Introduction to HydroLight

John Hedley, IOCCG Summer Class, 2022

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John Hedley

- Undergraduate Degree – Zoology
- Ph.D. – Remote Sensing of Coral Reefs
- ~10 years in a Coral Reef Ecology Group (Exeter University)
- Now work through my own company, working with academic and commercial sector.

Numerical Optics Ltd

Activites

- Numerical modelling of radiative transfer
- Shallow water remote sensing - coral reefs, seagrasses, satellite derived bathymetry
- Benthic photobiology
- Maintain and develop HydroLight

This lecture

What is HydroLight?

HydroLight is a well-known and widely used software for modelling radiative transfer in natural waters.

Sky radiance + IOPs → light field in water → AOPs inc. reflectance

The lecture will include:

- Modelling in general – i.e. the problem to be solved
- The method used in HydroLight
- Features and design of HydroLight
- Validation, optical closure
- EcoLight, and EcoLight-S for ecosystem models

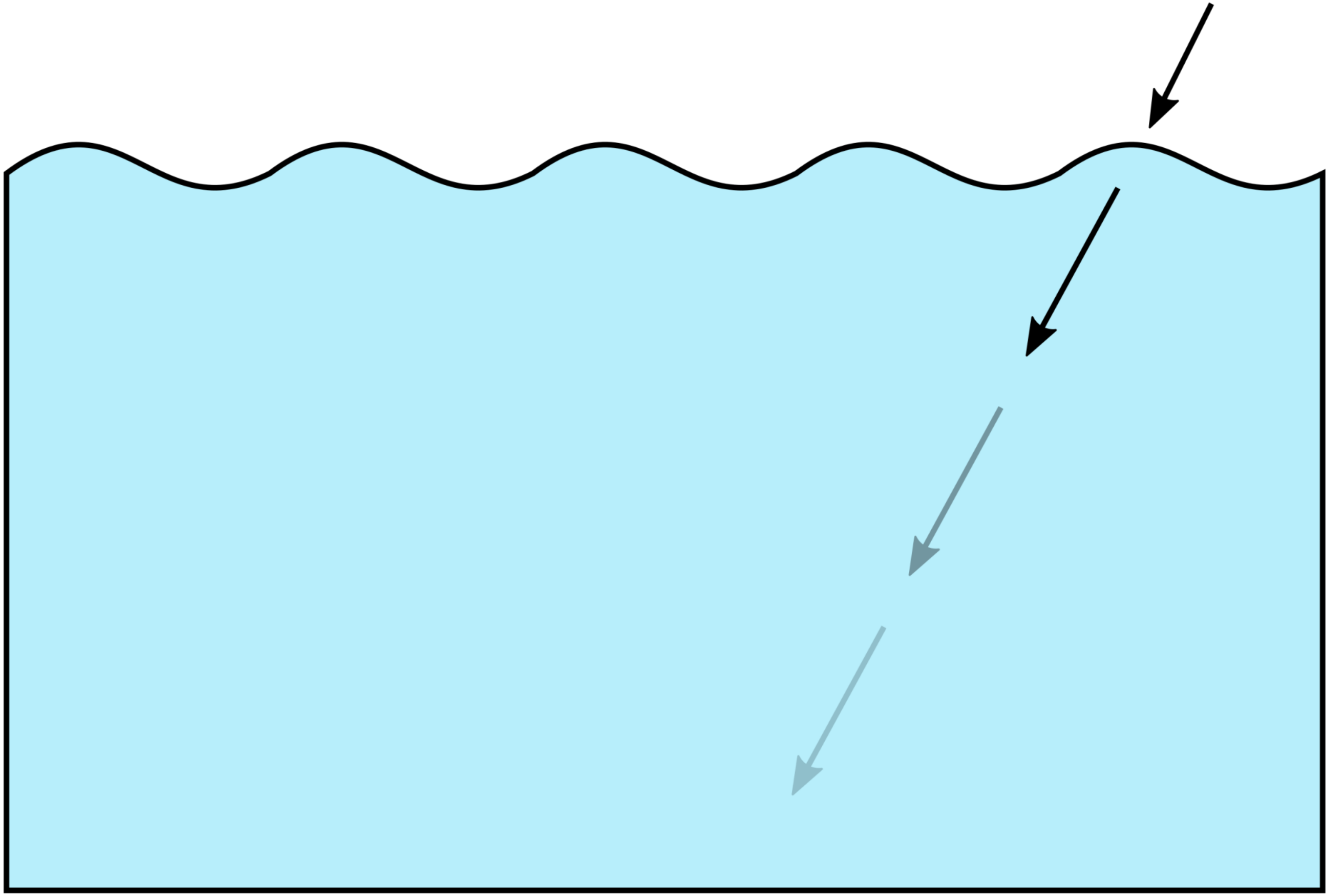
→ Followed by hands-on Lab this afternoon

History of HydroLight

- Developed by Curt Mobley working with Rudy Preisendorfer, starting in 1978.
- Commercial product on PC since 1998.
- Over 200 users in 30 countries and used in many publications.
- As of 2017 ownership of HydroLight passed to me (John Hedley) and is now a product of Numerical Optics Ltd.
- Commercial basis has always been and continues to be the only support for maintenance and development of the software.
- Latest version is version 6.0, now also available for Mac and Linux.

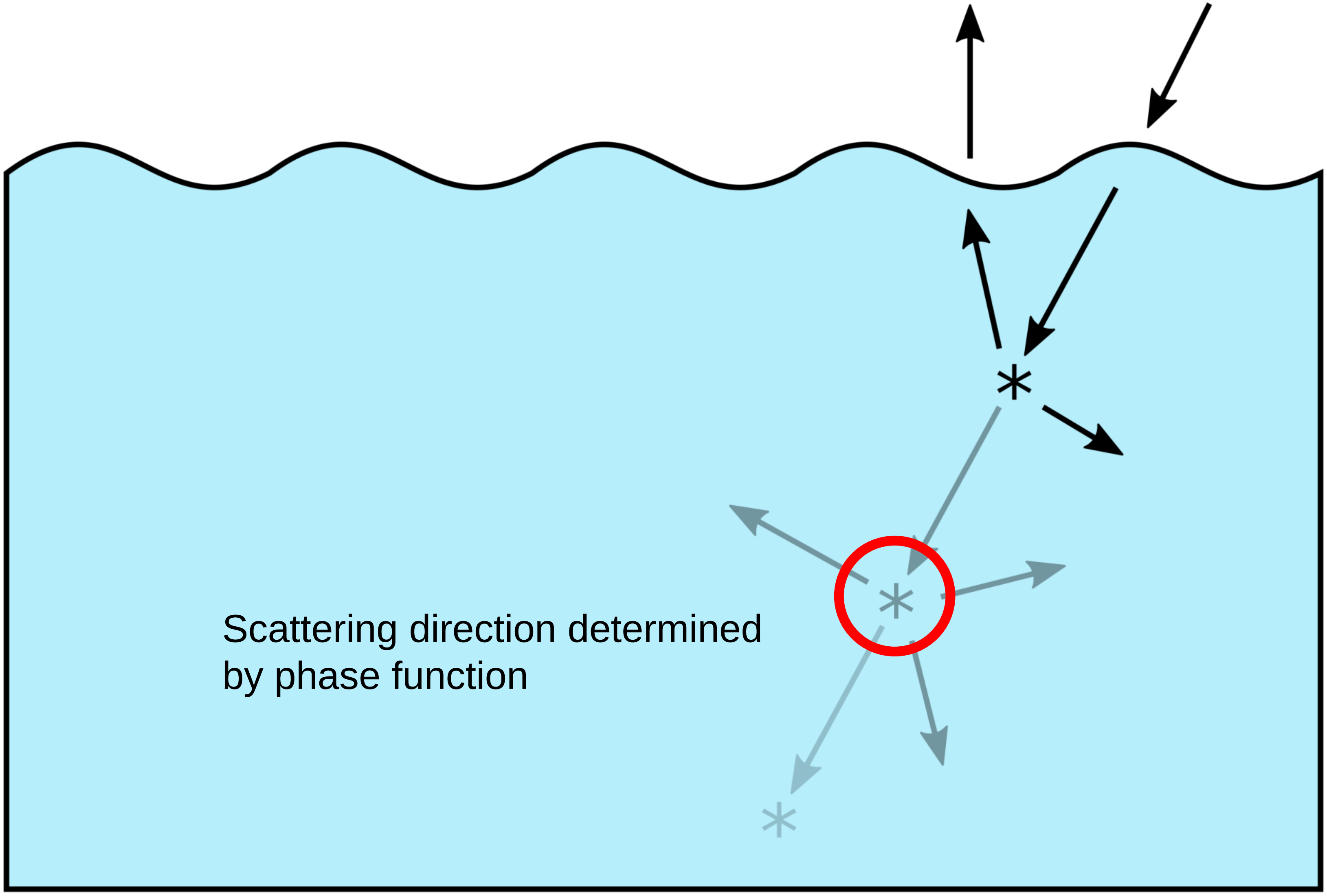
See the document *HydroLight_History.pdf* for more historical info.

The problem to be solved



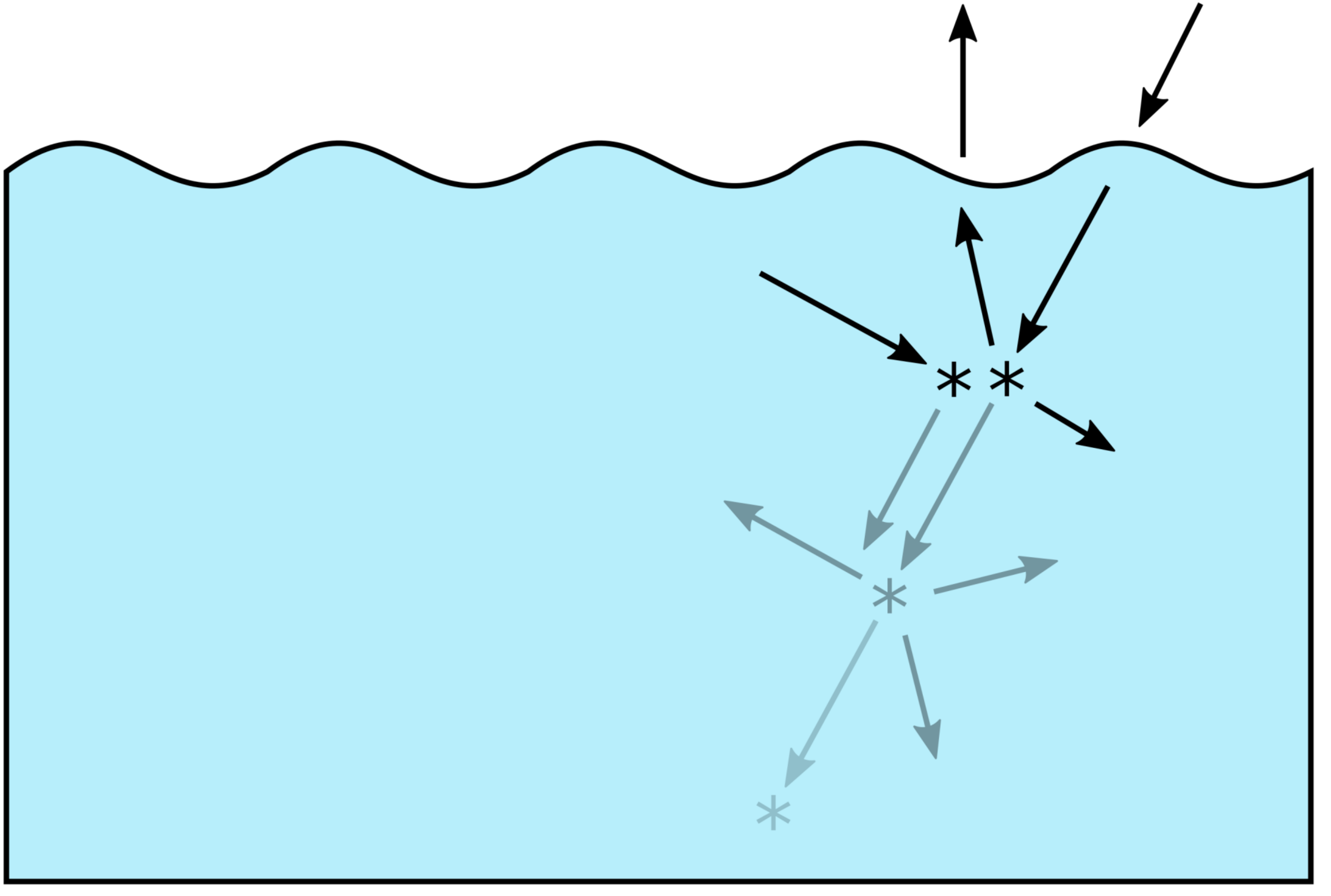
Example 1: No scattering, only absorption

Single scattering - losses to a beam



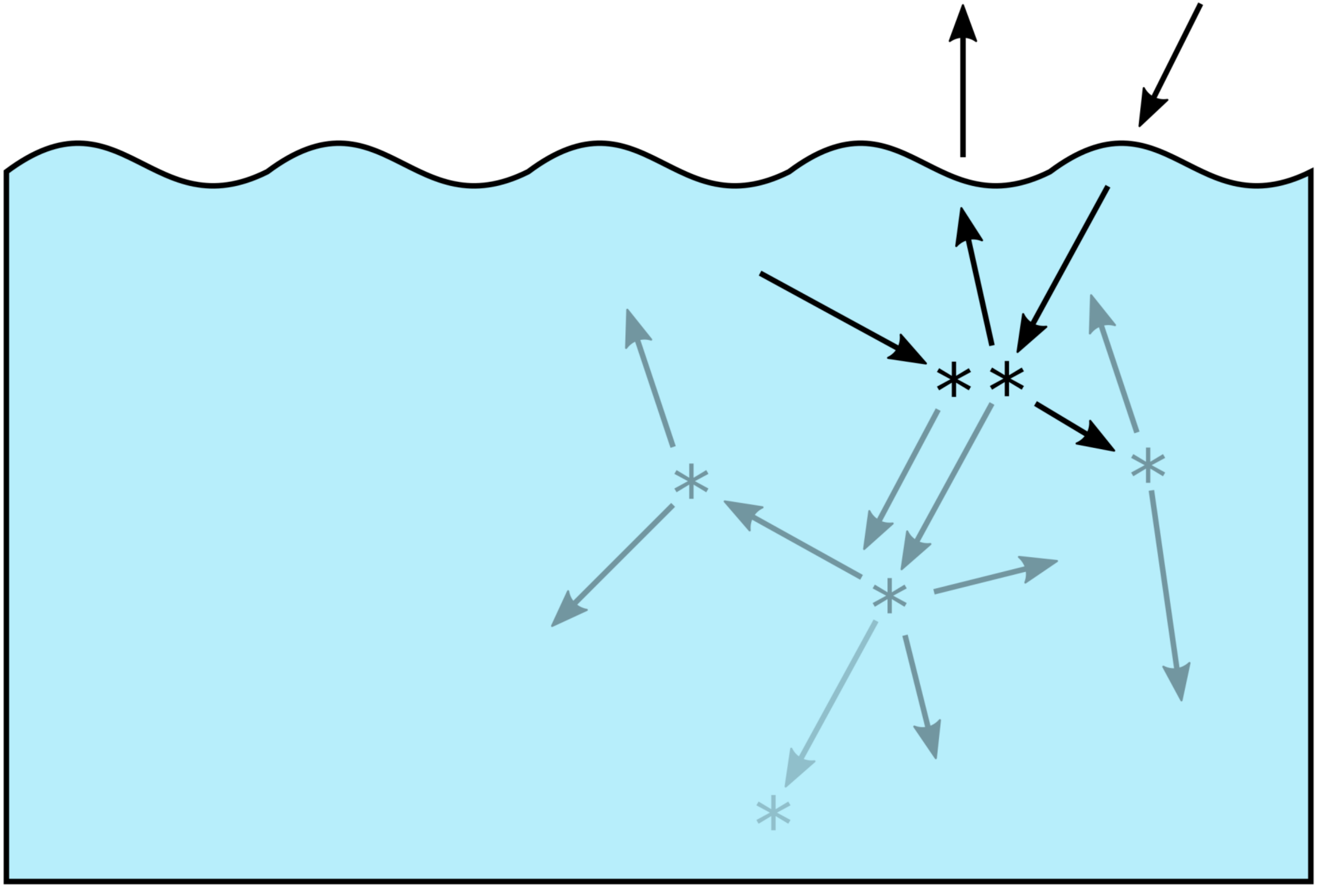
Losses due to absorption + scattering = beam attenuation (a + b = c)

In-scattering



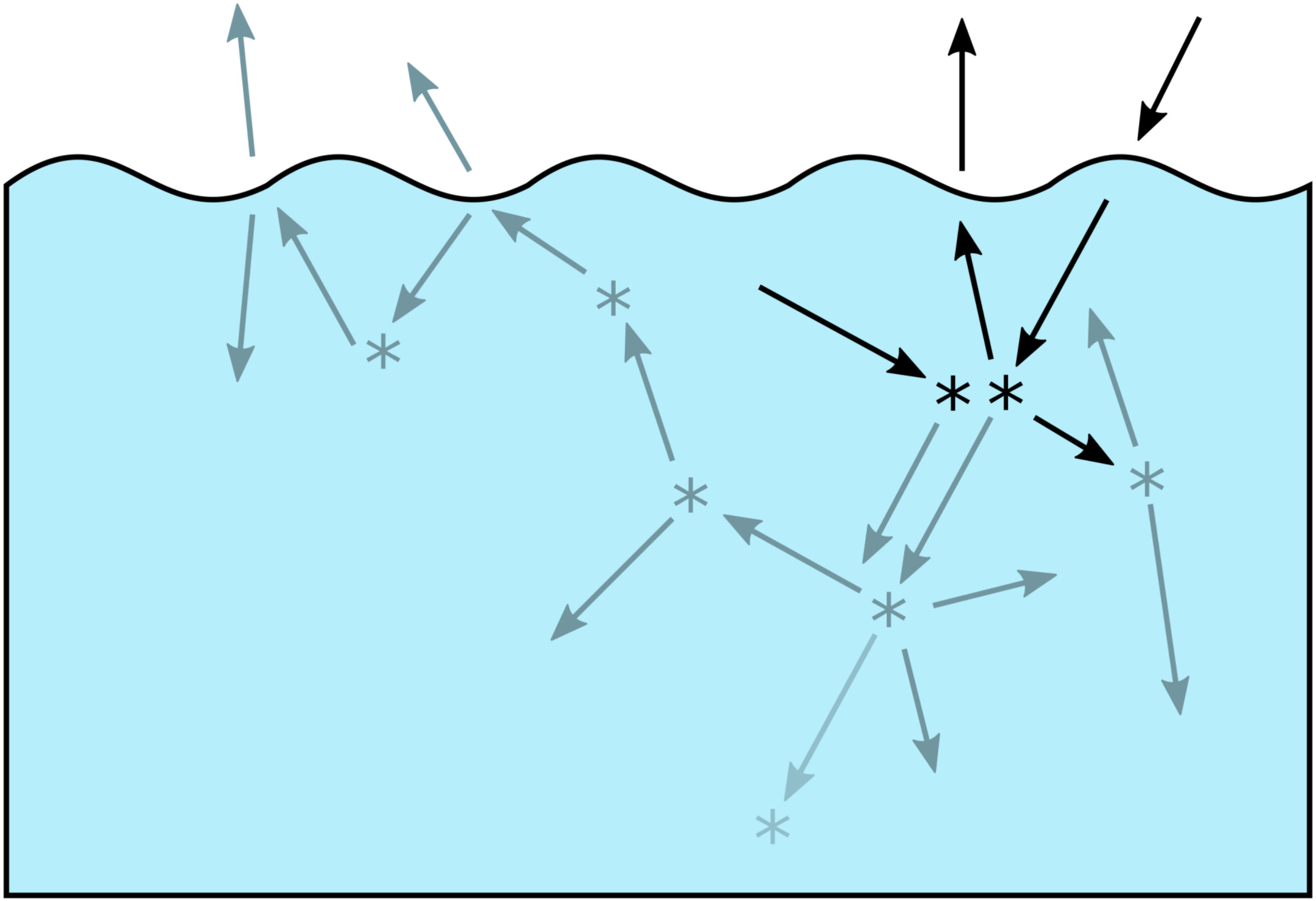
“In-scattering” of light from other directions - still a single scattering model

Multiple scattering



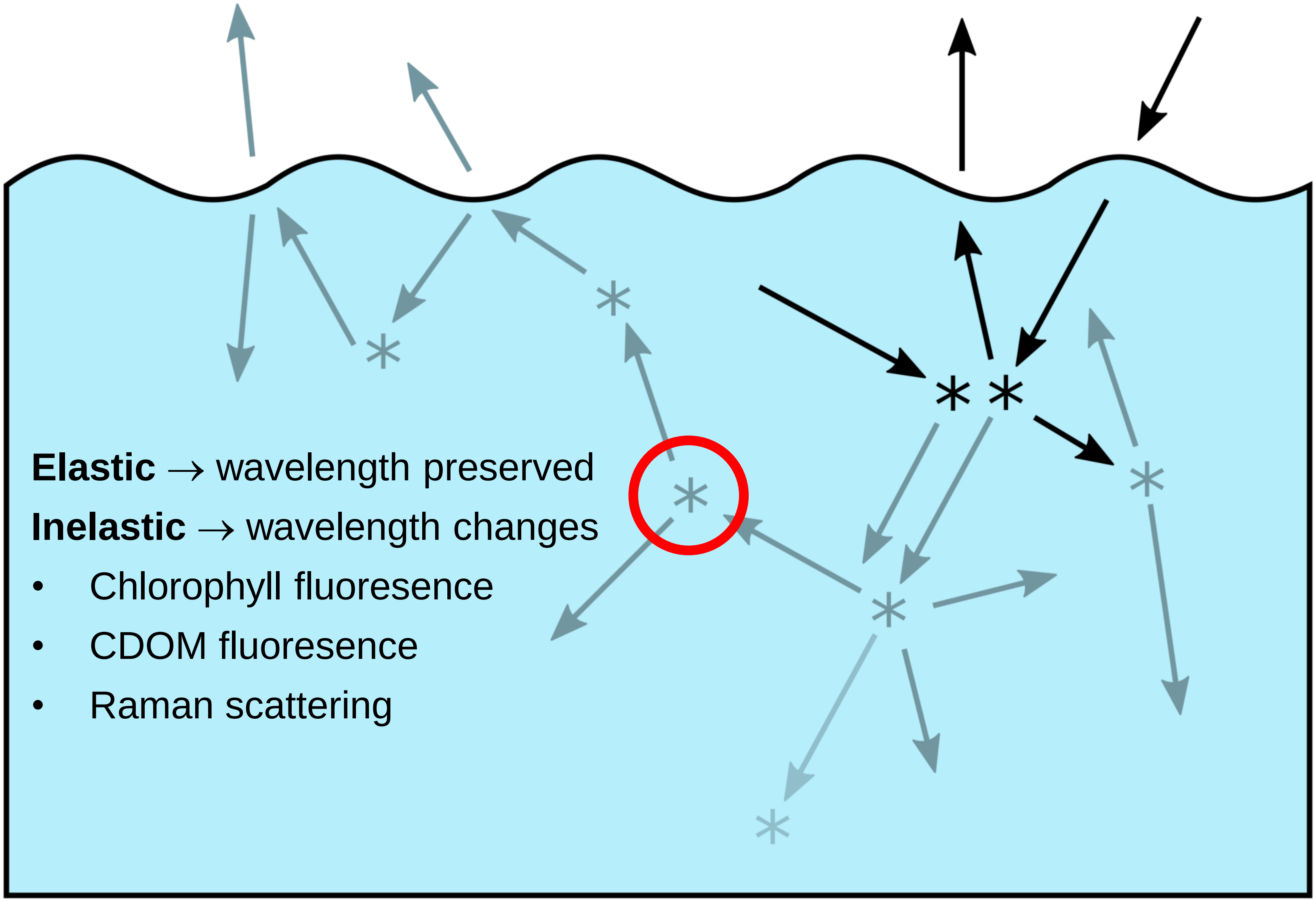
Two orders of scattering in water

Multiple scattering including air-water interface



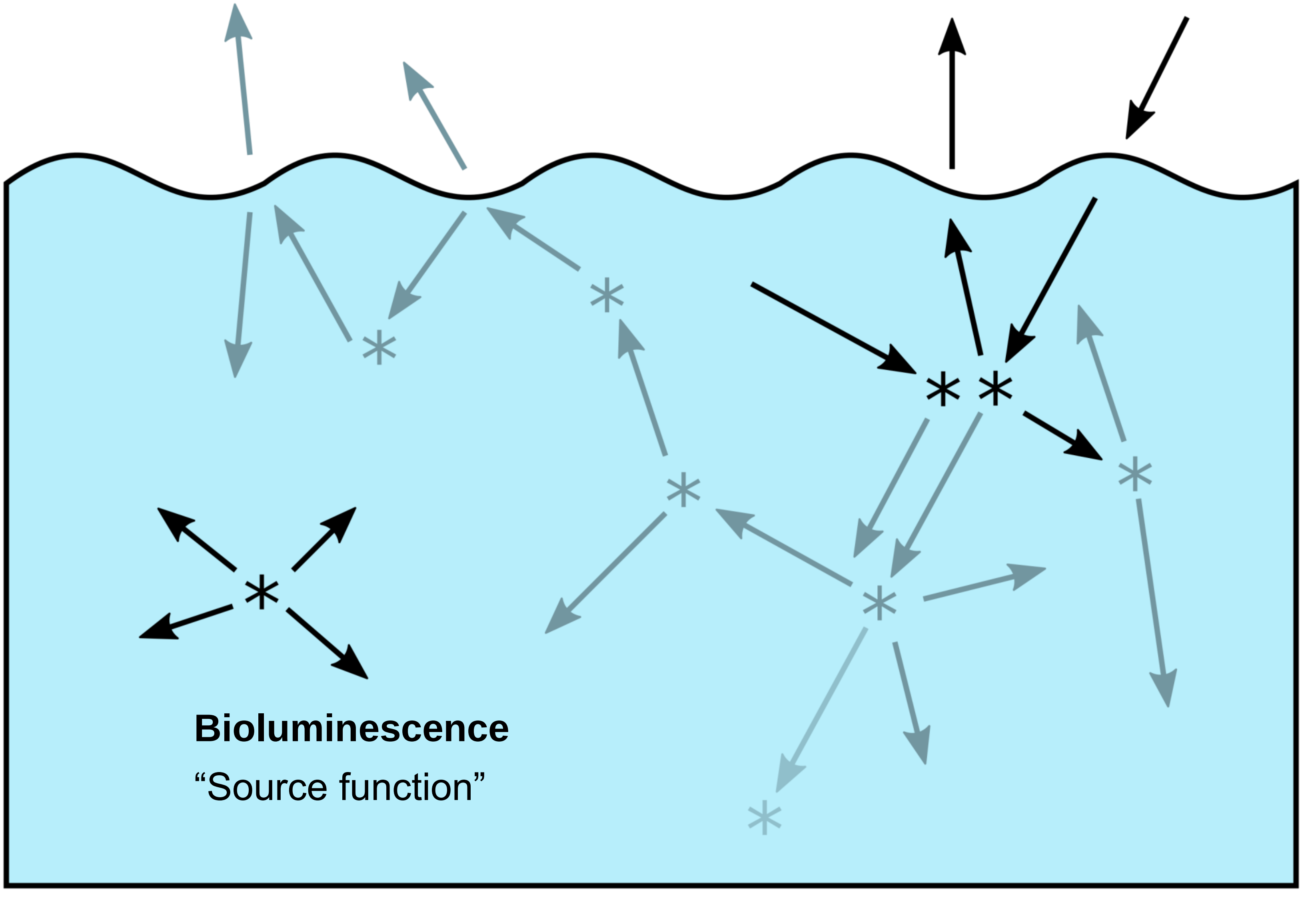
Multiple orders of scattering including from the water surface underside

Inelastic scattering (fluoresence) vs. elastic scattering



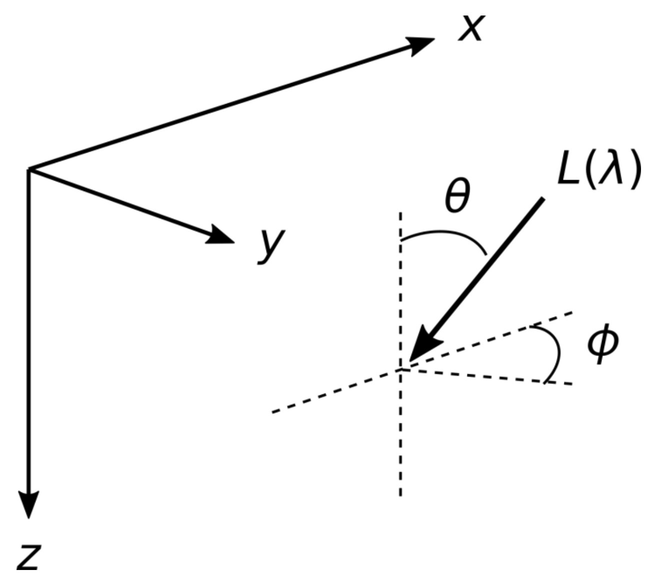
Typically wavelength gets longer (loss of energy) except for tiny fractions

Bioluminescence



A source of light within the system

The Complete Solution



Would be:

The radiance distribution (*L*)

- In every direction
- At every point in space
- For each wavelength

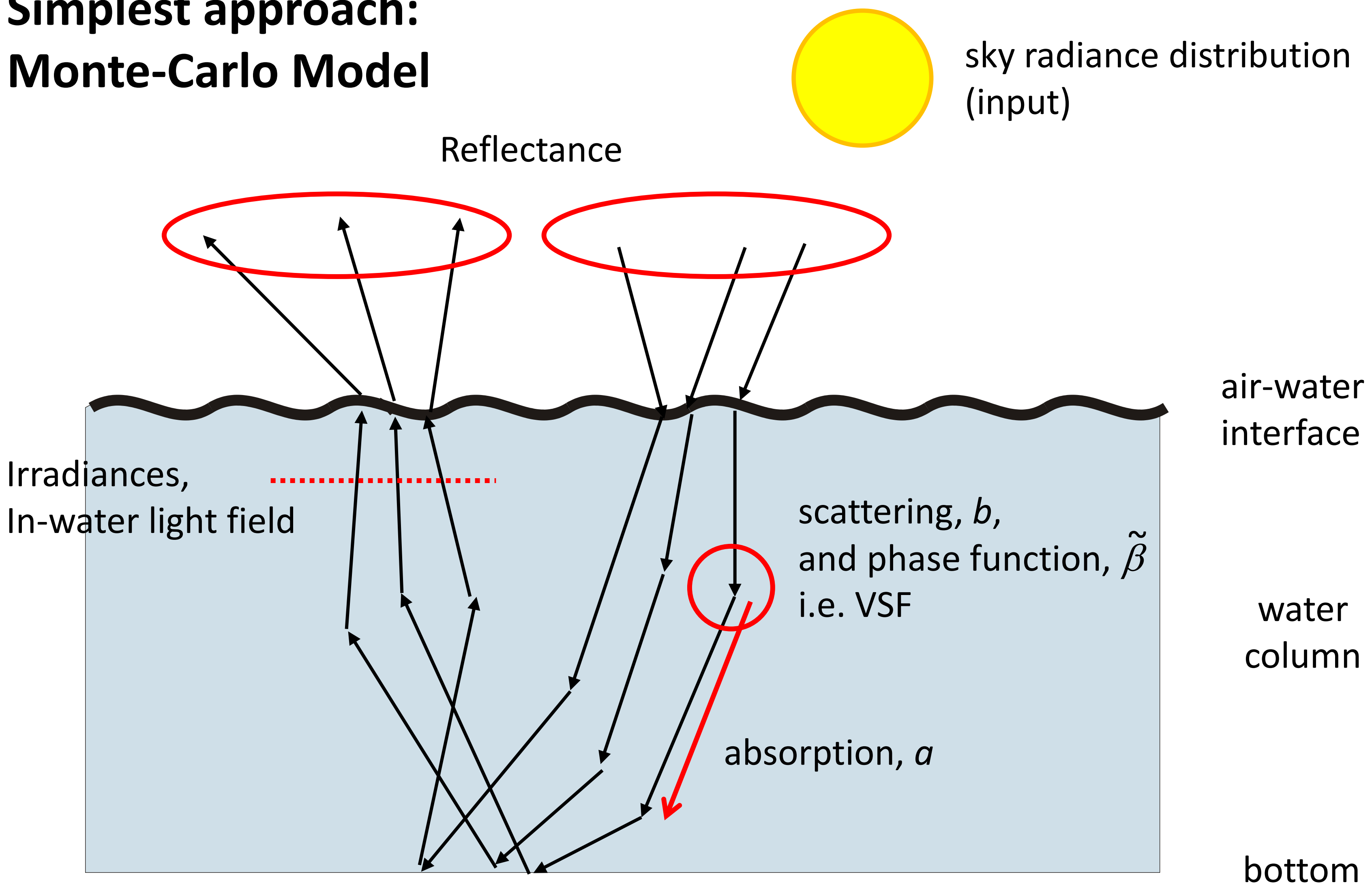
I.e.

$$L(x, y, z, \theta, \phi, \lambda) \qquad (\mathrm{Wm^{-2}sr^{-1}nm^{-1}})$$

From radiance every other radiometric quantity or property can be derived,

Irradiances, reflectances, diffuse attenuation coefficients (*K* values), etc.

Simplest approach: Monte-Carlo Model

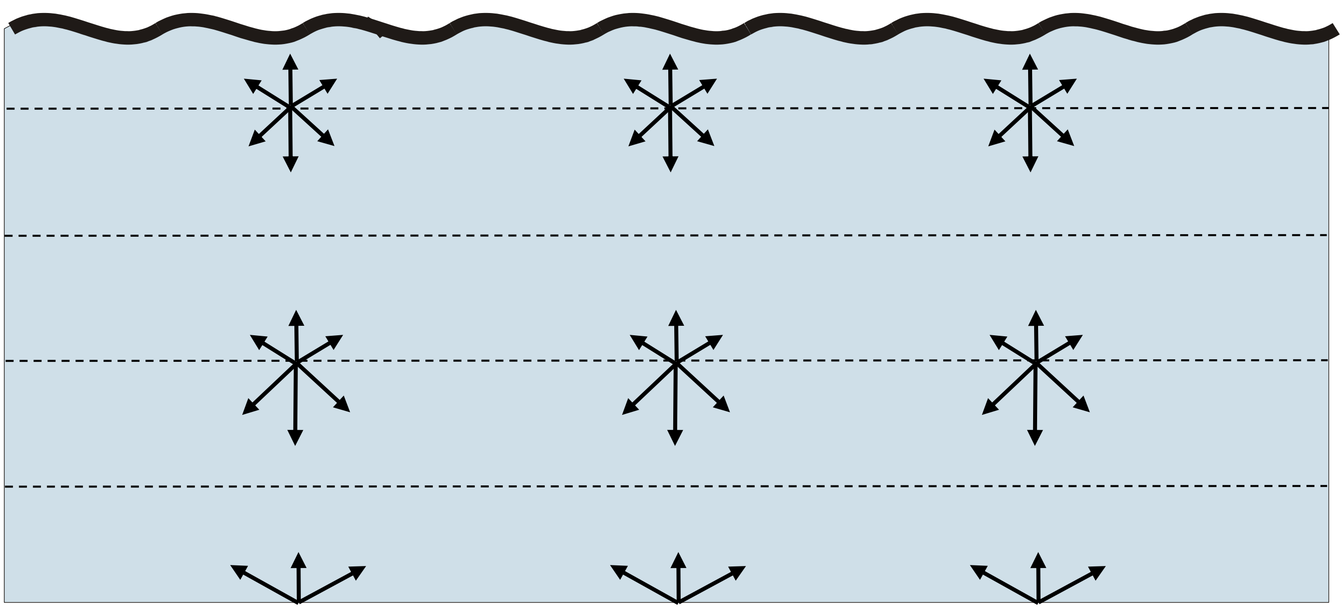


→ Close association between implementation and physical concepts

→ But, **inefficient** and subject to **statistical noise**

More efficient solution - First step, plane parallel model

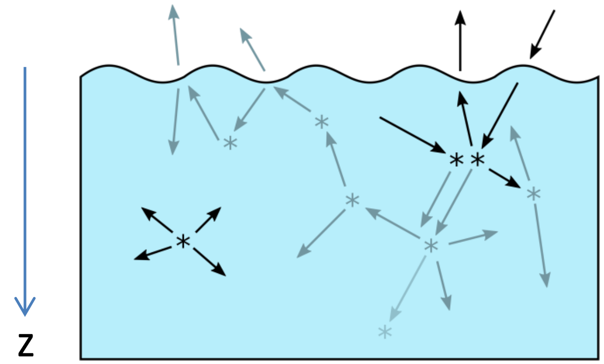
- Assume radiance distribution is the same across horizontal planes
- It does not depend on x and y (horizontal position)
- 3D problem becomes 1D
- Very reasonable approximation for deep water or homogenous bottoms



so now we want to determine this $L(z, \theta, \phi, \lambda)$ ($Wm^{-2}sr^{-1}nm^{-1}$)

Radiative Transfer Equation (RTE)

Change in radiance due to scattering and absorption when moving in +z can be captured by an equation.



One-dimensional, time independent, scalar RTE

$$\cos\theta \frac{dL(z,\theta,\phi,\lambda)}{dz} = -[a(z,\lambda) + b(z,\lambda)]\, L(z,\theta,\phi,\lambda)$$

$$+\, b(z,\lambda)\int_0^{2\pi}\int_0^{\pi} L(z,\theta',\phi',\lambda)\,\tilde{\beta}(z,\theta',\phi'\rightarrow\theta,\phi,\lambda)\,\sin\theta'\, d\theta'\, d\phi'$$

$$+\, S(z,\theta,\phi,\lambda)$$

attenuation

scattering

additional sources

What we want to know is: $L(z, \theta, \phi, \lambda)$ (as underlined in red)

This describes how the full directional radiance distribution changes as you take a small step down through the water column (i.e. *z* increases).

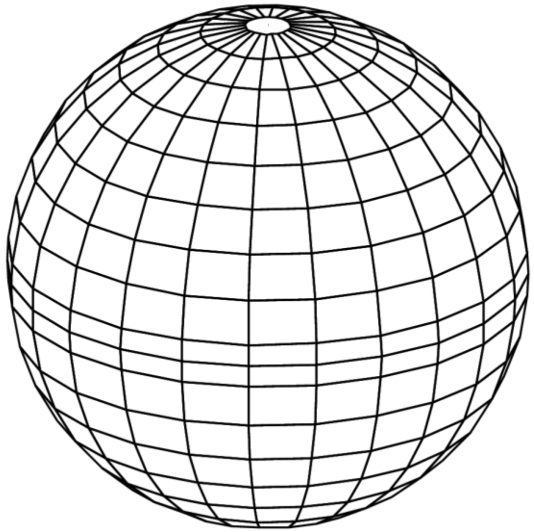
Next step - discretisation of direction

HydroLight standard discretisation

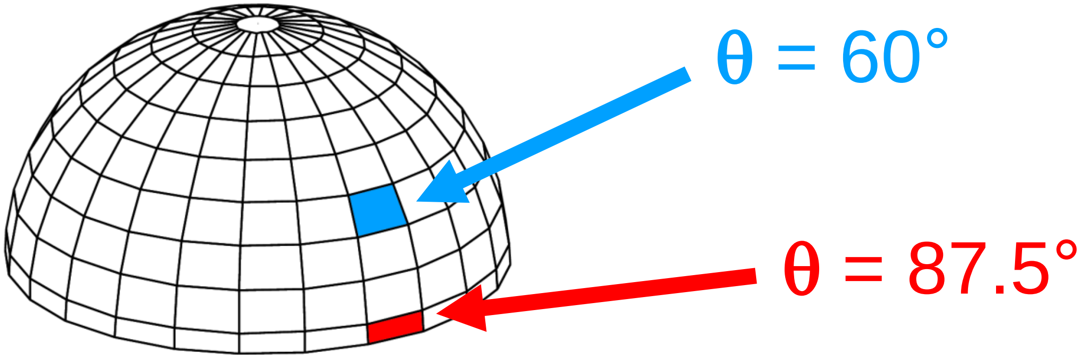
Resolution is $10^\circ \times 15^\circ$

Full sphere of directions 18 x 24 quads
plus end-caps = 434 entries

Work with <u>quad averaged</u> radiances



Or consider separate hemispheres
E.g. downwelling
quad averaged radiance

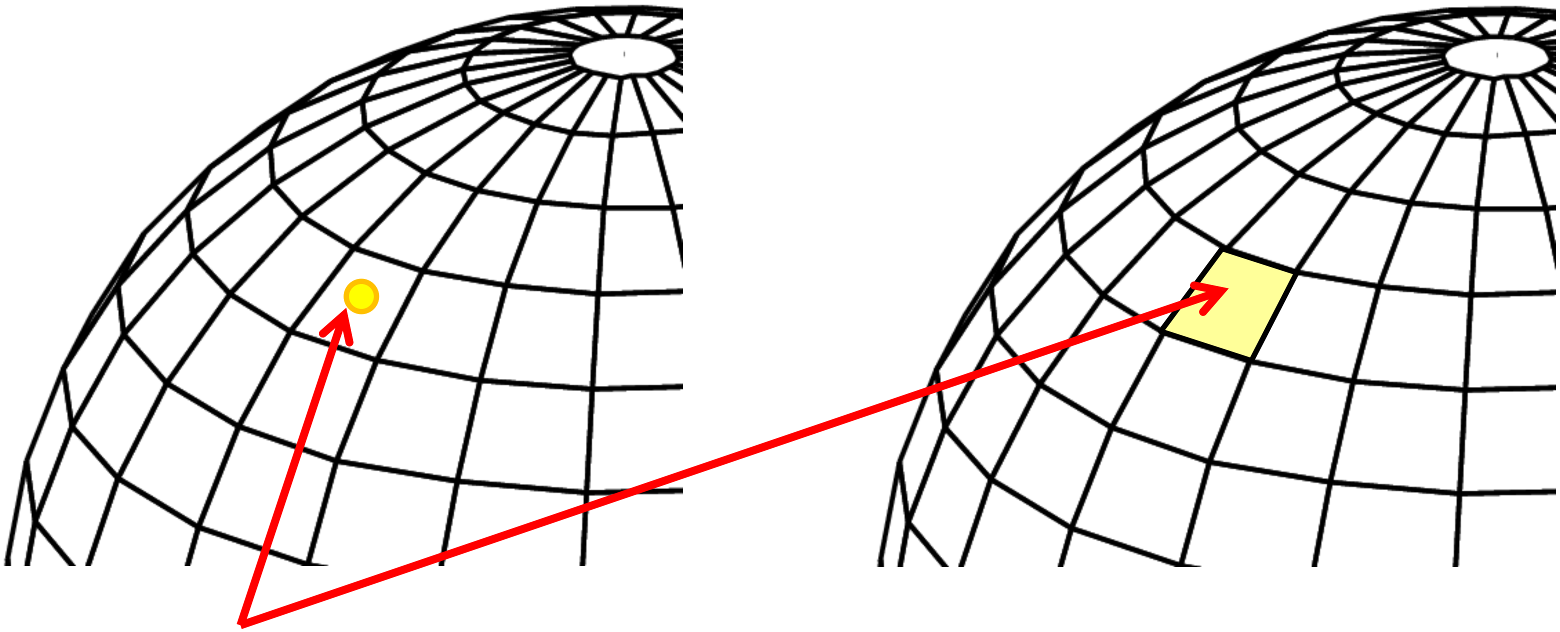


$L(z, \theta, \phi, \lambda) \Rightarrow$ a table of 434 numbers for any particular z and λ

Quad-averaged radiances

The solar disc is smaller than one quad

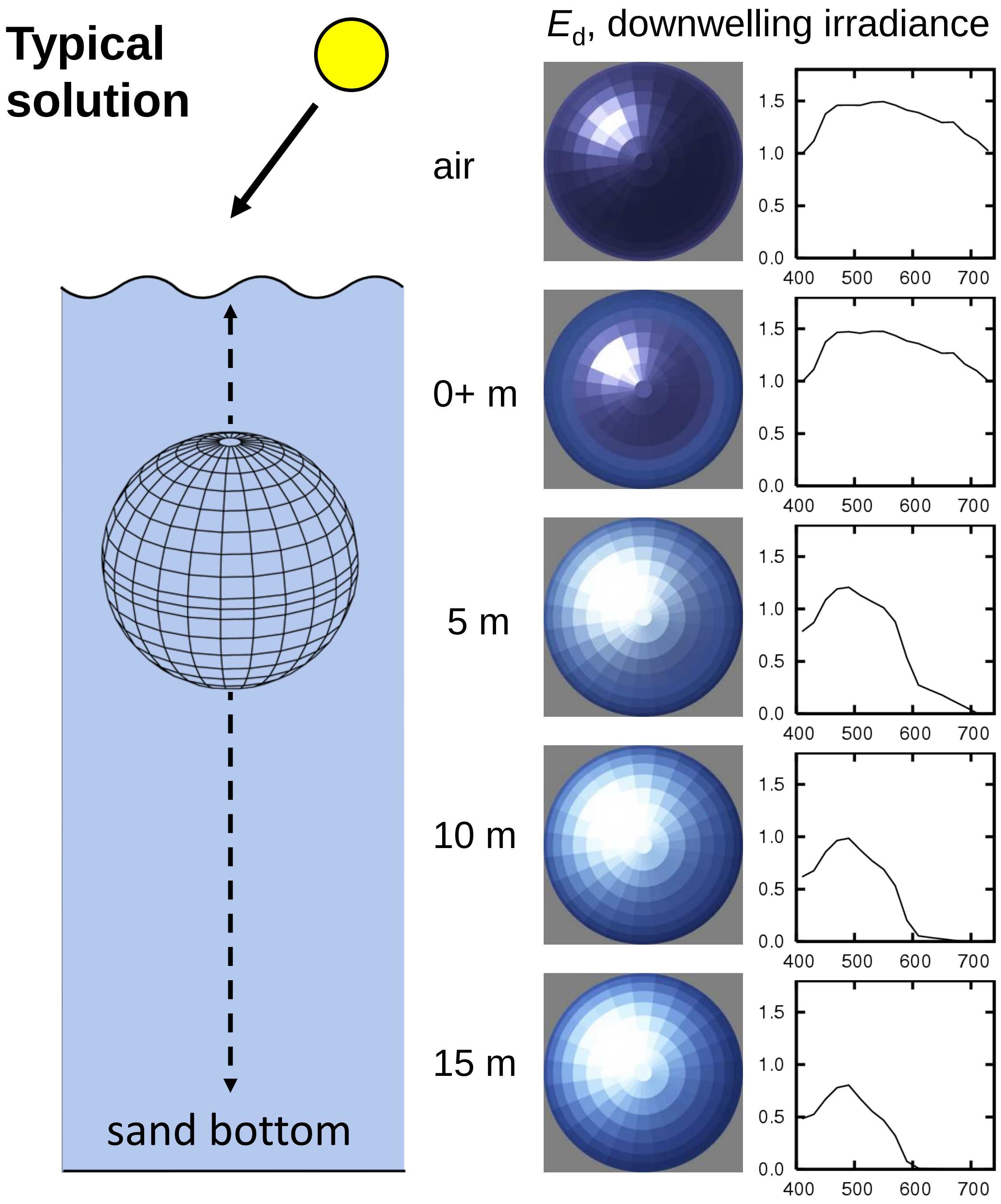
So one consequence is that the direct solar radiance is spread over the quad

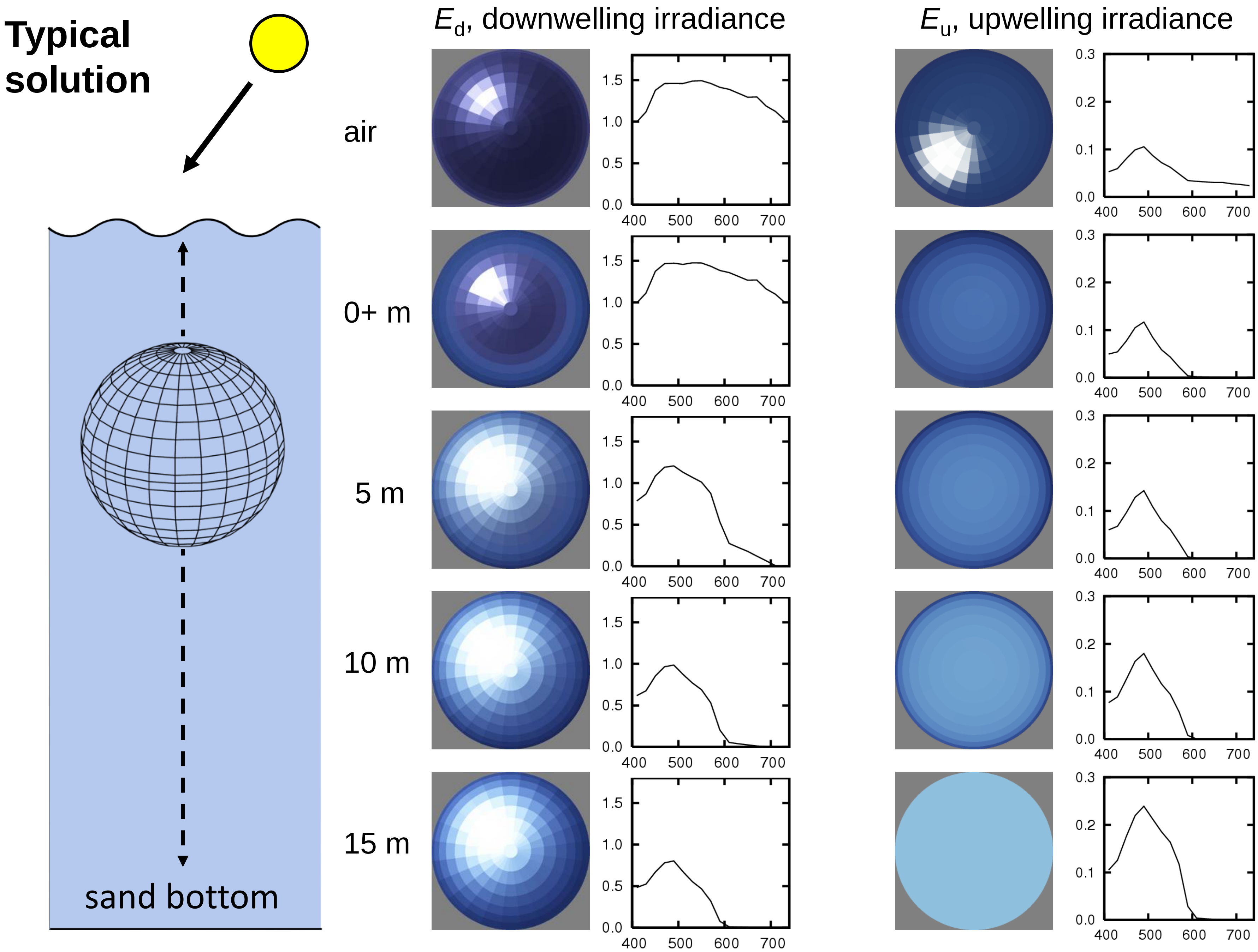


However the total energy as averaged over the quad is the same in both cases and correct.

Makes almost no difference to most quantities of interest, due to scattering the direct radiance is rapidly spread out underwater anyway.

See Tech Note: HTN2_AngularResolution.pdf


Typical solution
E_d, downwelling irradiance
air
0+ m
5 m
10 m
15 m
sand bottom
1.5
1.0
0.5
0.0
400
500
600
700



Typical solution
air
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E_d, downwelling irradiance
E_u, upwelling irradiance
0.0
0.5
1.0
1.5
0.1
0.2
0.3
400
500
600
700

Radiative Transfer Equation (RTE)

One-dimensional, time independent, scalar version

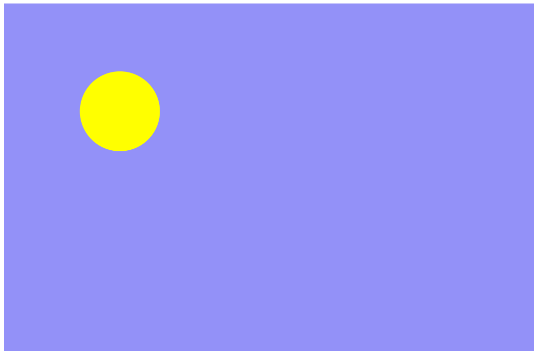
$$\cos\theta \frac{dL(z,\theta,\phi,\lambda)}{dz} = -[a(z,\lambda) + b(z,\lambda)]\, L(z,\theta,\phi,\lambda)$$
$$+\; b(z,\lambda) \int_0^{2\pi} \int_0^{\pi} L(z,\theta',\phi',\lambda)\, \tilde{\beta}(z,\theta',\phi' \rightarrow \theta,\phi,\lambda) \sin\theta'\, d\theta'\, d\phi'$$
$$+\; S(z,\theta,\phi,\lambda)$$

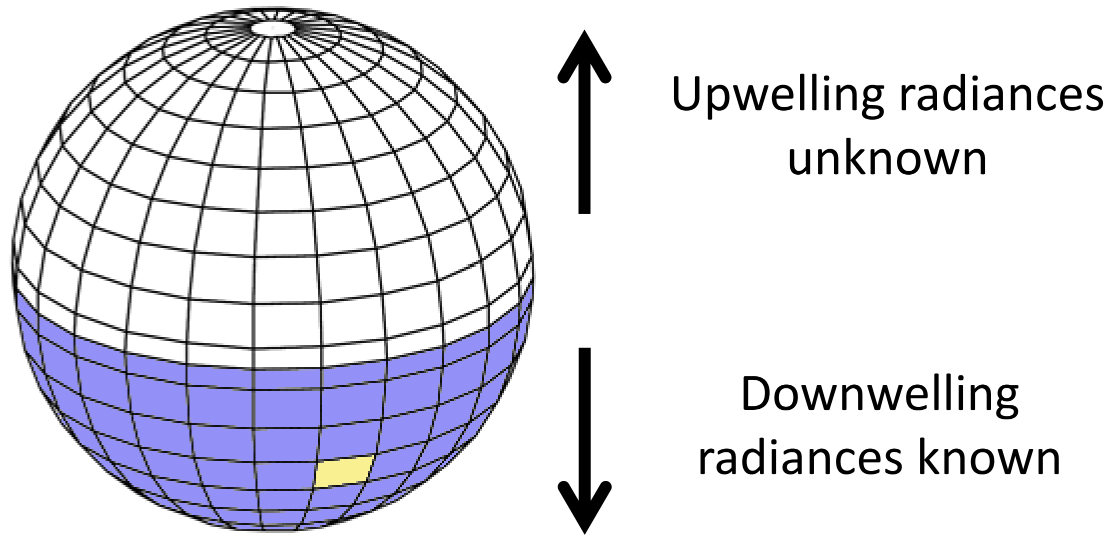
This describes how the full directional radiance distribution (the table of 434 numbers) changes as you take a small step down through the water column (i.e. *z* increases).

This is what we need to solve, but it is not straightforward, because at the start we don't know the full directional radiance distribution, only the downward part (sky radiance distribution).

Sky Radiance Distribution

Is an input, considered known, can be supplied or HydroLight has a built-in model.





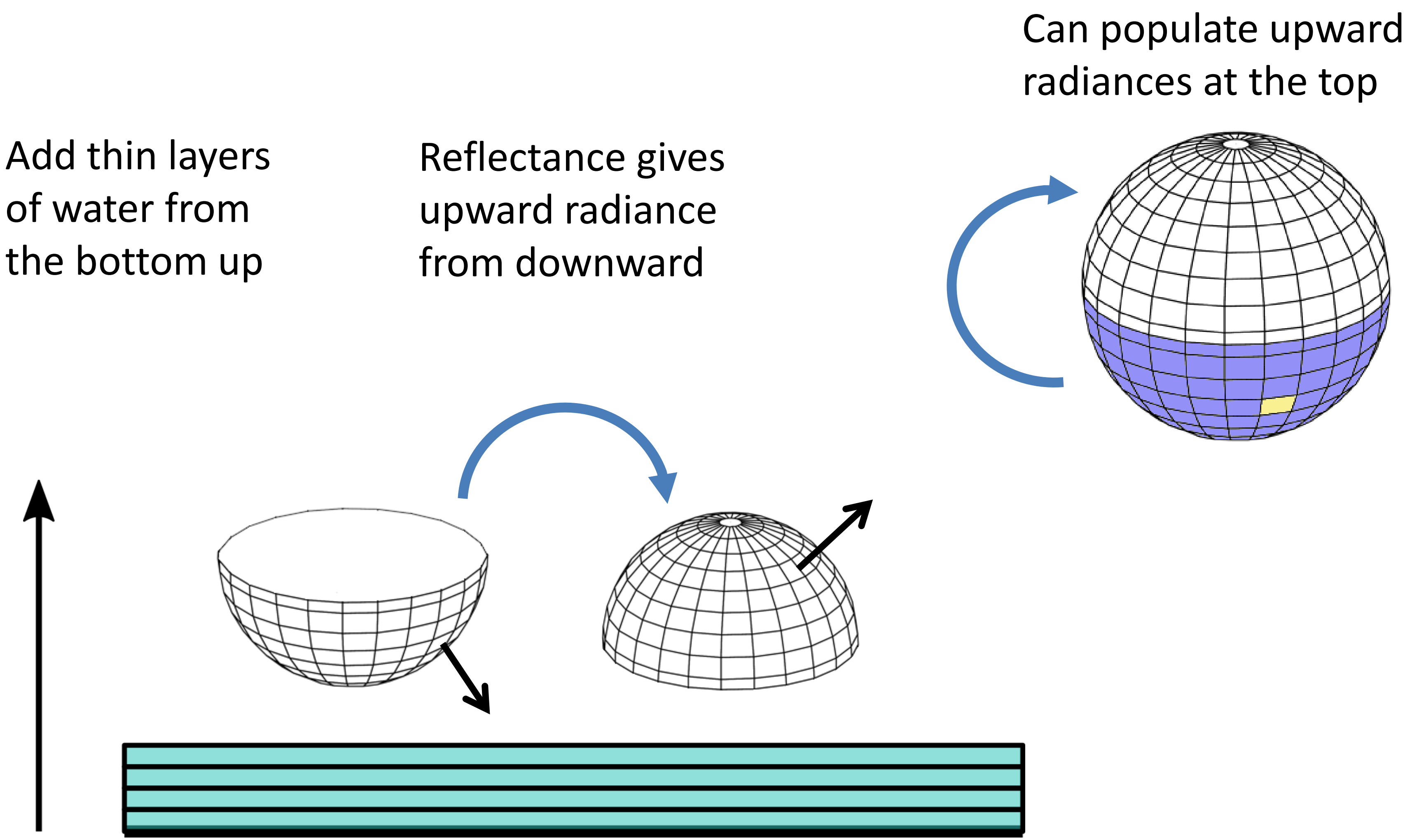
Reason why solving the RTE is non trivial is that at the start we only know the downwelling radiances at the top of the water column.

The other information we need is at the bottom boundary - either the bottom reflectance or the assumption of infinite depth.

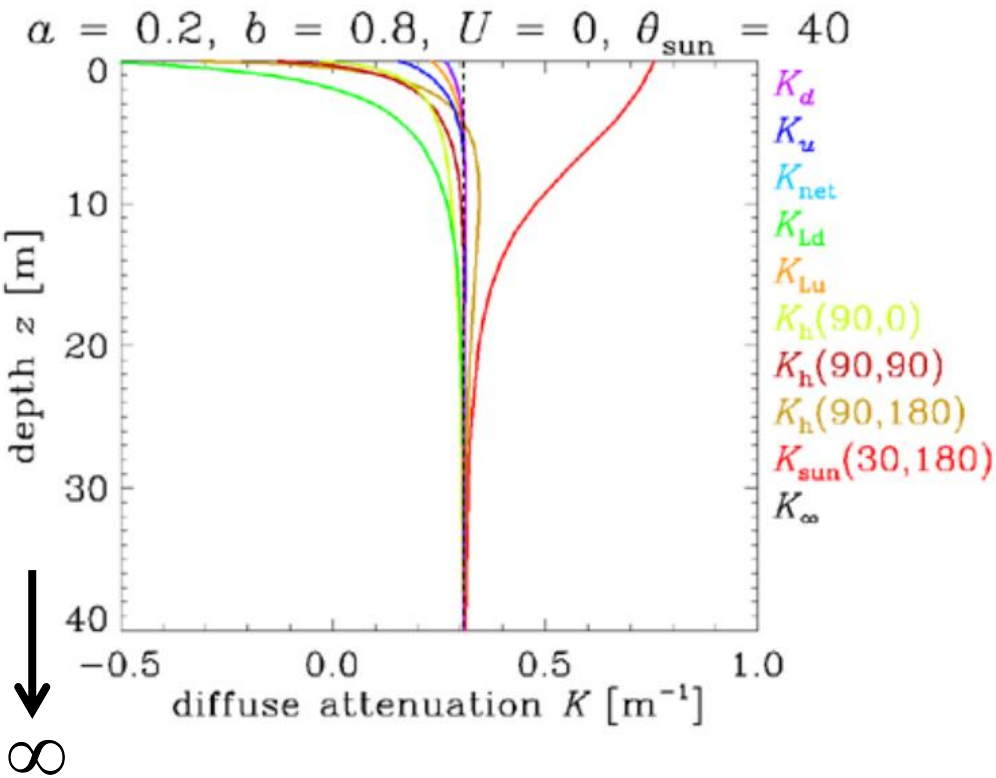
Mathematically a “two-point boundary value problem”

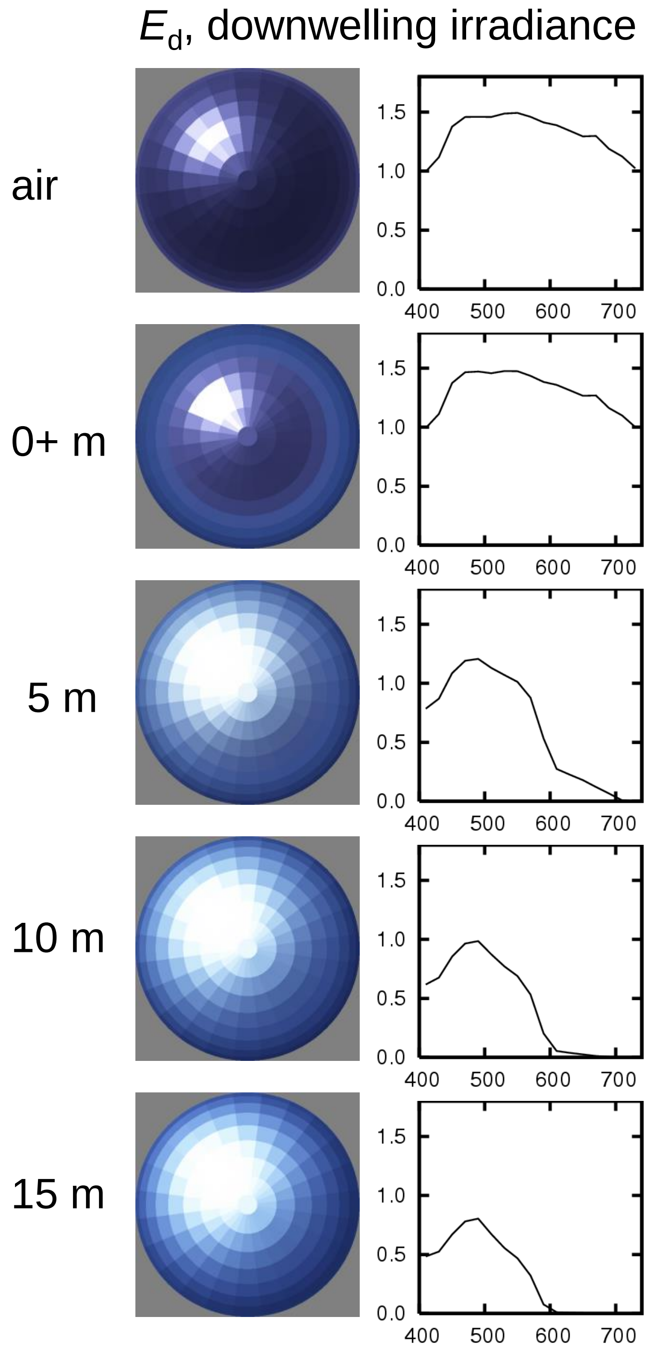
The invariant imbedded method

Reflectance is propagated to the top of the water column first



Infinite depth (homogenous IOPs)





Tends to a constant relative directional distribution of light

→ **Asymptotic radiance distribution**

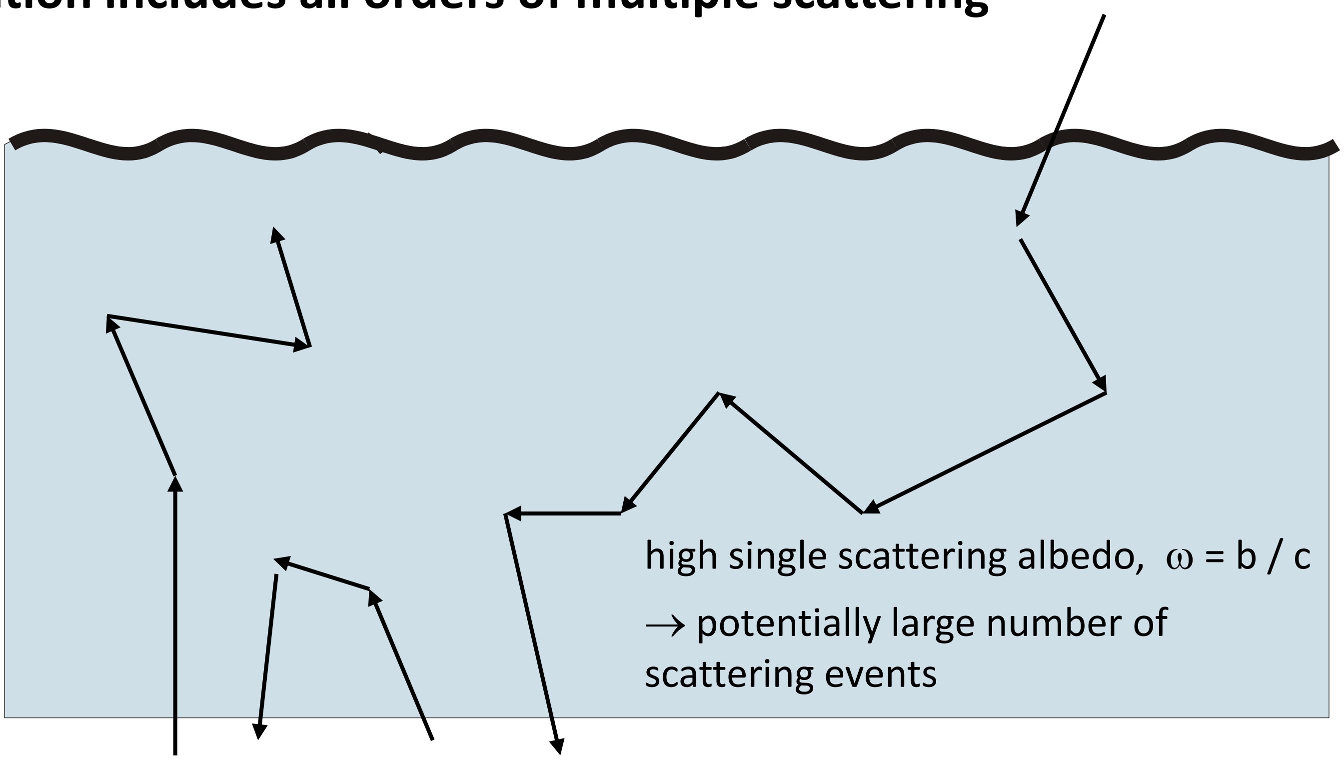
Amount of light decreases with depth according to an exponential function

Comparison of HydroLight vs. Monte Carlo

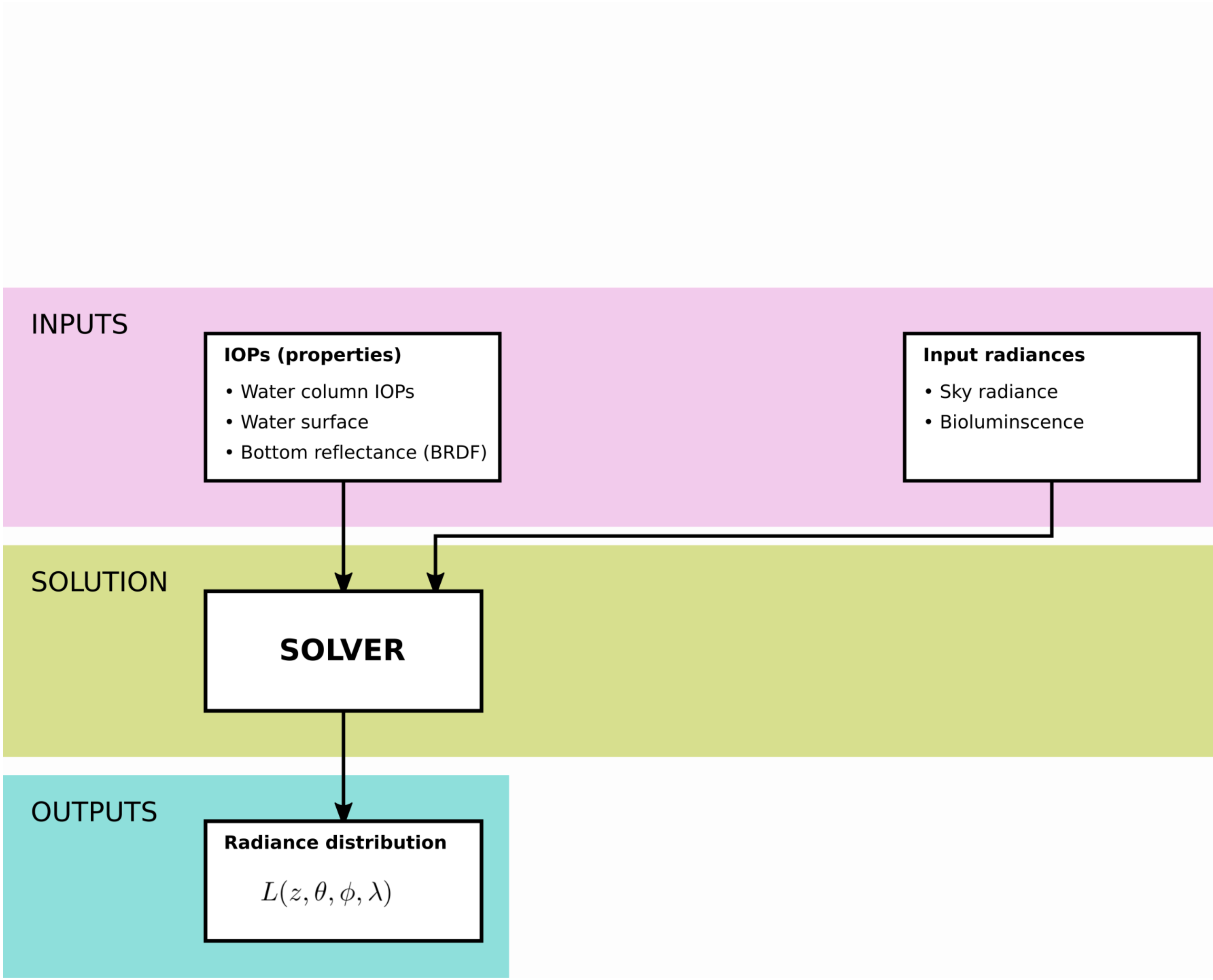
- **Run time linearly proportional to optical depth** (attenuation × physical depth)
  Monte Carlo ∝ exp(optical depth)

- **Run time independent of IOP(*z*) complexity, arbitrary depth resolution**
  not a set of homogeneous layers as used in some methods

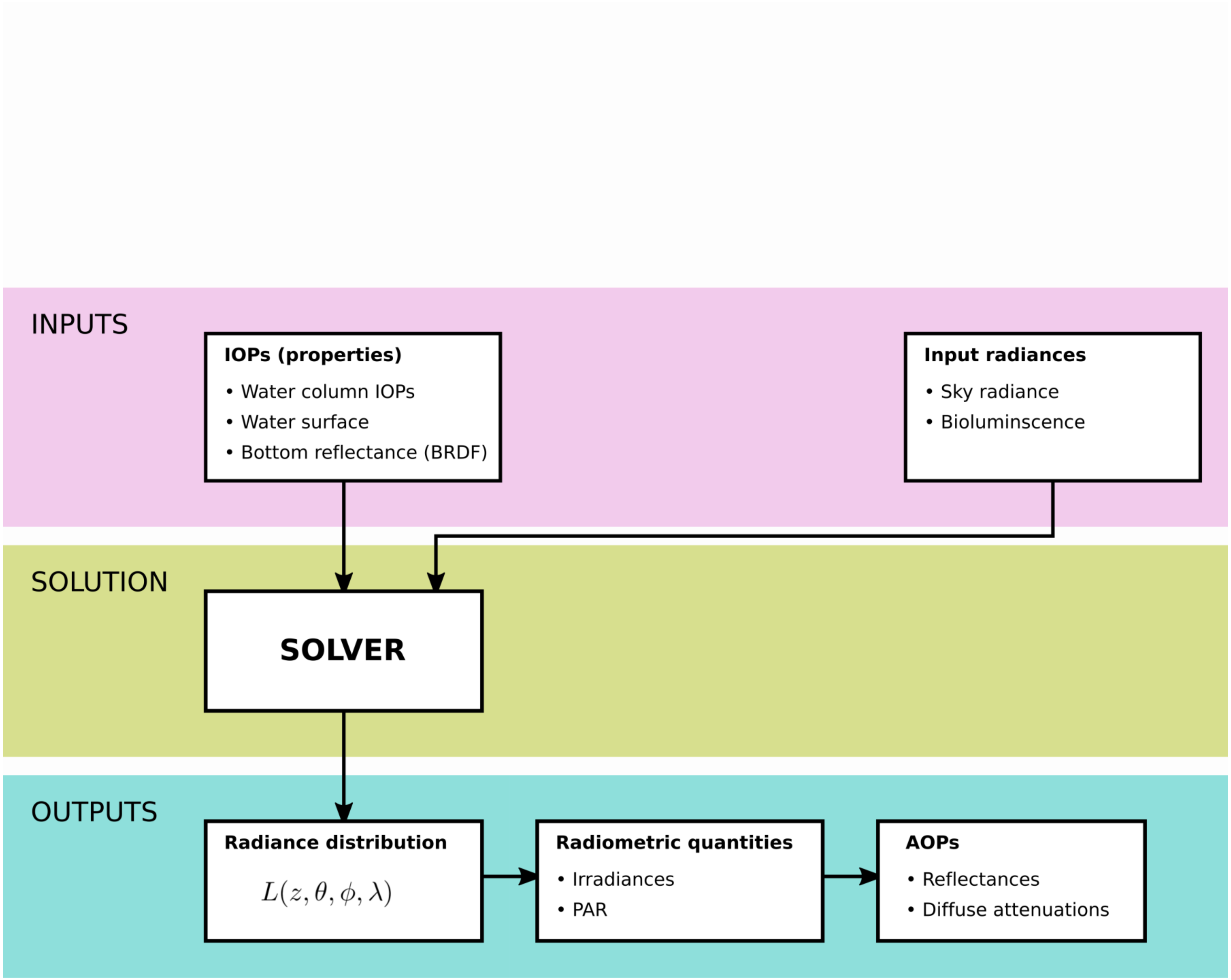
- **Solution includes all orders of multiple scattering**



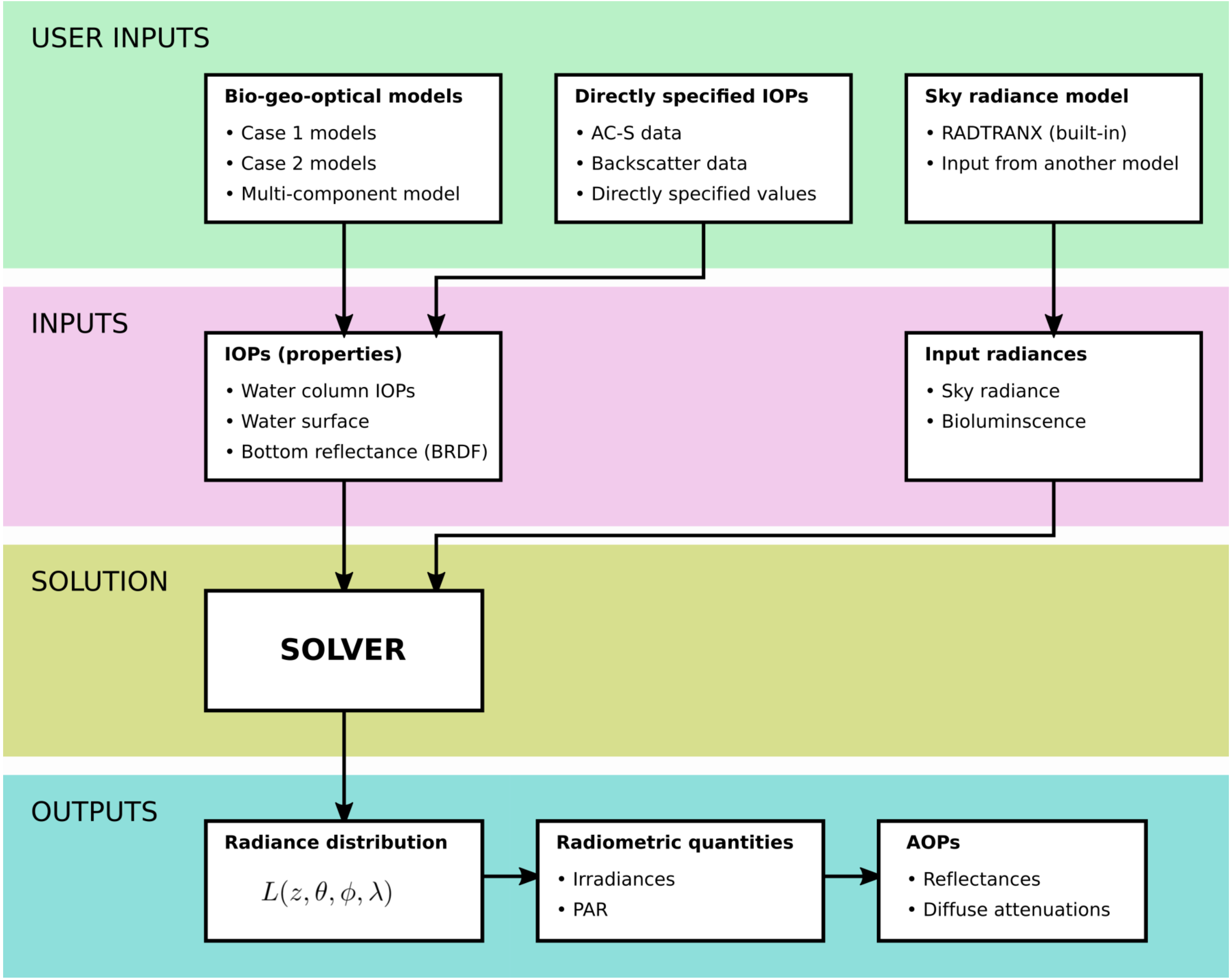
Structure of the HydroLight software



Structure of the HydroLight software



Structure of HydroLight



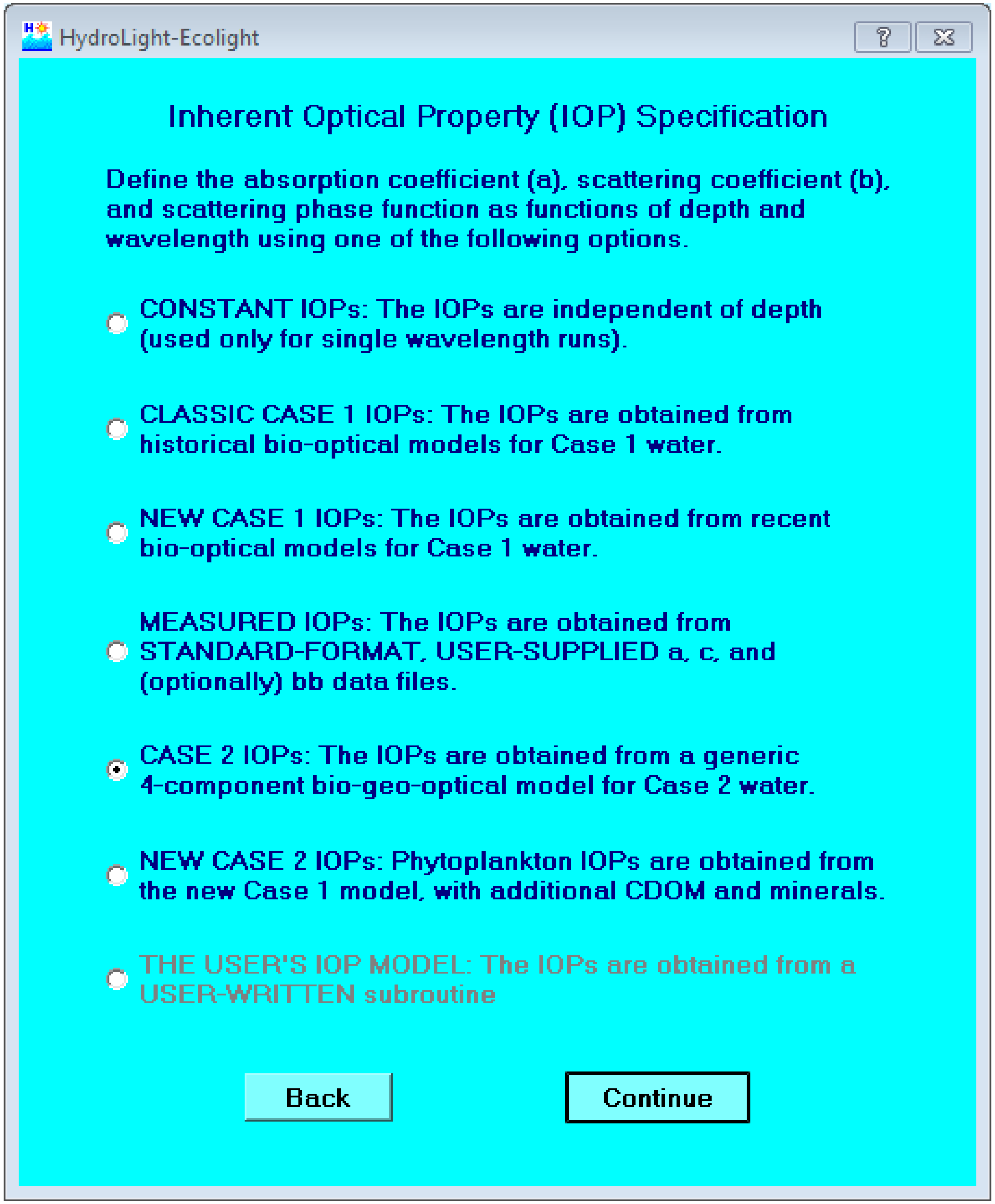
Specify IOPs

To model situations of interest for ocean colour we need to input appropriate IOPs

1. **Measured IOPs**
   – e.g. from AC-S

2. **Bio-geo-optical models**
   – produce IOPs from specified chlorophyll concentration, mineral concentrations, etc.

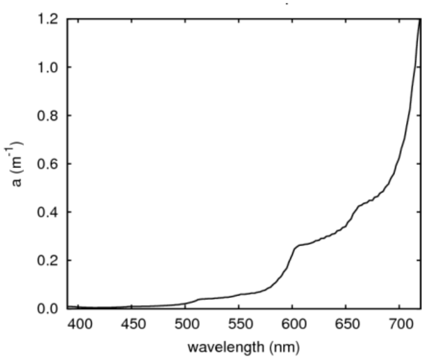
There is a step by step user interface to make this easy.



Total IOPs from multi-component models

IOP contributions of components can just be added to make the total

Pure water absorption



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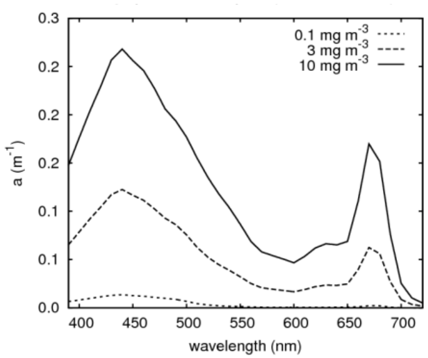
Phytoplankton absorption



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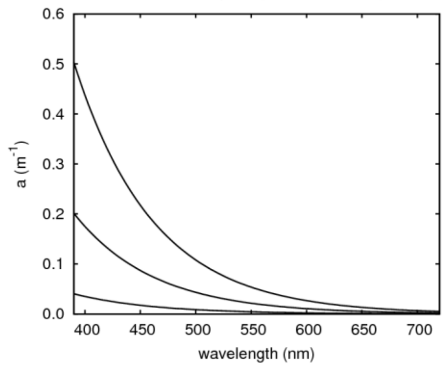
CDOM absorption



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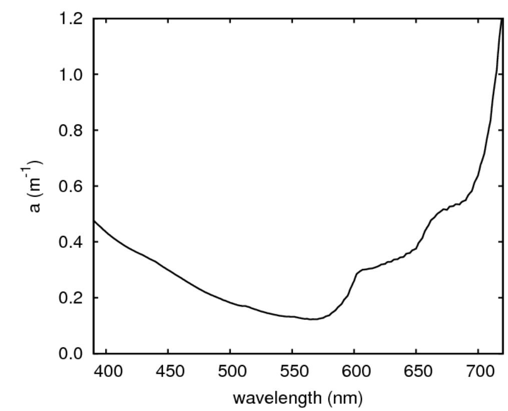
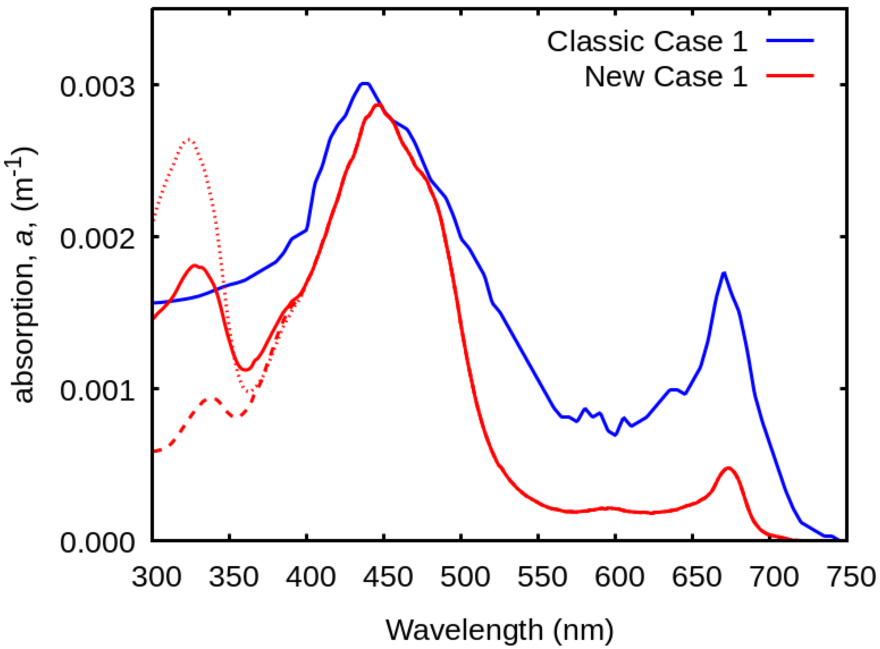
Total absorption



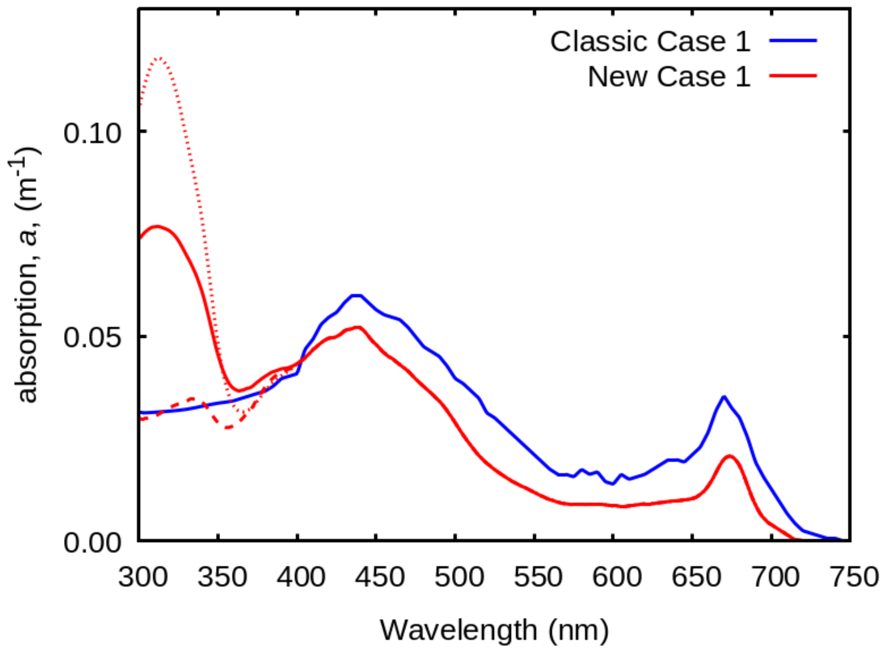
- HydroLight has a number of built-in multi-component models for Case 1 and Case 2 waters.
- Based on key papers from the literature.
- Various possible input data, e.g. depth profiles of conceration, mass specific absorption and scattering etc.

Example Case 1 phytoplankton component models

Chl 0.01 mg/m^3



Chl 1 mg/m^3

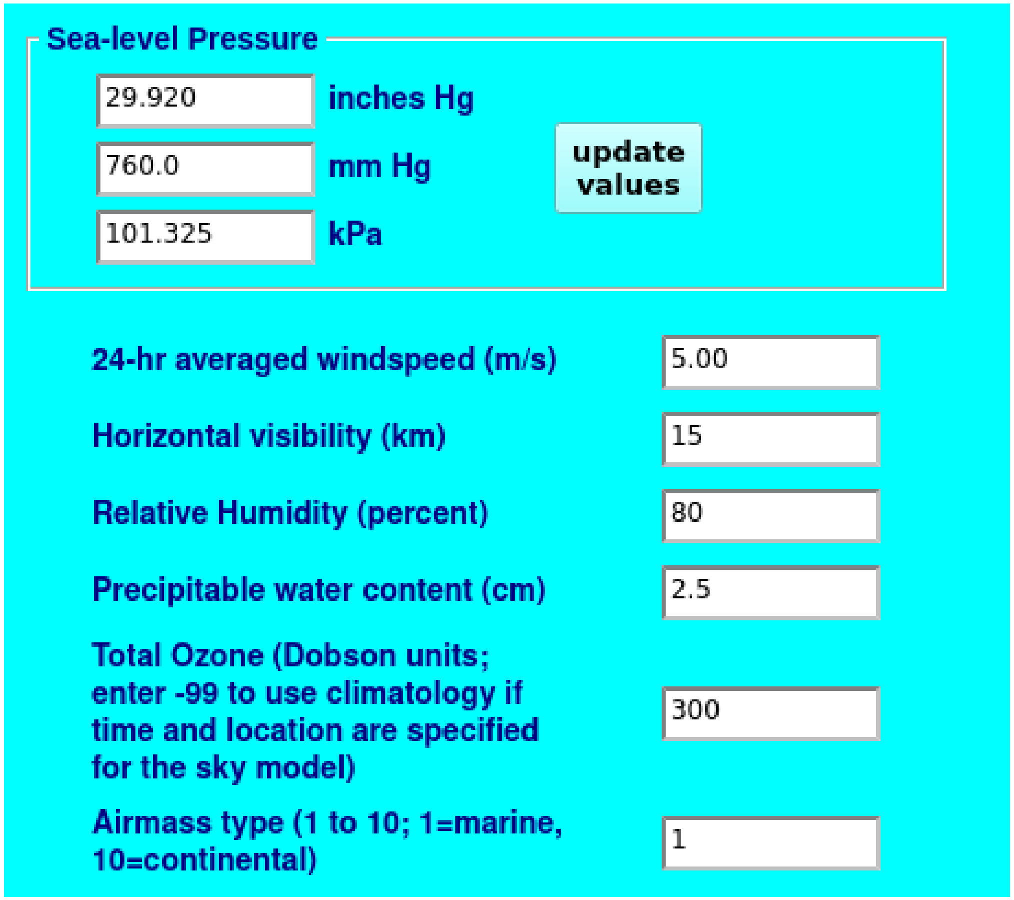


New Case 1 model has three treatments for UV absorption: high, mid, low

Note: these are **generic** models!

Sky Radiance Model

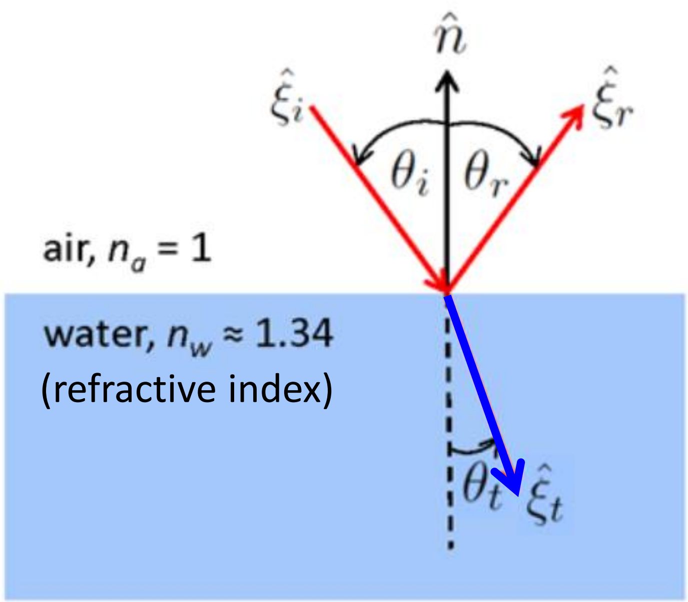
HydroLight includes a basic sky radiance model, RADTRANX



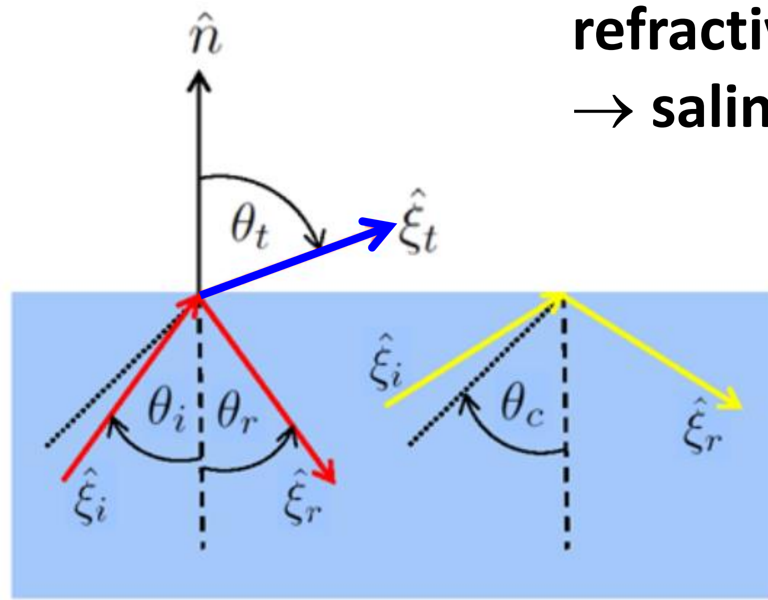
- Can also import sky radiance from other models, e.g. MODTRAN
- Reflectances and k-functions relatively insensitive to details of sky model

Air-water interface – flat surface (Fresnel equations)

air incident



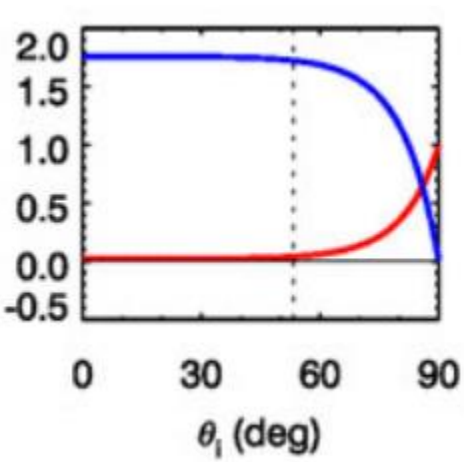
water incident



depends on refractive index → salinity

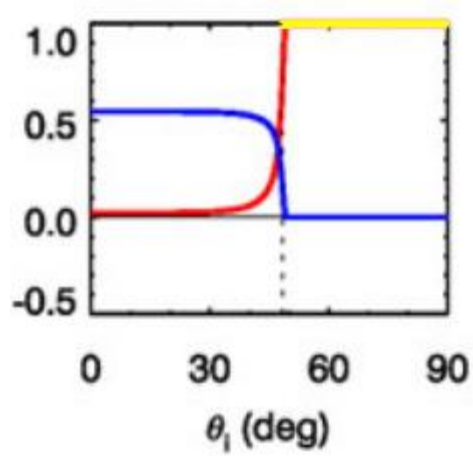
transmission

reflectance



transmission

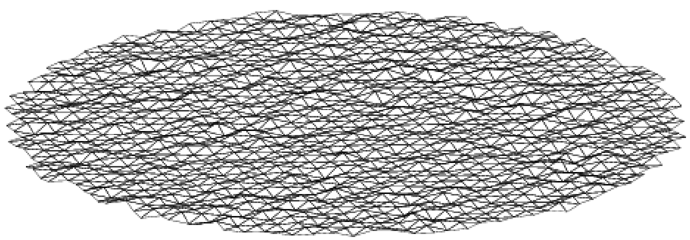
reflectance



total internal reflectance

Air water interface model – wind roughened surfaces

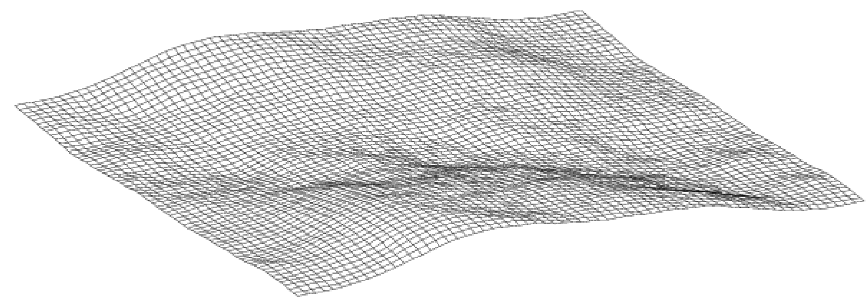
Cox-Munk slope statistics only



scale invariant

No wave structures

Slope and elevation statistics



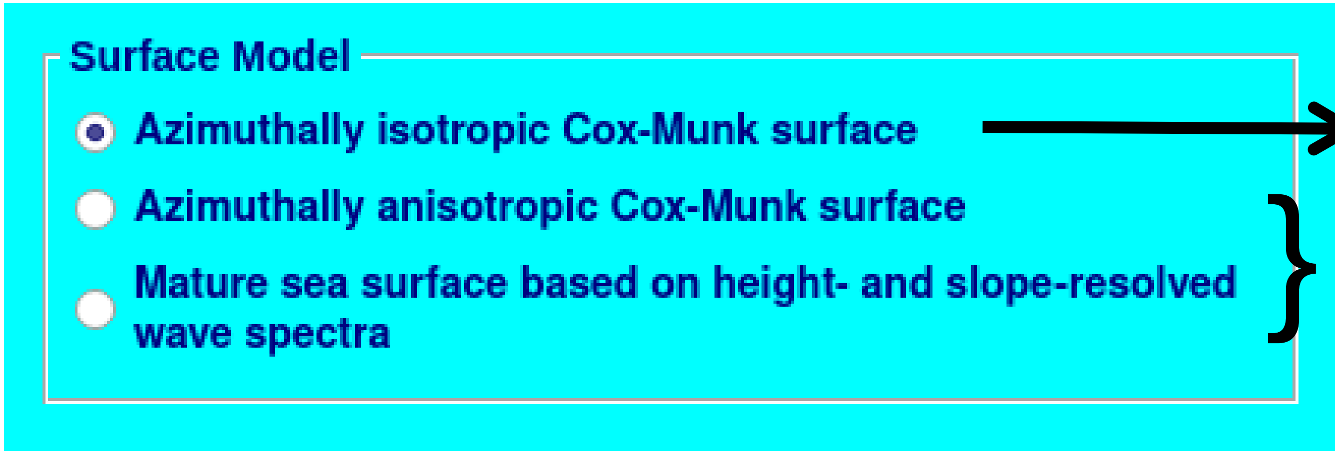
3 m

Needs to be large and detailed enough to cover features from 100s m to millimetres

- Ray tracing is used to characterise the directional reflectance and transmittance - pre-calculated functions.

Sea surfaces summary

The current options in HydroLight :



azimuthally averaged

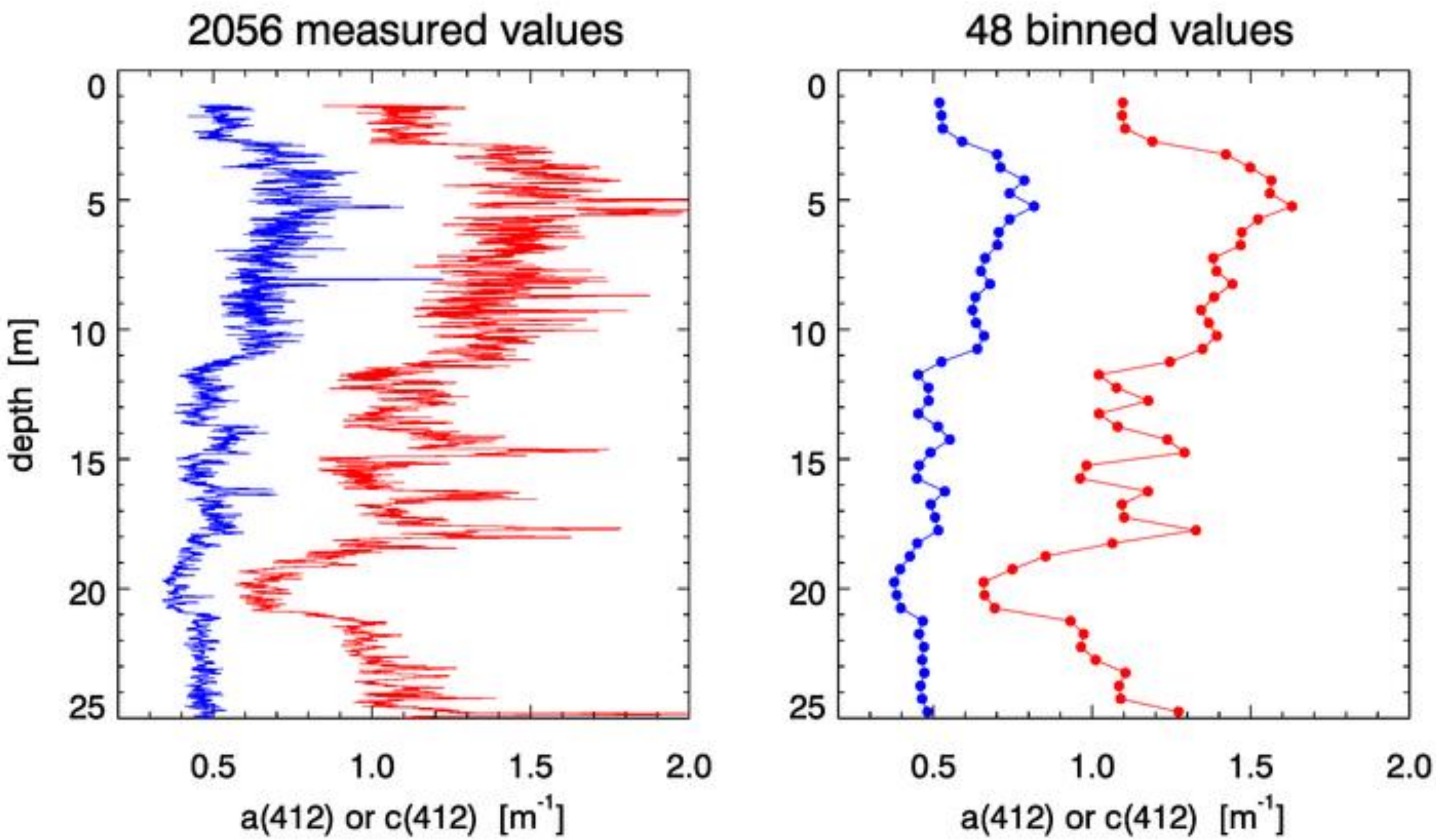
sun azimuth must be specified

As a function of :

- Wind speed (u_{10}, ms^{-1})
- Salinity (i.e. relative refractive index of water, range 1.32 - 1.38).
- And, for the second two – relative sun azimuth.

Measured IOP Input Data

Clean up your data before giving it to HydroLight!



absorption coefficient, *a*

attenuation coefficient, *c*

HydroLight summary of features and limitations

- time independent
- one spatial dimension (depth) - no restrictions on depth dependence of IOPs (not a “layered” model)
- no restriction on wavelengths included, from 300 to 1000 nm
- model for sky radiance onto sea surface, or can load arbitrary data
- Cox-Munk air-water surface (parameterizes gravity & capillary waves via the wind speed)
- infinite depth or supplied bottom reflectance are possible options
- includes all orders of multiple scattering
- includes Raman scatter by water
- includes fluorescence by chlorophyll and CDOM
- includes internal sources (bioluminescing layers)
- polarization not included (the biggest inaccuracy in HydroLight: gives errors in computed radiances of up to ~10%, ~1% in irradiances)
- whitecaps not included

“Validation” - general discussion

What does it mean?

Probably,

“Comparison of model outputs to empirical data are of acceptable accuracy”

Optical Closure:

E.g. measure IOPs → model reflectance → compare to satellite data

<u>Many different aspects that can be “wrong”:</u>

Physical concepts – plane parallel assumption, scalar approximation

Solution method – e.g. Monte Carlo vs. invariant imbedded

Implementation – is the program written correctly, any bugs?

Measurement of empirical data – uncertainties in empirical data

Where is HydroLight on these aspects?

Physical concepts

– physical concepts well accepted within the scope of the model definition
– e.g. scope includes plane parallel assumption, scalar approximation

Solution method

– invariant imbedded method is an “exact” physical solution

Implementation

– no serious bugs found in quite a while
– benefit of a long time code-base in use by many people
– still an ever present danger!

Measurement of empirical data

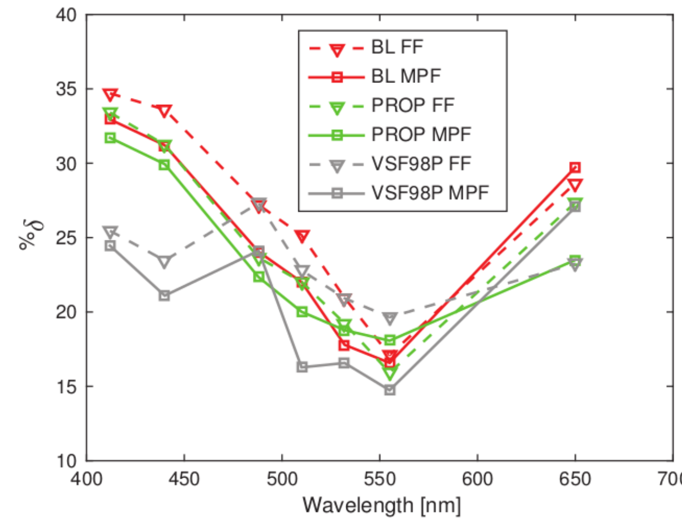
– main area for doubt, both in terms of inputs and output comparisons
– HydroLight includes built-in options, such as phase functions, Chl and CDOM fluoresence, etc. these are empirically based: **USER BEWARE**
– for some real data is scarce, e.g. CDOM fluoresence, only 1 paper!

Examples of optical closure using HydroLight

Tonizzo et al. (2017)
Applied Optics 56, 130-146.

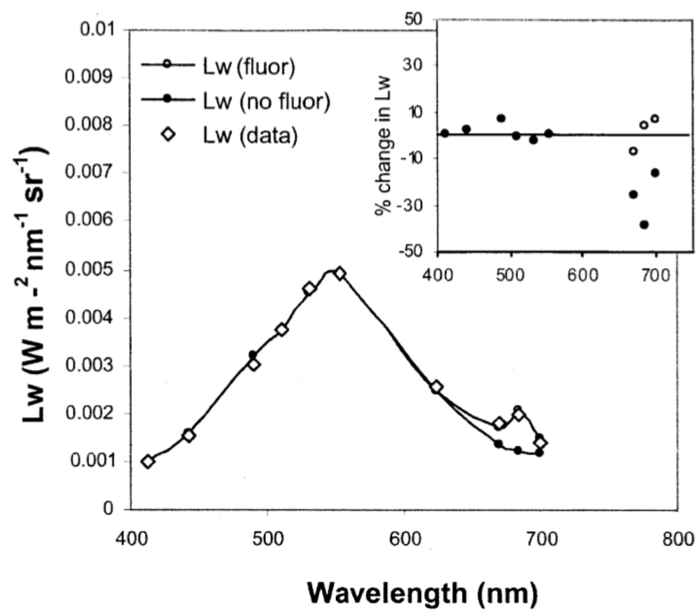
Overal discrepancies between measured R_{rs} and modelled:

- Using measured phase functions ~20%
- Fournier-Forand phase functons ~23%



Tzortziou et al. (2005)
Estuarine, Coastal and Shelf Science 68, 348-362.

Average % difference between modelled and measured water leaving radiances ~7% (0 - 20%)



→ Very careful studies – discrepances of 20% are in general a very good result.

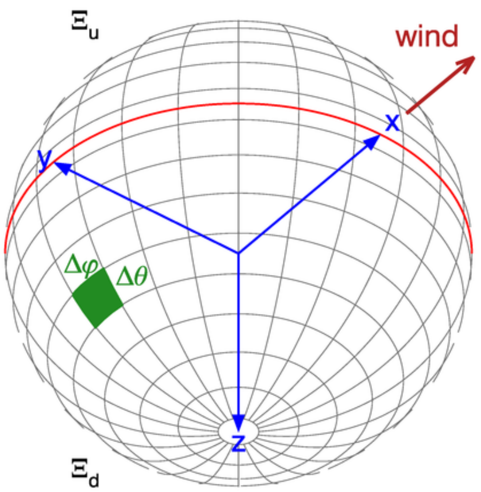
EcoLight

EcoLight is the same solution method as HydroLight but computes <u>azimuthally averaged radiances</u> within solid angle bands.

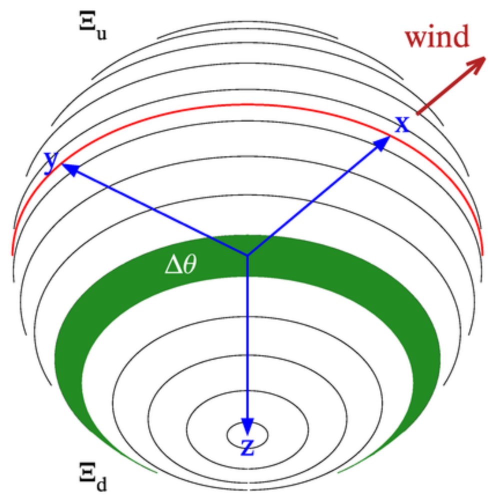
The <u>irradiances</u> and <u>polar cap radiances</u> are the same for HydroLight and EcoLight.

Diffuse attenuations (*K* values), reflectances R, R_{rs}, etc. are also the same.

HL



EL



$$L(z,\theta,\phi,\lambda) \rightarrow L(k,u,j) = \frac{1}{\Delta\lambda_j \, 2\pi \, \Delta\Omega_u} \int_{\Delta\lambda_j} \int_0^{2\pi} \int_{\Delta\Omega_u} L(z_k,\theta,\phi,\lambda) \sin\theta \, d\theta \, d\phi \, d\lambda$$

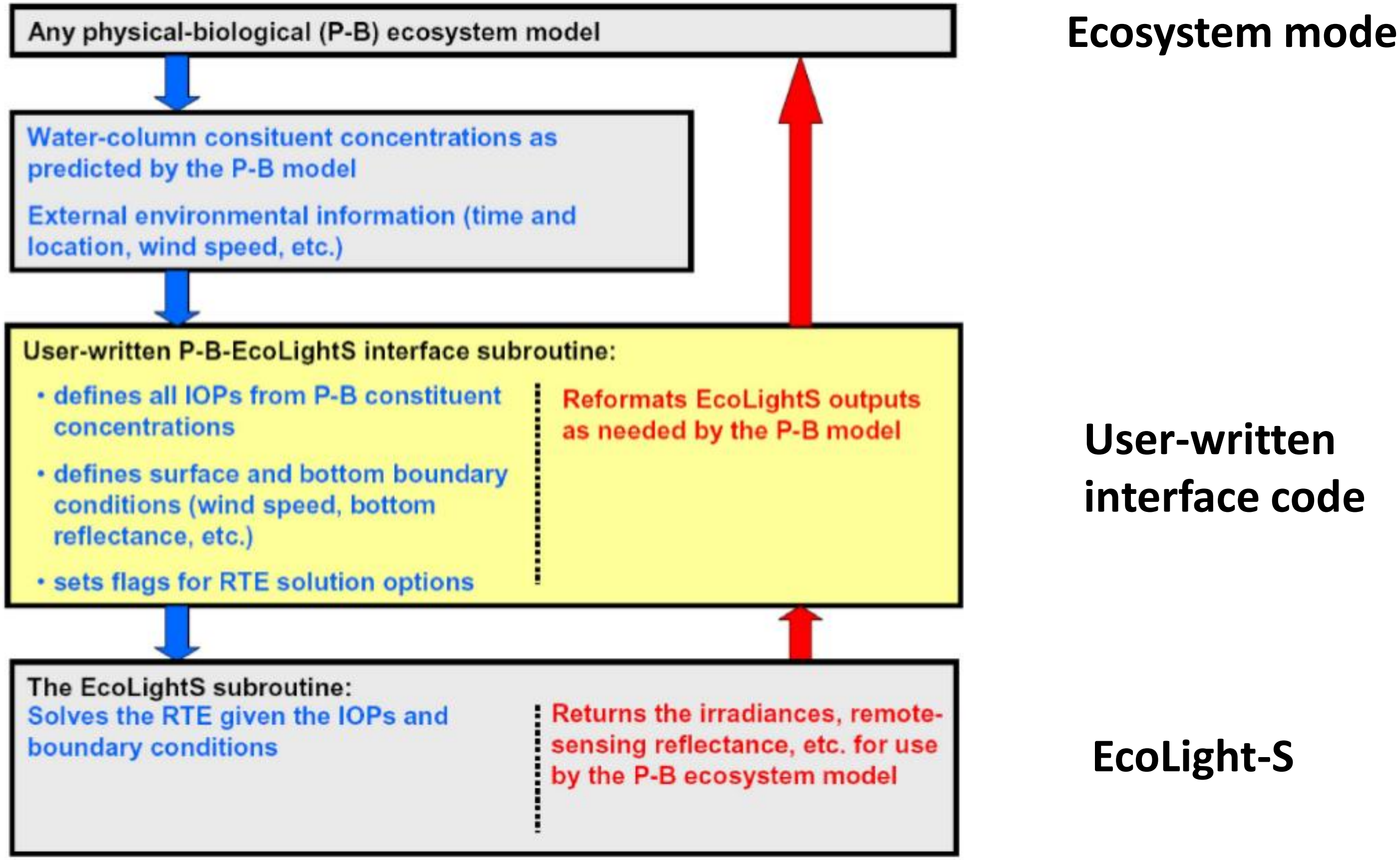
- EcoLight is typically 20 to 1000 times faster than HydroLight.
- To run HydroLight or EcoLight is an option at the end of the model setup.

What is EcoLight-S ?

EcoLight-S is the EcoLight solution method with some additonal optimisations, provided as a software function for inclusion into other software.

Can be used in ecosystem models to calculate light for photobiology and heating.

More accurate than broadband K_d(PAR) approximations.



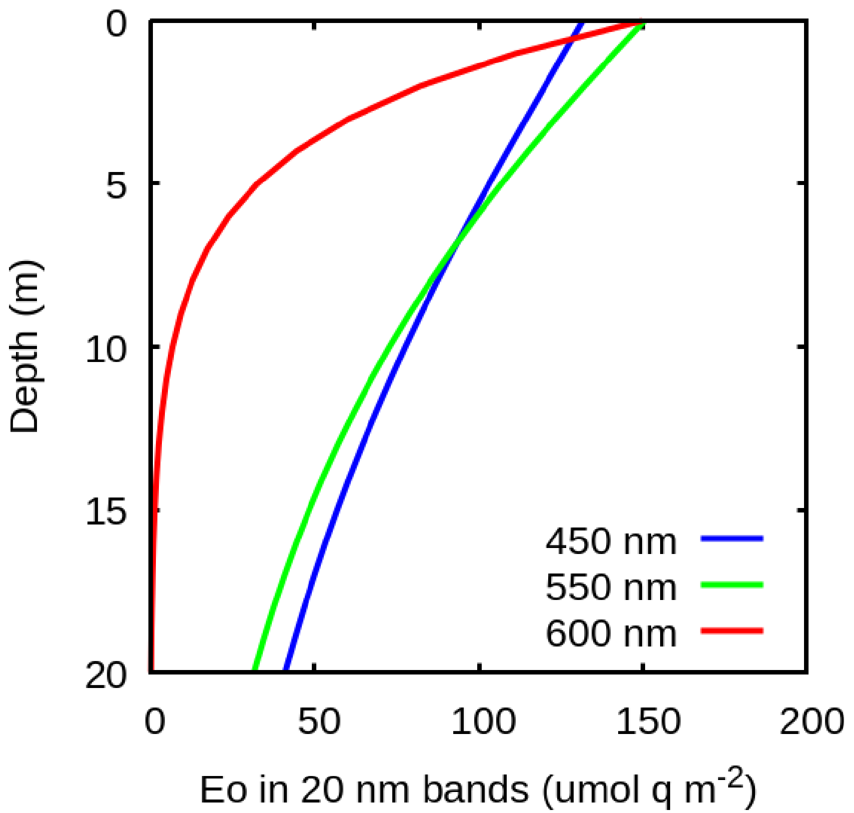
Mobley, 2011. Optics Express 19(20), 18927-18944)

Importance of modelling light correctly in an ecosystem model

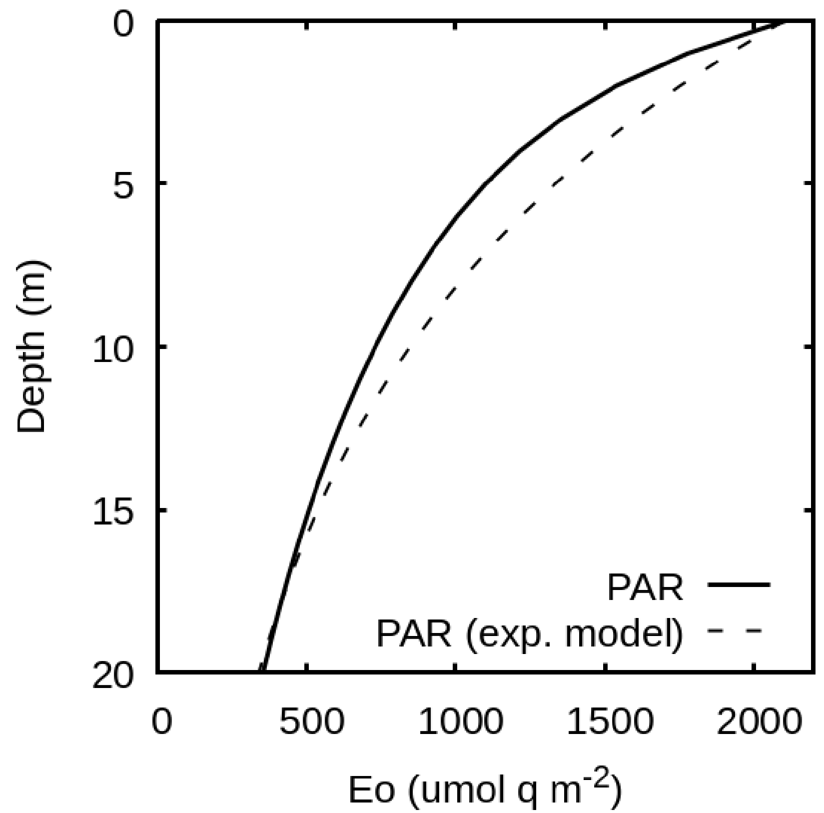
Simple 'broadband' models relate k_{PAR} to constituents

But the light field varies spectrally with depth

Example: Homogenous water column



PAR does not follow exponential model



Importance of modelling light correctly in an ecosystem model

Mobley CD, Chai F, Xiu P, Sundman LK (2014) *JGR Oceans*. doi: 10.1002/2014JC010588

ROMS (Hydrodynamic model) coupled with CoSiNE (Ecosystem model)

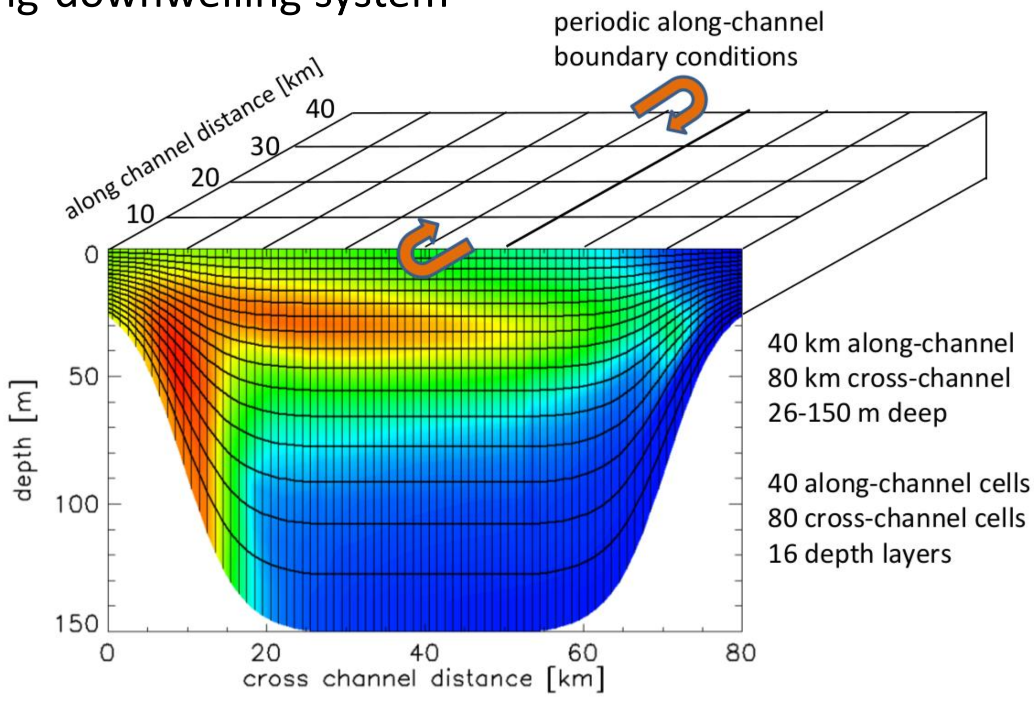
<u>Analytic</u> approach – independent broad-band diffuse attenuation light models for heating and photobiology.

$$E_d(z) = E_d(0)\exp[-\int_0^z K_d(z')z']$$

<u>EcoLight-S</u> – single consistent model using spectral calculations for light.

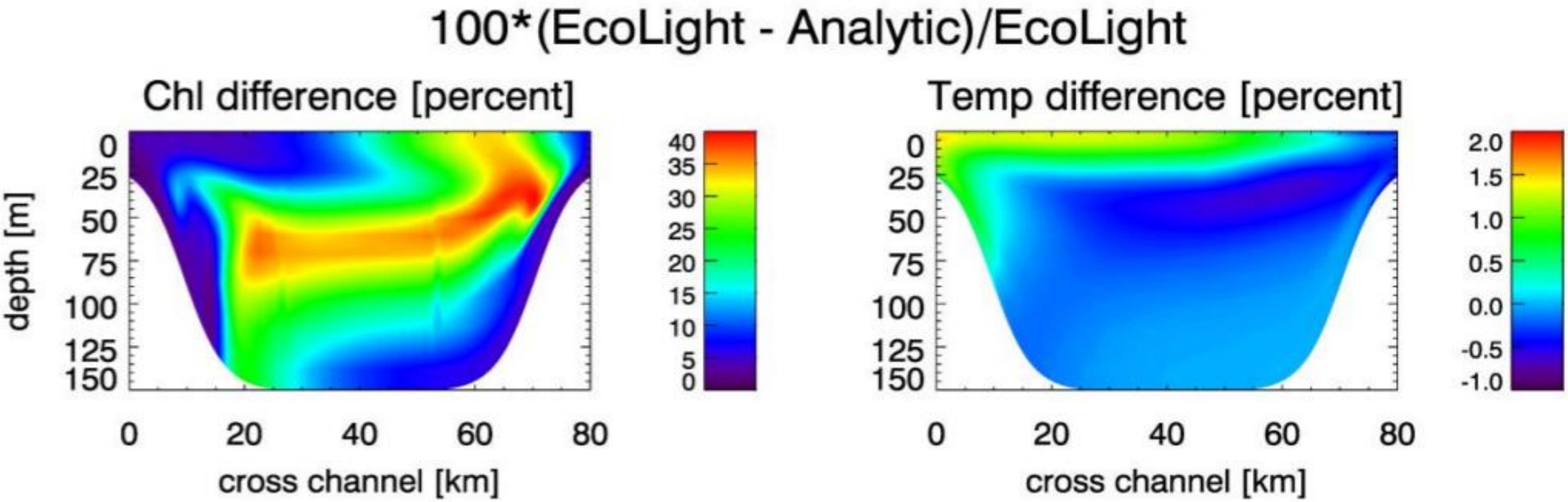
$$E_d(z) = \int_{400}^{700} E_d(z,\lambda)d\lambda$$

Idealized upwelling-downwelling system



Importance of modelling light correctly in an ecosystem model

After model time period of 14 days:



Run time:

Analytic **143 min**

EcoLight-S **170 min**

– only a 19% increase in run time
– no penalty for increasing accuracy of light calculations