Improved Ocean Ecosystem Predictions via Improved Light Calculations

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Quick Introduction

• B.S. Physics and Math, Univ. of Texas at Austin, 1969
• Physics at Tech. Hochshule (Univ. Fridericiana), Karlsruhe, Germany, 1969-70
• Ph.D. Meteorology (computational fluid dynamics), Univ. Maryland at College Park, 1977
• Got into optical oceanography and radiative transfer by accident while a postdoc
• Senior Scientist and VP for Science, Sequoia Scientific, since 1996; affiliate prof at U Washington and U Maine

Summer classes taught 16 times

Developer of HydroLight software; author of Light and Water; father of and main contributor to the Ocean Optics Web Book (www.oceanopticsbook.info)

Life outside the office: first mountaineering, then bicycling, now it’s sea kayaking
Photos at http://ann-and-curt.smugmug.com/

Trip leader for Wilderness Volunteers (www.wildernessvolunteers.org)

Don’t have a smart phone; read history books; completely nonmusical; no kids, no pets, no plants; don’t like coffee; 我会说一点儿汉语
Overview

• Overview of the problem

• Brief description of ROMS hydrodynamic and CoSiNE biological models

• Features and performance of the EcoLight-S radiative transfer model

• Example results from use of EcoLight-S in a simple ecosystem simulation
Ocean Ecosystem Modeling

• Predictive ecosystem models are playing an increasingly important role in our understanding of the oceans.

• Applications of such models range from predictions of water clarity for military purposes to management of coastal waters for fisheries to understanding the effects of global climate change.

• What must we know in order to predict ecosystem development, i.e., the growth of phytoplankton for a given species, which species dominate, upper ocean mixing, etc.?

  • temperature (phytoplankton growth rates, upper ocean mixing, ocean-atmosphere energy exchanges, …)

  • nutrients (sources and sinks of CO$_2$, NO$_3$, NH$_4$, Si(OH)$_4$, PO$_4$, Fe, etc.)

  • light (near UV to near IR (“shortwave radiation”); absorbed light heats the water, enables or inhibits photosynthesis; scattered light for visibility, remote sensing)
State of the Science

- Current hydrodynamical-biological-optical ocean ecosystem models often use
  - **very sophisticated treatments of the physics** (e.g., time-dependent, 3D Navier-Stokes solutions in terrain-following coordinate systems)
  - **increasingly realistic biology** (e.g., multiple biological components in complex food webs)
  - **grossly oversimplified treatments of the optics** (often just a single equation parameterizing PAR terms of the chlorophyll concentration and a few parameters such as the solar zenith angle)
- Optics is almost always the weakest part of ecosystem models. A simple PAR model parameterized by Chl is guaranteed to be wrong in Case 2 or optically shallow waters. PAR cannot model how different pigments (e.g., in different phyto species) absorb different wavelengths of light; differently pigmented species have competitive differences in different light environments.
- The argument has been “we can’t afford to do accurate light calculations because radiative transfer models (HydroLight. etc.) are much too slow, so we’ll do something simple and hope for the best.” This is no longer true.
ROMS: Regional Ocean Modeling System

• Widely used and very sophisticated and numerically efficient code developed at Rutgers Univ. Single processor or parallelized runs via automatic tiling.

• Free-surface, terrain-following, primitive-equation ocean hydrodynamic model

• In the horizontal, the primitive equations are evaluated using boundary-fitted, orthogonal curvilinear coordinates

• In the vertical, the primitive equations are discretized over variable topography using stretched terrain-following coordinates, which allow increased resolution in areas of interest, such as thermocline and bottom boundary layers

• Includes several coupled models for biogeochemical, bio-optical, sediment, and sea ice applications

See [http://www.myroms.org/](http://www.myroms.org/) for details and links to references
**First law of thermodynamics** (conservation of energy)

\[
\frac{\partial T}{\partial t} = -\frac{1}{c_v \rho} \frac{\partial (E_d - E_u)}{\partial z} \approx -\frac{1}{c_v \rho} \frac{\partial E_d}{\partial z}
\]

Total irradiance \((W \, m^{-2})\) over 400-1000 nm and 1 day

\[
\bar{E}_d(z) = \int_0^{\lambda_2} \int_{\lambda_1}^{\lambda_2} E_d(z, \lambda, t) \, d\lambda \, dt
\]

Change in temp (deg C) over 1 day for water between depths \(z_1\) and \(z_2\)

\[
\Delta T = -\frac{1}{c_v \rho} \frac{\bar{E}_d(z_1) - \bar{E}_d(z_2)}{z_1 - z_2}
\]

Paulson & Simpson (1977) parameterized \(E_d(z,400-1000)\) in terms of one of 5 Jerlov water types, based on only 5 measured profiles in homogeneous water: i.e., 5 sets of \(f, \xi_1, \xi_2\) tabulated values.

\[
\bar{E}_d(z) = \bar{E}_d(0) [f \exp(-z/\xi_1) + (1 - f) \exp(-z/\xi_2)]
\]

The P&S model for \(E_d(z)\)

The double exponential attempts to account for different attenuation rates for visible and near IR wavelengths.
The P&S model may or may not give good results, depending on the water body. As used in ROMS, you pick a Jerlov water type \textit{a priori} and use that everywhere and at all times.

Even if correct at the start of a run, P&S won’t stay correct as the IOPs change.

Even if correct at one location, P&S won’t be correct at locations with different IOPs.

The P&S irradiance model is simple, computationally fast, easy to use, and \textit{almost always wrong as used in ROMS}.
ROMS Heating: P&S vs EcoLight

Simple analytical $E_d(z)$ and $PAR(z)$ models cannot account for:
- $Chl(z)$, even in Case 1 water
- Case 2 waters
- near-surface boundary effects
- bottom reflectance

Don’t provide ancillary info like $R_{rs}$

Shortwave heating needs energy units (400-1000 nm)

Biology needs quantum units (400-700 nm)
CoSiNE: Carbon Silicon Nitrogen Ecosystem

Developed by Fei Chai at the Univ. of Maine and Richard Dugdale at San Francisco State Univ. Current version has 31 state variables (variables whose values are predicted and describe the biological state of the ecosystem):

- 3 phytoplankton functional groups: picoplankton, diatoms, coccolithophores
- 2 zooplankton functional groups: microzooplankton and mesozooplankton
- Multiple nutrients: nitrate NO$_3$, ammonium NH$_4$, silicate Si(OH)$_4$, phosphate PO$_4$
- Detritus: non-algal particles and biogenic silica bSiO$_2$
- Dissolved organic material: DOC/CDOM, DON
- Phytoplankton take up NO$_3$ and NH$_4$ by photosynthesis. In addition, diatoms utilize Si(OH)$_4$ in the silicification process. Microzooplankton graze on picoplankton. Mesozooplankton feed on diatoms, microzooplankton, and NAP.
- Full carbon cycle via dissolved inorganic C and total alkalinity
- Fe implicitly built in
CoSiNE: Carbon Silicon Nitrogen Ecosystem

Very complex web with many sources, sinks, interactions, rates, etc.
CoSiNE: Carbon Silicon Nitrogen Ecosystem

The 31 state variables. CoSiNE computes the IOPs $a(z,\lambda)$, $b(z,\lambda)$, $b_b(z,\lambda)$ from the red variables.

- Nitrate concentration
- Ammonium concentration
- Silicate concentration
- Phosphate concentration
- Small phytoplankton N
- Small phytoplankton C
- Small phytoplankton CHL
- Diatom concentration N
- Diatom concentration C
- Diatom concentration CHL
- Coccolithophores N
- Coccolithophores C
- Coccolithophores CHL
- Small zooplankton N
- Small zooplankton C
- Mesozooplankton N
- Mesozooplankton C
- Bacteria concentration N
- Detritus concentration N
- Detritus concentration C
- Biogenic silicate concentration
- Labile dissolved organic N
- Labile dissolved organic C
- Semi-labile dissolved organic N
- Semi-labile dissolved organic C
- Colored labile dissolved organic C
- Colored semi-labile dissolved organic C
- Particulate inorganic C
- Dissolved oxygen
- Total alkalinity
- Total CO2
CoSiNE: Analytical Light Model

CoSiNE-31 computes spectral $a(z,\lambda)$, $b(z,\lambda)$, $b_b(z,\lambda)$, 400-700 nm at 10 nm resolution, using Chl-specific absorp coefs for picoplankton and diatoms, which depend on current Chl:C ratio (allows for photoadaptation). Absorption by detritus and CDOM computed from exponentials referenced to 440 nm for detritus and 410 nm for CDOM. $b_b(z,\lambda)$ modeled by small and large organic particles, POC, and a background.

However, primary production and photo-oxidation are computed from broad-band $E_d$ in energy units ($W m^{-2}$), where $K(z)$ is parameterized by $a(z,490)$ and $b_b(z,490)$.

$$E_d(z) = E_d(0) \exp \left[ -K(z) z \right]$$

$E_d(0,400-700) = 0.9 \times 0.65 \times E_d(400-1000)$ used by ROMS

This is the default “analytical light model” for CoSiNE.
Original ROMS-CoSiNE Model

Hydrodynamics & thermodynamics with one light model
Biology with another light model
Physics affects biology, but **no feedback from biology to physics**

1. **wind, sky** $E(400-1000)$
2. **ROMS hydrodynamics & thermodynamics**
   
   $\frac{dT}{dt} = \text{Paulson & Simpson}$

   - currents, temp, mixing

3. **CoSiNE biology**

   $PP = f(E(z,400-700))$

   - concentrations

4. **water IOPs**

5. **IOP model**

6. **Analytic light model**

   - $E(z,\lambda), 400-700$

   - $\text{IOPs}(z, \lambda)$

   - $400-700$

   - assumed Jerlov water type
Optics for Ecosystem Models

**HydroLight:** Widely used; very accurate solution of the unpolarized radiative transfer equation (RTE) for any water composition (Case 1 or 2) and boundary conditions (deep or shallow with reflecting bottom; any sky) to get $L(z;\theta,\varphi,\lambda)$

Much too slow for use in ecosystem models with many grid points and time steps.

**Needed:** Just scalar irradiance $E_o(z,\lambda) = \int_{4\pi} L(z,\theta,\varphi,\lambda) d\Omega$ to bottom of euphotic zone (or PAR(z) in some models)

**Therefore:** Can solve

- azimuthally averaged radiative transfer equation (RTE)
- solve RTE only near sea surface where boundary effects are greatest, then extrapolate to greater depths [using $K_o = \mathcal{F}\{\text{absorp coef } a(z,\lambda)\}$]
- solve RTE at only some wavelengths (get unsolved $\lambda$ by interpolation)
- solve at only some grid points (rescale nearby solution for others)
- solve at only some time steps (rescale most recent solution)

The resulting code is called **EcoLight-S(subroutine)**. (details in Mobley, 2011. *Optics Express*)
EcoLight-S(subroutine) Features

- EcoLight-S solves the azimuthally averaged RTE for any water conditions and for any bottom and sky conditions (same as HydroLight).
- Gives the same irradiances and nadir-viewing $R_{rs}$ as HydroLight.
- Has various options for wavelength skipping, RTE solution to dynamically determined depths with extrapolation to greater depths, etc. to speed up the run time. Uses a stack of homogeneous layers for IOPs, as do most ecosystem models.
- Runs ~1000 times faster than HydroLight.
- Also computes ancillary optical quantities such as $R_{rs}(\lambda)$, $E_d(z,\lambda)$, $E_u(z,\lambda)$, and $L_u(z,\lambda)$, which are not available from analytic models. Having $R_{rs}$ allows for validation of ecosystem model predictions using remotely sensed data without having to convert $R_{rs}$ to Chl via a Chl inversion algorithm. $E_d$ and $L_u$ allow for ecosystem validation from easily made in-water measurements.
- Callable from any other code as a subroutine, with all communication via Fortran 95 modules.
Use of EcoLight-S in an Ecosystem Model

Any physical-biological (P-B) ecosystem model

- Water-column constituent concentrations as predicted by the P-B model
- External environmental information (time and location, wind speed, etc.)

User-written P-B-EcoLight-S interface subroutine:
- defines all IOPs from P-B constituent concentrations
- defines surface and bottom boundary conditions (wind speed, bottom refl., etc)
- sets flags for RTE solution options
- Reformats EcoLight-S outputs as needed by the P-B model

The EcoLight-S subroutine:
- Solves the RTE given the IOPs and boundary conditions
- Returns the irradiances, remote-sensing reflectance, etc. for use by the P-B ecosystem model

Use of EcoLight-S in an Ecosystem Model

your problem

my problem
EcoLight-S Philosophy and Optimization

Most current ecosystem models are based on PAR. Simple PAR models can be very inaccurate in some situations and can be an order of magnitude different than PAR computed by HydroLight for the same IOPs.

The goal: Make EcoLight-S run as fast as possible and still get PAR to ~10% at the bottom of the euphotic zone.

Optimizations:
• Solve the RTE at each $\lambda$ from the sea surface down to the depth where the irradiance has decreased to a given fraction $F_0$ of the surface value (e.g., $F_0 = 0.1$ solves to the 10% irradiance level), or
• Solve the RTE at each $\lambda$ from the sea surface down to the depth where the irradiance has decreased to a given value of $E_c$ [e.g., 1 W m$^{-2}$ nm$^{-1}$]
• Then extrapolate the RTE values at the last solution depth to greater depths
• Solve the RTE at only some wavelengths, and fill in the unsolved wavelengths by interpolation
Dynamic Determination of RTE Solution Depths

The IOPs(z,λ) are known (from the routine that calls EcoLight-S).

\[
E_0(z_0, \lambda) = E_0(0, \lambda) \exp \left[ - \int_0^{z_0} K_o(z, \lambda) \, dz \right]
\]

Definition of \( K_o \)

Except very near the sea surface, \( K_o \approx K_d \)

\[
K_d(z, \lambda) = \frac{a(z, \lambda) + b_b(z, \lambda)}{\bar{\mu}_d(z, \lambda)}
\]

Single-scattering approx for \( K_d \)

\( b_b << a \) and \( \mu_d \approx \frac{3}{4} \), so to a first approximation

\[
F_o = \frac{E_0(z_0, \lambda)}{E_0(0, \lambda)} \approx \exp \left[ - \int_0^{z_0} a(z, \lambda) \, dz \right]
\]

Pick \( F_o \) and solve for est. \( z_o \)
est. \( z_o > \) actual \( z_o \)

After the first wavelength, can use actual \( z_o \) depth at previous wavelength to estimate \( z_o \) at the current wavelength. This corrects for errors in neglecting \( \mu_d \), etc.
Depth Extrapolation Below the RTE Solution Depth

Most ecosystem models use homogeneous layers, with layer boundaries $z_0 = 0, z_1, ..., z_N = \text{the bottom}$. After determining the RTE solution depth $z_o$, solve the RTE to the next deeper layer boundary depth $z_k$.

The irradiances are then known from solution of the RTE down to depth $z_k$. Extrapolate to deeper depths using

$$\overline{\mu}(z_k) = \frac{E_d(z_k) - E_u(z_k)}{E_o(z_k)}$$

$$E_o(z, \lambda) = E_o(z_k, \lambda) \exp \left[ - \int_{z_k}^{z} \frac{a(z, \lambda)}{\overline{\mu}(z_k, \lambda)} \, dz \right]$$

The same is done for $E_d$ using

$$\overline{\mu}_d(z_k) = \frac{E_d(z_k)}{E_{od}(z_k)}$$
Depth Extrapolation Example

![Graph showing Chl depth vs wavelength with annotations]

- **Red**: RTE solution depth used
- **Blue**: Actual $F_\circ$ depth
- **Black**: Optical depth at 50 m

- Circles are in meters
- Diamonds are optical depths

- $F_\circ = 0.10$; 5 nm bands

- Huge computational savings at red $\lambda$ because run time is determined by optical depth.
Effect of Solution Depths

The RTE was solved to various $F_o$ depths ($F_o$ as a fraction of surface $E_o$) at a wavelength resolution of 5 nm. Dots in the second panel show the greatest solution depth (after the first wavelength) for each $F_o$. 
Effect of Skipping Wavelengths

The RTE was solved to 50 m at a wavelength resolution of 5 nm. Then solved for wavelength intervals of 10 nm (skipping every other 5 nm band), 15 nm (skipping 2 bands) etc.
Combined Dynamic Depths and Wavelength Skipping

Various $F_\theta$ depths ($F_\theta$ as a fraction of surface $E_\theta$) and number of 5 nm bands skipped.
Errors in $E_0(z,\lambda)$ for optimization with $F_0 = 0.2$ and 25 nm resolution vs. $F_0 = 0$ and 5 nm resolution

Unoptimized:
$F_0 = 0$ and 5 nm resolution

Optimized:
$F_0 = 0.2$ and 25 nm resolution
# HydroLight vs. EcoLight vs. Ecolight-S Run Times

<table>
<thead>
<tr>
<th>Model</th>
<th>Pure Water to 400 m</th>
<th>Turbid Case 2 to 40 m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1% PAR depth &gt; 400 m</td>
<td>0.1% PAR depth ≈ 20 m</td>
</tr>
<tr>
<td></td>
<td>Secchi depth ≈ 151 m</td>
<td>Secchi depth ≈ 4.9 m</td>
</tr>
<tr>
<td>HydroLight v. 5.1</td>
<td>811.4</td>
<td>462.0</td>
</tr>
<tr>
<td>EcoLight v. 5.1</td>
<td>13.0</td>
<td>7.9</td>
</tr>
<tr>
<td>EcoLight-S, no optimization</td>
<td>9.3</td>
<td>5.33</td>
</tr>
<tr>
<td>EcoLight-S, with optimization</td>
<td>0.61</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Table 1. Run time in seconds for simulations of pure water and turbid Case 2 water. For each simulation, the times in the left column are for a Xeon 2.00 GHz CPU and Windows XP/SP3; times in the right column are for an Intel Core i5, 2.40 GHz, 32 bit CPU and Windows 7. Runs were 400-700 nm by 10 nm. PAR values for all simulations were the same to within 3% at all depths for the respective simulations.

> 1200 times faster

from the EcoLight-S 1.0 Users’ Guide and Tech Doc
HydroLight vs EcoLight-S $R_{rs}$ Spectra

$R_{rs}$ is almost the same for HydroLight vs. optimized EcoLight-S

blue: pure water, Hydrolight with inelastic
green: Case 2 water, Hydrolight with inelastic
open circles: EcoLight–S unoptimized
dots: EcoLight–S with $F_o = 0.2$
ROMS-CoSiNE-EcoLight Model

We now have an extremely fast and acceptably accurate radiative transfer model.

Let’s use it in ROMS-CoSiNE to replace their simple analytical light models and see what differences there are in run times and ecosystem evolution.
Hydrodynamics, thermodynamics, biology, light are fully coupled via EcoLight-S
Example simulations of an idealized upwelling-downwelling system.

ROMS 3D Channel Geometry

- Periodic along-channel boundary conditions
- 40 km along-channel
- 80 km cross-channel
- 26-150 m deep
- 40 along-channel cells
- 80 cross-channel cells
- 16 depth layers
Simulation Options

2 sky conditions:
S1: 24 hour average sky irradiance (computed from diurnal values of S2 runs)
S2: diurnal sky irradiance with above-surface irradiance computed by RADTRAN

2 water-heating options:
H1: use Paulson & Simpson in-water attenuation model
H2: use EcoLight-S (400-1000 nm)

2 biology light-model options:
B1: use the original CoSiNE in-water irradiance model
B2: use EcoLight-S (400-700 nm)

2 Chlorophyll options:
CL: Low chlorophyll: biological model parameters (grazing rates, nutrient uptake rates, etc) tuned to allow a max Chl < 0.5 mg/m3
CH: High chlorophyll: biological model parameters tuned to allow a max Chl~ 5 m/m3

S1_H1_B1_Cx is the “old” way of doing things (24 hour avg sky irradiance, analytical light models)
S2_H2_B2_Cx is the new way (diurnal light, EcoLight for heating, EcoLight for biology)
Example Sequence of Temperature & Current Cross-sections

wind is applied in the along-channel direction

Ekman transport then gives a cross-channel flow that creates upwelling and downwelling
Example Sequence of Temperature & Current Cross-sections

Day 0.0: Temp [deg C] and Current [cm s^{-1}]

Day 1.5: Temp [deg C] and Current [cm s^{-1}]
Example Sequence of Temperature & Current Cross-sections

Day 0.0: Temp [deg C] and Current [cm s\(^{-1}\)]

Day 1.5: Temp [deg C] and Current [cm s\(^{-1}\)]

Day 7.5: Temp [deg C] and Current [cm s\(^{-1}\)]
Example Sequence of Temperature & Current Cross-sections

Day 0.0: Temp [deg C] and Current [cm s⁻¹]

Day 1.5: Temp [deg C] and Current [cm s⁻¹]

Day 7.5: Temp [deg C] and Current [cm s⁻¹]

Day 14.5: Temp [deg C] and Current [cm s⁻¹]
Example Sequence of Chlorophyll Cross-sections

initial Chl = 0.25 mg m$^{-3}$
Example Sequence of Chlorophyll Cross-sections

Day 0.0: Chl [mg m\(^{-3}\)]

Day 7.5: Chl [mg m\(^{-3}\)]
Example Sequence of Chlorophyll Cross-sections
Example Sequence of NO₃ Cross-sections

Day 0.0: NO₃ [mmol m⁻³]
Example Sequence of NO$_3$ Cross-sections

Day 0.0: NO$_3$ [mmol m$^{-3}$]

Day 7.5: NO$_3$ [mmol m$^{-3}$]
Example Sequence of NO$_3$ Cross-sections

Day 0.0: NO$_3$ [mmol m$^{-3}$]

Day 7.5: NO$_3$ [mmol m$^{-3}$]

Day 14.5: NO$_3$ [mmol m$^{-3}$]
Question: Does it matter if you use the 24-hour-average irradiance vs. diurnal irradiance to heat water and grow phytoplankton?

Note: For this sky (30% overcast), the ratio of $E(400-700)/E(400-1000)$ is 0.65, not the commonly used 0.46.
Daily-average vs diurnal incident irradiance
- Analytic biology and heating models
- High Chl case
- Radtran diurnal sky irradiances
- 24-hr averages from Radtran values

The heating isn’t much different, but the biology is much different because of how photosynthesis responds to the P-E curve

Day 14: 24-hr-avg vs Diurnal light (Analytic Models; High Chl)

24-hour-average Light

Diurnal Light

Diurnal - Average

Photosynthesis rate

Irradiance
• Same heating
• Different biology
• Biology affects $E(400-700)$ but not heating.

• Pauson and Simpson for heating
• Analytic vs Ecolight for biology.
The biology changes because of the different $\text{PAR}(z)$(40,747),(982,961)

High Chl case.

Ecolight Biol - Analytic Biol
• Same biology
• Different heating

• Ecolight for biology
• Paulson and Simpson vs Ecolight for heating.

• High Chl case

• Heating changes because Ecolight E(z, 400-1000) responds to changing IOP(z), P&S doesn’t

• The biology changes because the different heating changes the upper ocean mixing
• Different biology
• Different heating
• No coupling between biology and heating vs full coupling (biology affects heating and heating affects biology)

• Analytic biology & heating vs EcoLight Biology & heating

• High Chl case

• Biology and heating are significantly different
What is the computational cost of using EcoLight?

- 143 minutes total run time (1 processor) for Analytic biology and heating
- 170 minutes total run time (1 processor) for EcoLight biology and heating

Only a 19% increase to do light right
Other EcoLight-S Advantages

Even for runs where the individual analytic $E(400-700)$ and $E(400-1000)$ light models give good results, there are other advantages to using EcoLight.

- EcoLight output includes $R_{rs}(\lambda)$, $E_d(z, \lambda)$, $E_u(z, \lambda)$, $L_u(z, \lambda)$, which are not available from simple light models. These quantities can be used to validate ecosystem predictions using remote sensing or in-water data from moorings, gliders, etc.

- EcoLight $R_{rs}(\lambda)$ allows for model validation by direct comparison with measured $R_{rs}(\lambda)$, without the intermediate step of converting satellite $R_{rs}(\lambda)$ to chlorophyll for comparison with predicted chl.

- EcoLight $E(400-1000)$ gives consistent light for both heating and biology and couples biology and hydrodynamics.

- EcoLight is valid for all waters: Case 1 or Case 2, shallow or deep.
Evolution of $R_{rs}(\lambda)$ Across the Channel

Day 0.5: S2_H2_B2_CH

$R_{rs}$ at noon of first day: $R_{rs}$ spectra are very blue for Chl $\approx 0.25$ across the channel
Evolution of $R_{rs}(\lambda)$ Across the Channel

Day 7.5: S2_H2_B2_CH

$R_{rs}$ at noon of day 7:
$R_{rs}$ spectra decreasing and getting greener as Chl increases
Evolution of $R_{rs}(\lambda)$ Across the Channel

**Day 14.5: S2_H2_B2_CH**

$R_{rs}$ at noon of day 14: $R_{rs}$ spectra are now green in the high Chl downwelling area, still blue in the lower Chl upwelling area.
E(z) at noon of day 1 as computed by EcoLight (solid) and analytic (dashed). Same decay rates across the channel since almost the same low Chl values everywhere, but different rates for EcoLight and analytic models.
Noon of day 14 has much stronger attenuation for higher Chl values in downwelling area (low j values); EcoLight & analytic models much different.
Not shown...

• The spatial and temporal patterns are similar for other sets of ecosystem parameters, i.e. for low and medium Chl values; only the magnitudes differ
Conclusions

• Use of accurate light calculations makes significant differences in upper-ocean heating, hence in upper ocean stratification and circulation, for a wide range of conditions.

• Use of accurate light calculations makes significant differences in biological constituent concentrations and ecosystem evolution, for a wide range of conditions.

• Use of accurate light calculations increases total run times by only a few tens of percent. There is no longer any excuse for not doing accurate light calculations. Do Light Right!
Quotes

“I know of no competent biologist who considers this an important problem.”
--A renown biologist in a National Academy of Sciences review of whether NASA should build a satellite to measure chlorophyll.

“Petzold measured scattering in 1969, and there is no need to measure it again.”
--A reviewer on a proposal by me and others to build a new instrument for measuring the volume scattering function.

“The way light is computed in ecosystem models is adequate now and there is no need for the proposed improvements.”
--A reviewer on our proposal to NASA to apply our ROMS-CoSiNE-Ecolight model to the Pacific ocean, and validate the predictions using ocean color satellite data.
Acknowledgement

• The development of EcoLight-S and the work presented here were funded by the U.S. Office of Naval Research Ocean Biology and Optics Program via contracts to Curtis Mobley and Fei Chai.

• That program was closed down in 2011. It was good while it lasted.
Old Woman and Vajrapani, Lhasa
Nutrients for the high Chl run

Nutrients [mmol m\(^{-3}\)]; S2_H2_B2_CH

Day 0.0

Day 7.5

Day 14.5

File: ..\June2012Runs\June21\ocean_his_S2_H2_B2_CH.nc
Chl and Carbon, Analytic vs EcoLight for high Chl run

Note: Fixing C is the first level of ecosystem response; Chl is not the true measure of phytoplankton biomass.
C:Chl ratio varies with light conditions and nutrients. Photosynthesis is light, temp & nutrient driven. In this case, Chl/cell is higher at lower light (at depth) due to photoadaptation.