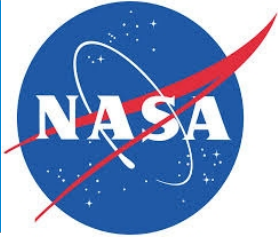


The Average Cosine is Not Constant

Samuel Johnson Wilson
Scripps Institution of Oceanography

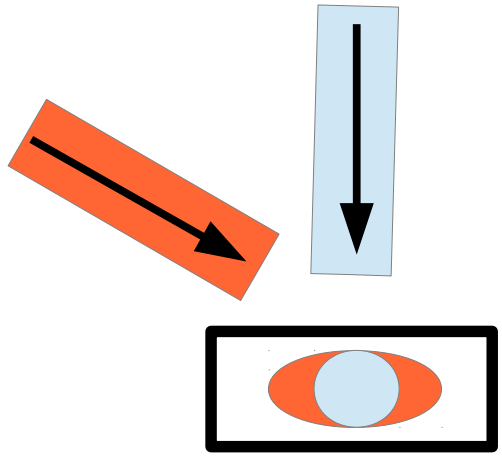
Darling Marine Center
University of Maine
NASA
Ocean Optics, 2013

Final Project
2-August-2013

Outline

- Definition
- Importance
- Uses
- Hydrolight
- Data
- Conclusions

Average Cosine

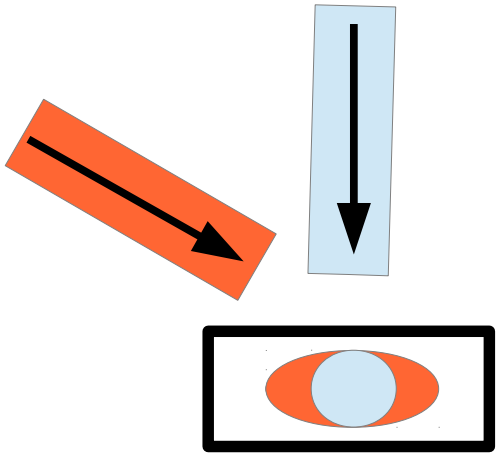


Definition

- *Light and Water*
  - "...the average value of the cosine of the polar angle of all the photons contributing to downwelling radiance at a given depth and wavelength."

$$\overline{\mu}_d(z;\lambda) \equiv \frac{\int_\Xi L(z;\theta,\phi;\lambda)\cos\theta d\Omega}{\int_\Xi L(z;\theta,\Phi;\lambda)d\Omega} \equiv \frac{E_d(z;\lambda)}{E_{od}(z;\lambda)}$$

eq. 3.14



More accurately called a "Weighted average cosine."

Standard Values

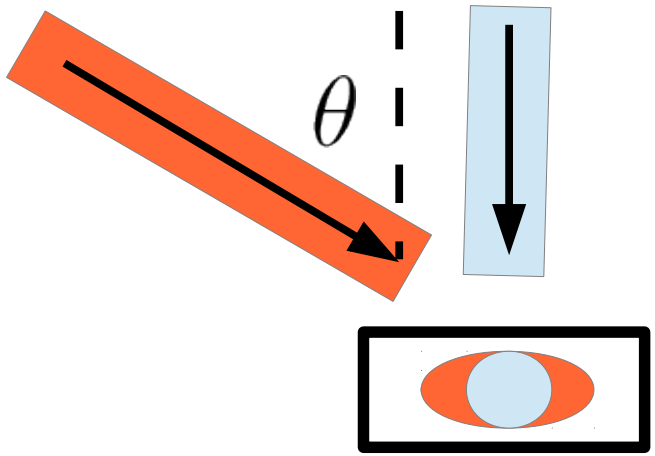
1 : Directly overhead
0.5 : Isotropic
0 : Directly sideways

Uses

Gordon (1989)

- The average cosine is often used to estimate the downwelling distribution function (Do).

$$\frac{K_d}{D_0} = 1.0395(a + b_b)$$



- Do can be thought of as correction for path length
- This is often used to connect AOPs with IOPs

Uses

Kirk (1994)

- Directly uses average cosine to normalize for IOPs.

$$K_d = \frac{1}{\mu_0}\left[a^2 + (g_1 + g_2\mu_0)\frac{b}{a}\right]^{1/2}$$

  g1, g2 are derived from the volume scattering function

- Less common in literature than Gordon, 1989.

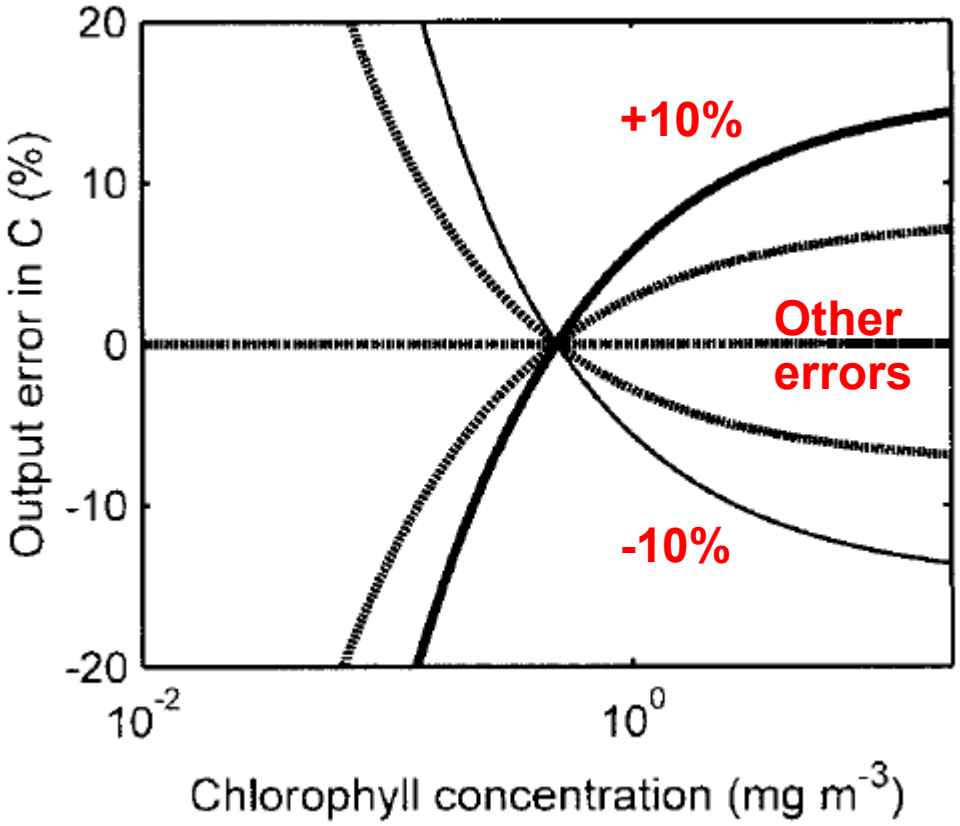
Uses

Paper	Description	Mu value
Xing, et al. 2012	Bio-argo	0.8
Bartlett, et al. 1998	Irradiance ratios on model data	0.9 at surface 0.7 at depth
Brown et al, 2004	AUVs	0.8
Nahorniak, et al 2001	Model proposal.	0.8 (with sensitivity analysis)
Ciotti et al, 1999	Accessory pigments from Ed, Lu.	0.7
Abbot and Letelier, 1998	Floats off California	0.8

Motivation

Important for accurate chlorophyll estimate.

Essential for understanding model error.



- 10% error in the average cosine could double model error of chlorophyll.
- Can be compounded over greater depths.

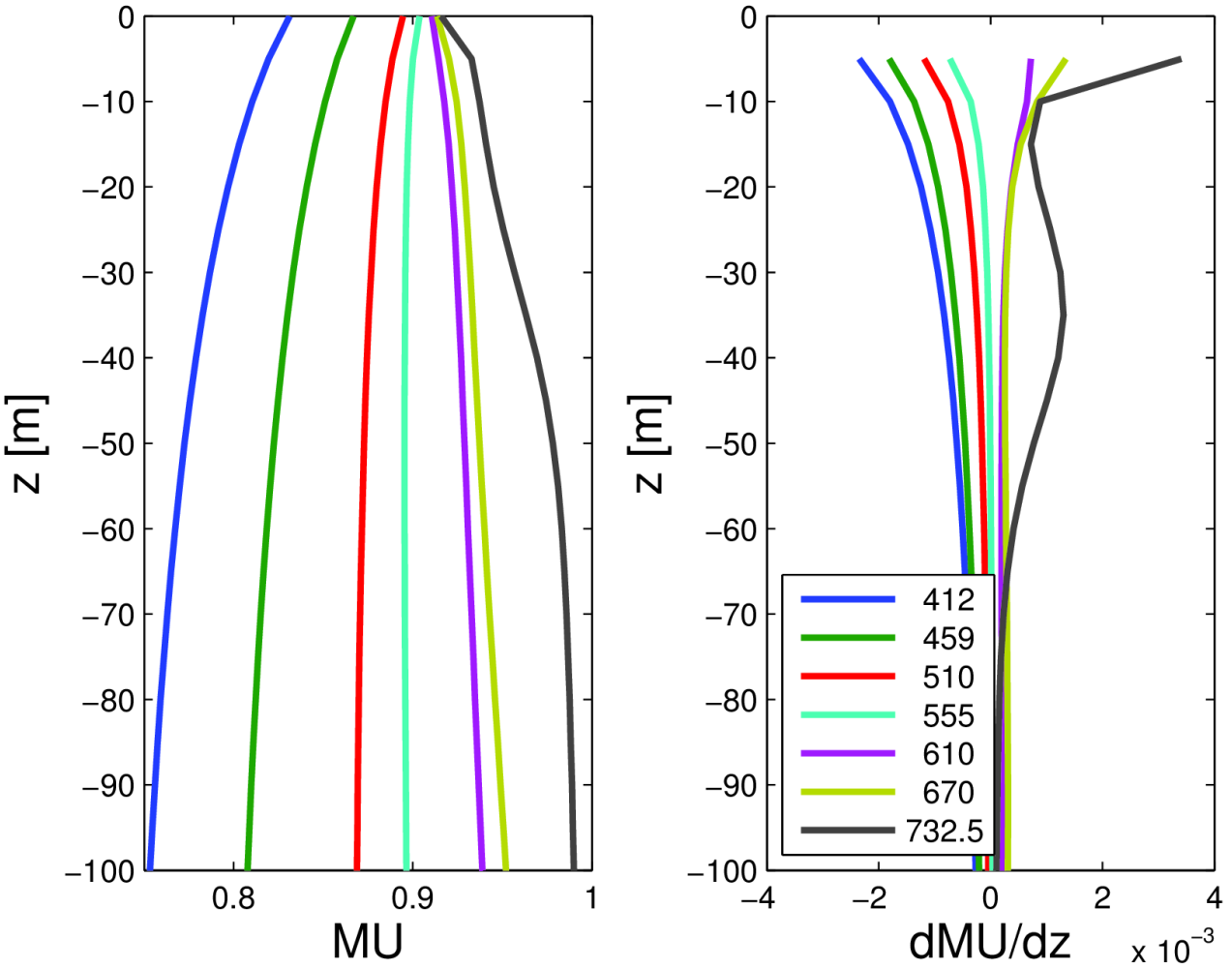
Nahorniak et al., 2001

Hydrolight

- Asymptotic values are based on IOPs
- Profile structure is based on light geometry

Zenith=30deg

<chl>= 0.03mg/m3

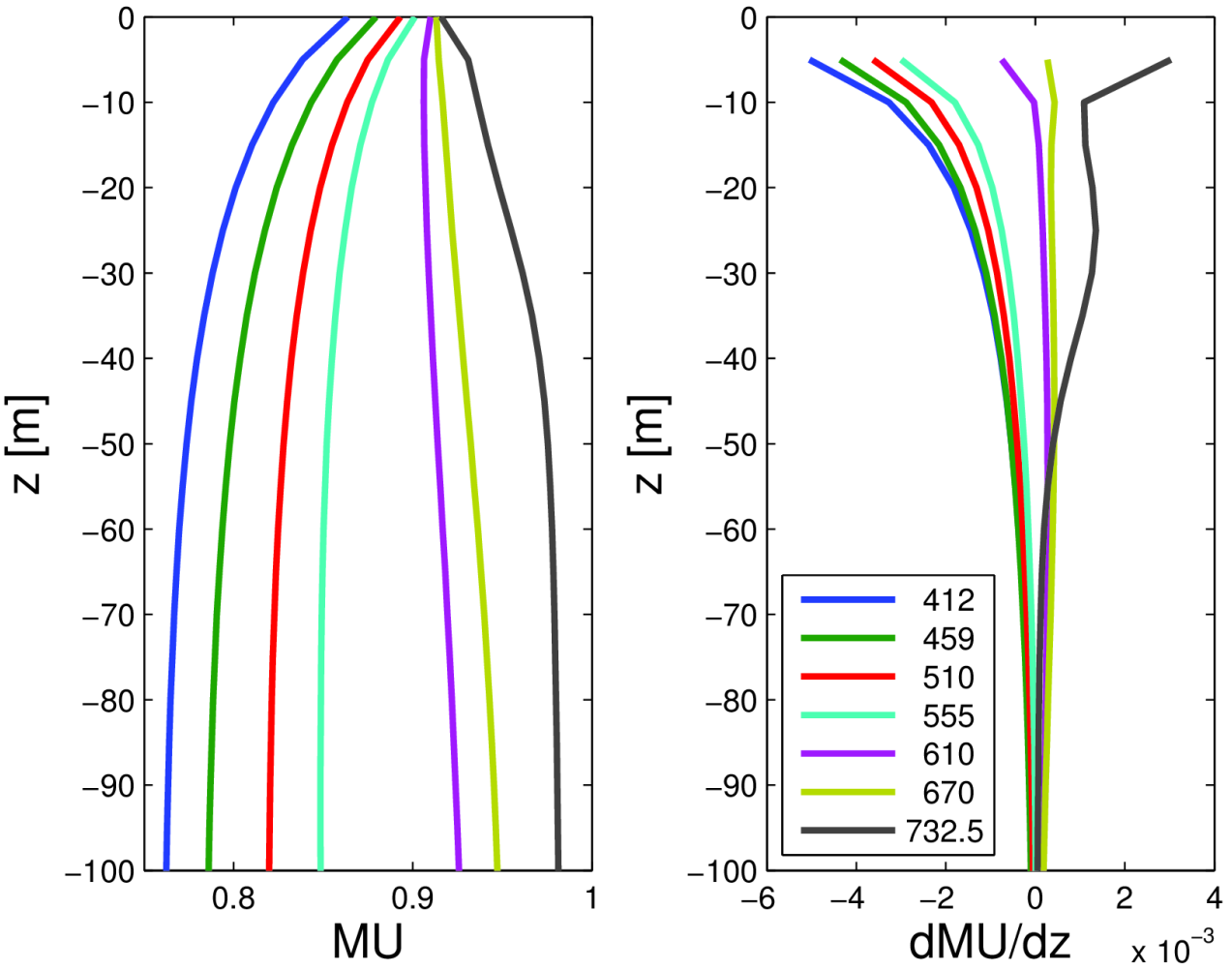


Hydrolight

- Asymptotic values are based on IOPs
- Profile structure is based on light geometry

Zenith=30deg

<chl>= 0.3 mg/m3

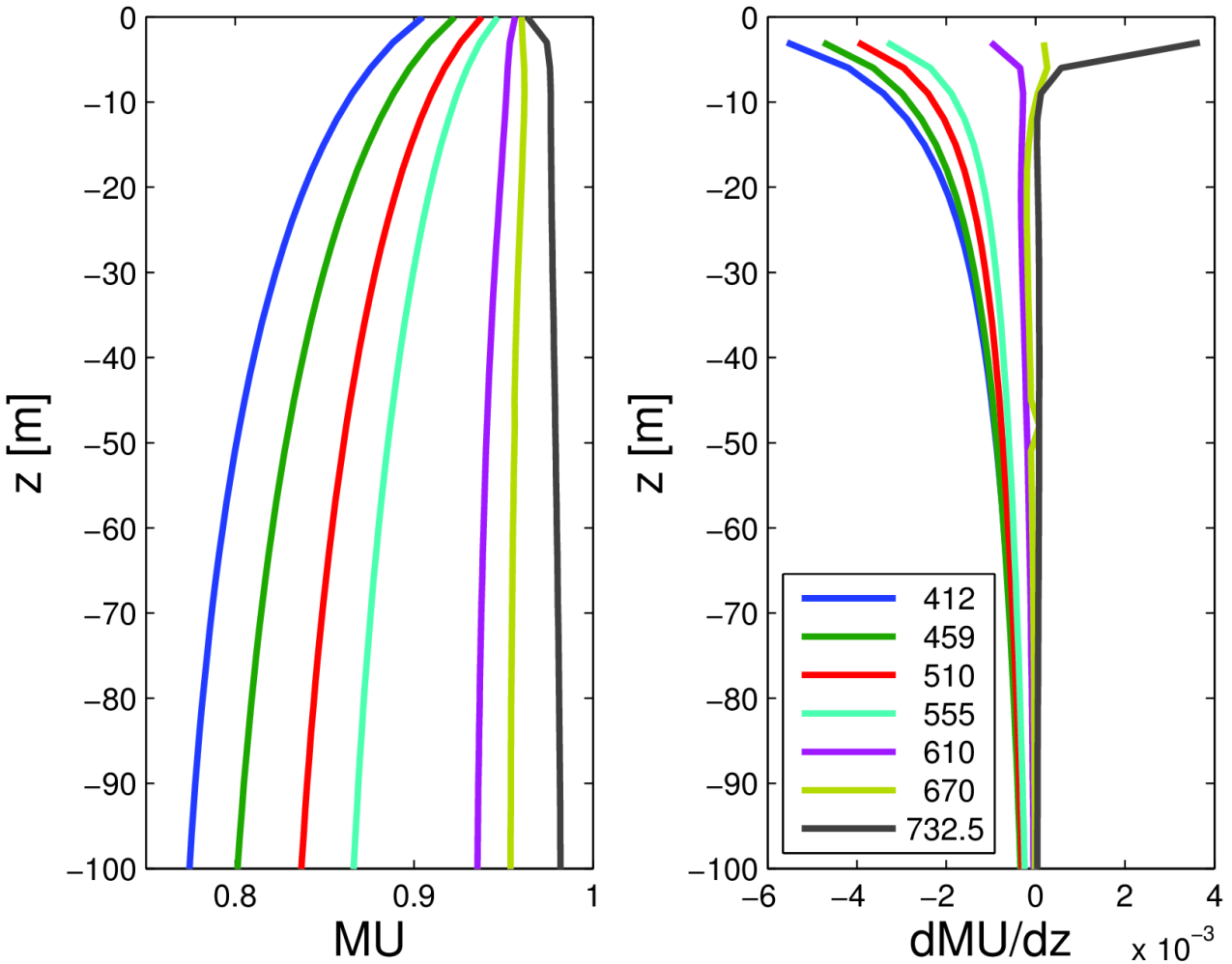


Hydrolight

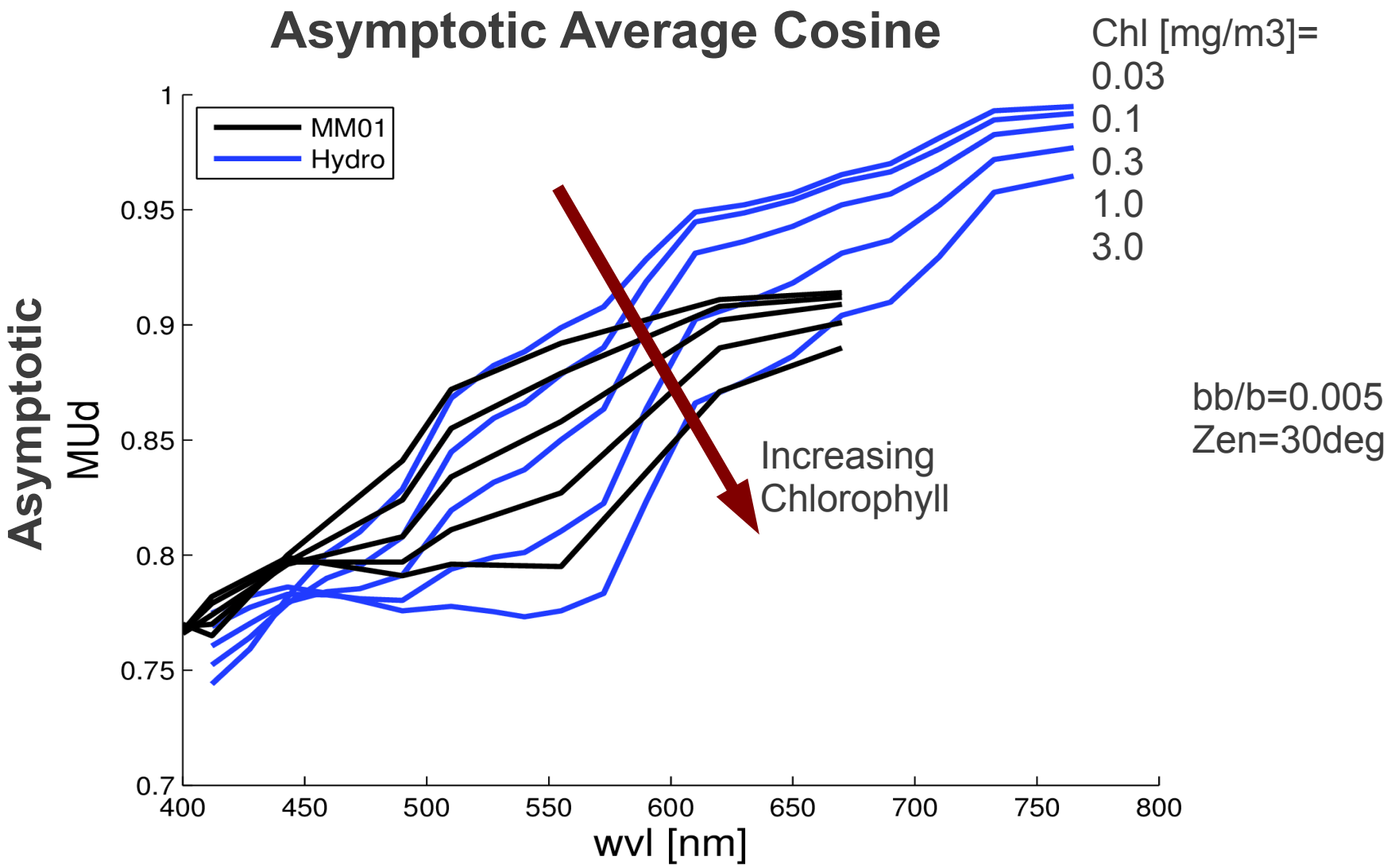
- Asymptotic values are based on IOPs
- Profile structure is based on light geometry

Zenith=10deg

<chl>= 0.3 mg/m3

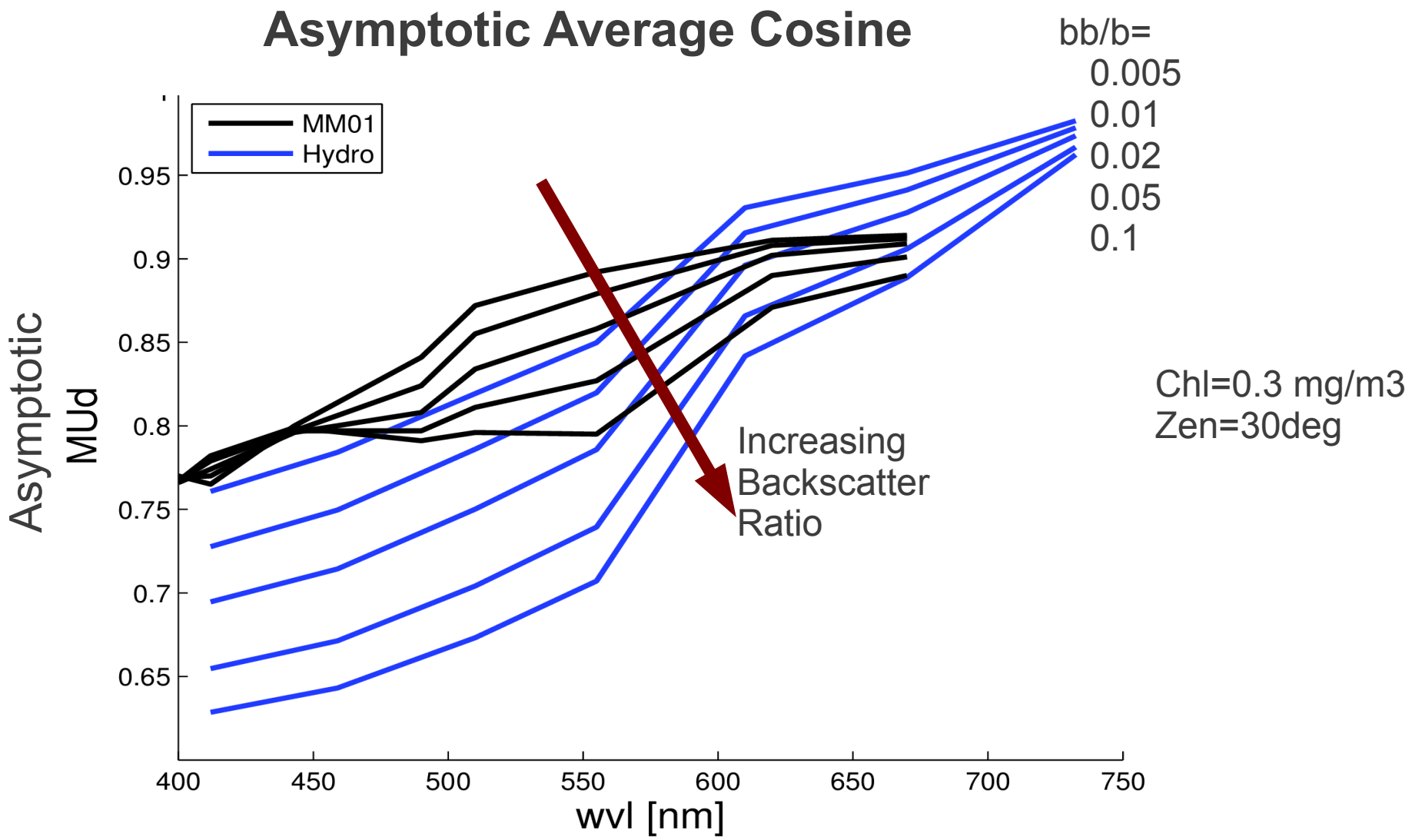


Hydrolight



Morel and Mariterena, 2001

Hydrolight

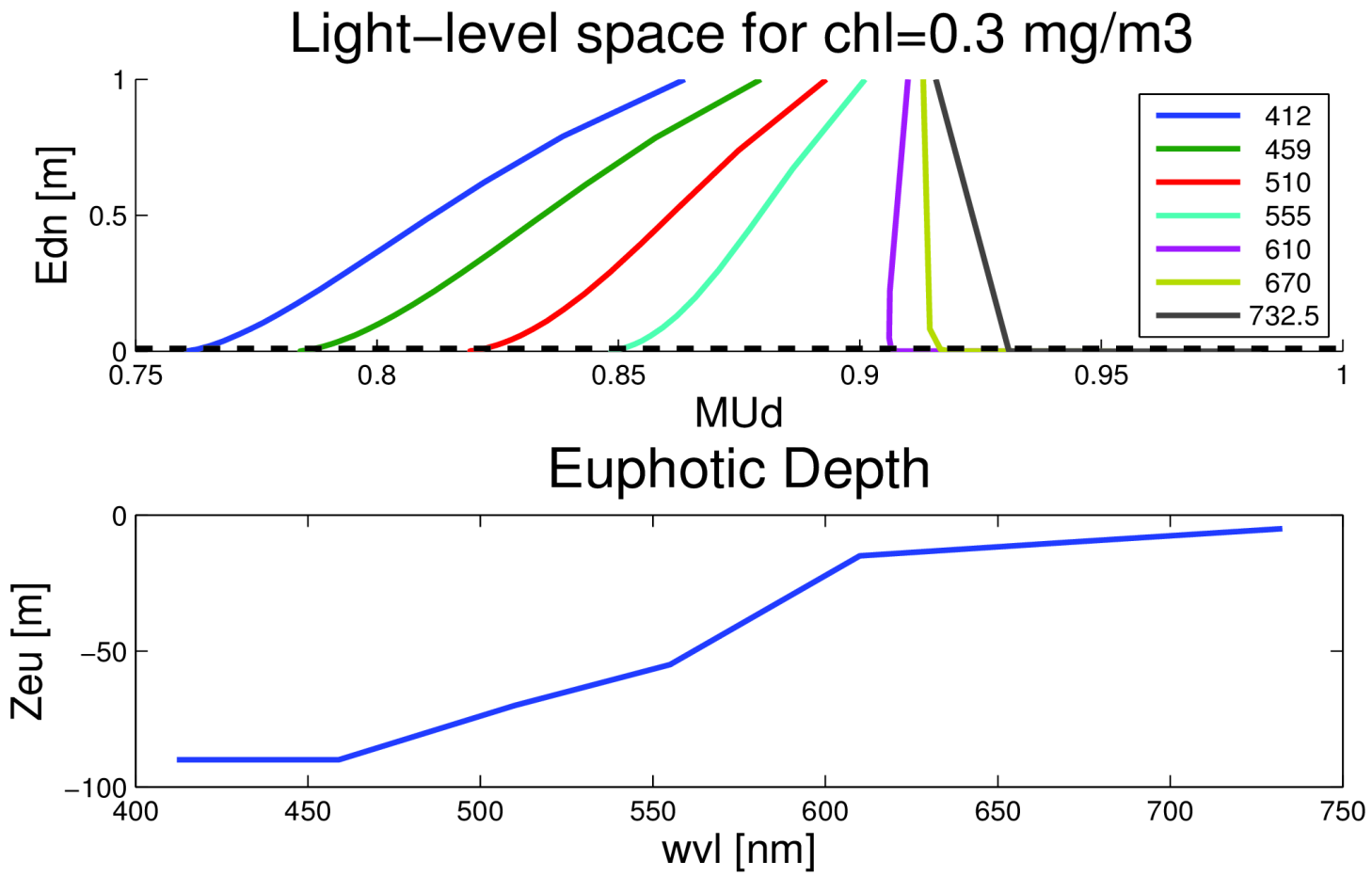


Morel and Mariterena, 2001 (only chlorophyll changes)

Hydrolight

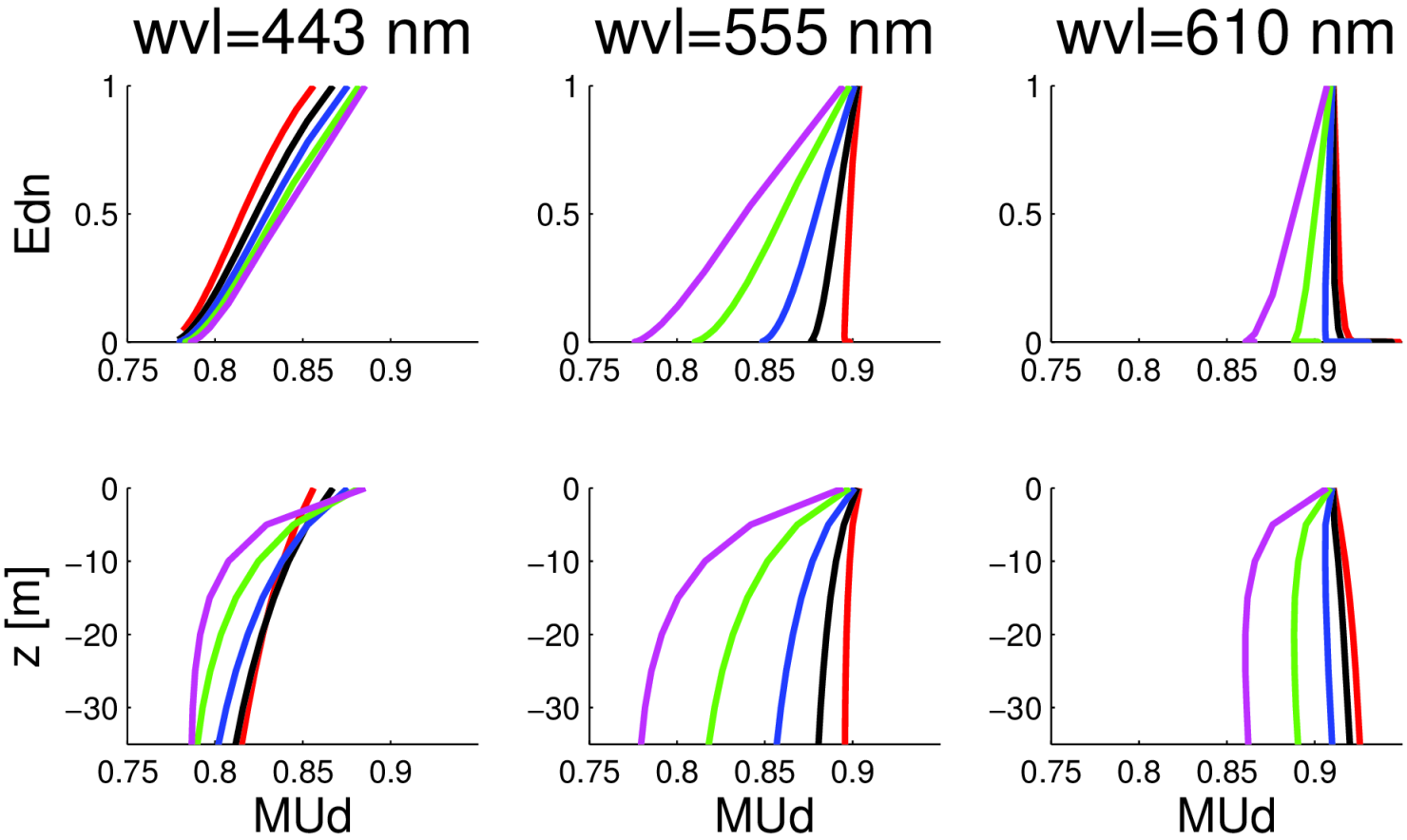
- Profile structure is more complicated.
  - Define Normalized Irradiance

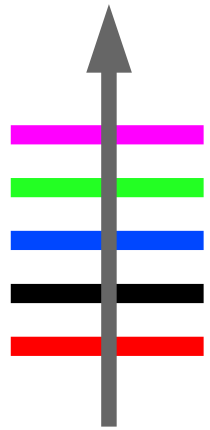
$$E_{dn} = \frac{E_d}{E_s^-}$$



Data

Constant Chlorophyll with Depth



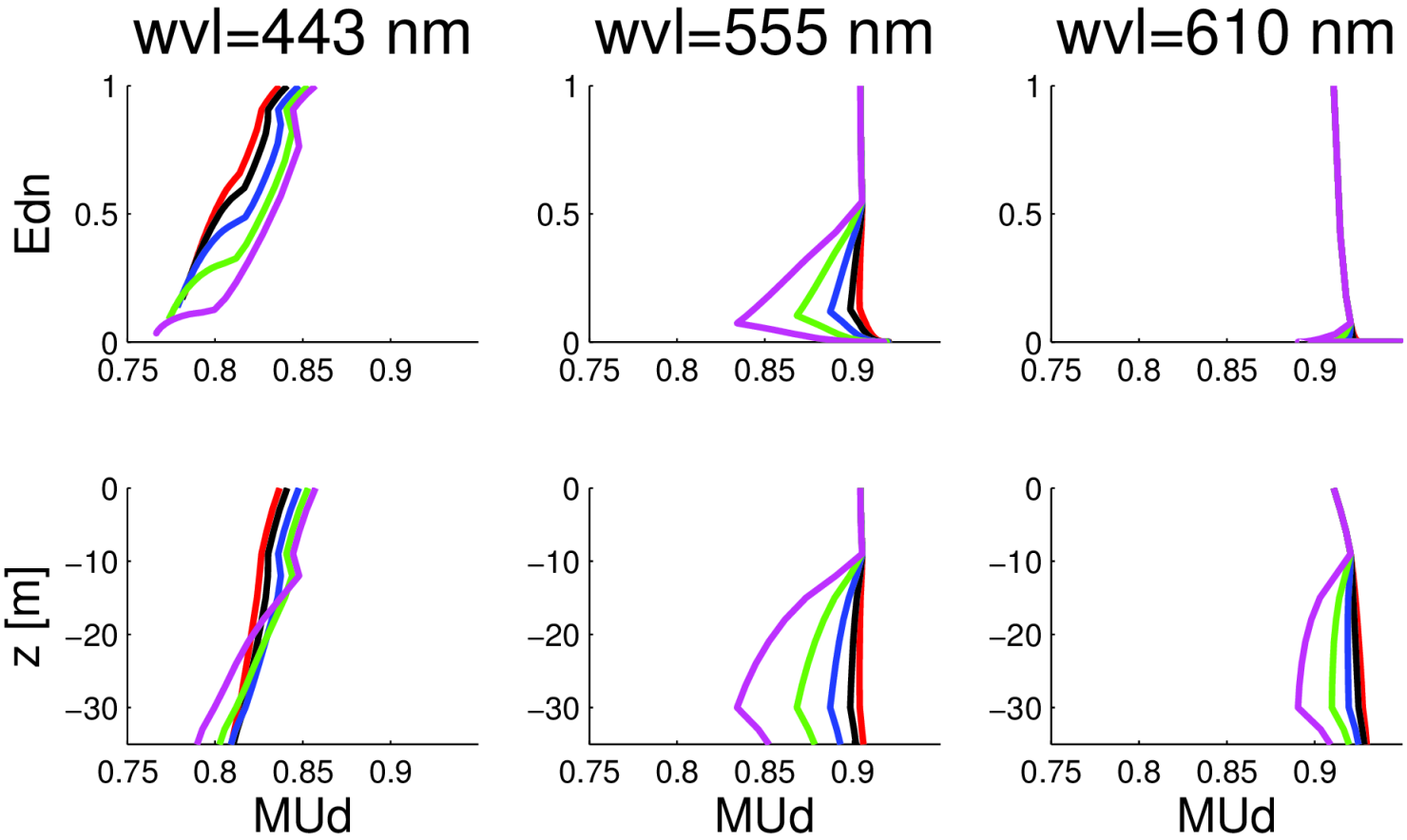


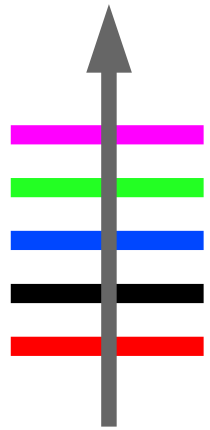
Increasing Chlorophyll

Changes across wavelengths due to changes in primary absorbing constituent.

Data

Chlorophyll layer at 10-30m



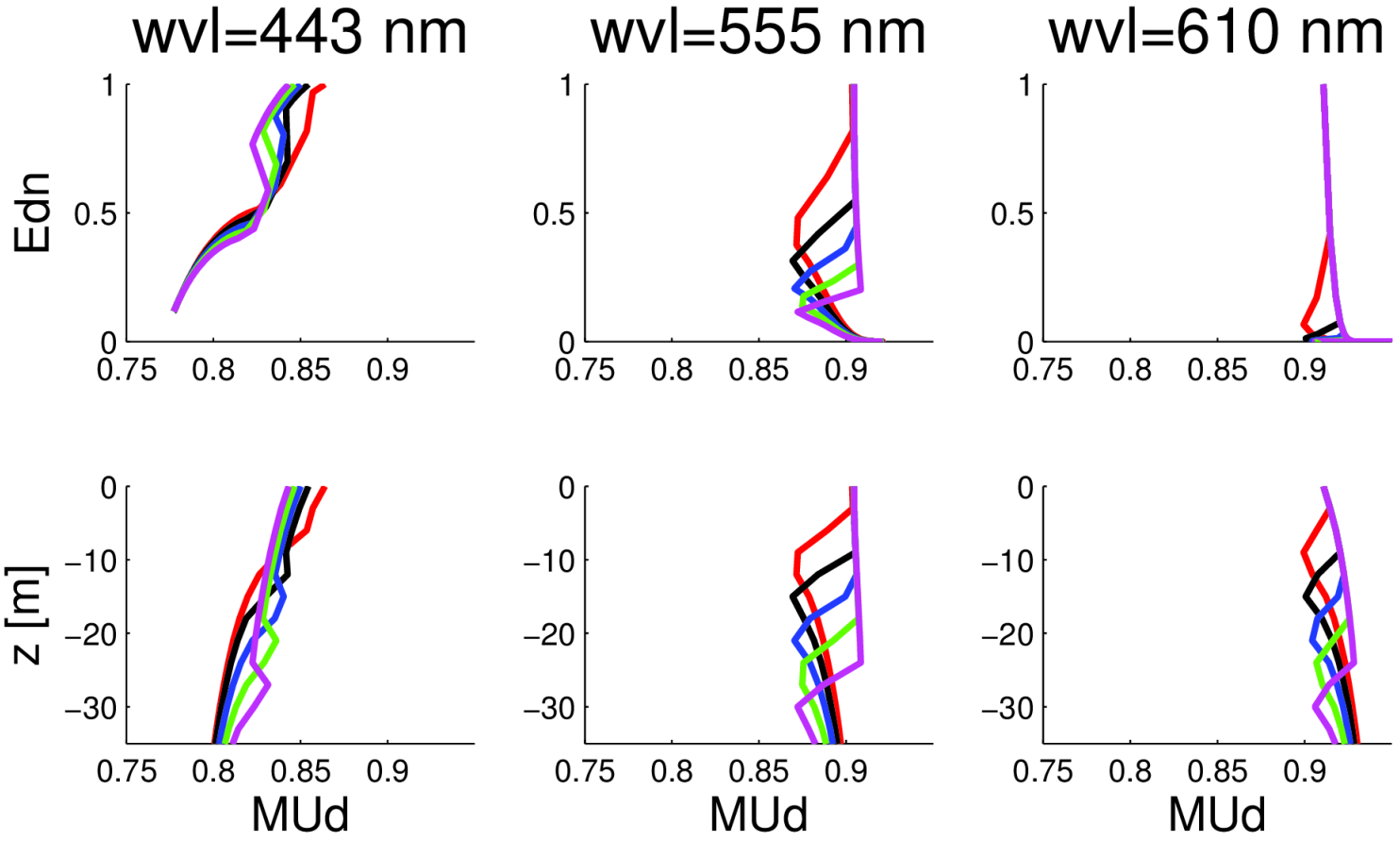


Increasing Chlorophyll Layer

Asymptote based on IOPs, depth of asymptote based on profile.

Data

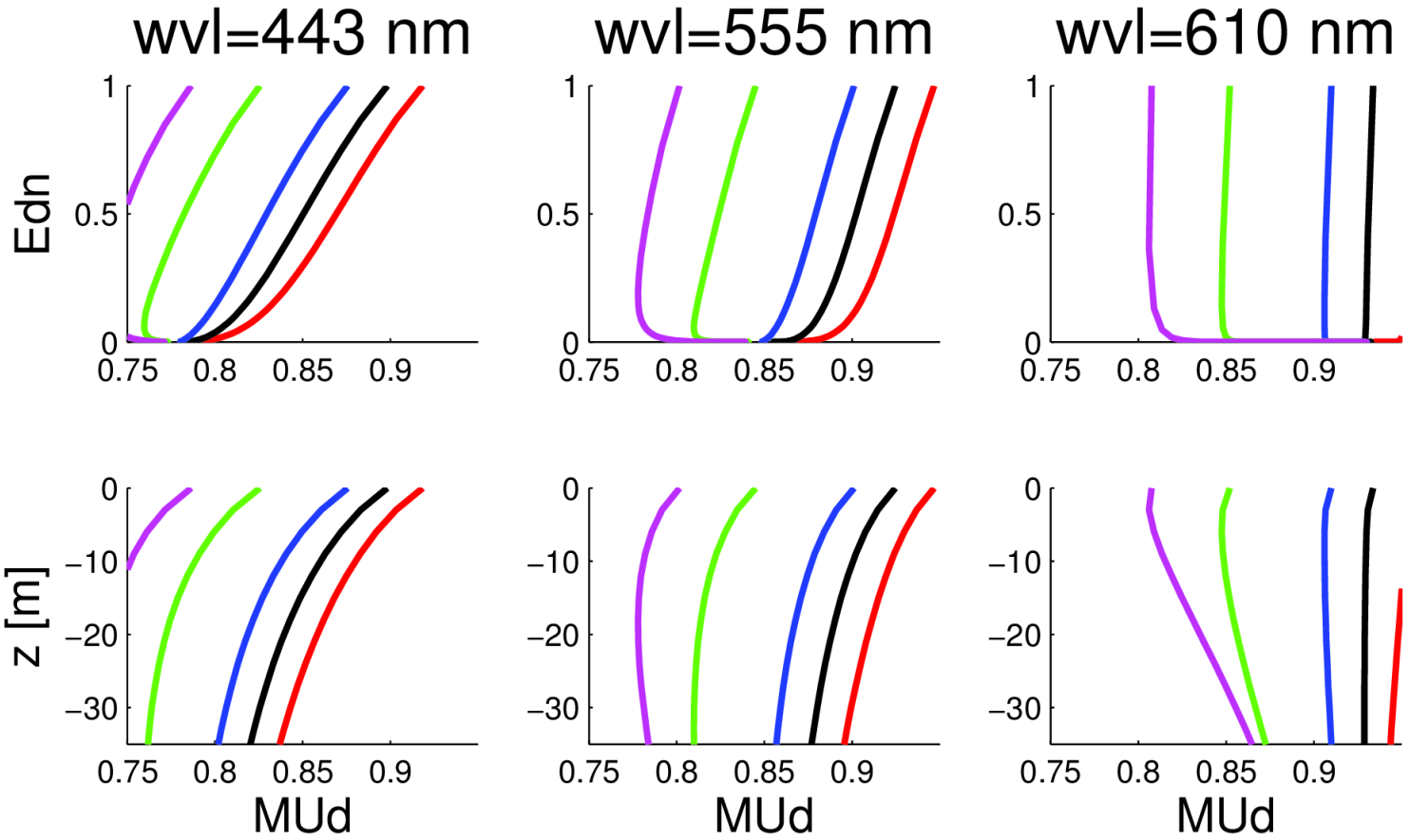
Constant chlorophyll layer, increasing depth

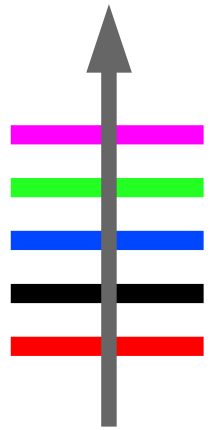


- Same asymptote, complicated profile shape.

Data

Zenith Angle



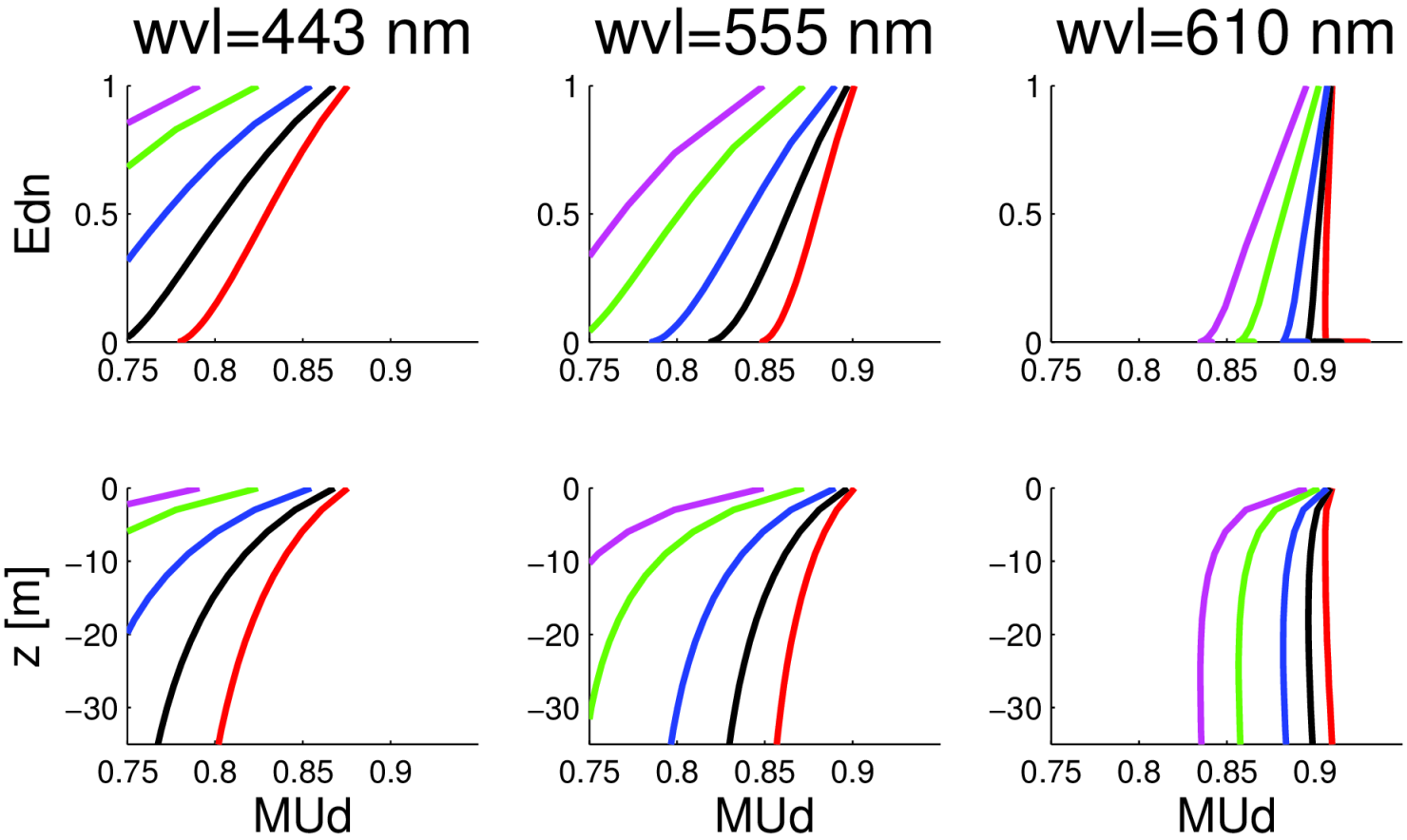


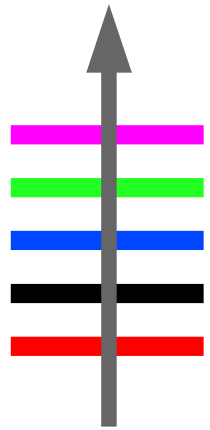
Increasing Zenith Angle

Changes value throughout euphotic zone.
Asymptotic value remains unchanged.

Data

Backscatter Ratio



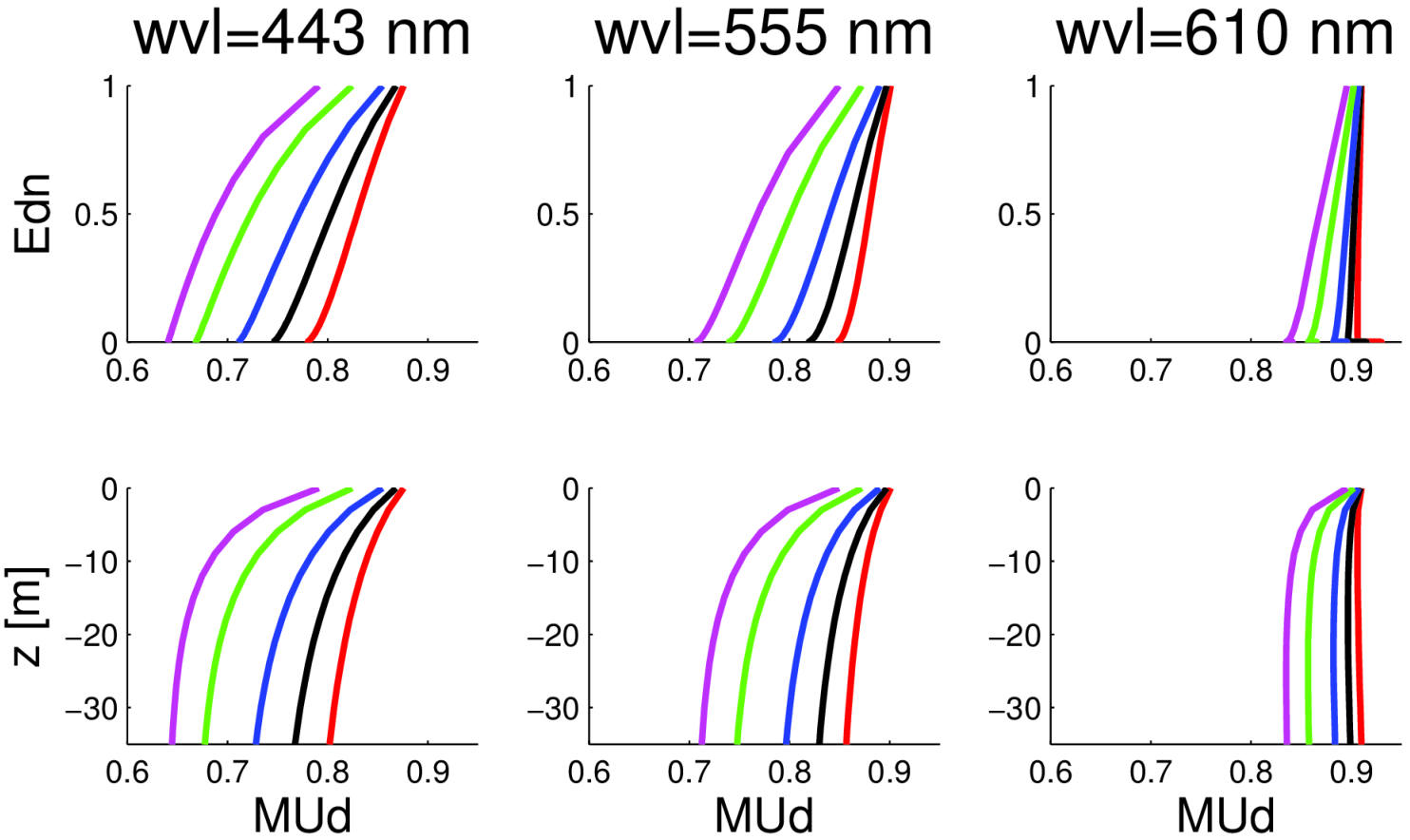


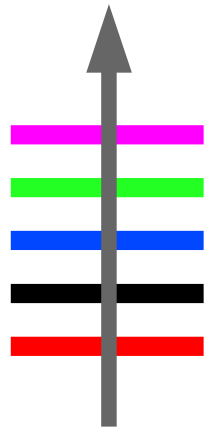
Increasing Backscatter ratio

Classic IOPs links absorption with scattering. Therefore, 443 nm is most affected.

Data

Backscatter Ratio



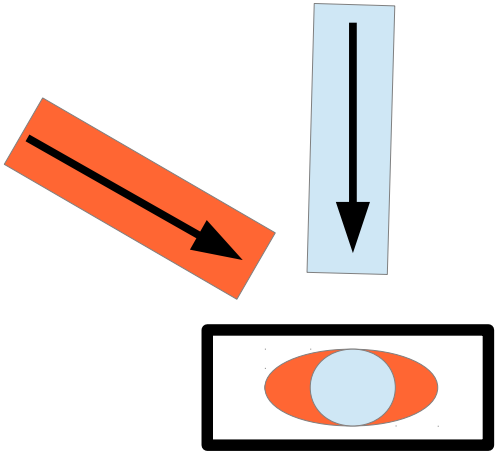


Increasing Backscatter ratio

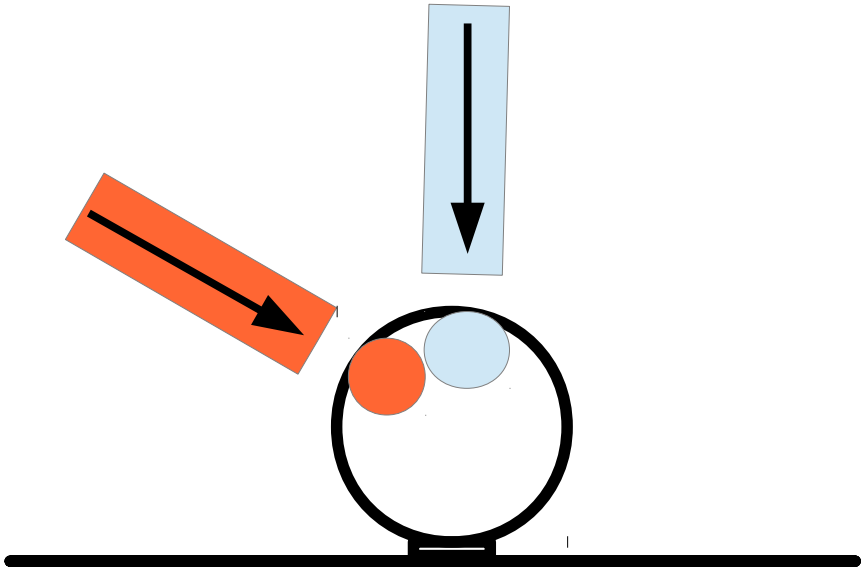
Classic IOPs links absorption with scattering. Therefore, 443 nm is most affected.

Data

- Is it possible to measure the Average Cosine?
  - Cosine collector, though very uncommon.



Ed



Eod

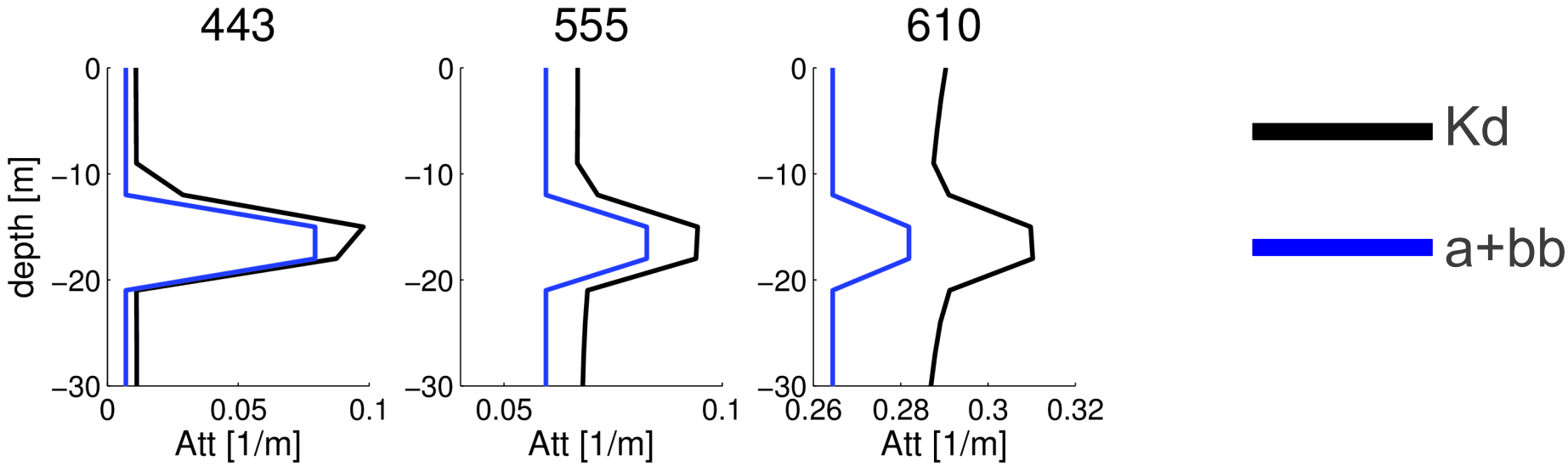
$$\overline{\mu}_d(z;\lambda) \equiv \frac{\int_\Xi L(z;\theta,\phi;\lambda)\cos\theta d\Omega}{\int_\Xi L(z;\theta,\Phi;\lambda)d\Omega} \equiv \frac{E_d(z;\lambda)}{E_{od}(z;\lambda)}$$

Data

Gordon (1989)

- Compare directly, diffuse and beam attenuation

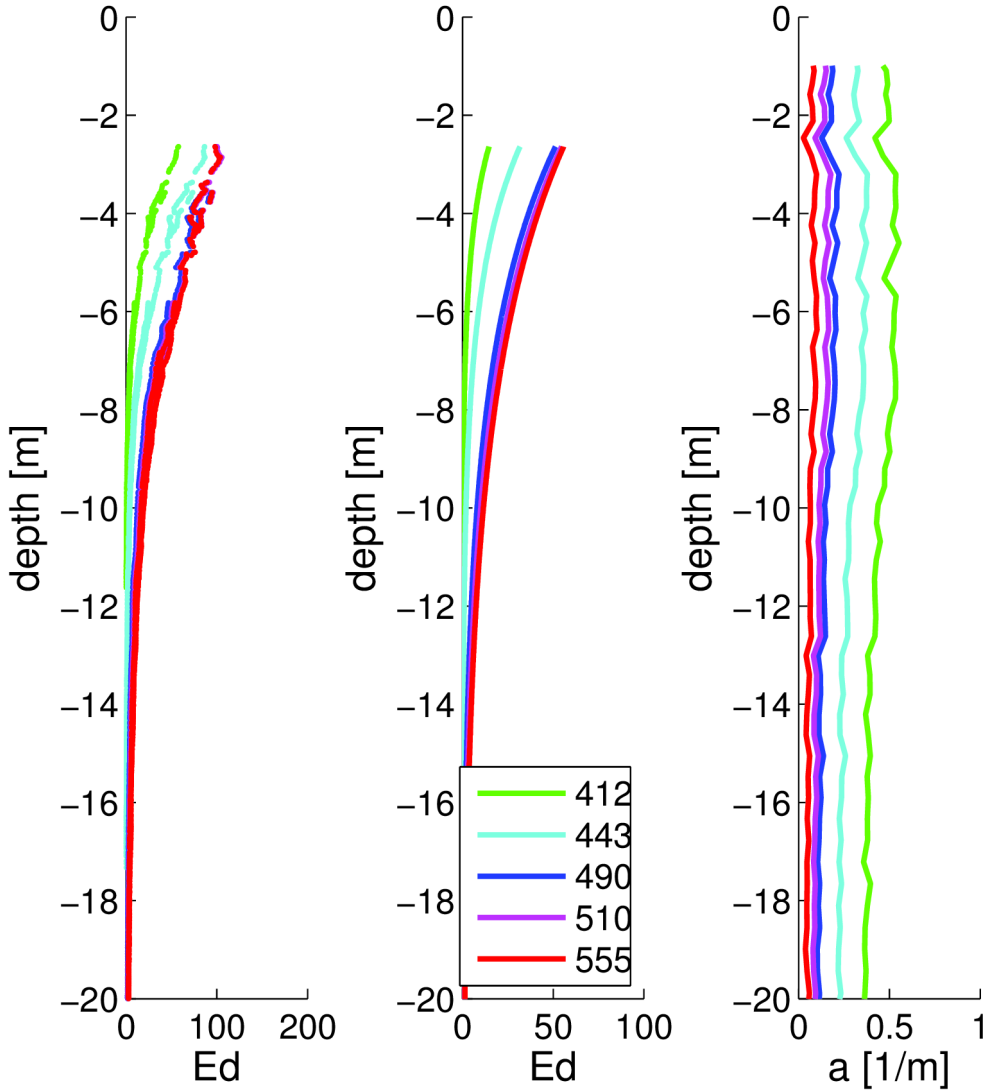
$$\frac{K_d}{D_0} = 1.0395(a + b_b)$$



- With accurate (non-scatter-corrected) ACS a-data, and smooth profiles of Kd, profiles of average pathlength.

Data

- Profile of Ed is very noisy.
  - Clouds, waves, instrument movement.
- Easiest to fit an exponential to find an average Kd for the water column.
- Similar for absorption data



Data

- With these measurements, arrive at pathlength and average cosine.

wvl[nm]	412	443	490	510	555
Do	1.3	1.4	1.9	2.2	3.7
Mu	0.77	0.67	0.53	0.46	0.27

- Values are similar to asymptotic expectations.
- Weighting by function of optical depth would give the average value for the collective photons.

Zaneveld et al, 2005

Conclusions

- Average Cosine describes the geometry of the light field.
- It is often used to connect AOPs with IOPs.
- Some important features
  - Chlorophyll:
    - Changes asymptotic value, very wavelength specific.
  - Chlorophyll Layers:
    - Changes asymptotic rate.
  - Zenith Angle:
    - Changes light geometry; effects can be felt throughout euphotic layer
  - Backscatter ratio
    - Correlates with isotropy; depends heavily on IOP model.
- Measurements
  - Very specific and difficult measurement to make.
  - Assumptions make it easier.

The Average Cosine is Not Constant

...but it is much easier to assume as much.

Literature

Paper	Quick Description	Mu discussion
Kirk, 1984 and 1991	AOP-->IOP model	
Gordon, 1989	AOP-->IOP model	
Morel and Mariterena, 2001 (MM01)	Model for chlorophyll from diffuse attenuation.	Lookup Table for mu based on solar angle, wavelength, and chlorophyll concentration.
Morel and Gentilli, 2004	Closer analysis of 2001 RT model	P14, “adoption of 'typical' values for the average cosines”. Fig 4: Kd vs (a+b)/mu for selected CHL. Mostly linear, Raman exception.
Loisel, 1999	It's in French	
Morel and Loisel, 1998	AOP dependence on molecular scattering.	Near fig 4. Uses Kirk eqn, but discussion of accuracy of Gordon equation shows 3% diff. Table 2: Changes due to non-molecular scattering contributions.

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