

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

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LONG-TERM GOAL

The goal of this effort was 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 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. In particular, we wanted to imbed the EcoLight-S radiative transfer model in a three-dimensional, time-dependent, coupled physical-biological-optical ecosystem model and then use that coupled model to quantify differences in ecosystem biological and thermal development when using approximate vs. accurate optics.

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 in multi-component food webs), but use grossly oversimplified treatments of the optics. 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 a three-dimensional, time-dependent, coupled physical-biological-optical ecosystem model. That coupled model was used to evaluate various strategies for updating the in-water spectral irradiance so as to obtain accurate light predictions while maintaining acceptably fast computation times in fully 3D ecosystem simulations.

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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 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 (including a full rewrite of the code) and imbed it into the 3D ROMS-CoSiNE physical-biological model. The final code, called EcoLight-S(ubroutine), is described in Mobley (2011). The CoSiNE (Carbon, Silicate, and Nitrogen Ecosystem) model is described in Chai et al., (2002, 2003, and 2007) and Fujii et al. (2007).

EcoLight-S 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-S 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. The details of the EcoLight-S calculations and performance are given in Mobley (2011).

It was originally intended that further evaluations also would be made with EcoLight-S embedded into the NCOM-CoSiNE model for application to the California Current System and the Monterey Bay area. However, that turned out to be impractical for non-technical reasons, so we based our study on the ROMS-CoSiNE model as applied to an idealized coastal upwelling system.

WORK COMPLETED

This year's work centered on the final development of EcoLight-S and imbedding it into the ROMS-CoSiNE code, and then doing studies of the differences in ecosystem predictions of chlorophyll, nutrients, and water heating for various environmental situations.

The original 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 two Fortran 95 modules. When calling EcoLight-S, the interface subroutine converts the user’s 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 the water column 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 the widely used HydroLight code. 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. We described our recent work at a Gordon Research Conference on coastal ocean modeling (Chai and Mobley, 2011). The development of EcoLight-S 1.0 is complete and the code has been thoroughly tested and evaluated. The EcoLight-S software was introduced to the potential user community at the Ocean Optics XX conference and in Mobley (2011). This work has now ended and the final report was filed in April 2011; additional publications are still in preparation.

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 example 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 next panel shows the optimizations and run times. 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. Irradiances at deeper depths are obtained by extrapolation based on the IOP profile below the last solved depth. $\lambda = 25$ means that the RTE was solved every 25 nm. Irradiances at unsolved wavelengths are obtained by interpolation between the solved wavelengths. The third 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. The right-most panel shows the PAR errors in quantum units. We see, for example, that the run time can be decreased from 1.42 s to less than 0.1 s while still obtaining PAR to within 4% of the unoptimized value down to 50 m (for these IOPs). Optimized EcoLight-S run times are more than 1,000 times faster than corresponding HydroLight runs.

Figure 3 shows chlorophyll values at day 24 for a ROMS-CoSiNE simulation of an idealized upwelling-downwelling system. The wind blew from right to left, so that the right side of the channel is upwelling and the left side is downwelling. The left panel shows the chlorophyll predicted when PAR was computed using the simple analytical model for Case 1 water that is the default in CoSiNE. The middle panel shows the chlorophyll obtained when PAR was computed by EcoLight-S. The right panel shows the EcoLight-S values minus analytical PAR values. The maximum chlorophyll values are about 4 mg m^{-3} , and the maximum difference is 0.67 mg m^{-3} . The EcoLight-S chlorophyll values typically are tens of percent greater (as much as 81% greater in the upwelling region) than the analytic values.

Figure 4 shows the temperatures at day 24 for the same simulation. For water heating by shortwave radiation, ROMS uses broad-band (400-1000 nm) irradiance profiles based on a crude parameterization in terms of an assumed Jerlov water type. The EcoLight-S run replaced that parameterization by irradiances computed over 400-1000 nm (the 400-700 range was used to obtain PAR for biological primary production in CoSiNE). EcoLight-S temperatures are greater by as much as 0.61 deg than the analytic values in the near-surface downwelling region, and as much as 0.29 deg less than the analytic values at depth in the upwelling region. Thus there is stronger temperature stratification when using accurate light calculations than with the analytic light model that is the default in ROMS.

Even when the analytic light models for primary production and water heating give good results, which they sometimes do, there is still good reason to use EcoLight-S in their place. Figure 5 shows remote-sensing reflectance spectra computed at one downwelling point (cross-grid point 10 in Figs. 3 and 4) at six-day intervals from days 0 to 24. The initial near-surface chlorophyll value was 0.24 mg m^{-3} , which gives a very blue remote-sensing reflectance. The day 24 value at the same point was about 3.5, which gives green water. Figure 6 shows the corresponding progression of colors on a CIE chromaticity diagram. This sort of information is routinely available when using EcoLight-S and allows for model validation from remotely sensed imagery or in-water optical measurements (e.g., from moorings, gliders, or AUVs).

These differences in chlorophyll and temperature are quite significant, and the ancillary optical data available from EcoLight-S are valuable for purposes of ecosystem model validation or prediction of underwater visibility. This simulation shows the importance of using accurate light calculations in ecosystem models. The run time increase when using EcoLight-S was less than 20%. This is a small computational penalty compared to the benefits of improved ecosystem predictions and availability of ancillary optical outputs.

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 was a continuation of the EcoLight development under previous contract N00014-08-C-0024. The present work was 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 was 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 also has been incorporated into the final version of the CRISTAL 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., 2011. Fast light calculations for ocean ecosystem and inverse models. *Optics Express* 19(20), 18927-18944.

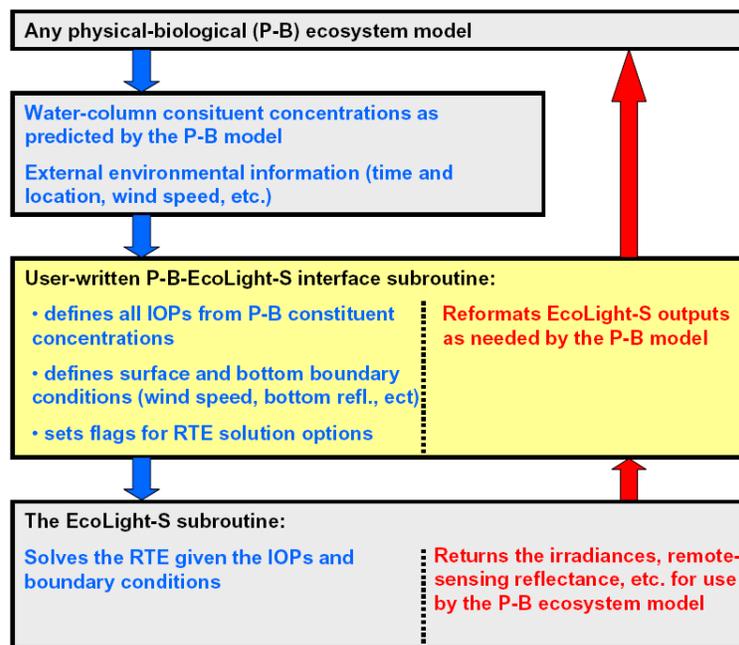


Fig. 1. Usage of EcoLight-S within any coupled physical-biological ecosystem model. The interface subroutine makes EcoLight-S independent of the calling model. [The figure shows a flowchart of calculations in a coupled physical-biological-EcoLight-S ecosystem model.]

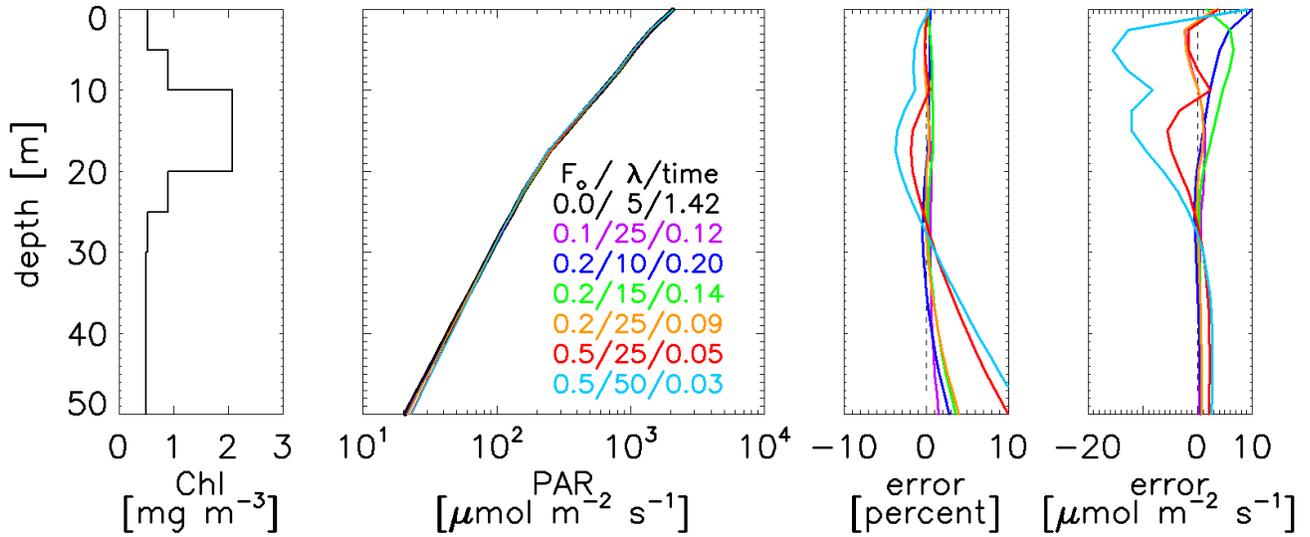


Fig. 2. PAR profiles computed for various levels of run-time optimization in the call to *EcoLight-S*. With no optimization, *EcoLight-S* took 1.42 s to solve the RTE at all wavelengths, 400 to 700 nm by 5 nm, to a depth of 50 m. For the optimized runs, $F_0 = 0.2$ means that the RTE is solved to the depth where the irradiance is 0.2 of its surface value at each wavelength, and $\lambda = 25$ means the run is at 25 nm resolution; the resulting run time is 0.09 sec. The third panel shows the percent errors in PAR for optimized vs unoptimized runs, and the fourth panel shows the errors in quantum units.

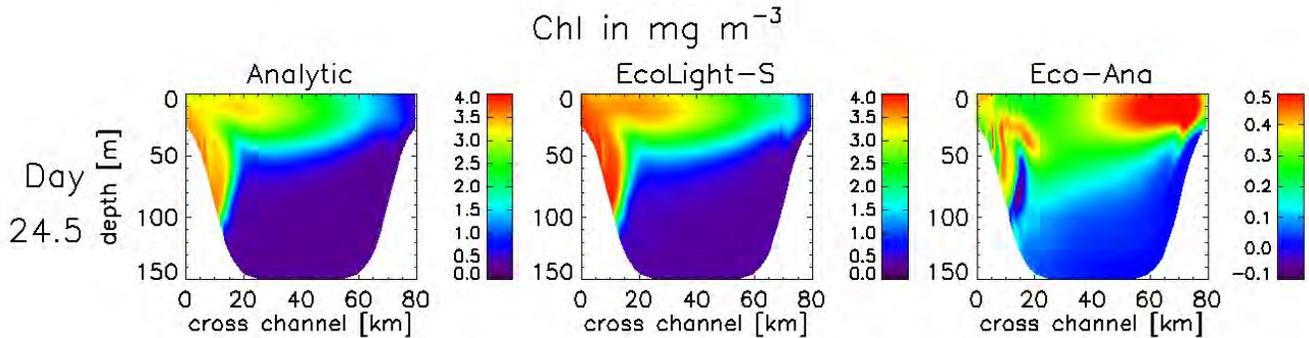


Fig 3. Comparison of chlorophyll values at day 24 of a simulation of an idealized upwelling-downwelling system. The left panel shows the chlorophyll predicted when using a simple analytic model for PAR at each time and grid point. The center panel shows the values when *EcoLight-S* was used to compute PAR. The right panel shows the difference (*EcoLight-S* predictions minus analytic model predictions). The *EcoLight-S* simulation gave chlorophyll values as much as 0.68 mg m^{-3} larger near the surface in the upwelling region. The difference in run times was less than 20%.

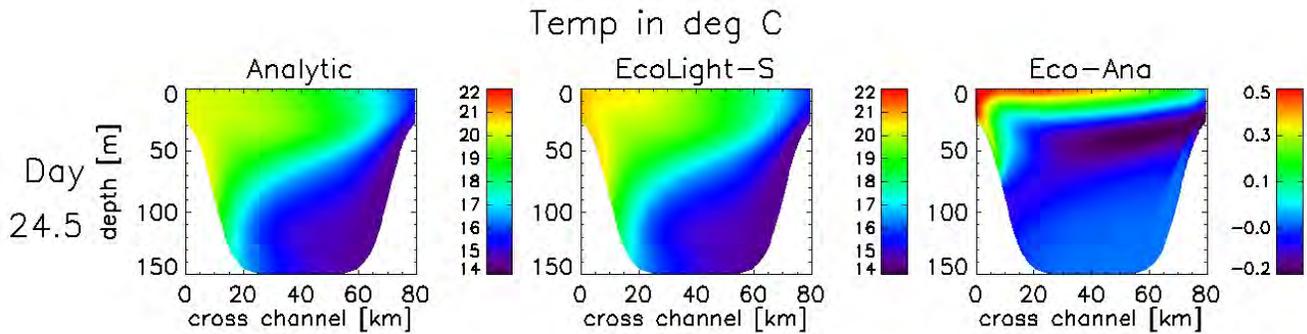


Fig 4. Comparison of water temperature at day 24 for the same simulation as Fig. 3. The difference in temperature was as much as 0.61 deg C near the surface in the downwelling region, and -0.29 deg C at depth in the upwelling region. Thus there is stronger temperature stratification when using accurate light calculations than with the analytic light model that is the default in ROMS.

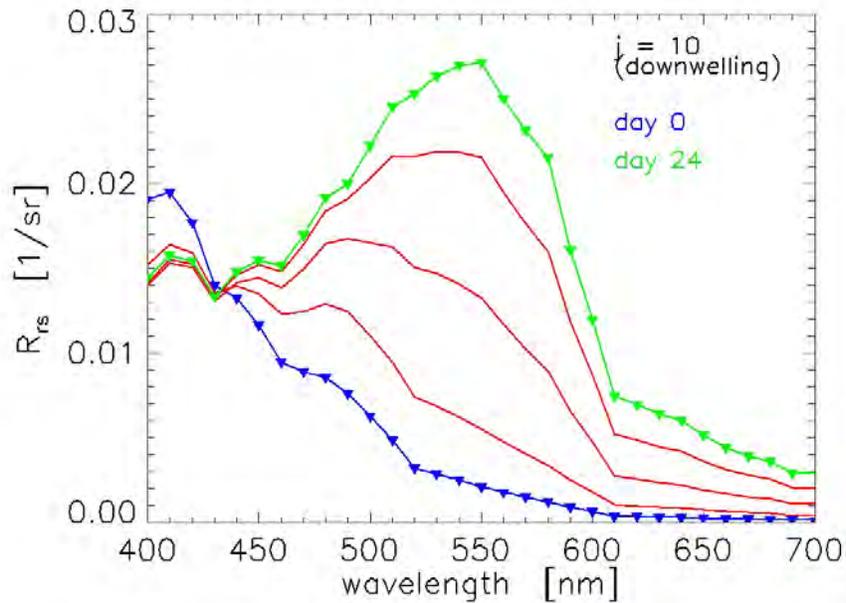


Fig. 5. Remote-sensing reflectance spectra R_{rs} at one grid point in the downwelling region at six-day intervals from days 0 to 24. The symbols on the day 0 (blue) and 24 (green) curves show the 10 nm wavelength resolution of the EcoLight-S run.

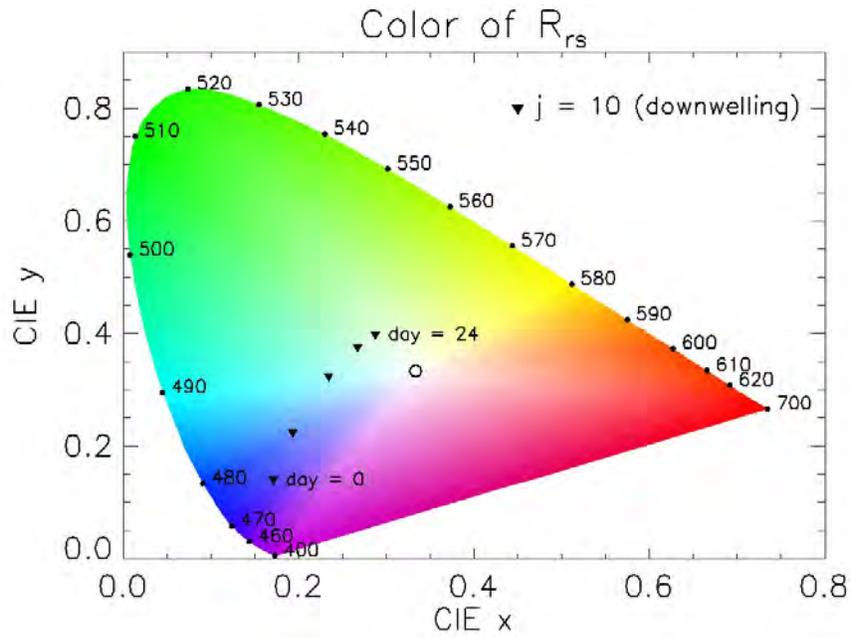


Fig. 6. A CIE chromaticity diagram showing the progression from blue water (day 0) to green water (day 24) at six-day intervals corresponding to the R_{rs} spectra shown in Fig. 5.