimated as:

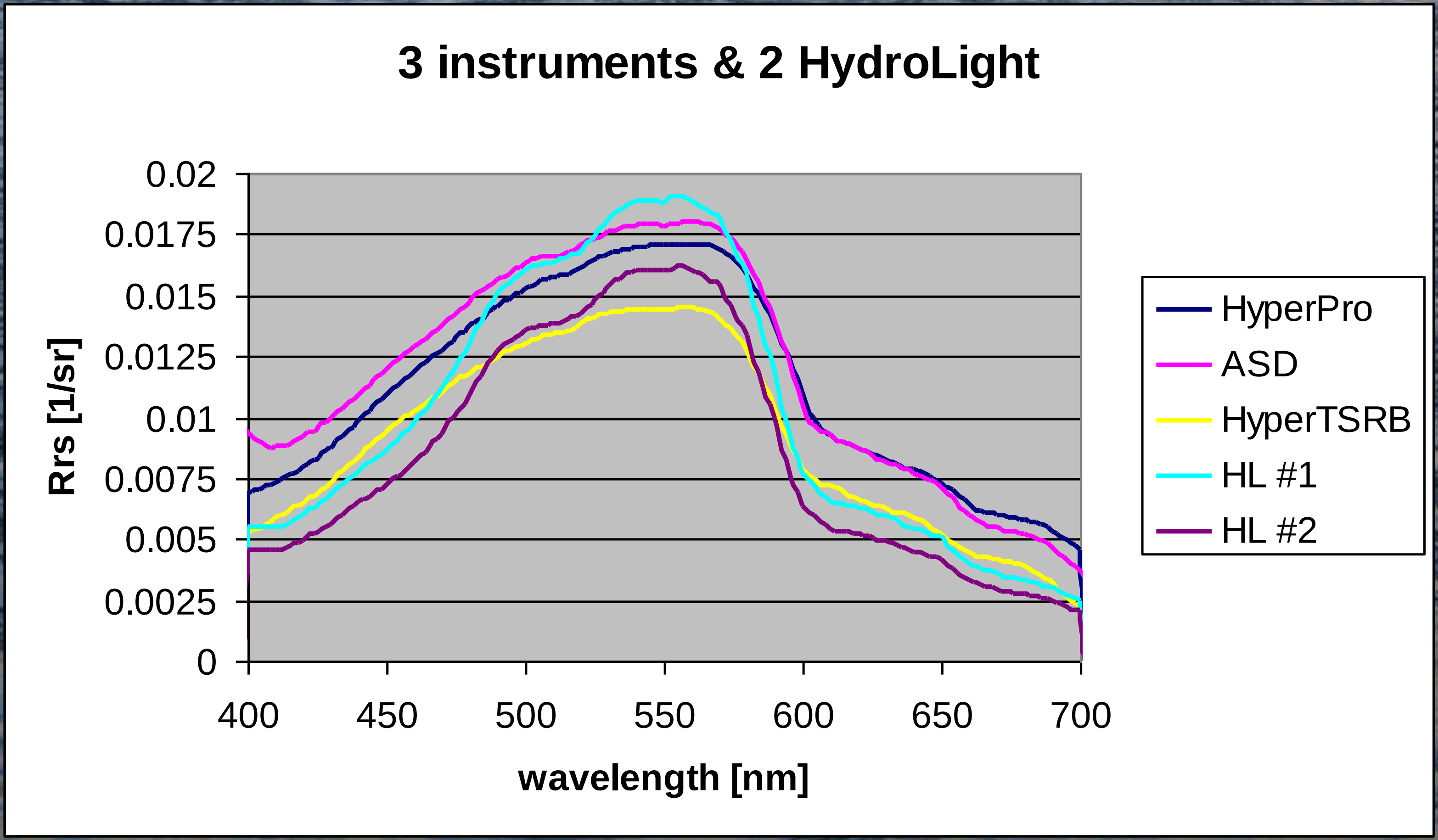
$$\frac{L_{w(\text{model})} - L_{w(\text{data})}}{\frac{1}{2}\left(L_{w(\text{model})} + L_{w(\text{data})}\right)} 100$$

Station/date	Wavelengths (in nm)						
	412	443	490	532	554	670	685
PI, 9/26/01	−21.7	−19.4	−22.3	−13.1	−14.3	−0.3	−15.8
HB, 9/26/01	−2.7	−5.5	−0.1	2.1	−2.8	−7.4	5
TI, 9/26/01	12.9	8.5	6.6	5.1	5.1	−0.6	15
JT, 9/26/01	1.8	−0.6	7.3	12	15.2	2.1	11.3
PI, 9/28/01	0.8	1.9	6.4	−2	0.6	−7.7	4.3
HB, 9/28/01	0.6	2.9	10.3	5.5	7	−3	11.7
TI, 9/28/01	−4.7	1.1	16.6	14	12.8	8	20.3
PI, 10/30/01	−19.7	−2.1	7.2	−4.6	1.2	−3.9	14.4
HB, 10/30/01	0.6	1.5	10.2	2.8	9.5	1.4	17
HB, 5/6/02	−10	−1.7	14.1	15.3	10	18.2	21.6
TI, 5/6/02	−14	−7.5	9.5	4.8	2.3	3.1	16.3
TI, 5/15/02	−1.9	15.9	22.7	3.8	−18.6	−22.4	−4.2
JT, 5/15/02	−2.8	1.9	−0.1	−5.1	−6.1	−7	5.9
PI, 5/22/02	−2.3	11.6	18.7	10.1	−2.7	−6.5	15.5
HB, 5/22/02	−11.5	−11	3.7	12.1	−1.8	−6.6	9.1
JT, 5/22/02	−13.6	−8.5	12.1	11.8	13.7	11.5	19.9
Avg. absolute % diff (standard deviation)	7.60 (7.1)	6.35 (5.7)	10.49 (6.9)	7.76 (4.6)	7.73 (5.8)	6.86 (6.1)	12.96 (5.7)

What else could be added to this study?

Measured vs HydroLight for CICORE Station ER01

CICORE data and analysis by Heidi Dierssen, Univ. Conn.; used measured ac-9 *a* and *b*; best-guess Fournier-Forand phase function, etc.]



Note that the 3 instruments disagree by about the same amount as the two H simulations (using different guesses for the phase function)

You Get the Idea

You do the best you can with the data you have. Sometimes very good, sometimes not so good, sometimes completely useless. That's science.

If you didn't measure the VSF, can you get the backscatter fraction from b_b/b? If not, treat b_b/b as a "fitting parameter" and tweak to get the best fit for R_{rs}, for example.

Even if you can't get agreement between measured and modeled E_d and L_u, for example, can you get agreement with L_u/E_d or with K_d?

Compare as many things as possible, e.g., the measured E_d from the HyperPro and from the ship deck cell and with H's default sky irrad model.

The disagreements are often where you learn the most.

Play around with HydroLight. Have fun!

Kayak Camp, Lofoten Islands, Norway, June 2010