Lecture 1b: Overview of Apparent Optical Properties

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Apparent Optical Properties (AOPs)

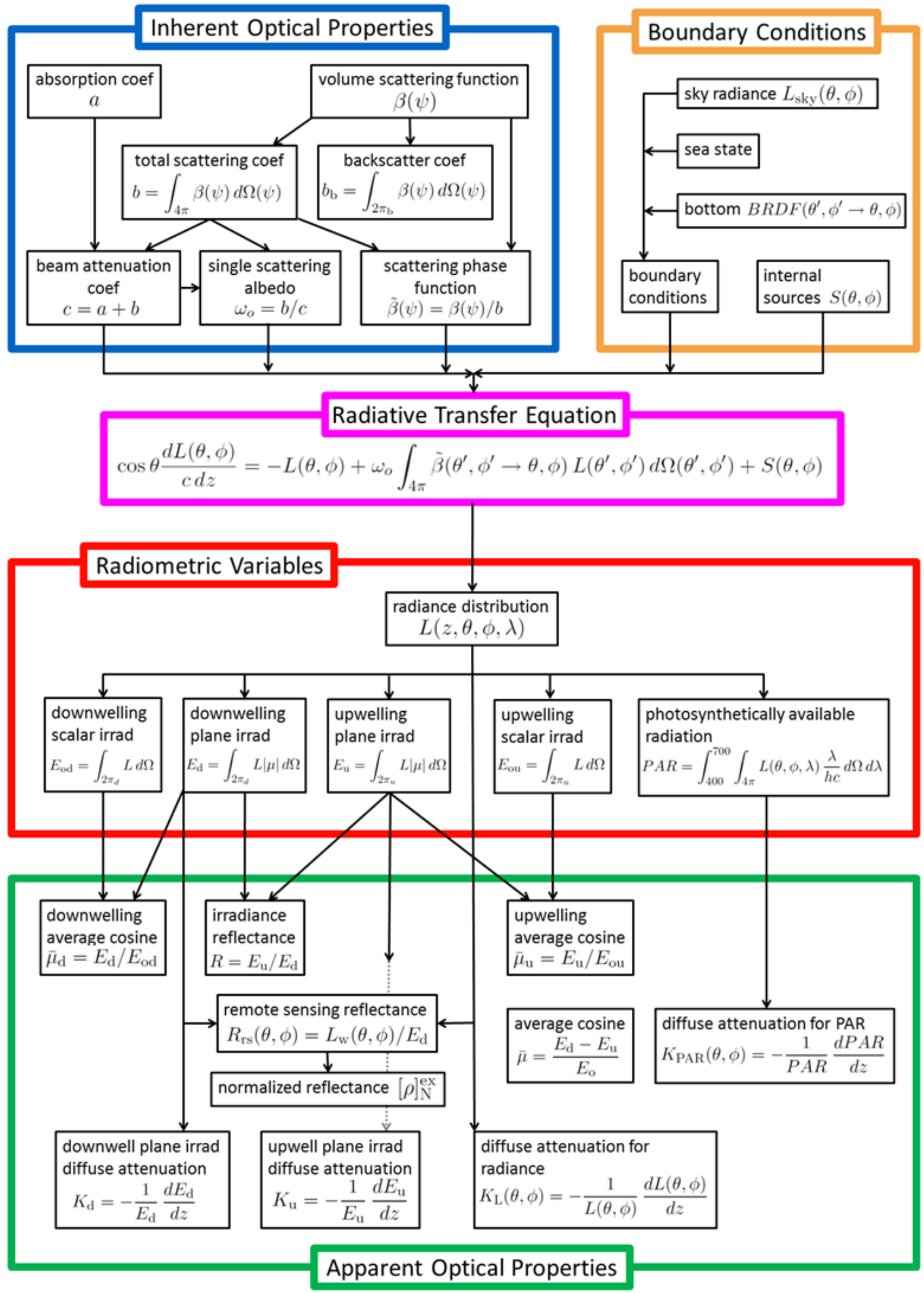
AOPs are quantities that

(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



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 polarization) 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 just irradiances or PAR. Likewise for the VSF vs just b or b_b.

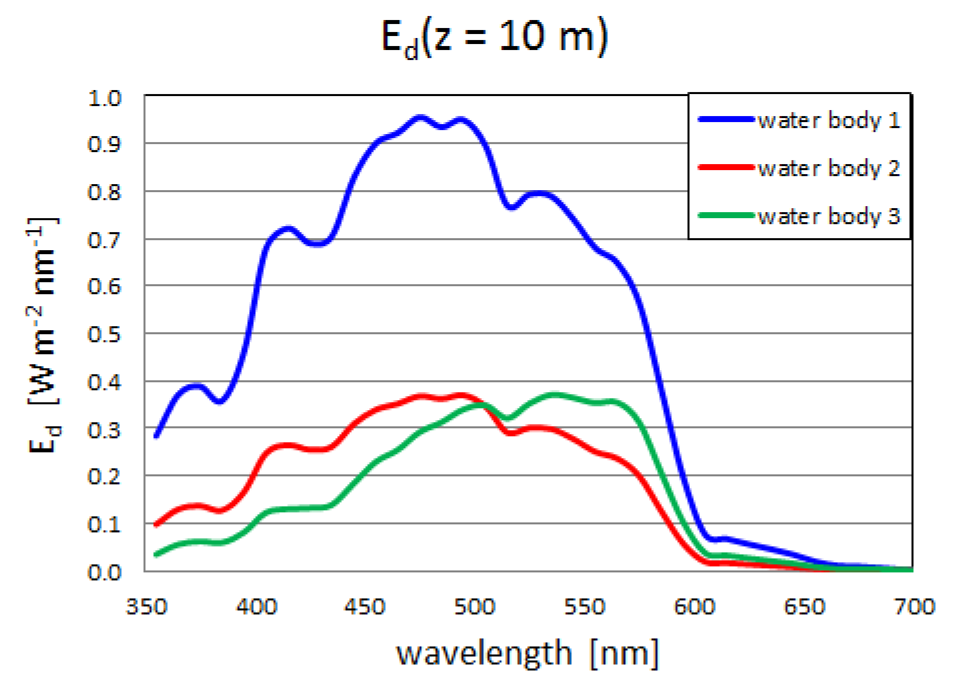
The Origin of AOPs

Need: We would like to know what is going on in the ocean: e.g., what are the concentrations of chlorophyll, CDOM, and minerals; what is on the bottom in shallow water, etc. We can measure these things by analysis of water samples or putting a diver in the water, but that requires a lot of time and money.

Question: Can we find simpler measures of the light field than the radiance that are (1) easily made and (2) are also useful for describing the characteristics of a water body?

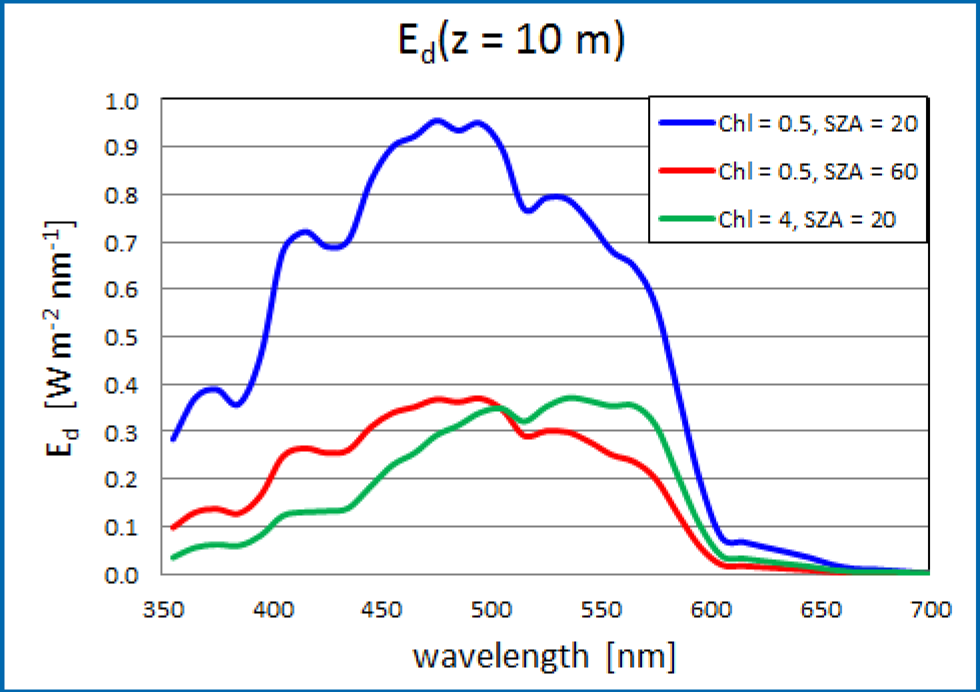
For example, is there a relatively simple optical mesurement from which we can deduce the chlorophyll condentration or bottom depth and type?

Can Radiometric Variables Be Used to Describe a Water Body?



This plots suggests that water bodies 2 and 3 are similar, but water body 1 is much different. Is this correct?

Can Radiometric Variables Be Used to Describe a Water Body?



Really, water bodies 1 (blue) and 2 (red) are identical. The difference in E_d is due to solar zenith angle.

Radiometric variables like E_d are NOT useful descriptors of a water body because they are strongly influenced by external environmental parameters like sun zenith angle, cloud conditions, and surface waves.

Apparent Optical Properties

We want an easily measured optical variable that depends on the water absorption and scattering but is insensitive to external environmental parameters like sun zenith angle, sky condition, or surface waves.

A good AOP depends weakly on the external environment and strongly on the water IOPs.

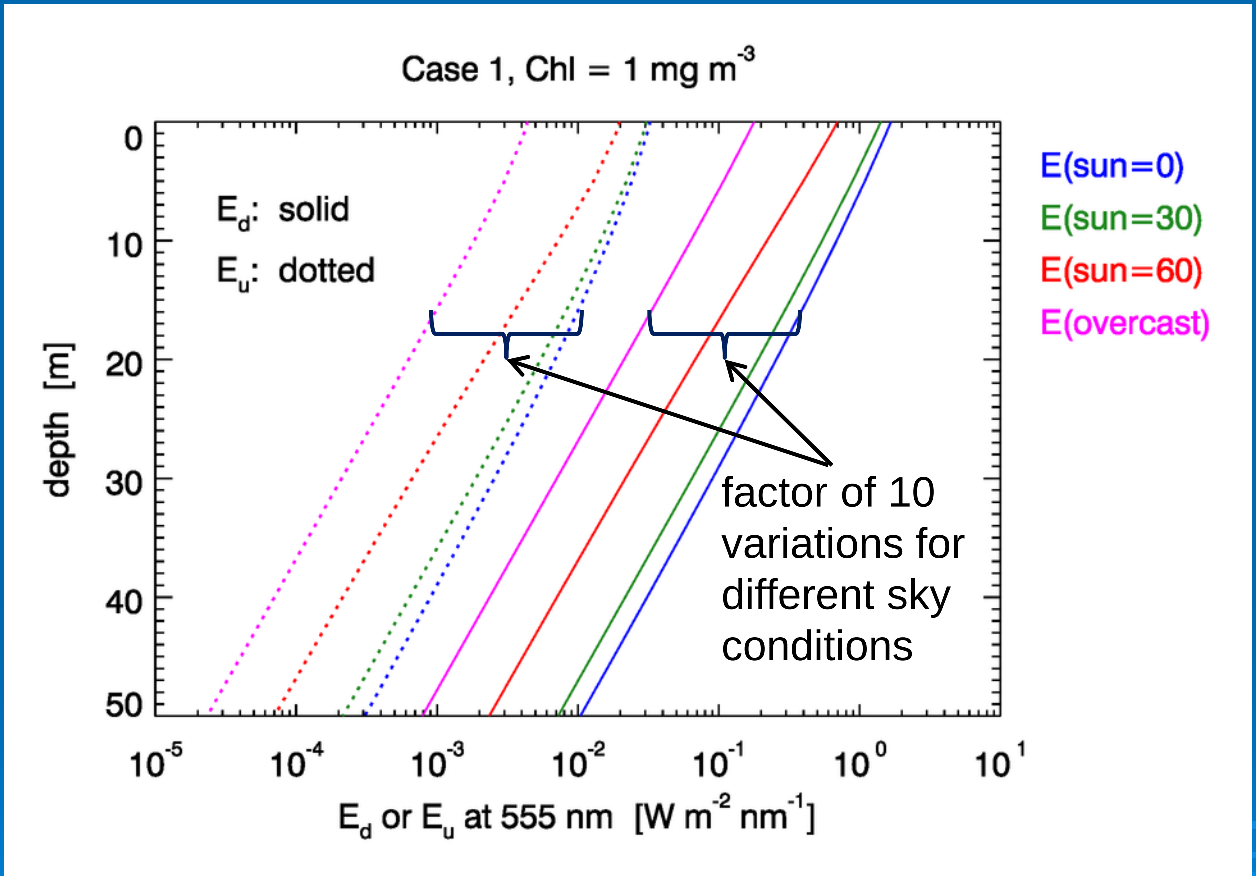
AOPs are usually ratios radiometric variables or depth derivatives of radiometric variables.

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).

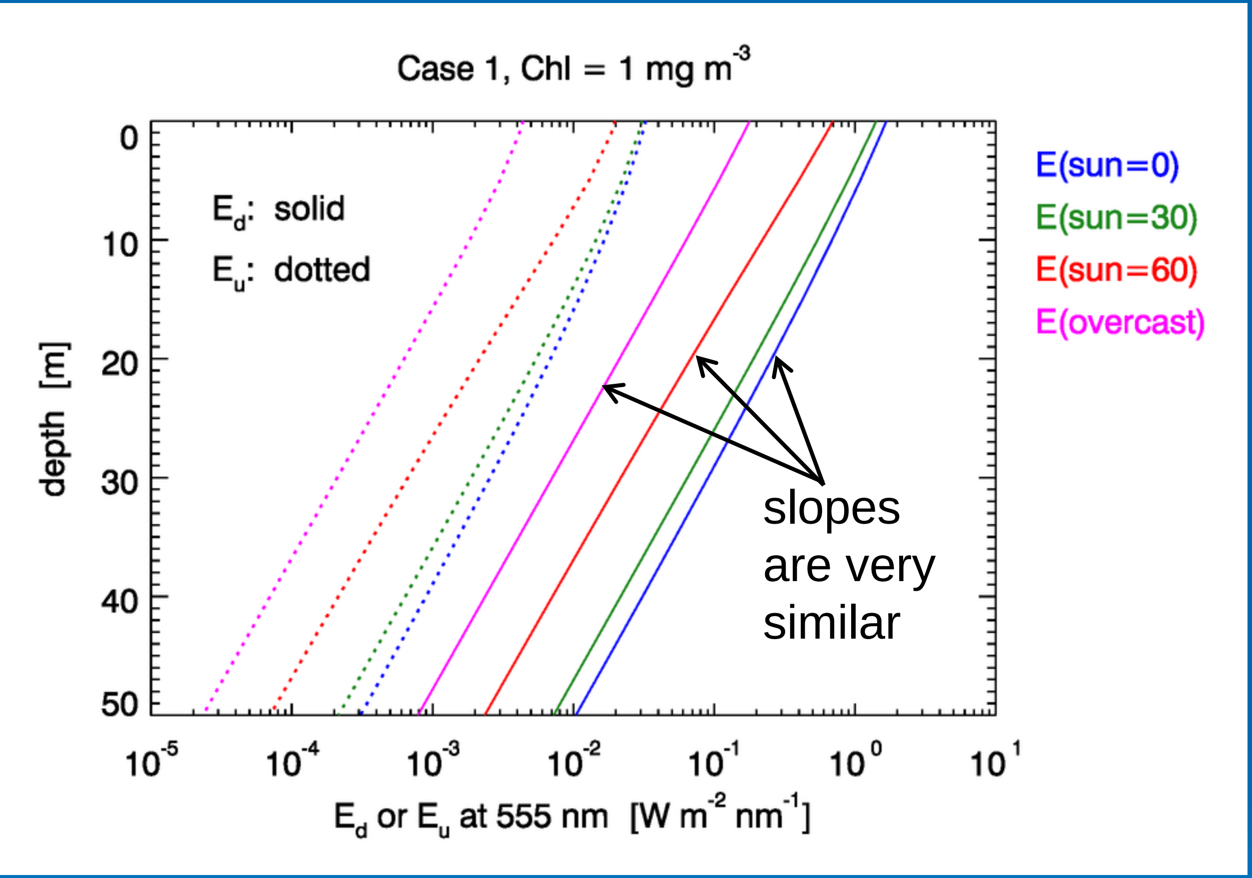
E_d and E_u

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...

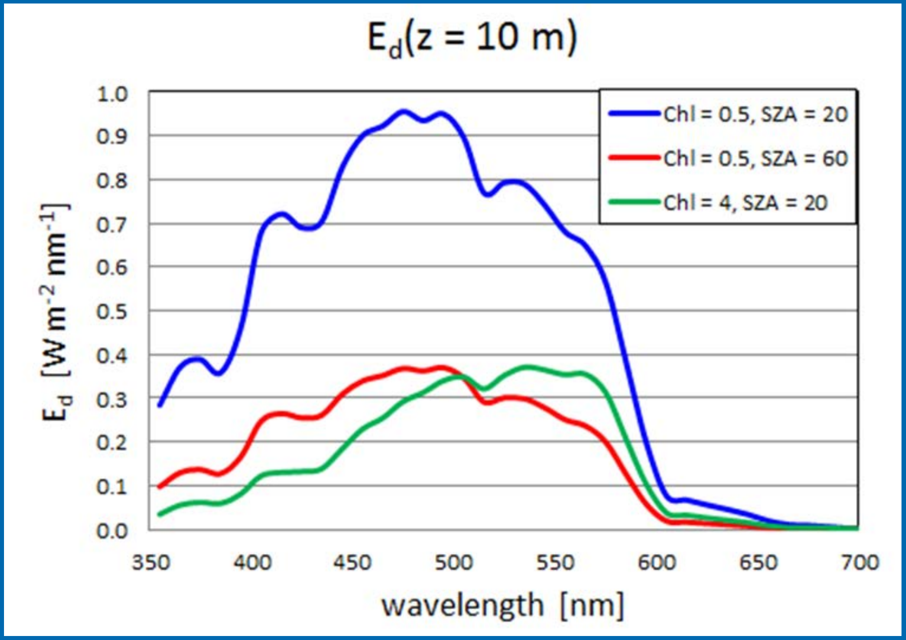
…the depth derivative (slope) on a log-linear plot as an AOP.

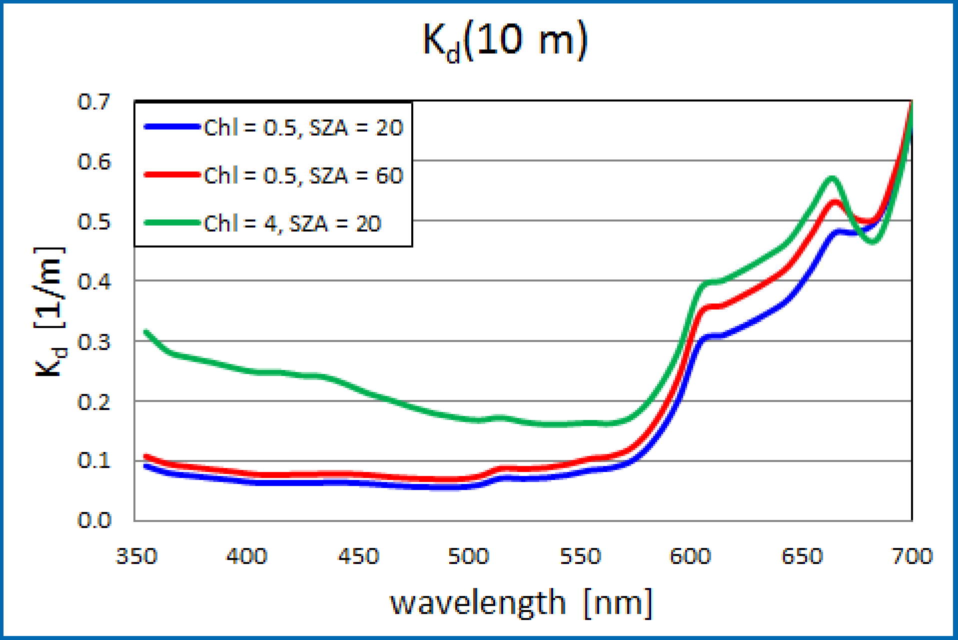
This leads to the diffuse attenuation coefficient for downwelling plane irradiance:

$$\begin{aligned} K_d(z,\lambda) &\equiv -\frac{1}{E_d(z,\lambda)}\frac{dE_d(z,\lambda)}{dz} \qquad [\mathrm{m}^{-1}] \\ &= -\frac{d\ln E_d(z,\lambda)}{dz} \end{aligned}$$

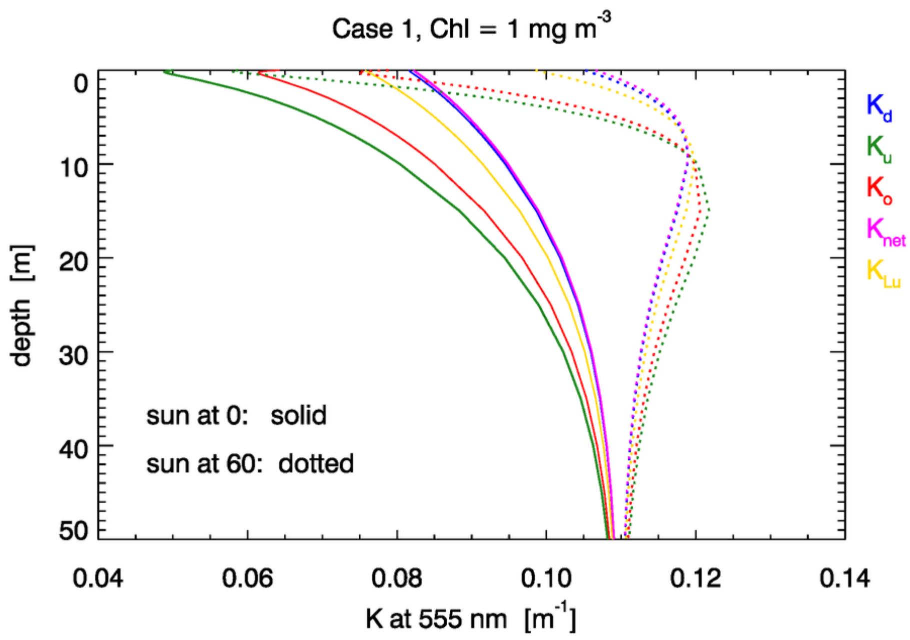
We can do the same for E_u, E_o, $L(\theta,\phi)$, etc, and define many different K functions: K_u, K_o, $K_L(\theta,\phi)$, etc.

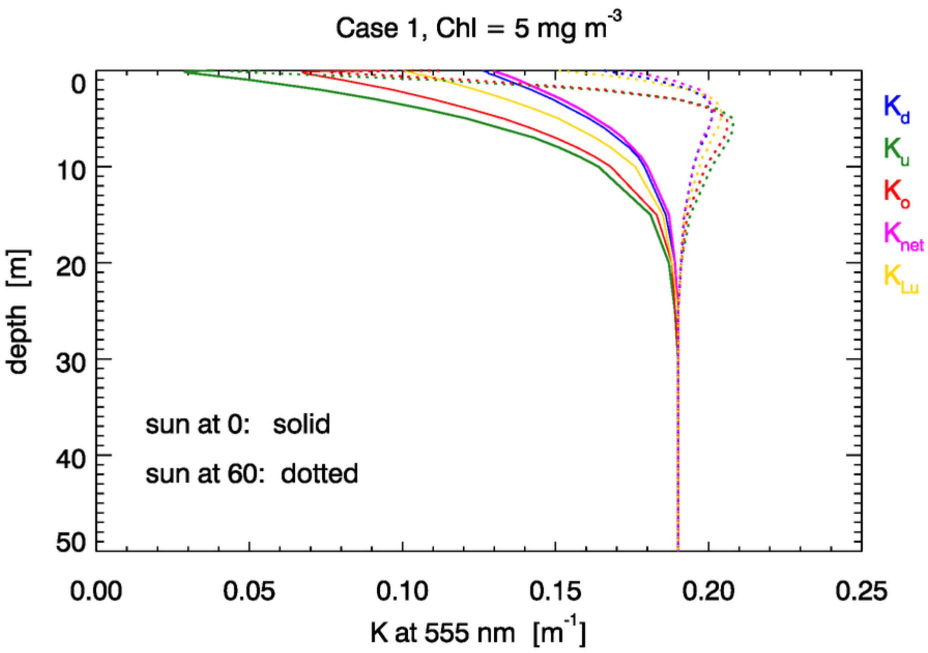
K_d Separates the Water Bodies





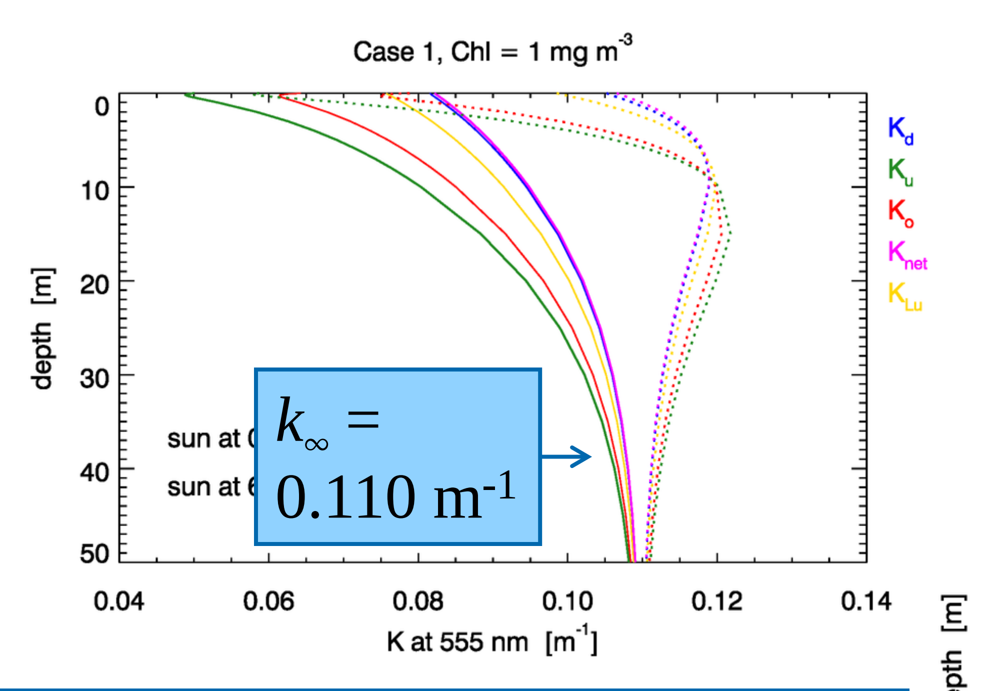
How similar are the different K's?

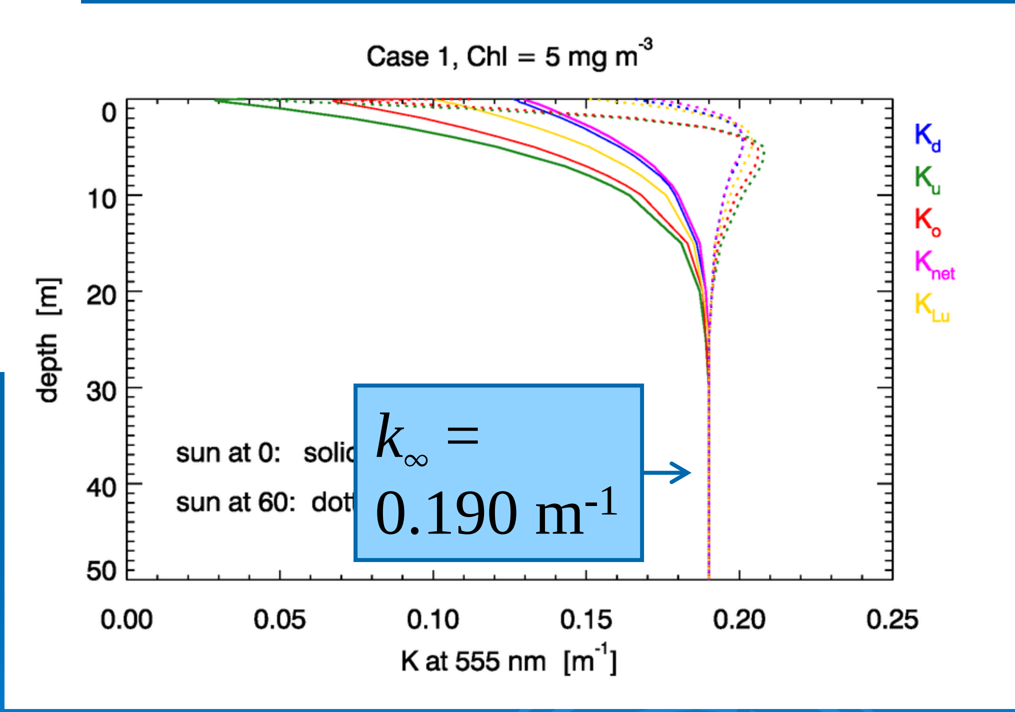




NOTE: The K's depend on depth, even though the water is homogeneous, and they are most different near the surface (where the light field is changing because of boundary effects)

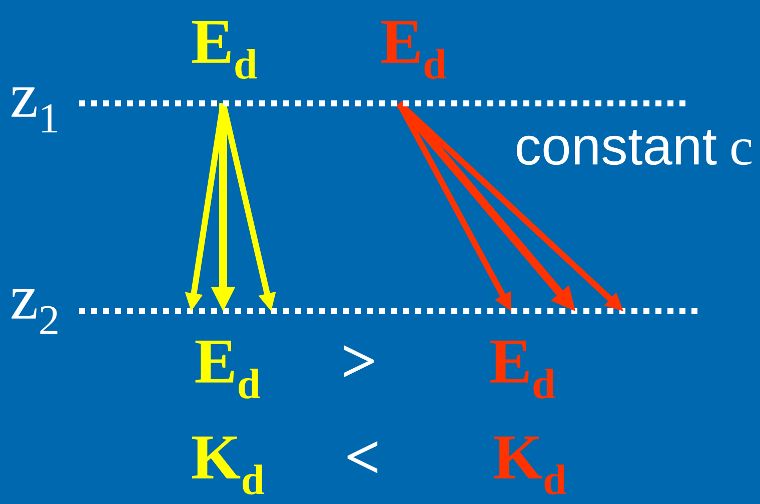
Asymptotic Values

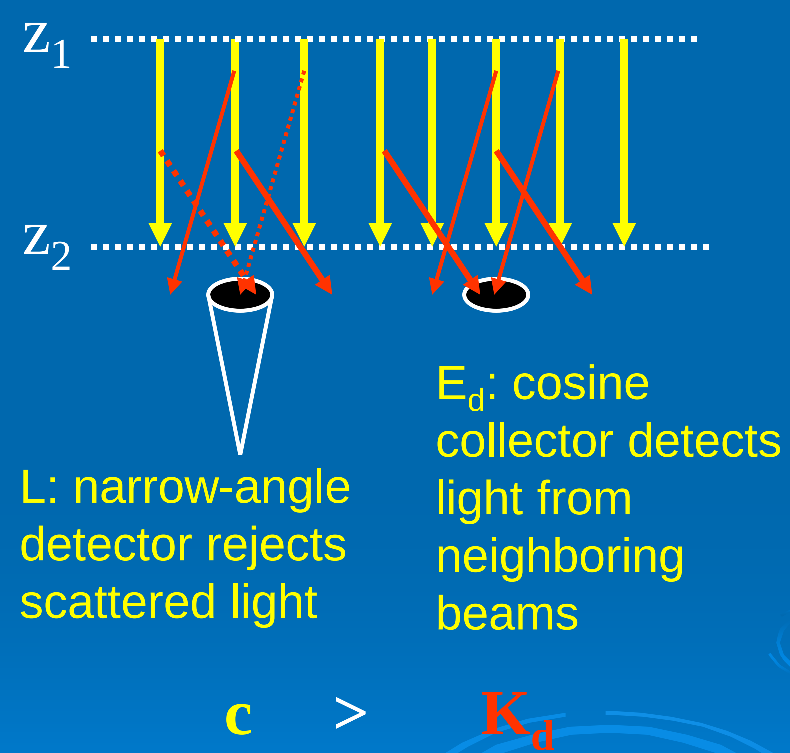




The K's all approach the same value as you go deeper: the asymptotic diffuse attenuation coefficient, k_∞, which is an IOP.

Beam attenuation $c \neq$ diffuse attenuation K





Virtues and Vices of K's

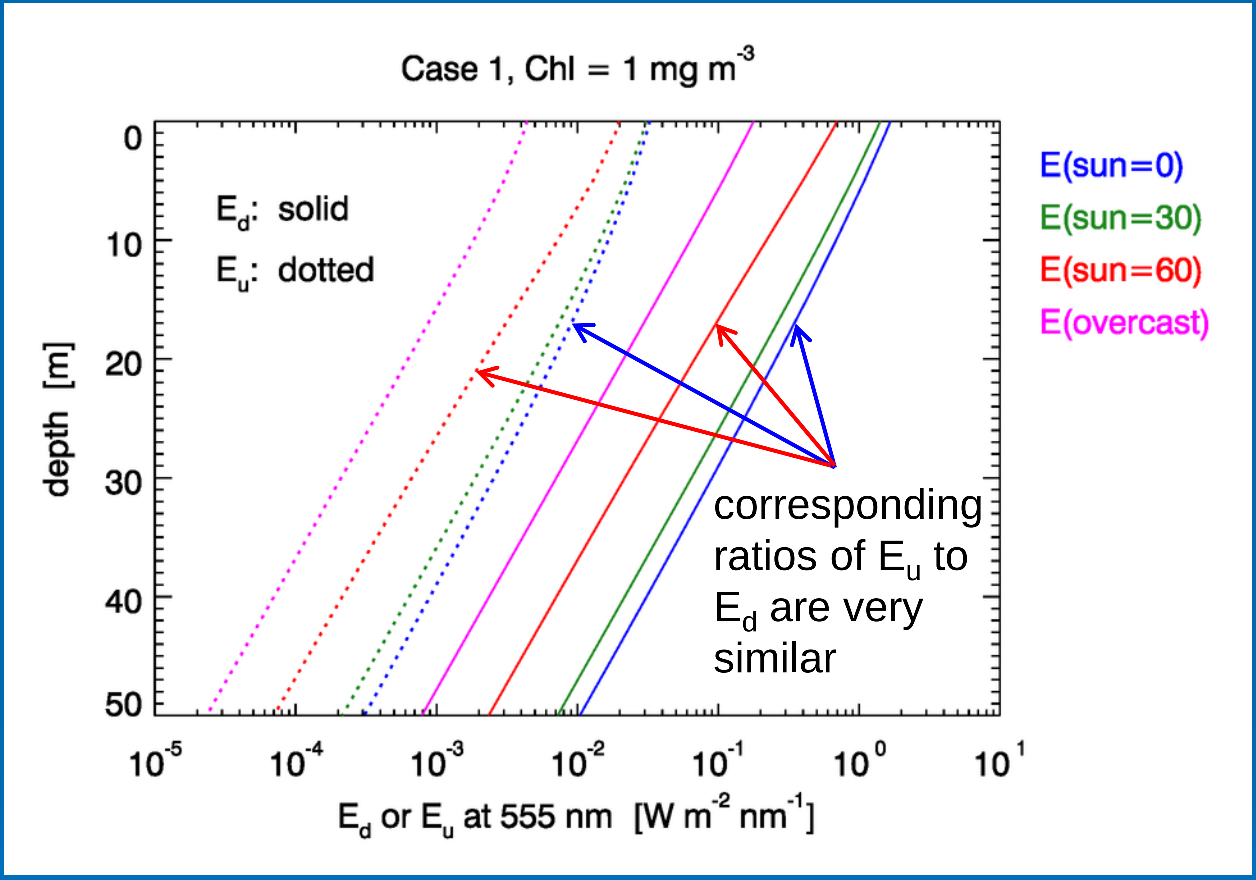
Virtues:

- 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 (e.g., 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



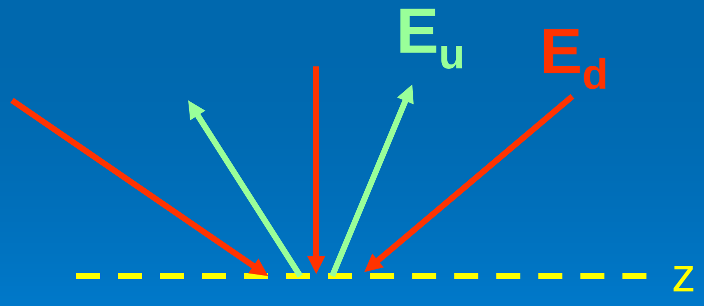
Magnitude changes are due to incident lighting (sun angle and sky condition); ratio of E_u/E_d is determined by water IOPs.

This suggests trying...

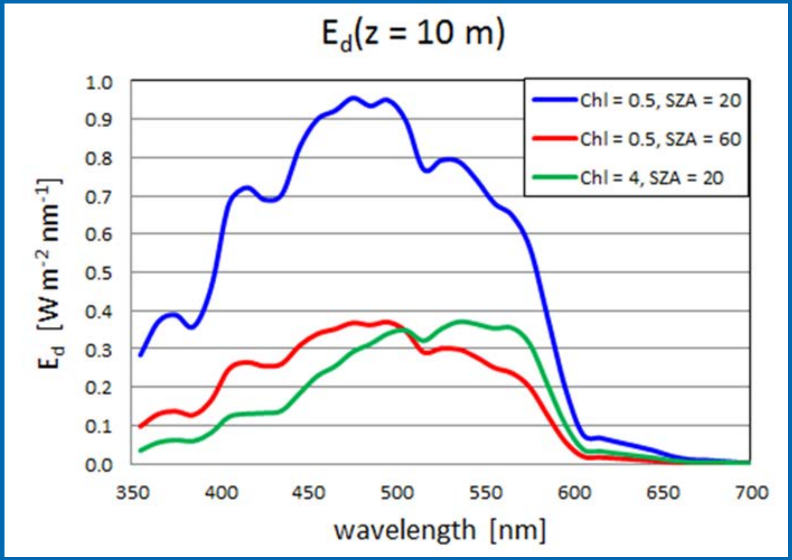
…the ratio of upwelling plane irradiance E_u to downwelling plane irradiance E_d as an AOP.

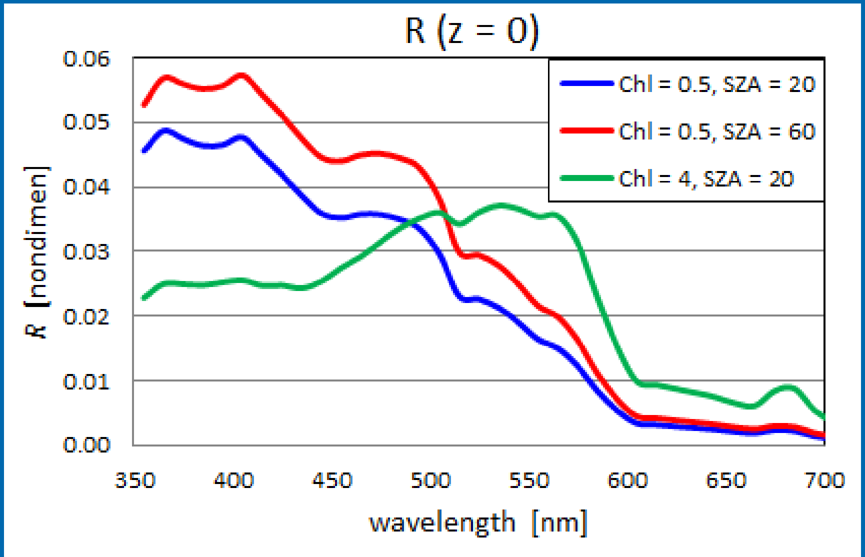
This is the irradiance reflectance R:

$$R(z,\lambda) = \frac{E_{\mathrm{u}}(z,\lambda)}{E_{\mathrm{d}}(z,\lambda)}$$

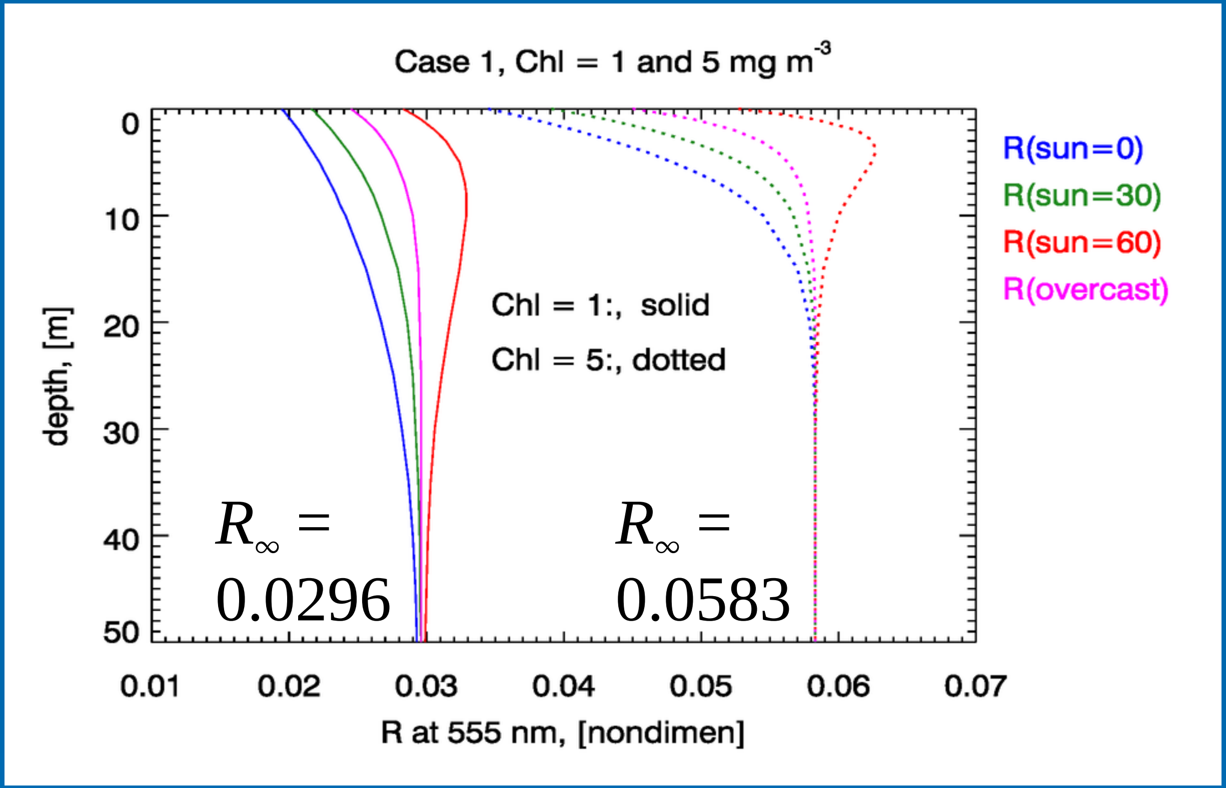


$R = E_u/E_d$ Separates the Water Bodies





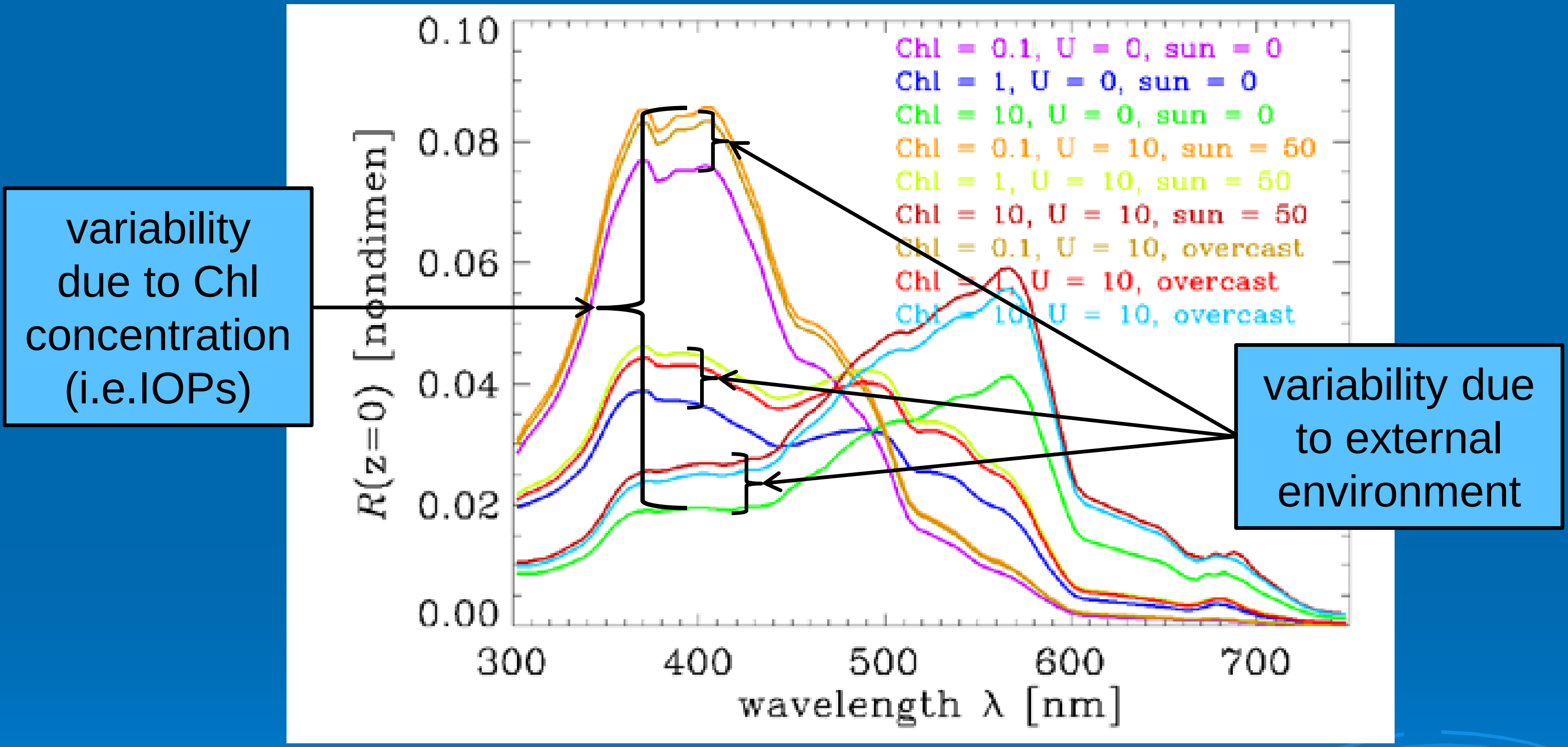
$R = E_u / E_d$



Like the *K*'s, *R* is somewhat affected by the external environment near the surface, but depends only on the IOPs as you go deeper. In general, in homogeneous water, AOPs become IOPs at great optical depth.

$R = E_u/E_d$

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

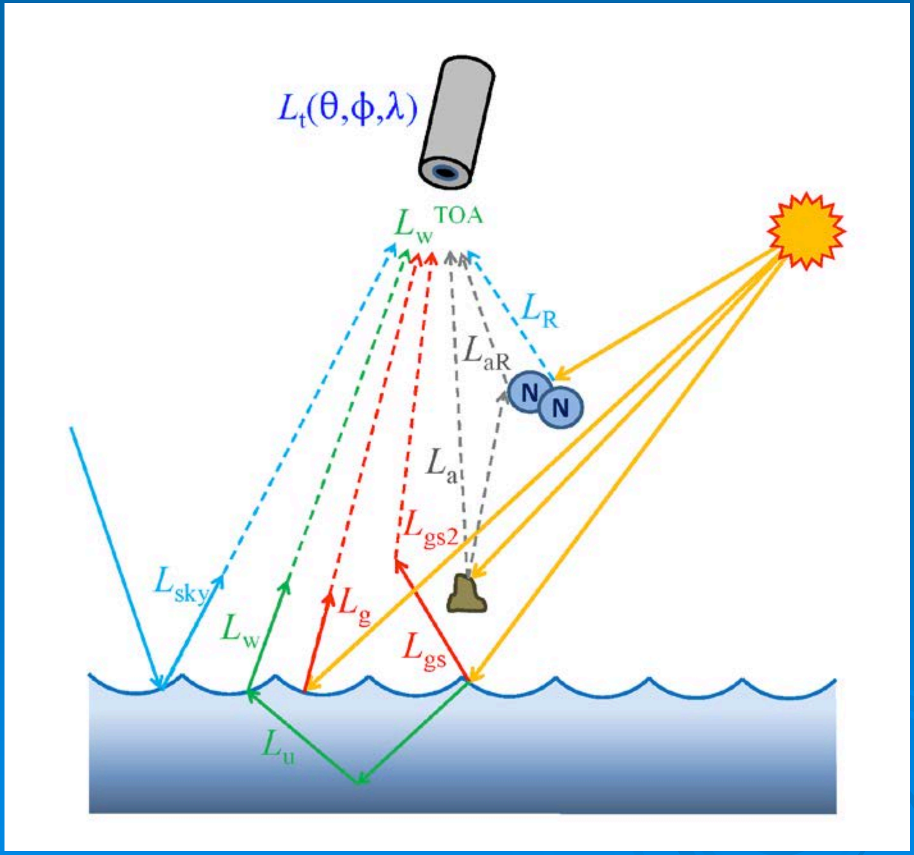


R depends weakly on the external environment and strongly on the water IOPs. Can we do even better?

Water-leaving Radiance, L_w

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

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



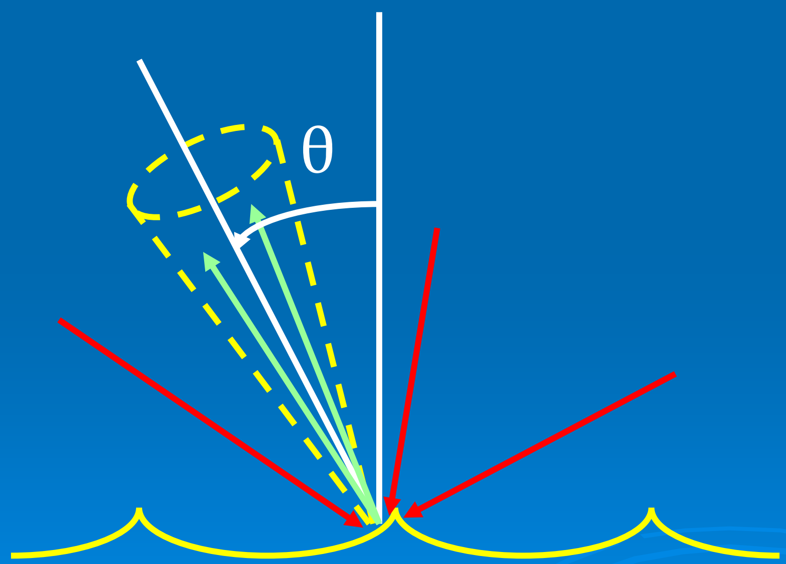
An instrument measures L_u (in air), but L_w is what tells us what is going on in the water. It isn't easy to figure out how much of L_u is due to L_w. This is the atmospheric correction problem (see Mobley et al. (2016) for how NASA does this).

Remote-sensing Reflectance R_{rs}

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

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

$$R_{\rm rs}(\theta,\phi,\lambda) \equiv \frac{L_{\rm w}(\text{in air};\theta,\phi,\lambda)}{E_{\rm d}(\text{in air};\lambda)} \qquad [\text{sr}^{-1}]$$



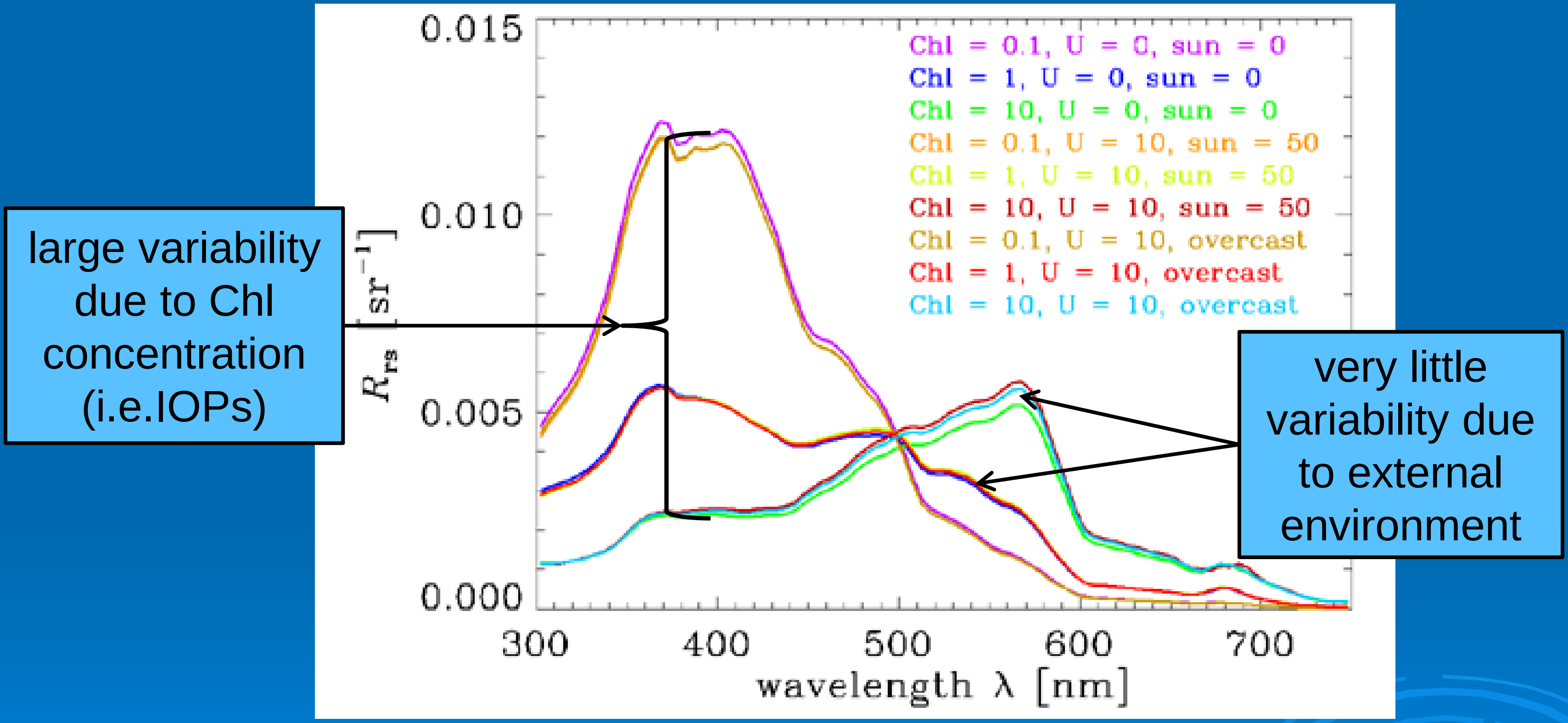
sea surface

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)

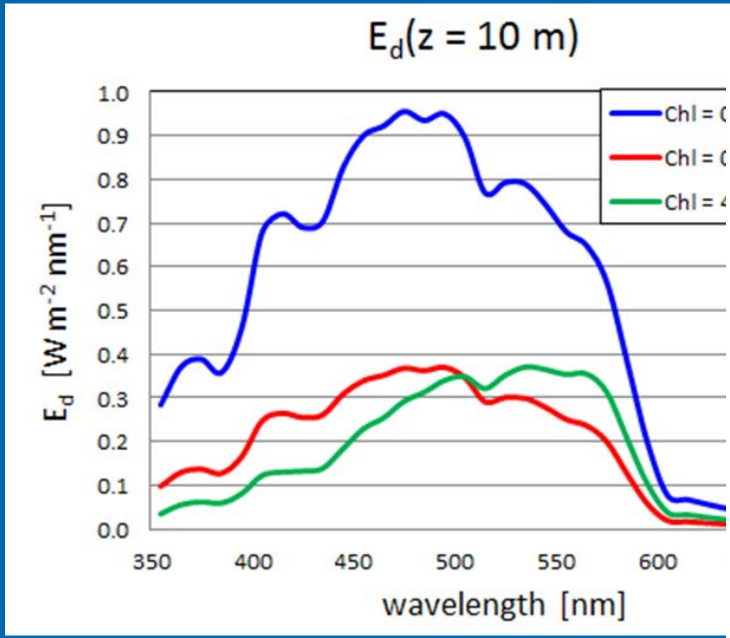
Example R_{rs} (nadir-viewing directions)

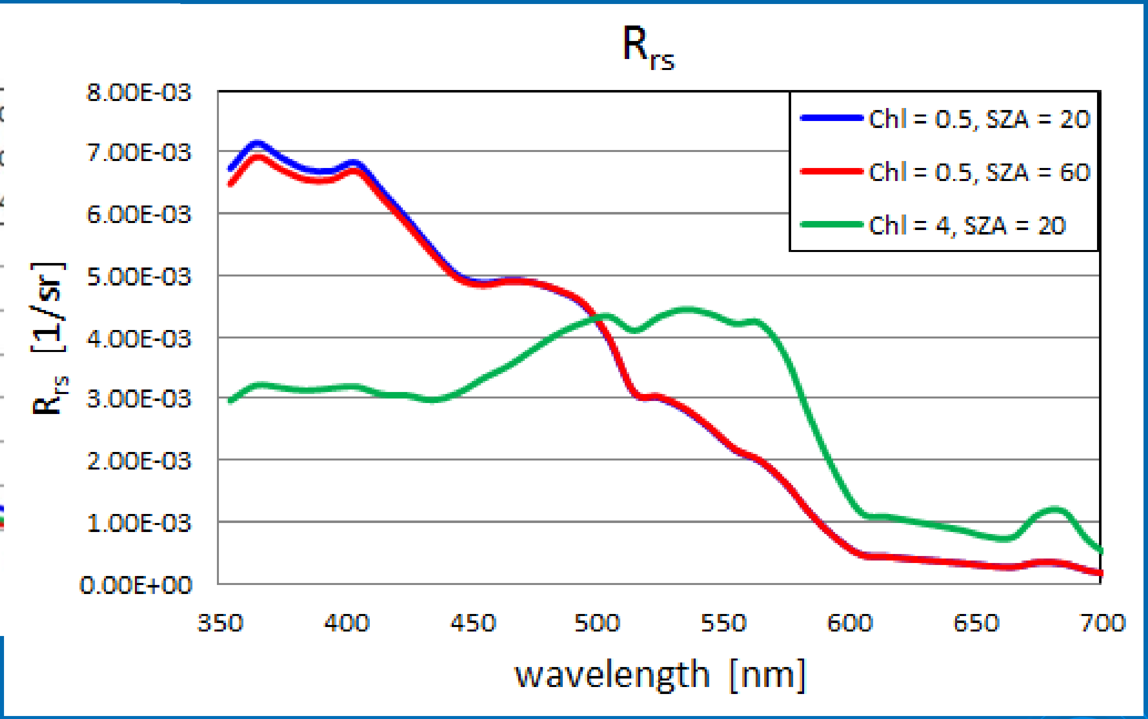
HydroLight runs: Chl = 0.1,1, 10 mg Chl/m^3
Sun at 0 and 50 deg in clear sky, overcast sky



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

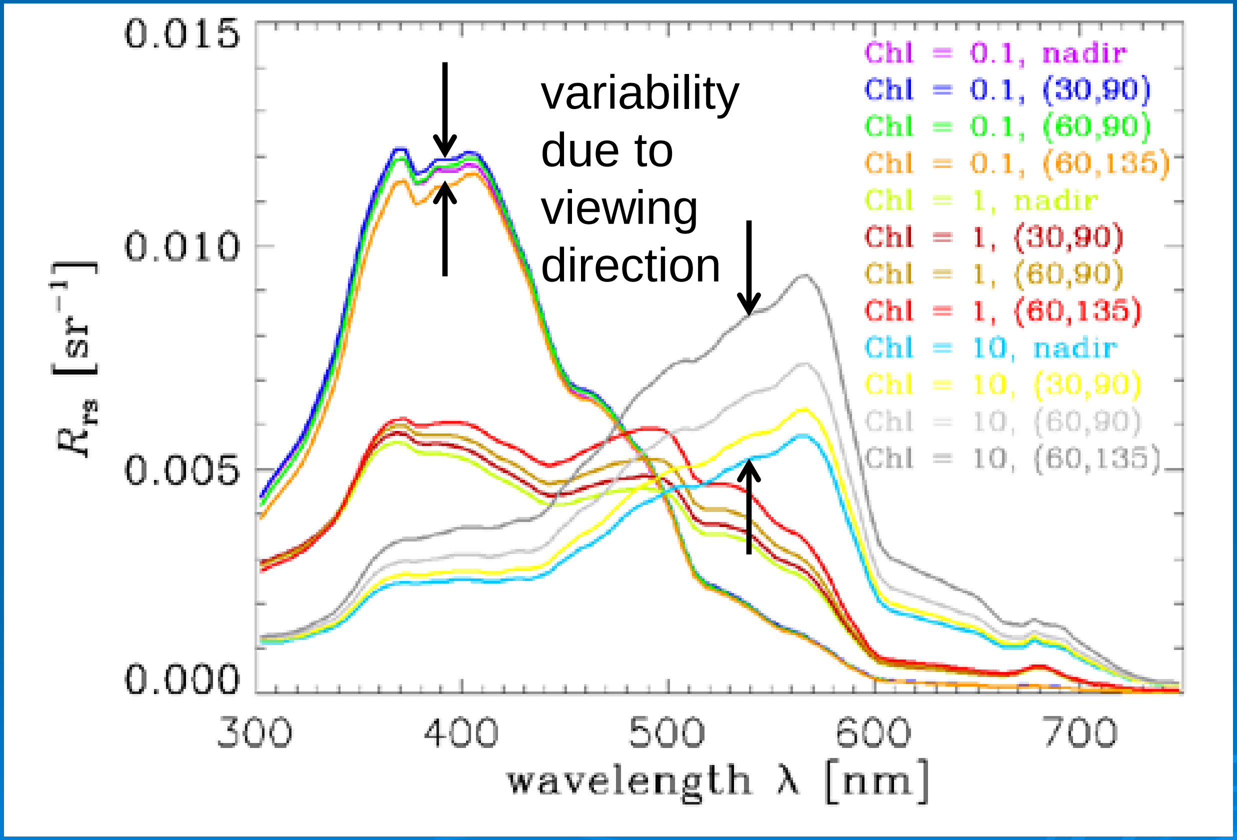
R_{rs} Separates the Water Bodies Very Well





Example R_{rs} (off-nadir viewing directions)

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



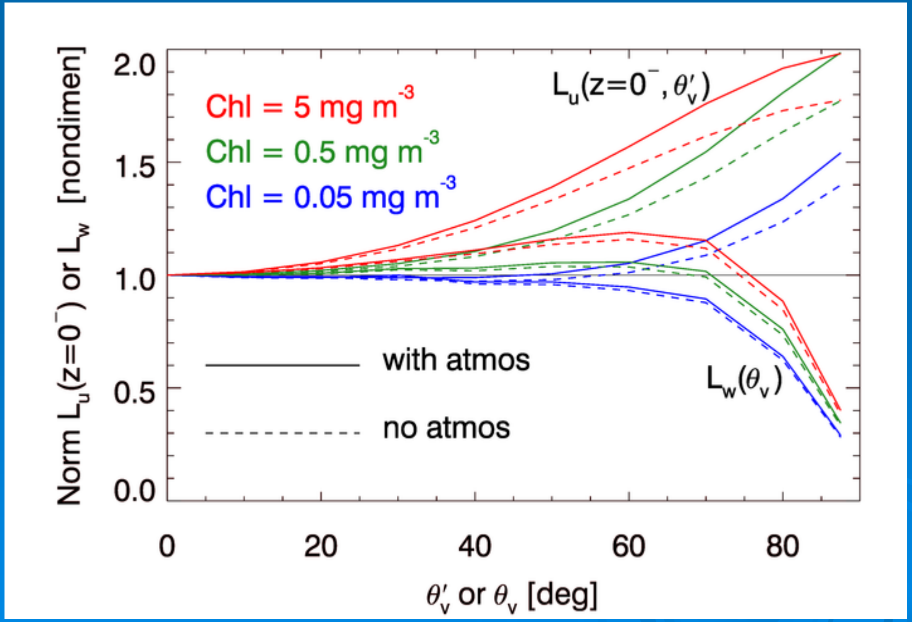
R_{rs} shows dependence on viewing direction but stronger dependence on the water IOPs—still a good AOP, but could be better…

Normalized Reflectance [Á]$_N$

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 [Á]$_N$

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.

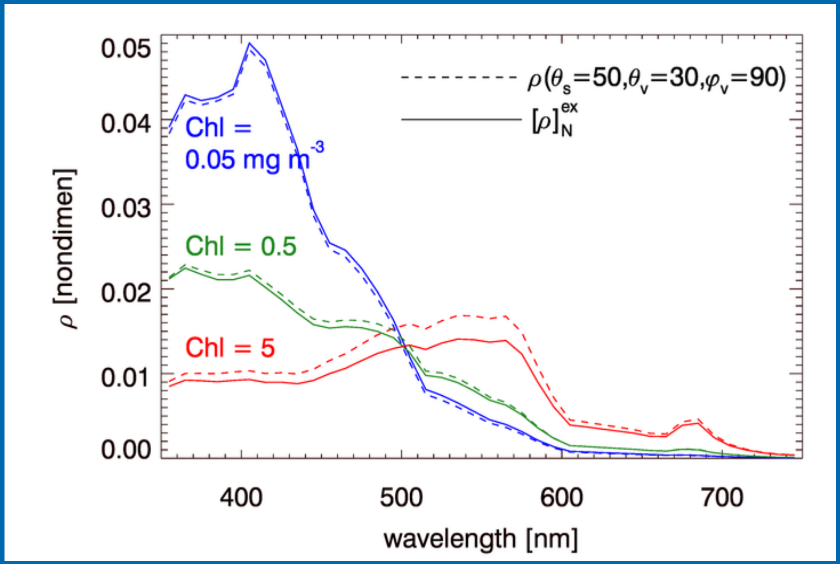
(3) The correction factors require knowing the Chl concentration.

(4) The BRDF correction factors are tabulated only for certain wavelengths as needed for SeaWiFS, MODIS, VIIRS.

Normalized Reflectance [Á]$_N$

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

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



Comparison of unnormalized and exact normalized reflectances

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

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

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 Reflectances for a full discussion of $[\rho_w]_N^{ex}$

Average or Mean Cosines

The average or mean cosines give the average of 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

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

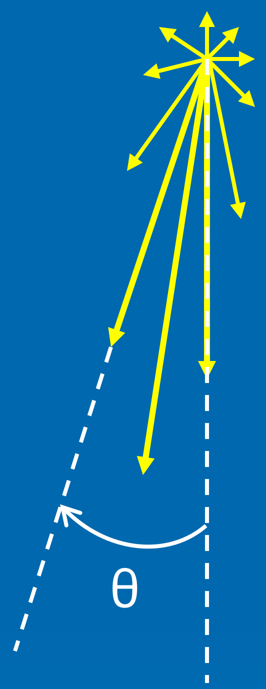
Likewise, for the upwelling radiance, $\bar{\mu}_u = \frac{E_{\mathrm{u}}}{E_{\mathrm{ou}}}$

For the entire radiance distribution,

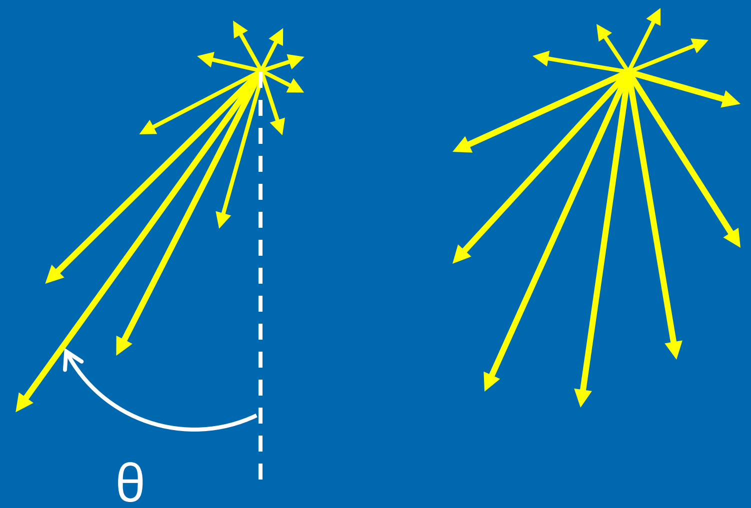
$$\bar{\mu} = \frac{\int_0^{2\pi}\int_0^{\pi} L(\theta,\phi)\cos\theta\ \sin\theta\, d\theta\, d\phi}{\int_0^{2\pi}\int_0^{\pi} L(\theta,\phi)\sin\theta\, d\theta\, d\phi} = \frac{E_{\mathrm{d}} - E_{\mathrm{u}}}{E_{\mathrm{o}}}$$

Note: $E_{\mathrm{o}} = E_{\mathrm{od}} + E_{\mathrm{ou}}$ but $\bar{\mu}_{\mathrm{o}} \neq \bar{\mu}_d + \bar{\mu}_u$

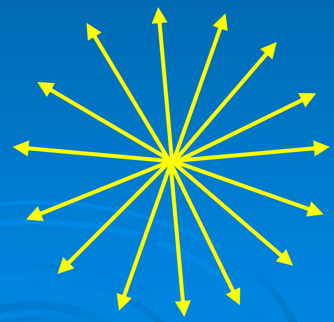
Mean Cosines



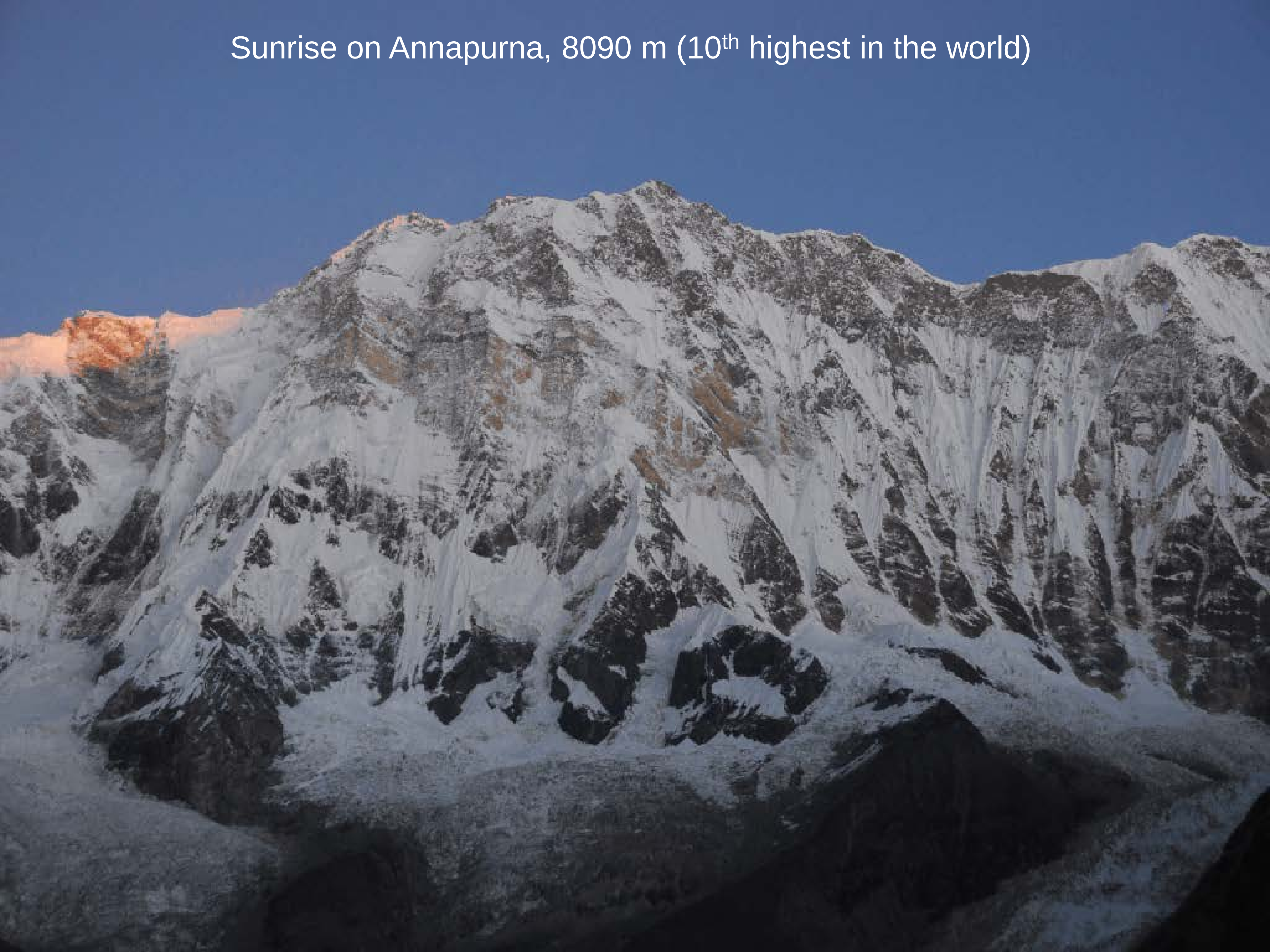
most photons heading
almost straight down:
small average θ, large μ_d



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



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



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

Rhino

Chitwan National Park, Nepal

2011