2015 Summer Course

on Optical Oceanography and Ocean Color Remote Sensing

Curtis Mobley

Apparent Optical Properties and the BRDF

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University of Maine
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Apparent Optical Properties (AOPs)

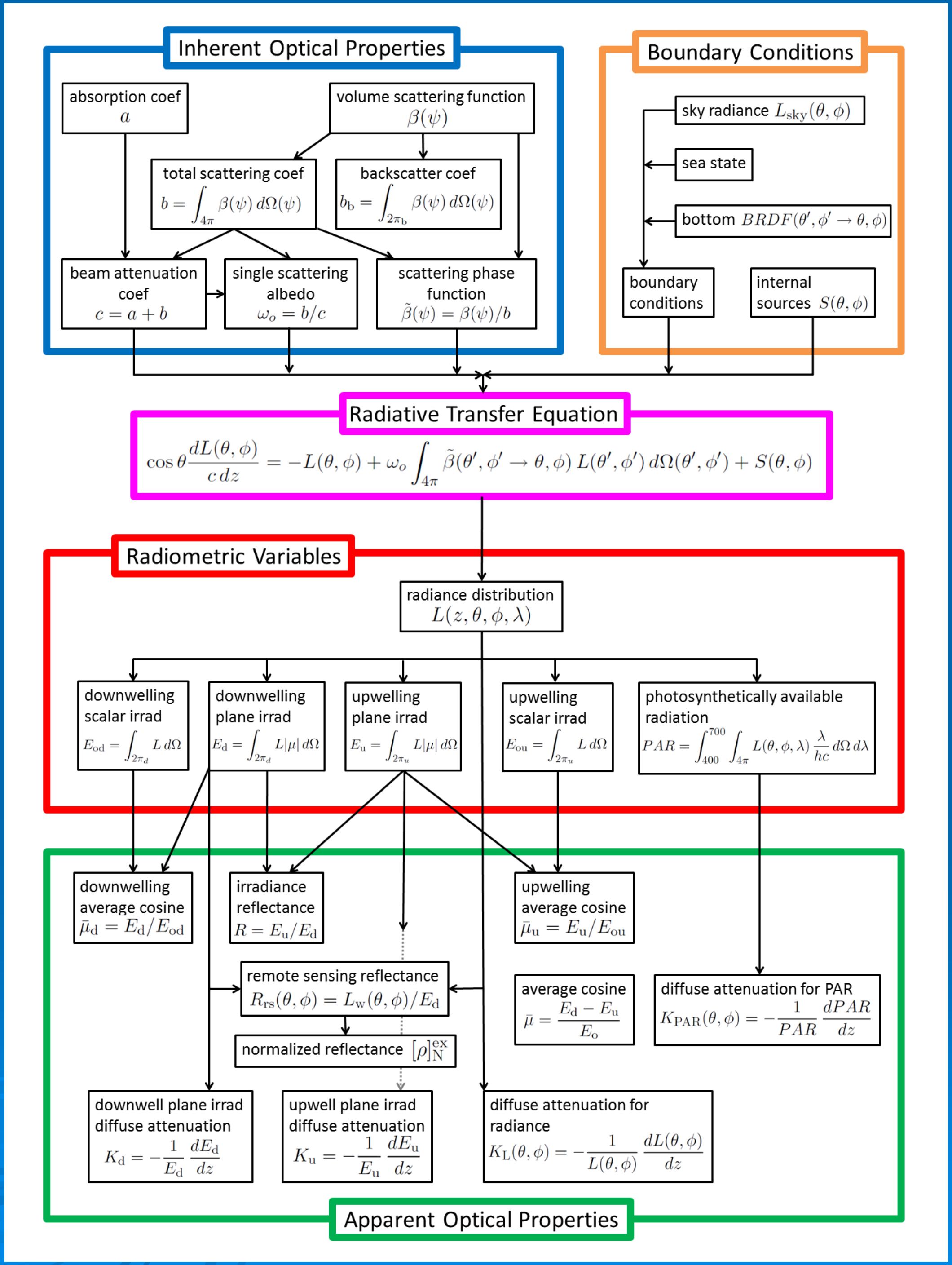
AOPs are quantities that

(1) depend on the IOPs and on the radiance distribution, and

(2) they display enough stability to be useful for approximately describing the optical properties of the water body

Radiance and irradiances are NOT AOPs—they don't have stability

AOPs can NOT be measured in the lab or on water sample; they must be measured in situ



Apparent Optical Properties

A good AOP depends weakly on the external environment (sun zenith angle, sky condition, surface waves) and strongly on the water IOPs

AOPs are usually ratios or depth derivatives of radiometric variables

Historically, IOPs were hard to measure (but easy to interpret). This is less true today because of advances in instrumentation.

AOPs were easier to measure (but are often harder to interpret).

In a Perfect World

Light Properties: measure the radiance as a function of location, time, direction, wavelength, $L(x,y,z,t,\theta,\phi,\lambda)$, and you know everything there is to know about the light field. You don't need to measure irradiances, PAR, etc.

Material Properties: measure the absorption coefficient $a(x,y,z,t,\lambda)$ and the volume scattering function $\beta(x,y,z,t,\psi,\lambda)$, and you know everything there is to know about how the material affects light. You don't need to measure b, b_b, etc.

Nothing else (AOPs in particular) is needed.

Reality

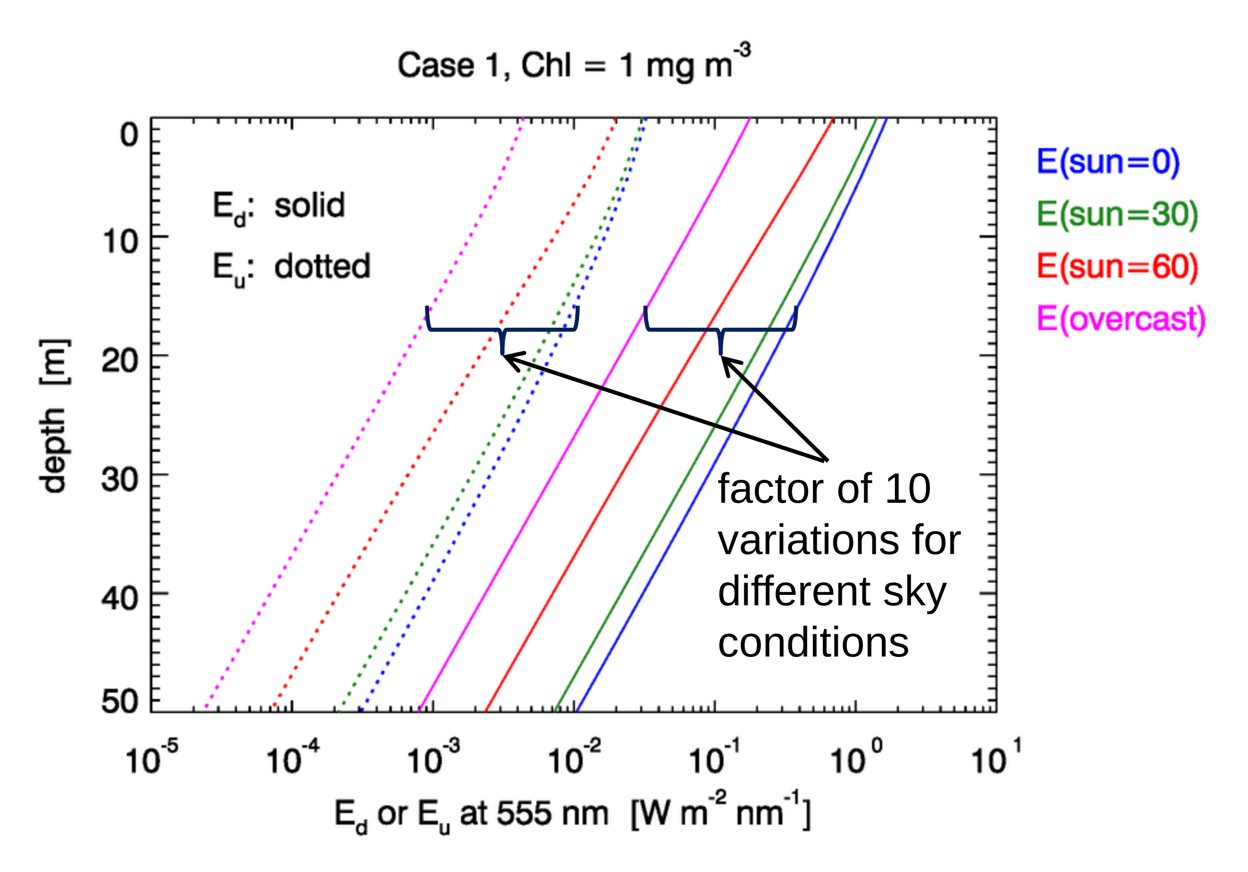
$L(x,y,z,t,\theta,\phi,\lambda)$ is too difficult and time consuming to measure on a routine basis, and you don't need all of the information contained in *L*, so therefore measure irradiances, PAR, etc. (ditto for VSF vs *b*, b_b,….)

Idea

Can we find simpler measures of the light field than the radiance, which are also useful for describing the optical characteristics of a water body (i.e., what is in the water)?

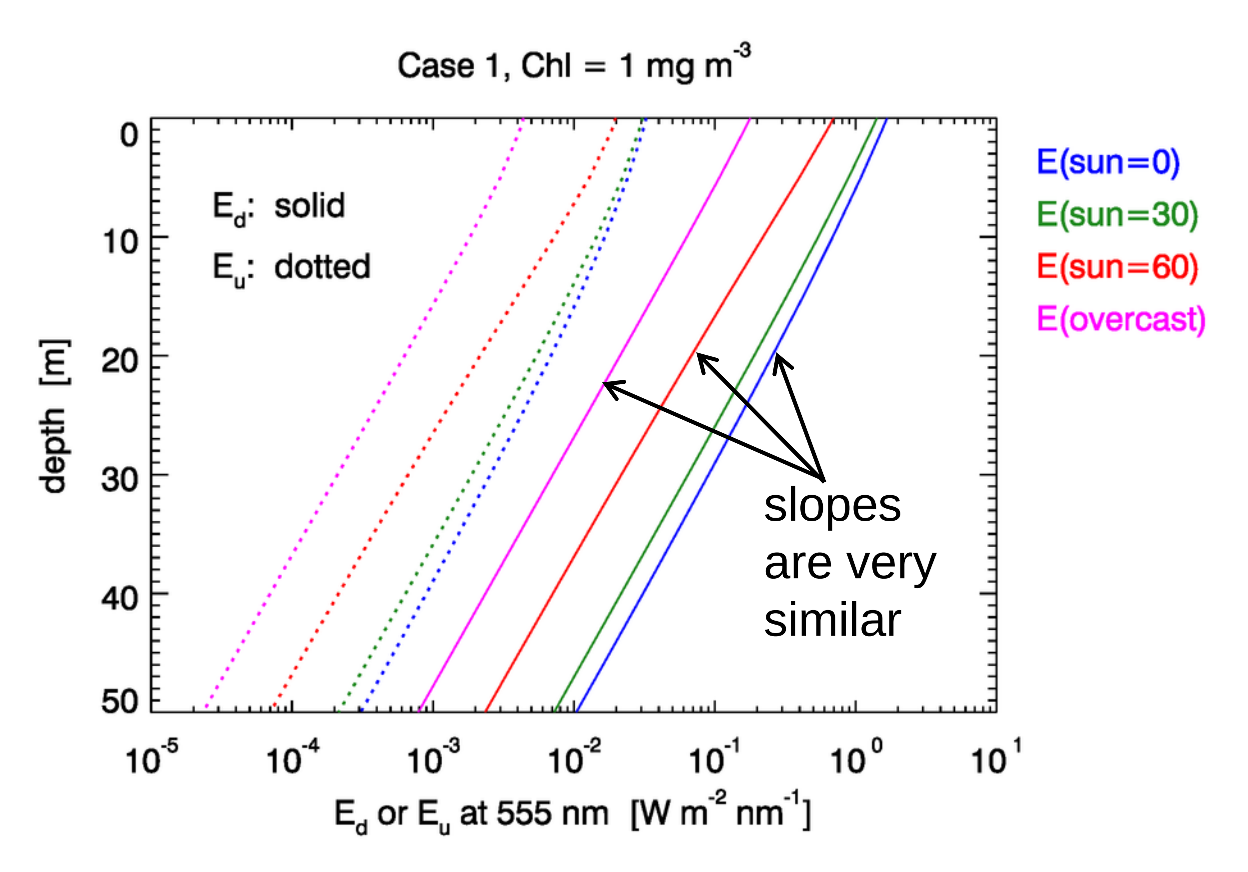
E_d and E_u

HydroLight runs: Case 1 water, Chl = 1.0 mg/m^3, etc
Sun at 0, 30, 60 deg in clear sky, and solid overcast



Note: E_d and E_u depend on the radiance and on the abs and scat properties of the water, but they also depend strongly on incident lighting, so not useful for characterizing a water body. Again: irradiances are NOT AOPs!

E_d and E_u



Magnitude changes are due to incident lighting (sun angle and sky condition); slope is determined by water IOPs.

This suggests trying...

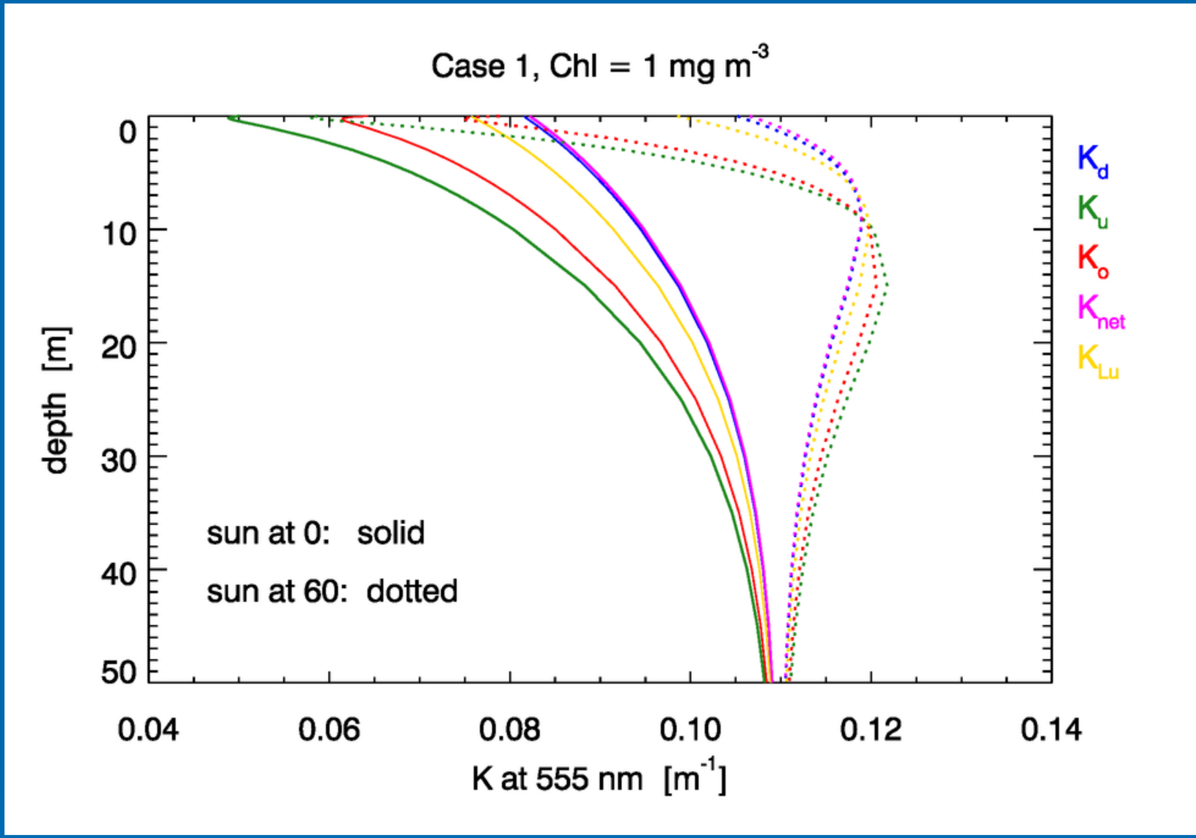
…the depth derivative (slope) on a log-linear plot as an AOP.

This leads to the diffuse attenuation coefficient for downwelling plane irradiance:

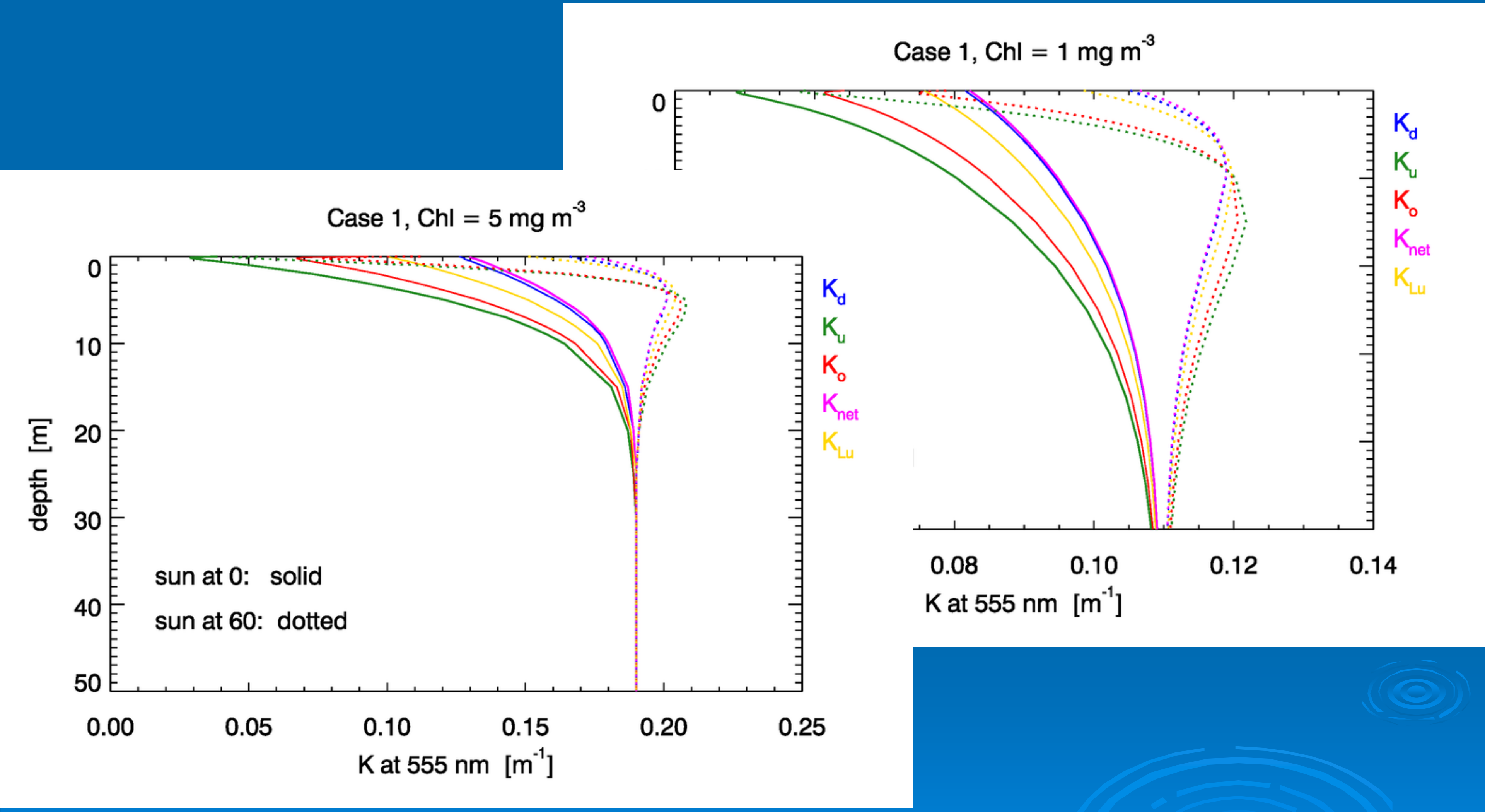
$$K_d(z,\lambda) = -\frac{d \ln E_d(z,\lambda)}{dz} = -\frac{1}{E_d(z,\lambda)} \frac{d E_d(z,\lambda)}{dz}$$

We can do the same for E_u, E_o, $L(\theta,\phi)$, etc, and define many different K functions: K_u, K_o, $K_L(\theta,\phi)$, etc.

How similar are the different K's?

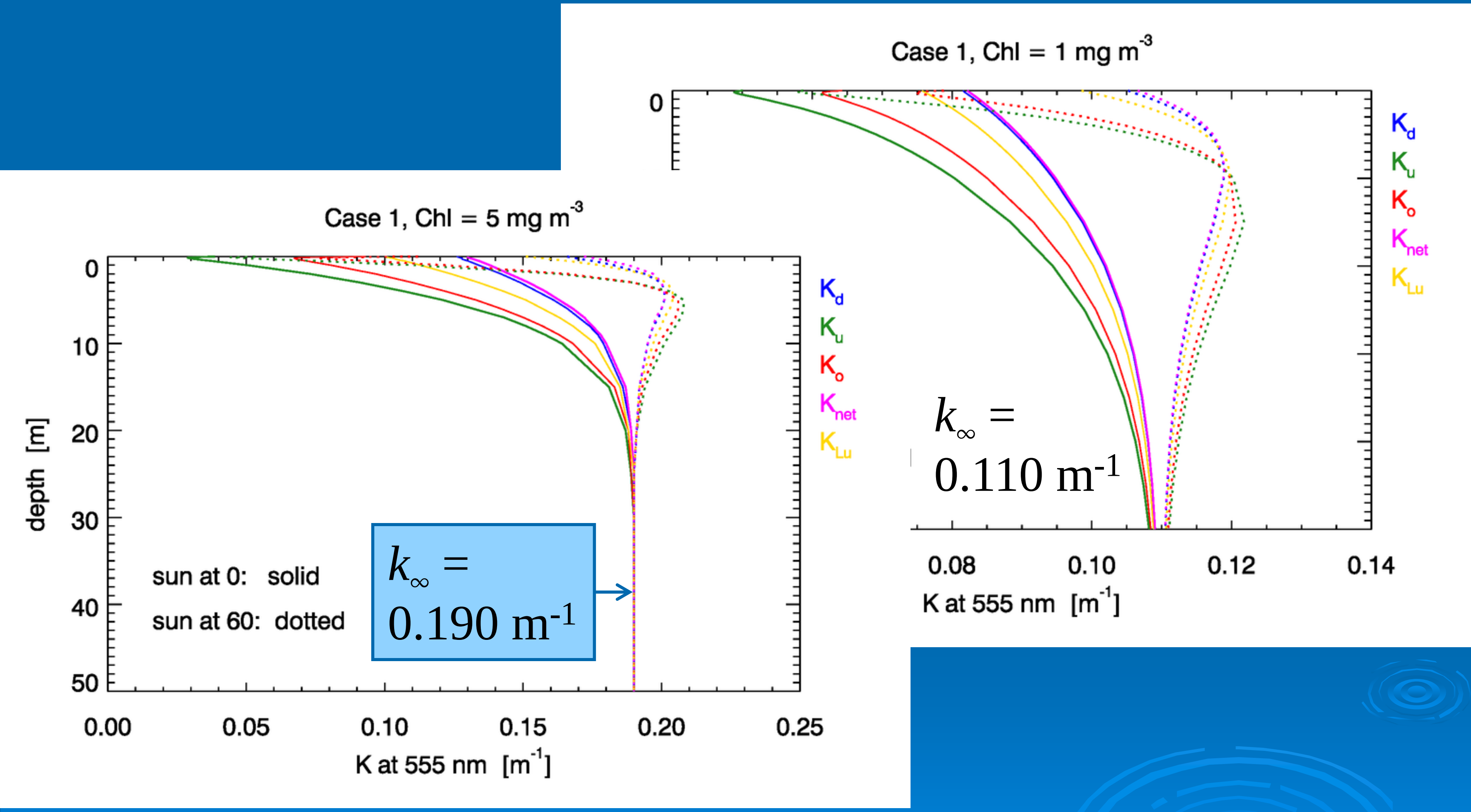


How similar are the different K's?



NOTE: The K's depend on depth, even though the water is homogeneous, and they are most different near the surface (where the light field is changing because of boundary effects)

Asymptotic Values

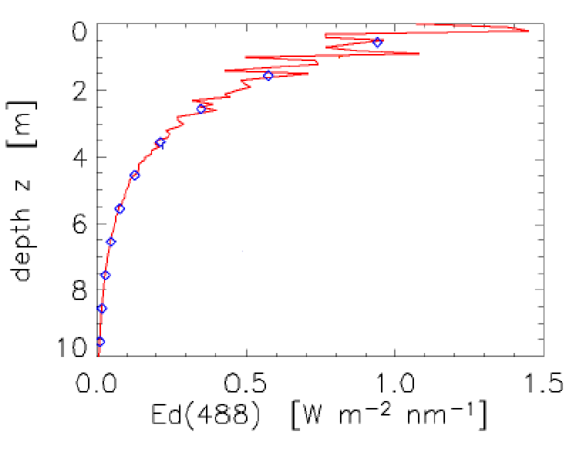


The K's all approach the same value as you go deeper: the asymptotic diffuse attenuation coefficient, k_∞, which is an IOP.

Something to Think About

- Suppose you measure $E_d(z)$
- but the data are very noisy in the first few meters because of wave focusing, or bubbles, or…
- so you discard the data from the upper 5 meters
- You then compute K_d from 5 m downward, and get a fairly constant K_d value below 5 m
- You then use $E_d(z) = E_d(0)\exp(-K_d\, z)$ and the computed K_d from 5 m downward to extrapolate E_d(5 m) back to the surface

How accurate is this $E_d(0)$ likely to be?



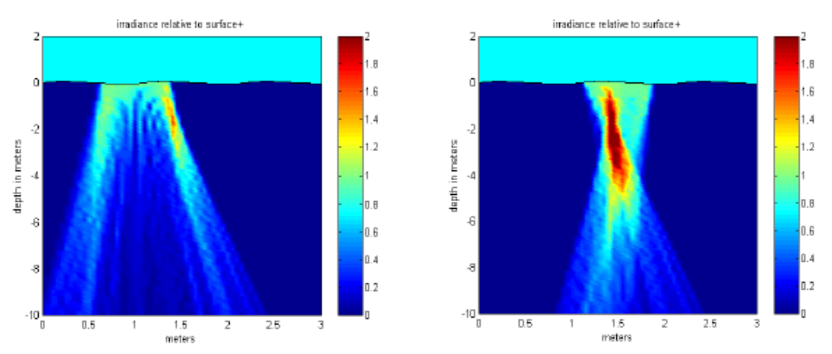
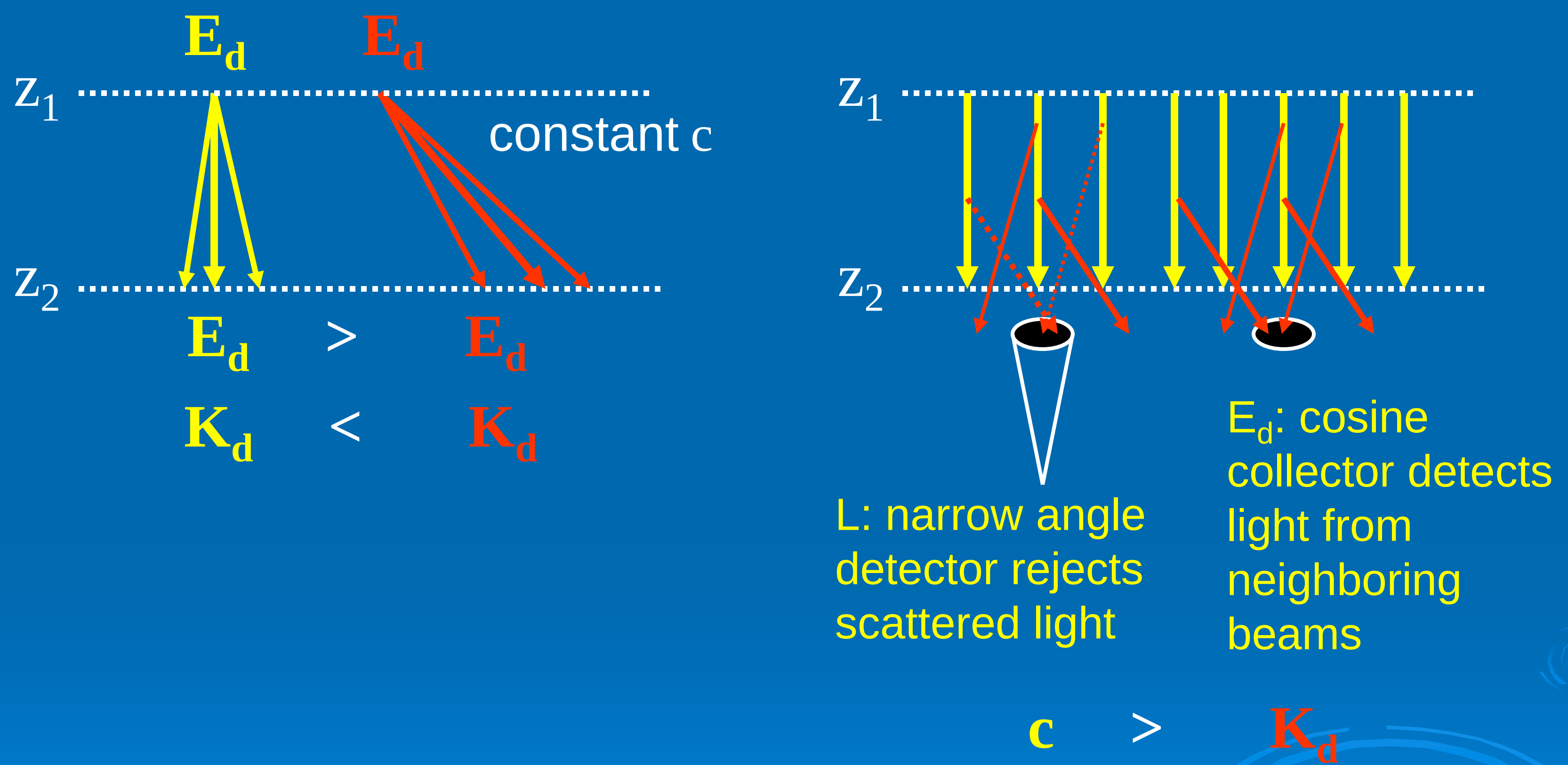


Fig. 2. An example of calculated irradiance relative to the irradiance just above the sea surface. The absorption coefficient is 0.07 m^{-1} and the scattering coefficient is 0.39 m^{-1}; the wave surface is wavelength L=[1.1 0.55 0.05] m and amplitude A= [0.05 0.01 0.0008]m. The beam is 0.8 m wide and enters vertically. Fig.3a shows the beam entering near the trough of a wave, generating a divergent beam. On Fig.3b the light enters near the crest of a wave, generating a convergent beam with a focal area.

wave focusing, from Zaneveld et al, 2001, Optics Express

Beam attenuation $c \neq$ diffuse attenuation K



Virtues and Vices of K's

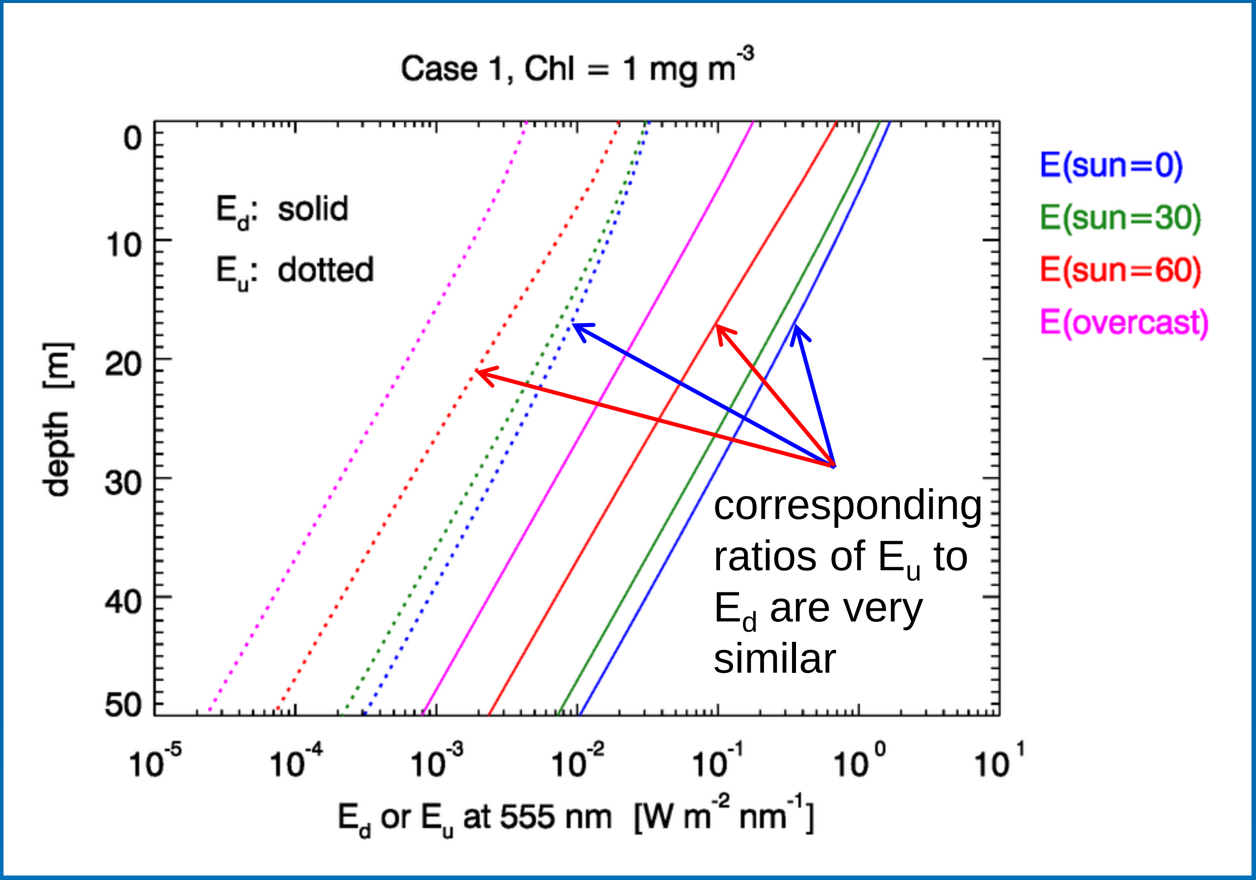
Virtues:

- K's are defined as rates of change with depth, so don't need absolutely calibrated instruments
- K_d is very strongly influenced by absorption, so correlates with chlorophyll concentration (in Case 1 water)
- about 90% of water-leaving radiance comes from a depth of $1/K_d$ (called the penetration depth by Gordon)
- radiative transfer theory provides connections between K's and IOPs and other AOPs (recall Gershun's equation: $a = K_{net}\,\mu$)

Vices:

- not constant with depth, even in homogeneous water
- greatest variation is near the surface
- difficult to compute derivatives with noisy data

E_d and E_u



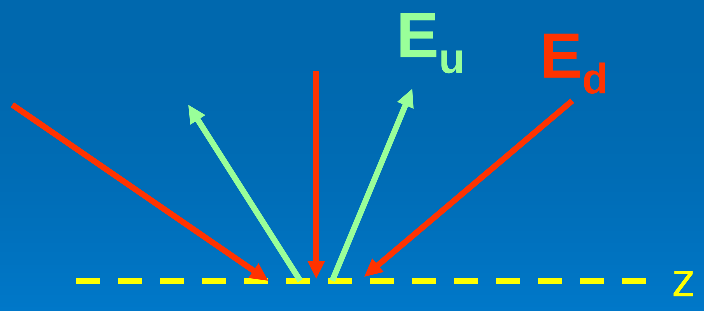
Magnitude changes are due to incident lighting (sun angle and sky condition); ratio of E_u/E_d is determined by water IOPs.

This suggests trying...

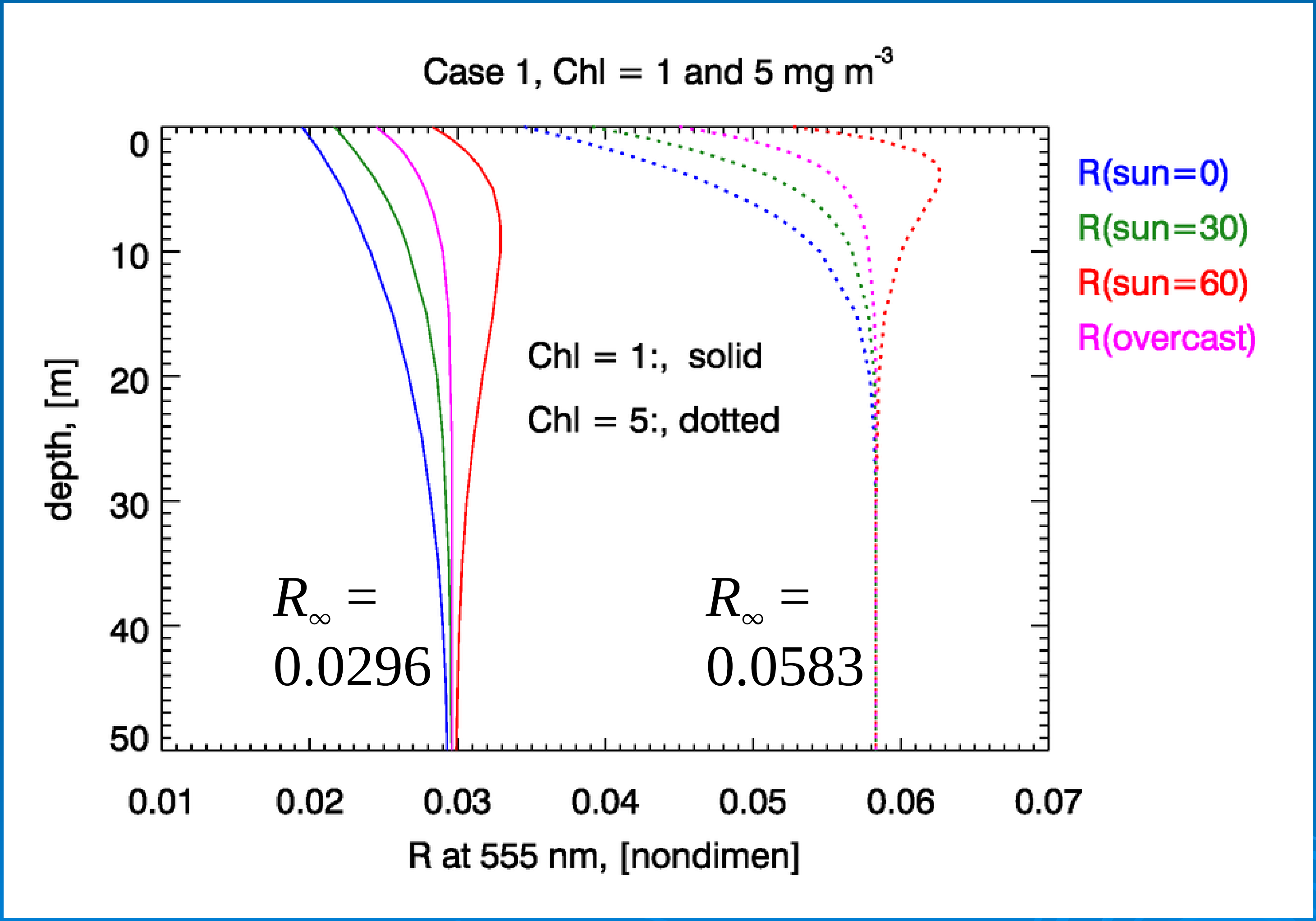
…the ratio of upwelling plane irradiance E_u to downwelling plane irradiance E_d as an AOP.

This is the irradiance reflectance *R*:

$$R(z,\lambda) \equiv \frac{E_u(z,\lambda)}{E_d(z,\lambda)}$$



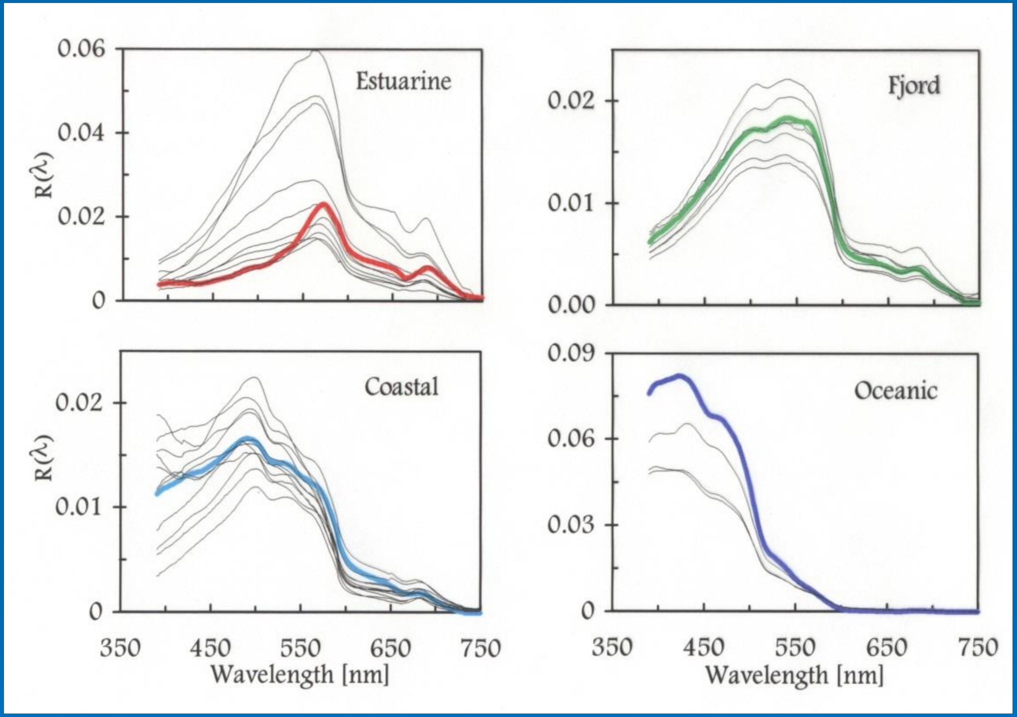
$R = E_u/E_d$



For given IOPs, the *R*'s all approach the same value as you go deeper: the asymptotic reflectance, R_∞, which is an IOP.

Examples of $R = E_u/E_d$

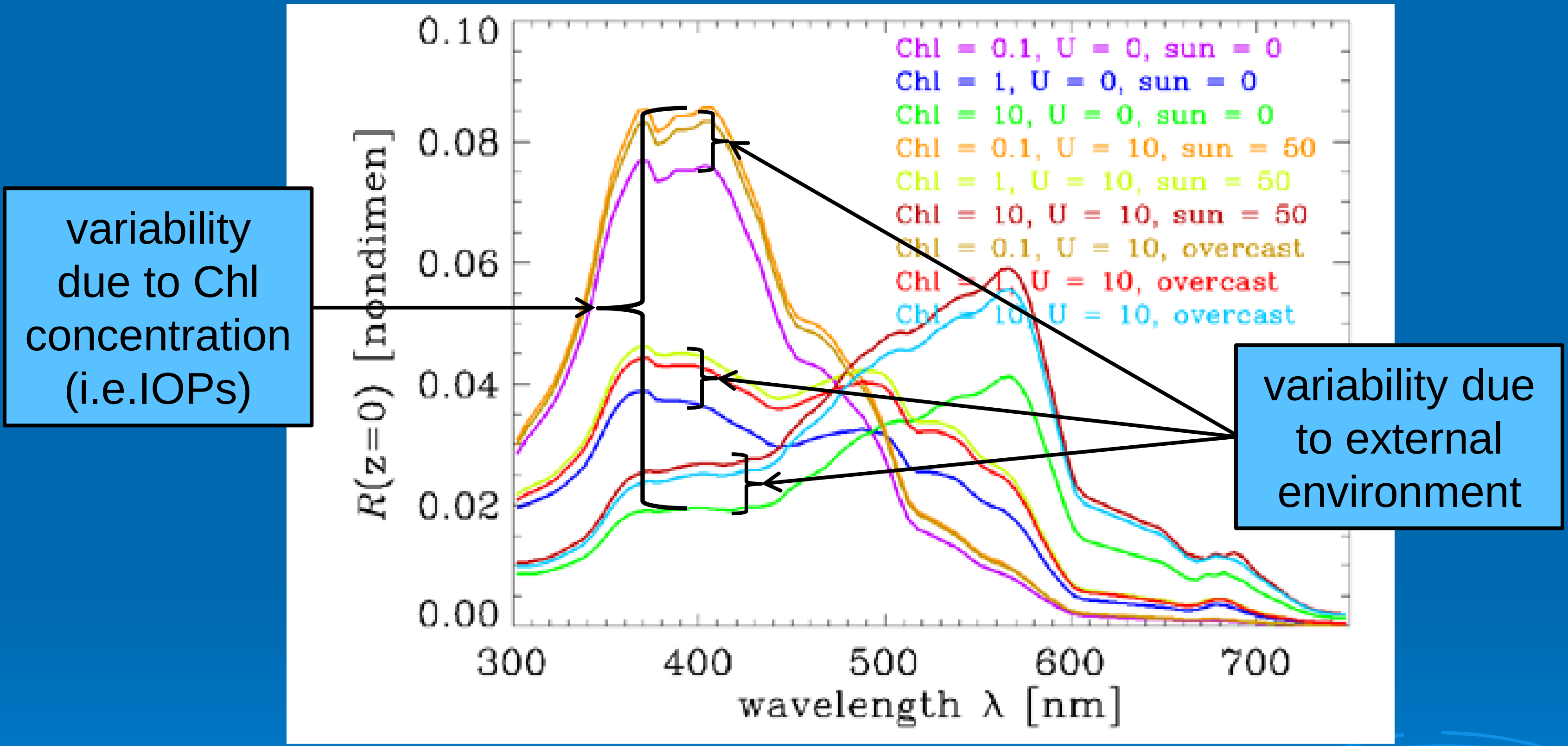
measurements from various ocean waters



Roesler and Perry 1995

$R = E_u/E_d$

HydroLight runs: Chl = 0.1,1, 10 mg/m^3
Sun at 0 and 50 deg in clear sky, and overcast

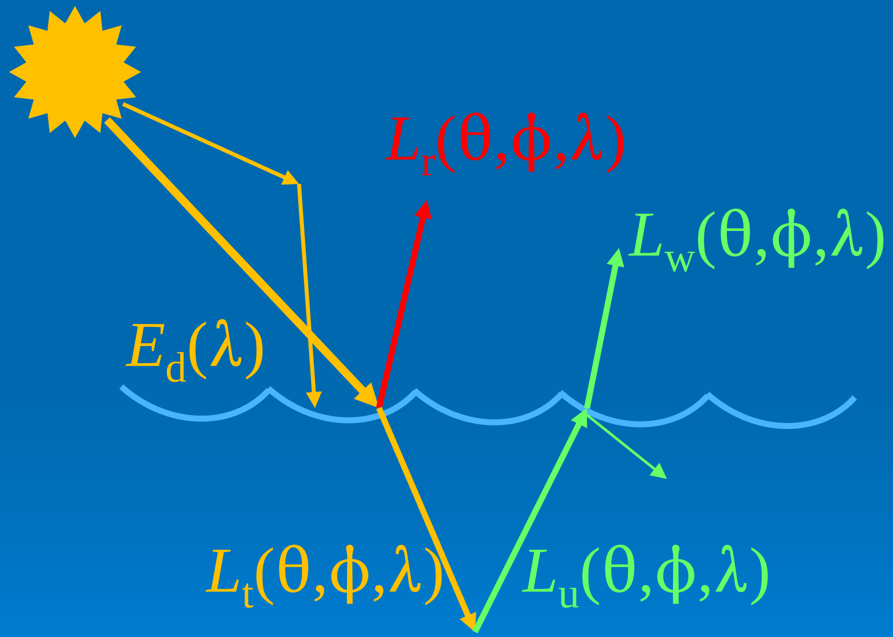


R depends weakly on the external environment and strongly on the water IOPs

Water-leaving Radiance, L_w

total upwelling radiance in air (above the surface) =
water-leaving radiance + surface-reflected radiance

$$L_u(\theta,\phi,\lambda) = L_w(\theta,\phi,\lambda) + L_r(\theta,\phi,\lambda)$$



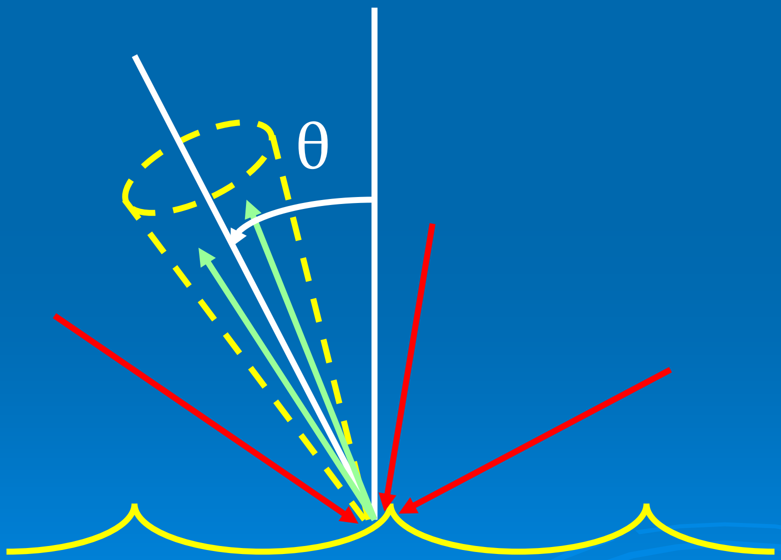
An instrument measures L_u (in air), but L_w is what tells us what is going on in the water. It isn't easy to figure out how much of L_u is due to L_w.

Remote-sensing Reflectance R_{rs}

$R_{rs}(\theta,\varphi,\lambda)$ =

$$\frac{\text{upwelling water-leaving radiance}}{\text{downwelling plane irradiance}}$$

$$R_{rs}(\text{in air}, \theta, \varphi, \lambda) \equiv \frac{L_w(\text{in air}, \theta, \varphi, \lambda)}{E_d(\text{in air}, \lambda)} \qquad [\text{sr}^{-1}]$$



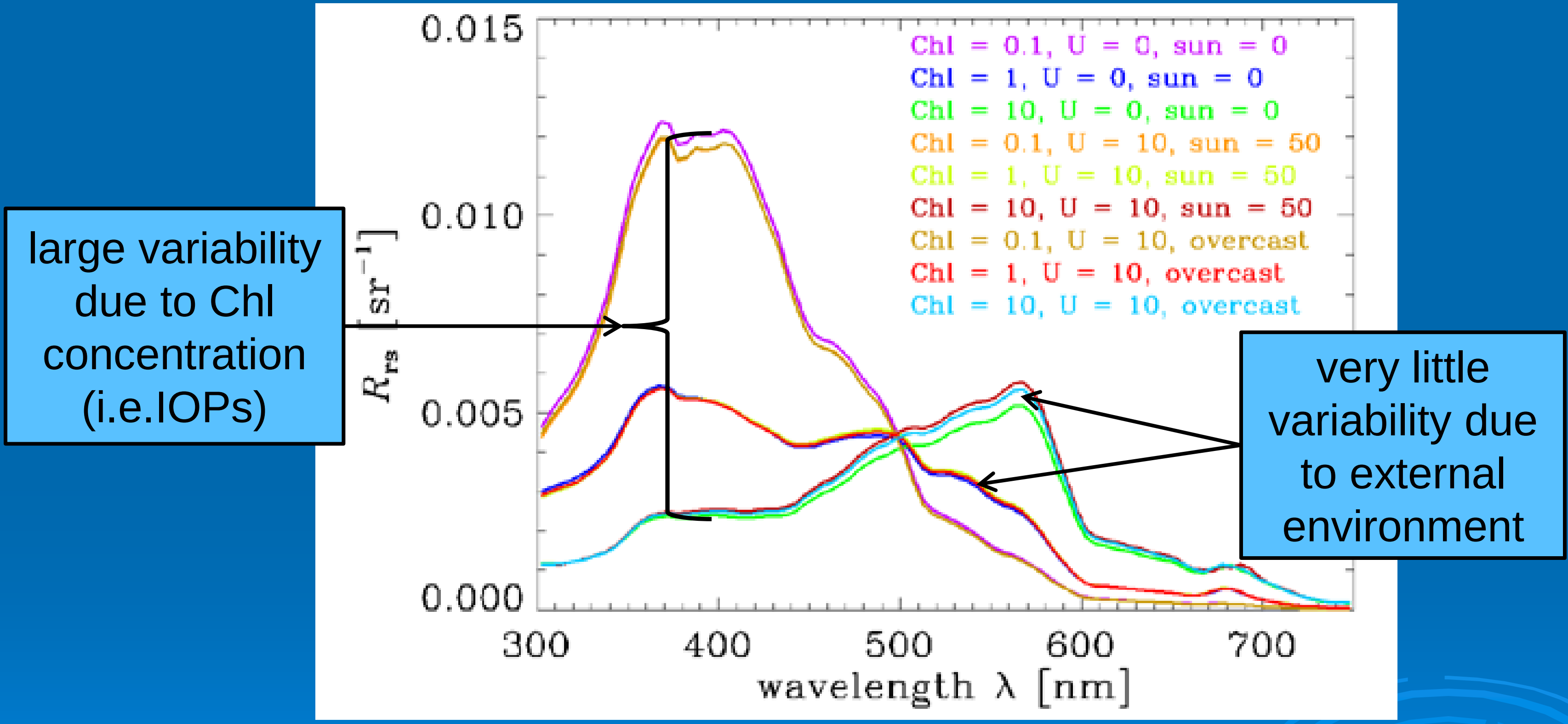
The fundamental quantity used in ocean color remote sensing

Usually work with a nondimensional version of the nadir-viewing R_{rs}, i.e.,with the radiance that is heading straight up from the sea surface (θ = 0)

sea surface

Example R_{rs}

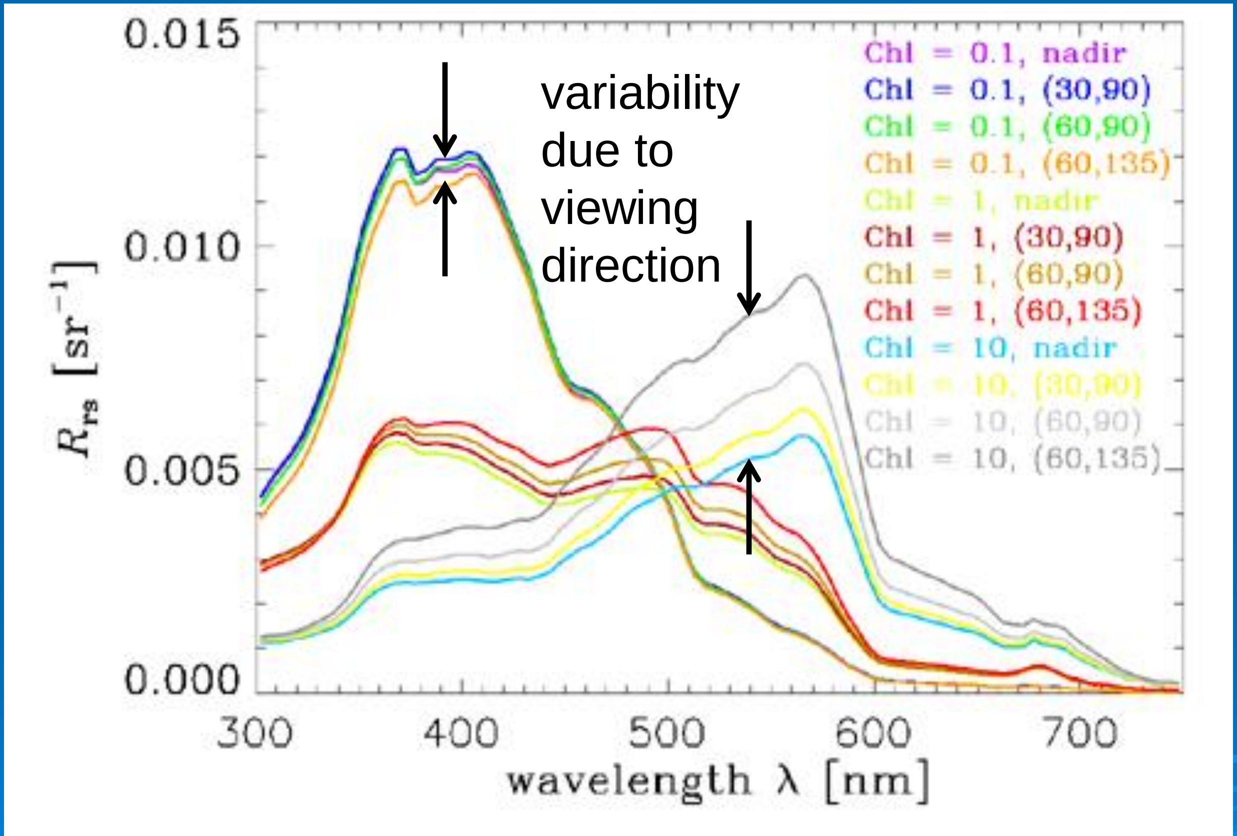
HydroLight runs: Chl = 0.1,1, 10 mg Chl/m^3
Sun at 0 and 50 deg in clear sky, overcast sky



R_{rs} shows almost no dependence on sky conditions and strong dependence on the water IOPs—a very good AOP

Example R_{rs}

HydroLight runs: Chl = 0.1,1, 10 mg Chl/m^3
Sun at 50 deg in clear sky
R_{rs} for nadir vs off-nadir viewing directions



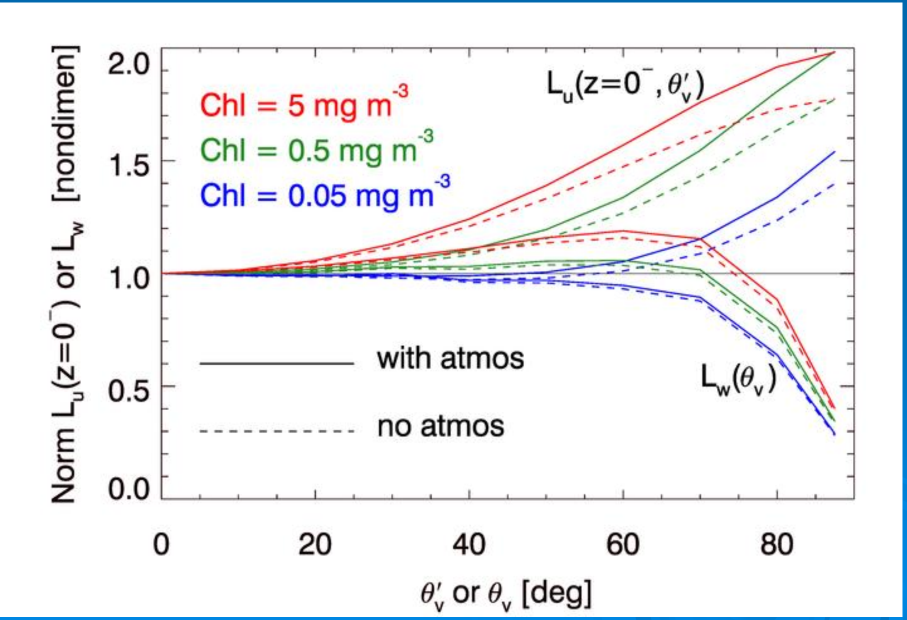
R_{rs} shows dependence on viewing direction but stronger dependence on the water IOPs—still a good AOP, but could be better…

Normalized Reflectance $[\rho]_N$

R_{rs} shows some variability with external environmental conditions and viewing direction. It would be nice to remove those effects.

The *normalized water-leaving radiance* is the water-leaving "*radiance that would be measured by a nadir-viewing instrument, if the Sun were at the zenith in the absence of any atmospheric loss, and when the Earth is at its mean distance from the Sun.*" (Morel et al., 1996, page 4852).

(Note: "absence of any atmospheric loss", not "absence of any atmosphere")



Differences in $L_u(z=0)$ and L_w for the sun at the zenith in a clear sky (typical marine atmosphere) vs no atmosphere (black sky)

Normalized Reflectance $[\rho]_N$

Let $L_w(\theta_s, \theta_v, \phi)$ be the water-leaving radiance for a given sun zenith angle and viewing direction. Then the "normalized water-leaving radiance" is

$$[L_w(\theta_v, \phi)]_N \equiv \left(\frac{R}{R_o}\right)^2 \frac{L_w(\theta_s, \theta_v, \phi)}{\cos\theta_s \, t(\theta_s)}$$

R = Earth-Sun distance at the time of the measurement
R_o = mean Earth-Sun distance
θ_s = solar zenith angle
$t(\theta_s)$ = the atmospheric diffuse transmittance of solar irradiance for the atmosphere at the time and location of the measurement. $t(\theta_s)$ is computed as part of the atmospheric correction process (precomputed look-up tables for a range of sun zenith angles and atmospheric conditions).

$[L_w(\theta_v, \phi)]_N$ still depends on viewing direction. Morel called this directional dependence the "BRDf effect."

Normalized Reflectance $[\rho]_N$

Morel et al. (2002) developed correction factors that account for surface roughness and the BRDF effect of atmospheric conditions, water IOPs, and sun and viewing direction:

$$[L_w]_N^{ex} \equiv [L_w(\theta_v, \phi)]_N \underbrace{\frac{\Re_o(W)}{\Re(\theta_v', W)} \frac{f_o(\mathrm{ATM}, W, \mathrm{IOP})}{Q_o(\mathrm{ATM}, W, \mathrm{IOP})} \left[\frac{f(\theta_s, \mathrm{ATM}, W, \mathrm{IOP})}{Q(\theta_s, \theta_v', \phi, \mathrm{ATM}, W, \mathrm{IOP})} \right]^{-1}}$$

Tabulated factors that depend on atmospheric conditions (ATM), wind speed (W), water IOPs (Chl conc), sun and viewing directions.

$$[\rho_w]_N^{ex} \equiv \frac{\pi}{F_o}[L_w]_N^{ex}$$

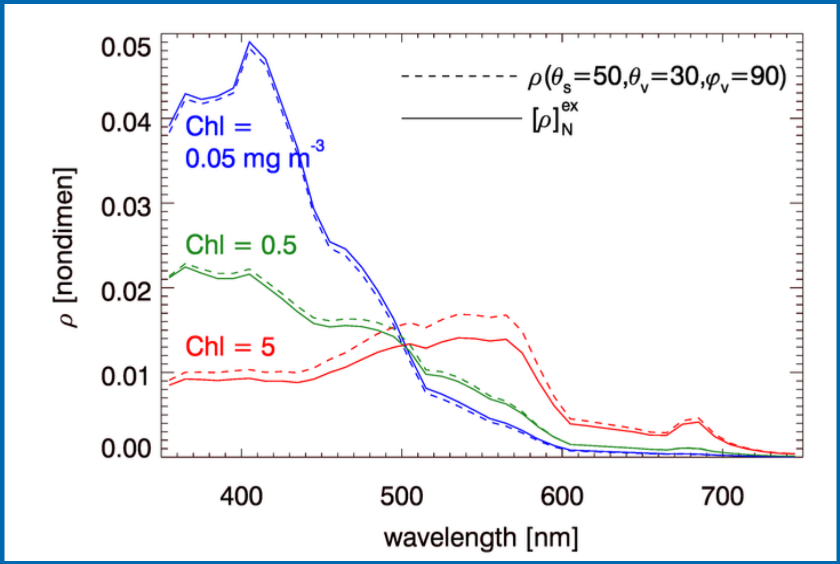
is the nondimensional "*exact normalized water-leaving reflectance*". F_o is the extra-terrestrial solar irradiance at the mean Earth-Sun distance.

Note: (1) Everything here depends on wavelength.
(2) The Morel BRDF correction factors were developed using a Case 1 IOP model, so they may not give good results for Case 2 water.
(3) The correction factors require knowing the Chl concentration.
(4) The BRDF correction factors are tabulated only for certain wavelengths as needed for SeaWiFS, MODIS, VIIRS.

Normalized Reflectance $[\rho]_N$

$[\rho_w]_N^{ex}$ is now the standard AOP used for comparisons of measured and remotely sensed reflectances.

$$R_{rs}(\mathrm{NASA}) = \frac{[\rho_w]_N^{ex}}{\pi} = \frac{[L_w]_N^{ex}}{F_o}$$



Comparison of unnormalized and exact normalized reflectances

To compute $[\rho_w]_N^{ex}$ in HydroLight, put the sun at the zenith; then π times the nadir-viewing R_{rs} is $[\rho_w]_N^{ex}$:

$$[\rho_w]_N^{ex} = \pi R_{rs}(\mathrm{HydroLight}; \theta_s = 0, \theta_v = 0)$$

Note: HydroLight works for any IOPs, so HydroLight can give you $[\rho_w]_N^{ex}$ for any IOPs, any bottom conditions, or any wavelength

See the Ocean Optics Web Book page on Normalized Reflectance for a full discussion of $[\rho_w]_N^{ex}$

Average or Mean Cosines

The average or mean cosines give the average of the cosθ for all of the photons making up the radiance distribution. This tells you something about the directional pattern of the radiance. For the downwelling radiance we have

$$\bar{\mu}_d = \frac{\int_0^{2\pi} \int_0^{\pi/2} L(\theta,\phi) \cos\theta \sin\theta \, d\theta \, d\phi}{\int_0^{2\pi} \int_0^{\pi/2} L(\theta,\phi) \sin\theta \, d\theta \, d\phi} = \frac{E_d}{E_{od}}$$

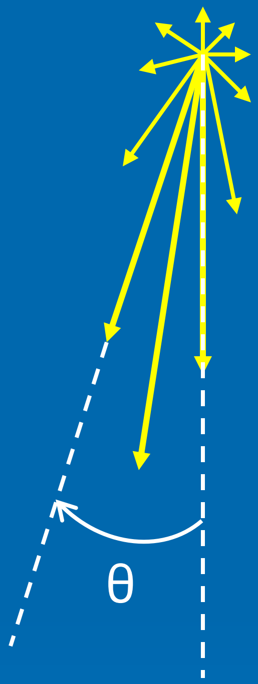
Likewise, for the upwelling radiance, $\bar{\mu}_u = E_u / E_{ou}$

For the entire radiance distribution,

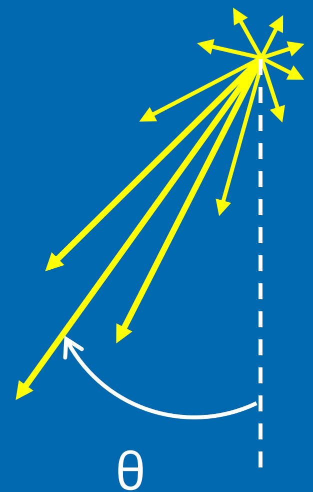
$$\bar{\mu} = \frac{\int_0^{2\pi} \int_0^{\pi} L(\theta,\phi) \cos\theta \sin\theta \, d\theta \, d\phi}{\int_0^{2\pi} \int_0^{\pi} L(\theta,\phi) \sin\theta \, d\theta \, d\phi} = \frac{E_d - E_u}{E_o}$$

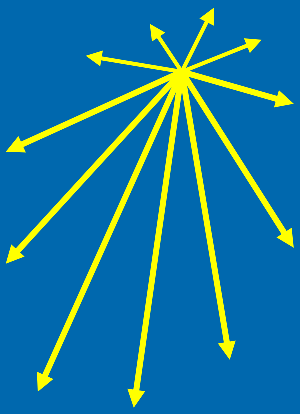
Note: $E_o = E_{od} + E_{ou}$, but $\bar{\mu} \neq \bar{\mu}_d + \bar{\mu}_u$

Mean Cosines

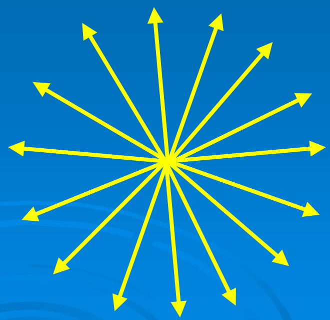


most photons heading
almost straight down:
small average θ, large μ_d



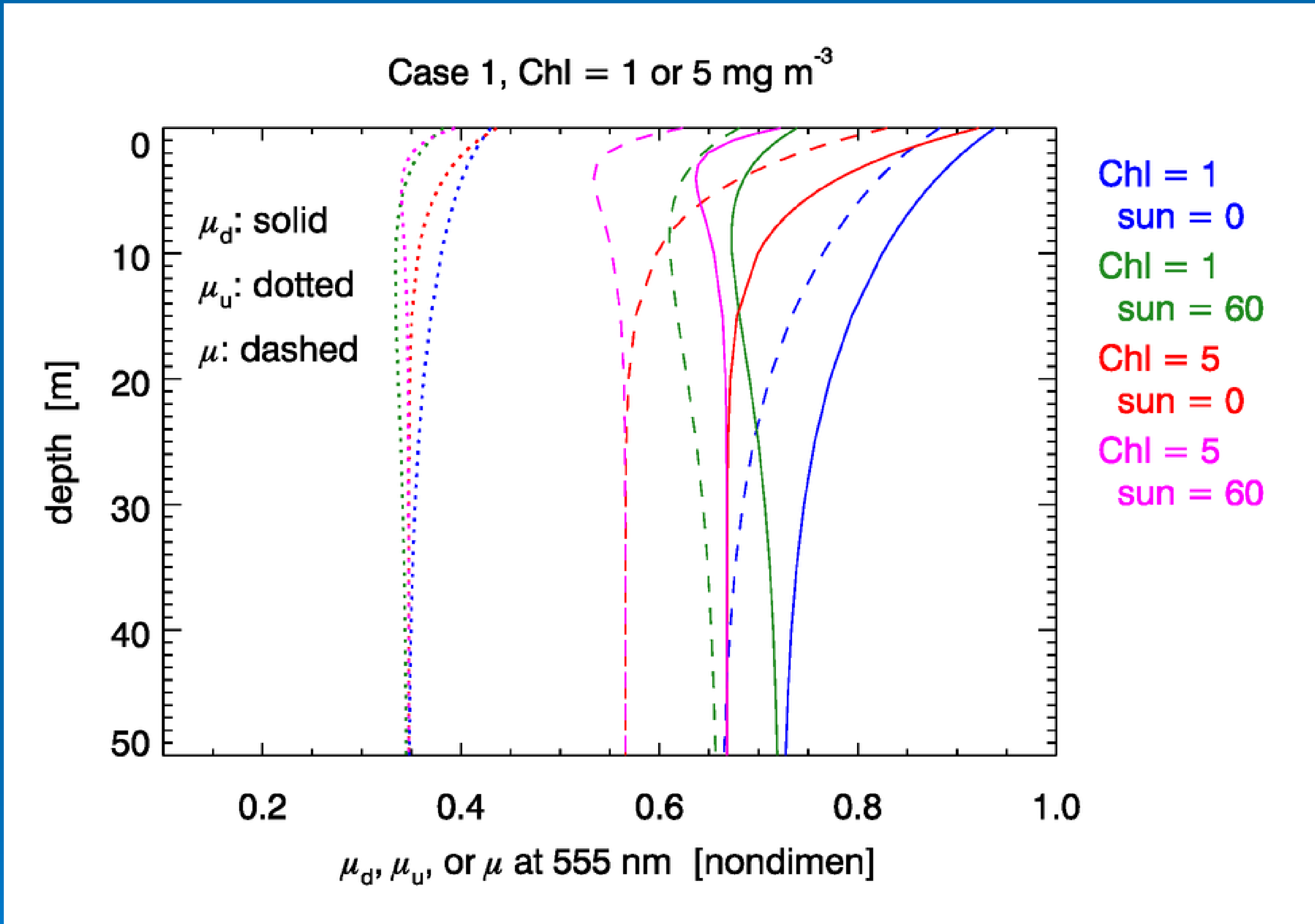


most photons heading at a large angle, or a
diffuse radiance: large average θ, small μ_d



isotropic radiance:
$\mu_d = \mu_u = 0.5$
$\mu = 0$

Mean Cosines



values at 555 nm:

Albedo of single scattering ω_o = b/c:

ω_o(Chl=1) = 0.85
ω_o(Chl=5) = 0.93

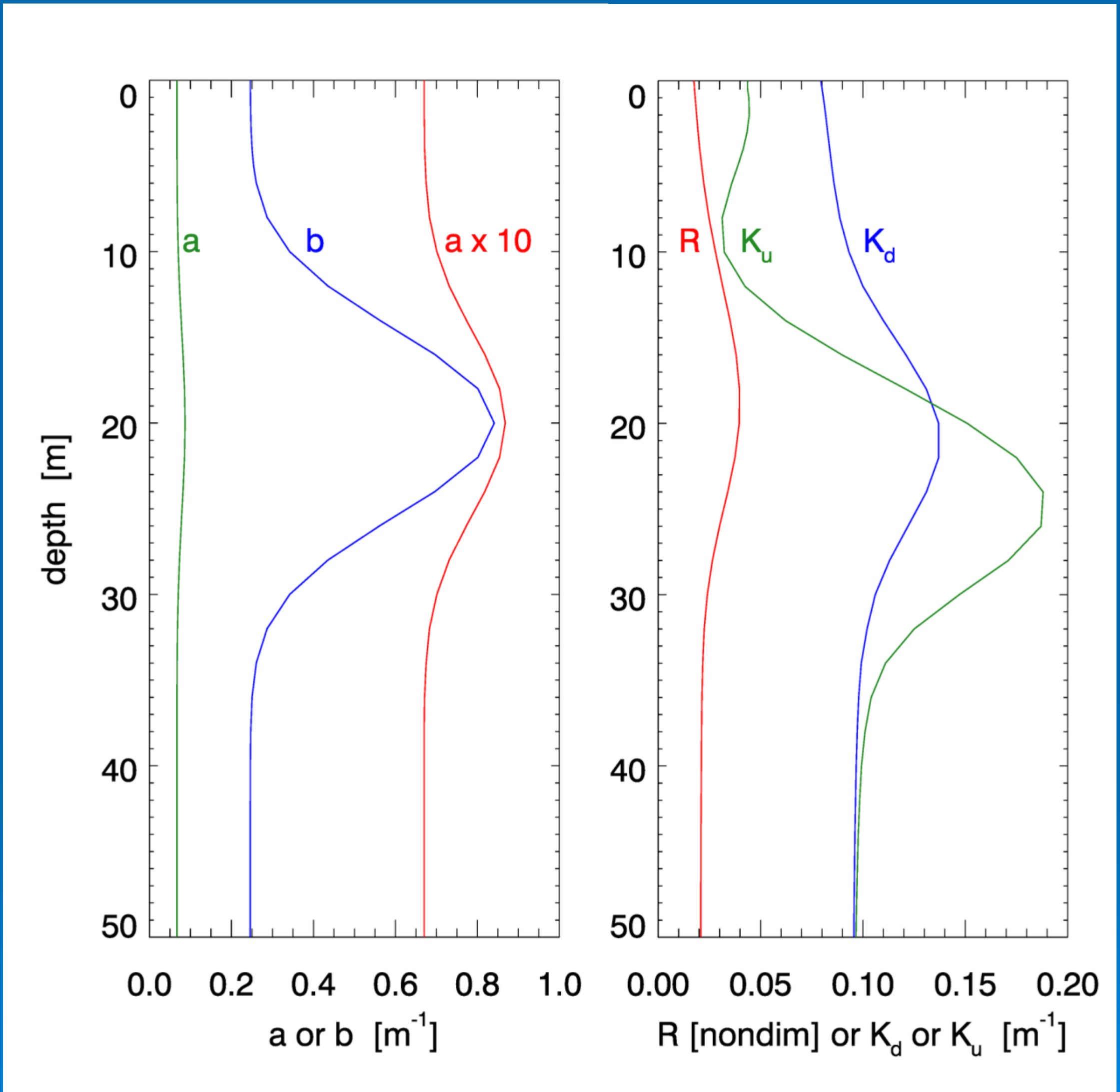
Asymptotic values:

Chl = 1:
$\mu_d(\infty) = 0.7222$
$\mu_u(\infty) = 0.3436$
$\mu(\infty) = 0.6600$

Chl = 5:
$\mu_d(\infty) = 0.6682$
$\mu_u(\infty) = 0.3473$
$\mu(\infty) = 0.5658$

Note: highly scattering water approaches asymptotic values quicker than highly absorbing water.

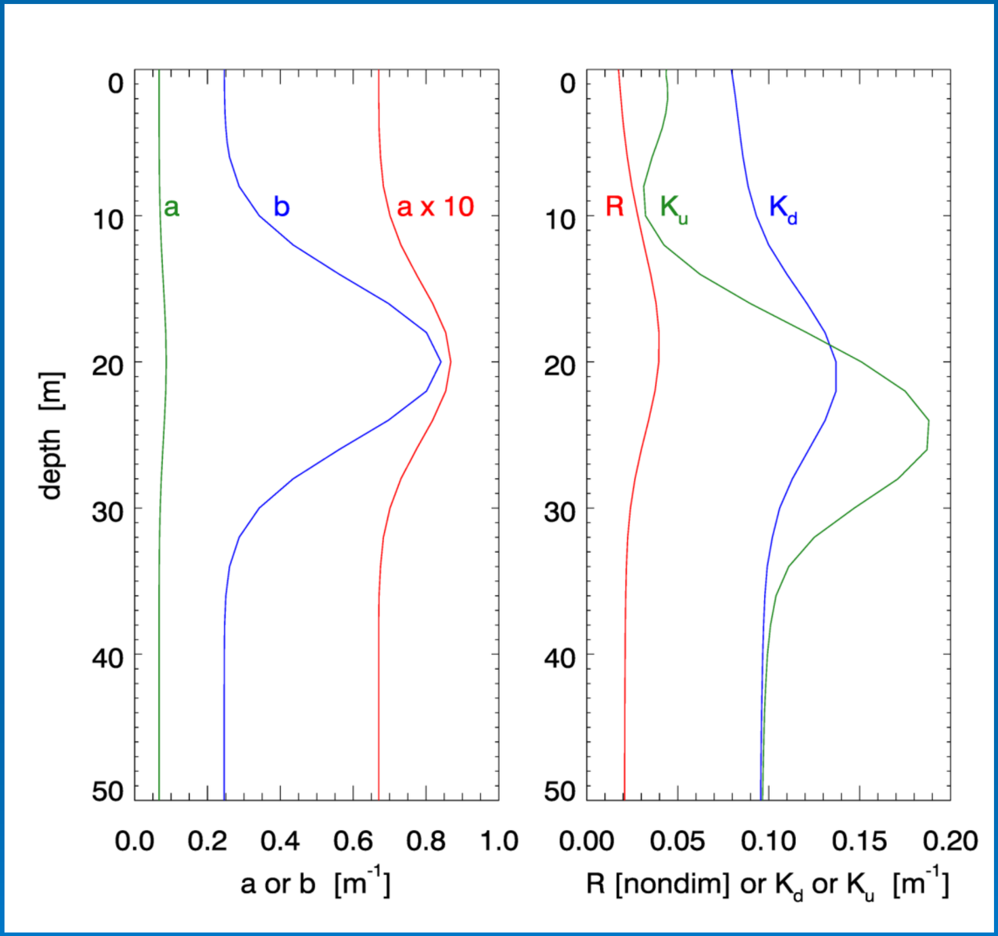
The Real World: Inhomogeneous Water



HydroLight run for Case 1 water with Chl = 0.5 mg/m^3 background and Chl = 2.5 mg/m^3 max at 20 m; sun at 30 deg in a clear sky, etc.

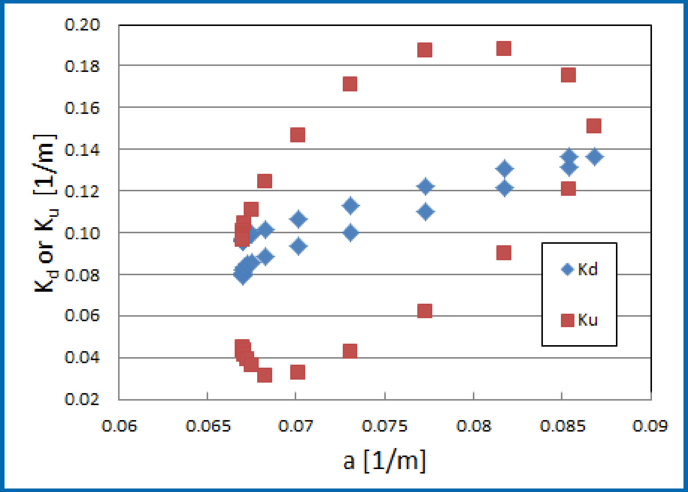
Note how well K_d correlates with the IOPs, but R is less affected. K_u is clearly affected by the IOPs, but in a more complicated way than K_d. Why?

The Real World: Inhomogeneous Water

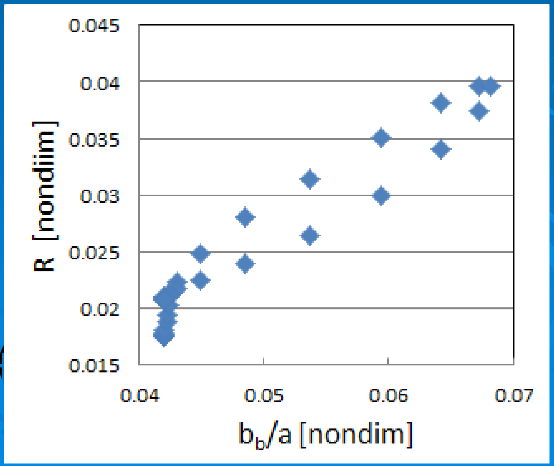


to first order, $K_d \propto a$

K_u is more compliated

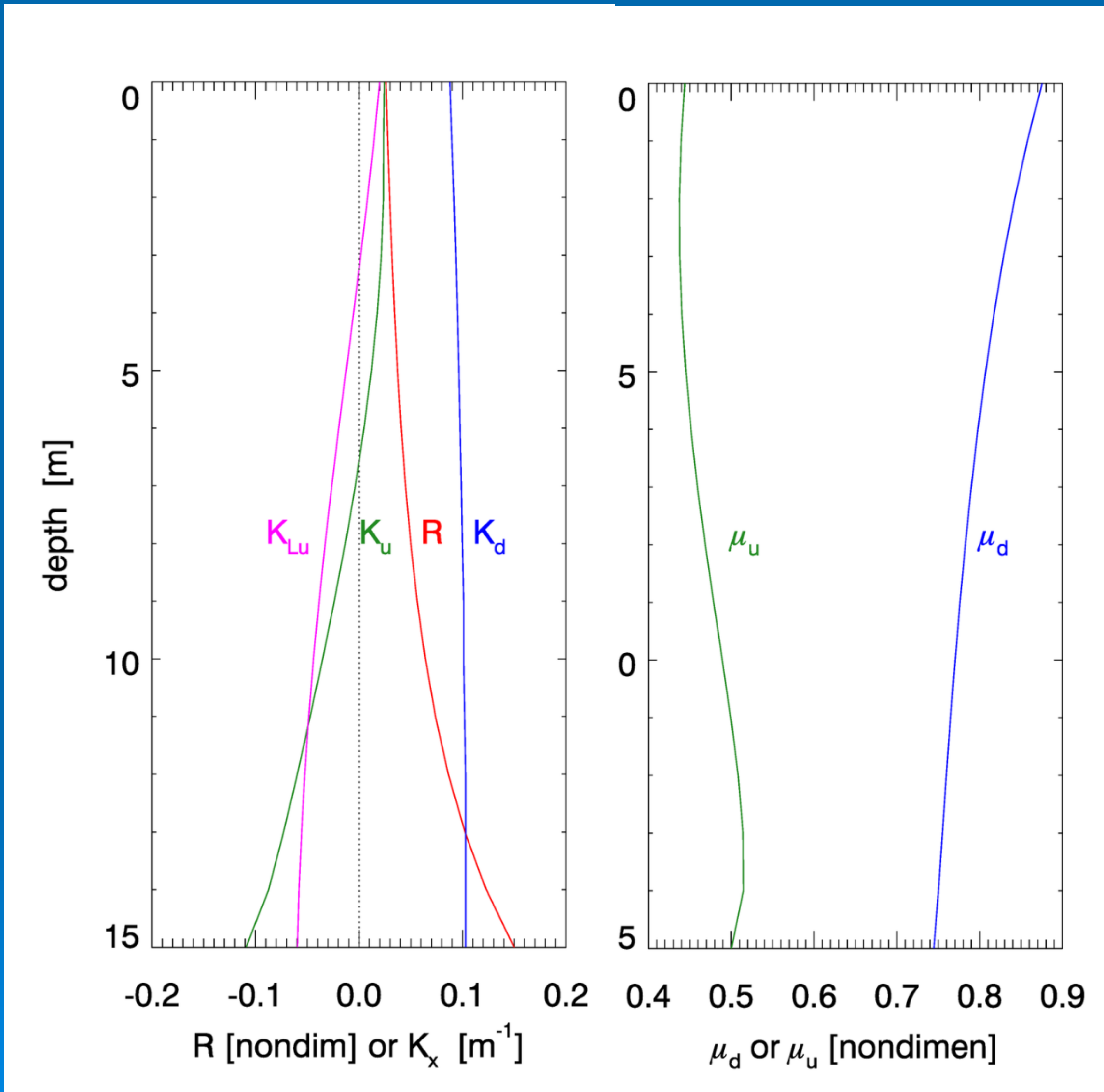


to first order, $R \propto b_b/a$



What would happen to K_d and R if there were a layer of highly scattering but non-absorbing particles in the water?

Explain These AOPs



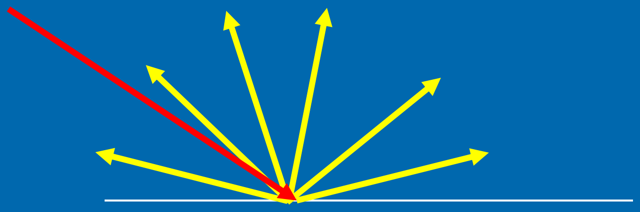
What does it mean for K_u and K_{Lu} to become negative?

What does $\mu_u = 0.5$ say about the upwelling radiance distribution at 15 m?

The Answer

The water was homogeneous (Case 1, Chl = 1 mg/m^3), but there was a Lambertian bottom at 15 m, which had a reflectance of R_b = 0.15

Lambertian means the reflected radiance is the same in all directions
(L_u is isotropic)



Exercise: compute μ_d, μ_u, and μ for an isotropic radiance distribution: $L(\theta,\phi) = L_o$ = a constant

The Bidirectional Reflectance Distribution Function (BRDF)

Recall: The fundamental IOPs, the absorption coeff. and the volume scattering function, tell you everything there is to know about how a volume of matter absorbs and scatters light.

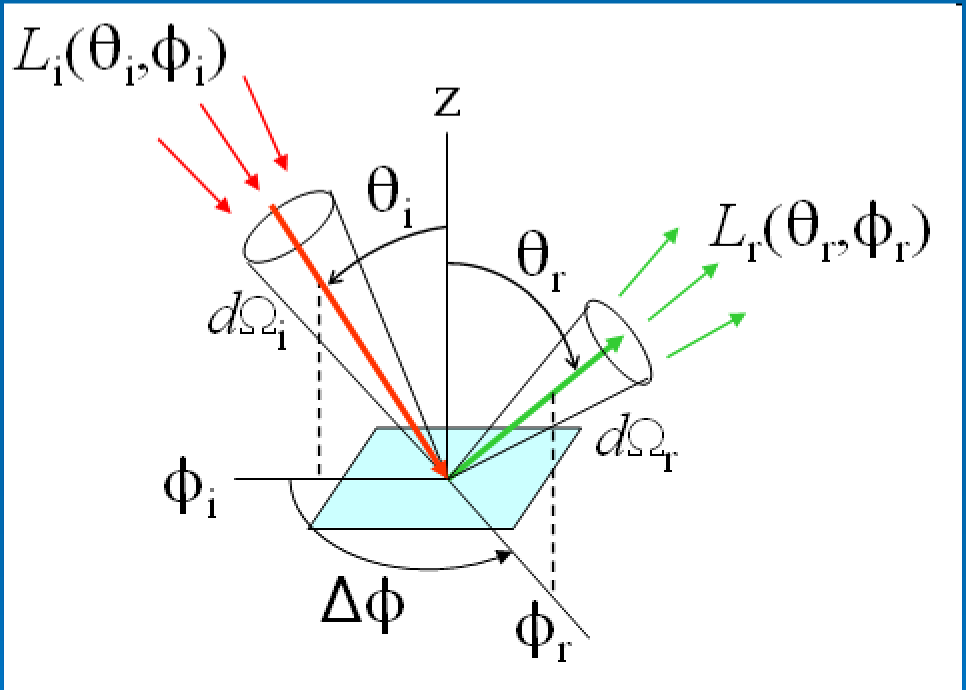
The BRDF is the IOP for surfaces (air-water surface, bottom sediment, a sea grass leaf, etc.)

The VSF describes how a volume scatters radiance from any incident direction into any reflected direction: $\mathrm{VSF}(\theta_i, \varphi_i, \theta_r, \varphi_r, \lambda) = \mathrm{VSF}(\psi, \lambda)$

The BRDF describes how a surface reflects radiance from any incident direction into any reflected direction: $\mathrm{BRDF}(\theta_i, \varphi_i, \theta_r, \varphi_r, \lambda)$

The Bidirectional Reflectance Distribution Function (BRDF)

The geometry of the BRDF(θ_i, φ_i, θ_r, φ_r, λ)



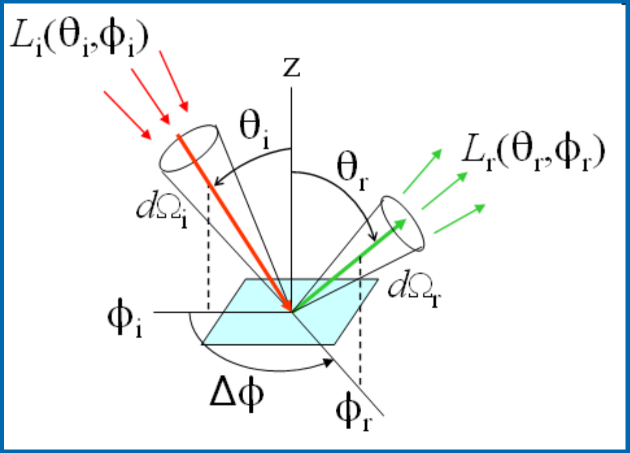
See www.oceanopticsbook.info/view/radiative_transfer_theory/level_2/the_brdf

The Bidirectional Reflectance Distribution Function (BRDF)

How the BRDF is defined:

$$BRDF(\theta_i, \phi_i, \theta_r, \phi_r) \equiv \frac{dL_r(\theta_r, \phi_r)}{L_i(\theta_i, \phi_i)\, \cos\theta_i \, d\Omega_i(\theta_i, \phi_i)}$$

How it's measured: $= \dfrac{L_r(\theta_r, \phi_r)}{E_d(\theta_i, \phi_i)} \qquad [\mathrm{sr}^{-1}]$



How the BRDF is used to compute the radiance reflected into a given direction by radiance incident from all directions (e.g., in HydroLight):

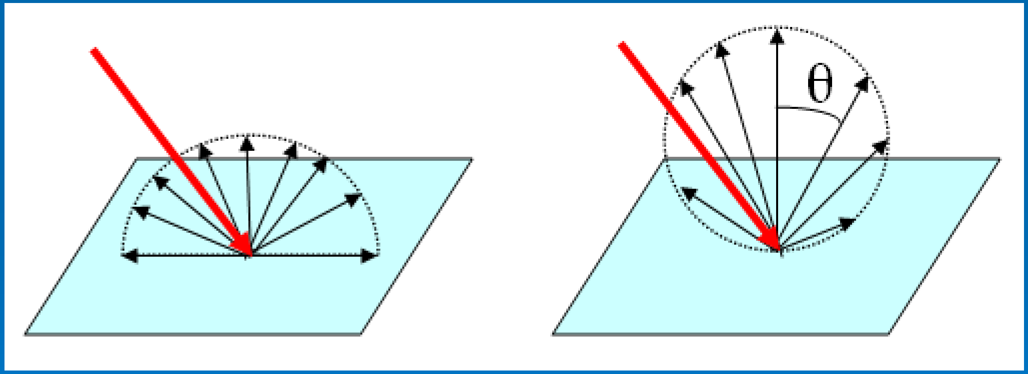
$$\begin{aligned} L_r(\theta_r, \phi_r) &= \int_{2\pi_i} L_i(\theta_i, \phi_i)\, BRDF(\theta_i, \phi_i, \theta_r, \phi_r)\, \cos\theta_i \, d\Omega_i \\ &\equiv \int_{2\pi_i} L_i(\theta_i, \phi_i)\, r(\theta_i, \phi_i, \theta_r, \phi_r)\, d\Omega_i \, . \end{aligned}$$

in L&W

Lambertian BRDFs

You will sometimes see statements like

- A Lambertian surface reflects “light” equally into all directions. Lambertian surfaces are therefore also called isotropic/uniform/perfectly diffuse reflectors.
- A Lambertian surface reflects “light” with a cosine angular distribution. Lambertian surfaces are therefore also called cosine reflectors.



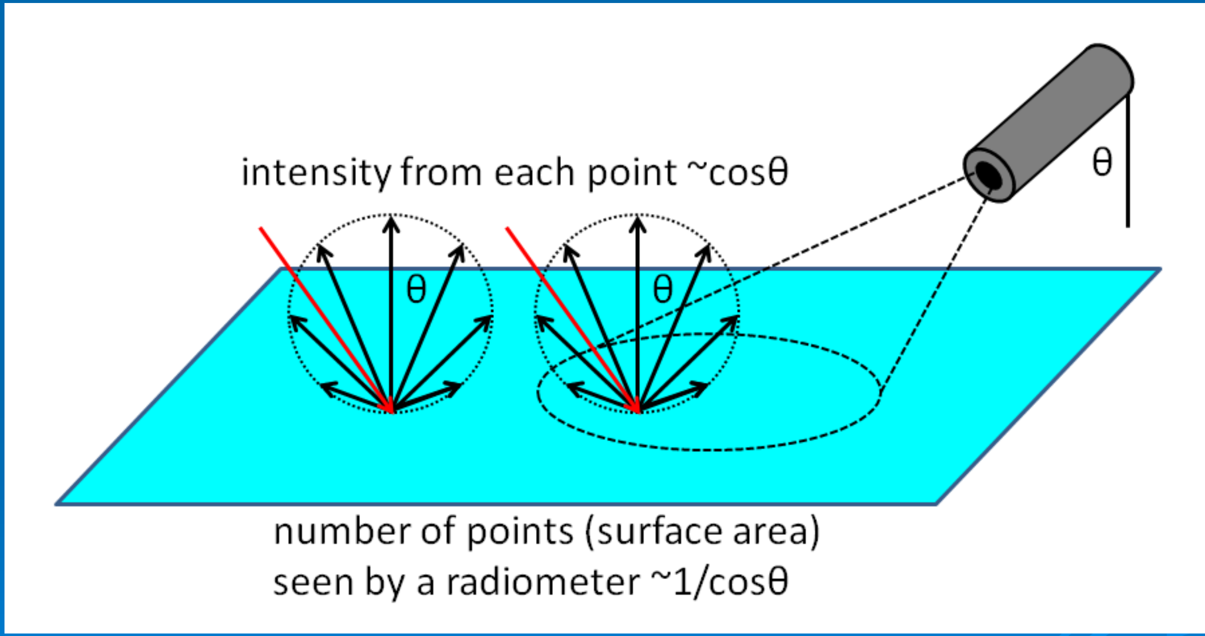
uniform reflectance　　　cosine reflectance

Which definition is correct?

Lambertian BRDFs

The correct statements are

- Each point of a Lambertian surface reflects intensity in a cosine pattern
- A Lambertian surface reflects radiance equally in all directions



See
www.oceanopticsbook.info/view/radiative_transfer_theory/level_2/the_lambertian_brdf

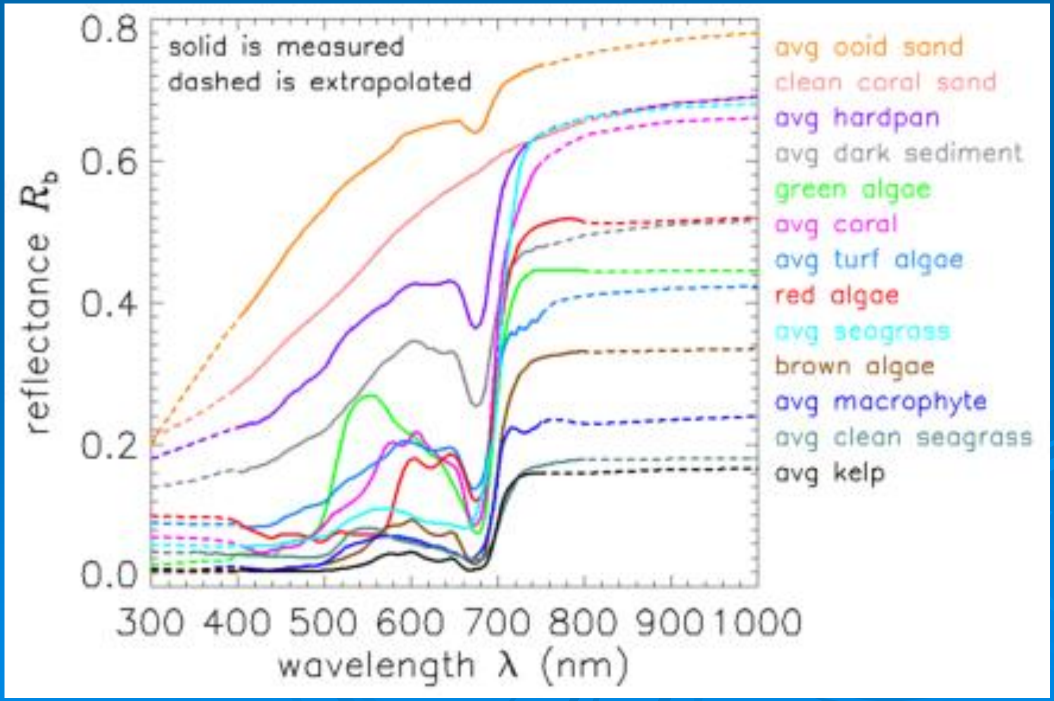
Lambertian BRDFs

The BRDF of a Lambertian reflector is fully specified by its *reflectivity* ρ, which equals the irradiance reflectance $R = E_u / E_d$ (see the web book for the math):

$$\mathrm{BRDF}_{\mathrm{Lamb}}(\theta_i, \varphi_i, \theta_r, \varphi_r, \lambda) = \rho(\lambda)/\pi = R(\lambda)/\pi$$

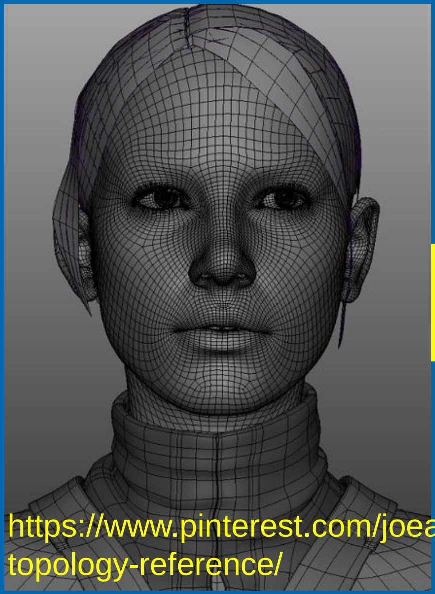
$\rho = 0$ for a "black" surface; $\rho = 1$ for a "white" surface

The default in HydroLight is to specifiy a bottom reflectance (really $\rho = E_u/E_d$), and H then assumes that the bottom is Lambertian.



Q: Who knows more about BRDFs than anyone else?

A: The movie and gaming CGI people



https://www.pinterest.com/joeatilano4/topology-reference/

add BRDFs

https://developer.nvidia.com/gpugems/GPUGems/gpugems_ch03.html

hair and skin: 20 years of research with unlimited funding and unlimited computer power

Wind-speed dependent BRDFs of a water surface

https://support.solidangle.com/pages/viewpage.action?pageId=6455768

Sunrise on Annapurna, 8090 m (10th highest in the world)

Rhino

Chitwan National Park, Nepal

2011