HYDROLIGHT 6.0
ECOLIGHT 6.0

USERS' GUIDE

John D. Hedley
Curtis D. Mobley

Numerical Optics Ltd.
Belmont House, 19 West Street
Tiverton, EX16 8AA, UK

2 December 2019

Update Note

This version of the the HydroLight-EcoLight Technical Documentation replaces the previous version of April 2016 for HydroLight-EcoLight version 5.3. This document applies to version 6.0.0. A pdf of this document with color figures is in the HE60/documents directory.

Copyright

Trademarks

Disclaimer

Technical Support

Technical support for HydroLight and EcoLight can be obtained in accordance with the user's license agreement from

John D. Hedley
j.d.hedley@numopt.com
Tel: + 44 1884 675070

If you encounter a problem during a HydroLight or EcoLight run, please e-mail us the following:

- The "Licensed to" name and Serial Number of the copy you are running. These are found on the opening form of the User Interface, and at the top of the printout.
- A description of the problem, error messages, or other pertinent information.
- The input file (the `Iroot.txt` file for the run, which is found in the HE60\run\batch directory, or Documents/HE60/run/batch on an Apple machine).
- The printout file (the Proot.txt file, from either the HE60\output\HydroLight\printout or HE60\output\EcoLight\printout directories, similarly under the respective directories under Documents/HE60/output/ on an Apple machine)
- Any user-supplied input data files used by the run.

  This information will greatly increase the speed at which we can troubleshoot the problem.

Acknowledgment

TABLE OF CONTENTS

1. INTRODUCTION

This Users' Guide is intended for new users of the HydroLight-EcoLight Version 6.0 software package. This guide gives a general overview of HydroLight and EcoLight, explains how to install the software, and shows how to make standard runs and examine the output. The Users' Guide is independent of any other publication and should be adequate for users who wish to run the software as a "black box." The Users' Guide assumes that the reader is familiar with the basic terminology and notation of optical oceanography. If this is not the case, then the text *Light and Water: Radiative Transfer in Natural Waters* (Mobley, 1994) and the "Ocean Optics Web Book" at http://www.oceanopticsbook.info/ contain the needed information.

The separate Technical Documentation provides additional detailed information and references for the IOP models, sky models, default data sets, etc. available in the version 6.0 software. The formats for input and output data files are also given there. The *Light and Water* text describes in considerable detail the mathematical methods employed in HydroLight. That book is the primary technical documentation for the HydroLight numerical model. The source code itself is documented by references to the equations in *Light and Water*.

Knowledge of the radiance distribution within and leaving a water body is a prerequisite for the solution of many problems in ocean color remote sensing, biological primary productivity, underwater visibility, and mixed-layer thermodynamics. Moreover, because radiance is the fundamental radiometric quantity, all other quantities of interest to optical oceanographers—various irradiances, diffuse attenuation functions, reflectances and the like—can be computed from their definitions once the radiance is known.

HydroLight and EcoLight are radiative transfer numerical models that compute radiance distributions and derived quantities for natural water bodies. In brief, these models solve the time-independent, unpolarized radiative transfer equation to obtain the unpolarized radiance distribution within and leaving any plane-parallel water body. Input to the models consists of the absorbing and scattering properties of the water body, the nature of the wind-blown sea surface, the reflectance properties of the bottom of the water column, and the sun and sky radiance incident on the sea surface. Output consists of archival printout and, optionally, Excel spreadsheets and files of digital data from which post-run numerical or graphical analyses can be performed.

The models are designed to solve a wide range of problems in optical oceanography and limnology. The input absorbing and scattering properties of the water body can vary arbitrarily with depth and wavelength. These inherent optical properties (IOPs) can be obtained from actual measurements or from analytical bio-geo-optical models. Analytical models of the IOPs can build up the total IOPs from contributions by any number of individual components such as water, photoplankton, and mineral particles. The input sky radiance distribution can be completely arbitrary in the directional and wavelength distribution of the direct solar and diffuse sky light. In its most general solution mode, HydroLight and EcoLight include the effects of inelastic scatter by chlorophyll fluorescence, by colored dissolved organic matter (CDOM) fluorescence, and by Raman scattering by the water itself. The models also can simulate internal layers of bioluminescing microorganisms.

HydroLight and EcoLight solve different versions of the radiative transfer equation, but their input and much of their output is the same. However, the models are intended for different applications and their run times differ by factors of tens to hundreds. In this Users' Guide, HydroLight-EcoLight version 6.0 will be called HE60 when referring to common features of the codes. Differences in HydroLight and EcoLight will be noted as necessary, in which case the individual names will be used.

The HE60 mathematical code is written in standard Fortran 95 in order to make it easily portable to almost any computer with a Fortran 95 compiler. Although it is popular to deride Fortran as an ancient language no longer spoken in computer science departments, the fact remains that Fortran always has been, is now, and likely will remain the best language for doing serious numerical computations such as solving differential equations—which is what HydroLight does for 90% of its run time. We therefore make no apology for keeping HE60 in Fortran.

The Graphical User Interface (GUI) is written in C++ and uses the Qt library for GUI elements. The GUI allows HE60 to be run in its "standard mode" (the usual way of running the software, which will account of the vast majority of runs made by most users). The same system-independent Fortran 95 and C++ source codes are compiled to create system-dependent executables for the Microsoft Windows, Linux, and Apple operating systems.

On Microsoft Windows the Lahey Fortran 95 Express compiler for Microsoft Windows is distributed with the HE60 license. The compiler is required to recompile the software if changes are mode to the code; under normal use recompilation is not required. On Apple and Linux machines the software gfortran can be used for recompiling, this is a free download and information on installation is given in Appendix C of the Technical Documentation.

All input and most output files are written as ASCII text files to insure easy transfer of files between computers with different operating systems. The exception is Microsoft Excel spreadsheets, which are created if requested.

The GUI is provided to make HE60 user friendly; it is not actually necessary to enter inputs via the GUI in order to run HE60 itself. As with previous versions, users can create or modify the needed input files with a text editor or other program and then submit HE60 runs from a command window. However users are cautioned that manual modification of the input files is tricky due to the complexity of the input, and is thus not recommended as the normal way of running HE60. The input file format is described in detail in Appendix A of the HE60 Technical Documentation.

Throughout this report, the names of mathematical variables are written in italics, e.g., *U*, *z*, or *zeta*. The names of computer programs, directories, and files are written in a sans serif font, e.g., IOP_case1.f or Pupcast2.txt. Path names are typically written using the DOS format with a backstroke, e.g., ..\HE60\data\phase_funtions\HydroLight. Where specific OS X or Linux paths are given these will be with a forward stroke as is used on those systems. Note that the HE60 directory structure and paths are identical on Windows and Linux machines, but there are slight differences on an Apple machines as explained in Section 2. User input to and output from programs is show in `Courier`. Options on the Graphical User Interface are shown in SMALL CAPS.

1.1 Source Codes and Run Procedure

The first lines of code for what later became HydroLight were written by Curtis Mobley in the early 1980s when he was a postdoc working with Rudolph Preisendorfer. That code was written in Fortran 77. For the full story, see HydroLight_History.pdf in the documents directory.

The Fortran 77 code persisted throughout the decades as HydroLight became a commercial product. However, as new features were added, the code became increasingly complex, confusing, hard to maintain, and just plain ugly. Therefore, in 2017 and 2018, Curtis Mobley rewrote every line (over 30,000 lines) of the HydroLight and EcoLight source code as very clean Fortran 95. (The exception is several Fortran 77 public code routines for basic mathematical operations such as solving differential equations, matrix inversion, and sorting. These routine are not yet available in Fortran 95.)

Similarly, the original GUI for Windows was written in Visual Basic 5, which runs only on computers with some version of the Microsoft Windows operating system. Visual Basic has morphed into VisualBasic.NET, which is considerably different and, in any case, does not meet the current requirements for a GUI. Therefore, John Hedley rewrote the Visual Basic GUI using C++ and Qt5, which is independent of the operating system.

These are the system-independent common source codes that underlie HE60. These codes are then compiled to create system-dependent GUIs and executable HydroLight and EcoLight files for Microsoft Windows, Linux, and Apple operating systems. This is shown in Fig. 1.
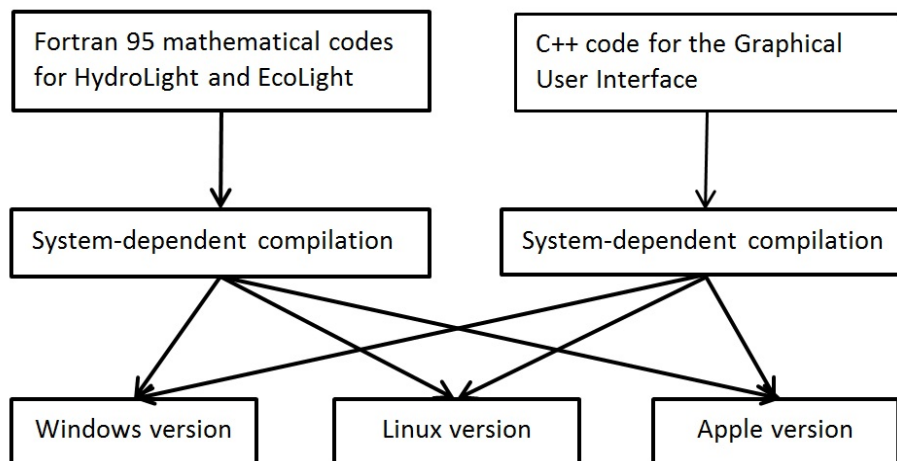

Figure 1. Code structure for HE60.

Figure 2 shows the layout of the code and of a typical run. At the top there is a directory (HE60/source_code/common_data_modules) that contains several Fortran 95 data modules. These modules define mathematical constants, array dimensions, common variables, and default values used throughout the HydroLight and EcoLight codes. All of the computational routines look to these modules to obtain global (used in more than just one routine) values, and the modules are used to pass information between routines as HE60 runs. For example, there is only one place in the code where an array to hold wavelengths is defined, and the values of the wavelengths are stored there during a particular run. Each routine then looks to the same place to obtain the current wavelength as needed. (These data data modules replace the inherently evil common blocks of Fortran 77.) The data modules all have names beginning with "mod_". Thus file mod_IOP_info.f95 is the data module that contains information needed by the IOP routines. The data modules do no computation.

There is a directory (HE60/source_code/common_code) that holds the computational routines that are identical for both HydroLight and EcoLight. These routines perform tasks such as reading data files or interpolation. The IOP models are found in the common_code directory. Routines that are specific to HydroLight or EcoLight are found in the respective directories HE60/source_code/HydroLight_code and HE60/source_code /EcoLight_code. These routines usually depend in some way on the angular resolution (quads in HydroLight and bands in EcoLight) or that solve the respective versions of the RTE (azimuthally dependent in HydroLight and azimuthally averaged in EcoLight). All computational routines have names of the form "*_mod.f95". Thus routine IOP_newCase1_mod.f95 in the common_code directory holds the code for the "new Case 1" IOP model.

Each of the computational routines (or groups of related routines) is placed in Fortran 95 modules via CONTAINS statements, rather than just being placed in files. This creates an "explicit interface" to the routines, which means that various properties of one routine are known to the other routines *at compilation time*. For example, if one subroutine is called with variable x as a floating point number, but another subroutine is called with x as an integer, this error will be caught during compilation. This greatly reduces the chance of hard-to-find bugs in the code. The only penalty paid for placing subroutines in modules is that all modules containing subroutines called by another subroutine must be compiled before the calling subroutine is compiled. This is handled by the make files that come with HE60.

```
Common Fortran 95 data modules
                |
                v
     Common Fortran 95 code
         /            \
HydroLight-specific code    EcoLight-specific code
        |                          |
        v                          v
   Compilation    Default data   Compilation
        |            files           |
        |         User-supplied      |
        |          data files        |
        |          GUI inputs        |
        v              |             v
  HydroLight  <--  Run input file  -->  EcoLight
  executable                            executable
        |                                   |
        v                                   v
   RTE solution                       RTE solution
        \        |        /    \       |       /
   Printout   Excel   Digital files
             spreadsheets
```
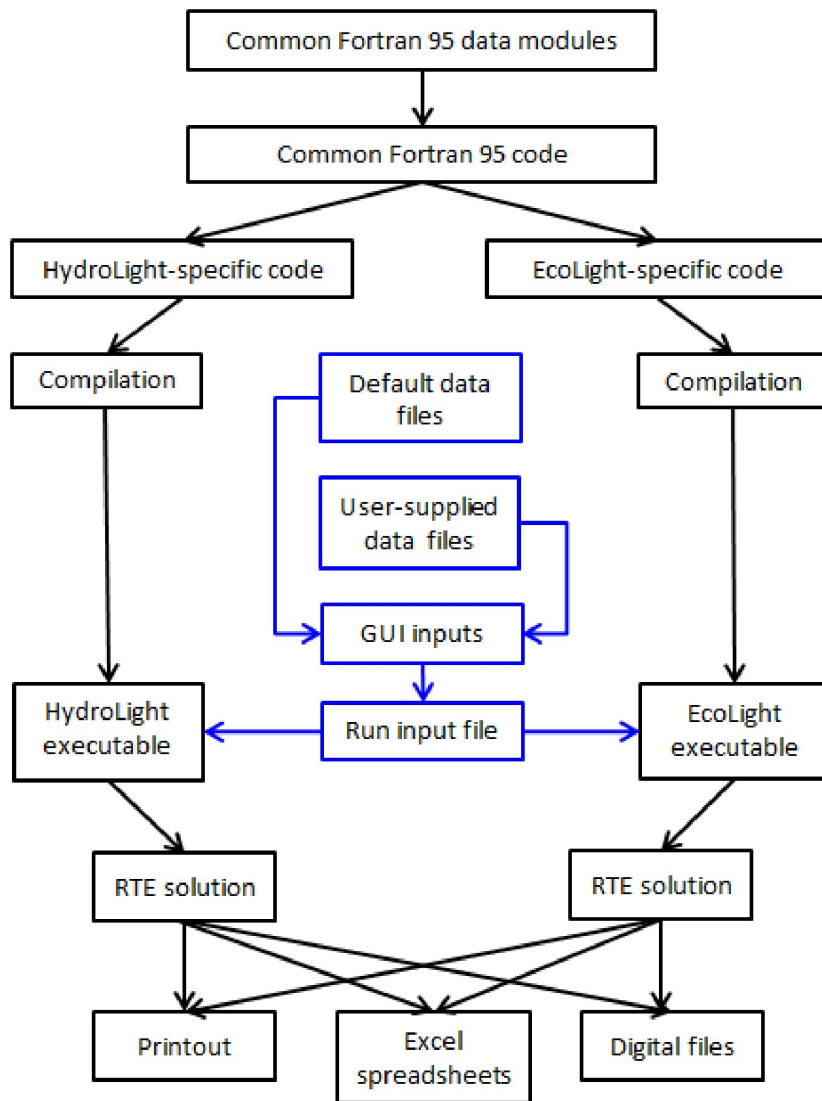
Figure 2. Structure of the HE60 code and of HydroLight and EcoLight runs.

The input to both the HydroLight and EcoLight executable files is identical, as seen in the blue central part of Fig. 2. The user uses the GUI to define the unique radiative transfer problem to be solved, as discussed in the Users' Guide. All runs will make use of some of the default data files that come with HE60, and a run may or may not use data files provided by the user. In any case, the GUI creates a run input file (the lroot.txt file) that contains all of the information needed to specify the run. The same input file is used to run either HydroLight or EcoLight. The appropriate RTE is then solved, and various types of output files are created.

1.2 Philosophical Comments, Warnings, and Excuses

It is important to understand that the HydroLight and EcoLight models per se are radiative transfer models, not models of oceanic optical properties. You, the user, must supply the inherent optical properties and boundary conditions to the HE60 core code. (Indeed, the HE60 model is not even restricted to the oceanic setting, although that is its usual application. If you supply HE60 with the optical properties of a bucket of orange paint, for example, HE60 will happily solve for the radiance distribution within and leaving the paint.) This requirement for user input gives HE60 great power—it can simulate any water body and each user can run the model for exactly the conditions of interest—but also requires considerable forethought and effort on the user's part, in order to specify IOPs and boundary conditions that correctly describe the water body of interest. Some users of previous versions have not understood their role in providing input to HE60, so let us say the following for emphasis:

> HE60 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 HE60. The various IOP models, phase functions, chlorophyll data sets, IOP data sets, etc. that come with HE60 are *examples* of how to provide IOP and other information to HE60. *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. Garbage in, garbage out, and HE60 is not idiot proof.

HE60 computes the radiance and other output (for a given set of input) more accurately than can be measured with standard instrumentation. However, as with any model, HE60's output is only as good as the input provided by the user. If you are using a simple "Case 1" bio-optical model for the absorption and scattering coefficients, guessing the phase function, and using the mid-ocean atmospheric parameters in the sky radiance model, you should not be surprised (and are not allowed to complain) if the HE60-predicted water-leaving radiances differ significantly from what you measured in your experiment in Case 2 coastal waters. Likewise, if you give HE60 a file with thousands of ac-9 data points generated by sampling at 6 Hz during a depth profile, HE60 will do its best to solve the radiative transfer equation with *exactly* the absorption and scattering profile you have given it. The result may be numerically disastrous if the ac-9 profile looks like random instrumental noise superimposed on a smoother signal, as illustrated in Fig. 3.
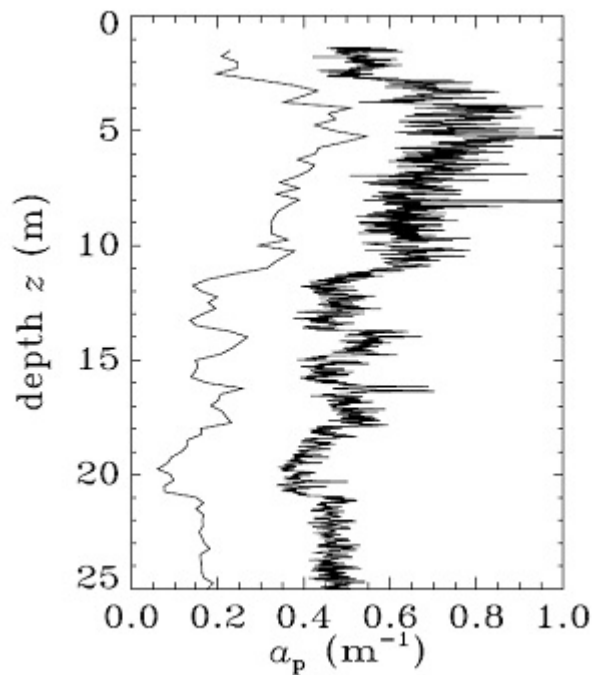
Figure 3. Smoothed and unsmoothed data. The right curve is 2,056 values of particulate absorption a_p obtained from an ac-9; this curve is too noisy to be used as input to HE60. The left curve (offset to the left by 0.3 for clarity) is the same data binned into 25 cm depth bins to give 95 a_p values; this curve is suitable for input to HE60 and still contains adequate depth resolution of the absorption fine structure.

It is your job to clean up noisy data, smoothing and massaging as much as your conscience and scientific expertise allow, before using it as input to HE60. HE60 does some checking for bad input, but there is still great opportunity for entering incorrect or unphysical input and getting incorrect output.

HydroLight has been a work in progress since Curtis Mobley first started working out the numerical algorithms as a postdoc (with Rudolph Preisendorfer) in 1979, and it will continue to be so. The first publically released version of HydroLight was version 3, which ran only on a mainframe computer or UNIX workstation. Version 4 was created in response to users' requests for a more user-friendly code with additional options, and for a code that would run on inexpensive personal computers. Version 5 continued that development with major modifications to the version 4 code to improve its internal numerical algorithms and to add various features requested by users. Most notably, version 5 included EcoLight, a fast version of HydroLight that solves the azimuthally-averaged radiative transfer equation. EcoLight can be used when all the user wants to know is the nadir-viewing remote-sensing reflectance, irradiances, diffuse attenuation functions, or other quantities that are obtained from an azimuthal integration over the full radiance distribution. The current versions 6 is a total rewrite of the version 5 code to bring it up to modern scientific programming standards. The version 6 GUI is totally new, even though the look is the same as version 5. Although the invariant imbedding algorithms at the core of HE60 are mature and well debugged after many

8

years of use in previous versions, some core code and options are new with version 6.

HE60 supports runs with wavelengths from 300 to 1000 nm. This is primarily because the databases underlying the atmospheric submodels, IOP models, and other data files cover only the 300 to 1000 nm range, which limits HE60 to that wavelength range. However, HE60 allows for input of user-generated files of sky radiance distributions. If that option is chosen, HE60 can run at any wavelengths for which the sky radiance is provided*, provided that the user also inputs the water inherent optical properties and any other information needed by the run at the wavelengths where the run is to be made.*

Although the source code is provided for both HydroLight and EcoLight, executable files are also provided. These executables can handle most situations of interest. The code needs recompilation only if the user if the user modifies a routine or adds a user-defined IOP model or concentration function.

2. INSTALLING HE60

This Section describes how to install the HE60 code on Windows, Linux, and Apple operating systems.

2.1 Computer Requirements

The HE60 package of source code and data files requires about 780 Mbytes of hard-drive storage as distributed. If it is desired to make changes and recompile the code, a Fortran 95 compiler must be also installed and will take additional storage. The minimum required amount of random access memory (RAM) is small by the standards of modern computers which typically have several gigabytes of RAM. The digital output files can be 10 Mbytes or larger for runs requesting output at many depths and wavelengths. Thus, disk storage can be consumed quickly in a series of simulations requesting extensive output. Moreover, some of the internal scratch files used during the solution of the radiative transfer equation can be many tens of Mbytes if many depths and wavelengths are included in the run. Again, most computers now have hundreds of gigabytes of hard drive space, which is more than sufficient.

HE60 is tested on Microsoft Windows versions from Windows 7 upwards, earlier versions are not supported. The MS Windows build is 32-bit and should work on both 32-bit and 64-bit versions of Windows. On Apple machines HE60 is 64-bit only and is tested on Mavericks (10.9.5) and Sierra (10.12.3); it should work on all OS X versions from 10.9.5 onward, earlier versions are not supported. There are many variants and versions of Linux distributions, so it's not possible to make a definitive statement of compatibility for Linux. HE60 for Linux is 64-bit only and is currently compiled and tested on Fedora 14 and Fedora 23.

2.2 Installation on Microsoft Windows Operating Systems

This section describes how to install HE60 on a PC running the Microsoft Windows operating system. Unlike previous versions it is no longer necessary to install the Lahey compiler before using HE60. The Lahey compiler is required only if it is intended to make modifications to code, it can be installed at a later date. Refer to Appendix C of the Technical Documentation for information on the installation of the Lahey compiler..

Depending on how you received HE60 it will either be on a CD or as a single file self-installing EXE file. To install the code on your PC, do the following:

Step 1 (CD only). Insert the HE60 CD into its drive. The installation program should start automatically. If it does not, browse on the CD using File Explorer and double-click on setup.exe. Alternatively, go to START ➜ RUN and run setup.exe from the CD (e.g., if the CD is in drive D you would type `d:\setup.exe` at the run prompt). If you have the installer EXE file, then double-click on it to run it.

Step 2 (CD or installation file). You will be asked to select the folder/directory in which HE60 will be installed; the default is C:\HE60, but you can choose another (e.g., C:\Program Files\HE60). A new folder HE60 will be created and placed in the folder you selected *unless* you select an *existing* folder named HE60, in which case the existing HE60 folder will be overwritten. Note that if you overwrite an existing HE60 directory you will lose all output files that may be under that directory, the installer will warn you of this. You will also be asked to read and accept the license agreement. The installer takes care of all aspects of the installation including: copying the files, updating and registering any system files needed by HE60, removing the read-only flags from the HE60 files, and creating shortcuts for HE60 in both the START ➜ PROGRAMS window and on the desktop.

Uninstalling. If at some future point you want to uninstall HE60 this can be done through the normal Control Panel option to uninstall a program.

On Windows 7 this is done as follows (the options may have slightly different names on different Windows versions):
    go to START MENU ➜ CONTROL PANEL ➜ UNINSTALL A PROGRAM
    select HydroLight-EcoLight and click on UNINSTALL
   follow the directions to remove all files associated with HE60

Warning: This will remove everything under the HE60 directory, including all output files under HE60\output - so be sure to move or copy any outputs you want to keep to another location first.

2.3 Installation on Apple Systems

This section describes how to install HE60 on a Apple machine. HE60 for OS X is distributed as a ZIP file. Installation simply requires unzipping the file and dragging HE60 to whereever you want it located on your system.

Step 1. Double click on the ZIP file.

Step 2. In the unzipped folder you will see the HE60 application and two folders that contain documentation and additional files. Drag the HE60 icon to wherever you would like to install it on the system. To install it under Applications so that it appears in the Launchpad, drag it to the Applications folder (see below), or it can equally be dragged to the desktop.
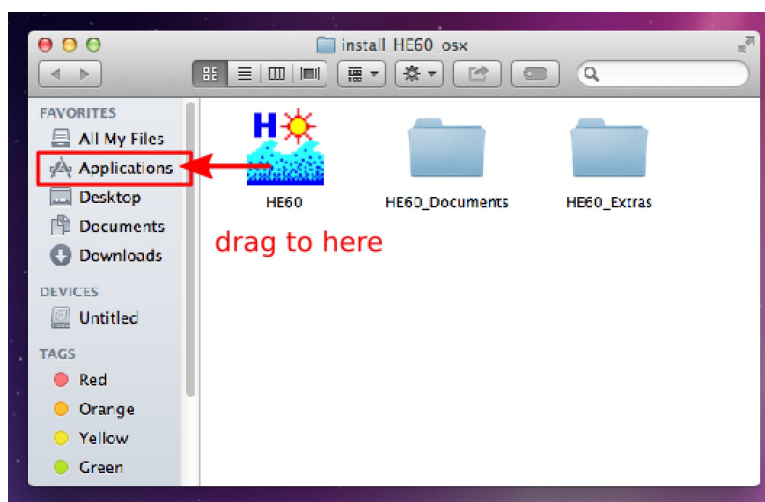
The HE60_Documents and HE60_Extras folders can also be dragged to any location as desired. This completes the installation.

There is an important difference regarding the layout of HE60 directory structure on an Apple system versus a Microsoft Windows system. On MS Windows the program, data files and outputs are all placed under a single top level directory called 'HE60', typically installed as C:\HE60. On an Apple machine this single directory structure is not possible because the program must be separated from the data and output files. When HE60 is first run a directory 'HE60' will be created under the user's standard 'Documents' directory, this contains the 'data/examples' and 'output' subdirectories. So after a run titled 'test1' the outputs can be found here:
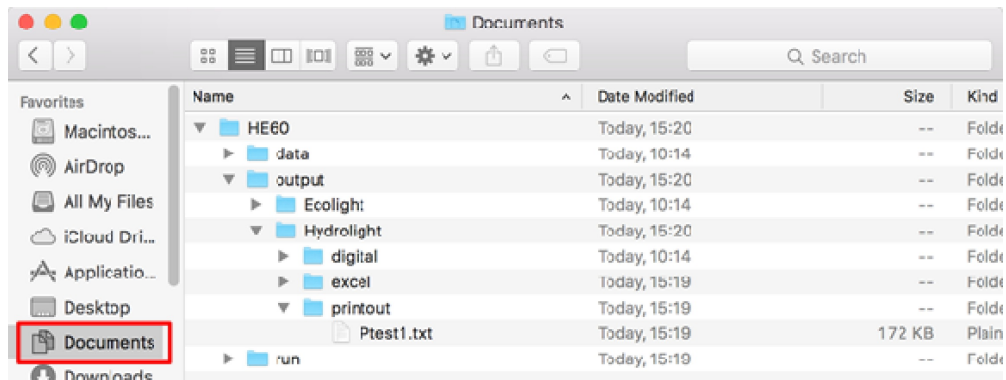
On an Apple machine the program itself is under a directory called 'HE60.app' and this is what is represented by the HE60 icon that was installed above (the '.app' extension on the name is not shown in the Finder window). If you Ctrl-Click on this icon the option 'Show Package Contents' will allow you to browse under 'HE60.app', under this there is a directory called 'Contents' - this directory is the equivalent of the C:\HE60 directory on an MS Windows system. More details on the directory layout are given in Section 4.

Uninstalling. To uninstall HE60 on an Apple machine simply drag the HE60 icon to the Trash or Ctrl-Click on it and select 'Move to Trash'. The data and output files under Documents/HE60 will not be affected and can be deleted separately if required.

2.4 Installation on Linux Systems

On Linux, HE60 is supplied as a self-extracting archive file with a '.run' extension. The name of this file will be something like 'install_HE60_x86_64_2018_10_21.run'. To install HE60 requires running this file from the command line. First start the terminal, the method for this will depend on the specific Linux version installed but is likely to be a menu options such as: `Applications > System Tools > Terminal`. Then 'cd' to the directory containing the install file. It is necessary for the file to have its executable permissions flag set in order to be able to run it. This can be checked with the command '`ls -l`':

The first two 'x' symbols in '-rwxrwxr-x-' means the file can be run. If these are not present type:

```
chmod 770 install_HE60_x86_64_2018_10_21.run
```

with whatever specific name the install file is called. Then to install type this command (with the initial './'):

```
./install_HE60_x86_64_2018_10_21.run
```

as below:

```
                              john@localhost:~
 File  Edit  View  Search  Terminal  Help

[john@localhost ~]$ ./install_HE60_x86_64_2018_10_21.run
Verifying archive integrity...  100%   All good.
Uncompressing Hydrolight-Ecolight (Linux) 6.0  100%
Enter the location where to install the HE60 directory [or press return for default /home/john]:█
```

The installer will prompt for a location to install HE60, if you just press RETURN then HE60 will be installed under your home directory, e.g. following the above example in the directory /home/john/HE60. Another directory may be specified, but note that system directories will require super-user privileges to install. So for example to install under /usr/local use 'sudo' to run the installer:

```
sudo ./install_HE60_x86_64_2018_10_21.run
```

If the directory HE60 already exists in the requested location the installer will quit and request that the existing directory be deleted first.

After the installation has completed, you can immediately run HE60 by typing:

```
./HE60/frontend/HE60
```

(assuming the installation directory was 'HE60' in the current directory), or via the equivalent path to HE60/frontend/HE60 wherever it was installed. The installer also attempts to create a desktop icon and a menu entry for 'HydroLight-EcoLight 6.0'. On some variants of Linux, and depending on the window manager employed, these shortcut icons may or may not be created. In any case, if desired, they can be manually created by following the instructions of your specific Linux version to create a shortcut to HE60/frontend/HE60, which is the GUI executable. Note that the entire installation of HE60 is contained under the 'HE60' directory created by the installer, so you can safely move this directory and its contents to any desired location.

Uninstalling. To uninstall HE60 on a Linux machine simply delete the HE60 directory, with a command such as '`rm -rf HE60`', or by using the File Explorer on your system. Note that all the files under HE60 will be deleted including any outputs under 'HE60/output'. Shortcut icons on the desktop or in menus should be manually deleted following the instructions for your specific Linux version.

3. OVERVIEW OF HE60

This section gives brief descriptions for new users of how HE60 can be used, of what assumptions are build into the code, of what input is required, and of what output can be obtained from a HE60 run.

3.1 Ways in Which HE60 Can Be Used

There are now literally hundreds of published papers that have used HydroLight in one way or another. Most applications have been to problems in bio-optical oceanography and ocean-color remote sensing. Some of the ways in which HE60 can be used are as follows:

- HE60 can be run with modeled input values to generate in-water light fields, which in turn become the input to models of primary productivity or mixed-layer thermodynamics. Such information is fundamental to the coupling of physical, biological, and optical feedback models.

- HE60 can be run with the IOPs of different water types to simulate in-water light fields for the purpose of selecting or designing instruments for use in various water types. Such information can aid in the planning of field experiments.

- HE60 can be run with assumed water inherent optical properties as input, in order to obtain estimates of the signals that would be received by various types or configurations of remote sensors, when flown over different water bodies and under different environmental conditions. Such information can guide the planning of specific operations.

- HE60 can be used to isolate and remove unwanted contributions to remotely sensed signatures. Consider the common remote-sensing problem of extracting information about a water body from a downward-looking imaging spectrometer. The detected radiance contains both the water-leaving radiance (the signal, which contains information about the water body itself) and sky radiance reflected upward by the sea surface (the noise). HE60 separately computes each of these contributions to the radiance heading upward from the sea surface and thus provides the information necessary to correct the detected signature for surface reflection effects.

- When analyzing experimental data, HE60 can be run repeatedly with different water optical properties and boundary conditions to see how particular features of the data are related to various physical processes or features in the water body (such as substance concentrations or external environmental conditions). Such simulations can be valuable in formulating hypotheses about the causes of various features in the data.

- HE60 can be used to simulate optical signatures for the purpose of evaluating proposed remote-sensing algorithms for their applicability to different environments or for examining the sensitivity of algorithms to simulated noise in the signature.

- HE60 can be used to characterize the background environment in an image. When attempting to extract information about an object in the scene, all of the radiance from the natural environment may be considered noise, with the radiance from the object being the signal. The model can then be used to compute and remove the environmental contribution to the image.

- HE60 can be run with historical (climatological) or modeled input data to provide estimates about the marine optical environment during times when remotely or in-situ sensed data are not available.

Such information can be provided in many forms: water-leaving radiances for remote-sensing applications, in-water apparent optical properties (such as K functions) for Lidar bathymetry applications, or ambient light field data as may be relevant to biological productivity or underwater visibility applications.

3.2 The Physical Model

Many problems of interest in optical oceanography and remote sensing can be solved using time-independent radiative transfer theory applied to plane-parallel geometries. The consideration of time-independent, plane-parallel problems is not as restrictive as it might seem on first glance. For example, although the oceans are horizontally inhomogeneous, the horizontal scales of significant optical variability (typically tens of meters to kilometers) are usually much greater than the vertical scales (centimeters to tens of meters). In this case we can think of the ocean as consisting of optically independent "patches" of water, for which

17

each patch can be well modeled as a horizontally homogeneous water body whose optical properties vary only with depth. (This is a one-dimensional geometry, with the one dimension being depth). We can then independently apply a one-dimensional radiative transfer model at the center of each patch in order to simulate the entire, horizontally inhomogeneous water body. In the analysis of imaging spectrometer data, one sometimes might even apply such a model to the water patch associated with each pixel in the image.

Such a piecewise simulation is justified so long as the horizontal size of each water patch is at least several times the inverse of the beam attenuation coefficient, which is usually called the mean free path. This is usually the case. In the open ocean, the mean free path is never more than 50 m (at blue wavelengths, and much less at other wavelengths) in even the clearest waters; horizontal variability in such waters is often on scales of kilometers. In coastal waters subject to river runoff, sediment resuspension, and variable shallow bottom topography, optical properties and boundary conditions can change horizontally on scales of meters to tens of meters. However, such waters tend to be rather turbid and have mean free paths of tens of centimeters to a few meters. In either case, the use of a one-dimensional radiative transfer model is justified.

The use of time-independent radiative transfer is valid whenever the time scales for changes in environmental conditions (typically seconds to seasons) are much greater than the time required for the light field to assume a steady state within the water body after a change in the optical properties or boundary conditions (milliseconds). Solving a sequence of time-independent, one-dimension radiative transfer problems in order to simulate a changing (in both time and space) water body is computationally much faster than solving one large time-dependent, three-dimensional problem.

Other physical considerations also dictate the generality required in an oceanic radiative transfer model. High absorption by water itself means that little light penetrates the ocean outside of the near-ultraviolet to near-infrared region from 300 to 750 nm. The presence of phytoplankton, absorbing minerals, or dissolved substances can greatly limit light penetration below 400 nm. Multiple scattering is almost always important, but polarization may be neglected for many applications. Inelastic scattering processes such as Raman scatter by the water itself and fluorescence by chlorophyll and CDOM can in some circumstances make significant contributions to the light field.

The HE60 physical model, which addresses the above considerations, can be summarized as follows:

- time-independent
- horizontally homogeneous IOPs and boundary conditions
- arbitrary depth dependence of IOPs
- wavelengths between 300 and 1000 nm
- finite or infinitely deep (non-Lambertian) water-column bottom
- includes all orders of multiple scattering
- can optionally include Raman scatter by water
- can optionally include fluorescence by chlorophyll and CDOM
- can optionally include horizontally homogeneous internal sources such as bioluminescing layers
- does not include polarization
- does not include whitecaps

Beginning in version 6.0, there are three options for how the sea surface is modeled. The most general of these is based on fully resolved gravity-to-capillary wave variance spectra. These surfaces account for wave shadowing effects by large-scale gravity waves as well as the effects of the optically important surface wave slopes down to the capillary wave scale. Two other surface options use the Cox-Munk wind speed-wave slope model to simulate the sea surface slope statistics; those surfaces do not account for wave height effects. These surface models are discussed in the Technical Documentation.

The use of scalar (unpolarized) instead of vector (polarized) radiative transfer theory is the limiting factor on the accuracy of HE60 radiometric output for most water bodies (for given inputs). Radiances in particular directions can be off by roughly ±10%, depending on the water IOPs, depth, direction, and wavelength, when computed by scalar rather than vector theory. However, these differences tend to average out when radiance is integrated over direction to get irradiances, and simulations with polarized codes show that irradiances are usually computed to within 1% accuracy using scalar theory. Thus, for many oceanographic applications, the use of vector theory is unnecessary.

3.3 The HydroLight Mathematical Model

The fundamental quantity that describes the time-independent, one-dimensional (unpolarized, depth-dependent) light field in the ocean is the spectral radiance $L(z,\theta,\varphi,\lambda)$, with units of W m^{-2} sr^{-1} nm^{-1}. The spectral radiance completely determines the depth (z), directional (θ,φ), and wavelength (λ) behavior of the light field. Therefore, all other quantities of interest, such as various irradiances, diffuse attenuation functions (K-functions), and reflectances, can be computed from their definitions once the spectral radiance is known. In order to predict the spectral radiance, HydroLight solves the integro-differential radiative transfer equation (RTE) along with its boundary conditions. Because of their mathematical complexity, these equations must be solved numerically for any realistic situation. The solution technique used in HydroLight is described in detail in Chapter 8 of *Light and Water*, and the source code is documented with references to that chapter.

Any radiance sensor actually measures an average of $L(z,\theta,\varphi,\lambda)$ taken over some finite solid angle $\Delta\Omega$, which is determined by the field of view of the instrument, and over some finite bandwidth $\Delta\lambda$, which is determined by the wavelength response of the instrument. Likewise, in order to solve the RTE numerically, it is discretized by averaging over direction and wavelength. In the HE60 model, this directional averaging is performed by first partitioning the set of all directions (θ, φ), $0 \leq \theta \leq 180°$, $0 \leq \varphi < 360°$, into regions bounded by lines of constant θ and constant φ, plus two polar caps as seen in Fig. 4. These quadrilateral regions and polar caps are collectively called "quads." The individual quads Q_{uv} are labeled by discrete indices $u = 1, 2, ..., M$ and $v = 1, 2, ..., N$ to show their θ and φ positions, respectively. The standard (default) quad layout is shown in Figure 2. In this layout, which has $M = 20$ and $N = 24$, the polar caps have a $5°$ half angle and the θ boundaries lie at 5, 15, 25, ...,75, 85, 90, 95, 105, ..., 175 degrees. For mathematical reasons there is no quad centered on the "equator" at $\theta = 90°$ (the red line in the figure). However, the radiances computed for the $85°$-$90°$ and $90°$-$95°$ quads can be averaged to give the "horizontal" radiance at a nominal angle of $\theta = 90°$. Thus the HydroLight standard quad layout essentially gives $10°$ resolution in θ and $15°$ in φ.
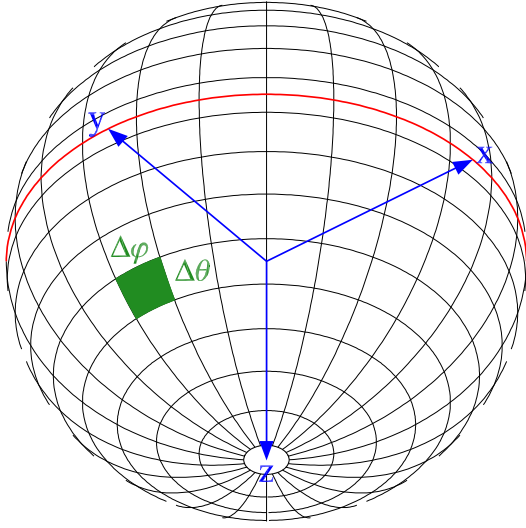
Figure 4. The HydroLight standard quad layout, which has a nominal angular resolution of $\Delta\theta = 10°$ and $\Delta\varphi = 15°$. The green shaded quad indicates a particular $10°\text{x}15°$ quad. The red line at the "equator" divides the upper and lower hemispheres of directions. This figure is drawn from the perspective of being in the water looking upward; note that the +z axis points downward.

Similarly, the wavelength region of interest is partitioned into a number of contiguous wavelength bands of width $\Delta\lambda_j$, $j = 1, 2, ..., J$. The $\Delta\lambda_j$ need not be the same size for different j values.

The fundamental output from HydroLight is then the quad-averaged radiances at any selected set of depths z_k, $k = 1, 2, ..., K$:

$$L(k,u,v,j) \equiv \frac{1}{\Delta\Omega_{uv}\,\Delta\lambda_j} \int_{Q_{uv}} \int_{\Delta\lambda_j} L(z_k,\theta,\varphi,\lambda)\,\sin\theta\,d\theta\,d\varphi\,d\lambda\ . \tag{1}$$

In addition to the radiances within the water, HydroLight computes the upwelling radiance in all directions (all quads) just *above* the sea surface. This upwelling radiance includes both the water-leaving radiance and that part of the incident direct and diffuse sky radiance that is reflected upward by the wind-blown sea surface. The water-leaving and reflected-sky radiances are computed separately in order to isolate the water-leaving radiance, which is the quantity of interest in many remote sensing applications. The development of the quad-averaged versions of the RTE and of the associated boundary conditions is given in full in *Light and Water*.

It must be noted that the quads "homogenize" the radiance within each quad, much like a frosted-glass window does. Thus, in the quad layout of Fig. 2, it is not possible to resolve the difference in the radiance for polar angles $\theta = 26°$ and $\theta = 34°$, because they both lie in the same quad extending from $\theta = 25°$ and $\theta = 35°$. However, there is a difference in $\theta = 34°$

21

and $\theta = 36°$, because those angles lie in different quads and thus are represented by different quad-averaged radiances. Although a finer quad resolution could be used, computer storage and run time are proportional to the square of the number of quads, so increasing the angular resolution would come with a considerable computational cost. Numerical experimentation shows that increasing the quad resolution beyond the standard quad partition shown in Fig. 2 will not significantly improve the accuracy of the computed irradiances and other quantities of general interest.

3.4 The HydroLight Coordinate System

HydroLight uses an x-y-z cartesian coordinate system with +x in the downwind direction and +z downward. For technical reasons in how the sea surfaces are modeled, the +x axis points downwind. This coordinate system is shown in Fig. 5. Directions are specified via the polar angle θ and azimuthal angle φ, with $\theta = 0$ being straight down and $\varphi = 0$ being downwind. The sun's polar angle θ_s is always measured from the zenith, as is customary. Thus the sun's radiance is then $L_d(z=a, \theta_s, \varphi_s) = L_{sky}(\theta_s, \varphi_s)$. In radiative transfer theory, direction (θ,φ) always refers to the direction the light is traveling; the corresponding radiance is $L(\theta,\varphi)$. Experimentalists, however, like to use (θ, φ) to denote the direction they are pointing their radiometer. The radiance measured by a radiometer pointing in direction (θ,φ) is $L(180-\theta,180+\varphi)$. Depending on which convention is chosen for HydroLight output, either the theoreticians or the experimentalists will be unhappy.

The HydroLight printout adopts the following convention, which is illustrated in Fig. 5. Polar angle θ is measured either from the nadir direction (the +z direction) or from the zenith direction (the -z direction), for instruments pointing downward or upward, respectively. When the instrument is pointing downward, we add a subscript "u" for "upward" to the radiance to remind us that we are referring to the upwelling radiance, i.e., to light traveling upward. When the instrument is pointing upward, we add a subscript "d" to the radiance to remind us that we are referring to downwelling radiance, i.e., to light traveling downward. Thus the theoreticians' radiance $L(\theta,\varphi)$ is denoted $L_d(\theta,\varphi)$ in the printout, and the theoreticians' radiance $L(180-\theta,180+\varphi)$ is denoted $L_u(\theta,\varphi)$. This u, d subscript convention is commonly used in optical oceanography. For example, E_d denotes the downwelling plane irradiance, which is measured by a cosine collector pointing upward. Likewise, in the printout, the horizontal radiance of light traveling in the $(\theta=90,\varphi=180)$ direction is denoted by $L_h(\varphi=0)$.
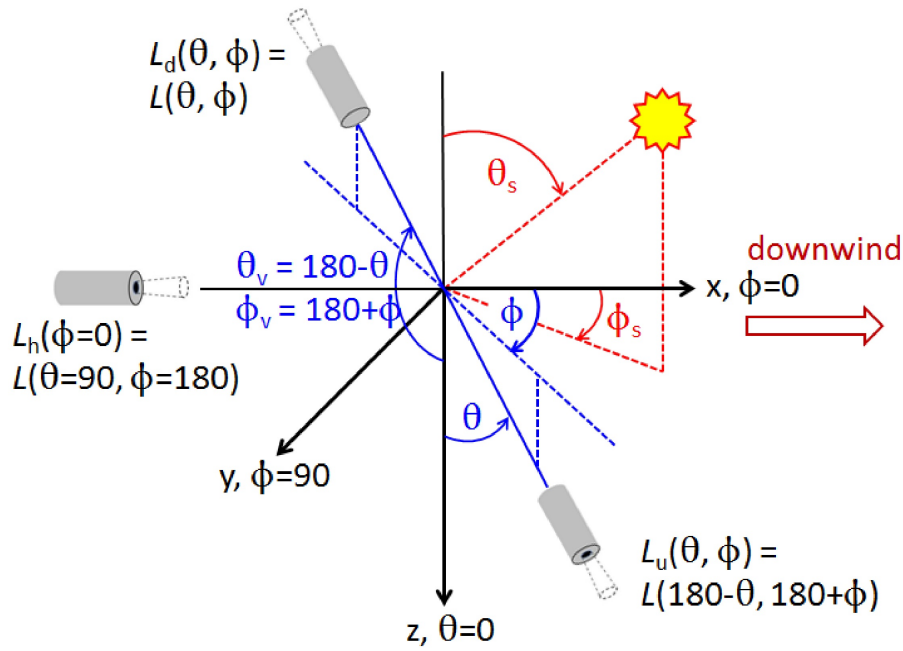
Fig 5. Coordinate system and notation conventions for radiance as used in HydroLight printout.

In the printout, a depth of $z = 0$ denotes a position within the water, just beneath the mean sea surface. A depth of $z = a$ or "in air" denotes a position in the air, just above the mean sea surface. Thus the radiance $L_u(z=0,\theta,\varphi)$ denotes the upwelling radiance just beneath the sea surface, and $L_u(z=a,\theta,\varphi)$ denotes the *total* upwelling radiance in the air. The total upwelling radiance in the air is the sum of the water-leaving radiance, $L_w(\theta,\varphi)$, plus the downwelling sky and sun radiance that is reflected upward by the sea surface itself (the sun glint), $L_{refl}(\theta,\varphi)$. The sky radiance seen when looking in the (θ,φ) direction is $L_{sky}(\theta,\varphi)$. These quantities are illustrated in Fig. 6. The sun's polar angle θ_s is always measured from the zenith, as is customary. Thus the sun's radiance is then $L_d(z=a, \theta_s, \varphi_s) = L_{sky}(\theta_s, \varphi_s)$.

In the optional digital output files, a depth of -1.0 is used to flag in-air values. One of the these files, the Lroot.txt files discussed in §3.7, gives a listing of the entire radiance distribution as a collection of *depth, theta, phi, wavelength, radiance* or $z, \theta, \varphi, \lambda, L$ records. In that file, θ and φ refer to the direction the light is traveling. Suppose, for example, that the sun is at a solar zenith angle of $\theta_s = 60$ deg and an azimuthal angle of $\varphi_s = 45$ deg as in Fig. 5, and that the run included the wavelength of 400 nm. Then in the Lroot.txt file, the sun's radiance at 400 nm above the sea surface ($z = -1.0$) will be the record with values
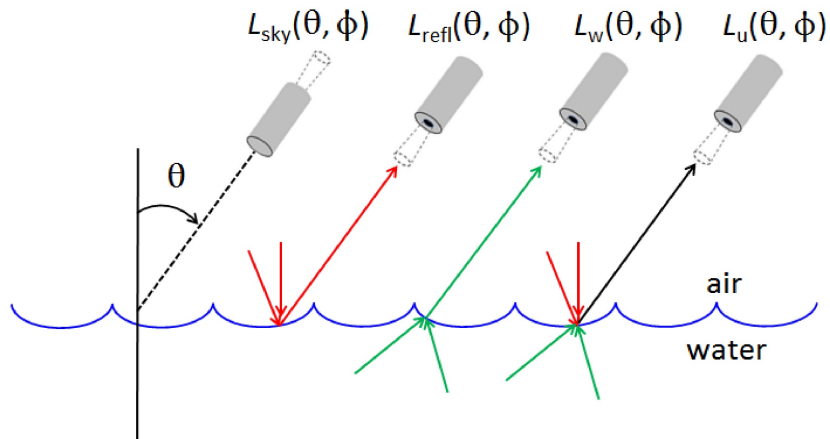
$L_{sky}(\theta, \phi)$ $L_{refl}(\theta, \phi)$ $L_w(\theta, \phi)$ $L_u(\theta, \phi)$

θ

air

water

Fig. 6. Illustration of the various radiances just above the sea surface.

```
-1.0    60.0    225.0    400      Lsun
```

where `Lsun` is the value of the quad-averaged radiance of the quad containing the sun. That is, the sun's light is heading downward ($\theta = 60$ deg from the nadir) in the azimuthal direction away from the sun ($\varphi = 180 + 45 = 225$ deg). For a level sea surface, the sun's specularly reflected radiance will be the record

```
-1.0    120.0    225.0    400       Lspecular
```

That is, the radiance is heading upward ($\theta = 180 - 60 = 120$ deg), and in the same azimuthal direction as the sun's radiance. The direction

```
-1.0    120.0    45.0    400      Lbackscat
```

gives the radiance that is heading directly toward the sun.

It should be kept in mind that any radiance labeled for convenience by exact depth, direction, and wavelength values (z,θ,φ,λ) represents the radiance at the exact depth z (not a value averaged over a finite depth interval), but which is directionally averaged over the quad containing direction (θ,φ) and which is wavelength averaged over the wavelength band containing the nominal wavelength λ. (Radiances computed when selecting the "single

24

wavelength" option can be thought of as being band averaged over a 1 nm wide band.) **Radiances are thus quad-averaged spectral radiances with units of W m^{-2} sr^{-1} nm^{-1}, not wavelength-band-integrated values. Likewise, irradiances are spectral values with units of W m^{-2} nm^{-1}. Note that all HE60 output is in SI units, as just shown.**

One of the most common user support questions is why HE60 values are a factor of 10 or 100 different than what the user measured. In these cases it always turns out that the user's instrument is putting out values in mW cm^{-2} nm^{-1} (a factor of 10 different from SI units) or mW cm^{-2} μm^{-1} (a factor of 100). The scary part of these user-support questions is that some users do not know what units their instrument is outputting, or whether the instrument is outputting band-averaged or band-integrated values, until they tell us that "something is wrong with HydroLight," we ask about units, and the user says, "I don't know, I'll have to ask my technician."

Finally, radiative transfer theory is formulated in terms of energy units, not quanta. In the HE60 output, the spectral scalar irradiance $E_o(z,\lambda)$ with units of W m^{-2} nm^{-1} is also converted to quanta units of mol quanta m^{-2} at the very end of the calculations for the convenience of photobiologists, and the corresponding PAR profile is computed. These values are given in the printout file. That output is given only if the run covers the PAR wavelengths, which are 400-700 nm by default. Similarly, the Secchi depth, CIE chromaticity coordinates, and the Forel-Ule color indices are computed only if the run covers at least 400-700 nm.

3.5 The EcoLight Mathematical Model

As just seen, HydroLight solves the RTE to obtain the radiance distribution as a function of depth, polar and azimuthal direction, and wavelength. This is computationally expensive but necessary if you need to know the radiance in different directions, e.g., for underwater visibility applications where directions toward or away from the sun's direction can have greatly differing radiances. However, many applications such as ecosystem modeling require only various irradiances or diffuse attenuation functions, which are obtained by integrating the radiance distribution over all azimuthal angles and over selected polar angles (such at the upper, lower, or both hemispheres of directions). Likewise, much remote sensing assumes a nadir-viewing direction, in which case no azimuthal angle is involved. In these cases, it is possible to solve an azimuthally averaged version of the RTE to obtain azimuthally averaged radiances, from which the irradiances can be quickly obtain. This is what EcoLight does. Solving the azimuthally averaged RTE requires much less computer time than solving the azimuthally dependent RTE. The tradeoff, of course, is that you do not get the full radiance

distribution.

In EcoLight, Eq. (1) above is replaced by

$$L(k,u,j) \equiv \frac{1}{\Delta\Omega_u \, 2\pi \, \Delta\lambda_j} \int\limits_{Q_u} \int\limits_0^{2\pi} \int\limits_{\Delta\lambda_j} L(z_k,\theta,\varphi,\lambda) \sin\theta \, d\theta \, d\varphi \, d\lambda \, .$$

Thus EcoLight computes azimuthally band-averaged radiances, where the radiance for each polar angle band is averaged over the azimuthal angle φ. Note that irradiances, which are integrals of the radiance over θ and φ are identical in HydroLight and EcoLight.

If your application requires only irradiances, diffuse attenuation functions, the irradiance reflectance, or the nadir-viewing remote-sensing reflectance, then you should run EcoLight. It should be noted that EcoLight gives the same irradiances, *K* functions, and polar-cap radiances as does HydroLight (except for very small differences due to slightly different numerical algorithms). Moreover, both HydroLight and EcoLight require exactly the same inputs for IOPs, and for sky and bottom boundary conditions. Therefore the GUI solicits the same inputs for both models. The decision of which model to run is then made on the last form of the GUI. You can even run one and then the other without repeating the input, if you wish to compare the results.
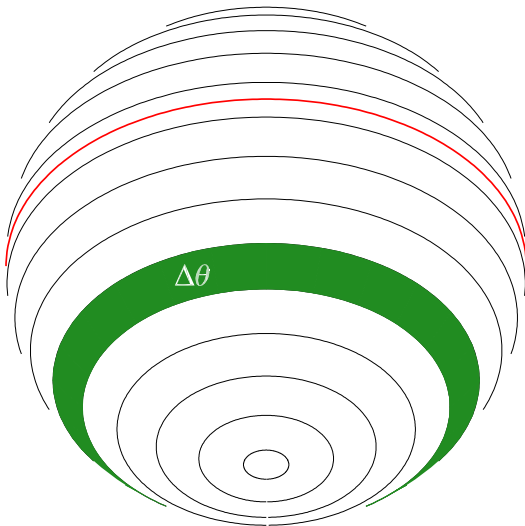

Figure 7. The EcoLight standard band layout, which has a nominal angular resolution of $\Delta\theta = 10°$ and no φ dependence; compare with the HydroLight quad layout of Fig. 4. The green band indicates a particular $\Delta\theta = 10°$ polar angle band. The red line is the "equator" between the upper and lower hemispheres of directions.

3.6 Input

In order to run HE60 to predict the spectral radiance distribution within and leaving a particular body of water during particular environmental (sky and surface wave) conditions, the user supplies the core models with the following information (via direct input in the GUI or via user-supplied data files):

- **The inherent optical properties of the water body**. These optical properties are the absorption and scattering coefficients and the scattering phase function (which are equivalent to the volume scattering function, the beam attenuation coefficient, and the albedo of single scattering). These properties must be specified as functions of depth and wavelength.

- **The state of the wind-blown sea surface**. The sea surface elevation and slope statistics are parameterized by the wind speed. The water surface reflectance and transmittance properties depend on the real index of refraction of the water, which depends weakly on wavelength, salinity, and temperature. The variability of index of refraction is generally not a large effect on computed light fields, but it can be important for some applications, especially near 300 or 1000 nm.

- **The sky spectral radiance distribution**. The sky radiance distribution (including background sky, clouds, and the sun) can be obtained from semi-empirical models that are built into HE60, from observation, or from a separate user-supplied atmospheric radiative transfer model (such as MODTRAN; Acharya, *et al.*, 1998). For most applications, the default sky radiance and irradiance models are adequate. The user can also specify the day of the year for very accurate computation of the earth-sun distance, which affects the incident solar irradiance by a few percent over the course of the year.

- **The nature of the bottom boundary**. The bottom boundary is described in terms of a bi-directional reflectance distribution function (BRDF). For finite-depth bottoms, the BRDF is computed from the given irradiance reflectance of the bottom, if the bottom is a Lambertian surface, or from a user-supplied BRDF, which can be non-Lambertian. For infinitely deep water, the inherent optical properties of the water body below the region of interest are used to compute the needed (non-Lambertian) BRDF that describes the

reflectance properties of the water below the region of interest.

The absorption and scattering properties of the water body can be provided to the HE60 model in various ways. For example, if actual measurements of total absorption are available at selected depths z and wavelengths λ, then these values can be read from a file provided at run time. An interpolation scheme is used to define absorption values for those z and λ values not contained in the data set. In the absence of actual measurements, the total absorption of the water body can be modeled in terms of contributions by any number of components. Thus the total absorption can be built up as the absorption by water itself, plus the absorption by chlorophyll-bearing microbial particles, plus that by CDOM, by detritus, by mineral particles, and so on. In order to specify the absorption by chlorophyll-bearing particles, for example, you can specify the chlorophyll profile of the water column and then use a bio-optical model to convert the chlorophyll concentration to the needed absorption coefficient. The chlorophyll profile also provides information needed for the computation of chlorophyll fluorescence effects. Each individual absorption component has its own depth and wavelength dependence. Similar modeling can be used for scattering.

Phase function information is often provided by using a Rayleigh-like phase function for scattering by the water itself, by using either a Petzold-like phase function or a phase function selected to have a given backscattering ratio for scattering by particles, and by assuming that dissolved substances like CDOM do not scatter. The individual-component phase functions are weighted by the respective scattering coefficients and summed in order to obtain the total phase function.

HE60 also requires the downwelling radiance incident onto the sea surface as input. The HE60 model does not carry out any radiative transfer calculations for the atmosphere *per se*. However, the sky radiance for either cloud-free or solid overcast skies can be estimated from simple analytical models or from semi-empirical models; such models are provided as a part of the HE60 code. Alternatively, if the sky radiance is actually measured, that data can be used as input to HE60 via a user-written subroutine. It is also possible to run an independent atmospheric radiative transfer model such as MODTRAN in order to generate the sky radiance coming from each quad of the sky hemisphere, and then give the (reformatted) MODTRAN-generated values to HE60 as input.

For finite-depth water columns, the bottom boundary BRDF is usually computed from the specified irradiance reflectance of the bottom and the assumption that the bottom is a Lambertian reflector. In general, the bottom reflectance is a function of wavelength and depends on the type of bottom—gray mud, ooid sand, sea grass, etc. HE60 contains the

spectral reflectances for a number of different bottom types. These can be selected in the GUI.

For infinitely deep water columns, the (non-Lambertian) BRDF is automatically computed *using the IOPs at the deepest depth where output is requested* in the simulation at hand. If the run does not include fluorescence, Raman scatter, or bioluminescence, this non-Lambertian bottom boundary conditions is then applied at the greatest user-requested depth. For runs involving inelastic scatter or internal sources, the bottom boundary condition is applied at a deeper depth in order to assure a good solution at the greatest depth requested by the user. See the Technical Documentation §3.3 and HydroLight Technical Note 6 (in the `HE60\documents` directory or `HE60_Documents` on Apple) for a detailed discussion of the bottom boundary conditions when the water in infinitely deep and inelastic scatter in included.

For a remote sensing simulation concerned only with the water-leaving radiance, it is usually sufficient to solve the radiative transfer equation only for the upper two "diffuse attenuation depths" [a depth of $2/K_d(\lambda)$], because almost all light leaving the water surface comes from this near-surface region. In this case, the bottom boundary condition can be taken to describe an optically infinitely deep layer of water below the depth corresponding to two diffuse attenuation depths. In a biological study of primary productivity, it might be necessary to solve for the radiance down to five (or more) optical depths, in which case the bottom boundary condition would be applied at that greater depth. In such cases HE60 computes the needed bottom boundary information from the inherent optical properties at the deepest depth of interest.

3.7 Output

Output from HE60 consists of both archival "printout" (an ASCII text file formatted for viewing with a text editor) and files of digital data (also ASCII, but less readably formatted). The default printout gives sufficient information to document the input to the run and to show the quantities of interest to most oceanographers (such as various irradiances, reflectances, mean cosines, irradiance *K*-functions, and radiances in selected directions). The printout is useful for taking a quick look at the results of a run, or for cutting and pasting a particular part of the output into another document or spreadsheet. Optionally, the printout can give the full radiance distribution (separated into direct and diffuse components), radiance *K*-functions, elastic-scatter path functions, and the like. The printout is easily tailored to the user's

requirements. Section 7.1 describes the printout in more detail.

An optional output file (the Droot.txt file) contains the complete input and output from the run including the computational grid; the component IOPs; the full direct and diffuse radiance distributions in air and water as a function of depth, direction, and wavelength; and various irradiances. This file is generally used as input to plotting routines to obtain graphical output of various quantities as functions of depth, direction, or wavelength, such as seen below in Fig. 12. A similar optional output file (the Lroot.txt file) contains only the total radiance distribution as a function of depth, direction, and wavelength. This file is useful for "slicing and dicing" the radiance distribution to create plots like those seen in Fig. 14.

Routines for graphical output are not a part of the HE60 code *per se* because of the wide variety of graphics packages in use and because different users generally want different kinds of plots. However, a few plotting routines written in the IDL language are included with HE60 as a convenience for users who have that popular software package. IDL routines are provided to read the Droot.txt and Lroot.txt output files. Section 7.3 comments further on the use of IDL for plotting HE60 output.

Output can also optionally include two versions of Microsoft Excel® spreadsheets. The "single-wavelength" version is formatted to facilitate the analysis of data one wavelength at a time. For example, you might want to plot various irradiances as a function of depth at one wavelength. The "multi-wavelength" version facilitates the analysis of one variable at a time, as a function of depth and wavelength. For example, you might want to plot the absorption coefficient or downwelling irradiance as a function of depth and wavelength. The two Excel spreadsheets contain the same information but in different formats.

The organization chart in Fig. 8 clarifies the inputs to and outputs from HE60. In that figure, the user inputs are everything in the blue and orange boxes. HE60 is then the purple box, where the radiative transfer equation is solved. The primary output is the radiance distribution, from which the irradiances in the red box and the apparent optical properties in the green box can all be computed. These quantities are all standard outputs of HE60.
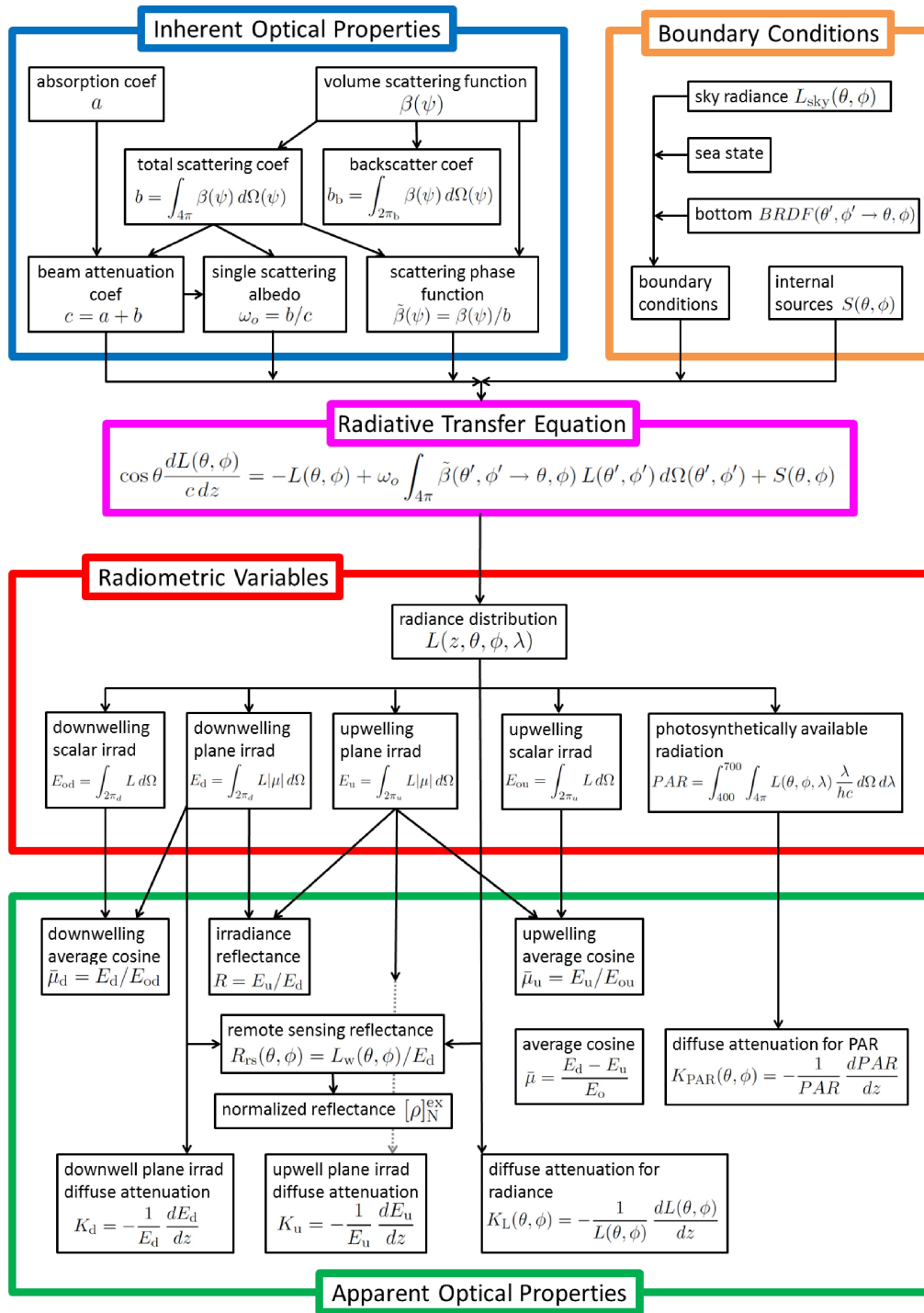
Figure 8. Ocean optics organization chart.

4. HE60 ORGANIZATION

This section describes how the HE60 code is organized. The different types of routines and data files are described, and the file-naming conventions and directory structure are established.

4.1 The HE60 Software Package

The HE60 software package consists of many different main programs, subroutines, and data files. The different routines and files can be classified as follows:

- **Core main programs and subroutines.** These core routines include both Fortran 95 HE60-specific routines and various Fortran 77 public-domain subroutines taken from sources such as LAPACK (Linear Algebra PACKage) and BLAS (Basic Linear Algebra Subroutines; see Dongarra and Grosse, 1987). The public-code routines are used by the HE60-specific routines for mathematical tasks such as matrix inversion, eigenvector-eigenvalue analysis, and solving differential equations. Only the most sophisticated users would even contemplate tampering with any of these highly mathematical core routines.

- **Default subroutines for inputs.** There are many routines for defining the IOPs, the sky radiance distribution, etc. These routines are provided with the HE60 code and are usually used as is. However, they can be modified as desired to alter the input to HE60, for example if the user wants to implement different equations to define the absorption or scattering coefficients as functions of chlorophyll or other concentrations.

- **Default data files.** These files provide input such as chlorophyll- or mass-specific absorption and scattering spectra for use in IOP models, scattering phase functions, sea-surface reflectance and transmission properties for different wind speeds, bottom reflectances, and atmospheric properties used by the default sky irradiance models. The distributed files will be sufficient for many users.

- **User-supplied data files.** Users can add to the default data files by putting their own data onto various "HE60 standard formats" as described in the Technical Documentation. This is done, for example, if the user wishes to input measured absorption and scattering

coefficients measured by a WetLabs ac-9 or ac-S instrument, or measured sky irradiances.

- **Example simulations.** The input file, run script, and output files for a few typical HE60 simulations are given for reference. Users can reproduce these simulations on their own computers in order to verify that HE60 is running properly on their computer.

- **Plotting routines written in IDL** (Interactive Data Language; IDL® is a product of Exelis Visual Information Solutions.). These routines are, strictly speaking, not a part of the HE60 code. A small collection of example IDL routines is included for the convenience of users who have the IDL software package. Users may wish to ignore these routines and use other software (such as MATLAB) for graphical analysis of the HE60 digital output.

Standard HE60 runs are those that result in a solution of the radiative transfer equation. The routines for performing standard runs are found in `HE60\source_code` (or `HE60.app/Contents/source_code` on Apple machines) and its subdirectories. These routines use the available collection of phase-function, sea-surface, and other data files along with the user input provided at run time to solve the radiative transfer problem defined by the input. Standard runs are often made in a series, with only minor changes in the input for each run (e.g., a change in the solar zenith angle or in the chlorophyll profile, with all other input being held constant from one run to the next). Standard runs will constitute almost all of the HE60 runs made by most users.

    Special runs are those that are made for adding either new phase functions (or new sea-surface data files) to the available collection of data files. Special runs are made only once for a given phase function or (surface model and wind speed and index of refraction). The routines in directory `HE60\source_code\Phase_function_code` (or `HE60.app/Contents/source_code/Phase_function_code` on an Apple machine) are used to prepare a scattering phase function for use by the HE60 main code. (This preparation is called discretizing the phase function.) These calculations need to be done only once for a given phase function and quad partition. The use of these routines is described in the Technical Documentation.

    Although users may occasionally wish to add their phase functions to the default collection, this is not the case for sea-surface files. Creating new sea surfaces is very complicated except for surfaces described by the Cox-Munk model, and those are already included in the default data sets. Therefore, the source code for generating new surface files is not included in HE60, except for the Cox-Munk surface model. Creating new surface files

is not trivial; contact us for user support if you think you need surface files for a different range of conditions (e.g., if you need to model an ocean of liquid methane on Saturn's moon Titan). Creating a new set of surface files can take several weeks of computer time.

HE60 contains surface data files for wind speeds from 0 to 15 m s^{-1} and water indices of refraction of $n = 1.32$ to 1.38. These values cover the ranges needed for most oceanic conditions and for which the underlying surface models are valid. (The surface data files themselves are found in the HE60\data\sea_surfaces directory and its subdirectories. A file named surface_1320.2 corresponds to an index of refraction of 1.320 and a wind speed of 2 m s^{-1}.) The files distributed with HE60 are adequate for almost any oceanographic application.

Note also that if you change the quad or band partitioning from the defaults shown in Figures 4 and 7, all phase functions and surface files must be recreated via special runs. This is a considerable undertaking; read the Technical Documentation and contact us for user support in the unlikely case that you need a different quad or band resolution.

4.2 File Naming Conventions

Part of the input to an HE60 run is a single-word "root" name that is used to construct the names of all GUI-generated input and output files associated with that run. Thus, after running the front-end, the input commands to HE60 will be found on a file named Iroot.txt, where "root" has been replaced by the chosen identifying name, e.g. Iupcast2.txt if root = upcast2. After the run finishes, the printout will be found on file Proot.txt (e.g., Pupcast2.txt), and so on. The following input file is created for every HE60 run:

Iroot.txt   the file containing the Input specifying the run (see the Technical Documentation for a detailed description of this input). Written by the GUI to the HE60\run\batch directory.

This input file is the same for either a HydroLight or EcoLight run.

The HE60\frontend directory (HE60.app/Contents/MacOS on Apple) contains two executables, run_hl.exe and run_el.exe, (or simply run_hl and run_el on Apple and Linux) and under the directory HE60\run (or Documents/HE60/run on Apple) are a list of runs to

be made, named runlist.txt.

When you make an HE60 run, you execute run_hl (by choosing "run HYDROLIGHT now" on the last form of the GUI, double clicking run_hl, or by running run_hl from the command line; see §10 of the Technical Documentation for instructions on making "manual" runs, e.g. during debugging of new code). The program run_hl reads the file runlist.txt containing a list of lroot.txt filenames (one or more) that are part of the current "batch" of runs. The runs listed in runlist.txt are submitted by run_hl sequentially to the HE60 Fortran code backend. Thus you can always re-run a simulation made earlier, and you can build up batches of previously defined runs by simply adding their lroot.txt filenames to the runlist.txt file in the run directory. The executable run_hl does the following:

1. takes care of submitting runs in a batch (even if the "batch" only has one run),
2. sends the run names to spawnHL_stnd.bat (in the backend directory) to be run, and
3. waits for the run to finish before starting the process for the next run listed in runlist.txt and repeating steps 2 and 3 until all runs are completed.

When you make an ECOLIGHT run, you execute run_el (by choosing "run ECOLIGHT now" from the GUI, double clicking run_el, or by running run_el from the command line. The program run_el reads the same input (lroot.txt) file as HE60 but submits runs to the EcoLight executable. In this way, once you have defined a run, you can choose to run it under HydroLight or EcoLight at any time without re-running the GUI or changing your input. If fact, from the final screen of the GUI, you can submit the run to both HydroLight and EcoLight for a side-to-side comparison of the irradiances or other common outputs.

After the run finishes, the printout for each run will be found on file Proot.txt (e.g., Pupcast2.txt), and so on. HydroLight printout is written to the HE60\output\HydroLight\printout directory (Documents/HE60/output/HydroLight/printout on Apple) and EcoLight printout is written to the HE60\output\Ecolight\printout directory (Documents/HE60/output/EcoLight/printout on Apple).

The following optional output files can be created for each run by checking the appropriate boxes on the OUTPUT OPTIONS form of the GUI:

Droot.txt   the file containing the full <u>D</u>igital output from the run (usually used as input to a graphics package). Written to the appropriate digital directory (i.e., to HE60\output\HydroLight\digital, or HE60\output\EcoLight\ digital, or equivalent directories under Documents/HE60 on Apple).

Lroot.txt   the file containing the full radiance output from the run. Written to the appropriate digital directory.

Mroot.xlsx   the file containing the <u>M</u>ulti-wavelength-format Excel spreadsheet. Written to the appropriate excel directory (HE60\output\ HydroLight\excel or HE60\output\EcoLight\excel, or equivalent directories under Documents/HE60 on Apple) There will also be a file Mroot.txt from which the spreadsheet is generated.

Sroot.xlsx   the file containing the <u>S</u>ingle-wavelength-format Excel Written to the appropriate excel directory, there will also be an Sroot.txt from which this spreadsheet is generated.

On the final form of the GUI, users have the option of selecting how much output is generated for their run. For example, a user who does not process output in EXCEL should elect not to generate the Sroot.xlsx and Mroot.xlsx files. Likewise, the Droot.txt and Lroot.txt files can be quite large, so do not create them if you are not planning to use them for plotting.

4.3 Directory Structure

The HE60 package is installed by default on the user's computer in a directory named HE60. On a Windows PC, this directory might have the full path name C:\HE60 or C:\Program Files\OceanOptics\HE60, depending on how the user likes to organize his or her computer system. You can, if desired, rename the main directory (for example, if you wish to have more than one copy of HE60 installed for work on different projects, or if different users are working on the same computer and each has his or her own copy of HE60.) In any

case, the HE60 code uses path names relative to the main directory so that the actual name of the main directory does not matter. ***The main HE60 directory has many subdirectories whose names must not be changed.*** All of the computations within an HE60 run are done within these subdirectories.

Figure 9(a) shows the layout and names of the subdirectories that are most important to users, as used for a Windows and Linux installation of HE60. For example, the HydroLight printout will be found in HE60\output\HydroLight\printout. There are many other subdirectories, which are not shown in Fig. 9 because they will not be accessed by most users. For example, the ..\data\sea_surfaces directory is subdivided into HydroLight and EcoLight subdirectories, each of which contains three subdirectories holding the surface files for the three different sea surface model options.

On Apple machines the directory layout is similar to Windows and Linux, except the subdirectories output, run, data/examples and data/user are found under the user's standard Documents directory, under Documents/HE60, see Fig. 9(b). These directories are created the first time the user runs the GUI and the example files are copied to Documents/HE60/data/examples. Currently this directory must be called Documents/HE60, if it is renamed or deleted then it will be recreated next time the GUI is run. The equivalent to the top level program directory, HE60, on MS Windows, is HE60.app/Contents on an Apple machine. If HE60 was installed under Applications the full path would be /Applications/HE60.app/Contents. Another difference is that the subdirectory containing the GUI code is called MacOS rather than frontend as on MS Windows. This structure is imposed by the OS X system. Note the user accessible directory Documents/HE60/data/examples contains the example input data files referred to later in this manual. There are duplicates of these files under HE60.app/Contents/data but these ones cannot be selected in the GUI since OS X does not allow file browsing inside the HE60.app directory.

For brevity in the remainder of this manual the majority of references to directory locations are for the Windows and Linux version, so bear in mind that the corresponding locations on an Apple machine are either under Documents or HE60.app/Contents.
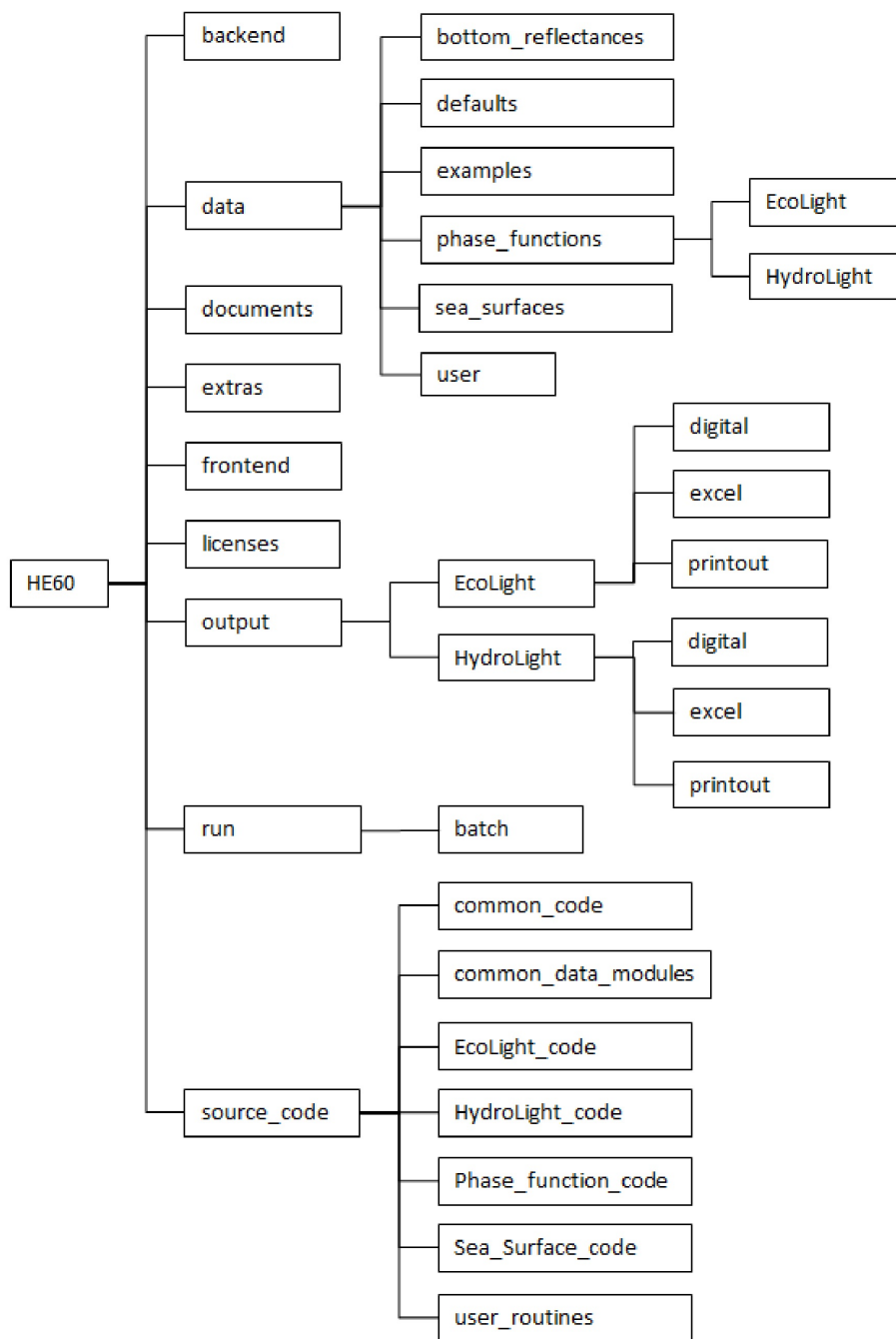
```
HE60 ─┬─ backend
       │
       ├─ data ─┬─ bottom_reflectances
       │        ├─ defaults
       │        ├─ examples
       │        ├─ phase_functions ─┬─ EcoLight
       │        │                   └─ HydroLight
       │        ├─ sea_surfaces
       │        └─ user
       │
       ├─ documents
       │
       ├─ extras
       │
       ├─ frontend
       │
       ├─ licenses
       │
       ├─ output ─┬─ EcoLight ─┬─ digital
       │          │            ├─ excel
       │          │            └─ printout
       │          └─ HydroLight ─┬─ digital
       │                         ├─ excel
       │                         └─ printout
       │
       ├─ run ─── batch
       │
       └─ source_code ─┬─ common_code
                       ├─ common_data_modules
                       ├─ EcoLight_code
                       ├─ HydroLight_code
                       ├─ Phase_function_code
                       ├─ Sea_Surface_code
                       └─ user_routines
```

Figure 9(a). The main HE60 directories on Windows and Linux, as used in standard runs.
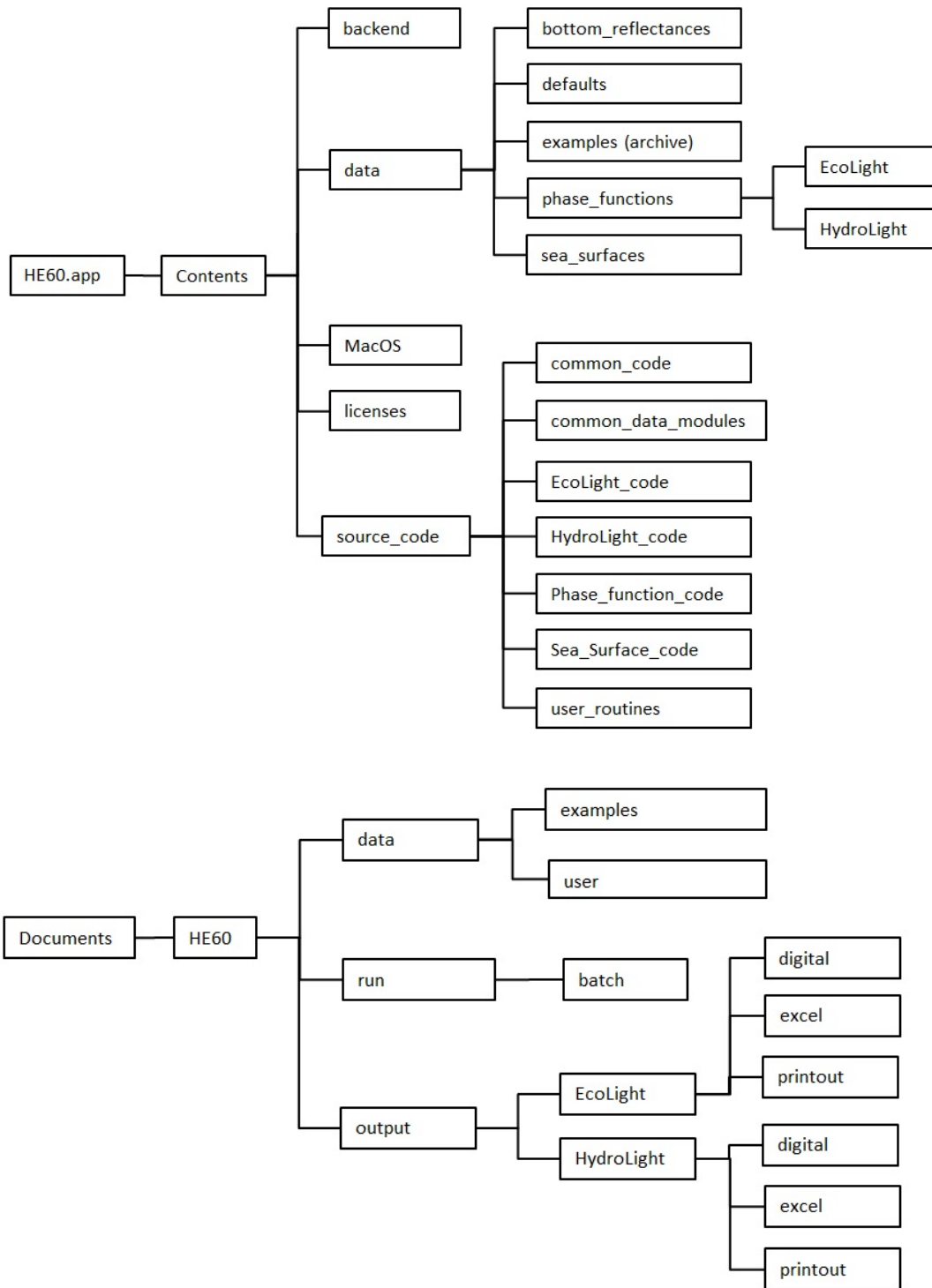
Figure 9(b). The main HE60 directories on Apple Mac, as used in standard runs.

The contents of the various HE60 directories are as follows:

backend   contains the executables that perform the actual calculations.

data   contains the input data files for a run. Initially, the subdirectories contain the default data sets. The user can add to these directories if needed, e.g., to add additional files of bottom reflectances, new phase functions, etc. Unless otherwise stated below these subdirectories are under Documents/data on an Apple machine. The various types of data are grouped as follows.

   bottom_reflectances   contains files of bottom reflectances. As distributed, this directory contains example files for different bottom types. Users can add their own files of measured bottom reflectances to this directory on the format described in the Technical Documentation.

   defaults   contains files of concentration-specific absorption and scattering coefficients, as taken from the literature, which are used by the IOP models. Users can add their own files of measured or modeled values to this directory.

   examples   contains examples of the various data file formats expected by HE60 for input. Some of these files are used in the example runs described in §6, but are not intended for general use.

   phase_functions   contains files of discretized phase functions created by the code in directory HE60\source_code\ Phase_Function_code. Initially, this directory contains files (named dpf_*.txt) for discretized phase function) for various phase functions. There are separate subdirectories for the HydroLight and EcoLight phase functions, since the phase function discretization depends on the quad and

40

band resolution. Users can add their own files of discretized phase functions to this directory by making special runs as described in the Technical Documentation §9. On Apple machines this directory is under HE60.app/Contents/data.

sensors   contains files defining sensor-specific wavebands. Users can add their own files of wavebands to this directory. The name of the sensor must be added to sensorlist.txt for the name to appear in the pull-down box of the GUI. Note: the file corresponding to a given sensor must be the sensor's name with the .txt extension added (e.g., the wavebands corresponding to SeaWiFS are stored in the SeaWiFS.txt file in this directory).

sea_surfaces   contains files of sea-surface information for different wind speeds and water indices of refraction. There are separate subdirectories for the HydroLight and EcoLight, since the surface files depend on the quad and band resolution, and for the three different surface model options. On Apple machines this directory is under HE60.app/Contents/data.

user   Users can add their own data files to this directory. It is a good idea to keep user data files separate from the distributed data files in the preceding directories. As distributed, this directory is empty.

documents   contains PDF versions of this Users' Guide, the Technical Documentation, various HydroLight Technical Notes, as well as any release notes.

extras   contains example IDL routines, and the input, run script, and output files for the example simulations presented in Section 6.

IDL_code   contains selected IDL routines used in producing the Users' Guide and Technical Documentation. These routines are designed to read the full-output digital data files (the optionally created Droot.txt and Lroot.txt files).

Example_runs   contains the input and output files for the four examples in §6 of this Users Guide.

frontend   contains the executable GUI front-end program as well as various files needed by the GUI. (This directory is HE60.app/Contents/MacOS on Apple.)

licenses   contains the HE6 License Agreement and user-specific license files

output   contains all of the output files written by HE60 during execution. There are separate subdirectories for the output from HydroLight and EcoLight runs. On Apple machines this directory is Documents/HE60/output.

EcoLight   contains the EcoLight run outputs in various subdirectories, as follows:

digital   is the directory where EcoLight writes the full-output digital data files (the Droot.txt and Lroot.txt files) if requested as output from the run.

excel   contains the EXCEL spreadsheets, if requested as output from the run.

printout   is the directory where HE60 writes the printout (file Proot.txt) from each run.

HydroLight   contains the corresponding subdirectories for output from HydroLight runs

Phase_Function   this directory is only present if the code to discretize phase functions has been used. If so it contains the

printout of that program, see Technical Documentation §9.

source_code contains the Fortran source code for HE60.

common_code contains the source code common to both EcoLight and HydroLight. This code includes IOP and other routines that do not depend on the directional quad or band partitioning.

common_data_modules contains Fortran 95 modules that define array dimensions and various defaults, and which pass data between the various routines.

EcoLight_code contains the source code particular to EcoLight. These routines depend on the band partitioning.

HydroLight_code contains the source code for HydroLight. These routines depend on the quad partitioning.

Phase_Function_code contains the source code for discretization of new phase functions.

Sea_Surface_code contains the source code for creating of sea surface data files for the Cox-Munk surface model. This code is included primarily for reference, since the Cox-Munk surface data files are included in the distributed code.

user_routines contains code that can rewritten by users to define component concentrations and IOPs. Also contains code used by the "ten-component" IOP model, for which the user defines the components.

run   contains a file named runlist.txt, which holds the names of one or more lroot.txt files created by the GUI. This file is written by the GUI.

                batch   is the directory where the GUI writes the lroot.txt input files for each run.

5. THE GRAPHICAL USER INTERFACE

Standard HE60 runs are those runs that solve the radiative transfer equation (RTE) for a given set of water IOPs and surface and bottom boundary conditions. Because this is the mode of running HE60 that is employed most of the time by all users and all of the time by most users, it is described first. Almost all users will find the standard HydroLight quad layout seen in Fig. 4 and the EcoLight band layout of Fig. 7, the available wind speeds (0 to 15 m s^{-1}), the available water indices of refraction (1.32 to 1.38), and the distributed selection of phase functions to be adequate. If this is not the case, then special runs to define new quad and band layouts, wind speeds, or phase functions must be made before making the desired standard runs. These special runs are described in the Technical Documentation §9.

A standard run takes information about the inherent optical properties of the water body and adds information about the sea-surface, the incident sky radiance distribution, and the bottom boundary. This information together completely defines a physical situation for which the RTE has a unique solution. The HE60 main code then solves the quad- or band-averaged RTE and generates the final outputs of the HE60 models. Monte Carlo ray tracing is used in the special runs that compute the sea-surface reflectance and transmittance functions. However, the standard computations are entirely deterministic; no Monte Carlo simulations are used to solve the RTE within the water body. This is one of the great numerical virtues of the invariant imbedding technique used in HE60.

The primary way to initiate a HE60 standard run is by running the user GUI front-end program. It is also possible to create the input file and run script with an ASCII text editor or other routine and then run HE60 from a command window. However, because of the many input options, this is a difficult endeavor and is therefore not recommended except in special applications by advanced users (such as running numerous HE60 simulations in parallel on a cluster of computers, for which the input files are mass produced by user-written codes). The input file format is described in detail in Appendix A of the Technical Documentation.

Standard runs are sometimes made in a series in which only one input variable such as the solar zenith angle, chlorophyll concentration, or bottom depth is changed between each run. Therefore, the User Interface has the option of saving the input values from the current run and using those values as the default values for the input to the next run. After making the first run of a series, the user then can quickly "click through" the GUI windows, pausing only to change the input values that are to be different in the next run. Similarly, a user *who is familiar with the input format* can quickly open the input file with a text editor, change a

number or two, re-save the file, and submit the new run. However, this should be attempted only by users who are very familiar with how information is passed into HE60, in order to prevent inconsistencies between what problem you are solving and what problem you *think* you are solving.

Regardless of how a run is initiated, the user must give HE60 input that defines a unique radiative transfer problem for the environmental conditions of interest. When running the GUI, these specifications are made by selecting allowed values for various parameters, by entering the names of files containing data such as chlorophyll profiles, or by entering lists of depths and wavelengths where the output is to be saved.

The purposes of the front-end program are to

- guide users through the specification of all of the input needed to define a unique radiative transfer problem,
- use the users' responses to generate the input file (lroot.txt file) needed to run HE60,
- run HE60 to solve the specified radiative transfer problem.

The GUI consists of a number of forms, each of which prompts the user for a particular type of information, e.g., what IOP model to use, what bottom boundary condition to use, or what depth and wavelength resolution is desired in the output.

The usual problem-solving sequence is to work through the GUI forms, run either HydroLight or EcoLight to solve the radiative transfer problem just defined, and then return to the start of the GUI to specify the input for the next run. It is also possible to define a series of HE60 runs from within the GUI and then run the whole series afterwards. In this case, the various input files are accumulated and then run as one "batch" run consisting of many individual, sequential HE60 runs.

This following pages briefly describe the input requested in the various windows of the GUI. Many of the GUI options have "tool tips" to provide additional information. Full documentation of the available models and features is given in the Technical Documentation.

5.2. Run Initialization

The Opening form. When running HE60 for the first time, you will need to read and accept the DISCLAIMER and the LICENSE AGREEMENT before continuing. On subsequent runs, you can proceed immediately by clicking CONTINUE. Any time you wish to return to the default values (as distributed with the code) for the various parameters, just click RESET DEFAULTS. The USER SUPPORT form gives the information needed to assist with debugging any problems with HE60.

The RUN IDENTIFICATION form. This form first asks for the "root" name to be used in generating the file names for the run. Keep the root as one word (blanks or special characters not allowed in file names), up to 32 characters. Also enter a descriptive title for the run. This title will appear in the printout and other output files generated by the run.
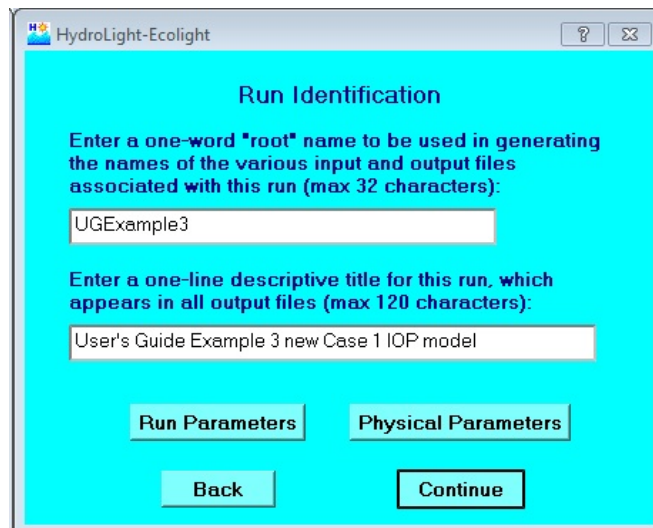
HE60 has the ability to accumulate a series of runs into a batch and then submit them all at once. HE60 will take care of remembering what runs you want to make and which models to use for each. However, **when creating a series of runs, be sure to give each one a new root name. If a subsequent run has the same root name as a previous run, the output from the previous run will be overwritten without any warning.**

The RUN PARAMETERS form. If you click RUN PARAMETERS on the RUN IDENTIFICATION form you will be taken to a special form to specify several model parameters including which wavelengths to include in PAR calculations and some advanced options that control aspects of how the GUI and model work. Most users will never need to change these defaults.
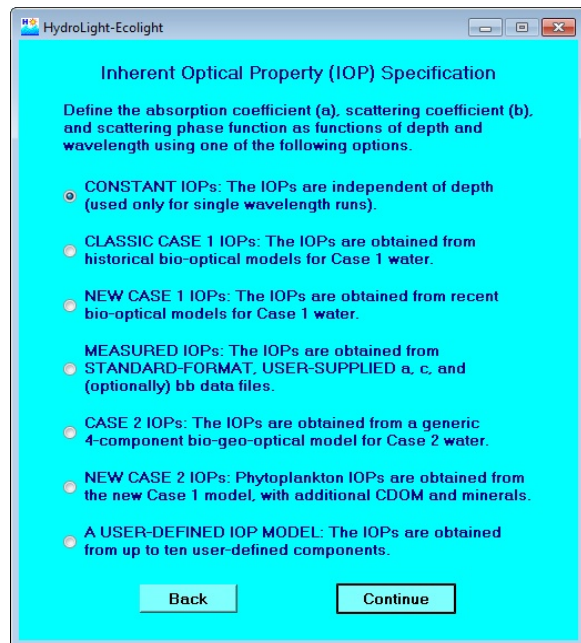
The PHYSICAL PARAMETERS form. If you click PHYSICAL PARAMETERS on the RUN IDENTIFICATION form you will be taken to a special form to specify several physical model parameters including the water temperature and salinity, which surface model to use, as well as inelastic scattering parameters such as fluorescent quantum efficiency. The temperature and salinity values may or may not be used in the model depending on the setting of later options, they can have a small effect on the IOPs of pure water and the interactions at the air-water interface. Most users will not need to change these defaults.

48

When you click CONTINUE from the RUN IDENTIFICATION form, a pop-up box will show you the names of the files that will be generated. You can select not to have this form displayed on subsequent runs.

HydroLight-Ecolight

Notice

This run will be added to the batch via runlist.txt.

The following files will be created:
IUGExample3.txt Input file
PUGExample3.txt Printout file

And dependent on the output options selected later:
LUGExample3.txt Radiance output file
DUGExample3.txt Digital output file
SUGExample3.txt and MUGExample3.txt (for speadsheet generation)
SUGExample3.xlsx and MUGExample3.xlsx - spreadsheet output files

☐ Do not show this notice again

OK

5.2. IOP Specification

The IOP SPECIFICATION form. This form requires you to pick an IOP model, i.e., a model for the absorption a and scattering b coefficients and scattering phase functions that describe the water body. **The available IOP models are described in detail in the Technical Documentation.** The input required by various IOP models differs; the needed information will be requested on the next forms, depending on which option is selected on this form. Seven options are available on this form:

❍ CONSTANT IOPS. This IOP model describes the water body by its total absorption and scattering coefficients and phase function; the water is taken to be homogeneous. This model is useful only for idealized radiative transfer studies done at one wavelength.

❍ CLASSIC CASE 1 IOPS. This IOP option selects a simple, frequently used and historically important ("Gordon-Morel" type) bio-optical model for Case 1water, which uses simple equations to obtain the absorption and scattering coefficients for chlorophyll particles and co-varying CDOM from a user-specified chlorophyll concentration. It is intended for use only in Case 1 water. This model is retained in HE60 for comparison purposes with the NEW CASE 1 IOP model. Users are encouraged to use either the NEW CASE1 or the CASE2 IOP models for general simulations. The CASE2 IOP model is the most general of the standard IOP models.

❍ NEW CASE 1 IOPS. This IOP model for Case 1 waters is based on recent publications. The absorption and scattering coefficients and the scattering phase function are all determined by the chlorophyll concentration. The details of the model are given in the Technical Documentation. This model is for use only in Case 1 water.

50

❍ MEASURED IOPS. The IOPs are constructed as the sum of pure water values plus "everything else"—particles and dissolved substances—as measured by a WETLabs ac-S or similar instrument, (other data on the same general format, e.g. from a WETLabs ac-9, can be processed with this model.) The input data file contains the absorption a and beam attenuation c coefficients as functions of depth and wavelength in the HE60 standard format described in the Technical Documentation. Optionally, backscatter coefficients measured by a WETLabs bb-9, HOBILabs HydroScat-6, or similar instrument can be used in conjunction with the a and c data to select phase functions with the measured backscatter fraction.

❍ CASE 2 IOPS. This general four-component Case 2 water model includes many options for specifying concentration profiles and IOP models for each of four components: water, chlorophyll-bearing particles, CDOM, and mineral particles. To make Case 1 runs using the Case 2 model, select the option to let CDOM "agree with the Case 1 model" and set the mineral concentration to zero.

❍ NEW CASE 2 IOPS. This model uses the New Case 1 IOP model for the chlorophyll-dependent IOPs, but allow the user to add additional amounts of minerals or CDOM to create Case 2 water.

❍ A USER-DEFINED IOP MODEL. If you decide not to use any of the IOP models described above, you can create your own IOP model with up to 10 components. In this case, you can use the GUI to specify your component IOPs by selecting this option, which will ask you to provide information for each component.

If you change the IOP model between saved runs you will see this notice to remind you that when you change your IOP model, you need to make verify that the IOPs specified are consistent with your new model. HE60 will require you to view each of the IOP specification pages (except for pure water) to make sure you are not accidentally using unintended values from a previous run.
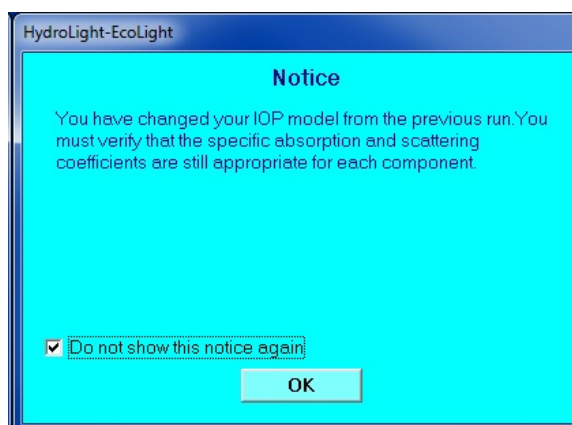
The next set of forms shows the input required by these different IOP models.

The CONSTANT form. This form requests the input needed by the CONSTANT IOP model. The water is modeled as a single component having the specified total absorption coefficient *a*, total scattering coefficient *b*, and phase function. Even though the water IOPs are specified once *a*, *b*, and the phase function have been selected, the form also requests a wavelength for the run; the wavelength may be needed by the sky and/or bottom reflectance models. Since the wavelength is specified here, the wavelength specification form (described below) will not appear with the CONSTANT model. The code for the CONSTANT model is in file HE60\source_code\common_code\IOP_constant_mod.f95.

52
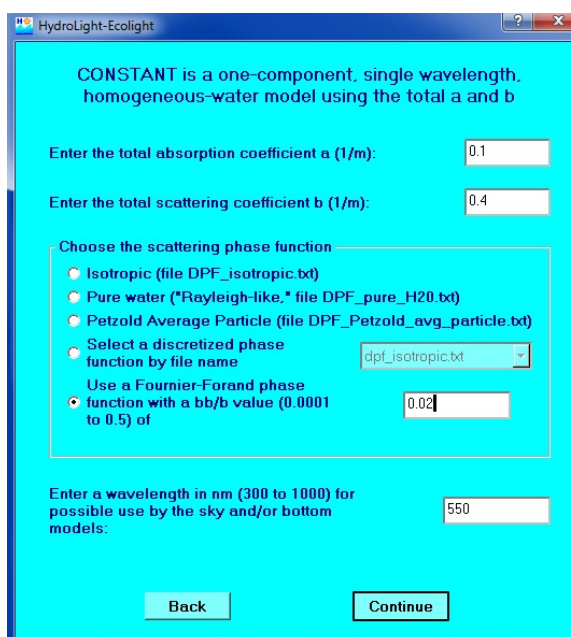
The CLASSIC CASE 1 form. This form requests the input needed by the bio-optical models used in the CLASSIC CASE1 IOP model. The water is modeled by three components: pure water, pigmented particles, and co-varying CDOM and non-algal particles. The absorption and scattering properties of the particles and CDOM are parameterized by the chlorophyll concentration, which in general is a function of depth. The code for the CLASSIC CASE1 model is in file HE60\source_code\common_code\IOP_classicCase1_mod.f95. Clicking on the "specify component IOPs" button will take the user to the IOP component specification form described below. Since the underlying model includes models for the specific absorption and scattering of chlorophyll-bearing particles (phytoplankton), they are not included on the component forms.
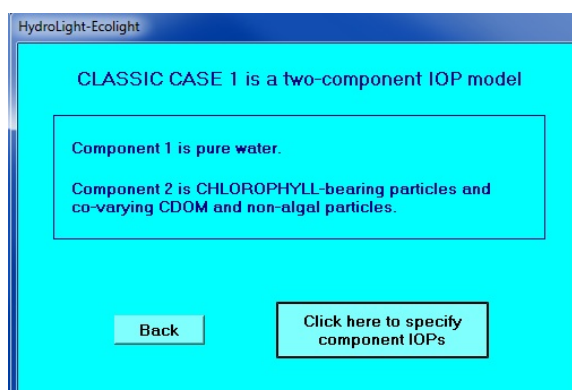
When using the IOP models other than the one above for constant, total IOPs, the first form shown after clicking on the button to specify the component IOPs shows the currently chosen IOPs for pure water. There are several options for specifying pure water absorption and scatter. The default (shown here) is to use "Pope and Fry" absorption values for the near-UV to near-IR range, and to use scattering coefficients for sea water. If the currently chosen values are OK, then just hit continue. If you want to change the pure-water values, the "specify pure water IOPs" button takes you to the next form.
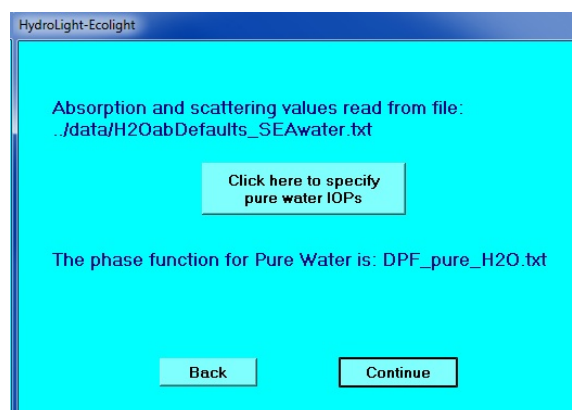
This form allows you to pick one of a number of options for the IOPs of the pure water component. There are three data sets for pure water absorption and scattering, and an option to read in your own file. Scattering values for fresh water can be used, and "Smith and Baker" values for absorption by the "clearest natural waters" can be used. The default option includes the effect of temperature and salinity as previously specified in the PHYSICAL PARAMETERS form whereas the others do not. The user can also read a file with his or her own water absorption and scattering values. The required format for user-supplied data files is described the Technical Documentation. Once the pure-water IOPs are chosen, they will be used for all IOP models until changed via this form.
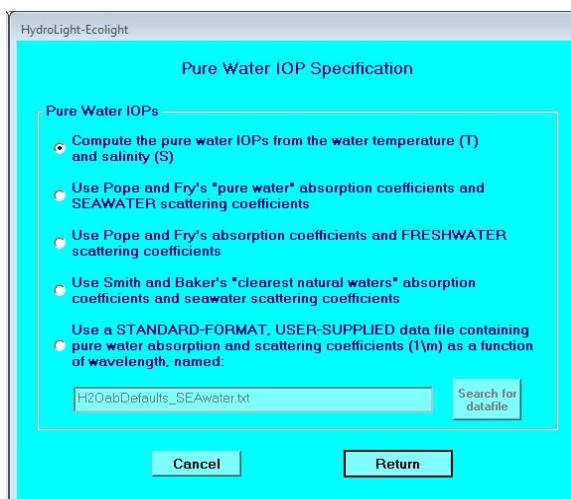
The NEW CASE 1 form. This is a recently developed alternate model for Case 1 water. This IOP model has four components: pure water, large particles, small particles, and CDOM, each of which covaries with the chlorophyll concentration. The chlorophyll concentration is the only input required by this model. The code for the NEW CASE1 model is in file
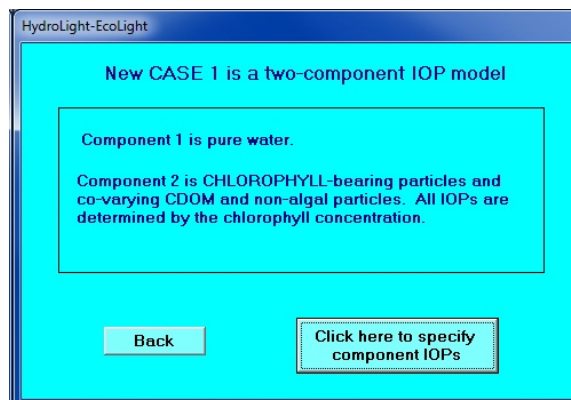
HE60\source_code\common_code\IOP_newCase1_mod.f95.

The MEASURED IOP DATA form. In this IOP model, the water is modeled by two components: pure water and "everything else" (particles and CDOM). Measured absorption (*a*) and beam attenuation (*c*) data as obtained from a WETLabs ac-9 (or ac-s or similar) instrument are used to determine the IOPs of the second component. An optional third component will be added if and only if CDOM fluorescence is included, in which case absorption due to CDOM will be specified after the inelastic scattering form, where the user will have the option of providing a filtered ac-9 file for that purpose.
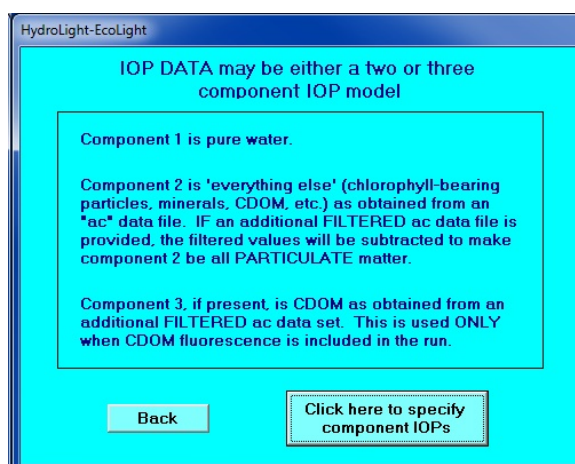
The component specification form for MEASURED IOP DATA is different than for the other IOP models. The absorption and beam attenuation coefficients are given as functions of depth and wavelength via a user-supplied data file, rather than as concentrations of chlorophyll or other components. There is an added option of specifying the phase function by using a file of backscatter data. If the backscatter data option is selected, the backscatter fraction b_b/b will be calculated for each depth and wavelength. A corresponding Fourier-Forand phase function will then be used. The code for this model is in file
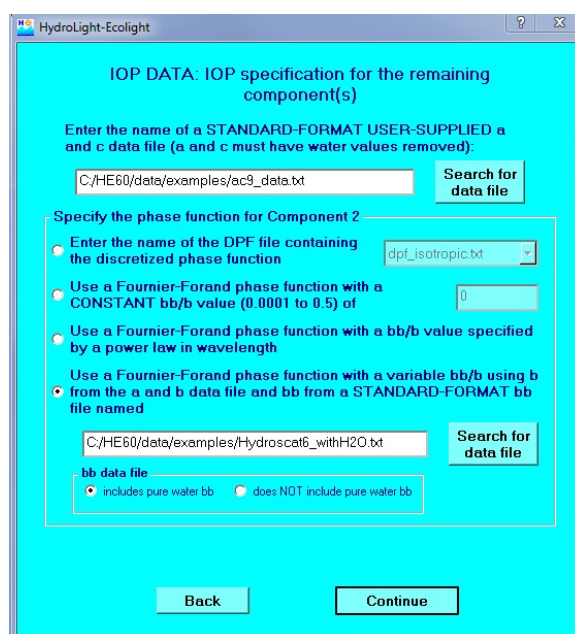
HE60\source_code\common_code\IOP_userData_mod.f95.

When processing ac-9, ac-S, or similar data, the convention is to remove pure water absorption and attenuation from the measured total values during the initial data processing (e.g., before performing scattering corrections). **HE60 therefore always assumes that files of *a* and *c* data do *not* contain pure water contributions.** On the other hand, there is no

convention about removal of pure water values from measured backscatter data. (In all but the clearest waters, the water contribution to backscatter is almost negligible.) Therefore, you have the option to read in backscatter data files that do or do not include pure water values; the corresponding option must be selected. If your backscatter data include water, HE60 will subtract the pure water backscatter to obtain particle backscatter from your data.

The Case 1 and 2 IOP models define the IOPs at any wavelength from 300 to 1000 nm. Real data, however, are limited in range and not continuous. WETLabs ac-9 and bb-9 data have values at only 9 wavelengths, typically starting at 412 nn and ending at 720 nm (depending on the particular instrument configuration). Likewise, the first data might be at a depth of 5.2 m, and the last at a depth of 55.5 m. If your data cover the 412-720 nm range, and you run HE60 from 420 to 700 nm by 10 nm, say, HE60 will then linearly interpolate between the given IOP values to obtain values at the needed wavelengths 420, 430, 440, ..., where the RTE must be solved. This is usually a reasonable approximation. However, if your data start at 412 nm, and you ask HE60 to run from 300 to 700 nm, it will do so, but HE60 will use the IOPs at the nearest wavelength, here 412 nm, for all wavelengths less than 412 nm. This might be OK for runs starting at 400 nm, but will cause serious errors in the IOP input for wavelengths too far below the first data wavelength or too far above the last. Likewise HE60 will interpolate between the given depths to obtain IOPs at depths between the first and the last in the data file. However, HE60 will use the IOPs at the first depth (5.2 m as mention here) for all depths between the surface (at depth 0) and the first depth measurement (5.2 m), and it will use the IOPs at the last measured depth (55.5 m) for all depths below the last depth (if the run goes deeper than the last depth measurment). IOPs are not constant in wavelength or depth. **Therefore, HE60 cannot be expected to give good results if it is run much beyond the wavelength and depth bounds of the input IOP measurements, or if the measured values being interpolated are too far apart for the intermediate behavior to be roughly linear.** When HE60 is run outside the bounds of the measured data, warning messages are included in the printout file and the run continues with values defined as described.

Finally, the smoothness of the a,c and b_b data can affect the run time when this model option is used. **Once again: it is not HE60's job to clean up, bin, or smooth your raw data.**

The CASE 2 form. A basic, flexible Case 2 water model is provided. The model has four components: pure water, chlorophyll-bearing particles, CDOM, and mineral particles. There are many options for specifying the IOPs of each component. The code is on file HE60\source_code\common_code\ IOP_genericCase2_mod.f95.
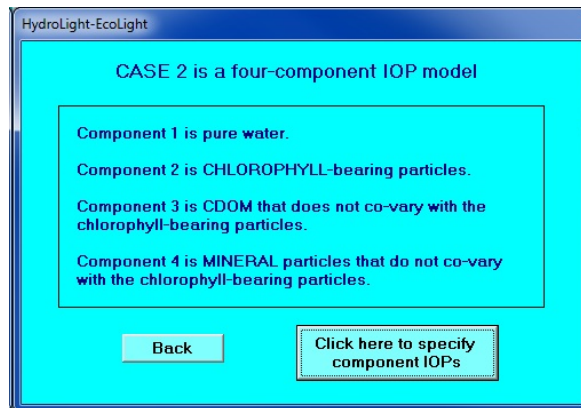
The New CASE 2 form. This is a model for Case 2 water that defines the chlorophyll-dependent (phytoplankton) IOPs using the New Case 1 IOP model described above, but with the option to add extra mineral particles or CDOM. If the mineral and CDOM concentrations are set to 0, this model reduces to the New Case 1 IOP model. This model is included for comparison with the new Case 1 and Case 2 models and is not recommended for general use. The code for the NEW CASE2 model is in file HE60\source_code\common_code\ IOP_newCase2_mod.f95.
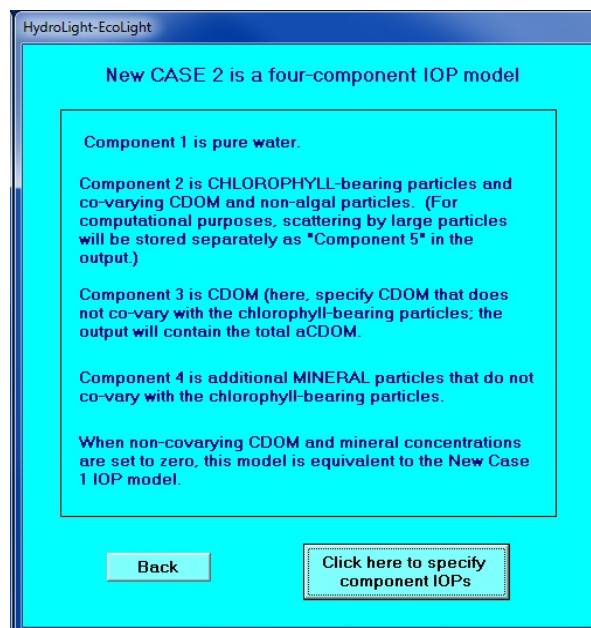
The USER-DEFINED IOP MODEL form. The User-defined IOP option allows you to define up to 10 IOP components. This form can be used to define IOP components that are not available in the standard bio-optical models underlying the other IOP options. Examples of "non-standard" IOP components include microbubbles, oil droplets, or multiple types of phytoplankton (e.g., to have different contributions by synechococcus, coccolithophores, and diatoms). Each component is treated equally in how the user can define its absorption and scattering properties, unless the user names the component either "water" or "pure water". In that case, the same pure water routine used in the standard IOP models is used to define the pure water component IOPs. However, the first component does not need to be pure water and, indeed, pure water does not even need to be one of the components. (This IOP option could even be used to simulate light propagation in the liquid hydrocarbon lakes on Saturn's moon Titan.) See the Technical Documentation, Section 2.8 for more information on how to configure this IOP model.

The IOP COMPONENT SPECIFICATION form. Once you have selected an IOP model, you will be asked to provide information specifying the IOPs of each component one at a time. In general, this will consist of providing the component concentration, information regarding the chlorophyll- or mass-specific absorption and scattering spectra for the component, and selecting a phase function. A series of windows will open, one for each component.

58

The needed chlrophyll concentration can be obtained by assuming it is constant with depth and entering its value, or by reading a *user-supplied* file containing measured depth vs. concentration values (as illustrated above). A third option is to call a *user-written* function named "Chlz_user_func", which *must* be on the file named Chlz_user_func_mod.f95, in the source_code\user_routines directory. In other words, a user can rewrite the example routine of that name that came with the HE60 code as distributed, and then recompile HydroLight and EcoLight to make the new routine available.

Note that your concentration values must be consistent with your concentration-specific absorption and scattering spectra. For chlorophyll, this normally means that concentrations are in mg m^{-3} and chlorophyll-specific absorption spectra are in m^{-1}/(mg m^{-3}) = m^2 mg^{-1} . For mineral particles, concentrations are often in g m^{-3}, in which case the mineral concentration-specific absorption and scattering spectra must be in units of m^{-1}/(g m^{-3}) = m^2 g^{-1}. The only requirement is that a concentration times a mass-specific absorption or scattering spectrum gives units of inverse meters.

In addition to specifying the absorption and scattering coefficients, you must also specify the scattering phase function for each component. (Only the NEW CASE 1 IOP model does this automatically using the given chlorophyll concentration.).

Phase function specification can be done in three ways. The first is to use the pull-down menu to choose a phase function by the name of the file containing the discretized phase function. This option is useful if you have created your own phase function (via a special run, as described in the Technical Documentation). For example, the file named dpf_Petzold_clear.txt contains the discretized Petzold particle phase function for clear ocean water of *Light and Water* Table 3.10. The second option is to specify a value for the particle backscatter fraction b_b/b, which can have any value between 0.0001 and 0.50. For this option, HE60 generates a Fournier-Forand phase function with the given b_b/b, as described in the Technical Documentation. The same phase function is then used at each depth and wavelength. The third option is to specify b_b/b as a power law in wavelength. When this option is selected, the parameters for the power law will be specified on the next screen, as seen above. For this option, HE60 again uses a Fournier-Forand phase function, but the particle backscatter fraction (i.e., the scattering phase function for the given component) will vary with wavelength but not with depth.
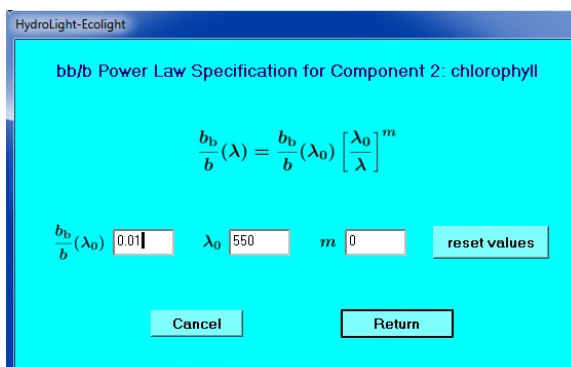
The ABSORPTION SPECIFICATION form. Clicking the button to specify the absorption properties of a component will lead the user to a new window with options that depend on what is known about the component. Depending on what the component is and what IOP model is being used, some of the options may be unavailable (greyed out) or not visible.

60
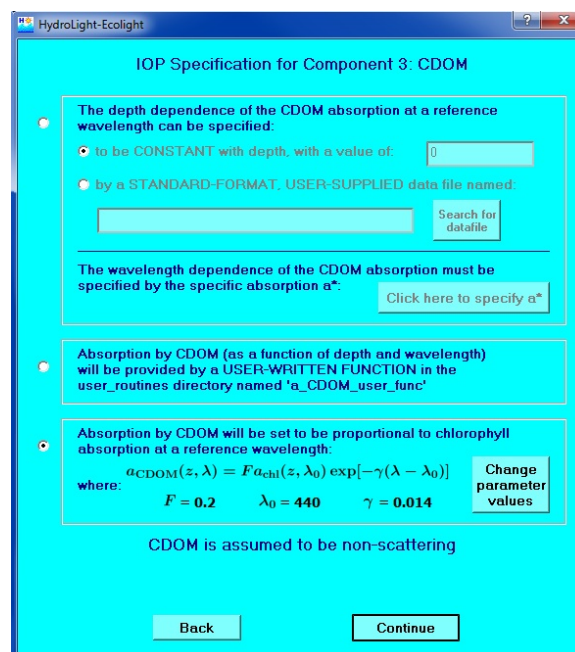
The SCATTERING SPECIFICATION form.
Similarly, clicking the button to specify the
scattering coefficient of a component will
lead the user to a new window with options
that depend on what is known about the
component. An example is that no phase
function or scattering coefficient options will
be given if the component is CDOM (which
is assumed to be nonscattering). There are a
number of options for specifying the
scattering coefficient. As discussed in the
Technical Documentation and as shown here,
one option is to specify the wavelength
dependence of the beam attenuation
coefficient *c*, which generally better fits a
power law in wavelength than does *b*, and then let HE60 obtain the scattering coefficient from
$b = c - a$.
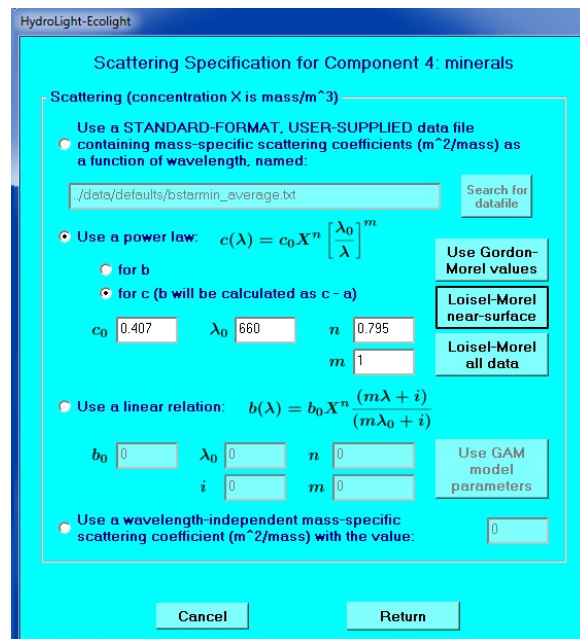
5.3   Inelastic   Scattering   and Bioluminescence

**The INTERNAL SOURCE AND INELASTIC
SCATTER form**. This form allows you to
specify whether the run will include internal
sources (e.g., *horizontal layers* of
bioluminescence) or various kinds of
inelastic scattering processes. Except for
Raman scattering, which is determined by
water alone, choosing one of these features
may require you to specify additional
information on subsequent forms. This most
often occurs when the IOP data model is
selected. That model lets you read in the total
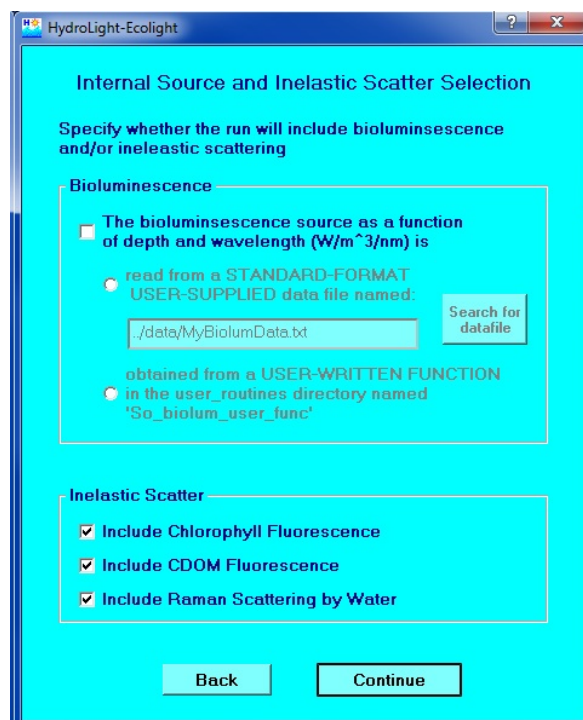
absorption and scattering coefficients, but it does not specify how much of the total absorption is due to chlorophyll or CDOM individually. If you wish to include chlorophyll or CDOM fluorescence, you must therefore specify how much of the total absorption is due to those components. The GUI will ask you for that information if needed.

If chlorophyll fluorescence is included, the absorption values specified by the run will be used, along with the chlorophyll fluorescence quantum efficiency (set on the CHANGE DEFAULTS form) and the appropriate wavelength redistribution function from the routines on file
source_code\common_code\ wave_redist_func_mod.f95.

If, for example, CDOM fluorescence is included in the run but CDOM is not a component of your IOP model, checking the "CDOM fluorescence" box causes a special form to appear allowing you to specify CDOM absorption.
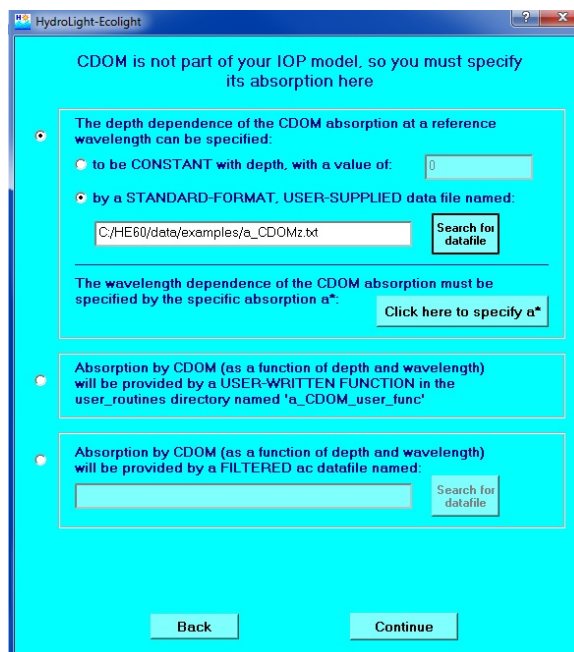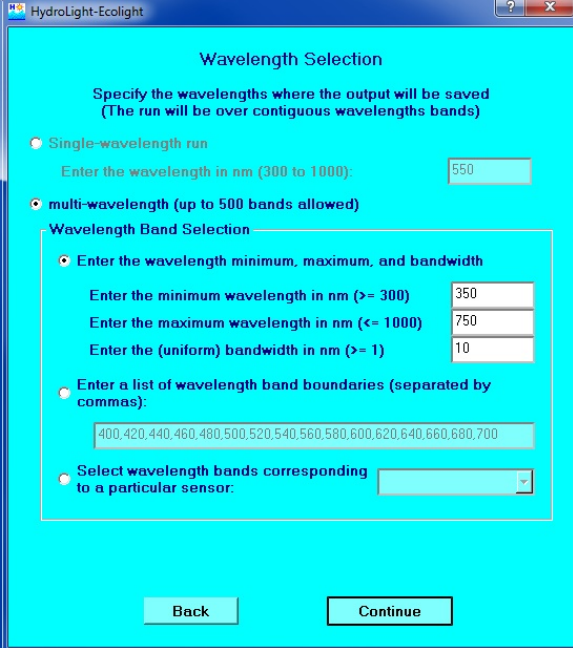
After you click CONTINUE, a notice box reminding you how the fluorescing components have been specified (earlier in the run) will appear. Note that if inelastic scatter is to be included in the run, the relevant excitation and emission wavelengths must be included (to be specified on the wavelength form). Therefore, the inelastic-scatter options are not available if you selected the IOP_constant IOP model, which is for runs at only one wavelength. Likewise, you cannot choose to do a run at only one wavelength if you have selected the option to include inelastic scatter.
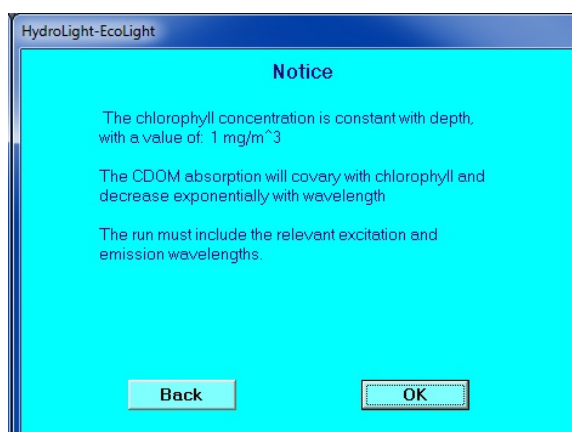
5.4 Wavelength Specification

The WAVELENGTH SELECTION form. This form allows you to select the wavelength range and bandwidths for the run. In the present example, the option of making the run at a single wavelength is not available because fluorescence and Raman scatter were included on the previous form. Suppose that you are interested only in the 400-700 nm range. In order to include Raman-scattered and CDOM-fluoresced light that is excited in the near UV and emitted at blue wavelengths, the run should be started at around 350 nm.

Rather than specifying the wavelengths explicitly, you can use the pull-down menu to select wavelengths that match various common sensors such as MODIS or MERIS. The output will then contain those sensor bands (plus intermediate bands; see Fig. 15 below) for ease of comparison with measurements.

If uneven bandwidths are desired (e.g., to exactly match the bandwidths of a particular sensor not available in the pull-down menu), the band boundaries can be entered manually, e.g., 400, 410, 425, 440, 450,.... Note that HE60 must always run with contiguous wavelength bands. For example, you cannot make a single run with a band from 400-410 and then another band from 435-445 nm without also including one or more bands in the 410-435 nm region. This is because the intermediate bands may contribute to the inelastically scattered light at the bands of interest.

5.5 The Air-Water Interface and Sky

The AIR-WATER SURFACE BOUNDARY CONDITIONS form. This form selects the wind speed to be used in modeling the roughness of the sea surface, and the sky model to be used in modeling the incident sky radiance distribution. Although HE60 itself uses wind speed in units of m s^{-1}, users can enter the current wind speed in any of three units of measure. Clicking the "update values" button will cause the GUI to recalculate in all three units.

The water temperature T and salinity S as previously specified on the PHYSICAL PARAMETERS form can be used to calculate a T- and S-dependent water index of refraction. This form then allows you to pick from several different options that specify how the incident sky radiance is modeled.

Finally, the form requires you to select the azimuthal angle between the downwind direction and the sun's azimuthal direction. If this is not known, use a value of 0. In many situations (low wind speed, high solar zenith angle), there is only a small effect of the sun's azimuthal angle relative to the wind direction, and almost no effect on AOPs. See the Technical Documentation for further discussion.

There are many options for specification of sky conditions. The most common, and what is recommended for routine simulations, is to choose the "semi-emprical" sky model option on the previous form, which leads to options for commonly used models for the sun and diffuse sky spectral irradiances, and for the angular pattern of the sky radiance distribution. This semi-empirical sky model is based on a wavelength-extended version of the RADTRAN code for clear-sky irradiances and a semi-empirical model for the angular distribution of the sky radiance, normalized to the radiance in the sun's direction.

The SEMI-EMPIRICAL SKY form for sun and cloud conditions. This is the first form that requests the input needed by the routines that together form the semi-empirical sky radiance model, which is based on the RADTRAN model for clear sky irradiances (Gregg and Carder, 1990, as extended in HE60 to the 300-1000 nm range. (See the RADTRAN-X discussion in the Technical Documentation §5.1 for details). You can specify either the solar zenith angle or the time and location, from which the solar zenith angle will be computed by HE60. If you choose the option below to use climatological ozone values, then the time and location information is needed to access the database of TOMS ozone values. See the Technical Documentation for a discussion of these climatological ozone values.

HE60 uses decimal format (day of year and decimal hour of day) for time. The GUI will calculate the day of the year and time in decimal format for you, if you prefer to use the month/day/year/hour/minute format. Simply click the SPECIFY TIME AS MDY... button. After you have entered the data and press continue, the GUI will perform the calculations and the decimal values will be placed in the appropriate boxes on the previous form.

Similarly, latitude and longitude can be specified in **d**egrees, **m**inutes and **s**econds (DMS) by clicking on the SPECIFY LOCATION IN DMS button.

The RADTRAN-X ATMOSPHERIC PARAMETERS form. VIEW ATMOSPHERIC PARAMETERS on the SEMI-EMPIRICAL SKY MODEL form allows users to specify various atmospheric parameters used by RADTRAN-X to calculate the irradiance at the sea surface. If not specified here, the 24-hour average windspeed will be set to be equal to the current windspeed (set in the air-water surface boundary form). An ozone concentration of -99 Dobson units will cause the climatological ozone value for your time and location to be used. The ozone concentration is important only if you are interested in irradiances below ~340 nm.

The SEMI-EMPIRICAL SKY form for Incident Light. When using the semi-empirical sky option, this form determines whether the sky irradiances are to be computed by RADTRAN-X or read from a user-supplied data file. There are three options for user-supplied sky irradiance data: (1) read in the total sun and sky irradiance $E_d(\lambda)$, in which case RADTRAN-X is used to partition this total into direct (sun) and diffuse (background sky) parts; (2) read in the direct and diffuse parts; or (3) read in the total and the fraction that is direct. In options (2) and (3), RADTRAN-X is not called. These options are discussed in the Technical Documentation §5.4, including the simulation of a lidar input at 1 wavelength in an otherwise black sky. The subroutine that sets the *angular pattern* of the sky radiance is also specified here. The default is HCNRAD, which gives the Harrison and Coombes Normalized Radiances; see Harrison and Coombes, 1988.

The IDEALIZED SKY MODEL form. This form requests the input needed by the routines for the idealized sky radiance model (see the Technical Documentation for details). This sky radiance model is intended only for idealized radiative transfer studies that require a simple analytical model for the sky radiance distribution (such as a sun in a black sky or a heavy overcast). This sky radiance model is by default available for use only with single wavelength runs, because it cannot account for the wavelength dependence of the sky radiance. However,

you can explicitly enable use of the idealized sky model in multiwavelength runs by checking the appropriate box on the RUN PARAMETERS form. One instance for which this can be useful is a simulation of nighttime bioluminescence effects with no input from the dark sky. This option can be used to set the total sun and sky radiance to 0.0, which gives a totally dark sky. The bioluminescence source function is then the only source of light for the simulation.
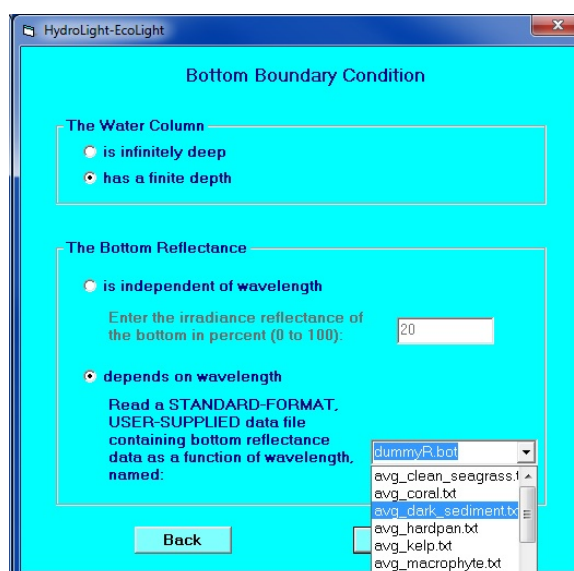
The USER-SUPPLIED SKY RADIANCE option. There is also an option to read a user-supplied file of sky radiances $L_{sky}(\theta,\varphi,\lambda)$ as a function of direction and wavelength. The use of this advanced option is discussed in the Technical Documentation §5.5 and in HydroLight Technical Note 12, which is in the HE60\documents directory. If this option is used, then all information about the sun and sky radiance (hence irradiance) is obtained from the user-supplied file, and the sky models described above are not used. This option allows HE60 to be run outside the 300-1000 nm range, with the caveats described in §5.6 of the Technical Documentation.

5.6 Bottom Boundary Condition
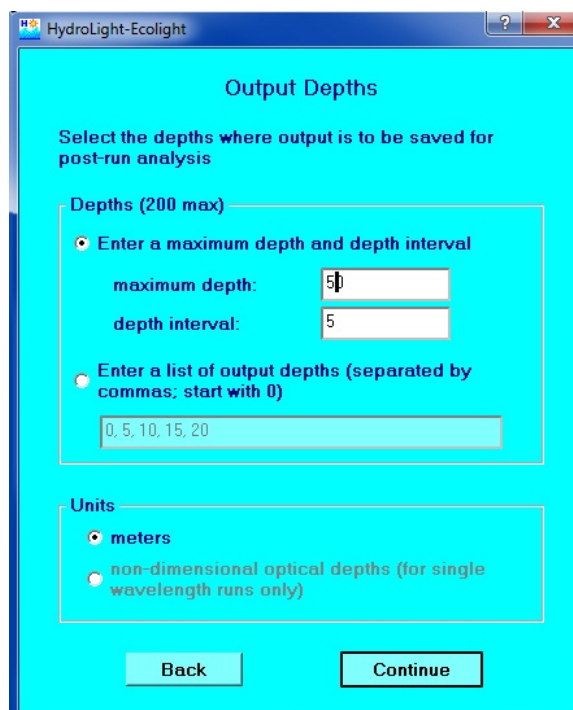
The BOTTOM BOUNDARY CONDITION form.
This form requests the information needed to specify the bottom boundary condition. If the water is infinitely deep, the IOPs at the deepest depth of interest (to be specified on the output depth form) will be used to compute the reflectance (actually, the non-Lambertian BRDF) of the infinitely deep layer of water below the region of interest. If the water is finitely deep, the irradiance reflectance of the bottom must be specified. In the option shown, the pull-down menu is used to select one of the available files of user-supplied bottom reflectance vs. wavelength data for a Lambertian bottom.

5.7 Output Depth Options

The OUTPUT DEPTHS form. This form specifies the depths at which output from the run is to be saved for later analysis. Note that *the depths at which output is to be saved does not affect the value or accuracy of the output at a given depth.* In the example shown, output is saved every 5 m down to 50 m. However, if output were being saved only at depths 0, 15, and 30 m, the output at those three depths would be the same, but you would not have the additional values at the other depths. Note that the option of having the listed depths be optical depths is not available in this example, because we already have chosen to have a multi-wavelength run. If you wish to have irregularly spaced output

68

depths, e.g., to obtain greater resolution near the surface or bottom boundary or near an internal scattering or absorbing layer, you can enter the desired output depths explicitly. You can change the maximum number of output depths in mod_DimensDefaults.f95, after which recompilation is necessary.

There is an important point to make about the output depths as used in when computing the diffuse attenuation functions K_d, K_u, K_{Lu}, etc. from the corresponding irradiance or radiance. $K_d(z,\lambda)$ for example, is computed from $E_d(z,\lambda)$ using the definition of K_d as a logarithmic derivative, which is then approximated as a finite difference using two output depths z_2 and z_1, where $z_2 > z_1$:

$$K_d(z,\lambda) \equiv -\frac{d \ln E_d(z,\lambda)}{dz} \approx -\frac{\ln E_d(z_2,\lambda) - \ln E_d(z_1,\lambda)}{z_2 - z_1} \approx -\frac{\ln[E_d(z_2,\lambda)/E_d(z_1,\lambda)]}{z_2 - z_1}$$

HE60 computes these finite differences using two very closely spaced depths z_2 and z_1. To obtain the needed pairs of closely spaced depths, HE60 automatically adds another depth just below each output depth requested by the user. Thus if you request output to be saved at depths of 0.0, 1.0, 5.0, and 10.0 m, HE60 will actually save output at depths of 0.0, 0.01, 1.0, 1.01, 5.0, 5.01, 10.0, and 10.01 m. (In this example, the last depth will be at 10.01 m if the water is infinitely deep. If the bottom is finite depth at 10.0 m, the extra depth will be placed at 9.99 m.) The closely spaced pairs of depths used by HE60 to compute the K functions are then $[z_1, z_2] = [0.0, 0.01]$, $[1.0, 1.01]$, $[5.0, 5.01]$, and $[10.0, 10.01]$. These extra output depths are used only for computing K functions; the remainder of the output is given only at the requested depths. There are also options (set in HE60\source_code\common_data_modules\mod_run_info.f95) to compute the K functions as non-dimensional optical depth functions, and to compute them as layer averages. However, the defaults as described above are what most users will want.

There is also a subtlety in determining the depth where the bottom boundary condition is applied when the water column is infinitely deep and the run includes internal sources or inelastic scatter. This is discussed in §3.3 of the Technical Documentation, and in detail in HydroLight Technical Note 6 in the HE60\documents directory. This situation is automatically handled in HE60 when the default option ALLOW DYNAMIC LOWER BOUNDARY DEPTH is selected on the RUN PARAMETERS form.

5.8 Output and Run Options

The FINAL form. All of the input required to solve the RTE has now been obtained, and the corresponding files required for the run have been saved in various directories. You now have several options.

If you wish, you can use CHANGE OUTPUT OPTIONS to change the amount and type of output to be generated by the run. If you check the CLICK HERE TO SAVE THIS INPUT box, the input you have just entered in the GUI will be saved and will become the default values for the various forms the next time you run the GUI. This will minimize the input required, if the next run is similar to the one now being made.

If you wish to define and add another run to this batch, click the ADD ANOTHER RUN TO BATCH SCRIPT button. You will then pass through the GUI again to specify the inputs for the next run. You can "stack up" any number of runs, which will then be made one after the other by a single execution of HydroLight or EcoLight. Do not forget to give each batch run a unique root name on the RUN ID form.

Once you are done defining the run inputs, the normal procedure is to select whether to run HydroLight or EcoLight with the inputs just created. When you then click on CONTINUE, a command window will be spawned and either HydroLight or EcoLight will run in that window. After the command window is spawned, HE60 is running independently of the GUI. The ADD ANOTHER RUN button will change to DEFINE A NEW BATCH RUN and you can begin entering the input for the next HE60 run. Note, however, that **the next run should not be started until the present run has finished.** (You can, if you wish, run HydroLight and then run EcoLight using the same inputs, by clicking one run button and then the other. This is of interest only if you wish to compare the two types of outputs or compare their run times for the same problem.)

70
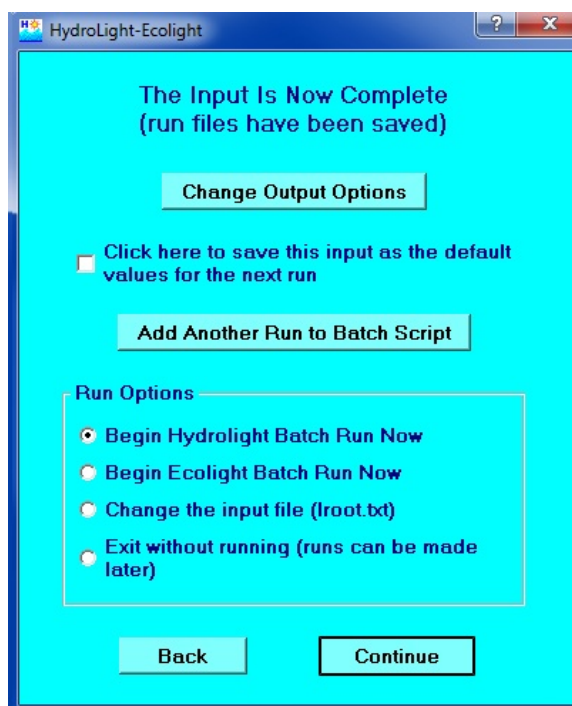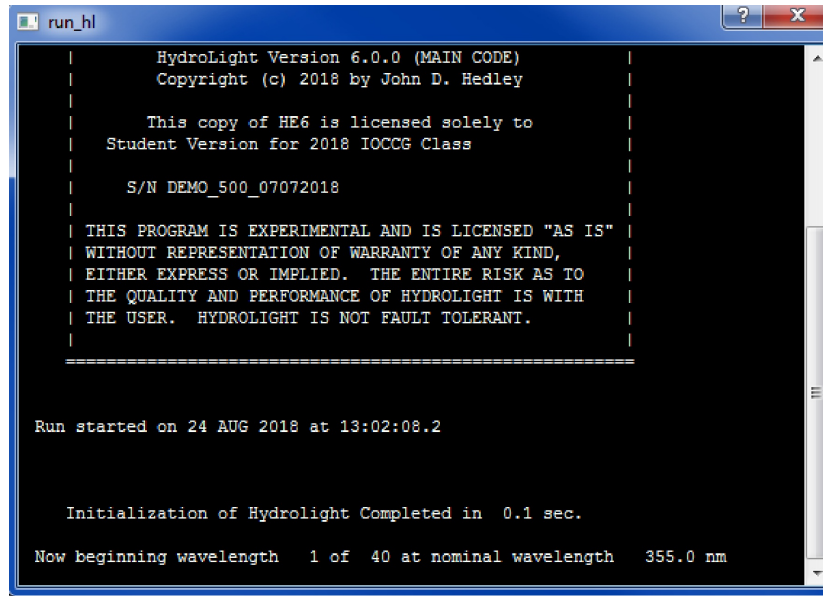
The lroot.txt input file generated by the GUI also can be viewed and edited to change some of the run inputs before the run is made; this feature is convenient for advanced users who are familiar with the format of the input file (described in the Appendix A of the Technical Documentation). Changes to the input file cannot be stored into the GUI default values.

The OUTPUT OPTIONS form. If CHANGE OUTPUT OPTIONS is selected on the FINAL form, a screen will appear giving the user several options for selecting the type and amount of output generated from a run. These values are stored as defaults and will persist for all future runs until they are changed by the user. These settings will only be stored for future runs if SAVE THIS INPUT AS DEFAULT is selected **after** these settings are selected. Note that the Droot.txt and Lroot.txt output files can be quite large if there are many wavelengths and output depths, so do not create these files unless you intend to use them. Likewise, if you do not intend to look at your output using Excel, you do not need to create those output files. For users who like to look at their output in Excel, the multi-wavelength format is usually the most useful. Those who want to use IDL to plot the output should save the Droot.txt file (and the Lroot.txt file if the full radiance distribution is to be plotted).

After clicking on the BEGIN HYDROLIGHT (or ECOLIGHT) BATCH RUN NOW button, a progress window and a command window will open and the run will begin. At the end of the run, you can click on a box saying that the run is finished, which will close these windows.

An example command window showing that HydroLight is running.

If a problem occurs as soon as HE60 starts to execute, then the command window may open and close within a fraction of a second, and there may not be a printout file, which normally receives error messages. These sorts of problems usually occur because the user has changed the code and introduced a bug, or a user-supplied data file is not on the correct format and HE60 error exits when trying to read the file. If this happens, it is possible to "manually" do a run and force the command window to stay open after run termination, so that error messages can be read. See §10 of the Technical Documentation for a discussion of how to do this.

6. EXAMPLE HE60 RUNS

This section briefly describes several example HE60 runs. The input and output files for these examples are all found on the HE60\extras\example_runs directory. You can reproduce these runs on your own computer and compare your output with that from the example runs to verify that HE60 is performing correctly on your computer. The example runs were all made on a 2.4 GHz Intel Xeon dual core processor. Run times (shown in the printout) on your computer will be longer or shorter, depending on the speed of your computer. (Note also that the "run time" given in the printout is "wall clock" time, not true computation time. Therefore, identical runs may show different run times in the printout, if the computer also was performing other tasks while HE60 was running.) The output from your runs should be identical to that from the examples to within numerical roundoff errors, which may cause very slight differences in some output values. All of the input and output files for these example runs can be found in the HE60\extras\example_runs directory.

6.1: Example 1: A Simple Radiative Transfer Simulation

This tutorial will walk you through your first run of HE60. Each run is specified by only one file: The input Iroot.txt file was named IUGExample1.txt, in this example. This file, along with the various output files for this run can be found in the HE60\extras\example_runs\Example1 directory.

This example illustrates running HE60 in a manner that is often used in idealized radiative transfer studies. This example solves the monochromatic RTE for a homogeneous, infinitely deep water body. For pedagogic purposes, suppose that we wish to define the inherent optical properties of the water body by the phase function and the albedo of single scattering, $\omega_o = b/c$. Here $c = a + b$ is the beam attenuation coefficient. We shall use $\omega_o = 0.75$ along with a b_b/b ratio of 0.023 (2.3% backscatter fraction). The output will be requested at various optical depths ζ, as is customary in radiative transfer studies.

To begin, double-click on the HE60 icon on your desktop that you made during installation (or double click HE60.exe in the HE60\frontend directory). To make sure you have a "clean slate" click the RESET defaults button on the first screen. You will need to read the license agreement and understand the disclaimer before you can CONTINUE.

The next screen you see will be the Run Identification screen. For this example, the root name is UGExample1 (for Users' Guide Example 1). After entering a root name and run title,

click CONTINUE. A screen will pop up showing you the names for the various output files. Note that the name is always made by adding a letter to the front of the selected rootname. Click OK.

This run is made by selecting the constant IOPs model. Select CONSTANT IOPS and press CONTINUE. You will not get the message box described earlier reminding you that you have "changed your IOP model" and will need to check your options carefully. Hit CONTINUE.
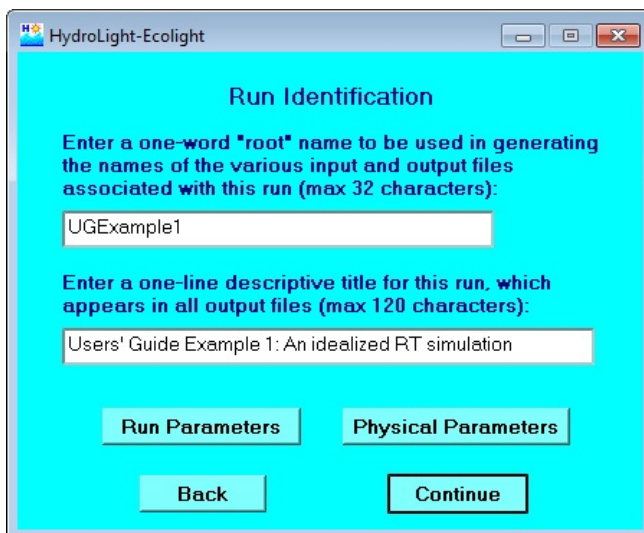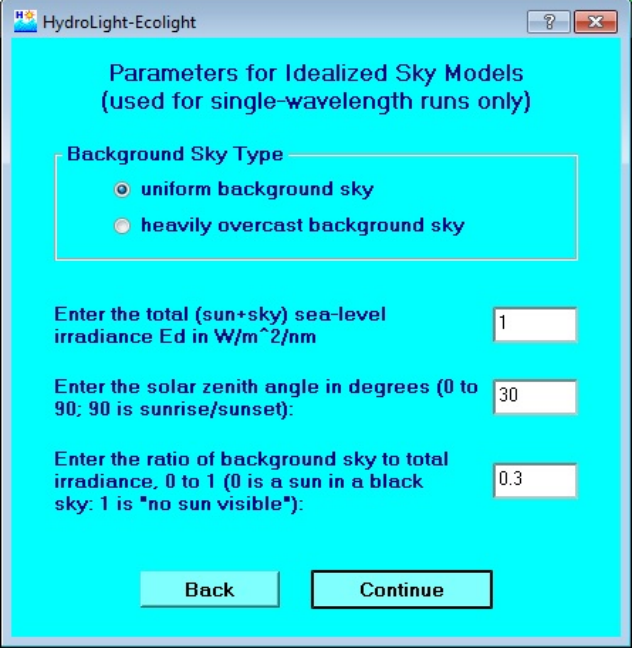
Next, you will get a screen asking you to specify the IOPs for this run. The input for this model needs a and b, not ω_o. However, we can use *any* values for a and b that give the desired value for ω_o, because we are requesting the output as a function of optical depth. The actual values of a and b are relevant only if we wish to convert optical depth to geometric depth via $z = \zeta/(a + b)$. Therefore, let us use $a = 0.1$ m^{-1} and $b = 0.3$ m^{-1}, which give $\omega_o = 0.3/(0.1 + 0.3) = 0.75$, as desired.
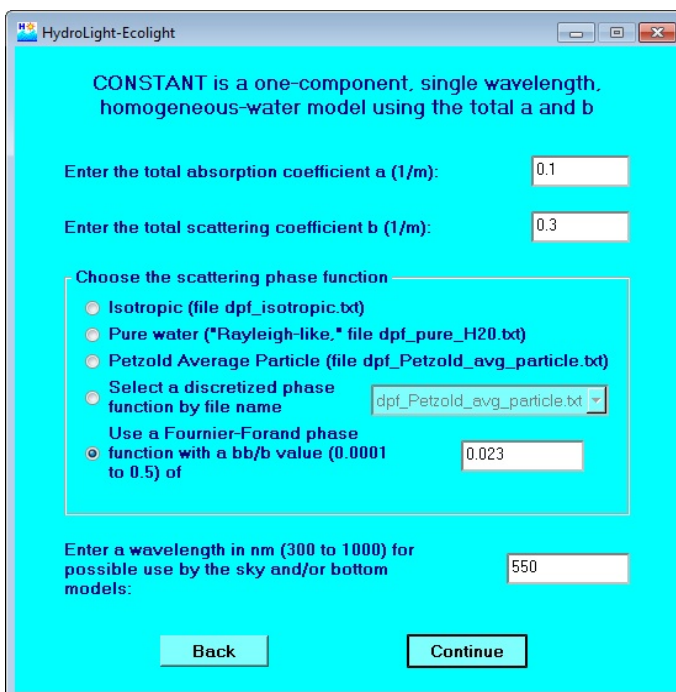
The desired phase function will be selected by HE60 to have a b_b/b ratio 0.023. Since this model can only be run in a single-wavelength mode, we can specify our wavelength here to be 550 nm (may be used by sky model or if we use a spectrally-dependent bottom reflectance). Hit CONTINUE.

The next form gives the opportunity to include bioluminescence in this run. Note that the various types of inelastic scattering are "greyed out" because they require a multi-wavelength run, and we are solving a monochromatic case. Do not include bioluminescence and hit CONTINUE.

For this example run select a level surface (wind speed = 0 m s^{-1}). The wind speed is displayed in three units of measure. You do not need to click UPDATE every time you change the wind speed. The wind speed is converted to m s^{-1} (if needed) and the values updated when you leave this form. Use the constant index of refraction set to 1.34 and select the IDEALIZED SKY MODEL. Hit CONTINUE.

Select a uniform sky with a total downwelling irradiance E_d of 1.0 W m^{-2} nm^{-1}, the sun at a 30 degree zenith angle, and a uniform background sky with a diffuse-to-direct irradiance ratio of 0.30. Click CONTINUE.

On the next form (not shown here), select the water to be infinitely-deep. Hit CONTINUE.

For this run we will solve the monochromatic RTE to $\zeta = 15$ optical depths with irregularly-spaced output depths. Since we want to solve our problem in terms of non-dimensional optical depth rather than geometric depth (in meters), select the depths units to be optical depths at the bottom of the form. This option is only available with monochromatic runs. Hit CONTINUE.

We have now provided HE60 with all the information it needs to make the run. On the final form (not shown) you can choose to save your input for future runs. For instance, you might want to process several data files or vary some parameters to study their effects. You can also view and change your printout options. Select the RUN HYDROLIGHT NOW option on the final form and click CONTINUE.

The progress and command windows open when HE60 begins running. Once the command window appears, you are free to return to the ID form of the GUI and begin specifying your next run. However, **do not begin executing** (by selecting RUN ... NOW on the final form) **your next run until the previous run has finished.** If you select RUN ECOLIGHT NOW (it is not necessary to pass through the GUI again), you can repeat the same run using the much faster EcoLight code and compare the HydroLight and EcoLight outputs.

As an example of the type of output that can be obtained from HE60, Fig. 10 shows how various K functions approach the asymptotic value K_∞. This plot was generated by the IDL routine HE60UG_Fig10.pro, which is found in the HE60\extras\IDL directory. Routine HE60UG_Fig10.pro reads the HydroLight digital output file DUGExample1.txt (in the HE60\output\Hydrolight\digital directory) as input. Because this run was made in terms of optical depth, the K functions have been plotted as non-dimensional quantities: K(non-dimen) $= K$(dimen)$/c$; see Note 3 below. Note that the values in Fig. 10 are local estimates of the K's,

76

which were computed from closely spaced pairs of depths, as explained in §5.7. The various K's differ near the sea surface because of surface boundary effects, but they all approach the same asymptotic value K_∞ as the depth increases.
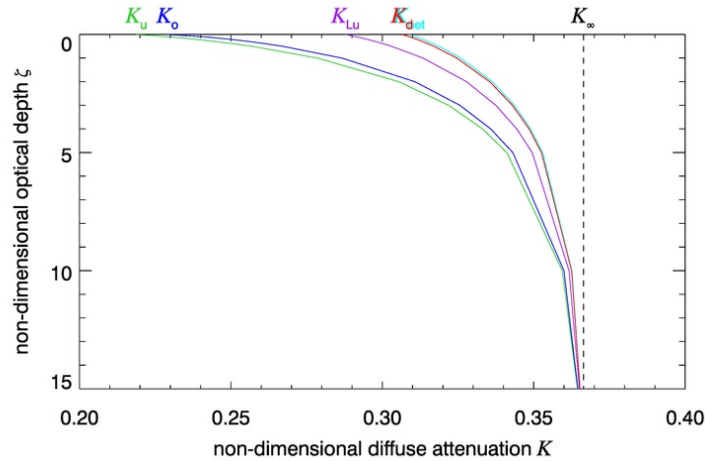
Fig. 10. Selected non-dimensional diffuse attenuation functions, as computed by the HydroLight run for Example 1. (Figure plotted by the IDL routine on HE60\examples\IDL\HE60UG_Fig10.pro.)

Note 1. The constant IOP model is for runs at a single wavelength, which was taken to be 550 nm. However, the wavelength is irrelevant in this run, because the run used the idealized sky model and had infinitely deep water. Had the run used the semi-empirical sky model or had it used a finite-depth bottom with a wavelength-dependent bottom reflectance, the wavelength would have been needed to obtain the sky or bottom information at a the run wavelength. Because the run was at a single wavelength, there was no option of including inelastic-scattering.

Note 2. For the values of $a = 0.1$ m^{-1} and $b = 0.3$ m^{-1} used in this run, 15 optical depths corresponds to $15/c = 37.5$ m of geometric depth. If you make another run with, say, $a = 1.0$ m^{-1} and $b = 3.0$ m^{-1} (and all else the same), you will find that the radiances and irradiances are all the same as a function of optical depth, even though 15 optical depths is then 3.75 m. Moreover, the run times will be the same, because it is optical depth that matters in the solution of the RTE.

Note 3. Even though the run saved its output at the specified optical depths, the *K* functions in the DUGExample1.txt file were computed using geometric-depth derivatives; the *K* functions therefore have units of inverse meters, as is customary. If you want non-dimensional *K* functions computed with optical-depth derivatives, you can multiply the values in the DUGExample1.txt file by $1/c$ (= 2.5 m in the present case). Routine HE60\source_code\common_code\K_functions_mod.f95, which computes the *K* functions, also has the option of printing out a table of non-dimensional *K* functions. This table is seen in the printout on file PUGExample1.txt. Note also that the dimensional *K* functions will be different for the (*a, b*) = (0.1, 0.3) and (1, 3) runs even though the non-dimensional *K* functions (computed using optical-depth derivatives) are the same at corresponding optical depths.

6.2: Example 2: A Simulation of Case 1 water with the Classic IOP Model

Now that you have made your first run of HE60, let's consider a multi-spectral Case 1 water simulation. The various input and output files for this run can be found in the HE60\extras\example_runs\Example2 directory. In this case, the root name for this run is UGExample2. After you have entered the root name and a run title, hit CONTINUE. When the informative page pops up listing the various file names for this run, hit CONTINUE.

Once you get to the IOP Specification form, select CLASSIC CASE1 IOPS and then hit the CONTINUE button. Next, you will see a form briefly telling you about the components included in the model you have selected. Click the SPECIFY COMPONENT IOPs button.

The first IOP specification form will appear next for pure water (your first component). All you need to do is check that the pure water values are the ones you want (here, the default temperature and salinity based values are used). Hit CONTINUE.

For the second component, chlorophyll-bearing particles, you will need to specify the concentration profile and the phase function. This example uses a user-supplied data file containing

78

the chlorophyll concentration as a function of depth. An example of such a file comes with HE60. Click on the SEARCH FOR DATAFILE button and browse until you find the file Chlzdata.txt in the ..\data\examples directory.

Next you need to specify the phase function for this component. Select the option to pick a phase function (a "DPF" or discretized phase function file) by the name of the file and use the pulldown menu to select Petzold's average-particle phase function, which is on the file named dpf_Petzold_avg_particle.txt. Hit CONTINUE.

Next, you will need to decide whether to include any inelastic scattering (fluorescence) or sources in the run. Check the chlorophyll fluorescence and Raman scattering boxes. Then hit CONTINUE. A notice will appear informing you that the data file Chlzdata.txt will be read to get the chlorophyll concentration, and reminding you to be sure to include enough wavelengths to make the fluorescence calculations relevant.

Next, we need to select the wavebands for the run. Since we have selected fluorescence and inelastic scattering we are not allowed to select the single-wavelength option; this button is "grayed out." For this run, select the "min/max/bandwidth" option and set the run to go form 350 nm to 700 nm with 10 nm wide bands. Hit CONTINUE.

On the next form set the wind speed to 5 m/s. Click the UPDATE button to see how many knots this is. Select the option to let the index of refraction vary with wavelength with the temperature and salinity as set by default (these are set on the Physical Parameters window at the start of the configuration). Select the SEMI-EMPIRICAL SKY MODEL option. Because we are making a multi-wavelength run, the option to use an idealized sky model is not available. Set the sun's azimuthal angle relative to the downwind direction to 0. Press CONTINUE.

On the next form, set the sun zenith angle to 30 degrees and use a 0% cloud cover, i.e. a clear sky. You can view (and change) the atmospheric parameters—but leave them at their preset values for this run. Press CONTINUE.

Use the annual average earth-sun distance on the next form, press CONTINUE. We will use RADTRAN-X to calculate the irradiance for our given atmosphere and sky conditions and use the Harrison and Coombes normalized sky radiance model to specify the distribution of sky radiance (by selecting the subroutine hcnrad, which is the only option in the distributed code).After selecting these options, click CONTINUE.

To specify the bottom boundary condition, select the finite depth bottom condition option and set the bottom reflectance to be 20%, independent of wavelength (an approximation of "gray mud"). Click CONTINUE.

The sea floor will be placed at the maximum output depth selected on this form. If we had selected an infinitely-deep bottom, the IOPs below this depth would be assumed constant with the value at this depth. Select a maximum depth of 20 meters with output every 2 meters. We must use geometric depths since we are making a multi-wavelength run. Don't forget that the accuracy of the calculations will not be affected by the number or locations of output depths.

We now arrive at the same final form as before, having provided HE60 with all the information it needs to solve the RTE. The run is completely specified by the input file

(IUGExample2.txt). Hit CHANGE OUTPUT OPTIONS on the last form and check the boxes to made the Droot.txt and Lroot.txt files. Also check the box to save this input as the default values for the next run so that we do not have to re-enter everything in the next example run.

Select the BEGIN HYDROLIGHT BATCH RUN NOW option and click CONTINUE. After the HydroLight run completes, select the BEGIN ECOLIGHT BATCH RUN NOW option and repeat the same run for comparison of HydroLight and EcoLight outputs. These runs took 47.4 seconds for HydroLight and 5.5 seconds for EcoLight on a 2.4 GHz PC. Note that the outputs from these corresponding HydroLight and EcoLight runs go into the respective HE60\output\HydroLight and HE60\output\EcoLight directories.

Figure 11 shows both the HydroLight- and the EcoLight-computed nadir-viewing remote-sensing reflectances $R_{rs} = L_w / E_d$ (where L_w is the water-leaving radiance, i.e., the total radiance minus the reflected sky radiance; and E_d is evaluated just above the water surface). The red line shows the R_{rs} computed by HydroLight; the blue dots show the values computed by EcoLight The two models give the same R_{rs} to within 0.02% (the differences are due to numerical differences in the algorithms used to solve the RTE). Since EcoLight ran almost ten times faster than HydroLight, it clearly makes sense to run EcoLight if the only output needed is the nadir-viewing R_{rs} or a similar quantity such as an irradiance, for which the two models give essentially the same output. However, note this is only true if the azimuthally averaged isotropic Cox-Munk sea surface model is selected (the default, in the Physical Parameters window at the start of the configuration). For the azimutally dependent Cox-Munk or FFT sea surfaces the EcoLight and HydroLight outputs may differ. HydroLight needs to be run only for output that depends on the full radiance distribution or on the azimuthal dependence of the radiance. Another example of such output is the off-nadir remote-sensing reflectance, for any sea surface model. In this example, R_{rs} is greatest at near-UV and blue wavelengths, which is expected for Case 1 water with a near-surface chlorophyll concentration of approximately 0.5 mg/m³. Note that HE60 computes the water-leaving and reflected-sky radiances separately, so the remote-sensing reflectance shown here is exact, not an approximation obtained via any semi-empirical correction for reflected-sky radiance or for transmitted upwelling radiance from below the surface.

Since Examples 2 and 3 cover the 400-700 nm range, the bottom of the printout files includes *PAR(z)* profiles, CIE chromaticity coordinates and Forel-Ule color indices for various quantities, and the Secchi depth (computed by three different models for Secchi depth).

81
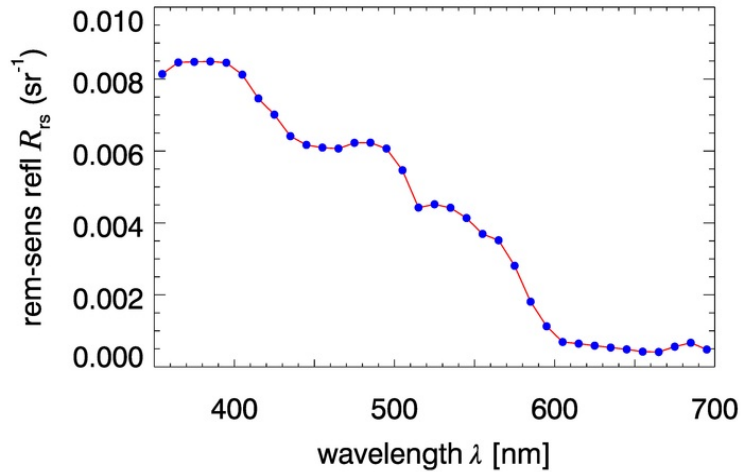
Figure. 11. The remote-sensing reflectance as a function of wavelength for the CLASSICCASE 1 water of Example 2. The red line was computed by HydroLight, the blue dots were computed by EcoLight. (Figure plotted by the IDL routine on HE60\extras\IDL_code\HE60UG_Fig11.pro, using the run output on the HydroLight and EcoLight DUGExample2.txt files)

6.3: Example 3: A Simulation of Case 1 water with the NEW CASE 1 IOP Model

Some features of the Classic Case 1 IOP model date back to the early 1980s and do not account for recent advances in optical oceanography. HE60 therefore contains a new Case 1 IOP model based on more recently published bio-optical models. The new Case 1 IOP model is described in detail in the §2.4 of the Technical Document. For this example, we will select the NEW CASE 1 IOP model on the IOP form but otherwise keep everything the same as in the previous example.

Check the box to save the Example run 2 input as the default values for the next run, if you haven't already done this. Then click the Select DEFINE A NEW BATCH RUN on the last form of the GUI to return to the Run ID form. Enter a new root name, e.g. UGExample3. Select the "medium UV Chlorophyll specific absorption" option (only affects wavelengths < 400nm) on the IOP model form. Note that now the phase function is automatically determined based on the ratio of small to large particles, which is a function of the chlorophyll concentration. You can just click past the remaining forms, since nothing is changed on those forms.
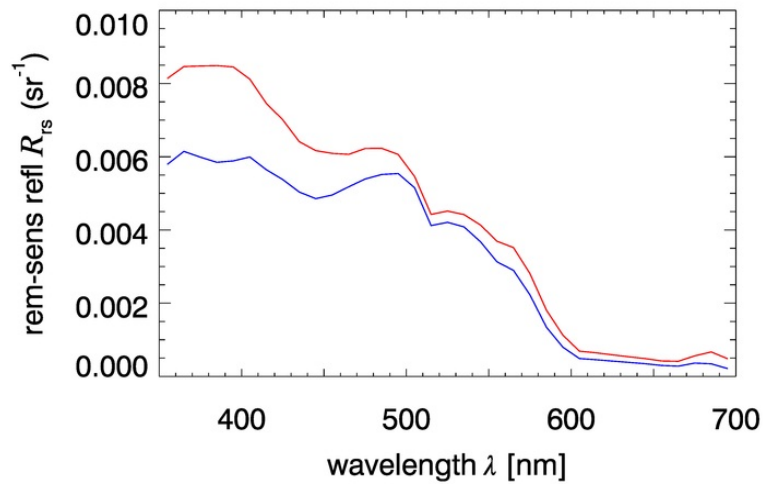
Figure.12. Remote-sensing reflectances for the classic (red) and new (blue) IOP models for Case 1 water. (Figure plotted by the IDL routine on HE60\extras\IDL\ HE60UG_Fig11.pro.)

Figure 12 shows the resulting HydroLight remote-sensing reflectance R_{rs} for the classic Case 1 IOP model (red, redrawn from Fig. 11) along with the HydroLight R_{rs} for the new Case 1 IOP model (blue). The differences show how these two different IOP models for Case 1 water can generate significantly different light fields. In this simulation, R_{rs} is less for the new Case 1 IOP model primarily because the particle backscatter ratio is less than the value of 0.0183 (the value for the Petzold average particle phase function) used in the classic model.

The two curves in Fig. 12 highlight an important point that is often forgotten when comparing HE60 output with field measurements. As with any model, it's garbage in, garbage out. HE60 gives an accurate solution of the RTE *for the given inputs*. When HE60 values disagree with measured irradiances, reflectances, or other light measurements, twenty years of HydroLight experience show that it is almost always because the input IOPs did not accurately describe the water body where the light measurements were made. Making good IOP measurements is extremely difficult. Unless people have multiple types of instruments for measuring absorption and scattering, they tend to assume that their IOP measurements are perfect, when in reality they easily may be off by tens of percent or more. **The papers by Tzortziou et al. (2006) and Tonizzo et al. (2017) should be thoroughly studied by anyone comparing HE60 outputs with measured values.**

6.4: Example 4: A Simulation of Case 2 Water

As a more complicated example of running HE60, consider a simulation the light field in shallow Case 2 water. The water is modeled as a four-component system:

- Component 1: pure water
- Component 2: chlorophyll-bearing particles (with no co-varying yellow matter or non-algal particles)
- Component 3: CDOM (yellow matter) that does *not* covary with the chlorophyll concentration
- Component 4: mineral particles that do *not* covary with the other components.

The corresponding IOP routine is found on file HE60\source_code\common_code\IOP_genericCase2_mod.f95. Several methods of specifying concentration and component IOP models are available, so this IOP routine provides a good starting place for simulating Case 2 water.

This example will use user-written functions for the chlorophyll concentration as a function of depth, and for the CDOM absorption as a function of depth and wavelength. **User-written functions MUST be placed in the HE60\source_code\user_routines directory, and they must have specific names, which cannot be changed.** There are four such options, which are seen in Table 1. (In addition to these four functions, which can be used in several IOP models, there are also ten functions named CompConc1_user_func to CompConc10_user_func, which are for use only in the ten-component user-defined IOP model.) Users can rewrite these example user routines as desired, e.g. to define a different chlorophyll concentration as a function of depth, but the names of the functions must not be changed.

Function name	File name in the user_routines directory	Purpose
Chlz_user_func	Chlz_user_func_mod.f95	returns the chlorophyll concentration given the depth
Minz_user_func	Minz_user_func_mod.f95	returns the mineral particle concentration given the depth
a_CDOM_user_func	a_CDOMz_user_func_mod.f95	returns the CDOM absorption coefficient given the depth and wavelength
So_biolum_user_func	So_biolum_user_func_mod.f95	returns the bioluminescence source magnitude give the depth and wavelength

Table 1. User-written functions in HE60. If any changes are made to these routines, the code must be recompiled for them to take effect.

To make this run, start HE60 as before and provide a root name and run title. On this Physical Parameters form, enter a temperature of 10 deg C and a salinity of 25 PSU, which are typical for Puget Sound, Washington, USA. Then on the next form, select the CASE2 IOPs option from the IOP model form. After you see the form reminding you about the four components in this model, you will be taken through a set of forms to specify the IOPs for each of the four components. There is considerable freedom in specifying IOPs with the Case 2 water model, and you therefore will find that more information is requested by the GUI.

Going though the forms, specify the components as follows:

● **Component 1: pure water**
For pure water you will need to specify the pure water absorption and the phase function. For the absorption, select the default temperature and salinity based model as before. The scattering phase function on file dpf_pure_H2O.txt will be used automatically.

85

- **Component 2: chlorophyll-bearing particles**

For Component 2 you need to specify the concentration, chlorophyll-specific absorption and scattering spectra, and the scattering phase function. In this example, the concentration will be obtained from a function subroutine named Chlz_user_func, as shown in Table 1. **This is an example of a user-written function. It is not for general use in modeling water bodies.** This example routine is already in the distributed code, for use in this example run. Select the option for a USER-WRITTEN FUNCTION for the chlorophyll concentration. Select a backscatter fraction of 0.005, which is appropriate for phytoplankton. A Fournier-Forand phase function with a b_b/b ratio of 0.005, or 0.5% backscatter, will then be used.
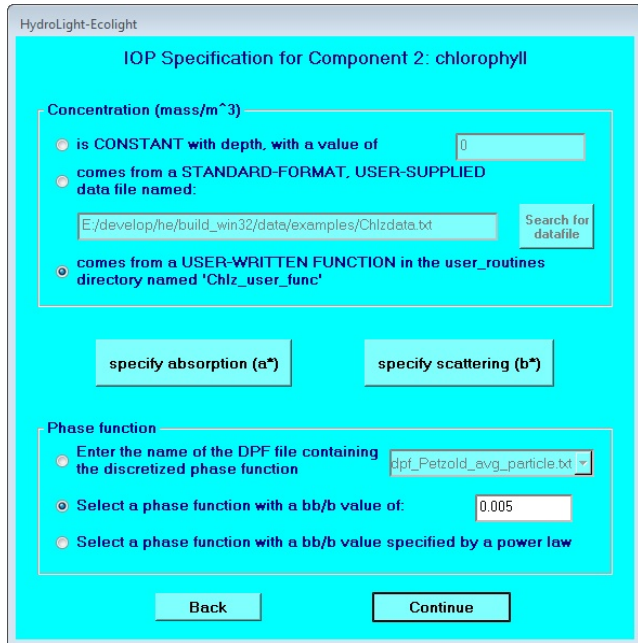
As you can see by looking at the function on file Chlz_user_func_mod.f95, the chlorophyll value is defined by a background value plus a Gaussian function of depth, with the maximum value at a depth of 5 m. For the 8 m water depth chosen below, the chlorophyll concentration varies from 0.61 mg m^{-3} at the surface to 3.00 mg m^{-3} at $z = 5$ m, and then decreases to 1.31 mg m^{-3} at $z = 8$ m.

On the SPECIFY ABSORPTION form for the chlorophyll component, select the option for a "chlorophyll-based model for Case 1 water." On the SPECIFY SCATTERING form, select the linear scattering model with the default values (hit the USE GAM MODEL PARAMS button to fill in the blanks), but then reset b_0 to 0.30.
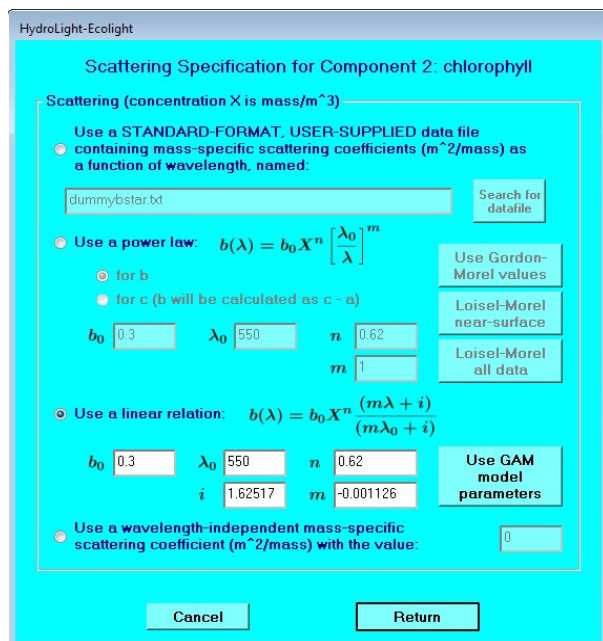
- **Component 3:   CDOM**

    In this run, CDOM absorption will be provided as a function of depth and wavelength by a user-supplied subroutine named a_CDOM_user_func. Just as for the chlorophyll concentration user function, this function as distributed is just and example for use in the present run. It is not intended for general use. This function can be rewritten by the user as desired, so long as the name is not changed.

    The depth and wavelength functions in file a_CDOMz_user_func_mod.f95 as distributed define the CDOM absorption coefficient $a_{CDOM}(z,\lambda)$ so that at 440 nm, the absorption by CDOM is 0.1 m^{-1} at the surface; this value decreases exponentially to 0.02 m^{-1} at 8 m (to crudely simulate a near-surface layer of CDOM as might arise from river input). The CDOM absorption decreases exponentially with wavelength; it is negligible at red wavelengths, but was triple the above values at 350 nm.

    Note that there is an option (not chosen here) to select CDOM to covary with chlorophyll with the same functional form used in the "classic Case 1" IOP model. However, the CASE2 model explicitly separates the chlorophyll and CDOM components and allows the user to define each IOP component independently of the others. The CHANGE PARAMETER VALUES option allows the user to set the parameters of the CDOM exponential absorption function to be whatever is desired.

- **Component 4:   minerals**

    The minerals in this run will be modeled as red clay particles. The concentration will be provided by the data file minzdataEx4.txt in the HE60\data\examples directory. This concentration profile crudely simulates a layer of resuspended sediment. The mineral concentration on this data file varies from 0.1 gm m^{-3} at the surface to 1.0 gm m^{-3} at 8 m.
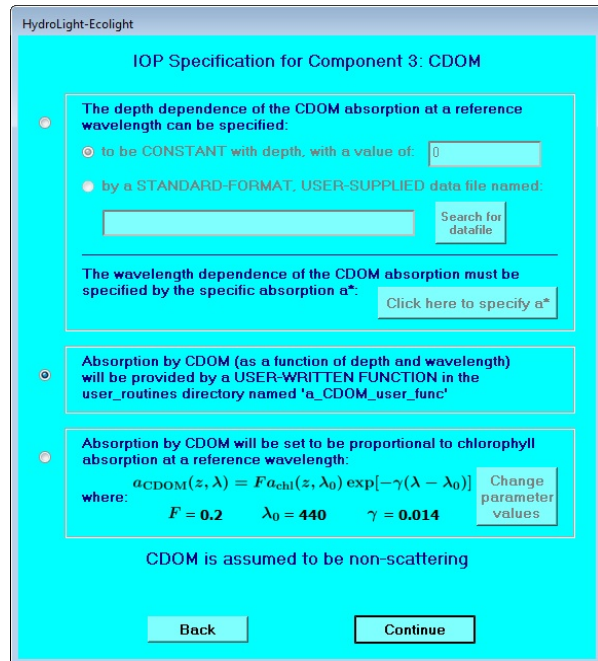
The specific absorption and scattering coefficients will be provided by the data files astarmin_redclay.txt and bstarmin_redclay.txt, respectively. These files are in the directory HE60\data\examples\minerals. Browse for these files on the forms that solicit the absorption and scattering information for the mineral component. Note: HE60 cannot know if you have made an error in picking such files. You can, for example, pick the file for red clay absorption and the file for yellow clay scattering. That is a perfectly valid radiative transfer problem, but it probably is not the one you intended to solve. Have HE60 choose a mineral particle phase function (Fournier-Forand) with a backscattering ratio of b_b/b that varies with wavelength according to a power law, as shown on the next form.

Include Raman scattering and fluorescence by chlorophyll and CDOM on the inelastic form. On the wavelengths form, select the wavebands to match those of SeaWiFS. Note that the first SeaWiFS wavelength band is 402-422nm. Raman scatter and CDOM fluorescence are excited by wavelengths shorter than 400nm, so there will be some inaccuracy in the inelastic-scatter calculations, but this will be a minor effect for this turbid Case 2 water body. Select a wind speed of 4 m s^{-1}. Put the sun azimuthal angle at 0, which means that the sun is in the downwind direction. In the present run, the sun azimuth angle will not matter because the run is using the azimuthally averaged Cox-Munk sea surface model.

Use the "semi-empirical" sky model. Use the time and location options to specify a date of 15 June 2013 (year day 166), 23:00 GMT (mid afternoon in Puget Sound), latitude 48.5 degrees North, and longitude of 123 degrees West (value of -123, Puget Sound). (The corresponding solar zenith angle, computed during the HE60 run, is 41.55°.) Assume a clear sky (cloud cover value of 0).

Use VIEW ATMOSPHERIC OPTIONS to set the airmass type to 3 (mixed marine and continental aerosols). Enter the ozone concentration as -99 Dobson units, which will cause the TOMS climatological ozone value for this date and location to be used, as described in §5.1 of the Technical Documentation. (This ozone value is 339.8 Dobson units, as seen in the printout.) Use the defaults for the other atmospheric parameters. Pick RADTRAN-X on the Sky Models–Incident Light form.

Take the water column to have a finite depth. Use the pull-down menu to select a bottom reflectance for "average sea grass." On the next form, place the bottom at 8 m (i.e. set as the maximum depth as 8 m) and save the output at 0.5 m intervals.

These inputs give HE60 everything needed to solve the RTE. On the final form, click the CHANGE OUTPUT OPTIONS button and make sure that the run is creating the Droot.txt and Lroot.txt output files. If you check the CLICK HERE TO SAVE THIS INPUT button, all of the inputs entered above will become the default values for the next run. This makes it easy to do multiple runs with slightly different inputs (e.g., different bottom reflectances or sun angles) just by clicking through the GUI forms and changing only a value here and there. If doing another run, be sure to give each run a new run ID on the first form, or the next run will overwrite the output of the previous run with the same ID.

You can now hit the BEGIN HYDROLIGHT BATCH RUN NOW button. HydroLight will then begin to run. After the run is completed, you can click on the OK button to close the run progress window and the command window. Both HydroLight and EcoLight take exactly the same inputs, so you can repeat the same run using EcoLight just by clicking on the BEGIN ECOLIGHT BATCH RUN NOW button.

The printout for this run on file HE60\output\HydroLight\printout\PUGExample4.txt shows that, depending on the depth and wavelength, the total absorption at blue to green wavelengths is dominated by any of phytoplankton, CDOM, or minerals. Absorption by water of course dominates at red wavelengths. Scattering can be dominated by either phytoplankton or minerals, depending on the depth and wavelength; the CDOM was assumed to be non-scattering. This model for a and b gave total albedos of single scattering, ω_o, that ranged from only 0.08 at 765 nm near the surface, where absorption by the water is high, to more than 0.90 at green wavelengths where the total absorption was lowest. The geometric depth of 8 m corresponded to 8.26 optical depths at 412 nm (where both CDOM absorption and particle scattering were high), to about 6.7 optical depths near 570 nm, to 24.7 optical depths at 765 nm.

This HydroLight run required 26.8 seconds on a 2.4 GHz Xeon dual-core processor. This simulation required the solution of the radiative transfer equation for 20 wavelength bands, including intermediate bands between the SeaWiFS bands (see Fig. 13 below), which were needed for the inelastic scattering calculations, with three types of inelastic scattering connecting the bands. On average, each wavelength solution was taken to about ten optical depths. Thus the HydroLight run time corresponded to about 0.15 seconds per wavelength per optical depth. The printout file is less than 0.5 Mbytes, but the digital output file DUGExample4.txt (which contains all inputs and outputs at all depths, directions, and

90

wavelengths) is about 5 Mbytes, and the LUGExample4.txt file (which contains the full radiance distribution at all depths, directions, and wavelengths, but on a different format than DUGExample4.txt) is 14 Mbytes. These files include the the direct, diffuse, and total radiances within the water. The Excel spreadsheets are found in the output\Hydrolight\excel directory. Those files are about 0.5 Mbytes. Note in the printout that PAR was not computed for this run because the SeaWiFS wavelength range does not cover 400-700 nm.

The corresponding EcoLight run required only 2.7 seconds. The EcoLight printout and Excel files are similar to the corresponding HydroLight files. The EcoLight LUGExample4.txt file is much smaller than the HydroLight Lroot.txt file. This is because the EcoLight radiances are band-averaged values; there is no azimuthal dependence. The EcoLight Lroot.txt files also write only the total band-averaged radiance within the water. The EcoLight Lroot.txt files are therefore not of much use, although they can be created.

The following figures show some of the input to and output from this simulation. Figure 13 shows selected component and summed IOP's (the sum of phytoplankton, CDOM, and minerals, but not including water) as functions of depth and wavelength. These figures were all plotted using IDL routine on HE60\extras\IDL\HE60UG_Fig13.pro, which reads the DUGExample4.txt file.) Figure 14 shows plots of the radiance distribution in the plane of the sun's rays as a function of viewing direction and wavelength, at depths of 0, 4, and 8 m. (This figure was generated using IDL routine HE60UG_Fig14.pro.)

Figure 14 illustrates how the HydroLight-computed radiance distribution changes with depth, polar angle, azimuthal angle, and wavelength. (This figure was generated using IDL routine HE60UG_Fig14.pro.) Radiance plots contain a wealth of information, but their interpretation requires care. Although the present Example 4 simulation has a wind speed of $U = 4$ m/s, let us start with the same simulation (same IOPs, etc.) except for a wind speed of $U = 0$, so that the sea surface is level. Figure 14(a) shows the radiance in air (just above the sea surface) as a function of the polar viewing angle and wavelength, in the azimuthal plane of the sun, for $U = 0$. To understand this plot, recall from §3.4 that in HydroLight the polar angle is measured from the $+z$ or downward direction. Thus light heading straight down has a polar angle of $\theta = 0$. This plot uses the *viewing* direction (θ_v, φ_v), which is the direction an instrument would point when measuring the radiance. Thus the polar viewing angle of $\theta_v = 0$ means looking straight down and seeing the radiance heading straight up (the nadir-viewing radiance; light traveling in the $\theta = 180$ deg direction). The sun is always located at $\varphi = 0$ (recall Fig. 5). This figure shows the full range of polar angles in the $\varphi = 0$-180 deg plane of the sun. A polar angle of $\theta_v = +90$ deg corresponds to looking horizontally towards the sun, and $\theta_v = -90$ deg corresponds to looking horizontally away from the sun. The sun's radiance

is the large spike at θ_v = 140 deg, which corresponds to looking upward (θ_v > 90 deg) at a zenith angle of 40 deg in the φ = 0 azimuthal direction, where the sun was located in this simulation. The smaller spike at θ_v = 40 deg is the sun's specular reflection, seen looking downward (θ_v < 90 deg) and towards the sun. The ratio of the sun's specular reflectance to the sun's direct beam is 0.026 (computed from the radiance values tabulated in the LUGExample4.txt file), consistent with the Fresnel reflectance for this incidence angle and water index of refraction. The broader radiance peak near θ_v = -90 deg is the bright near-horizon sky radiance and its reflection by the sea surface, seen looking away from the sun. Figure 28 of the Technical Documentation shows a similar sky radiance distribution plotted in a different way. Note in that figure that the sky radiance increases somewhat near the horizon when looking away from the sun.

Figure 14(b) is the same as Fig. 14(a), except that the wind speed is U = 4 m/s, as selected in the present Example 4 simulation. Note that the sun's specular reflection has been smeared out by the wind-blown sea surface. The other radiance features remain about the same as for the level-surface simulation.
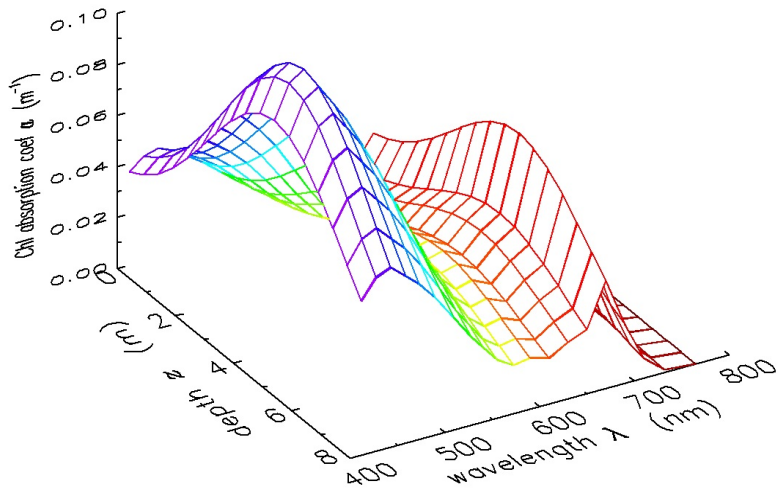
Fig. 13(a). The absorption coefficient for chlorophyll-bearing phytoplankton as function of depth and wavelength, as used in Example 4.
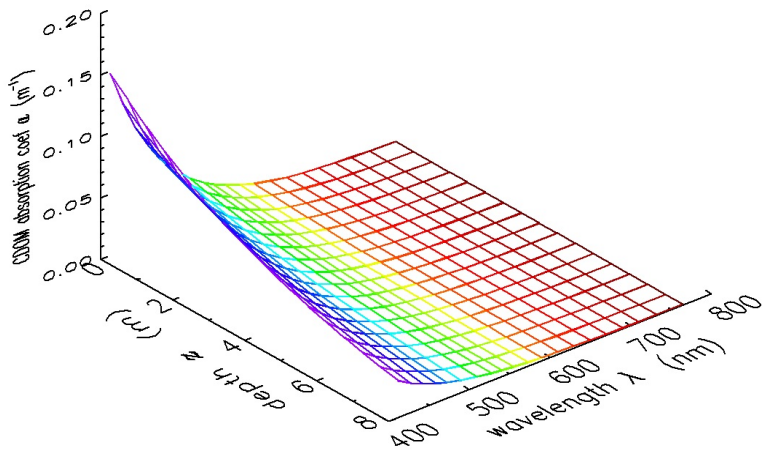
Fig. 13(b). The absorption coefficient for CDOM as function of depth and wavelength, as used in Example 4.
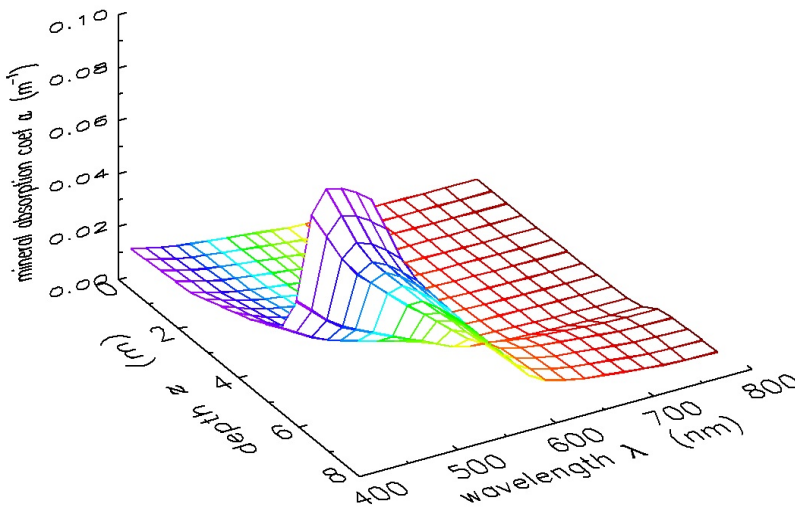
Fig. 13(c). The absorption coefficient for mineral particles as function of depth and wavelength, as used in Example 4.
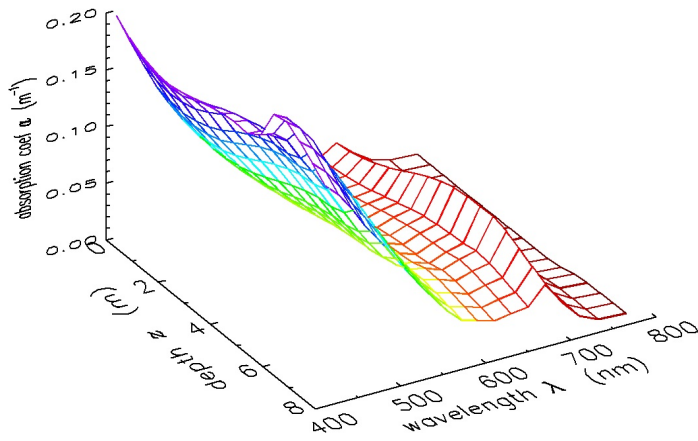
Fig. 13(d). The sum of particle and CDOM absorption (not including water) as a function of depth and wavelength, as used in Example 4.
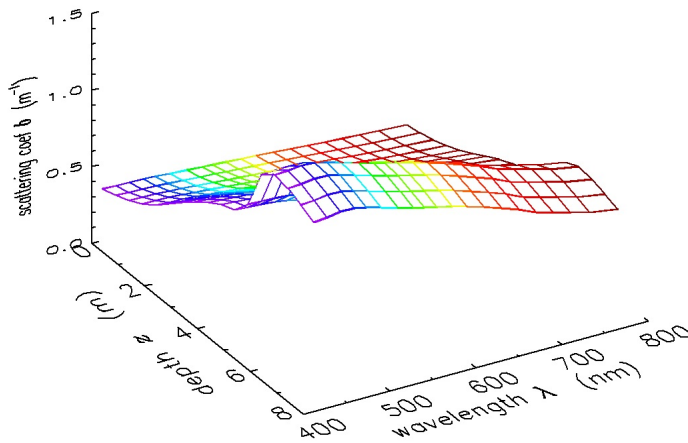
Fig. 13(e). The sum of phytoplankton and mineral particle scattering (not including water) as a function of depth and wavelength, as used in Example 4.
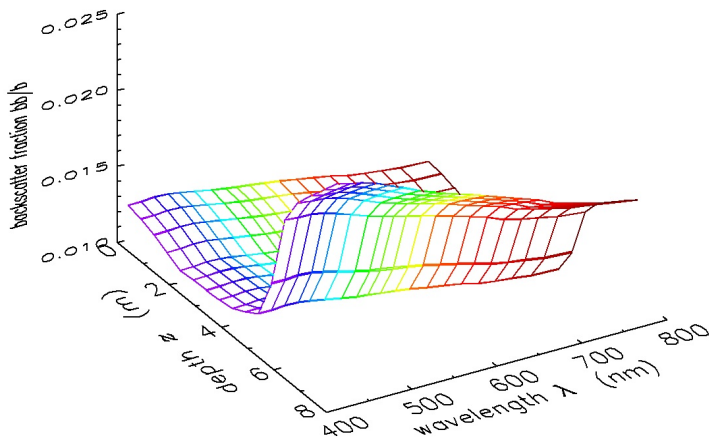
Fig. 13(f). The particle backscatter fraction b_b/b as a function of depth and wavelength, as used in Example 4.

94
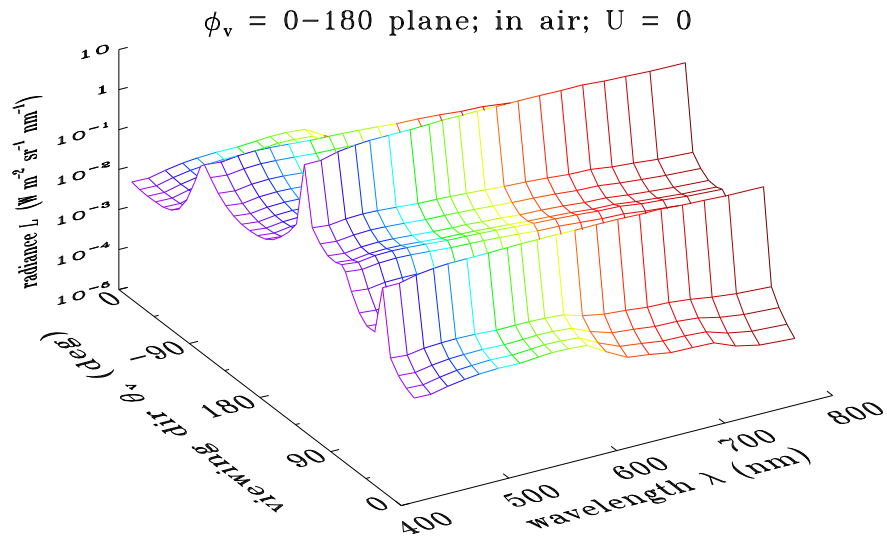
Fig. 14(a). The radiance distribution in the plane of the sun's rays, as a function of viewing direction and wavelength, in air just above the level air-water surface. Note that the radiance axis is logarithmic.
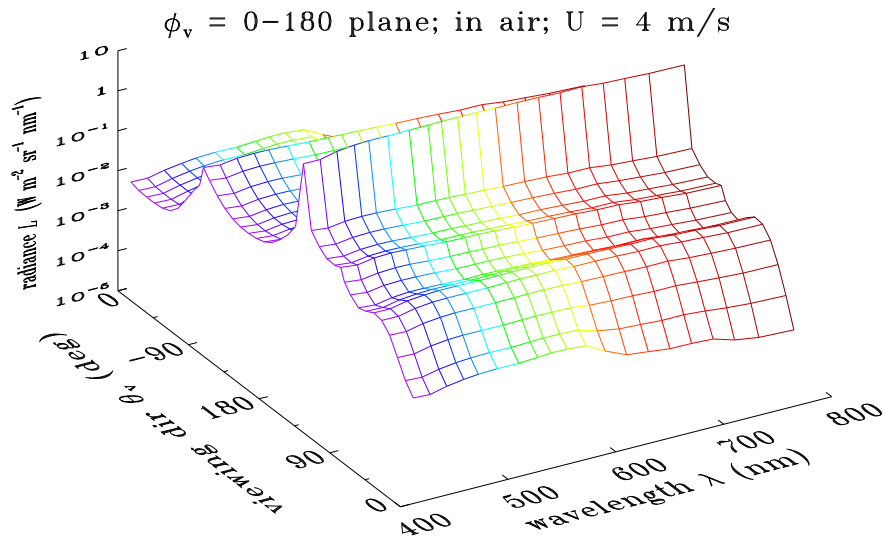
Fig. 14(b). The same as for Fig. 14(a), except that the wind speed is 4 m/s. Note that the sun's specular reflection seen in Fig. 14(a) has been smeared out by the ruffled sea surface.

95
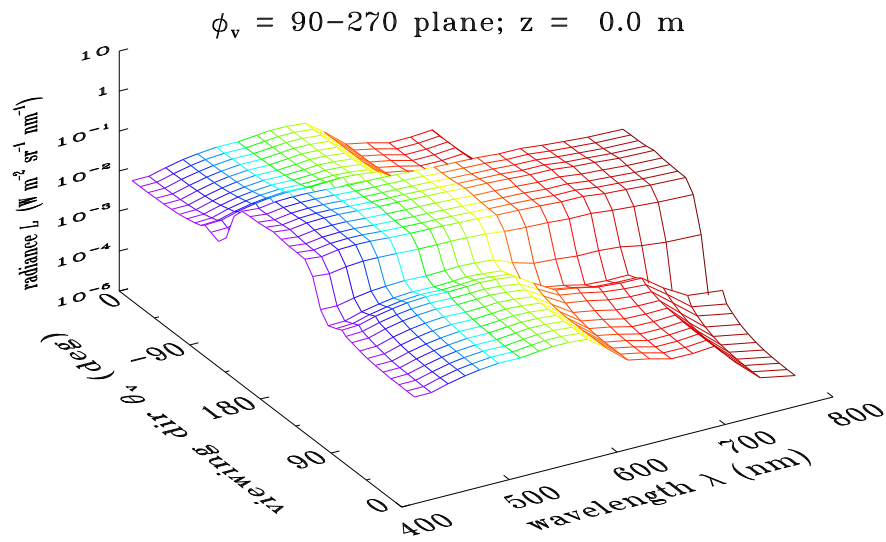
Fig. 14(c). The radiance just below the sea surface, in the plane perpendicular to the sun's azimuthal direction.
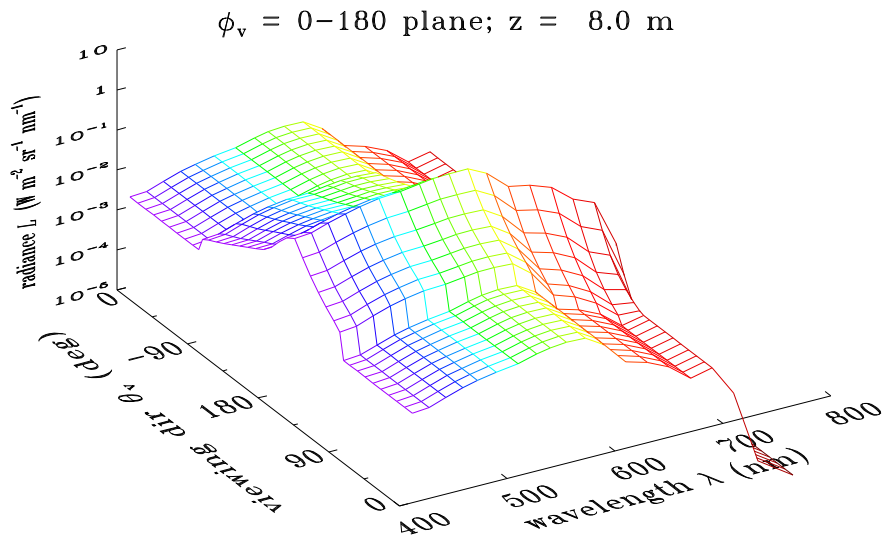
Fig. 14(d). The radiance distribution in the plane of the sun's rays, just above the sea floor at a depth of 8 m. The constant radiance in the upward directions is a consequence of the Lambertian bottom.

Figure 14(c) shows the radiance at depth $z = 0$, just below the wind-blown sea surface, and in the azimuthal plane perpendicular to the sun's direction. The radiance is now symmetric about the zenith direction $\theta_v = 180$ deg. The radiance (mostly transmitted sky radiance) is fairly uniform looking upward in "Snel's window," (and yes, it's Snel not Snell) which extends about 50 deg to either side of the zenith ($\theta_v = 180$ deg) direction. The small bump in the upwelling radiance near 685 nm is due to chlorophyll fluorescence.

Finally, Fig. 14(d) shows the radiance distribution in the plane of the sun's rays just above the sea floor at a depth of 8 m. The sharp spike of the sun's direct beam seen near the surface has been broadened by multiple scattering and decreased in magnitude by absorption. The constant radiance in the upward directions (θ_v between 0 and ± 90 deg) is a consequence of the Lambertian bottom, which reflects the downwelling radiance equally into all upward directions. The radiance at wavelengths beyond ~700 nm has been greatly reduced in magnitude by water absorption.

Figure 15 shows the remote-sensing reflectance $R_{rs} = L_w / E_d$ (where L_w is the water-leaving radiance, i.e., the total upwelling radiance in air minus the surface-reflected sky radiance; and E_d is evaluated just above the water surface). R_{rs} is greatest near 550 nm, showing that this is "green" Case 2 water. (Compare this with the "blue" water simulation of Example 2, Fig. 11.) The bump at 690 nm shows the effect of chlorophyll fluorescence. The gray bands show the nominal SeaWiFS sensor bands. This simulation chose the SeaWiFS bands on the form for wavelength output. Note that the output includes the SeaWiFS wavelengths as requested, as well as additional wavelengths as needed for the inelastic scatter calculations. As in Fig. 11, the HydroLight-computed R_{rs} is the red line; the EcoLight-computed values are the blue dots. The agreement between HydroLight and EcoLight is again excellent, and EcoLight ran ten times faster than HydroLight (2.7 vs 29 seconds, respectively). However, only HydroLight can provide the azimuthal information contained in the full radiance distribution, as seen in the plots of Fig. 14.
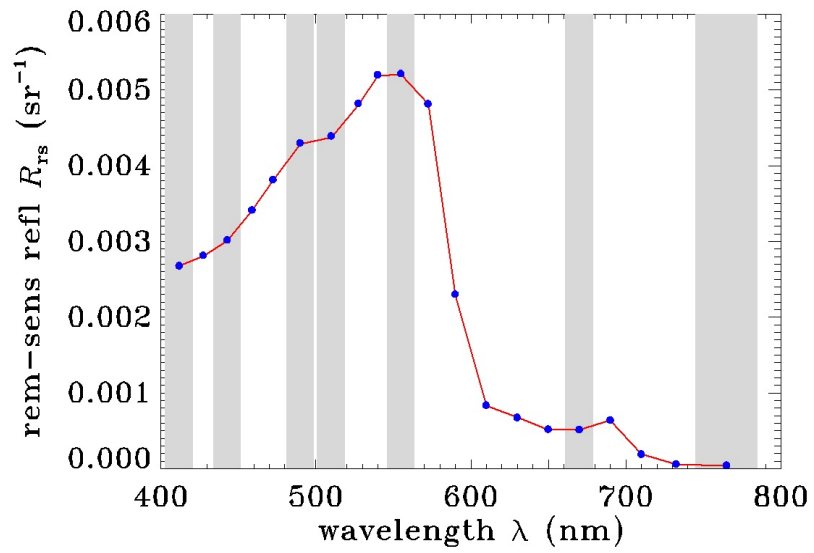
Fig. 15. The remote-sensing reflectance as a function of wavelength for the Case 2 water of Example 4. The gray bars show the nominal SeaWiFS sensor bands. (This figure was generated by IDL routine HE60UG_Fig11.pro.)

7. OUTPUT FROM STANDARD RUNS

The examples just discussed showed example graphical output obtained by using IDL to plot data in the digital output files. Now, we will discuss the different forms of output and what is included in each.

7.1 The Default Printout

Every standard HE60 run generates an ASCII text file of "printout" (the Proot.txt file found in the output\Hydrolight\printout or output\Ecolight\printout directory) that is designed to be viewed with a text editor (or word processor). This file shows, in an easily read format, information such as

- A description of all of the options selected for the run
- The names of all data files read
- Any warnings or error messages generated during the run
- The atmospheric parameters used in the sky radiance model

Then, for each wavelength in turn:

- The absorption, scattering, backscattering, and attenuation coefficients for each component of the IOP model
- Various irradiances (upward and downward scalar and plane irradiances)
- Nadir- and zenith-viewing radiances (HydroLight runs also show horizontal radiances at selected azimuthal directions relative to the sun's position)
- Various apparent optical properties (mean cosines, reflectances, and diffuse attenuation functions)
- Quantities of interest in ocean-color remote sensing (incident and reflected sky radiance, water-leaving radiance; for nadir-viewing only in EcoLight runs, for selected additional directions in HydroLight runs)
- PAR, 1931 CIE chromaticity coordinates, Forel-Ule color index, and Secchi depth for runs covering at least 400 to 700 nm

Quantities that are common to all wavelengths (e.g., atmospheric conditions or the IOP model selected) are grouped at the top of the printout. Quantities that depend on wavelength (e.g., IOP values or the bottom reflectance) are shown for each wavelength. Where

appropriate, these quantities are tabulated at the user-defined depths where output was saved.

It is strongly recommended that you always take a look at the printout after an HE60 run terminates. This is easily done by opening the file with NotePad or WordPad; you can also use a word processor such as Microsoft Word® to view the file. Scan the input to make sure the inputs were what you intended. Check for error messages warning about problems with the input data. Inspect the computed output to see if it looks physically plausible. If you see something peculiar in the output, try to figure out the cause—incorrect input, lack of intuition on your part about underwater light fields, or (perish the thought) a bug in HE60. For some purposes, it may be convenient to copy output from the default printout and paste it into graphics or spreadsheet software for further analysis.

The default printout gives a reasonable amount of information for most users. You can obtain more or less printout by selecting a different option in the Printout form of the GUI (accessible from the FINAL form by selecting VIEW OUTPUT OPTIONS).

Some of the HydroLight radiance printout can be confusing until you are familiar with the directional conventions of radiative transfer theory and the HydroLight coordinate system shown in Figs. 5 and 6. Figure 16 therefore shows an annotated snippet of the default radiance printout from a HydroLight run, with selected quantities labeled.


```
                     Looking upward    Looking away    Looking toward
                                        from the sun       the sun
         Looking downward

Selected Spectral Radiances [units of W/(m^2 sr nm)] and Radiance-Irradiance Ratios at  350.0 nm

[(theta,phi) are the directions of radiance propagation (theta = 0 is downward, phi = 0 is downwind).]

 iz      z      zeta      Lu(z)        Ld(z)     Lh(z,phi=0)  Lh(z,phi=90) Lh(z,phi=180)    Lu/Ed
        (m)             (theta=180)   (theta=0)   (theta=90)   (theta=90)   (theta=90)      (1/sr)

          in air      7.817E-03    8.711E-02    9.705E-02    8.659E-02    1.232E-01    1.208E-02

   1    0.00     0.00   5.416E-03    1.579E-01    8.608E-03    9.281E-03    1.148E-02    8.553E-03
   3    0.63     1.00   4.677E-03    1.773E-01    9.153E-03    1.015E-02    1.504E-02    8.573E-03
   5    1.26     2.00   4.020E-03    1.864E-01    8.526E-03    9.704E-03    1.488E-02    8.589E-03
   7    1.89     3.00   3.443E-03    1.863E-01    7.693E-03    8.937E-03    1.395E-02    8.601E-03
   9    2.52     4.00   2.941E-03    1.791E-01    6.823E-03    8.058E-03    1.270E-02    8.611E-03
```

Fig. 16. Example HydroLight radiance printout with selected directions labeled. Note, for example, that to detect radiance traveling in the φ = 0 direction you are looking away from the sun, which was in the φ = 0 azimuthal direction.

Figure 17 likewise shows the above-surface radiance printout from a run with the sun at a 30 deg zenith angle (and in azimuthal direction 0).
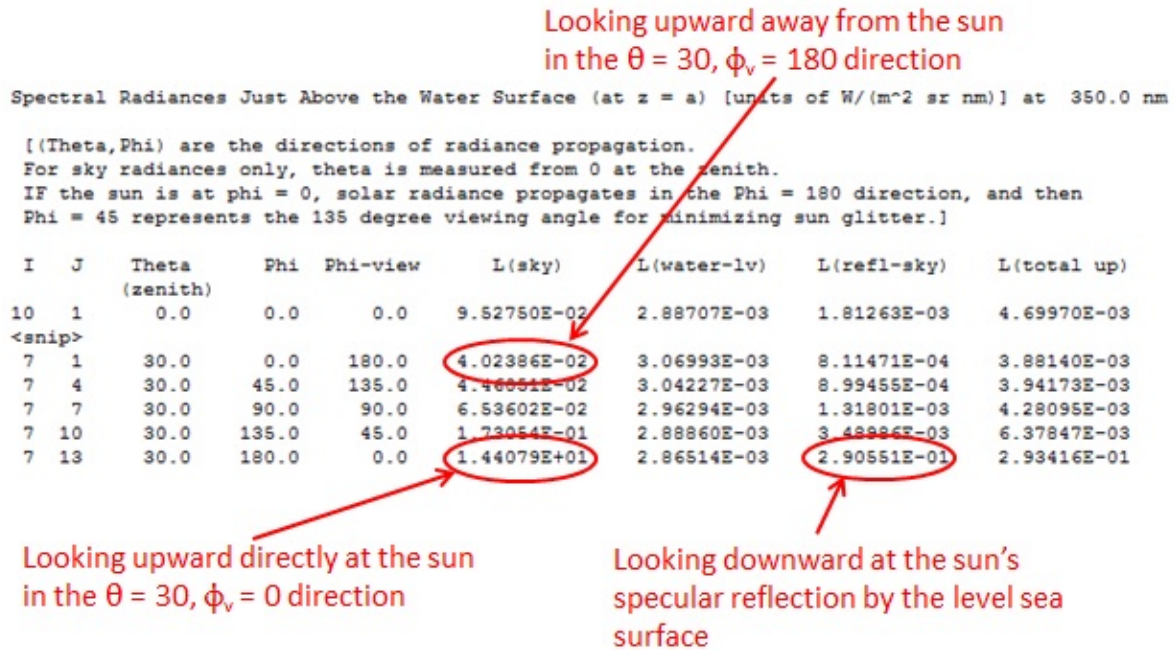
Fig. 17. Annotated snippet of HydroLight above-surface radiance printout. The sun was at (θ_{zenith} = 30, φ = 0).

Note 1. The depth indices iz shown in the default HydroLight printout (e.g., as seen in Fig. 16) may cause confusion. When you specify the depths where output is to be saved, *HydroLight* automatically adds a second depth just below each depth you specify. As explained in §5.7, these pairs of closely spaced depths (0.01 m apart by default) are used to compute diffuse attenuation functions (K functions) by finite-difference approximations to their definitions. However, most output is given only at the depths you requested. This can make it appear that output is being given at every other depth (indices iz = 1, 3, 5, ... as seen in Fig. 16); the omitted indices (iz = 2, 4, 6, ...) correspond to the extra depths used to compute K functions and can be disregarded.

Table 2 shows an example of the default printout for the irradiances and mean cosines. Note also that both the optical depth ζ ("zeta" in the printout) and the geometric depth z (in meters) are shown in the printout. Values in the air, just above the sea surface, are also shown where appropriate. Table 3 shows the corresponding printout for various K functions. The closely spaced pairs of depths (z_k, z_{k+1}) are shown in the printout as (z_{upper}, z_{lower}). The small increment used in computing derivatives, which is 0.01 m by default, is set in the data module source_code\common_data_modules\mod_DimensDefaults.f95. Picking depths only 0.01 m apart exceeds the ability of oceanographic instruments to measure the corresponding changes in the light field, but such closely spaced values gives excellent depth resolution of K profiles in the numerical model.

```
 Irradiances (units of W/m^2 nm), Mean Cosines (Mubars), and Irradiance Reflectance
iz   zeta   z(m)      Eou        Eod        Eo         Eu         Ed       MUBARu  MUBARd   MUBAR    R = Eu/Ed

         in air  9.7675E-02  9.5298E-01  1.0507E+00  2.9105E-02  5.9866E-01  0.2980  0.6282  0.5421   4.8616E-02

1   0.00   0.00  2.3508E-02  6.7162E-01  6.9513E-01  9.4290E-03  5.7898E-01  0.4011  0.8621  0.8193   1.6286E-02
3   1.91   1.00  1.1631E-02  3.0982E-01  3.2145E-01  4.4336E-03  2.5288E-01  0.3812  0.8162  0.7729   1.7532E-02
5   3.82   2.00  5.1328E-03  1.3393E-01  1.3907E-01  1.9295E-03  1.0722E-01  0.3759  0.8006  0.7571   1.7995E-02
7   9.56   5.00  3.8325E-04  9.8290E-03  1.0212E-02  1.4244E-04  7.7349E-03  0.3716  0.7869  0.7435   1.8415E-02
9  19.11  10.00  4.6379E-06  1.1866E-04  1.2330E-04  1.7210E-06  9.3190E-05  0.3711  0.7853  0.7418   1.8467E-02
```

Table 2. Example of the default printout showing various irradiances, mean cosines, and the irradiance reflectance. The line labeled "in air" gives the values just above the air-water surface. Depth 0.00 is in the water, just below the surface. The user-requested output depths were $z = 0, 1, 2, 5, 10$ m. These are the odd-indexed depths ($iz = 1, 3, 5, 7, 9$); the even depths are used to compute K functions and are not shown in the default printout.

```
 K-functions (units of 1/meter) (valid only when zupper and zlower are closely spaced)

  zupper    zlower      z      Kou(z)    Kod(z)     Ko(z)     Ku(z)     Kd(z)    Knet(z)    KLu(z)

   0.000     0.010    0.005   0.53271   0.69107   0.68571   0.65229   0.79845   0.80088   0.77136
   1.000     1.010    1.005   0.78821   0.81967   0.81853   0.80976   0.84798   0.84866   0.83940
   2.000     2.010    2.005   0.83970   0.85297   0.85248   0.84853   0.86592   0.86623   0.86168
   5.000     5.010    5.005   0.87829   0.88019   0.88012   0.87955   0.88207   0.88212   0.88124
  10.000    10.010   10.005   0.88430   0.88422   0.88423   0.88424   0.88410   0.88409   0.88406
```

Table 3. The default printout showing the K functions corresponding to the irradiances of Table 2. The closely spaced pairs of depths (z_{upper}, z_{lower}) used to compute the K functions are now shown explicitly.

7.2 Examining Output with EXCEL

Selected output is optionally written to two Microsoft EXCEL spreadsheets. These files contain roughly the same information as the default printout (and, likewise, can be tailored by advanced users to the individual user's desires).

At this point you are simply using EXCEL without regard to how the workbook was created or to the fact that the data came from HE60. You can, for example, now block out data and use the EXCEL plotting functions to create simple plots of the HE60 output. However, it is not the purpose of this users' guide to teach you EXCEL, so good luck and call the folks at Microsoft if you have questions about EXCEL. Figure 18 shows the first few rows of the first sheet of the workbook created during the Users' Guide Example 3 run.

⊿	A	B	C	D	E	F	G	H
1	HydroLight Run Title: User's Guide Example 3: new Case 1 IOP model (31 AUG 2018 16:37)							
2	abs coef a (1/m)							
3								
4	wavelen	0	2	4	6	8	10	
5	355	6.30E-02	6.80E-02	7.28E-02	8.08E-02	9.16E-02	1.02E-01	1.1!
6	365	5.42E-02	5.86E-02	6.29E-02	7.00E-02	7.96E-02	8.87E-02	1.04
7	375	5.15E-02	5.58E-02	5.99E-02	6.69E-02	7.61E-02	8.49E-02	9.9!
8	385	4.90E-02	5.32E-02	5.73E-02	6.41E-02	7.32E-02	8.17E-02	9.6
9	395	4.66E-02	5.07E-02	5.47E-02	6.12E-02	7.00E-02	7.83E-02	9.2
10	405	4.38E-02	4.79E-02	5.18E-02	5.83E-02	6.70E-02	7.51E-02	8.8
11	415	4.41E-02	4.82E-02	5.22E-02	5.87E-02	6.75E-02	7.57E-02	8.9
12	425	4.47E-02	4.87E-02	5.26E-02	5.90E-02	6.75E-02	7.54E-02	8.8(
13	435	4.57E-02	4.97E-02	5.36E-02	5.99E-02	6.83E-02	7.61E-02	8.9
14	445	4.63E-02	5.00E-02	5.36E-02	5.95E-02	6.72E-02	7.44E-02	8.6;
15	455	4.51E-02	4.85E-02	5.17E-02	5.70E-02	6.40E-02	7.04E-02	8.1(
16	465	4.30E-02	4.61E-02	4.91E-02	5.40E-02	6.04E-02	6.64E-02	7.6;
17	475	4.14E-02	4.43E-02	4.70E-02	5.14E-02	5.73E-02	6.27E-02	7.1(

a / b / bb / bb fraction / Ed_in_air / Lu / Eod / Eou

Fig 18. The first few rows and columns of an EXCEL multi-wavelength format work sheet. There is one variable (here, the total absorption coefficient *a*) displayed as a function of wavelength (rows) and depth (columns). The component absorption coefficients are found in blocks of data below (at larger row numbers) the one shown.

Figure 19 shows the single-wavelength workbook corresponding to the multiwavelength format workbook of Fig. 18.

SUGexample3.xlsx						
	A	B	C	D	E	F	G
1	HydroLight Run Title: User's Guide Example 3: new Case 1 IOP model (31 AUG 2018 16:37)						
2	Wavelength = 355.0 nm						
3	depth	a	b	c	omega0	bb	bb/b
4	(m)	(1/m)	(1/m)	(1/m)		(1/m)	
5	0	0.063	0.2917	0.3547	0.8224	0.00855	0.0293
6	2	0.068	0.3209	0.3889	0.8252	0.00873	0.02719
7	4	0.0728	0.3488	0.4216	0.8274	0.00889	0.02549
8	6	0.0808	0.3952	0.476	0.8302	0.00916	0.02317
9	8	0.0916	0.4569	0.5485	0.833	0.0095	0.02079
10	10	0.1017	0.5147	0.6165	0.835	0.0098	0.01904
11	12	0.1189	0.6114	0.7303	0.8372	0.01029	0.01683
12	14	0.1349	0.7009	0.8358	0.8386	0.01071	0.01529
13	16	0.1375	0.7152	0.8527	0.8387	0.01078	0.01507
14	18	0.127	0.6569	0.7839	0.8379	0.01051	0.016
15	20	0.1161	0.5958	0.7119	0.8369	0.01021	0.01714
16							
17	Wavelength = 365.0 nm						
18	depth	a	b	c	omega0	bb	bb/b
19	(m)	(1/m)	(1/m)	(1/m)		(1/m)	
20	0	0.0542	0.288	0.3421	0.8417	0.00781	0.02713
21	2	0.0586	0.3172	0.3758	0.844	0.00799	0.02519

IOPs / IRRAD / AOPs / K funcs

Fig. 19. The first few rows of a single-wavelength format worksheet. Note that there are several variables (columns) shown as functions of depth (rows), with a separate block of data for each wavelength.

The Fortran routines that write the Mroot.xlsx and Sroot.xlsx files are found on file source_code\common_code\mod_excel.f95. Those routines contain extensive documentation explaining how to modify the routines to obtain more or less output for conversion to EXCEL spreadsheets. If any changes are made to those routines, the code must be recompiled for them to take effect.

7.3 Plotting Output with IDL

Many HE60 users use the IDL software package for plotting output from HE60 runs (IDL is Interactive Data Language, a product of Excelis Visual Information Solutions, Inc.). The HE60\extras\IDL_code directory distributed with the HE60 code contains several of the routines used to plot some of the figures in this User's Guide. If you are familiar with IDL (and of course have the IDL software on your computer), running these routines will be straightforward. If you do not want to use IDL, you do not need the files on the HE60\extras\IDL_code directory. These IDL routines are NOT a part of HE60 per se, but are provided "as is" for the benefit of IDL users.

The IDL routine read_H_Dfile_v6.pro reads the HE60 format Droot.txt files. Likewise, read_H_Lfile_v6.pro reads the Lroot.txt files, and read_E_Dfile_v6.pro reads EcoLight Droot.txt files. The Droot.txt files contain *all* of the output from an HE60 run. The Lroot.txt files contain the full radiance distribution. These files can be very large and are formatted for ease of reading into IDL. All of the information contained in a Droot.txt or Lroot.txt file is made available to the IDL main program via common blocks. A main IDL program can then generate the desired plots using the appropriate HE60 output. For example, to regenerate Fig. 11:

- Start IDL by double clicking on routine HE60\extras\IDL_code\HE60UG_Fig11.pro. Alternatively, start IDL and then and change into the HE60\extras\IDL_code directory by typing:
    ```
    cd, 'c:\HE60\extras\idl_code'
    ```
  at the IDL command prompt.
- Compile the code (this must be done each time you launch IDL) by typing
    ```
    .run HE60UG_Fig11
    ```
- Run the code by typing `plot_Rrs` (the name of the program in file HE60UG_Fig10.pro). The program will prompt you to browse for the Droot.txt file(s) you wish to process. (Other IDL routines may prompt you for additional information, such as the depths or wavelengths to be plotted.)

Note: These commands work for IDL version 6.4 and earlier. IDL version 7.0 had a totally different interface and did things differently; you're on your own figuring out how to use IDL 7.0. IDL 7.0 was apparently not well received, so IDL version 8.0 went back to a more 6.4 way of doing things and the above commands work at least through version 8.3.

Note 1. IDL will want to know the *filename* that contains the code it needs to compile, not the name of the program contained therein. For instance, the IDL routine `plot_Rrs` is contained in the file HE60UG_Fig11.pro, hence you compile file HE60UG_Fig11.pro (not `plot_Rrs`) and the run the main program `plot_Rrs` found therein.

Note 2. There is a point of perpetual confusion when using IDL to plot HE60 output. In HE60, an N-dimensional array $A(i)$ is usually (but not always) indexed from 1 to N, i.e. $A(1)$ to $A(N)$. In IDL, array indices begin with 0, so that the same array is indexed as $A(0)$ to $A(N-1)$. This can be especially confusing when you are trying to extract blocks from multidimensional arrays in order to generate, for example, plots of the radiance distribution as seen in Fig. 14. To make matters worse, some HE60 arrays are also indexed beginning with 0. For example, the arrays that store irradiances use depth index 0 to store the irradiance in the air, just above the surface. In this case, the HE60 and IDL array indices are the same. Most IDL users have learned to live with these sorts of indexing mismatches, but if you have not, be forewarned and do some extra debugging of your IDL routines to make sure you are plotting exactly the HE60 output you want and not something that is off by one element in the array.

8. ADVICE ON RUNNING HE60

This section gives a few words of advice that may help you run HE60 more efficiently.

8.1 Depth Considerations

The relevant measure of depth in radiative transfer theory is the dimensionless *optical depth* ζ, not the geometric depth z. This can lead to confusion in understanding HE60 run times. For example, in homogeneous clear water at blue wavelengths, where the beam attenuation is $c \approx 0.02$ m^{-1}, 50 m is only about $\zeta = cz = (0.02$ m$^{-1})(50$ m$) \approx 1$ optical depth. In highly absorbing or scattering water with $c = 1$ m^{-1}, 50 m corresponds to 50 optical depths. In this case, HE60 will require about 50 times as long to obtain a solution to the same geometric depth as it does in the clear water. This dependence of run time on optical depth causes an unavoidable run-time penalty when running HE60 at red or near-IR wavelengths (especially beyond 750 nm; the absorption coefficient of pure water becomes as large as 45 m^{-1} at 970 nm). Runs to even a few meters of geometric depth require the solution of the RTE to many optical depths at long wavelengths, even in pure water. Thus, much of the total run time can be expended in solving the RTE at the longer wavelengths. Therefore, ***do not run HE60 to longer wavelengths or deeper depths than are really necessary to solve your problem***.

There is a trick that can enormously speed up the HE60 run time in one special situation. *If* (and only if) *you are modeling a homogeneous, infinitely deep water body, and neglecting any fluorescence or internal sources, and the only output you need is the water-leaving radiance, then you can apply the bottom boundary condition at a nominal depth* (say, 0.1 m). (That is, request output only at depths 0.0 and 0.1 m and select the "infinitely deep water" bottom boundary condition.) The water-leaving radiances will be *exactly* the same as if you had solved the RTE to a greater depth, but the run time will be minimal. If you use this trick, you will of course not have any output for the light field below 0.1 m within the water, but that is irrelevant for remote-sensing studies. Note that the water-leaving radiances will not be the same in these "deep" and "shallow" simulations if the water IOPs vary with depth or if the water is actually shallow and the bottom boundary has significant effects on the emerging light field. Also, the inelastic-scatter effects cannot be computed unless you run the simulation to sufficient depth.

HE60 automatically solves the RTE with extremely fine depth resolution in the IOP's. The numerical algorithms can take very small depth steps ($\sim 10^{-6}$ optical depths or less) when solving the Riccati equations (*Light and Water*, Eqns. 8.74-8.85) that lie at the core of the HE60 calculations. These calculations typically require about 90 percent of the HydroLight run time. As already noted, the primary factor influencing the run time is the optical depth to which a calculation is performed. The run time is much less influenced by the depth dependence of the IOPs. Thus, for example, solving the RTE for the binned absorption profile seen in Fig. 1 (the left-hand curve) does not require much more time than solving the RTE for a homogeneous water body with the same average absorption profile. (This statement does have it limits, though, as discussed in Section 1.1.) This near independence of run time on IOP depth structure is one of the most powerful features of HE60, compared to other solution techniques.

HE60 *saves* the computed radiances only at the *user-selected output depths* z_k, $k = 1, 2,$ ..., K, which are specified along with the other input to a standard run. The output depths can be arbitrarily spaced in order to get detailed output in the regions of greatest interest, such as near the sea surface or near strong gradients in the IOP's, and less output in regions where there is little "fine structure." *It is very important to note that the solution of the RTE is independent of where output is to be saved for later analysis.* For example, you might request output at one-meter depth intervals, i.e., $z_1 = 0$, $z_2 = 1.0$ m, $z_3 = 2.0$ m, ..., $z_6 = 5.0$ m, ..., and so on. On the other hand, you might request output at $z_1 = 0$, $z_2 = 5.0$ m, ..., and so on. The output at 5.0 will be exactly the same in both cases; the only difference is that you will have more output between 0 and 5.0 m in the first case. In particular, HE60 does *not* solve the RTE with "one-meter depth resolution" in the first case and with "five-meter resolution" in the second case. The number of depths where output is saved does not significantly affect the run time (the only difference is the small amount of time required to write the output files). The size of the output files is, of course, directly proportional to the number of depths where output is saved.

The HE60 default array dimensioning (set in `HE60\source_code\ common_data_modules\mod_DimensDefaults.f95`) supports output at 100 user-specified depths (strictly speaking, at 100 pairs of closely spaced depths, as described in Section 7.1).

Most oceanographers want output at *geometric* depths z_k, measured in meters, for ease of comparison with observational data. However, in some cases the output depths also can be specified as dimensionless *optical* depths ζ_k. This option is available only if the model is being run at just one wavelength, because the wavelength dependence of the IOP's makes a given optical depth correspond to different geometric depths (different physical locations in

the water column) at different wavelengths. Computations in terms of optical depths are convenient for general monochromatic radiative transfer studies, as opposed to specific oceanographic studies. Note that if the model is being run with optical depths, then the IOP routine must be written to accept optical depth as input. Of the example routines distributed with HE60, only the constant IOP model accepts both optical and geometric depths.

8.2 Wavelength Considerations

The various data sets built in to HE60 give it the ability to run anywhere in the wavelength domain 300-1000 nm, which is of interest in optical oceanography.

There are two basic options for specifying the needed wavelength information. The first is to run HE60 at a single wavelength. HE60 then solves the *monochromatic* RTE with the IOPs, sky radiances, and bottom reflectance being taken equal to their values at the specified wavelength. Some routines, for example the "semi-analytical" RADTRAN sky irradiance model, have built-in data that are accurate to 1 nm resolution. Other routines, for example the absorption and scattering coefficients for pure water, have data built in at 5 nm or 10 nm resolution. Such routines generally use linear (optionally, cubic spline) interpolation to obtain IOP's at the requested wavelength. A run at a single wavelength can include an internal source term at that wavelength. Such a source term can represent a bioluminescing layer, for example. The output depths can be either geometric or optical depths. Monochromatic runs are most useful for general radiative transfer studies.

The second option is to run HE60 over one or more contiguous wavelength bands with bandwidths $\Delta\lambda_j, j = 1, 2, ..., J$. When this option is chosen, the model automatically averages the input sky radiance over each wavelength band. This averaging smooths out the large nanometer-to-nanometer fluctuations in the sky radiance magnitude owing to Fraunhofer lines in the solar spectrum. However, *the absorption and scattering coefficients are taken to be the values at the band centers*. In principle, $a(z,\lambda)$ and $b(z,\lambda)$ also should be averaged over each band. However, this averaging would have to be performed every time the IOP subroutine is called with a new depth during the solution of the RTE; such averaging would be an enormous computational expense. If the band widths are of size $\Delta\lambda \leq 20$ nm, then the replacement of band-averaged IOP values by band-center values will be acceptably accurate for most purposes, because oceanic IOP's (unlike the solar irradiance and atmospheric IOPs) do not fluctuate wildly on a nanometer scale.

Most present-day oceanographic and remote-sensing sensors have bandwidths of 5-20 nm. The bandwidths of an HE60 run can be matched to these sensor bandwidths if desired. There is no requirement that the bandwidths $\Delta\lambda_j$ be equal for different j values (recall Fig. 15). If the user wishes to simulate a wider-bandwidth instrument, then HE60 should be run with a number of smaller bandwidths. The final output for the smaller bandwidths then can be averaged to get band-averaged output for the wide band. This approach properly accounts for the wavelength variation of the IOP's within the large band. Note that it is seldom necessary to make high-wavelength resolution runs. Figure 20 shows R_{rs} for a given set of IOPs and other input, but with output requested at resolutions of 1, 5, 10, 20, and 50 nm. Even with a resolution of 50 nm, the calculated R_{rs} *at the middle of the band* is nearly indistinguishable from the high resolution result. The reason is that HE60 uses the IOP values at the middle of the bandwidth in its calculations.
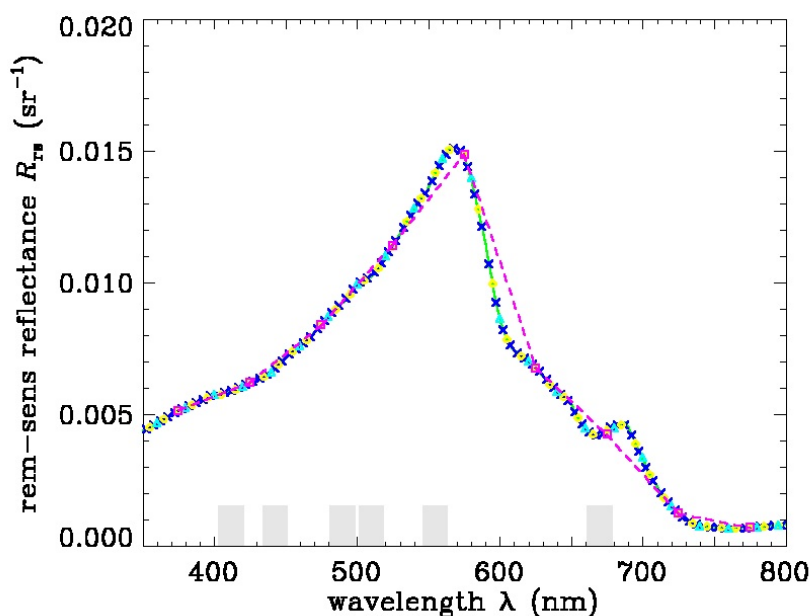
Figure 20. Remote sensing reflectance in a simulated Case 2 water body (5 mg/m^3 *Chl*, moderate CDOM, and 2 g/m^3 mineral) with output resolutions of 1 nm (solid green line), 5 nm (dark blue x), 10 nm (yellow circles), 20 nm (light blue triangles), and 50 nm (magenta squares connected by dashed line). The gray bars show the SeaWiFS bands.

For calculations of PAR and fluorescence, HE60 assumes the values across the bandwidth are constant and equal to the "mid band" value. You will need to select the resolution based

on what you are trying to calculate. For instance, in Fig. 20, 50 nm resolution might be acceptable if all you want is a few specific R_{rs} values, however it is not sufficient to resolve the true shape of the R_{rs} curve as a function of wavelength. In general, most HE60 runs should have bandwidths no larger that 20 nm.

Another consideration in the choice of wavelength bands arises in connection with inelastic scattering effects. Suppose, for example, that you wish to simulate the light field in the 450-500 nm region. If you are uninterested in inelastic-scattering effects from shorter wavelengths, then you could run HE60 with five bands chosen as 450-460 nm, 460-470 nm, ..., 490-500 nm, for example. However, if we wish to include the contributions of fluorescence or Raman scattering to the light field in the 450-500 nm region, then HE60 must be run for all wavelengths less that 450 nm for which there might be an inelastic-scattering contribution to the region of interest. Thus to include Raman scatter, the model should be run starting with a band from 390-400 nm, because wavelengths near 400 nm will Raman scatter into wavelengths near 450 nm. If CDOM fluorescence is to be included, then HE60 should be run starting at 350 nm, because CDOM fluorescence can be excited by ultraviolet wavelengths and because CDOM fluoresces throughout the visible.

8.3 Inelastic Scattering and Bioluminescence

HE60 has the option of running with or without inelastic scattering and internal sources being included in the RTE. The inelastic scattering processes included are chlorophyll fluorescence, CDOM fluorescence, and Raman scattering. The internal source usually is tailored to represent a horizontal layer of bioluminescence. If these effects are all omitted from the run, then HE60 carries out a sequence of independent solutions of the monochromatic, source-free RTE. The solutions for different wavelength bands are then completely independent. However, if one or more of these effects are included, then the appropriate source terms are automatically added to the RTE, as described in *Light and Water*, Sections 5.14-5.16 and 8.7. In the case of inelastic scattering, the solutions in different wavelength bands are coupled by the inelastic scattering from shorter to longer wavelengths. The inelastic-scattering and internal-source computations in some cases call upon user supplied routines.

HE60 models CDOM fluorescence using the spectral fluorescence quantum efficiency function of *Light and Water* Eq. (5.101), as shown in *Light and Water* Fig. 5.11. This particular function is built in to routine `wrfCDOM` on file `HE60\source_code\common_code\wave_redist_func_mod.f95`. The user can replace

this default function with another, if desired.

Because Raman scattering depends only on the water itself, no user-supplied information is required. Various parameter values, such as the Raman cross section and wavelength dependency and chlorophyll fluorescence quantum efficiency, can be set on the RUN PARAMETES form of the GUI. The interpretation of Raman-scattered light can be somewhat tricky; see HydroLight Technical Note 10 for examples.

Some additional computational expense results from the addition of the source terms seen in Eqs. (8.74)-(8.85) of *Light and Water*. However, the main increase in computation time when inelastic scattering is included arises from the need to run the model over wavelengths shorter than the wavelengths of interest, as was illustrated in the previous subsection. In the example discussed there, where the interest was only on 450-500 nm, including CDOM fluorescence effects on the 450-500 nm band requires about three times the computational expense, because the model then must be run from 350-500 nm.

HE60 includes chlorophyll and CDOM fluorescence and bioluminescence as formulated in Sections 5.15 and 5.16 of *Light and Water*. However, Raman scatter is included using an azimuthally averaged effective source term that is equivalent to the formulation seen in Appendix A of Mobley, et al. (1993). This simplification allows the Raman effective source term to be computed from the scalar irradiance (as is the case for fluorescence), rather than from the full radiance distribution. The azimuthally averaged formalism yields the correct Raman contribution to irradiances, which are computed from the azimuthally averaged radiance. However, the Raman contribution to the radiance is correct only as an azimuthally averaged value.

8.4 Setting Defaults

Many of the calculations performed within HE60 assume default values for various parameters in order to minimize the input required from users for each run. These defaults can be simple numbers, such as the chlorophyll-fluorescence quantum efficiency; entire data sets, such as are used by the atmospheric models contained within the sky radiance models; or functions, such as the excitation-emission spectrum for CDOM fluorescence. In most cases, the default values are set to typical or average values for the marine environment; these default values may or may not be adequate for your particular simulation. Defaults are also used to set the amount and type of output obtained from a run.

Various defaults are set in the data modules in the HE60\source_code\common_data_modules directory. Some physical parameters can

112

be changed on the RUN PARAMETERS form within the GUI.

8.5 Making Special Runs

A special HE60 run is required in three circumstances: (1) a new phase function is to be prepared and added to the collection of available phase functions, (2) a new surface wind speed or water index of refraction is needed, or (3) a new quad or band layout is needed. Because of the infrequent need (never, for most users) for making special runs, control of these runs is not incorporated into the GUI. Special runs can be made only by creating the needed input file with a text editor and then submitting the run from a command window. Special runs are described in §9 of the Technical Documentation.

REFERENCES

Acharya, P. K., et al., 1998. MODTRAN User's Manual, Versions 3.7 and 4.0 - Draft, Air Force Research Lab, Hanscom AFB, Ma 01731-3010, 79 pages.

Dongarra, J. J. and E. Grosse, 1987. Distribution of mathematical software via electronic mail, *Commun. ACM*, 30(5), 403-407.

Gregg, W. W. and K. L. Carder, 1990. A simple spectral solar irradiance model for cloudless maritime atmospheres, *Limnol. Oceanogr.*, 35(8), 1657-1675.

Harrison, A. W. and C. A. Coombes, 1988. An opaque cloud cover model of sky short wavelength radiance, *Solar Energy*, 41(4), 387-392.

Mobley, C. D., 1994. *Light and Water: Radiative Transfer in Natural Waters*, Academic Press, San Diego, 592 pp.

Mobley, C. D., B. Gentili, H. R. Gordon, Z. Jin, G. W. Kattawar, A. Morel, P. Reinersman, K. Stamnes, and R. H. Stavn, 1993. Comparison of numerical models for computing underwater light fields, *Appl. Opt.*, 32, 7484-7504.

Tonizzo, A, M. Twardowski, S. McLean, K. Voss, M. Lewis, and C. Trees, 2016. Closure and uncertainty assessment for ocean color reflectance using measured volume scattering functions and reflective tube absorption coefficients with novel correction for scattering *Applied Optics*, 56(1), 130-146.

Tzortziou, M, J. R. Herman, C. L. Gallegos, P. J. Neale, A. Subramaniam, L. W. Harding Jr., and Z. Ahmad, 2006. Bio-optics of the Chesapeake Bay from measurements and radiative transfer closure. *Estuarine, Coastal and Shelf Sci.* 68, 348-362.

APPENDIX A

LICENSE AGREEMENT FOR USE OF HYDROLIGHT-ECOLIGHT 6.0

This license agreement is also contained in the source code and in the GUI.

HydroLight-Ecolight version 6.0 SINGLE-USER LICENSE AGREEMENT

HYDROLIGHT-ECOLIGHT version 6.0 is Copyright © 2019 by John D. Hedley. HYDROLIGHT and ECOLIGHT are owned by John D. Hedley and are protected by the copyright laws of England and Wales and international treaties.

These computer programs, named HYDROLIGHT and ECOLIGHT and consisting of various main programs and subroutines, hereafter referred to collectively as "HYDROLIGHT-ECOLIGHT version 6.0," "HYDROLIGHT," "ECOLIGHT," or "HE60", are being licensed to the User on a non-exclusive, non-transferable license for use in scientific research.

The following requirements, which with the preceding paragraphs constitute an agreement for use of HYDROLIGHT- by the User (hereafter called "the Agreement") are to be upheld:

(1) An initial license purchase of HYDROLIGHT-ECOLIGHT version 6.0 allows installation on a maximum of two computers simultaneously, of the same operating system type (Microsoft Windows, Linux or OS X). Additional HE60 licence purchases for any operating system can be made upon request, each additional licence allows installation on a single additional computer of the operating system that additional licence is for. You may not network HE60 or otherwise use it on more computers or computer terminals than your licence(s) permit at a time.

(2) This entire notice must be retained within each main program of the source code.

(3) The following notice must be legibly displayed on the monitor or other output when HE60 is performed:

> HYDROLIGHT-ECOLIGHT version 6.0 is Copyright (c) 2019 by John D. Hedley
>
> HYDROLIGHT-ECOLIGHT IS EXPERIMENTAL AND IS LICENSED "AS IS" WITHOUT REPRESENTATION OF WARRANTY OF ANY KIND, EITHER EXPRESS OR IMPLIED. THE ENTIRE RISK AS TO THE QUALITY AND PERFORMANCE OF HYDROLIGHT-ECOLIGHT IS WITH THE USER.

(4) Title to HE60 and all portions thereof shall at all times remain with John Hedley. HE60 is licensed, not sold, to the user.

(5) Any alterations, variations, modifications, additions, or improvements to HE60 or merger into other program material to form a derivative work made by the User shall be made or done at the User's own risk and expense. Any modification or combination shall not dilute or limit John Hedley's rights with respect to those portions of any derivative work (in original, modified, or combined form) incorporating any portion of HE60. Any portion of HE60 included in a derivative work shall remain subject to the terms of this Agreement.

(6) The User acknowledges that HE60 is valuable to John Hedley and shall be held in confidence as proprietary to John Hedley, and that HE60 is licensed solely for the User's use subject to the terms of this Agreement. The User agrees not to disclose or provide HE60, in any form, to any person, party, or entity without the prior written consent of John Hedley, except that the User may provide HE60 to his employees, consultants, or students as reasonably necessary to exercise his rights under this Agreement.

(7) The User agrees that HE60 (including any documentation and/or instructions for its use) is made available without warranty of any kind expressed or implied or statutory, including but not limited to the implied warranties of merchantability, fitness for a particular purpose, or conformity with whatever documentation, user manuals or other literature as may be issued by John Hedley or Numerical Optics Ltd. from time to time. The user is warned that HE60 is not fault tolerant, and must not be relied upon in situations where financial loss, disruption of business or research, or other pecuniary loss could occur from an inability to use HE60 or from the incorrectness of its output.

(8) In no event shall John Hedley and/or Numerical Optics Ltd. be liable for costs of procurement of substitute products or consequential damages, however caused and on any theory of liability, arising out of or related to this Agreement, even if John Hedley and/or Numerical Optics Ltd. have been advised of the possibility of such damages.

(9) The User agrees to defend, indemnify and hold John Hedley and Numerical Optics Ltd. harmless from any loss, cost, expense, claim, liability, demand or cause of action arising in any way from the User's use of HE60, or any products based on HE60.

(10) In the event that the User desires to develop a product, system, or service based in whole or in part on HE60 or which incorporates any portion of HE60, the User will not manufacture, sell or otherwise commercially exploit such a resultant product, system, or service before obtaining a written agreement from John Hedley granting such rights, which may be granted by John Hedley at his sole discretion.

(11) This agreement is governed by the laws of England and Wales.

(12) This license will terminate automatically if the User fails to comply with the conditions and limitations described herein. On termination, the User must uninstall HE60 and destroy all copies of the software and documentation.

(13) It is requested, but not required, that the use of HE60 be suitably referenced or acknowledged in publications, papers, reports, presentations, or other communications for which HE60 was used as a part of the study being reported upon. It is requested, but not required, that the user of HE60 provides to John Hedley a copy of all publications, reports, or other documents in which the use of HE60 is acknowledged.

THE USE OF HYDROLIGHT-ECOLIGHT 6.0 IMPLIES THE USER'S ACCEPTANCE OF THE ABOVE AGREEMENT.