# Improved Ecosystem Predictions of the California Current System via Accurate Light Calculations

Curtis D. Mobley
Sequoia Scientific, Inc.
2700 Richards Road, Suite 107
Bellevue, WA 98005
phone: 425-641-0944 x 109 fax: 425-643-0595 email: curtis.mobley@sequoiasci.com

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## LONG-TERM GOAL

The goal of this effort is to incorporate extremely fast but accurate light calculations into coupled physical-biological-optical ocean ecosystem models as used for operational three-dimensional ecosystem predictions. Improvements in light calculations will lead to improvements in predictions of chlorophyll concentrations and other water-quality parameters (such as visibility), and of upper-ocean thermal structure, relevant to naval needs.

## OBJECTIVES

Currently available ecosystem models often use very sophisticated treatments of the hydrodynamics (e.g., primitive equation solutions in terrain-following coordinate systems to obtain the advection and upper-ocean thermodynamics and mixing), fairly sophisticated biology (e.g., primary production, nutrient utilization, and grazing), but use grossly oversimplified treatments of the. The optics component of coupled ecosystem models is sometimes just a single equation parameterizing the scalar irradiance or PAR (photosynthetically available radiation) in terms of the chlorophyll concentration and a few parameters such as the solar zenith angle. Such simple light models often fail even in Case 1 waters, and they can be wrong by orders of magnitude in Case 2 or optically shallow waters.

The objective of this year's effort was therefore to further improve the previously developed EcoLight radiative transfer model and incorporate it into three-dimensional, time-dependent, coupled physical-biological-optical ecosystem models. Those coupled models will be used to evaluate various strategies for updating the in-water spectral irradiance so as to obtain accurate ecosystem predictions while maintaining acceptably fast computation times in fully 3D simulations. In particular, I wish to address questions about how often in time and space the spectral irradiance needs to be updated when modeling complex and dynamic ecosystems.

## APPROACH

ONR previously funded (under contract N00014-08-C-0024) the initial development of EcoLight, a very fast radiative transfer model designed for use in coupled physical-biological-optical ecosystem models. During its development and initial evaluations EcoLight was embedded in an idealized

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ecosystem model based on a special version of the ROMS-EcoSim physical-biological model with a 6x6 horizontal grid and periodic lateral boundary conditions. The periodic-boundary version of ROMS-EcoSim was chosen for development and initial evaluation of EcoLight because of its geometric simplicity and small run times even for multi-year simulations. Ten-year simulations of an idealized open-ocean, Case 1 water, ecosystem showed that EcoLight can replace the simple analytic light model used in the original EcoSim code with less than a 30% increase in total run times. That previous work is described in Mobley et al. (2009).

Given the success of the initial idealized simulations with the ROMS-EcoSim-EcoLight code, the next step was to further improve EcoLight and imbed it into a 3D ROMS-CoSiNE physical-biological model with boundary conditions representative of tropical Pacific mid-ocean waters. The CoSiNE (Carbon, Silicate, and Nitrogen Ecosystem) model is described in Chai et al., (2002, 2003, and 2007) and Fujii et al. (2007). It was originally intended that further evaluations also would be made with EcoLight embedded into the NCOM-CoSiNE model for application to the California Current System and the Monterey Bay area. However, the present intention is to apply the ROMS-CoSiNE-EcoLight model to simulations of the Gulf of Maine after completion of the Pacific Ocean runs now underway.

EcoLight takes the following philosophy. It is necessary to solve the radiative transfer equation (RTE) in order to incorporate the effects of the surface boundary conditions and to account for all inherent optical property (IOP, namely the absorption, scatter, and backscatter coefficients) effects. However, once an accurate value of the scalar irradiance $E_o(z,\lambda)$ has been computed to some depth $z_o$ deep enough to be free of surface boundary effects, it is not necessary to continue solving the RTE to greater depths, which is computationally expensive. In many cases of practical interest, it is possible to extrapolate the accurately computed upper-water-column irradiances to greater depths and still obtain irradiances that are acceptably accurate for ecosystem predictions. Likewise, it is not necessary to solve the RTE at every wavelength in order to obtain acceptably accurate irradiances at the needed wavelength resolution. Omitting every other wavelength, for example, cuts the run time by roughly one half. There are several user-selectable parameters in the EcoLight code that allow the user to define the level of accuracy of the computed irradiances. The trade off is of course between run time and accuracy.

## WORK COMPLETED

The initial version of EcoLight used in the ROMS-EcoSim-EcoLight simulations seen in Mobley et al. (2009) was written with the goal of getting it working correctly within the ROMS-EcoSim package, without much time being spent on streamlining the code. In particular, the input and output for the initial EcoLight code was tied to the EcoSim code in how information was passed between EcoSim and EcoLight.

Given the success of the initial simulations shown in Mobley et al. (2009), EcoLight was completely rewritten from scratch in Fortran 95 to (1) bring it up to the standards of the ROMS-CoSiNE code, (2) remove various un-needed calculations and, most importantly, (3) make the code completely independent of the particular physical-biological model calling it. The re-written code is called EcoLight-S (for Ecosystem Light Subroutine) version 1.0. EcoLight-S is a re-entrant “black-box” subroutine package that can be called by any ecosystem (or other) model. To incorporate EcoLight-S into a particular physical-biological model, the user needs only write an interface subroutine to define the inputs needed by EcoLight-S to solve the RTE. All communication between EcoLight-S and the user’s program is via Fortran 95 modules. When calling EcoLight-S, the interface subroutine converts the physical-biological model outputs (component concentrations as a function of depth at a given time and grid location; other information such as time, location, sky conditions, bottom depth and reflectance in shallow waters; and wavelengths and depths where irradiances are needed by the calling model) into IOPs and boundary-condition information on the format needed by EcoLight-S to solve the RTE. After solving the RTE for the given IOPs and boundary conditions, EcoLight-S returns the spectral scalar irradiance and ancillary quantities (e.g., remote-sensing reflectance, down- and up-welling plane irradiances, and zenith and nadir radiances) at the requested depths and wavelengths. The user's interface subroutine then reformats the EcoLight-S output as needed by the calling physical-biological model.

The EcoLight-S inputs and outputs are fixed and well documented in a User's Guide and Technical Documentation (Mobley, 2010). Thus an EcoLight-S user does not have to consider the internal workings of EcoLight-S, and the EcoLight-S code can be maintained and further developed without consideration of what models will call it. EcoLight-S is thus an RTE solver only; it does not include IOP and other sub-models, or a graphical user interface, as does HydroLight. The usage of EcoLight-S within a physical-biological ecosystem model is illustrated in Fig. 1.

F. Chai and I reported on our initial work at an ecosystem modeling workshop held at the NATO Undersea Research Center in La Spezia, Italy, December 14-18, 2009. The development of EcoLight-S 1.0 is complete and the code has been thoroughly tested and evaluated. The Users' Guide and Technical Documentation are available. The EcoLight-S software will be introduced to the user community at the Ocean Optics XX conference at the end of September 2010.

**RESULTS**

Most ecosystem models (CoSiNE in particular) use PAR as the measure of how much light is available for photosynthesis. It is possible to compute PAR to the bottom of the euphotic zone in a fraction of a second of computer time, with errors of no more than a few percent. Figure 2 shows PAR profiles computed by EcoLight-S with varying degrees of run-time/accuracy optimization. The un-optimized run was at 5 nm resolution from 400 to 700 nm, with the RTE being solved to 50 m at each wavelength. The chlorophyll profile is seen in the left panel of the figure. The center panel shows the optimizations and run times. Parameter *nwskip* defines the number of wavelength bands to skip between solutions of the RTE. Thus in this simulation, *nwskip* = 3 means solve the RTE at 400 nm, then skip 405, 410, and 415, and then solve the RTE at 420 nm, and so on. Irradiances at unsolved wavelengths are obtained by interpolation between the solved wavelengths. Parameter $F_o = 0.1$ means, for example, that the RTE was solved to the depth where the scalar irradiance was 0.1 (10%) of the surface value at each wavelength. The $F_o = 0.1$ depth varied from more than 30 m near 500 nm to less than 5 m near 700 nm. Irradiances at deeper depths are obtained by extrapolation based on the IOP profile below the last solved depth, as described in Mobley (2010). The right panel shows the percent difference in the unoptimized (the RTE was solved at all wavelengths and to 50 m depth) PAR profile and PAR computed with various levels of optimization. We see that the run time can be decreased from 4.81 s to less than 0.5 s while still obtaining PAR to within 4% of the unoptimized value down to 50 m (for these IOPs). PAR was obtained to within 10% at all depths with a run time of only 0.09 s.

Figure 3 shows computed PAR profiles from an ecosystem simulation in which EcoLight-S was embedded in the combined physical-biological model described in Mobley et al. (2009). The chlorophyll profile used for this figure was the profile predicted for local noon of day 90 (March 30) of a five-year simulation of Case 1 water off the coast of New Jersey. The chlorophyll values varied from about 3.5 mg $m^{-3}$ near the surface to less than 0.5 near 100 m depth. For the corresponding IOPs the 0.1% PAR level (roughly the bottom of the euphotic zone) is at about 35 m. The unoptimized run took almost 17 s for the solution down to 100 m at 5 nm wavelength resolution. The run time decreases to 3.80 s if only every fifth wavelength band is solved (*nwskip* = 4), which gives an RTE solution every 25 nm and interpolation to 5 nm resolution in between. For this optimization, the PAR profile is the same as the unoptimized value to within 0.7% to the bottom of the euphotic zone (35 m), and within 5% down to 100 m. Further optimization reduces the run time to only 0.31 s with PAR still the same as the unoptimized run to within 4% down the 35 m, and to within 30% at 100 m.

Table 1 shows the times for HydroLight 5.1, EcoLight 5.1, and unoptimized and optimized EcoLight-S runs for simulations of optically pure sea water and very turbid case 2 water containing phytoplankton, extra CDOM, and “brown earth” mineral particles. The great decrease in run times between HydroLight 5.1 and EcoLight 5.1 are due to the difference in solving the full RTE vs. the azimuthally averaged RTE. The difference in EcoLight 5.1 vs. the unoptimized EcoLight-S is due to the greater efficiency of the re-written code. These runs show that it is possible to compute PAR to the bottom of the euphotic zone in both very clear and very turbid waters to within a few percent of the correct value (taken here to be the HydroLight values) in less than one second of computer time. The optimized EcoLight-S runs are all over 1,200 times faster than the corresponding HydroLight runs.

## IMPACT/APPLICATION

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. The incorporation of the EcoLight-S model into coupled ecosystem models will give improved accuracy in the predictions of primary production and related quantities made by such models. As the coupled models become more trustworthy in their predictions, they will become even more valuable as tools for ocean science and aquatic ecosystem management. We therefore expect that EcoLight-S will find wide use beyond its initial applications in the work described here.

It should be noted that chlorophyll-based analytic light models underestimate the scalar irradiance in simulations of optically shallow waters with bright reflective bottoms. In such waters, bottom reflectance significantly increases the in-water scalar irradiance and proportionately affects biological productivity and water-column heating rates. The EcoLight-S solution of the RTE to a given optical depth is not dependent on whether the IOPs describe Case 1 or 2 water. Its fast run times are therefore retained in applications to all water bodies. Unlike simple analytic light models, EcoLight-S can account for the effects of shallow bottoms and is valid for Case 2 waters. EcoLight-S also computes related quantities such as the nadir-viewing remote-sensing reflectance corresponding to the bio-optical state of the ecosystem. This allows for validation of ecosystem model predictions using satellite ocean color radiometry, without an intervening step to convert a satellite-measured radiance to a chlorophyll concentration via an imperfect chlorophyll algorithm.

## RELATED PROJECTS

This work is a continuation of the EcoLight development under previous contract N00014-08-C-0024. The present work is a collaboration between myself and Lydia Sundman of Sundman Consulting (embedding EcoLight-S into ROMS-CoSiNE) and Fei Chai (ROMS and CoSiNE issues, and running of large-scale 3D simulations) at the University of Maine. Chai is funded separately for his work.

Eric Rehm, a Ph.D. student at the University of Washington, is using EcoLight-S as the radiative transfer core of an implicit inversion algorithm that retrieves IOPs from in-water measurements of downwelling plane irradiance and upwelling radiance.

The EcoLight-S code is also being incorporated into the final version of the spectrum-matching and look-up-table software described in the report on contract N00014-10-C-0209. In that software, EcoLight-S is used to compute extensive remote-sensing reflectance databases as needed for inversion of hyperspectral imagery to obtain IOPs, bathymetry, and bottom classification.

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**PUBLICATIONS**

Mobley, C. D., L. K. Sundman, W. P. Bissett, and B. Cahill, 2009. Fast and accurate irradiance calculations for ecosystem models. *Biogeosci. Discuss.* 6, 10625-10662 and www.biogeosciences-discuss.net/6/10625/2009/ [in revision, refereed]

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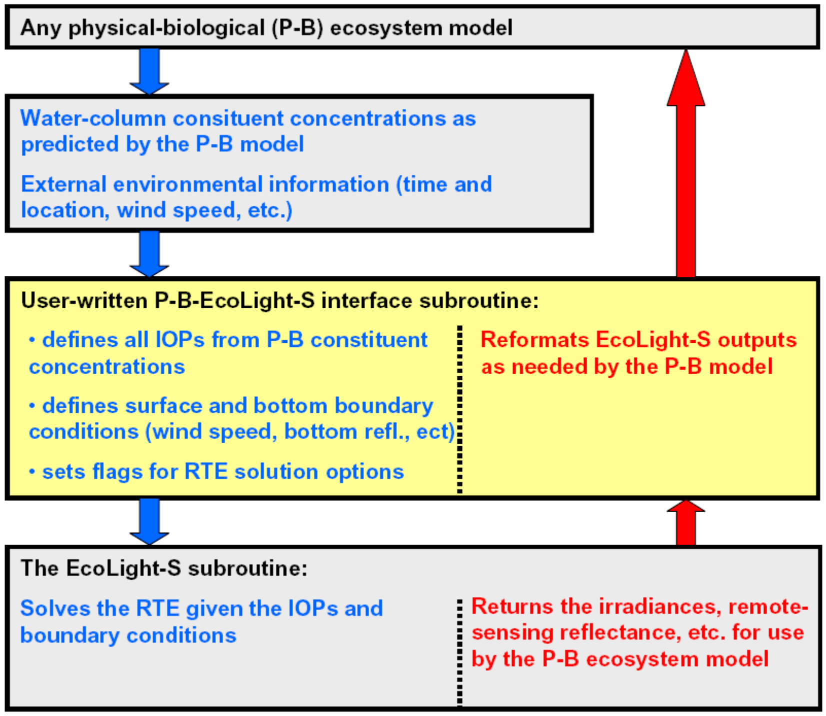


*Fig. 1. Usage of EcoLight-S within any coupled physical-biological ecosystem model. The interface subroutine makes EcoLight-S independent of the calling model. [The figure shows a flowchart of calculations in a coupled physical-biological-EcoLight-S ecosystem model.]*

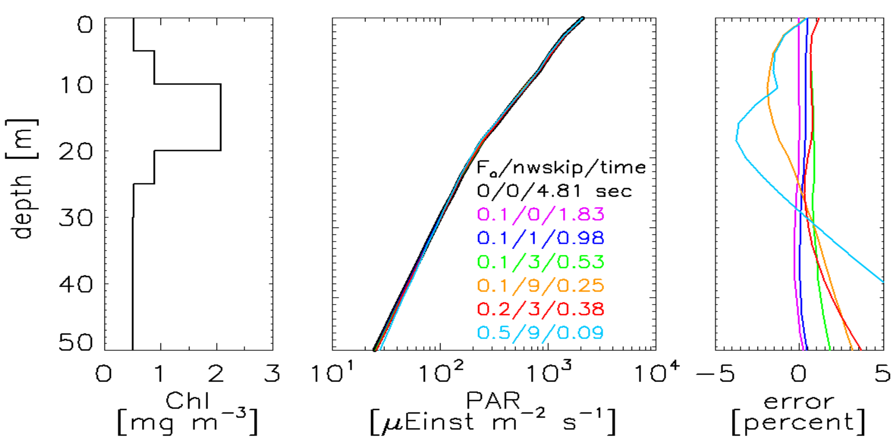


*Fig. 2. PAR profiles computed for various levels of run-time optimization in the call to EcoLight-S. With no optimization, EcoLight-S took 4.81 s to solve the RTE at all wavelengths to a depth of 50 m. PAR can be computed to within a few percent of the unoptimized value in less than 0.5 s of run time. [The left panel shows the chlorophyll vs. depth profile used in all simulations. The center panel shows the PAR vs. depth profiles for various levels of optimization. The right panel shows the percent differences between the unoptimized and optimized solutions.]*

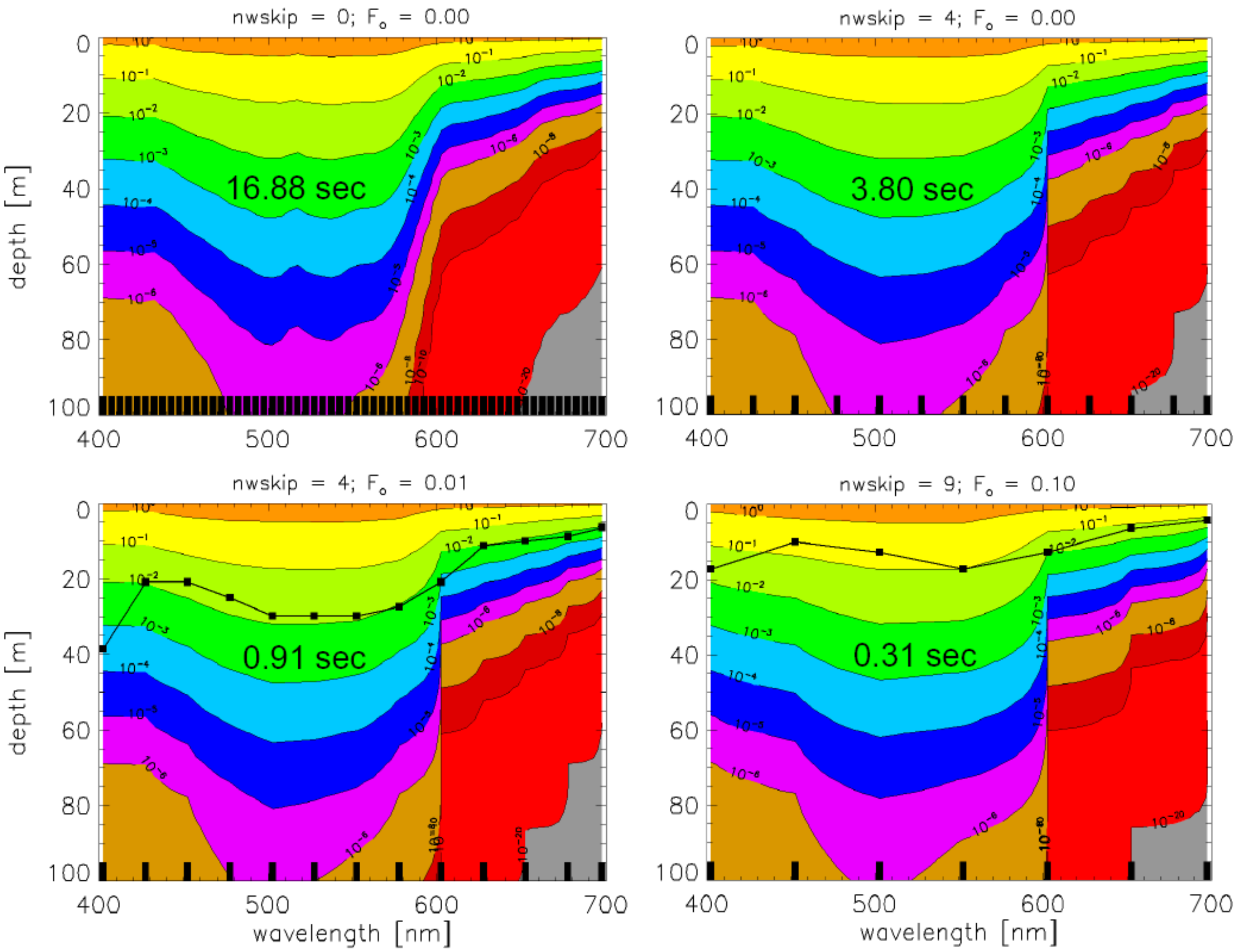


***Fig 3. Depth vs. wavelength contours of the spectral scalar irradiance $E_o(z,\lambda)$ for various levels of optimization. Contour values are in W $m^{-2}$ $nm^{-1}$. The black bars at the bottom of the figures show the wavelength bands where the RTE was solved. The black symbols in the bottom two panels show the depths to which the RTE was solved at the solved wavelengths. The unoptimized run (upper left) took 16.88 s; the most-optimized run (lower right) took only 0.31 s while giving the same PAR profile to within 4% to the bottom of the euphotic zone near 35 m.***

***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.***

| **model** | **pure water to 400 m<br>0.1% PAR depth > 400 m<br>Secchi depth ≈151 m** | | **turbid Case 2 to 40 m<br>0.1% PAR depth ≈20 m<br>Secchi depth ≈4.9 m** | |
|---|---|---|---|---|
| HydroLight v. 5.1 | 811.4 | 229.8 | 462.0 | 123.2 |
| EcoLight v. 5.1 | 13.0 | 4.5 | 7.9 | 3.0 |
| EcoLight-S, no optimization | 9.3 | 2.78 | 5.33 | 1.61 |
| EcoLight-S, with optimization | 0.61 | 0.19 | 0.30 | 0.09 |