

Introduction to HydroLight



John Hedley, IOCCG Summer Class, 2018

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Who am I? - John Hedley

College – Maths, Further Maths, Physics, Electronics

~~Undergraduate Degree – Mathematics and Oceanography~~

Undergraduate Degree – Zoology

Ph.D. – Remote Sensing of Coral Reefs

~10 years in a Coral Reef Ecology Group (Exeter University)

Now run my own company, working with academic and commercial sector.

Activites

- Numerical modelling of radiative transfer
- Shallow water remote sensing - esp. coral reefs and seagrasses
- Benthic photobiology
- Applied work – Satellite derived bathymetry
- Maintain HydroLight

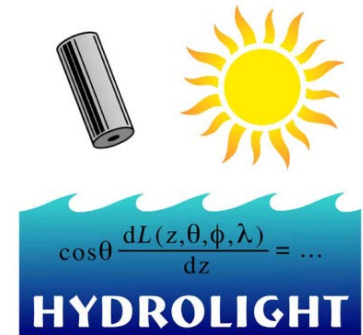
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This lecture

What is HydroLight?

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



The lecture will cover:

- Modelling in general
- Modelling approaches and the method used in HydroLight
- Features and design of HydroLight
- Validation, optical closure
- Example runs using HydroLight

→ Followed by hands-on Lab this afternoon

HydroLight History

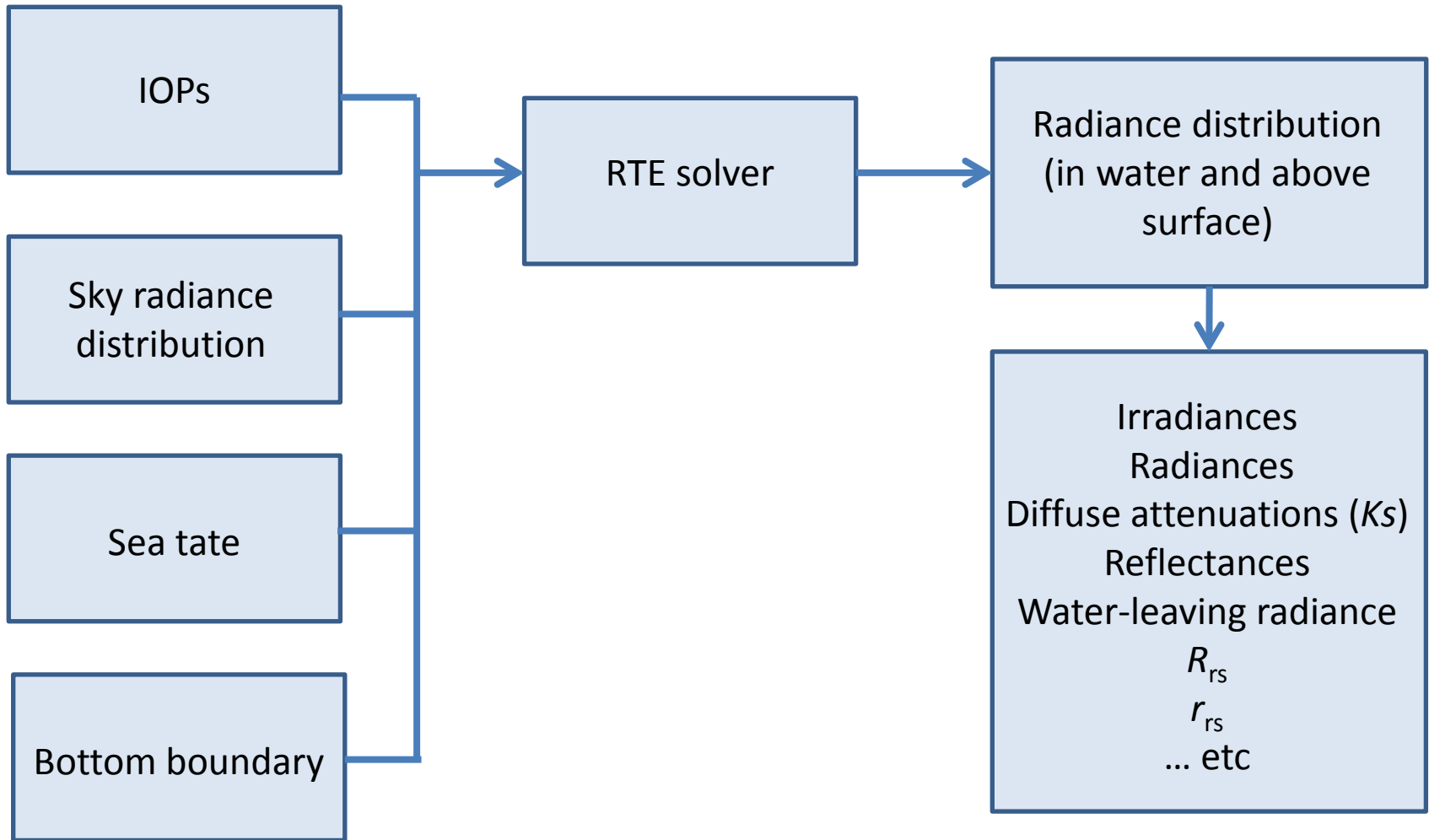
- Developed by Curt Mobley working with Rudy Preisendorfer, starting in 1978.
- Commercial product on PC since 1998. S E Q U O I A
- Over 200 users in 30 countries and used in many publications.
- As of 2017 ownership of HydroLight passed to me (John Hedley) and is now a product of Numerical Optics Ltd.
- Commercial basis has always been the only support for maintenance and development of the software.
- Currently undergoing a complete rewrite of GUI and backend, and development of Mac and Linux versions – version 6.0 imminent



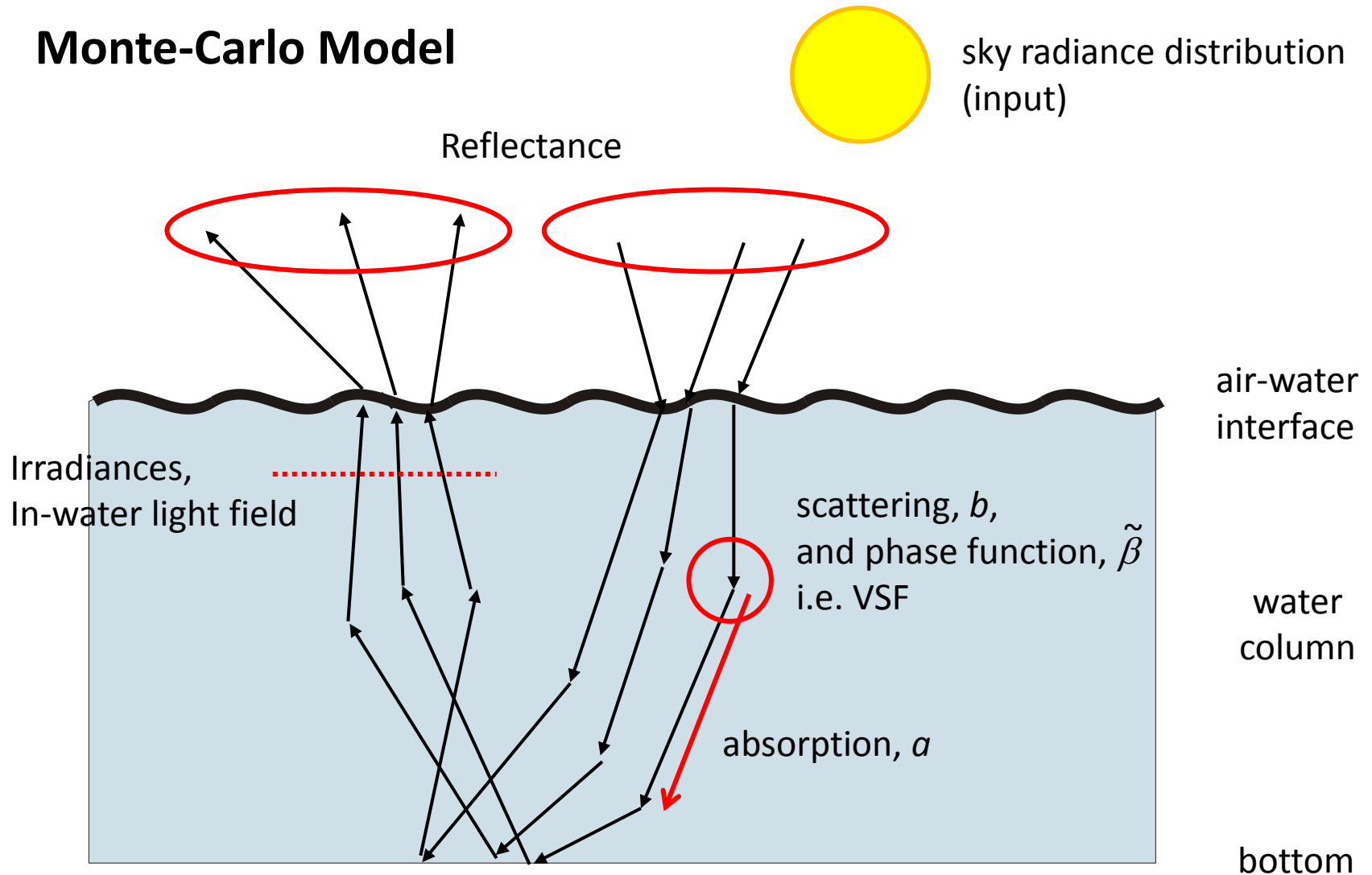
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See the documents *HydroLight_History.pdf* and *HydroLight_Future.pdf* for more info.

What does HydroLight do?



Monte-Carlo Model



→ Close association between implementation and physical concepts

The Complete Solution

Would be:

The radiance distribution (L)

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

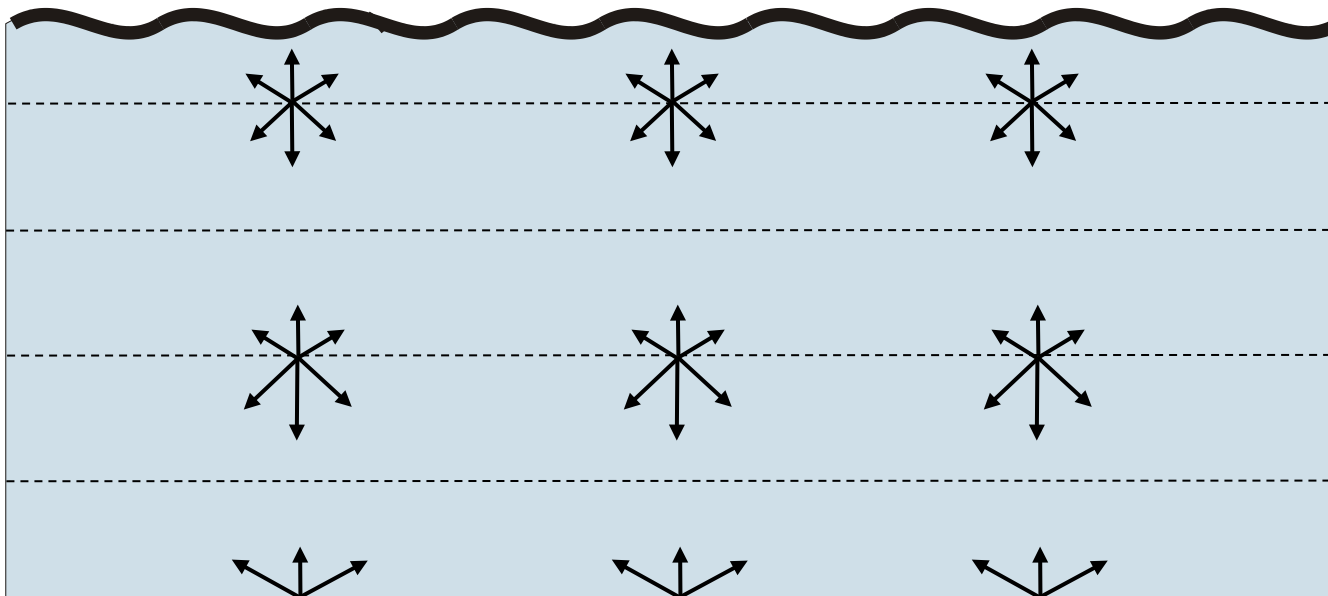
I.e.

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

From radiance every other radiometric property can be derived,
Irradiances, reflectances, diffuse attenuation coefficients (K values), etc.

First approximation - 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 $L(z, \theta, \phi, \lambda)$ ($\text{Wm}^{-2}\text{sr}^{-1}$)

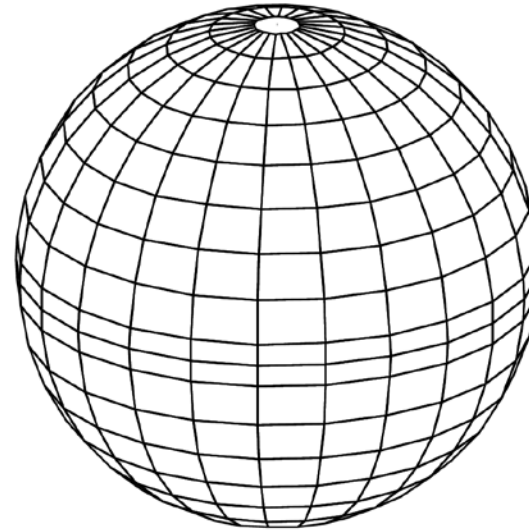
Next step - discretisation of direction

HydroLight standard discretisation

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

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

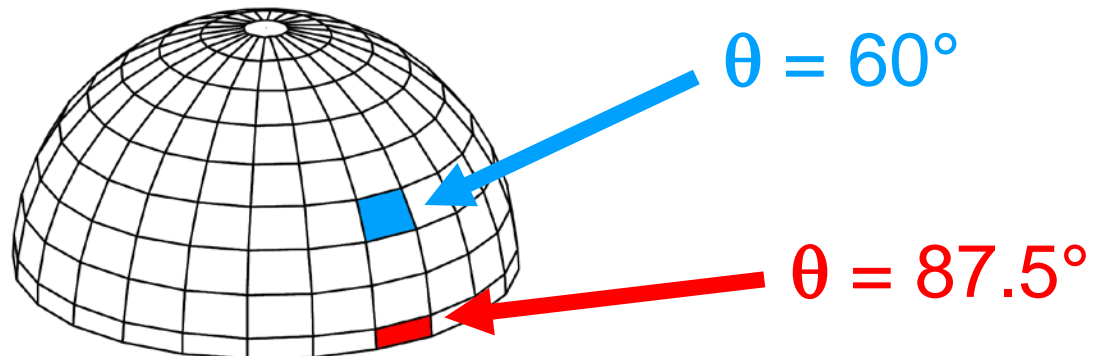
Work with quad averaged radiances



Or consider separate hemispheres

E.g. downwelling

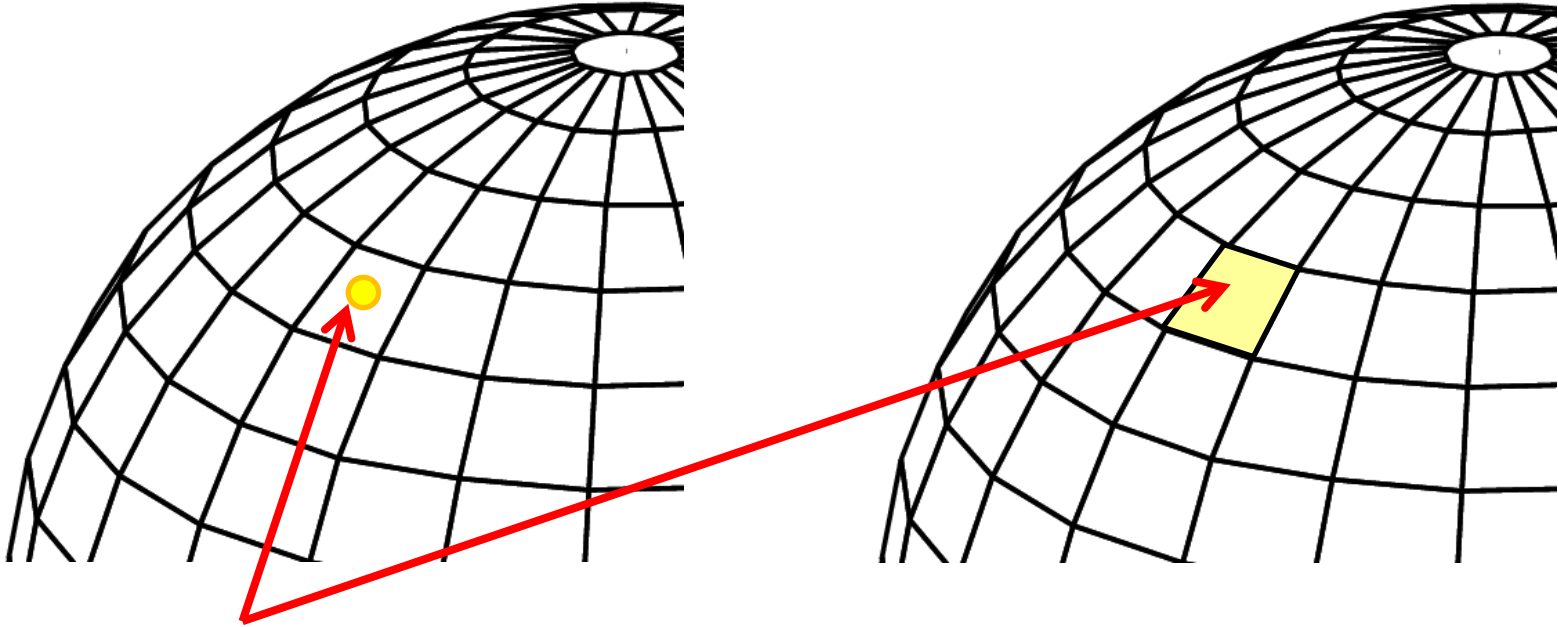
quad averaged radiance



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

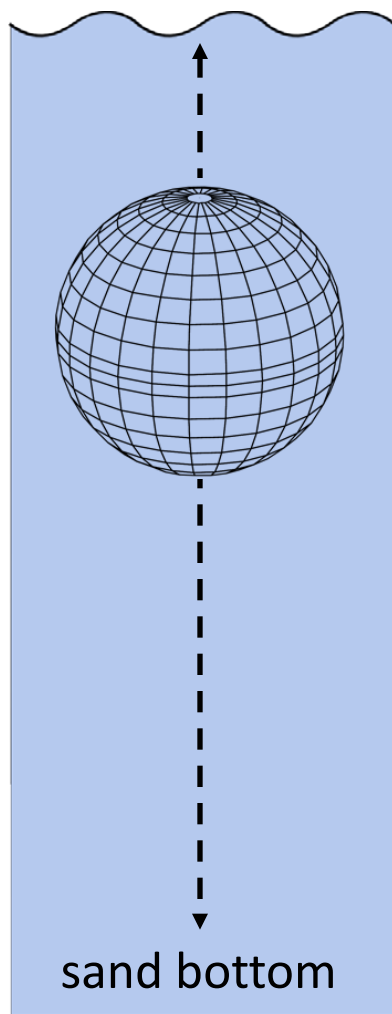


However the total energy as averaged over the quad is the same in both cases and correct.

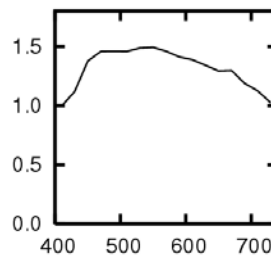
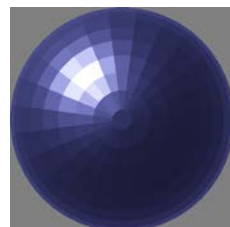
Makes almost no difference to most quantities of interest, due to scattering the direct radiance is rapidly spread out underwater anyway.

See Tech Note: *HTN2_AngularResolution.pdf*

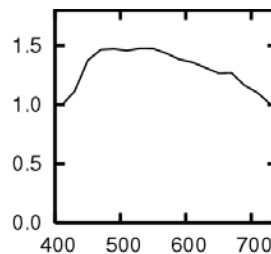
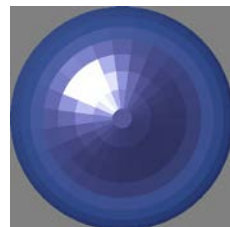
Typical
solution



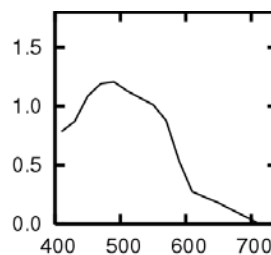
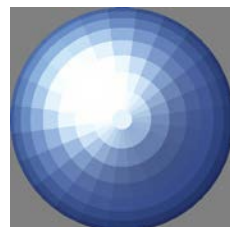
air



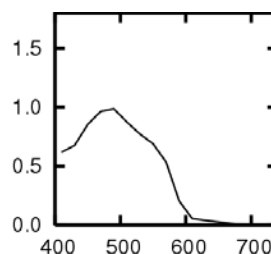
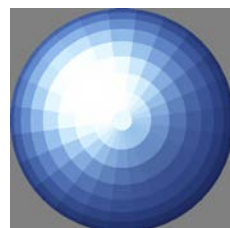
0+ m



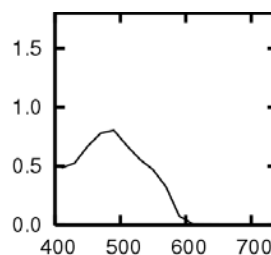
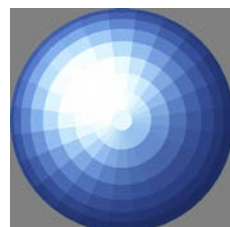
5 m



10 m



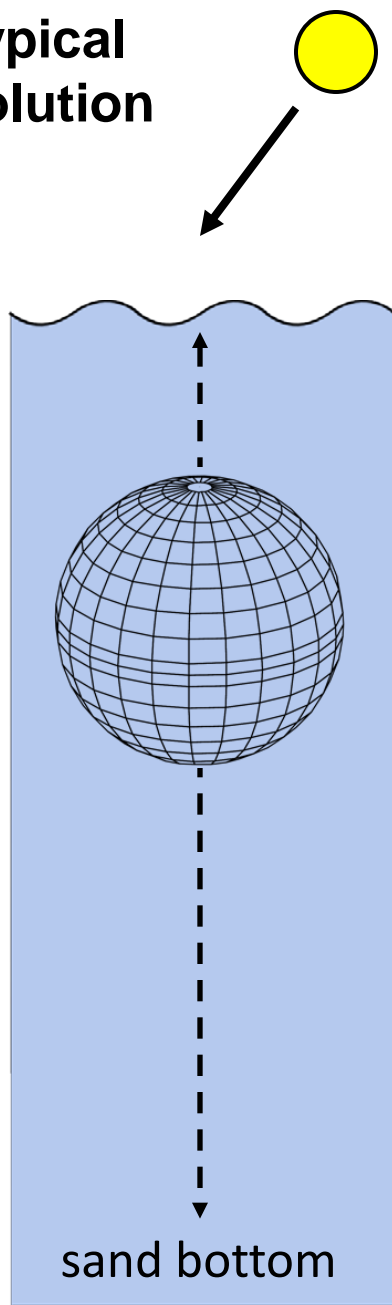
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sand bottom

E_d , downwelling irradiance

Typical
solution



air

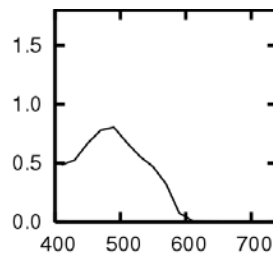
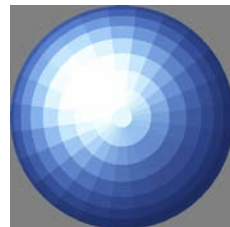
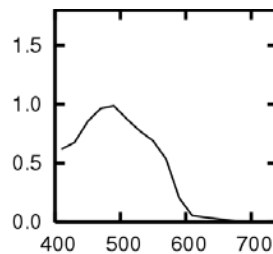
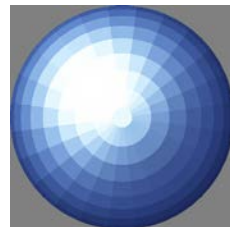
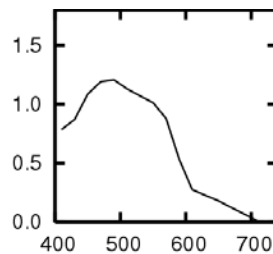
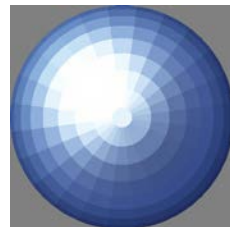
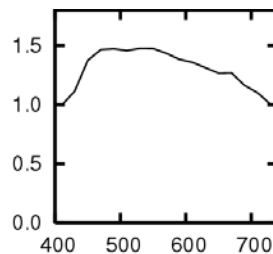
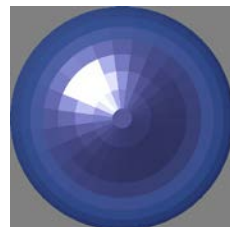
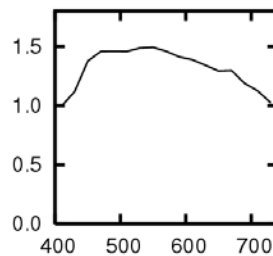
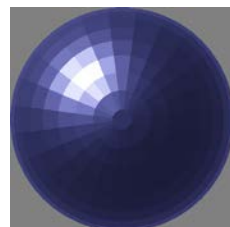
0+ m

5 m

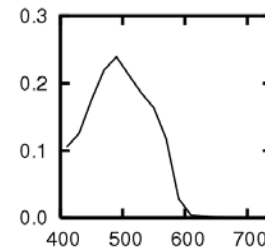
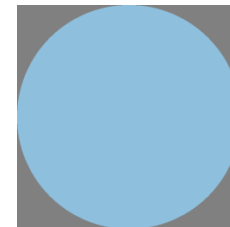
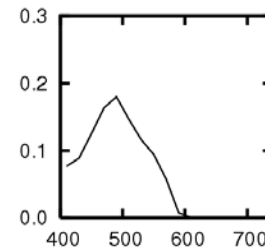
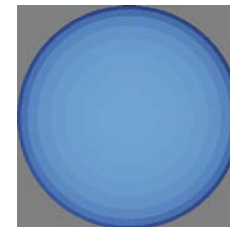
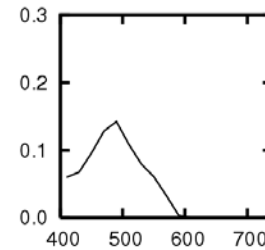
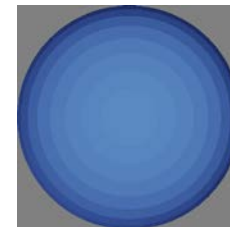
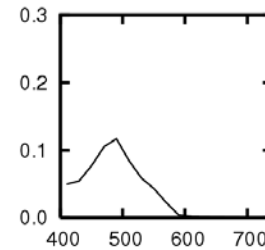
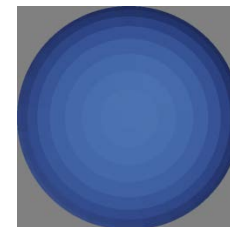
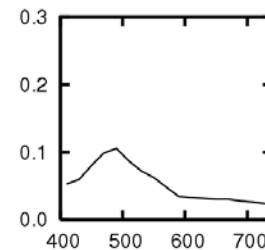
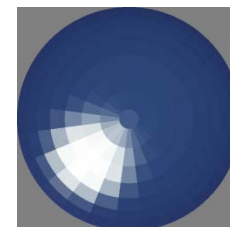
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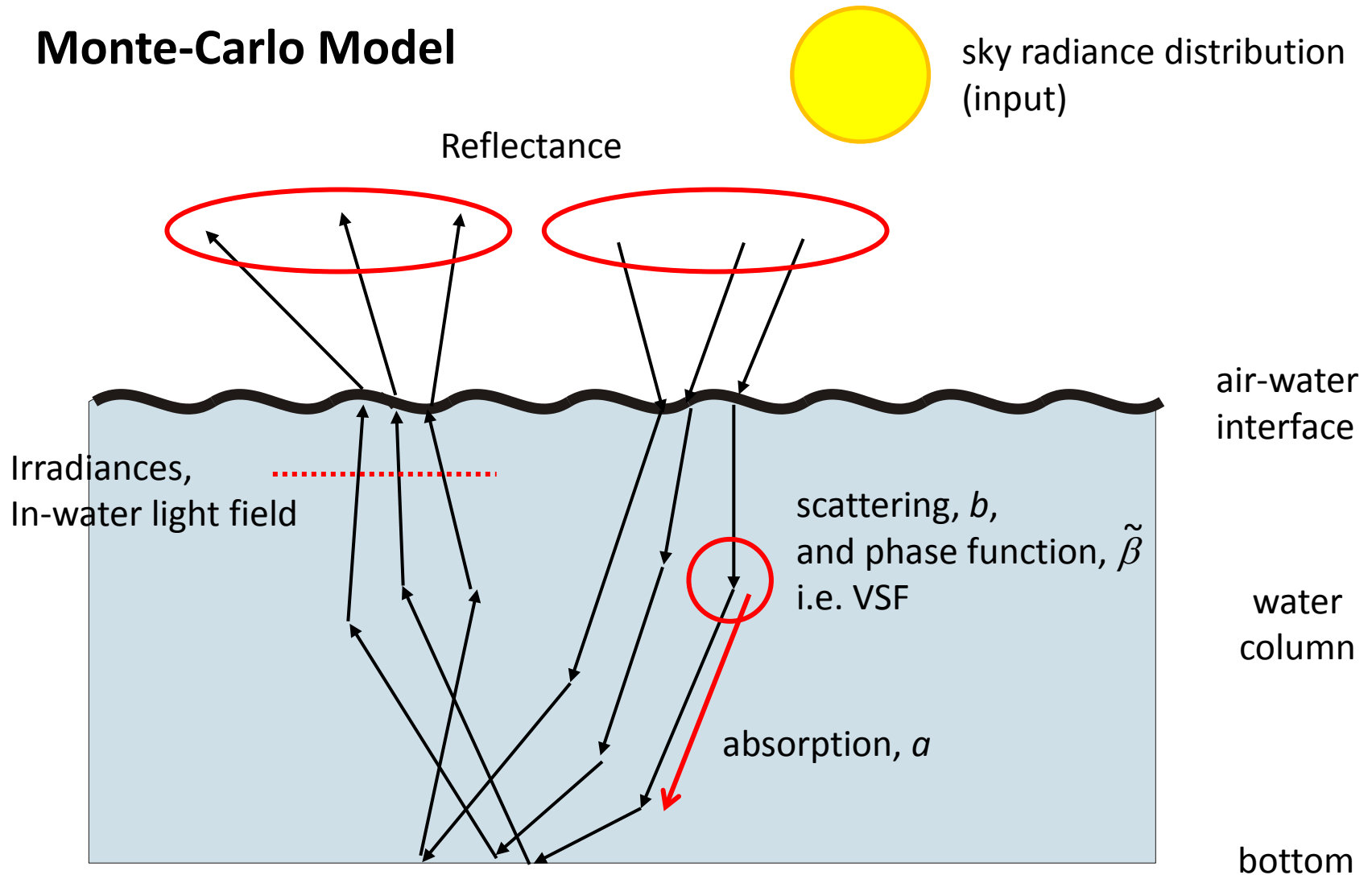
E_d , downwelling irradiance



E_u , upwelling irradiance



Monte-Carlo Model



→ Close association between implementation and physical concepts

Radiative Transfer Equation

One-dimensional, time independent, scalar version

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

Diagram annotations:

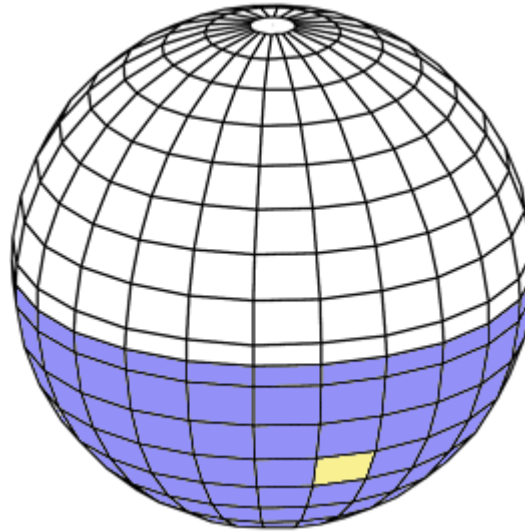
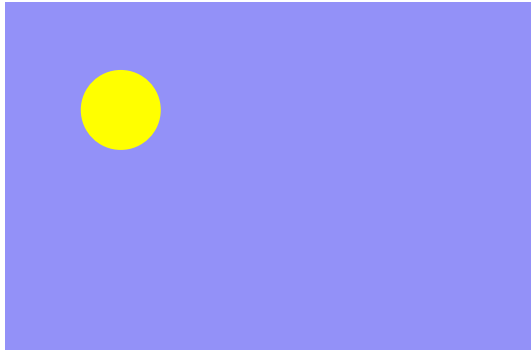
- attenuation**: points to the term $-[a(z, \lambda) + b(z, \lambda)] L(z, \theta, \phi, \lambda)$
- scattering**: points to the integral term $b(z, \lambda) \int_0^{2\pi} \int_0^\pi L(z, \theta', \phi', \lambda) \tilde{\beta}(z, \theta', \phi' \rightarrow \theta, \phi, \lambda) \sin\theta' d\theta' d\phi'$
- additional sources**: points to the term $S(z, \theta, \phi, \lambda)$

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 HydroLight solves, 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.



Upwelling radiances
unknown



Downwelling
radiances known

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.

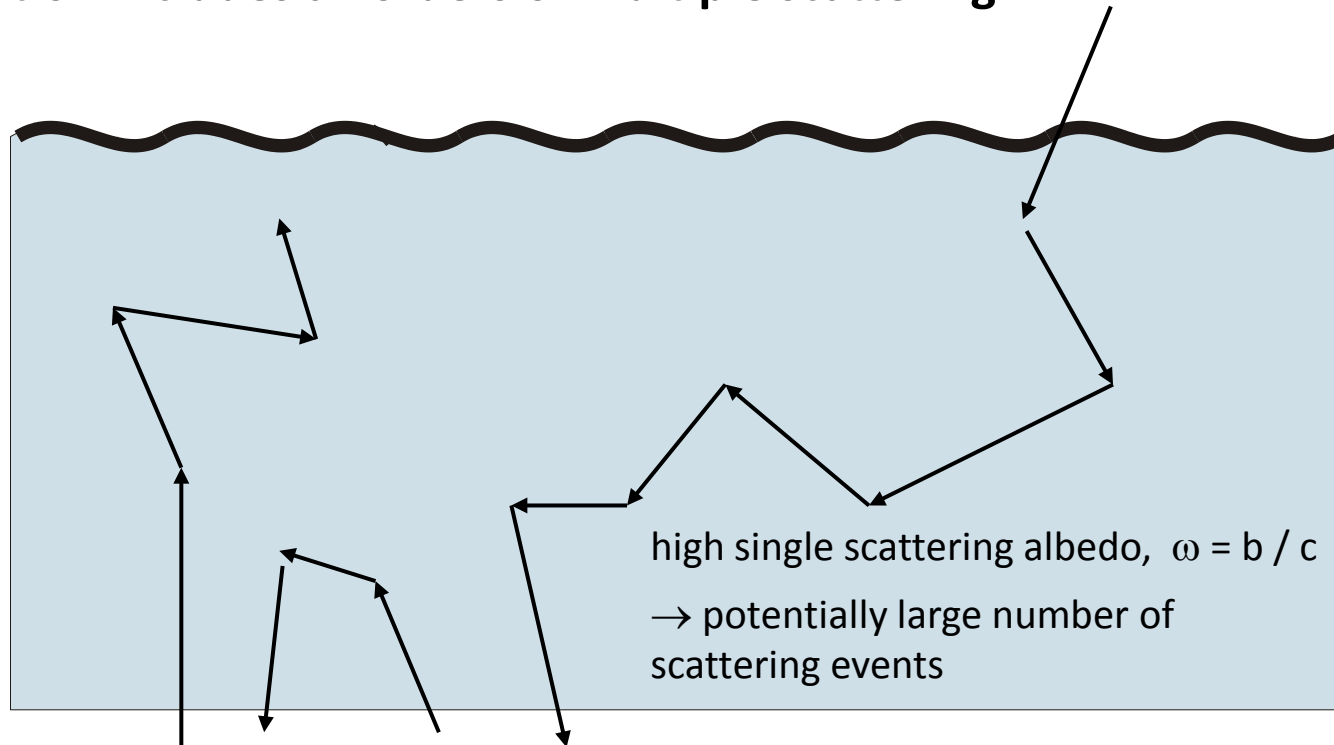
The other information we need is at the bottom boundary - either the bottom reflectance or the assumption of infinite depth.

Mathematically a “two-point boundary value problem”

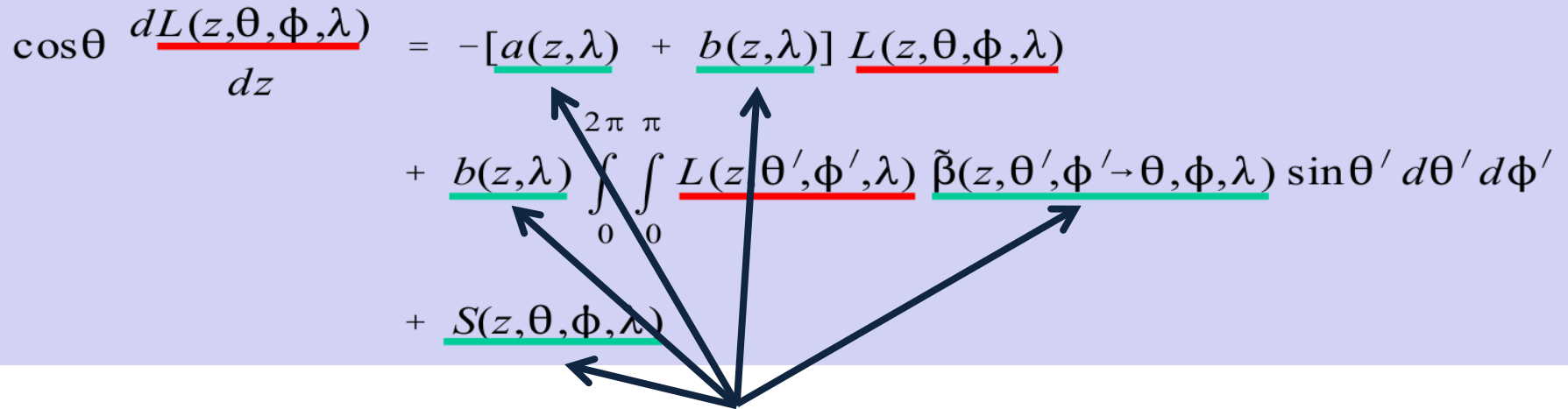
Solution is the **invariant imbedded method** - brings reflectance to the top.

Comparison of HydroLight vs. Monte Carlo

- **Run time linearly proportional to optical depth** (attenuation \times physical depth)
Monte Carlo $\propto \exp(\text{optical depth})$
- **Can handle any IOP(z) profile, arbitrary depth resolution**
not a set of homogeneous layers (e.g. discrete ordinates method)
- **Solution includes all orders of multiple scattering**



Practical use of HydroLight

$$\cos\theta \frac{dL(z,\theta,\phi,\lambda)}{dz} = -[\underline{a(z,\lambda)} + \underline{b(z,\lambda)}] \underline{L(z,\theta,\phi,\lambda)} + \underline{b(z,\lambda)} \int_0^{2\pi} \int_0^\pi \underline{L(z,\theta',\phi',\lambda)} \underline{\tilde{\beta}(z,\theta',\phi' \rightarrow \theta,\phi,\lambda)} \sin\theta' d\theta' d\phi' + \underline{S(z,\theta,\phi,\lambda)}$$
A diagram with four arrows originating from a single point at the bottom center. One arrow points to the term $\underline{a(z,\lambda)}$ in the first bracket. Another arrow points to the term $\underline{b(z,\lambda)}$ in the first bracket. A third arrow points to the term $\underline{L(z,\theta,\phi,\lambda)}$. A fourth arrow points to the term $\underline{\tilde{\beta}(z,\theta',\phi' \rightarrow \theta,\phi,\lambda)}$ in the double integral.

HydroLight solves the RTE in terms of vertical profiles of:

- absorption coefficient, $\underline{a(z,\lambda)}$
- scattering coefficient, $\underline{b(z,\lambda)}$
- phase function, $\underline{\tilde{\beta}(z,\lambda)}$
- any source terms $\underline{S(z, \theta, \phi, \lambda)}$ (bioluminescence, fluorescence)

And boundary conditions

- input sky radiance distribution, $\underline{L(0-, \theta, \phi, \lambda)}$ for downward directions
- bottom boundary reflectance, $\underline{R(\lambda)}$, or infinite depth bottom boundary condition

The IOPs used by the solver are the total values and the solution method in HydroLight does not care what they represent.

Specify IOPs

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

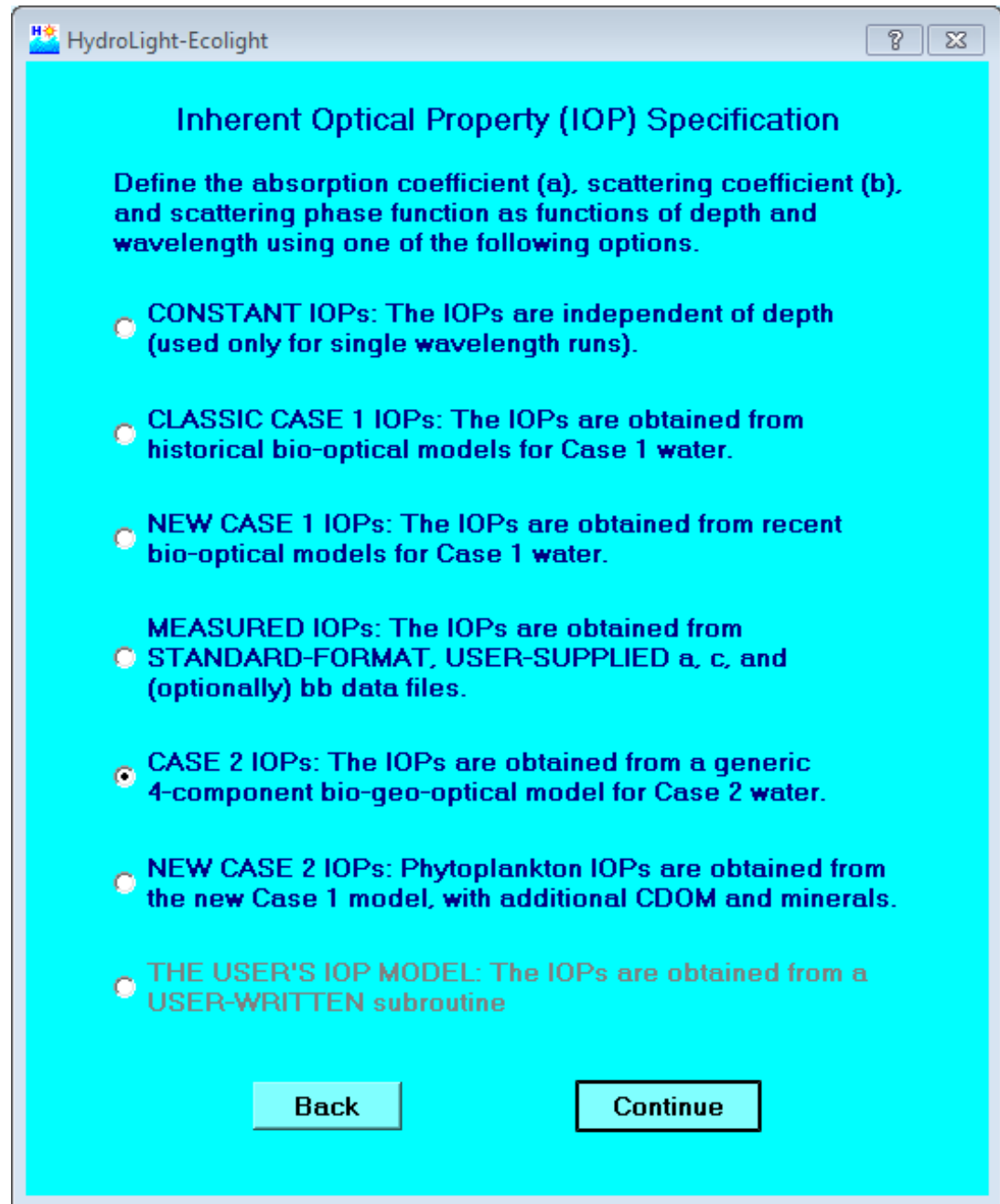
1. Measured IOPs

– 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.



HydroLight-Ecolight

Inherent Optical Property (IOP) Specification

Define the absorption coefficient (a), scattering coefficient (b), and scattering phase function as functions of depth and wavelength using one of the following options.

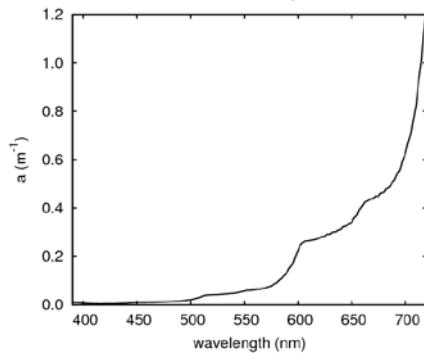
- ☐ CONSTANT IOPs: The IOPs are independent of depth (used only for single wavelength runs).
- ☐ CLASSIC CASE 1 IOPs: The IOPs are obtained from historical bio-optical models for Case 1 water.
- ☐ NEW CASE 1 IOPs: The IOPs are obtained from recent bio-optical models for Case 1 water.
- ☐ MEASURED IOPs: The IOPs are obtained from STANDARD-FORMAT, USER-SUPPLIED a, c, and (optionally) bb data files.
- ☒ CASE 2 IOPs: The IOPs are obtained from a generic 4-component bio-geo-optical model for Case 2 water.
- ☐ NEW CASE 2 IOPs: Phytoplankton IOPs are obtained from the new Case 1 model, with additional CDOM and minerals.
- ☐ THE USER'S IOP MODEL: The IOPs are obtained from a USER-WRITTEN subroutine

Back Continue

Total IOPs from multi-component models

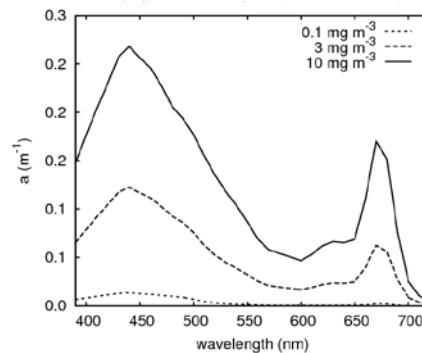
IOP contributions of components can just be added to make the total

**Pure water
absorption**



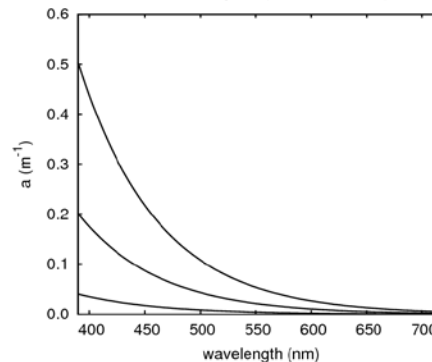
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**Phytoplankton
absorption**



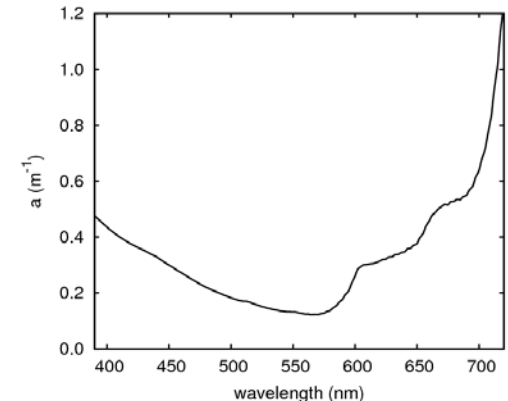
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**CDOM
absorption**



=

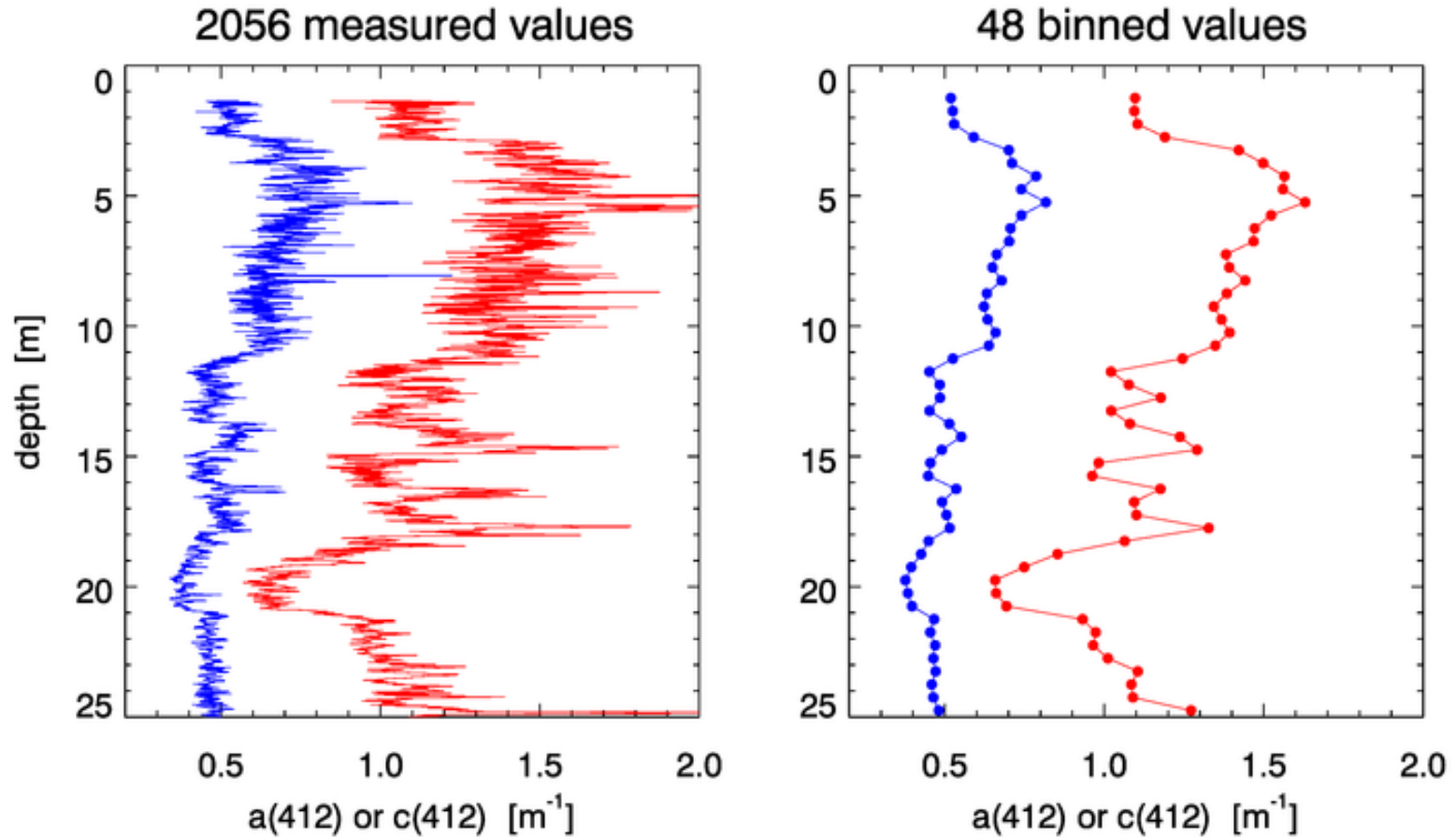
**Total
absorption**



- 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 concentration, mass specific absorption and scattering etc.

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

Many different aspects that can be “wrong”:

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 fluorescence, etc. these are empirically based: **USER BEWARE**
- for some real data is scarce, e.g. CDOM fluorescence, only 1 paper!

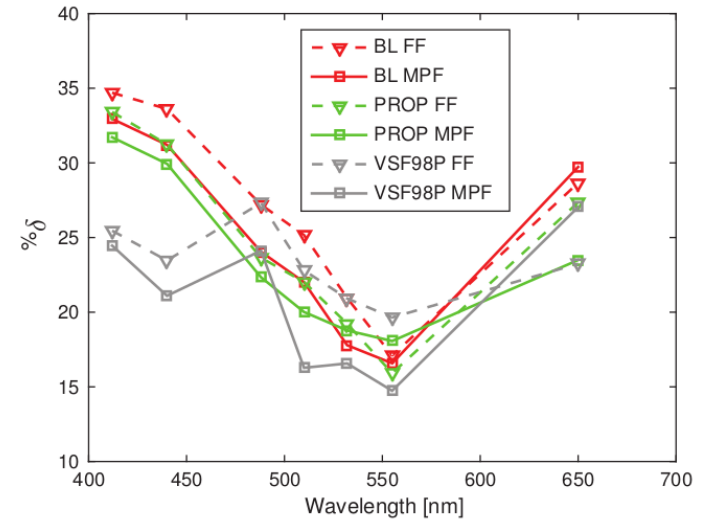
Examples of optical closure using HydroLight

Tonizzo et al. (2017)

Applied Optics 56, 130-146.

Overall discrepancies between measured R_{rs} and modelled:

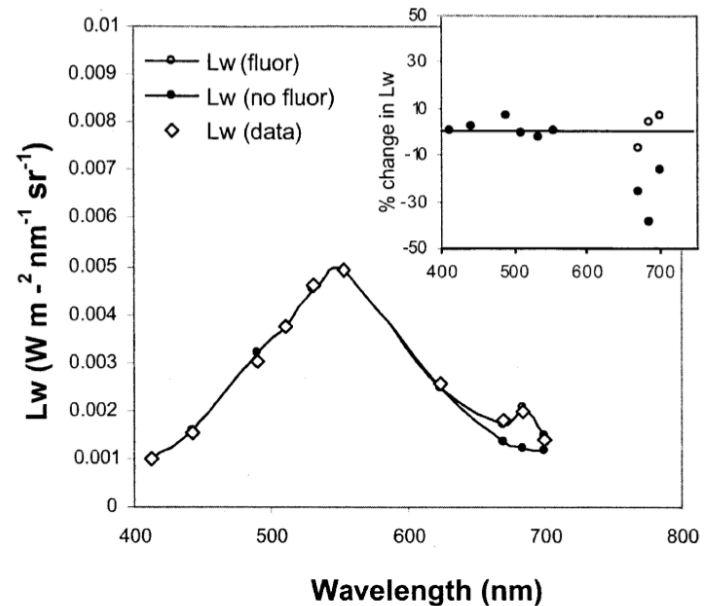
- Using measured phase functions ~20%
- Fournier-Forand phase functions ~23%



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 – discrepancies of 20% are in general a very good result.

Main Caveat – From the Users' Guide

...the HydroLight model per se is a radiative transfer model, not a model of oceanic optical properties. You, the user, must supply the inherent optical properties and boundary conditions to the HydroLight core code.

HydroLight does not know the inherent optical properties, or the chlorophyll profile, or the depth, or anything else about the water body you are interested in. *You* must provide this information to HydroLight. The various IOP models, phase functions, chlorophyll data sets, ac-9 data sets, etc. that come with HydroLight are *examples* of how to provide IOP and other information to HydroLight. *You* will need to replace these example routines and data sets with your own, in order to simulate the water body of interest to you.

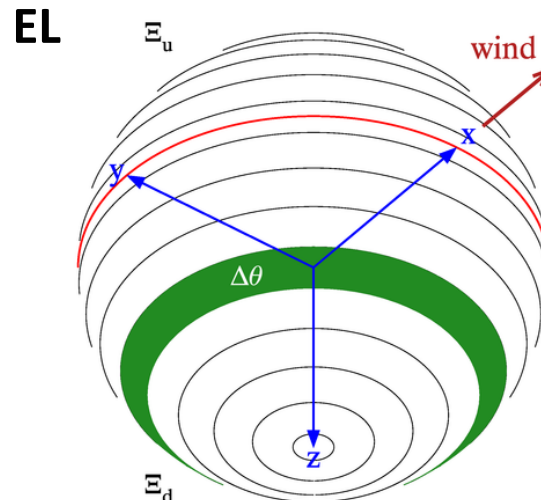
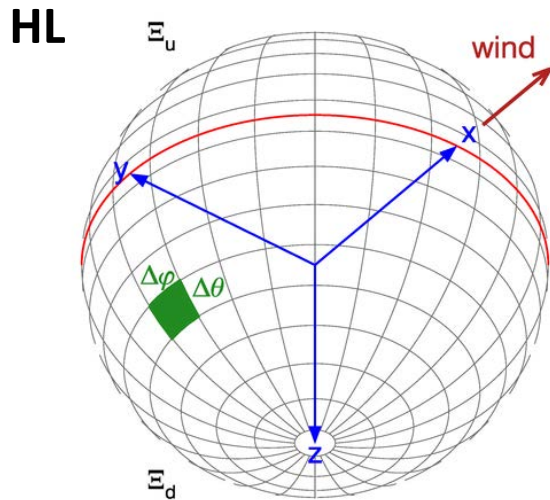
It is not idiot proof. Garbage in, garbage out.

EcoLight

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

The irradiances and polar cap radiances are the same for HydroLight and EcoLight.

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



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

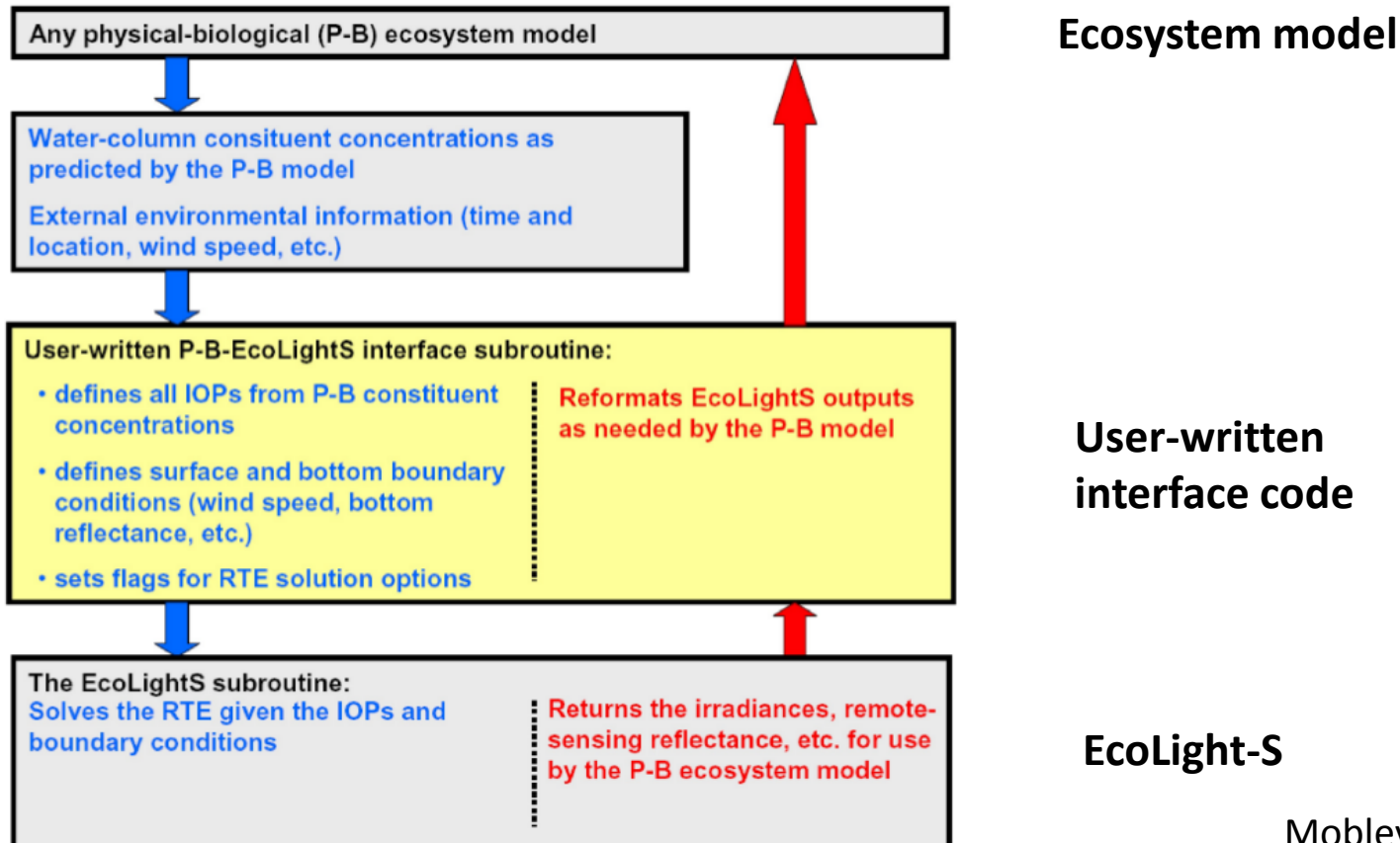
- EcoLight is typically 20 to 1000 times faster than HydroLight.
- To run HydroLight or EcoLight is an option at the end of the model setup.

What is EcoLight-S ?

EcoLight-S is the EcoLight solution method with some additional 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.



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)

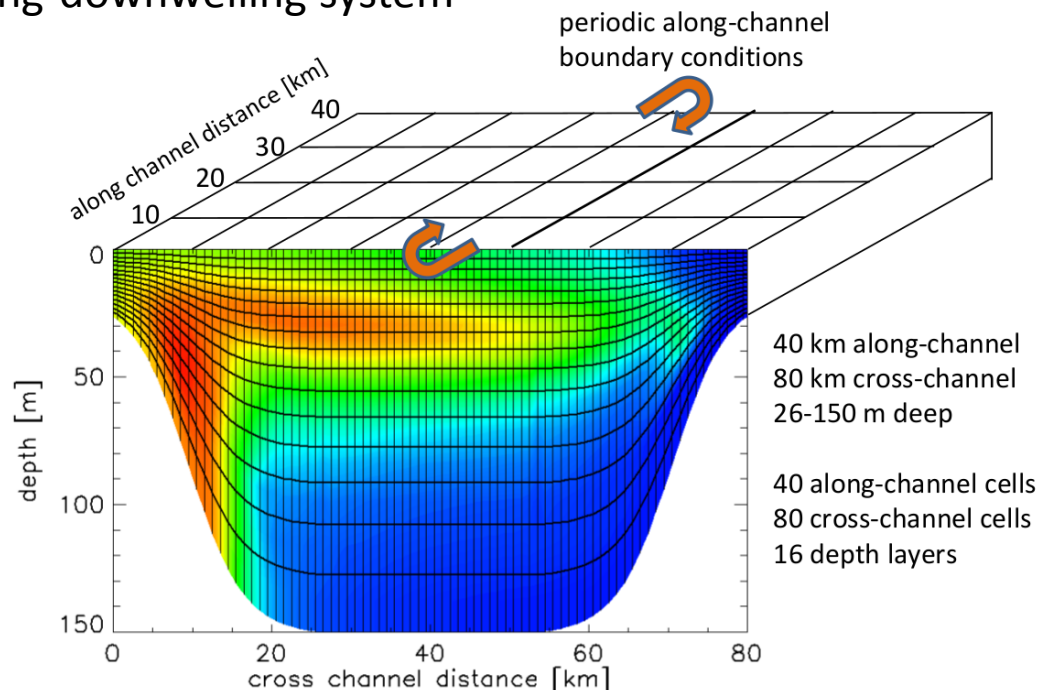
Analytic approach – independent broad-band diffuse attenuation light models for heating and photobiology.

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

EcoLight-S – single consistent model using spectral calculations for light.

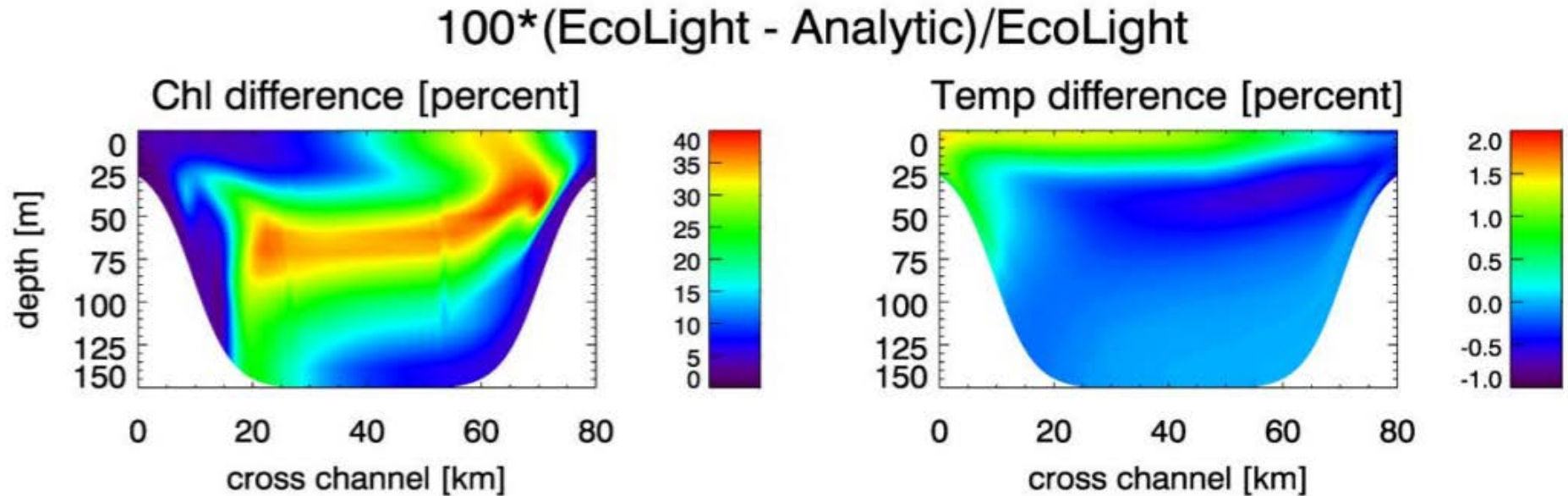
$$E_d(z) = \int_{400}^{700} E_d(z, \lambda) d\lambda$$

Idealized upwelling-downwelling system



Importance of modelling light correctly in an ecosystem model

After model time period of 14 days:



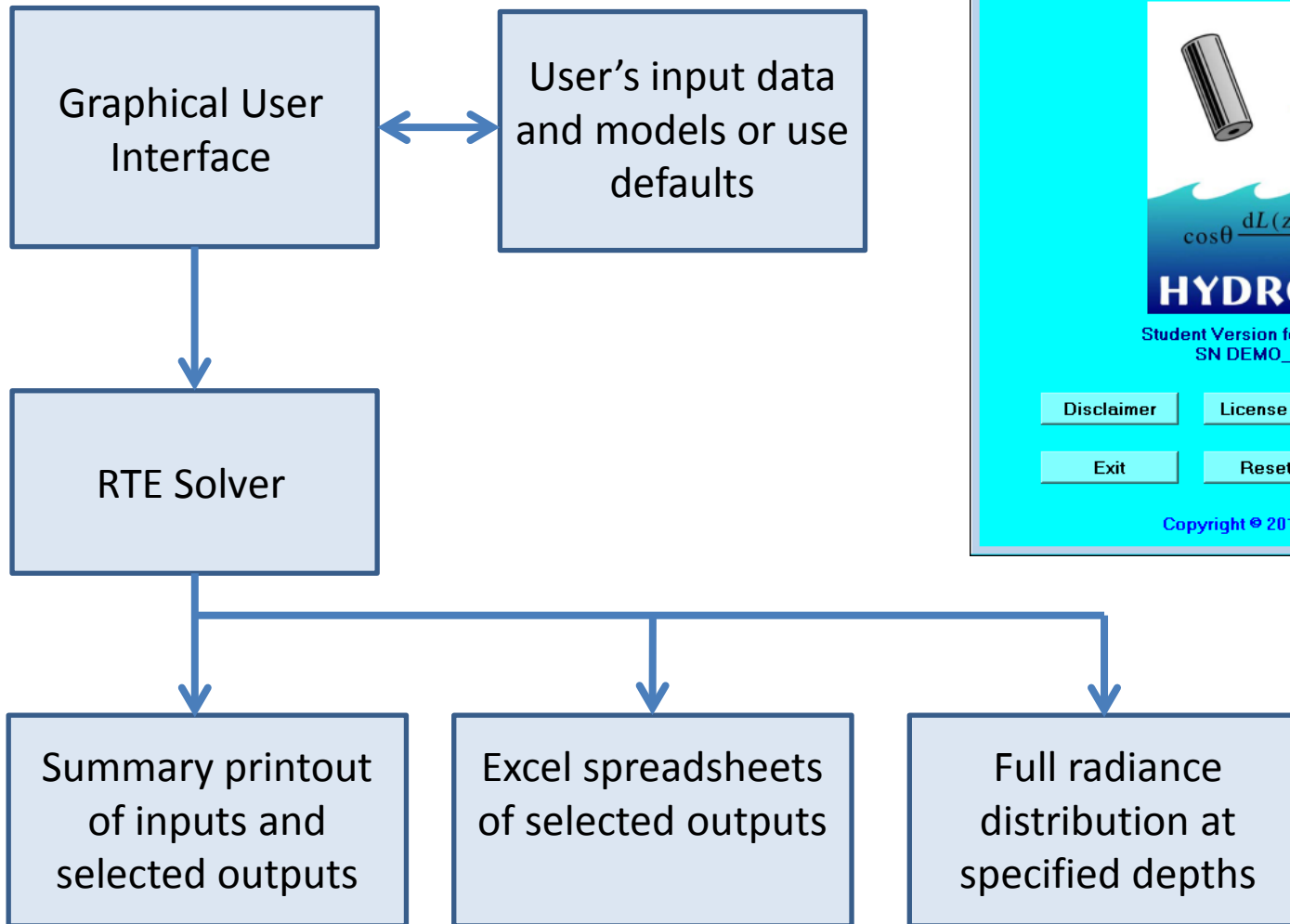
Run time:

Analytic **143 min**

EcoLight-S **170 min**

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

The HydroLight software package



Demo Version

The code provided to students for this course is an executable version of HydroLight-EcoLight version 6.0 beta. This code does not have all of the features of the full HE code and does not include the source code. The code for this class will run for 500 executions or until 7 July 2018, whichever comes first.

The development and continued improvement of HydroLight is entirely funded by the commercial revenue it generates. Just as with instruments, it must pay its own way as a commercial product. HydroLight is a commercial product of Numerical Optics Ltd. and is copyrighted code. It is not in the public domain.