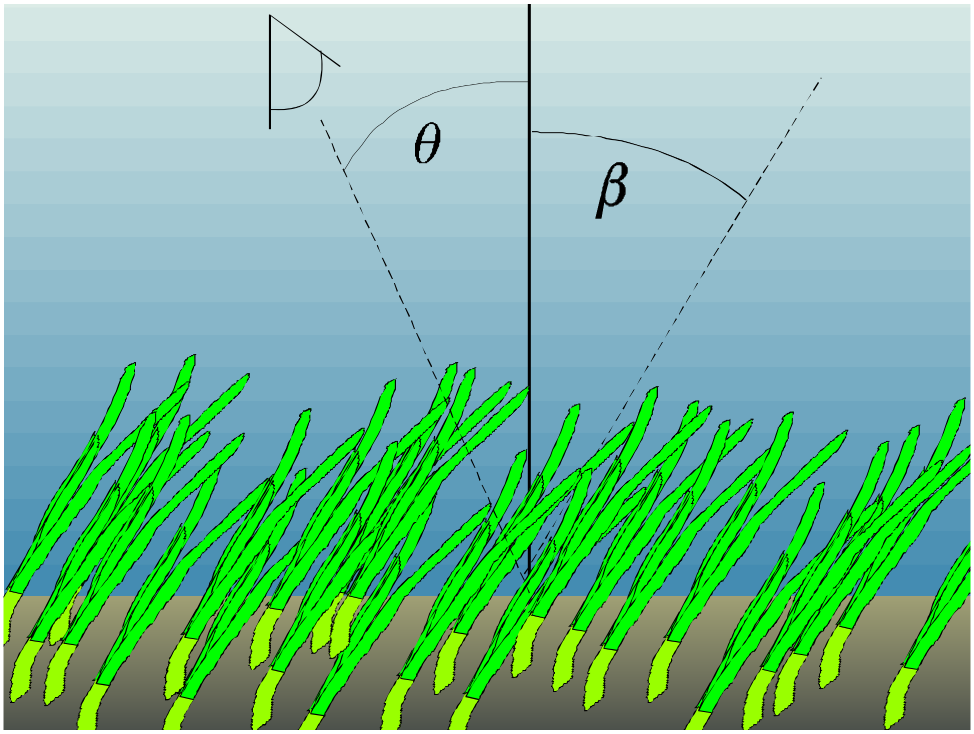
GrassLight 2.14 User's Guide

A Simulation Model of Radiative Transfer and Photosynthesis in Submerged Plant Canopies



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Technical Support

Limited technical support for program execution and operation may be provided by Richard C. Zimmerman (rzimmerm@odu.edu) and Charles L. Gallegos (gallegosc@si.edu), at our discretion. However, the authors reserve the right to refuse to provide technical support, at our discretion, without providing any reason whatsoever for such refusal.

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1. INTRODUCTION

This User's Guide is intended for new users of the *GrassLight* software package. It explains essential computer requirements, how to install the software and perform basic operations through the interactive menu options. The information provided here should be adequate run the software as a " black box" model, and assumes the user is familiar with the basic principles and terminology of radiative transfer theory, optical oceanography and aquatic photosynthesis. More detailed information about the general theory of radiative transfer and the field of aquatic optics can be found in (Mobley 1994) and(Kirk 1994). Those seeking a deeper understanding of photosynthesis in aquatic environments should consult (Falkowski and Raven 2007) . See (Gallegos 1994, 2001) for information about the specific implementations of transfer functions used to derive spectral diffuse attenuation coefficients from water quality parameters. See (Zimmerman 2003, 2006) for more information on the development of the seagrass canopy radiative transfer model.

GrassLight is a coupled model of 2-flow radiative transfer and photosynthesis in submerged plant canopies. The model computes the spectral diffuse attenuation coefficient $K_d(\lambda)$, an apparent optical property (AOP), for an optically homogeneous water column beneath a clear (cloudless) sky from user-provided estimates of sun angle (geographic position and date), phytoplankton abundance (as Chl *a* concentration), total suspended matter (TSM) concentrations, and absorption by colored dissolved organic matter (CDOM). It also computes the depth resolved diffuse attenuation and photosynthetic absorption coefficients [$K_{can}(z)$, $a_{can}(z)$, respectively] through the submerged plant canopy from user-supplied information on vertical canopy architecture and leaf optical properties. The diffuse attenuation coefficients for the optically homogeneous water column and vertically defined plant canopy are then used to solve the time independent, unpolarized 2-flow radiative transfer equations to obtain the vertical distribution of upwelling and downwelling irradiance within a plant canopy submerged in plane parallel body of water, and the photosynthesis resulting from light absorption by the plant canopy. No direct knowledge of water column inherent optical properties (IOPs include absorption, scattering and beam attenuation coefficients, volume scattering functions, etc.) are required, and it is beyond the scope of this model to directly relate IOPs to AOPs for the purpose of computing the irradiance distributions. Users wishing to explore the relationships between

IOPs and AOPs of natural waters, or to perform radiative transfer calculations on a vertically inhomogeneous water column are referred to the commercially available radiative transfer model *HYDROLIGHT* (C. Mobley, Sequoia Scientific Inc.), which uses invariant embedding theory to compute the exact radiance distribution and derived AOPs from user-provided IOPs. It should be noted, however, that *HYDROLIGHT* is not capable of simulating radiative transfer through a discrete plant canopy whose geometry and optical properties are distinct from the optical properties of the bulk water column in which it is embedded.

GrassLight 2.14 is provided as an executable application with associated input files required for its execution. The source code, which is written entirely in FORTRAN (mostly FORTRAN 77 and some FORTRAN 95) is also available for users wishing to compile their own version, or wishing to modify and help improve the model. We have tested the code using the 2012 release of the Intel® FORTRAN 64-bit compiler for Windows 7 and up, as well as the Absoft Pro 8.0 FORTRAN Compiler Interface.

We support the concept of open-source software development, and will consider incorporating user revisions in future releases of *GrassLight* providing no copyright restrictions are placed on our ability to freely distribute the updated version. Please notify us of any publication incorporating *GrassLight,* and include the following statement in the *Acknowledgements* section of any publication:

> *GrassLight* Ver X.XX was provided free of charge by Richard C. Zimmerman and Charles L. Gallegos.

Throughout this document, the symbols for mathematical variables will be written in italics, e.g. $E_d(\lambda,z)$, using both Roman and Greek symbols. The names of executable programs, data files and directories are written in Arial font (e.g. gl210.exe). User input and program display output are shown in `Courier`.

2. INSTALLING *GrassLight* 2.14

2.1 Computer Requirements

Executable versions of *GrassLight* are available for the following operating systems:

- Windows 95 to XP (32-bit systems): gl214_32.exe
- Windows 7 and 8 (64-bit systems): gl214_64.exe
- Apple MacIntosh OS 10 and up: gl214_mac

The FORTRAN source files should enable users of other operating systems (e.g. LINUX, UNIX, etc.) to create an executable version of *GrassLight* using an appropriate FORTRAN compiler. *GrassLight* 2.14 requires at least 15 Mb of disk space (1.6 Mb for the executable file, plus 13 Mb of space for the required data files used for data input and transfer among the subroutines). All files, including the executable, must be installed in a single directory. All output files will be written in that same directory, and additional space will be required for output files generated by each run. *GrassLight* cannot access or create files across different folders.

2.2 Installing *GrassLight*

Installation simply involves copying all files to a single directory of the user's choice. *GrassLight* does not require any modification of system parameters, including PATH designations, in order to operate. No automated installation routines are available or required for Ver. 2.14. Successful installation will result in the following files located in the directory:

Required File	Function
GL214_64.EXE **GL214_32.EXE**	Executable source code for *GrassLight* Ver 2.14, for 64-bit Windows Ver. 7 or later Executable source code for *GrassLight* Ver 2.14, for 32-bit WindowsXP or earlier
DEFAULT.DAT	Provides *GL* with initial conditions for run execution
***.BOT**	Bottom reflectance data defining the optical properties of the sediment layer under the plant canopy. Three files representing different sediment types are provided with *GL* 2.14
***.LOP**	Leaf optical property data for different plant types. Two files, one for *Zostera marina,* one for *Thalassia testudinum* are provided with GL 2.14
EXAMPLE.IRR	File of downwelling spectral irradiance and diffuse attenuation at the top of the seagrass canopy, for the example run detailed in this User's Guide. Users will make new files for specific runs
CANHTZ.TXT	An internal *GL* file used to transfer data among the subroutines. Necessary for proper execution, but direct user modification is not required or recommended.

IOPArrays.txt	Provides spectral values for absorption and scattering of pure water, and the chlorophyll-specific *in vivo* absorption spectrum [$a^*(\lambda)$] for phytoplankton. These parameters are necessary for quantifying $K_d(\lambda)$ from Chl *a* concentration.
IOPcnsts.txt	Provides important constants required to determine $K_d(\lambda)$ from water quality parameters
E0InputArrays.txt	Provides radiant flux at top of atmosphere and absorption spectra of atmospheric components
Atmos.txt	Provides atmospheric constants for determining downwelling plane irradiance at the surface of the earth
SiteData.txt	Provides information on geographic position (latitude, longitude), date, time, water depth, CDOM absorption at 440 nm (m^{-1}), Chl *a* concentration ($\mu g\ m^{-3}$) and turbidity (NTU).

2.3 Uninstalling *GrassLight*

GrassLight can be removed from your computer simply by deleting the folder in which you copied the executable and data files. Before deleting the folder, be sure to transfer any files you want to keep to a safe location.

3. OVERVIEW OF *GrassLight*

This section provides brief descriptions of the ways *GrassLight* can be used to understand the interaction of submerged plant canopies with the submarine light environment.

3.1 Application of GrassLight

To date, *GrassLight* has been used to determine:

- the effect of canopy architecture (shoot density, leaf morphology and leaf orientation) on light absorption and photosynthesis by seagrass canopies
- whole plant carbon balance (daily photosynthesis:respiration, *P*:*R*) for a given light environment (date/time, water transparency, depth).
- the effect of water quality (Chl *a*, TSM, CDOM) on seagrass canopy productivity and light-limited depth distribution of seagrasses across the submarine landscape.
- the fraction of the day that canopy photosynthesis is light-saturated or light-limited, with subsequent effects on stable carbon isotope composition ($\delta^{13}C$)
- the total reflectance of spectral irradiance from the submerged plant canopy as a function of canopy architecture

- the influence of epiphyte load on seagrass canopy productivity and light limited depth distribution across the submarine landscape
- the influence of climate change (temperature and CO_2 availability) on seagrass canopy productivity and light limited depth distribution across the submarine landscape

3.2 The Physical Model

GrassLight simulates the propagation of photons through a vertically defined plant canopy submerged in an optically homogeneous water column using a two flow approach. The water column is divided into a series of discrete layers of finite thickness (Δz) containing separately defined optical properties for the water and the submerged plant canopy. The 1-dimensional nature of the *GrassLight* model assumes a horizontally (but not vertically) homogeneous distribution of leaf and water column optical properties. Exact solutions to the radiance transfer equations have been developed for natural waters in which the optical medium is a continuous material composed of randomly arranged scattering elements separated by large distances relative to the wavelength of light (Mobley 1994). Plant leaves, however, represent a dense packaging of optically active material, which violates the single-scattering assumptions of these exact solutions. Consequently, models of irradiance distribution in plant canopies often rely on more empirical relationships between leaf optical properties and light attenuation by the bulk canopy (Goudriaan 1988; Shultis and Myneni 1988; Ganapol and Myneni 1992). Although less precise mathematically than recently developed global illumination models for aquatic radiative transfer (Hedley and Enríquez 2010), the two-flow simulation of irradiance transfer provides a computationally efficient, quasi-mechanistic framework for understanding the relationship between water column optical properties, submerged plant canopies and irradiance distribution in shallow waters.

3.3 The *GrassLight* Mathematical Model

3.3.1 The Water Column. The light environment above and within the submerged plant canopy is defined by the time-independent, depth dependent (one dimensional) downwelling and upwelling spectral plane irradiances:

$$E_{\mathrm{d}}(\lambda,z)=\int_{2\pi} L(\lambda,z,\theta,\phi)\cos\theta d\omega \tag{1}$$

$$E_{\mathrm{u}}(\lambda,z)=\int_{-2\pi} L(\lambda,z,\theta,\phi)\cos\theta d\omega \tag{2}$$

which represent the upper and lower hemispheric integrals of the spectral radiance [$L(\lambda,z,\theta,\phi)$] passing through a horizontal plane at a specified depth (z). The zenith and azimuthal directions of the solid angle dΩ are defined by θ and ϕ, respectively. Irradiances at depths equivalent to the top of the seagrass canopy, $E_d(\lambda,z_{\mathrm{can}})$ are determined according to the Lambert-Beer law:

$$E_{\mathrm{d}}(\lambda,z_{\mathrm{can}})=E_d(\lambda,0^-)\exp\left[-K_d(\lambda)z_{\mathrm{can}}\right] \tag{3}$$

where $E_{\mathrm{d}}(\lambda,0^-)$ is the spectral irradiance just beneath the water surface (0^-), and z_{can} is the depth of water above the seagrass canopy.

Spectral diffuse attenuation coefficients are calculated from water column IOPs by the equation of Lee et al. (2005), which was developed using extensive simulations with the mechanistic radiative transfer model *Hydrolight* (Mobley 1994):

$$K_{\mathrm{d}}(\lambda)=(1+0.005\theta_0)a_{\mathrm{t}}(\lambda)+4.18\left[1-0.52\exp(-10.8a_{\mathrm{t}})\right]b_{\mathrm{b}}(\lambda) \tag{4}$$

where θ_0 is the above-water solar angle of incidence (degrees). The wavelength-dependent IOPs are $a_{\mathrm{t}}(\lambda)$, the total absorption coefficient and $b_{\mathrm{b}}(\lambda)$, the backscattering coefficient, both of which are dimensionalized as m^{-1}.

GL partitions the absorption coefficient into contributions due to different substances:

$$a_{\mathrm{t\text{-}w}}(\lambda)=a_{\mathrm{g}}(\lambda)+a_{\varphi}(\lambda)+a_{\mathrm{p\text{-}\varphi}}(\lambda) \tag{5}$$

where $a_{\mathrm{t\text{-}w}}$ is the total absorption coefficient for all dissolved and suspended components except for water, and $a_{\mathrm{g}}(\lambda)$, $a_{\phi}(\lambda)$, and $a_{\mathrm{p\text{-}\phi}}(\lambda)$ are the spectral absorption coefficients due to CDOM, phytoplankton, and non-algal particulates (NAP), respectively (Gallegos 2001, Biber et al. 2008).

GL uses the absorption spectrum of pure water from (Pope and Fry 1997). The water column IOPs are calculated from user provided concentrations of water quality constituents using mass-specific absorption and scattering coefficients, with the exception of CDOM, which is calculated directly from absorption coefficients. *GL* represents absorption by CDOM as a negative exponential scaled by the absorption at 440 nm (Bricaud et al. 1981, Roesler et al. 1989):

$$a_{\mathrm{g}}(\lambda) = a_{\mathrm{g}}(440)\exp\left[-s_{\mathrm{g}}(\lambda - 440)\right] \tag{6}$$

where s_g is the spectral slopes for absorption by CDOM. Absorption by NAP is represented as the product of a specific-absorption spectrum, $a^*_{\text{p-}\phi}(\lambda)$, multiplied by a measure of the concentration of NAP, which may be turbidity (NTU), or, for illustration here, total suspended solids, *TSS*:

$$a^*_{\text{p-}\varphi}(\lambda) = c_1 + c_2 \exp\left[-s_{\mathrm{NAP}}(\lambda - 440)\right] \tag{7}$$

$$a_{\text{p-}\varphi}(440) = a^*_{\text{p-}\varphi}(440)\left[TSS\right]^{\nu_{sa}} \tag{8}$$

where c_2 scales the absorption by NAP at 440 nm, c_1 allows for some small amount (typically $\leq$2% of value at 440 nm, Bowers and Binding 2006) of absorption at long wavelengths, s_{NAP} is the spectral slope of absorption by NAP, and ν_{sa} allows for non-linearity in the relationship with *TSS*. The chlorophyll specific-absorption spectrum, $a_\phi^*(\lambda)$, was determined by regression of measured phytoplankton absorption against Chl *a* for various sites around Chesapeake Bay (Gallegos and Neale 2002, Magnusen et al. 2004):

$$a_{\varphi}(\lambda) = a^*_{\varphi}(\lambda)\left[\mathrm{Chl}a\right]^{\upsilon_\varphi} \tag{9}$$

where the exponent, v_ϕ, allows the possibility of a non-linear relationship (Bricaud et al. 1995).

The particulate scattering spectrum, $b_p(\lambda)$, is a power function of wavelength (Snyder et al. 2008)):

$$b_{\mathrm{p}}(\lambda) = b_{\mathrm{p}}(555)\left(\frac{555}{\lambda}\right)^{\eta} \tag{10}$$

where b_p = particulate scattering coefficient, and η is a spectral exponent. As with absorption by NAP, we scale the magnitude of scattering at the reference wavelength by a specific-scattering and TSS:

$$b_p(555) = b_p^*(555)[TSS]^{\nu_{sb}} \tag{11}$$

where $b_p^*(555)$ is the specific-scattering coefficient for TSS (or turbidity) at 555 nm and the exponent, ν_{sb} allows for non-linearity. We calculate backscattering by multiplying the particulate scattering spectrum by a constant backscattering ratio, $b_{bp}:b_p$, with a default value of 0.0159 measured in lower Chesapeake Bay (Zimmerman et al., unpubl). Presently there is no basis for generalizing the spectral shape of the backscattering ratio (Snyder et al. 2008). By scaling the overall magnitude near the center of the visible spectrum (555 nm), errors in calculated $K_d(\lambda)$ due to spectral variability of $b_{bp}:b_p$ are minimized (Snyder et al. 2008).

3.3.2. The Submerged Plant Canopy. The next step in developing a robust theory of seagrass-light interactions requires a mathematical description of the distribution of leaf biomass within the canopy. Most seagrass species bear leaves that emerge more-or-less vertically from the base of a vertical shoot. The basal origin of the leaves allows the vertical distribution of canopy biomass to be represented as a sigmoid function of height above the substrate. The relative amount of biomass [$B(z)$] at any depth (z) depends on four separate parameters: (i) the percentage of biomass at the base of the canopy (ψ), (ii) the height of that point above the seafloor [$h(z)$],(iii) an intermediate point within the canopy (I), and (iv) a shape factor (s):

$$B(z) = \frac{\psi}{1 + \left[\frac{h(z)}{I}\right]^s} \tag{12}$$

Specific values of ψ, I and s can be provided by the user from measurements of leaf length and width data for a given population, or more easily approximated from knowledge of canopy height (h_c). The absolute amount of leaf biomass (or area) in any depth layer (z) is then determined by the product of total leaf area index of the canopy (L) and shoot density:

$$l(z) = L \cdot B(z) \tag{13}$$

In this case, $l(z)$ represents the leaf area index at depth z within the canopy.

After defining the vertical biomass distribution, *GrassLight* next accounts for the geometric orientation of the leaves because the light absorbed by a flat seagrass leaf is strongly dependent on the angular relationship between the leaf and the submarine light field. Consequently, interception of the downwelling irradiance by the canopy depends on the horizontally projected leaf area [$l_p(z)$] , which is a function of the total leaf area in that layer [$l(z)$] and nadir bending angle (β) of the leaf:

$$l_p(z) = l(z)\sin\beta \tag{14}$$

Light absorption or reflection by the horizontally projected leaf area requires further correction for the angular distribution of irradiance incident on the leaf. The Cosine Law defines this correction as $\frac{l_p(z)}{\cos\theta}$, where θ represents the zenith angle of a collimated beam incident on $l_p(z)$. The angular distribution of diffuse downwelling irradiance in natural waters can be very complex, but the *average* distribution is usefully approximated by the average cosine, denoted as $\bar{\mu}$. Thus, the ratio $\frac{l_p(z)}{\bar{\mu}_d}$ approximates the average geometric relationship between seagrass leaves and downwelling plane irradiance. In contrast, phytoplankton respond to the submarine light field as scalar irradiance collectors, as the amount of light absorbed (or shadow cast) by a phytoplankton cell is more-or-less independent of its orientation with respect to the illuminating beam.

The *GrassLight* two-flow approach computes the downwelling plane irradiance emerging from layer (z) within the canopy as:

$$E_d(\lambda,z) = E_d(\lambda,z-1)\cdot\left[1-\rho_d(\lambda,z)\right]\cdot\exp\left[-\left\{a_L(\lambda)\cdot t_L + a_{epi}\right\}\cdot\frac{l_p(z)}{\bar{\mu}_d(z)} - K_d(\lambda,z)\cdot\Delta z\right] \tag{15}$$

where $E_d(\lambda,z\text{-}1)$ represents the spectral downwelling plane irradiance emerging from layer above (z-1). The term [1-$\rho_d(\lambda,z)$] accounts for the loss of downwelling spectral irradiance by upward reflection back into layer (z-1), which depends on the reflectance spectrum of pure leaves [$\rho_L(\lambda)$] normalized to the horizontal silhouette of leaf area and the average cosine for downwelling irradiance:

$$\rho_d(\lambda,z) = \rho_L(\lambda)\frac{l_p(z)}{\bar{\mu}_d(z)} \tag{16}$$

The amount of light transmitted through layer (z) is controlled by the exponential loss term

$$\left[-\left\{a_{\mathrm{L}}(\lambda)\cdot t_{L}+a_{\mathrm{epi}}\right\}\cdot\frac{l_{\mathrm{p}}(z)}{\bar{\mu}_{\mathrm{d}}(z)}-K_{\mathrm{d}}(\lambda,z)\cdot\Delta z\right]$$

that includes (canopy + epiphyte) and water column effects. Light absorption by epiphytes (a_{epi}) is determined by epiphyte mass density (mg DW cm^{-2}) and optical density, which can be specified from the user menu. If there is no leaf biomass in layer (z) [i.e., if $l_{\mathrm{p}}(z) = 0$], $\rho_{\mathrm{d}}(\lambda,z) = 0$ and the exponential attenuation of light is determined by the attenuation coefficient of the water and the thickness of the water column $\left[\text{i.e.,} -K_{\mathrm{d}}(\lambda,z)\cdot\Delta z\right]$. Attenuation of light by the canopy, then, is defined by the product of the leaf absorption coefficient [$a_{\mathrm{L}}(\lambda)$], the thickness of the leaf (t_{L}), and the geometric correction factor defined as $\frac{l_{p}(z)}{\bar{\mu}_{\mathrm{d}}(z)}$. The value of the average cosine $\left[\bar{\mu}_{\mathrm{d}}(z)\right]$ can be approximated assuming that scattering is hemispherically isotropic (bi-lambertian) about the leaf surface (Shultis and Myneni 1988). This means that scattering by the leaf canopy will cause the average cosine for downwelling irradiance to become increasingly isotropic [i.e., $\bar{\mu}_{\mathrm{d}}(z)\rightarrow 0.5$] in proportion to the horizontally projected leaf area in each layer through which the light passes. It also means that the light attenuation coefficient for the water column [$K_{\mathrm{d}}(\lambda,z)$] will increase with depth in proportion to $\bar{\mu}_{\mathrm{d}}$ (Zimmerman 2003). Mathematically, this effect is implemented in *GrassLight* as:

$$\bar{\mu}_{\mathrm{d}}(z)=\bar{\mu}_{\mathrm{d}}(z-1)-\left\{\left[\bar{\mu}_{\mathrm{d}}(z-1)-0.5\right]\cdot l_{\mathrm{p}}(z)\right\} \tag{17}$$

where the notation (z-1) refers to the value of $\bar{\mu}_{\mathrm{d}}$ for light entering layer (z). Upon reaching the sea floor, a portion of the light is reflected back in the upward direction. This reflected light is then attenuated by the plant canopy and water column along its path back to the sea surface in a process symmetrical to that for downwelling irradiance:

$$E_{\mathrm{u}}(\lambda,z)=\left\{\left[E_{\mathrm{d}}(\lambda,z)\cdot\rho_{\mathrm{d}}(\lambda,z+1)\right]+E_{\mathrm{u}}(\lambda,z+1)\right\}\cdot\left[1-\rho_{\mathrm{u}}(\lambda,z)\right]\cdot\exp\left[-a_{\mathrm{L}}(\lambda)\cdot t_{\mathrm{L}}\cdot\frac{l_{\mathrm{p}}(z)}{\bar{\mu}_{\mathrm{u}}}-K_{\mathrm{u}}(\lambda)\cdot\Delta z\right] \tag{18}$$

The total upward irradiance incident on layer z, $\left\{\left[E_{\mathrm{d}}(\lambda,z)\cdot\rho_{\mathrm{d}}(\lambda,z)\right]+E_{\mathrm{u}}(\lambda,z+1)\right\}$, represents the sum of the downward irradiance reflected from, and the upward irradiance propagated through the layer (z +1) below. In reality, the downwelling irradiance incident on layer z also includes some upwelling light reflected downward by upper layers of the canopy. This two-flow approach, however, ignores the secondary reflection, which is so low $\left[E_u(\lambda, z) \cdot \rho_u(\lambda, z-1) < 0.005 \cdot E_d(\lambda, z)\right]$ that its contribution to $E_d(\lambda,z)$ is extremely difficult to measure practically, and its contribution to photosynthesis is insignificant.

The two-flow approach described by Eqs. (11) and (14) provides a mechanistic density-dependence to the determination of in-canopy light fields because it links absorption and reflection to leaf area [l(z)] in each layer, and, therefore, the total leaf area index (L) of the canopy. Self-shading within the canopy, however, is ultimately determined by the projected leaf area [$l_p(z)$], which is a function of leaf orientation as well as shoot density.

3.3.3 Photosynthesis and Carbon balance of the Submerged Plant Canopy. The photosynthetically used radiation [$PUR(z)$] represents the amount of light absorbed by the seagrass canopy for photosynthesis. *PUR* is less than the total irradiance attenuated by the canopy [$E_d(\lambda,z\text{-}1)\text{-}E_d(\lambda,z)$], which includes losses due to reflection and non-specific absorption. The calculation of $PUR(z)$ requires spectral integration of the total plane irradiance normalized by the photosynthetic absorptance [$A_p(\lambda)$] of the leaf and the horizontally projected leaf area [$l_p(z)$]:

$$PUR(z) = \sum_{\lambda} A_p(\lambda) \cdot l_p(z) \cdot \left[\frac{E_d(\lambda, z\text{-}1) \cdot (1-\rho_d)}{\bar{\mu}_d(z-1)} + \frac{E_u(\lambda, z+1) \cdot (1-\rho_u)}{\bar{\mu}_u(z+1)} \right] \qquad (19)$$

Although the two flow equations are equally valid whether irradiance is expressed in terms of energy or quanta, the stoichiometry of photosynthesis requires that we express PUR(z) in quantum units, where:

$$\text{quanta s}^{-1} = \text{Watts} \cdot \lambda \cdot 5.03 \times 10^{15} \qquad (20)$$

Knowledge of $PUR(z)$ allows the instantaneous photosynthetic rate of layer (z) to be calculated using the cumulative one-hit Poisson function, which provides a mechanistic relationship between photosynthetic yield and the amount of light absorbed by the leaf (Falkowski and Raven 2007):

$$P(z) = l(z) \cdot P_{max} \cdot \left\{ 1 - \exp\left[-\frac{\phi_p \cdot PUR(z)}{P_{max}} \right] \right\} \qquad (21)$$

In this relation, P_{max} represents the light-saturated rate of biomass-specific photosynthesis and ϕ_p is the quantum yield of photosynthesis (mol C mol^{-1} *PUR*) which should not be confused with the more commonly reported (and more vaguely defined) α, which represents the slope of photosynthesis vs. *incident*, not absorbed, light.

Determination of the instantaneous photosynthesis rate in layer (z) allows *GrassLight* to calculate whole canopy production (P_c) by summation of $P(z)$ over all layers (z):

$$P_c = \sum_z P(z) \tag{22}$$

Daily production (P_d) of the canopy is approximated by numerical integration of P_c over the photoperiod, using a time step of 10 minutes. This integration makes two important assumptions:

(i) The top-of-canopy irradiance used to initiate the radiative transfer calculations and determine P_c represents local solar noon.

(ii) The daily variation in $[E_d(\lambda,0)]$ is sinusoidal function of photoperiod.

The resulting photosynthesis rates are used to determine whole plant carbon balance by normalizing P_d to the daily respiratory demand:

$$\text{Daily}\, P:R = \frac{P_d}{\left(R_{\text{Leaf}} + R_{\text{Root}} + R_{\text{Rhizome}}\right)} \tag{23}$$

The ratio of Daily P:R provides a convenient index of whole plant or canopy production. Carbon accumulates and growth is possible under light-replete conditions that produce Daily P:$R > 1$. Conversely, the canopy is light limited if the Daily P:$R < 1$. Growth and survival under light limitation require mobilization of stored internal reserves, reducing the total carbon density of individual shoots and the seagrass meadow. If internal reserves are insufficient to provide for growth and survival, shoots will die and the meadow will thin.

The daily respiratory carbon demand, defined by ($R_{\text{Leaf}} + R_{\text{Root}} + R_{\text{Rhizome}}$), accounts for the combined metabolic consumption by above- and below-ground tissues. Leaf respiration is constant day and night and he anaerobic rate of metabolic carbon consumption by roots slows to about 65% of the aerobic rate (Smith et al. 1984, Smith et al. 1988, Smith 1989).

3.4 Input

GL requires numerous parameters to be specified for each run. Some of these specifications (including file names) are provided by direct user inputs via the menu options, others are read from internal data files provided with and/or created by *GL* during the run. The following files are required for the execution of a *GL* run, and should be present in the folder containing the executable file (GL211_64.EXE or GL211_32.EXE)

DEFAULT.DAT contains default settings for all required *GL* inputs, including the names of irradiance (**.IRR**), sediment reflectance (**.BOT**) and leaf optical property (**.LOP**) files. The file can be modified using a simple text editor (do NOT use a word processor), but care must be made to retain the original formatting of each input and save the file as a simple ASCII text file, without any formatting characters. File names specified by **DEFALT.DAT** are limited to 16 alphanumeric characters, including the file type separator ("."). *GL* provides a run-time option to overwrite the contents of **DEFALT.DAT** with new settings created by the user. You can save multiple settings simply by copying **DEFALT.DAT** to a new file with a different name (e.g., **DEFAULT.OLD**), but *GL* will only read **DEFALT.DAT** **.**

***.BOT** files provide bottom reflectance spectra used as a lower optical boundary for the model. Three text files are provided in the distribution folder, and contain spectral reflectances of bright coral sand (**CARBONAT.BOT**), medium brown siliciclastic sand (**SILICA.BOT**), and dark estuarine mud (**MUD.BOT**). Users can create new "**.BOT**" files by replicating the format of the existing files or modify the existing ones using a simple text editor (do NOT use a word processor), but care must be made to retain the original formatting of each input and save the file as a simple ASCII text file, without any formatting characters. The first 10 lines of each file are reserved for header information to describe the content of the files. Numerical data, consisting of 2 columns (wavelength and reflectance) start on line 11. Wavelength is denominated in nanometers (nm) and reflectance in relative units such that a value of 1 is equivalent to 100% reflectance. The file can contain up to 100 spectral values, but spectral resolution and wavelength registration must match those of the "**.LOP**" and "**.IRR**" files used in a particular run. The last line of the file must contain two "-1.0" values separated by at least 1 space, indicating the end of the file. The "**.BOT**" file type designator is optional; file names can be any alphanumeric string consisting of 16 or fewer characters, including the file type separator (".").

***.LOP** files contain leaf optical properties of absorption and reflectance spectra for a seagrass leaf oriented normal to an incident beam, as measured in a spectrophotometer using an integrating sphere. Absorption coefficients are provided as *natural log* values (=2.303*spectrophotometric absorbance) per unit leaf thickness. Reflectance values represent the fraction of the incident irradiance backscattered from the leaf. Two files are provided in the distribution folder. **ZOSTERA.LOP** contains average spectral values for leaf absorption and reflectance for clean eelgrass (*Zostera marina*) leaves collected from Monterey Bay, California. **THALASS.LOP** contains optical properties for turtlegrass leaves collected on the Great Bahama Bank. Users can create new leaf **LOP** files by replicating the format provided in the distribution files or modify the existing ones using a simple text editor (do NOT use a word processor), but care must be made to retain the original formatting of each input and save the file as a simple ASCII text file, without any formatting characters. The file can contain up to 100 spectral values and needs to terminate with the last line of data, but spectral resolution and wavelength registration must match that of the "**.BOT**" and "**.IRR**" files used in a particular run. The "**.LOP**" file type designator is optional; file names can be any alphanumeric string consisting of 16 or fewer characters, including the file type separator (".").

***.IRR** files provide spectral irradiance [$E_d(\lambda,0)$, W m^{-2} nm^{-1}] and the diffuse attenuation coefficient for downwelling plane irradiance [($K_d(\lambda,0)$, m^{-1}] of the water column at the top of the seagrass canopy. These files can be created by *GL* from user provided inputs of date, time, latitude, and optically active water column constituents (CDOM absorption, Chl *a* concentration and turbidity) using the relationships developed by (Gallegos 1994, 2001) by selecting menu option

```
13) Irradiance and Kd from FILE:
```

and following the instructions for creating a new "**.IRR**" file. Radiant energy fluxes absorbed by the plant canopy are converted by *GL* to quantum units for calculation of photosynthetic rates, and integrated over the wavelength increments (10 nm in the example file. Files can also be created from other sources using a text editor, and irradiance values *must be in units of radiant energy* (W m^{-2} nm^{-1}), not quantum flux

(μmol quanta m^{-2} s^{-1} nm^{-1}). The file can contain up to 100 spectral values and needs to terminate with the last line of data, but spectral resolution and wavelength registration must match that of the "**.BOT**" and "**.LOP**" files used in a particular run. The "**.IRR**" file type designator is optional; file names can be any alphanumeric string consisting of 16 or fewer characters, including the file type separator (".").

CANHTZ.TXT is a *GL* internal file used to transfer user-defined values of canopy height, water depth and photoperiod among subroutines. It will be generated each time *GL* is run, initially using the default values provided in **DEFAULT.DAT**. The user is cautioned against directly modifying this text file.

IOPArrays.txt provides spectral values for absorption and scattering of pure water, and the chlorophyll-specific *in vivo* absorption spectrum [$a^*(\lambda)$] for phytoplankton. These parameters are necessary for quantifying $K_d(\lambda)$ from Chl *a* concentration. Optical properties of pure water are based on (Pope and Fry 1997). Users wishing to employ different $a^*(\lambda)$ spectra than the one provided with *GL* can edit this file with any text editor (do NOT use a word processor), providing its name is unchanged and it is saved as a simple ASCII text file (no embedded formatting characters).

IOPcnsts.txt provides important constants required to determine $K_d(\lambda)$ from water quality parameters:

(i) Spectral slope of CDOM absorption
(ii) Absorption cross section for non-algal particles (NAP) at 440 nm
(iii) Spectral slope of NAP absorption
(iv) Baseline NAP absorption
(v) Scattering cross section of turbidity
(vi) Scattering spectral exponent
(vii) Particulate backscattering ratio (b_{bp}/b)
(viii) Chl-specific absorption at 675 nm

These values can be changed within *GL* by selecting menu option

`13) Irradiance and Kd from FILE:`

and following the instructions for creating a new "**.IRR**" file. Files for specific runs can also be created by editing **IOPcnsts.txt** with any text editor. Avoid editing the file with word processors that embed formatting, font and other character information in the file. The file must be saved as a simple ASCII text file (no embedded formatting characters).

Atmos.txt provides atmospheric constants for determining downwelling plane irradiance at the surface of the earth:

(i) Air mass type, 1-10 as defined by (Gregg and Carder 1990). The air mass type is one of three parameters used to estimate the aerosol particle size distribution. A value of 1 represents marine aerosols far from land, and 10 is for continental air masses. Marine aerosols have larger particles that attenuate light less efficiently than continental aerosols. The determination of air-mass type is not always straightforward. In the open ocean a value of 1 is reliable, but in coastal areas the value depends on the origin of the prevailing air mass which can be defined by the wind direction. Use a value of 1 if the prevailing wind originates from the ocean and 10 if from land. Use intermediate values if mixtures of continental and marine air sources can be determined.

(ii) Windspeed averaged over prev 24 h, 1-10 m/s

(iii) Instantaneous windspeed, 1-20 m/s

(iv) Relative humidity

(v) Atmospheric pressure, mb

(vi) Precipitable water vapor, cm

(vii) Aerosol scale height

(viii) Visibility, km, 5-25

These values are not accessible within *GrassLight,* but values stored in **Atmos.txt** can be changed with any text editor. **This should only be attempted by a user who is familiar with the reasonable ranges and effects of these parameters on the resulting surface irradiance.** Avoid editing the file with word processors that embed formatting, font and other character information in the file. The file must be saved as a simple ASCII text file (no embedded formatting characters).

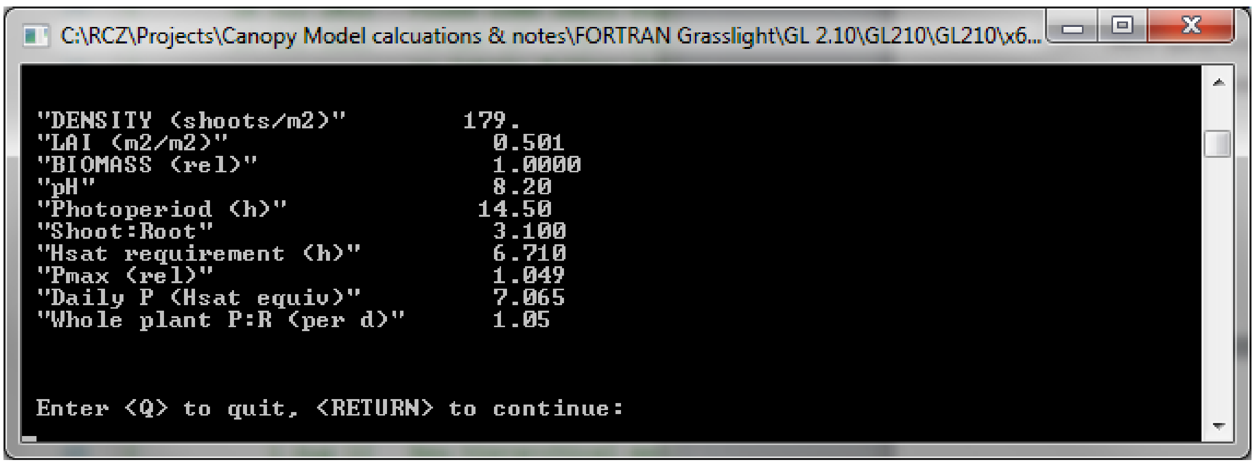
SiteData.txt provides information on geographic position (latitude, longitude), date, time, water depth, CDOM absorption at 440 nm (m^{-1}), Chl *a* concentration ($\mu g\ m^{-3}$) and turbidity (NTU). Values can be changed within *GL* by selecting menu option

`13) Irradiance and Kd from FILE:`

and following the instructions for creating a new "**.IRR**" file. Files for specific runs can be created under a different name by editing **SiteData.txt** with any text editor (do NOT use a word processor), providing it is saved as a simple ASCII text file (no embedded formatting characters).

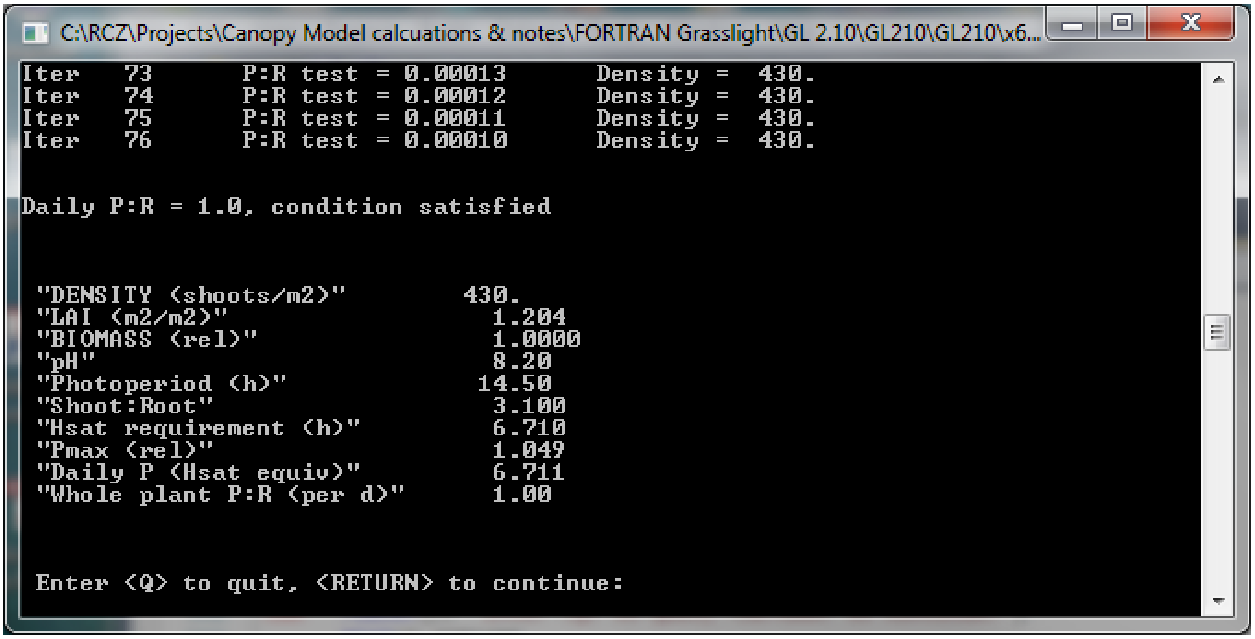
3.5 Output

GrassLight provides three forms of output. For the `Single Run` option (see Menu Item 17), the successful run displays a list of non-optical results, emphasizing metabolic carbon balance for a particular run:



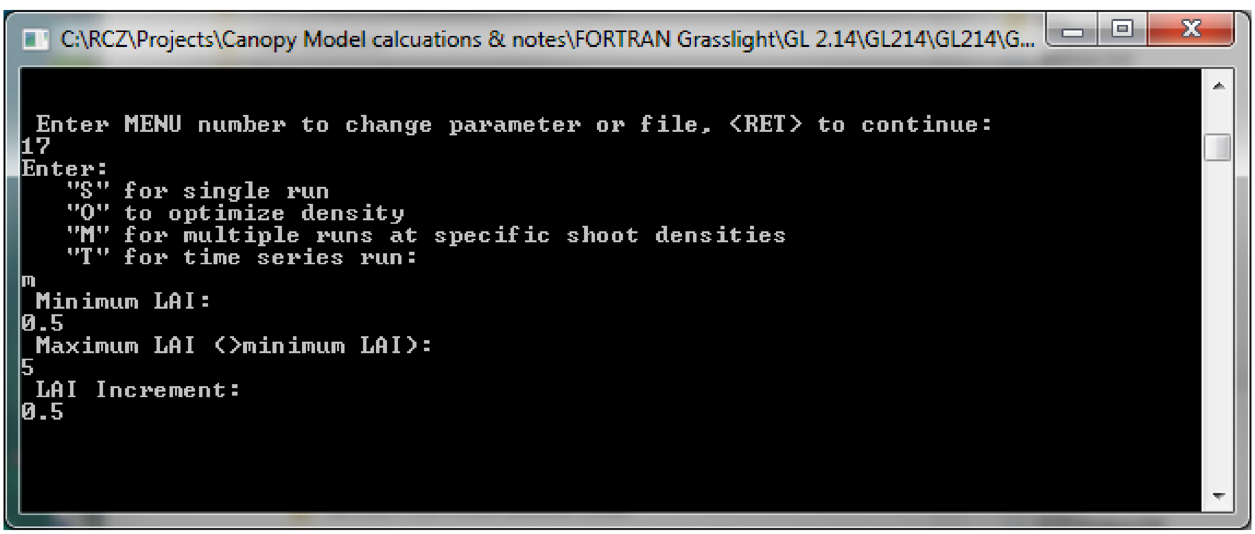
```
C:\RCZ\Projects\Canopy Model calcuations & notes\FORTRAN Grasslight\GL 2.10\GL210\GL210\x6...

"DENSITY (shoots/m2)"          179.
"LAI (m2/m2)"                    0.501
"BIOMASS (rel)"                  1.0000
"pH"                             8.20
"Photoperiod (h)"               14.50
"Shoot:Root"                     3.100
"Hsat requirement (h)"           6.710
"Pmax (rel)"                     1.049
"Daily P (Hsat equiv)"           7.065
"Whole plant P:R (per d)"        1.05


Enter <Q> to quit, <RETURN> to continue:
```

These results are also written to a text file each time a run is executed. The default name for this file, which can be changed using the main menu (Option 18), is **GLRESULT.DAT.** If the `O` or `optimize density` option is chosen, *GL* performs all computations in a loop in which the shoot density is changed for each iteration until the daily P:R =1 condition is satisfied:

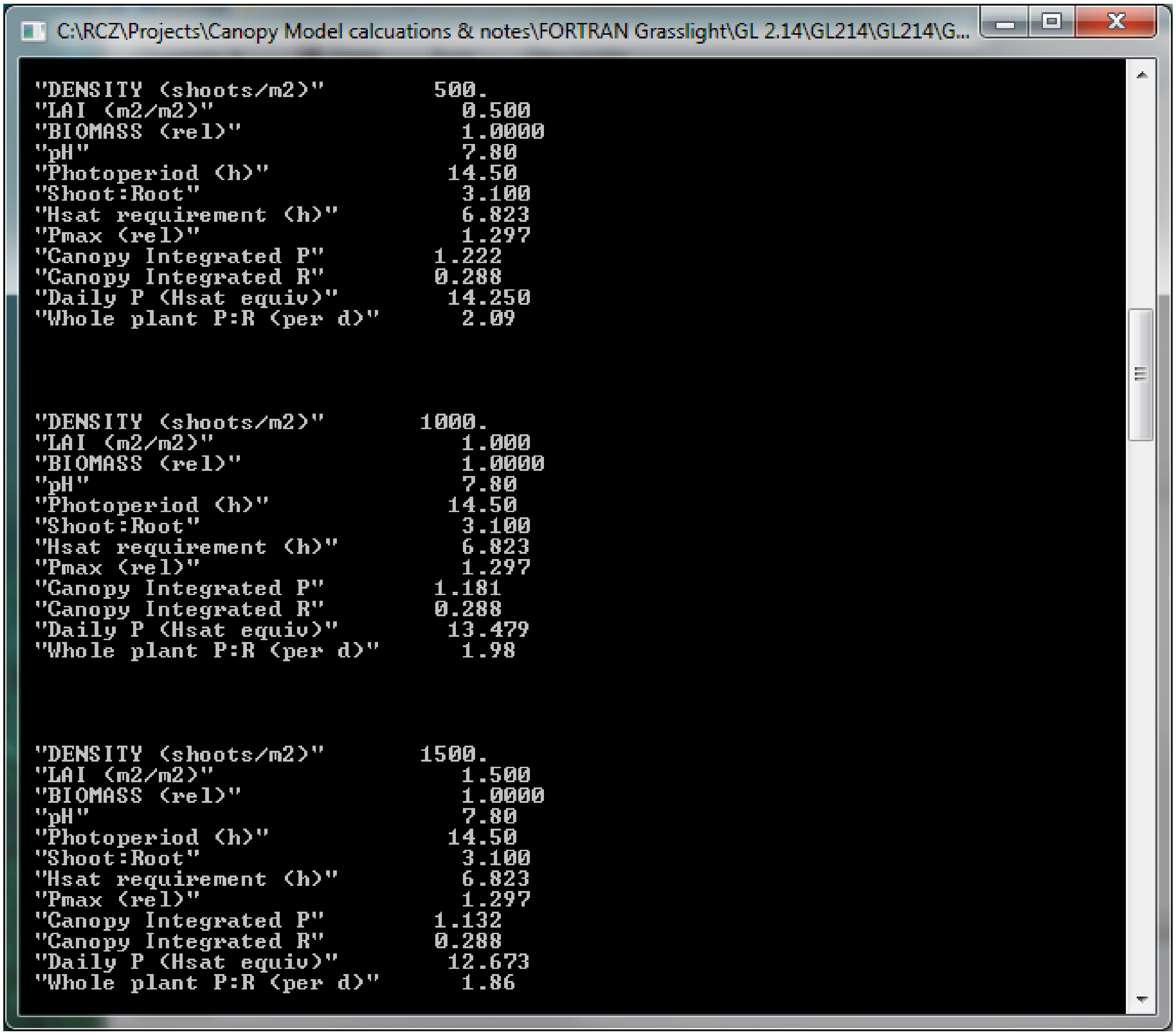


As with the single run, complete results for the *final iteration* are written to the output file **GLRESULT.DAT**.

The `M` or `multiple runs` option will run *GrassLight* at a range of LAIs. The user must provide the minimum LAI, maximum LAI and the LAI increment over which the runs will be performed. All other input values will be identical for each run.



Grasslight will then perform a single calculation for each LAI. The display screen woll present summary results from each run as:



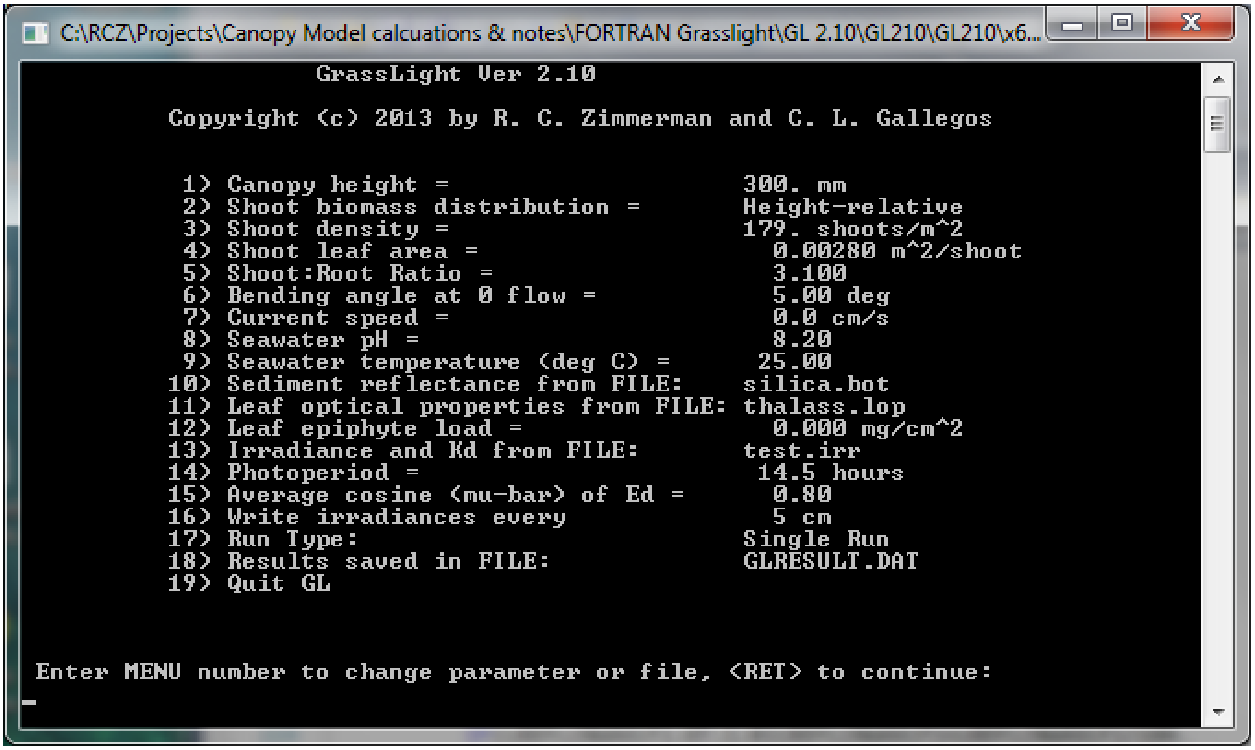
All data from each run will be written to the output file (**GLRESULT.DAT** or whatever you have named it), including the summary results, upwelling and downwelling irradiances and vertical distributions of canopy photosynthesis.

If the irradiance file used to drive the model was created within *GrassLight* (Main Menu Option 13), a file (**SFCIRR.TXT**) containing the latitude, longitude, in-water downwelling spectral plane irradiance [$E_d(\lambda)$, W m^{-2} nm^{-1}] at the sea surface and diffuse attenuation coefficient [$K_d(\lambda)$] (both at5 nm resolution) is created that may be useful for interpreting sensitivity analyses, post-processing and plotting of your results. You must re-name the file if you want to save the surface irradiance results of a particular run, as **SFCIRR.TXT** will be over-written the next time *GL* creates a new **.IRR** file.

4. THE MENU INTERFACE

4.1 The Main Menu

GrassLight provides a menu interface for the user to specify all conditions necessary to execute a model run:



The model is initialized at startup using the information in DEFAULT.DAT, a simple text file containing the required input parameters and data file names in a single column, followed by a short text description of each value or file name. This file can be modified to create new default settings with the text editor, or through the menu options provided in *GrassLight.* To change a particular run setting, the type the MENU number after the prompt:

To run *GL* with all parameters at their default settings, press the Return key (<RET>) until execution commences.

4.2 Seagrass Biomass Properties

`1) Canopy height`

allows you to change the maximum height of the seagrass canopy. At the prompt, type "1", followed by the "Enter" key:

```
Enter MENU number to change parameter or file, <RET> to continue:
1
New canopy height (mm):
```

You then enter the new value for canopy height, in mm, and *GL* re-displays the main menu with the updated canopy height. Canopy heights are limited to 1,000 mm (1 m) or less in *GL* 2.14

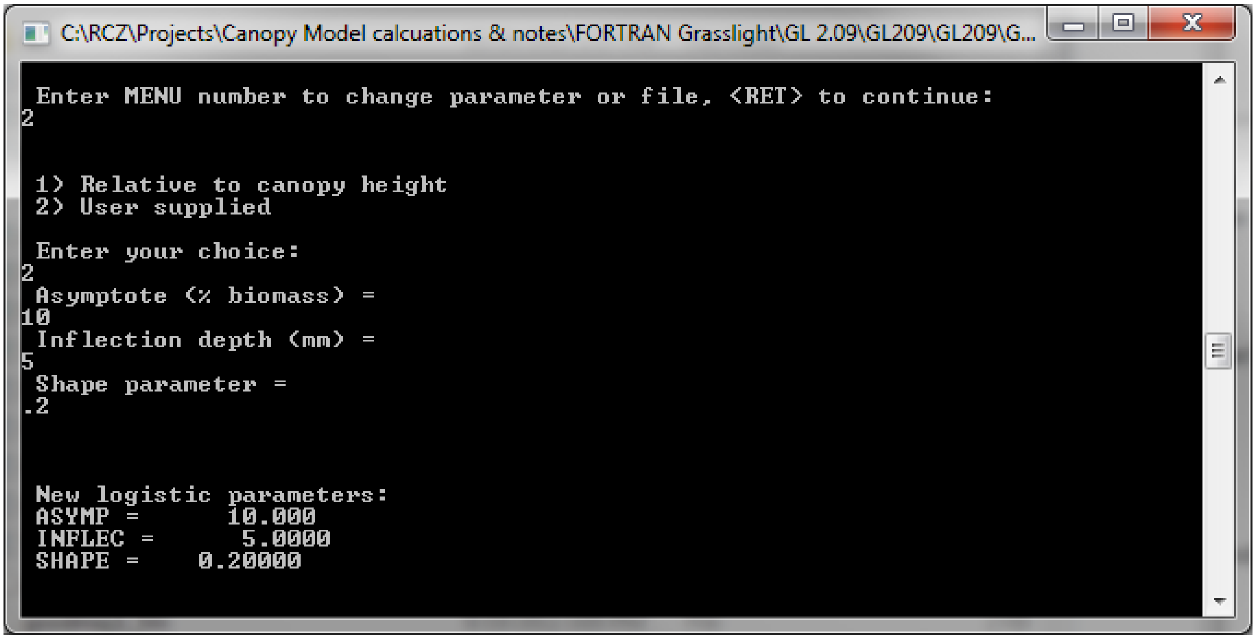
`2) Shoot Biomass Distribution`

allows you to change the biomass distribution parameters, which requires you to make two additional choices:

```
Enter MENU number to change parameter or file, <RET> to continue:
2


1) Relative to canopy height
2) User supplied

Enter your choice:
```

Submenu Option `1) Relative to canopy height` uses the value for canopy height (menu option 1) to determine values for ψ, *I* and *s,* based on the relationships presented in Fig. 2 of (Zimmerman 2003).

Submenu Option `2) User supplied` allows you to enter specific values for the asymptote (ψ), inflection depth (*I*) and shape parameter (*s*), respectively. This can be very useful if you have specific information on leaf size frequency distribution for a given population, and Submenu Option 1) does not provide the biomass distribution you want. Examples of specific parameter values for a variety of eelgrass and turtlegrass populations can be found in Table 2 of (Zimmerman 2003):



USER BEWARE - The newly entered values are listed for you to see, but they are not checked for mathematical consistency. Incorrect values will force the model to generate unpredictable errors. Entering a non-numeric value will cause the program to terminate, and you may lose all the settings you changed. Once the selection is complete, the main menu is updated to indicate that the biomass distribution parameters are now user-supplied.

`3) Shoot Density:` allows you to change the shoot density for the run:

GL will accept any value ≥ 0. If you enter negative values, *GL* will prompt you to re-enter a value. Entering a non-numeric value will cause the program to terminate, and you may lose all the settings you changed.

`4) Shoot leaf area:` represents the *mean* one-sided leaf area (m^2 leaf $shoot^{-1}$) of the shoots in the population. *GL* will prompt you to re-enter a value if you type a value ≤ 0. Entering a non-numeric value will cause the program to terminate, and you may lose all the settings you changed.

`5) Shoot:Root Ratio:` allows the user to select the relative distribution of photosynthetic (shoot) and non-photosynthetic (roots & rhizomes) biomass, which can affect total plant respiration and daily carbon balance.

`6) Bending angle at 0 flow:` Values are represented as degrees (not radians) from the vertical (= 0°) in still water. *GL* 2.14 limits the bending angle to a minimum value of 5° to prevent $l_p(z)$ from going to 0 at very small bending angles (β). Prior versions of *GL* (2.09 and earlier) did not put a limit on this value, allowing the canopy to "disappear" at 0°.

4.3 Water Column Properties

`7) Current speed:` causes the leaf canopy to bend, or become increasingly horizontal as a function of flow. This increases the horizontally projected leaf area and total light absorption by the canopy, but photosynthesis may actually decrease due to self-shading. This implementation of current speed does not affect boundary layer processes, which are assumed not to be limiting to metabolic activity in *GL* 2.14.

`8) Seawater pH:` This feature allows light-saturated photosynthesis to increase exponentially as pH (a proxy for CO_2) declines, according to (Invers et al. 2001).

`9) Seawater temperature:` affects leaf *P* and *R* of all tissues using Q10 relationships as well as the interaction between pH and leaf photosynthesis (Zimmerman et al. 1989), Zimmerman, et al., in review (Estuaries & Coasts).

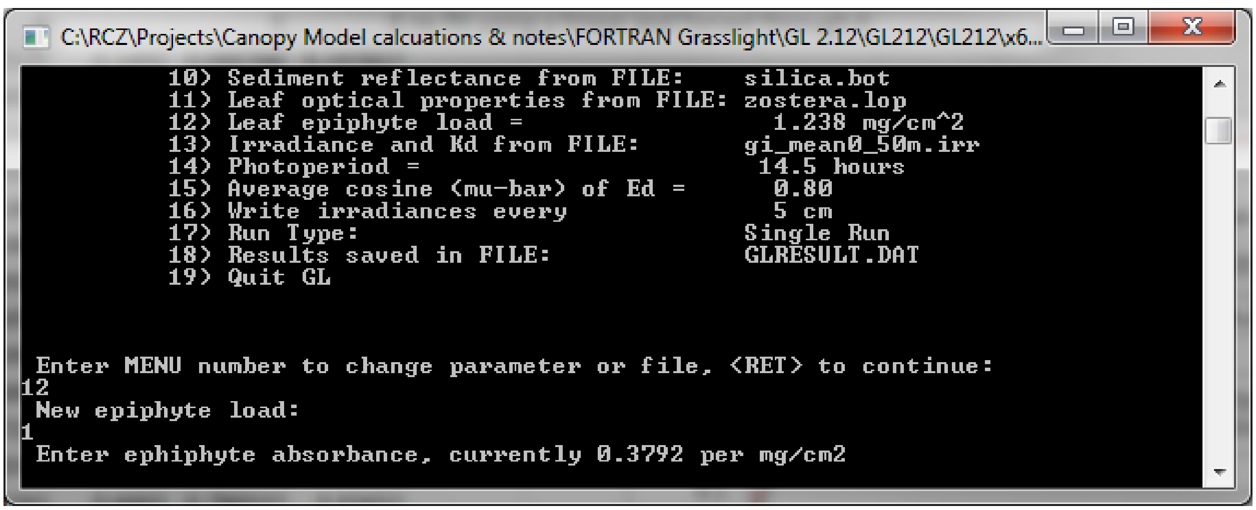
`10) Sediment reflectance from FILE:` provides the reflectance spectrum for the substrate at the base of the plant canopy. Three "**.BOT**" files, representing different sediment types are provided with *GL* 2.14. Users can create additional files by following the format of the "**.BOT**" files, which are described in Sec. 3.4

4.4 Sediment and Leaf Optical Properties

`11) Leaf optical properties from FILE:` provides average absorption and reflectance spectra for plant leaves, which are assumed constant throughout the vertical distribution of leaf biomass. Two "**.LOP**" files, representing the average optical properties of

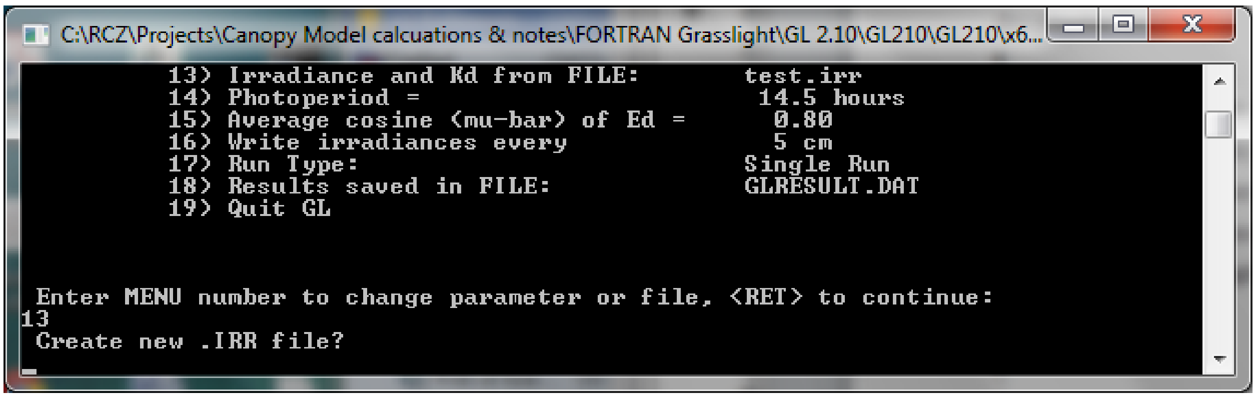
Zostera marina (eelgrass) and *Thalassia testudinum* (turtlegrass) leaves are provided with *GL* 2.14. Users can create additional files by following the format of the "**.LOP**" files, which are described in Sec. 3.4.

`12) Leaf epiphyte load:` will attenuate light reaching the seagrass leaves according to a linear function of density (mg dry wt cm^{-2}) on the leaf surface. In *GL* 2.14, epiphytes are simulated as neutral density attenuators, based on the data in Figure 4 of (Bulthuis and Woelkerling 1983), but the regression is forced through the origin (0 epiphyte absorbance at 0 density). For clean leaves, enter an epiphyte load of 0 mg cm^{-2}. The slope of optical density vs. epiphyte load can also be changed using this menu option (default value = 0.3792 Absorbance Units cm^2 mg^{-1}).



4.5 Creating Irradiance Files

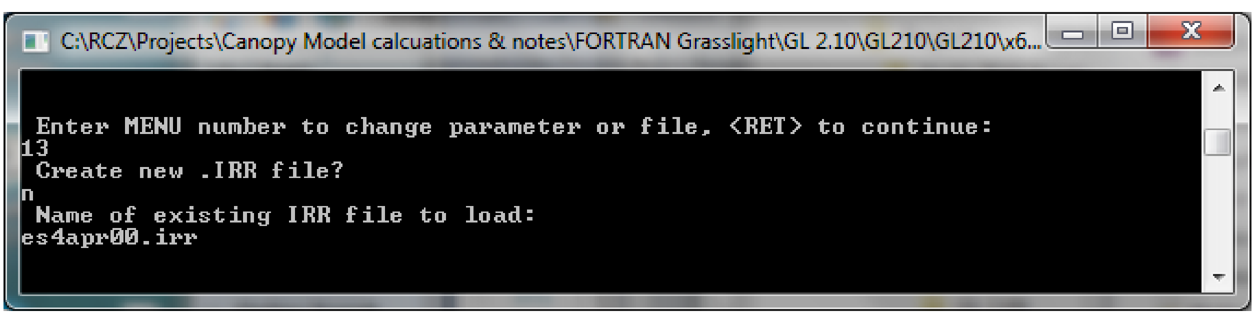
`13) Irradiance and Kd from FILE:` provides spectral downwelling irradiance [$E_d(\lambda)$, W m^{-2} nm^{-1}) and the coefficient of diffuse attenuation [$K_d(\lambda)$, m^{-1}] for the water column without the plant canopy. GL 2.14 provides one file (**EXAMPLE.IRR**) as an example, and to permit the user to test program operation. Users can create additional files by following the format of the "**.IRR**" files, which are described in Sec. 3.4, or by following the submenu features provided under Menu Option 13).



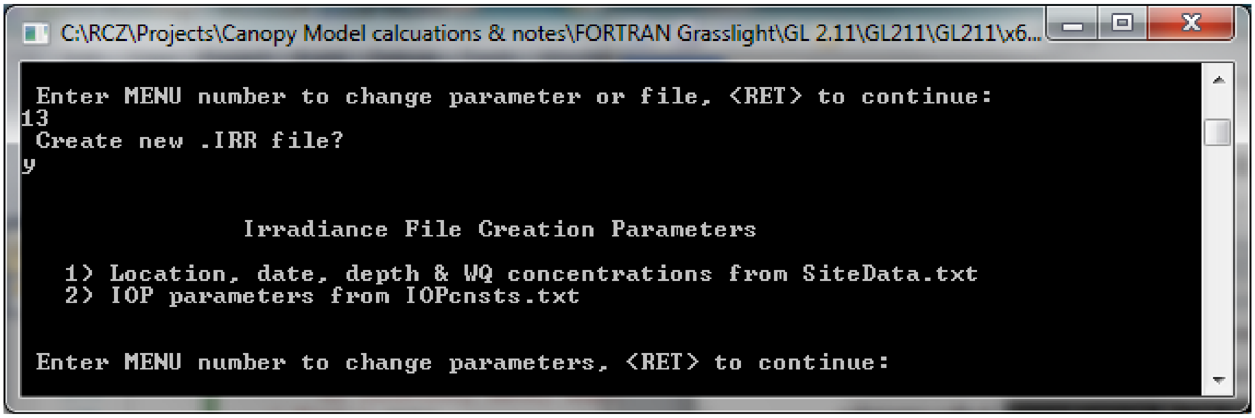
The initial angular distribution of downwelling plane irradiance at the top of the plant canopy can be adjusted by selecting Menu Option

`8) Average cosine (mu-bar) of Ed.`

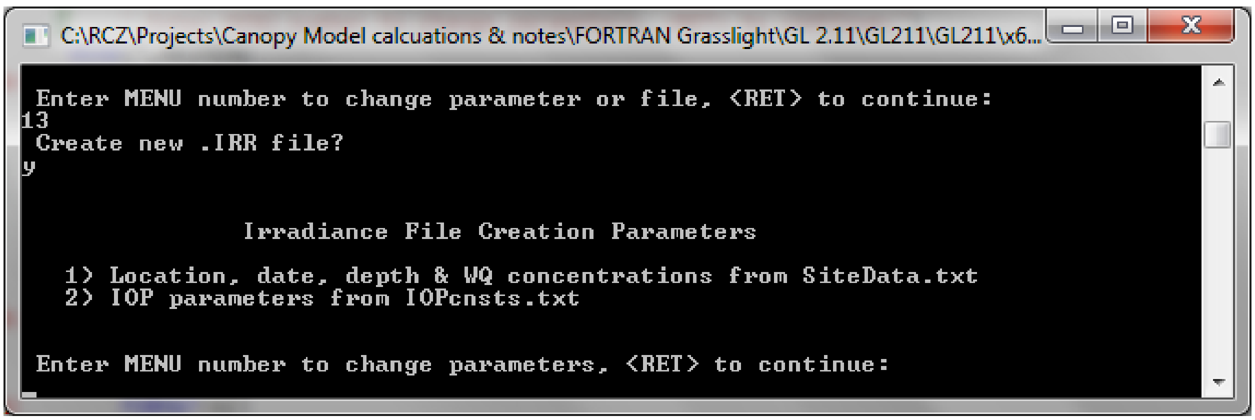
You can direct *GL* to use a different, but existing, file by responding with "N" or "n" for NO, to the request to create a new .IRR file. You will then be prompted for the name of the file, and returned to the main menu:



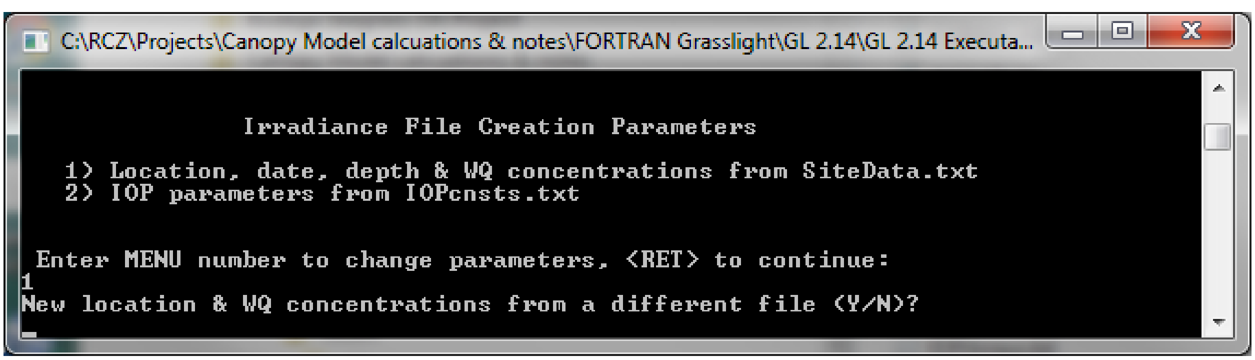
In the case illustrated, *GL* will load the file "**es4apr00.irr**" and return to the main menu. *GL* can also create new ".IRR" file from astronomical and water quality data provided by the user. To `Create new .IRR file`, `respond` with a "`Y`" or "`y`" for YES, which brings up a submenu called "`Irradiance File Creation Parameters`":



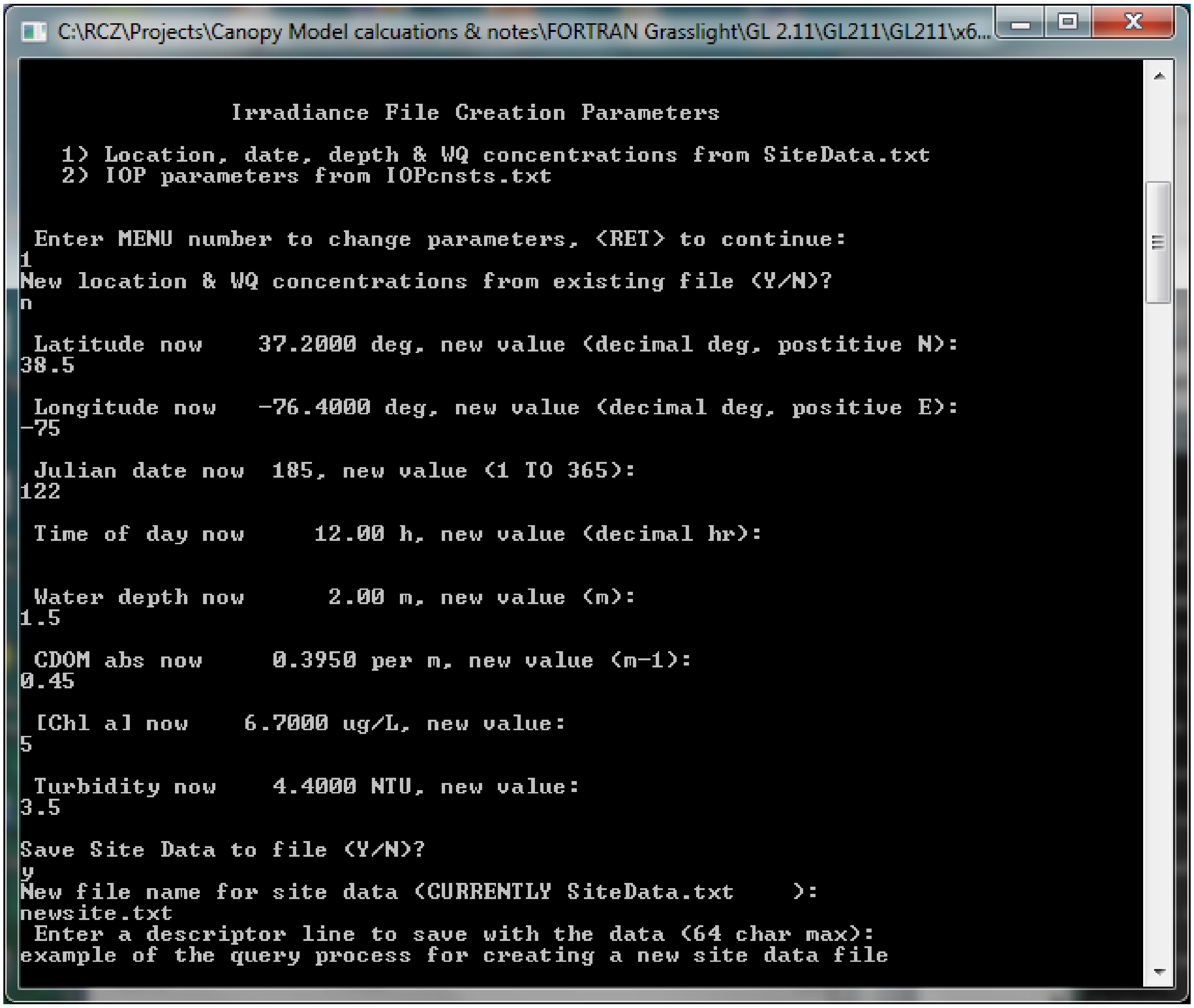
To change location, date, depth or water quality (WQ) concentrations from the current values provided in **SiteData.txt**, enter MENU number 1:



You can then load new location and WQ information from a different, but existing file, by answering "Y" or "y", and then enter the new file name at the prompt:



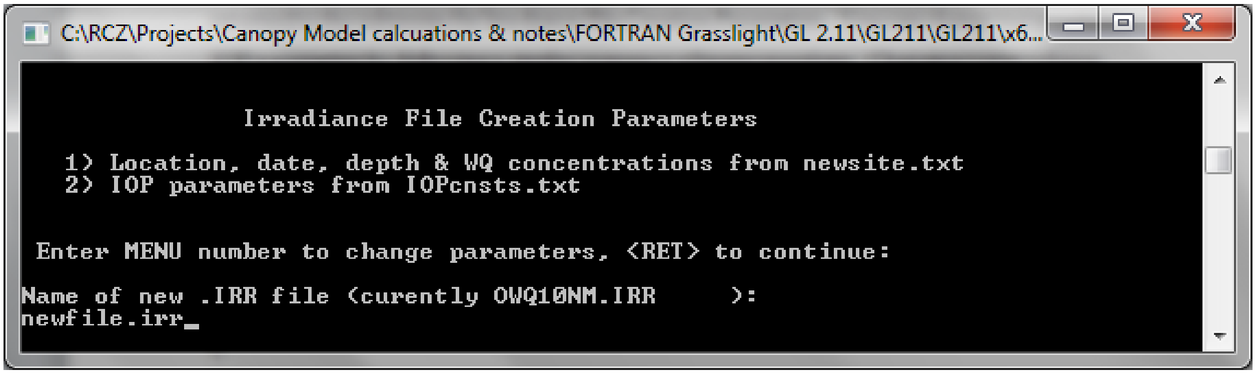
You can create a new location file by responding “N” or “n” to the query, and entering the new data in response to the prompts:



If you do not wish to change a particular value, simply hit “Enter” at the prompt and *GL* will retain the old value. At the end of the sequence, you will be asked to enter a new file name and allowed to enter a 64 character descriptor line to be saved with the new file. You will then be returned to the submenu for Irradiance File Creation Parameters. You can change water column IOP parameters by following a similar sequence of menu questions. Changing water column IOP parameters requires a relatively sophisticated understanding of the way $K_d(\lambda)$ is ultimately calculated from these parameters, and should not be done lightly. The parameters provided with

GL should work for most moderately energetic, polyhaline coastal environments. Additional guidance is provided in Appendix 1.

Once all Irradiance File Creation Parameters have been selected, simply hit "Enter" and you will be prompted for the name of the new file to be created:



In this case, test2.irr will be created for use by *GrassLight* in the next run, and the main Menu will be refreshed, with the new file now listed under Option 13) in the main menu. If the **.IRR** file is created by *GrassLight*, the photoperiod (Main Menu Option 14) will be updated to reflect the date and position (Latitude, Longitude) provided as part of the Irradiance File Creation Parameters. Users may change the value of menu option `14) Photoperiod` manually, but should do so only if the "**.IRR**" file was NOT created by *GrassLight.*

`15) Average cosine (mu-bar) of Ed` is a scalar value that controls the average cosine for downwelling irradiance (E_d). It is independent of wavelength. A value of 1 creates a collimated beam of downwelling irradiance (E_d). Values < 1 cause the light to become increasingly diffuse. A value of 0.5 creates an isotropic light field in which the radiant intensity is equal over all directions of the downward hemisphere. The angular distribution of $E_d(z)$ changes as light is propagated downward through its interaction with the plant canopy.

4.6 Other Run Controls

`16) Write irradiances every:` allows the user to control the amount and spatial resolution of spectral irradiance data written to **GLRESULT.DAT**. For a 300 mm tall canopy (=30 cm), *GL* will output 7 lines of irradiance data each for $E_d(\lambda)$ and $E_u(\lambda)$.

`17) Run Type:` provides options for:

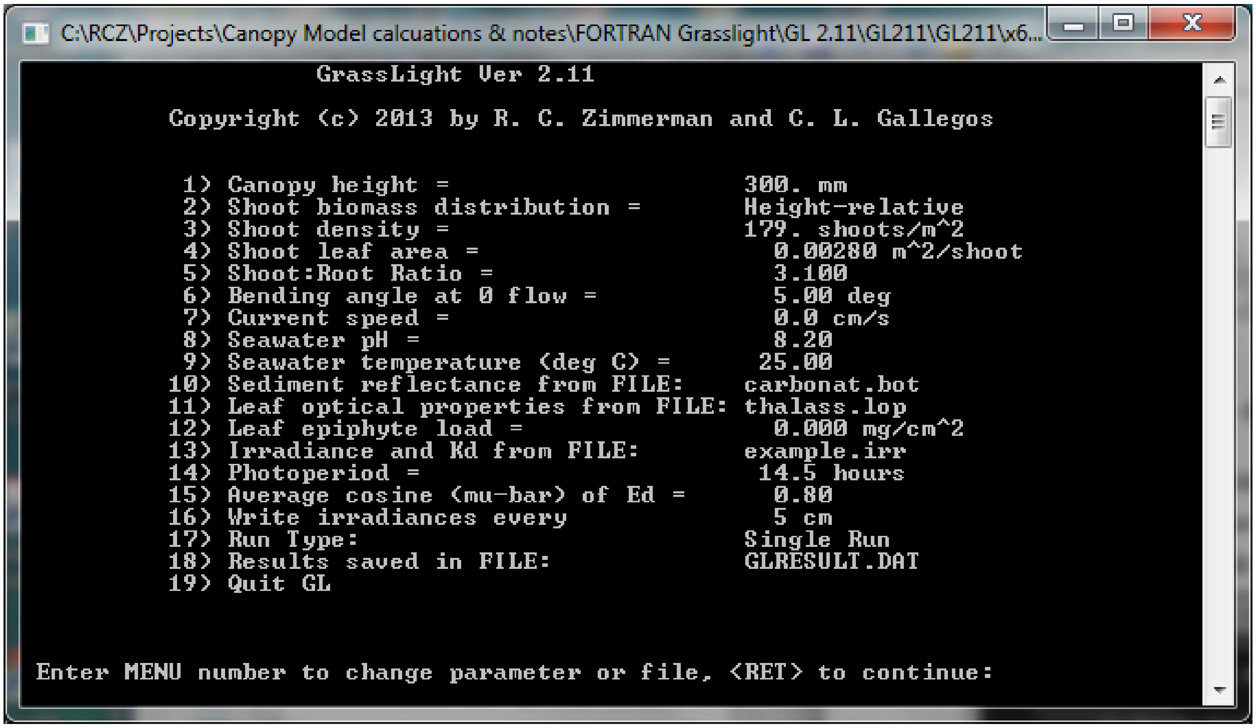
1) A single run (“S”) based on the existing parameters
2) A density optimization run (“O”), which will execute *GL* in a loop that changes shoot density until whole plant daily *P*:*R* =1. This represents the maximum sustainable density for the parameters established. See **Sec. 3.5 Output** for more details on this run option.
3) Multiple runs (“M”) across a range of shoot densities. You must specify a minimum LAI, maximum LAI and LAI increment for the runs. NOTE: the maximum LAI must be greater than the minimum. The number of simulations at different densities is determined by the LAI increment. If the difference between maximum and minimum LAI is not evenly divisible by the increment, *GL* will increment the LAI for each run as indicated but the number of runs will be determined by the *integer quotient* of (maxLAI – minLAI)/incLAI
4) The Time Series Option (“T”) has not been implemented in *GL* 2.14.

`18) Results saved in FILE:` allows the user to change the name of the output file for each run. The default name is **GLRESULT.DAT.**

`19) Quit GL:` terminates program and closes all open files, saving any new ones that were created during execution.

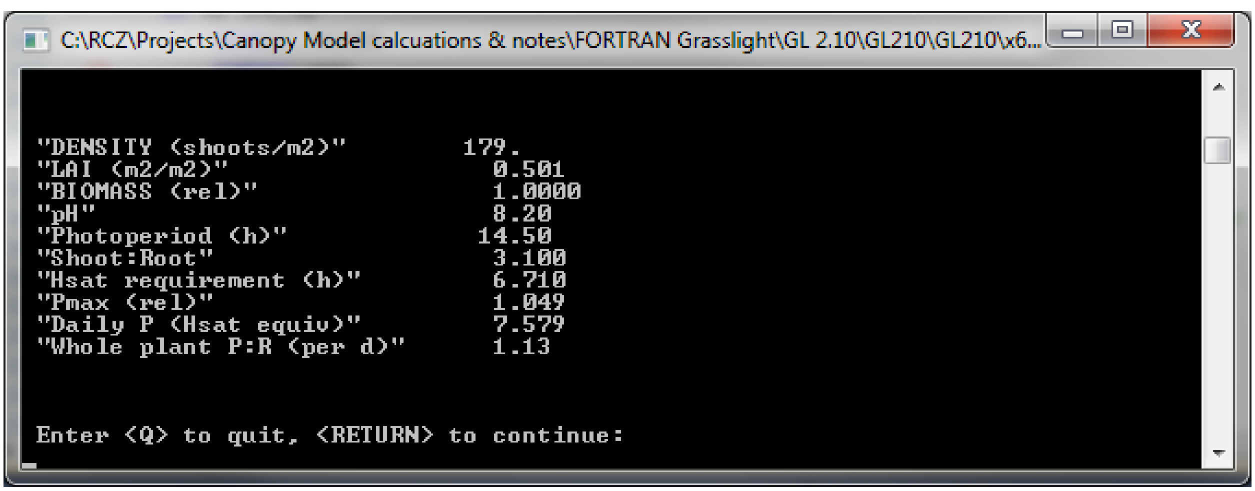
5. EXAMPLE RUN AND OUTPUT

The *GL* 2.14 distribution folder includes an example irradiance file (**example.irr**) and default conditions (**default.dat**) that can be used to explore basic program execution. The first time you run *GL*, **default.dat** will parameterize the settings as:



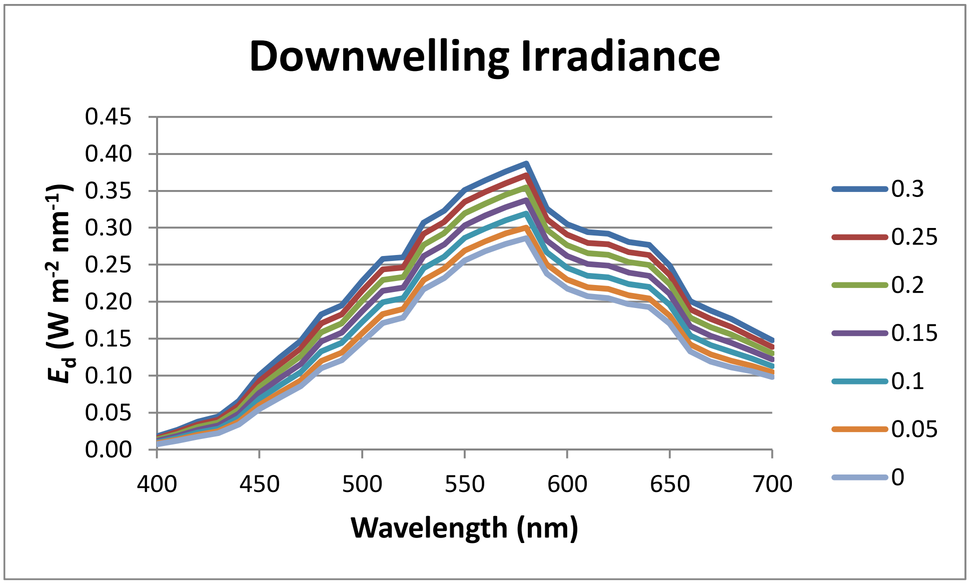
```
C:\RCZ\Projects\Canopy Model calcuations & notes\FORTRAN Grasslight\GL 2.11\GL211\GL211\x6...
                    GrassLight Ver 2.11

          Copyright (c) 2013 by R. C. Zimmerman and C. L. Gallegos

           1) Canopy height =                   300. mm
           2) Shoot biomass distribution =      Height-relative
           3) Shoot density =                   179. shoots/m^2
           4) Shoot leaf area =                   0.00280 m^2/shoot
           5) Shoot:Root Ratio =                  3.100
           6) Bending angle at 0 flow =           5.00 deg
           7) Current speed =                     0.0 cm/s
           8) Seawater pH =                       8.20
           9) Seawater temperature (deg C) =     25.00
          10) Sediment reflectance from FILE:   carbonat.bot
          11) Leaf optical properties from FILE: thalass.lop
          12) Leaf epiphyte load =                0.000 mg/cm^2
          13) Irradiance and Kd from FILE:      example.irr
          14) Photoperiod =                      14.5 hours
          15) Average cosine (mu-bar) of Ed =     0.80
          16) Write irradiances every             5 cm
          17) Run Type:                         Single Run
          18) Results saved in FILE:            GLRESULT.DAT
          19) Quit GL


 Enter MENU number to change parameter or file, <RET> to continue:
```

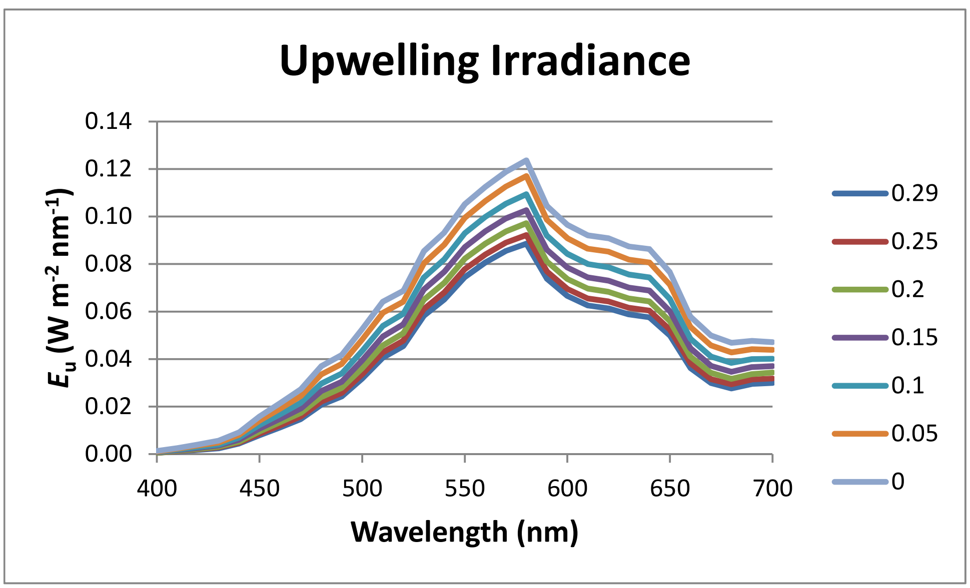
Execution by pressing <RET> in response to prompts will yield the following results printed to the screen and saved in **GLRESULT.DAT**:



```
C:\RCZ\Projects\Canopy Model calcuations & notes\FORTRAN Grasslight\GL 2.10\GL210\GL210\x6...

 "DENSITY (shoots/m2)"        179.
 "LAI (m2/m2)"                  0.501
 "BIOMASS (rel)"                1.0000
 "pH"                           8.20
 "Photoperiod (h)"             14.50
 "Shoot:Root"                   3.100
 "Hsat requirement (h)"         6.710
 "Pmax (rel)"                   1.049
 "Daily P (Hsat equiv)"         7.579
 "Whole plant P:R (per d)"      1.13


 Enter <Q> to quit, <RETURN> to continue:
```

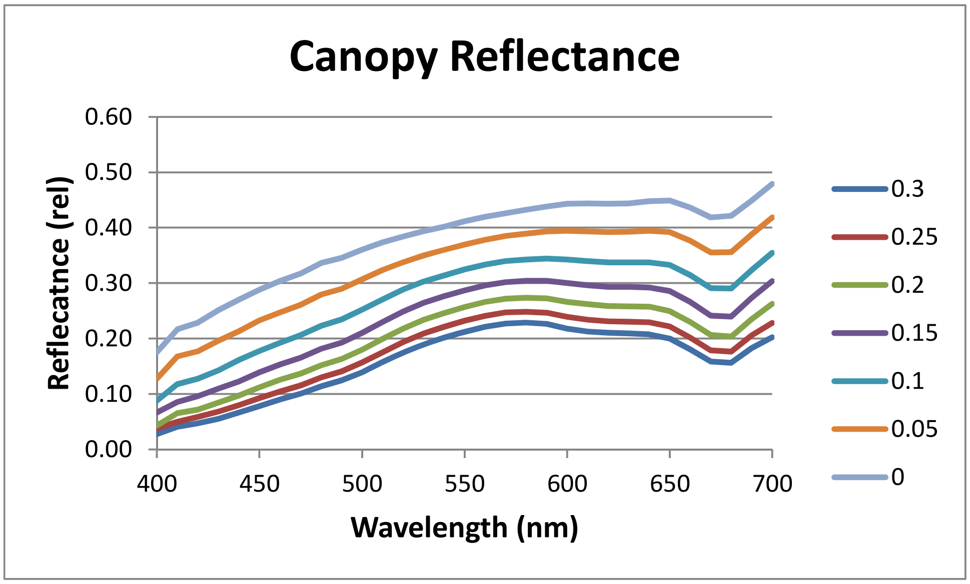
Downwelling and upwelling spectral irradiances (plotted using Excel) should appear as follows:





In this case, irradiance spectra are plotted as a function of canopy height (m) above the bottom. $E_d(\lambda)$ is greatest at the top of the canopy and decreases as it is propagated downward. $E_u(\lambda)$ is greatest at the base of the canopy and decreases as it is propagated upward, and the spectrum is more peaked in the green, relative to $E_d(\lambda)$ as blue and red wavelengths are preferentially absorbed by the water and seagrass canopy.

Results provided in **GLRESULT.DAT** can also be used to calculate spectral reflectance through the canopy, defined as $E_u(\lambda,z)/E_d(\lambda,z)$. In this example, the canopy reflectance is relatively high, and dominated by the optical properties of the underlying sediment (**carbonat.bot**) at the base of the canopy (ht = 0), and decreases, but becomes increasingly green as height above the seafloor increases. In this case, the reflectance at 0.3 m represents the spectral reflectance emanating from the top of the seagrass canopy as a result of the 2–flow propagation of irradiance through the canopy.



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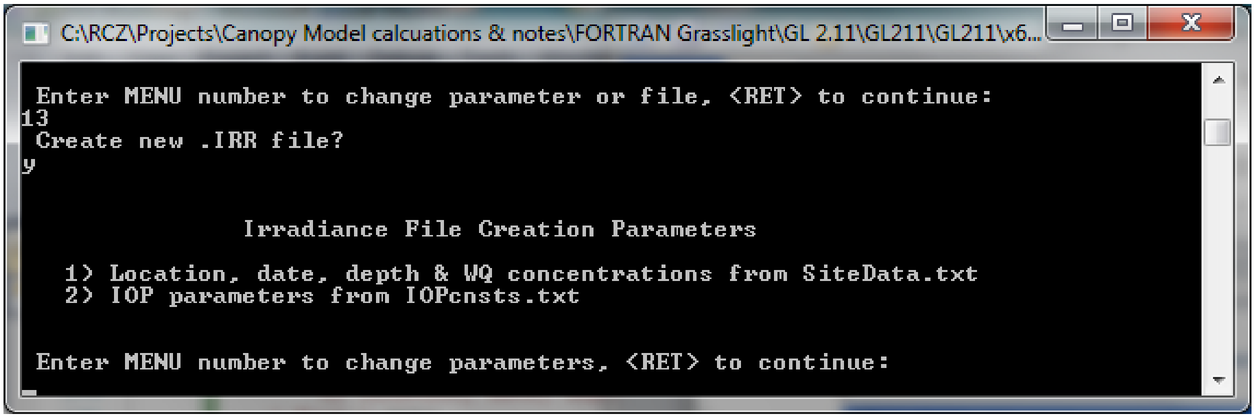
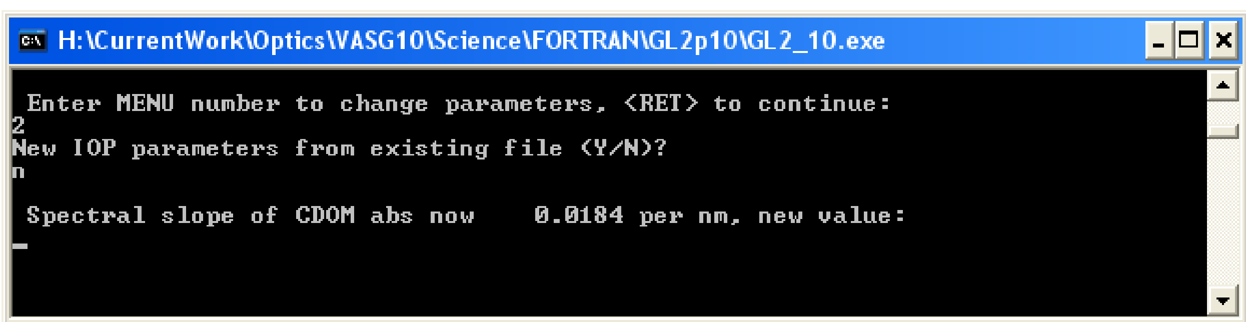
7. APPENDIX: Alteration of Water Column IOPs

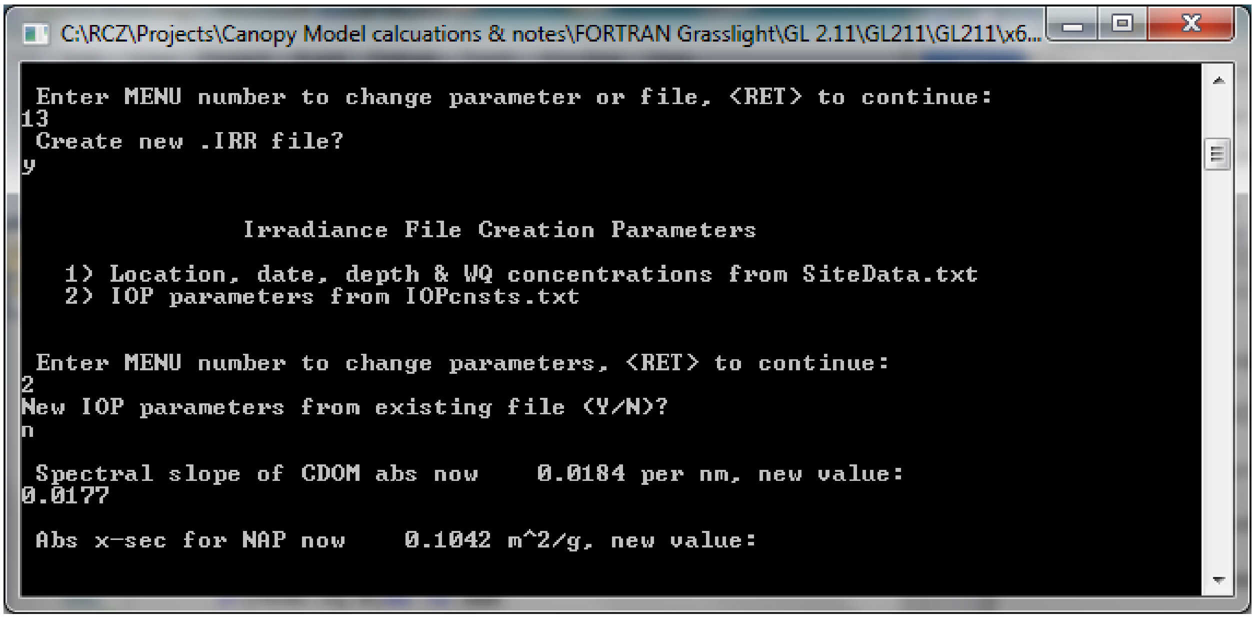


Entering 2 in response to the `Irradiance File Creation Parameters` prompt provides the option to specify a new file with IOP constants, or to enter new constants manually. Entering "Y" or "y" for YES in response to the "`New IOP parameters from existing file (Y/N)?`" query will prompt the user for a new file name. Entry of a valid file name will return you to the `Irradiance File Creation Parameters` menu. Entering "n" or "N" for NO will prompt you to change the parameters individually.



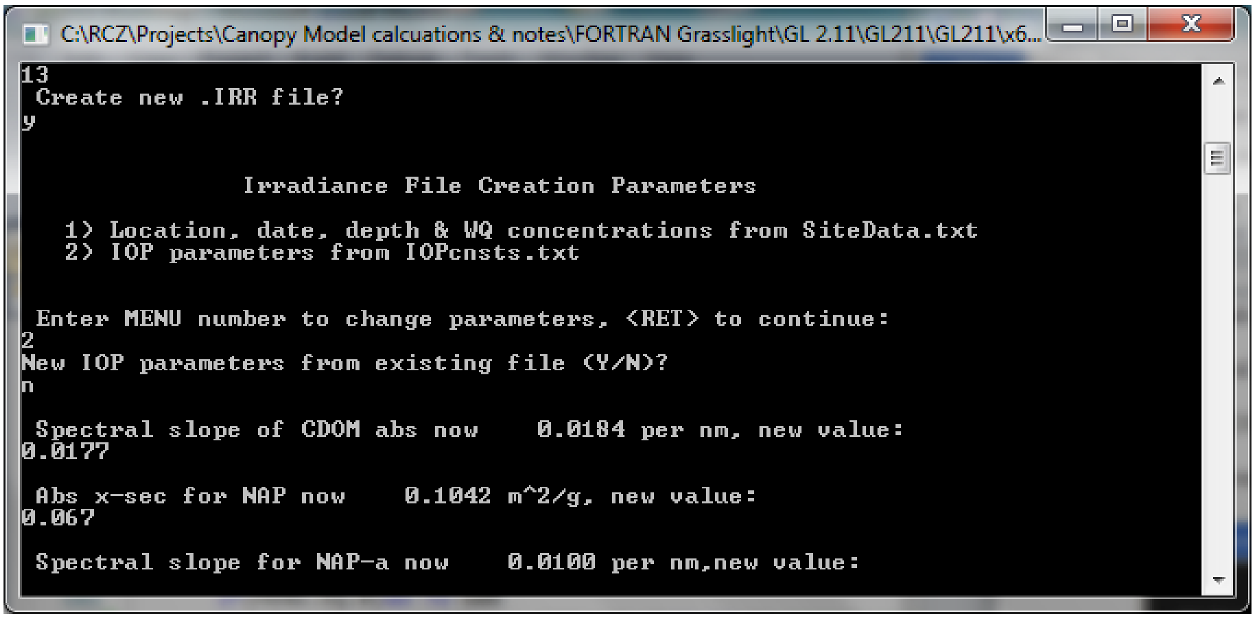
The first parameter is the spectral slope of CDOM absorption. Ideally the user should enter measured values for this parameter. Reasonable values for the spectral slope of CDOM absorption range from 0.012 to 0.020 (nm^{-1}). Lower values ($\leq 0.014\ nm^{-1}$) are characteristic of "new" CDOM near its freshwater source or recently released from phytoplankton. Photobleaching and microbial degradation of CDOM over time preferentially remove long-wave absorbing components of the CDOM pool, resulting in higher values of the spectral slope. The value provided, 0.0184 nm^{-1}, is for lower Chesapeake Bay, characteristic of relatively "old", degraded CDOM.

Entry of a value for spectral slope of CDOM brings up a series of prompts for the optical properties of NAP, beginning with the absorption cross section of NAP at 440 nm, coefficient c_2 in Equation (7). Before discussing these parameters, a note on the measurement of magnitude (concentration) term for NAP is in order.

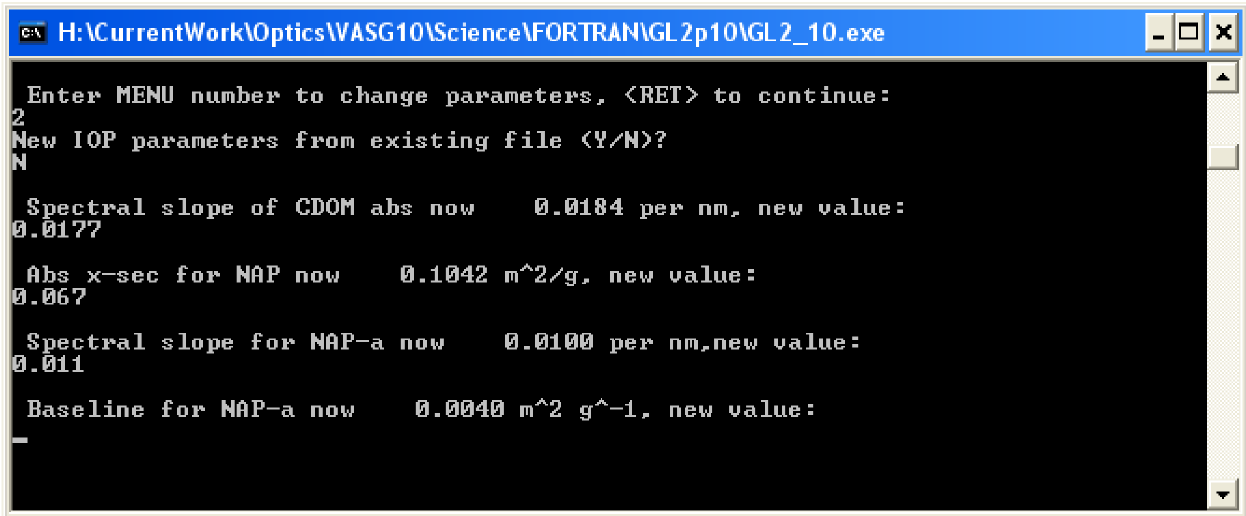


The water column light attenuation routine in *GL* can accept either turbidity (NTU) or total suspended solids (TSS, mg L^{-1}) as a measure of NAP concentration, provided that all of the constants in Equations (7-8) and (10-11) are scaled by the same measure, NTU or TSS. Literature guidance for the values of the absorption and scattering cross sections is more readily available as mass-specific values, i.e. scaled to TSS. Nevertheless, there can be an advantage to using an optically based measurement of NAP concentration when making repeated measurements at a mooring site, or spatially extensive mapping using a flow-through system (Madden and Day 1992). However, it is well known that the interconversion between NTU and TSS depend on the size and composition of the particulate matter, as well as the optical configuration (wavelength and scattering angle) of the instrument, which varies among manufacturers (Davies-Colley and Smith 2001). For a thorough discussion and field trials of various instruments in relation to determining particulate matter concentration see Boss et al. (2009). The default values for IOPs of NAP in *GL 2.14* are normalized to turbidity (NTU) measured by a YSI-6600 sonde on particulate matter near the mouth of the York River, Virginia. Nevertheless, the following survey is for mass-specific coefficients (normalized to TSS).

The absorption cross-section of NAP at 440 nm depends on the size, coloring, and composition of the particulate material, ranging from nearly undetectable for coarse grained quartz-and calcite-rich particulates to nearly 1 $m^2\ g^{-1}$ for some fine grained iron-rich minerals (Babin et al. 2003a, Babin and Stramski 2004). Regional means for c_2 compiled by Bowers and Binding (2006) ranged from 0.024 to 0.067 $m^2\ g^{-1}$, with about ±50% variability within any particular region, and the high region being the eutrophic Baltic Sea.

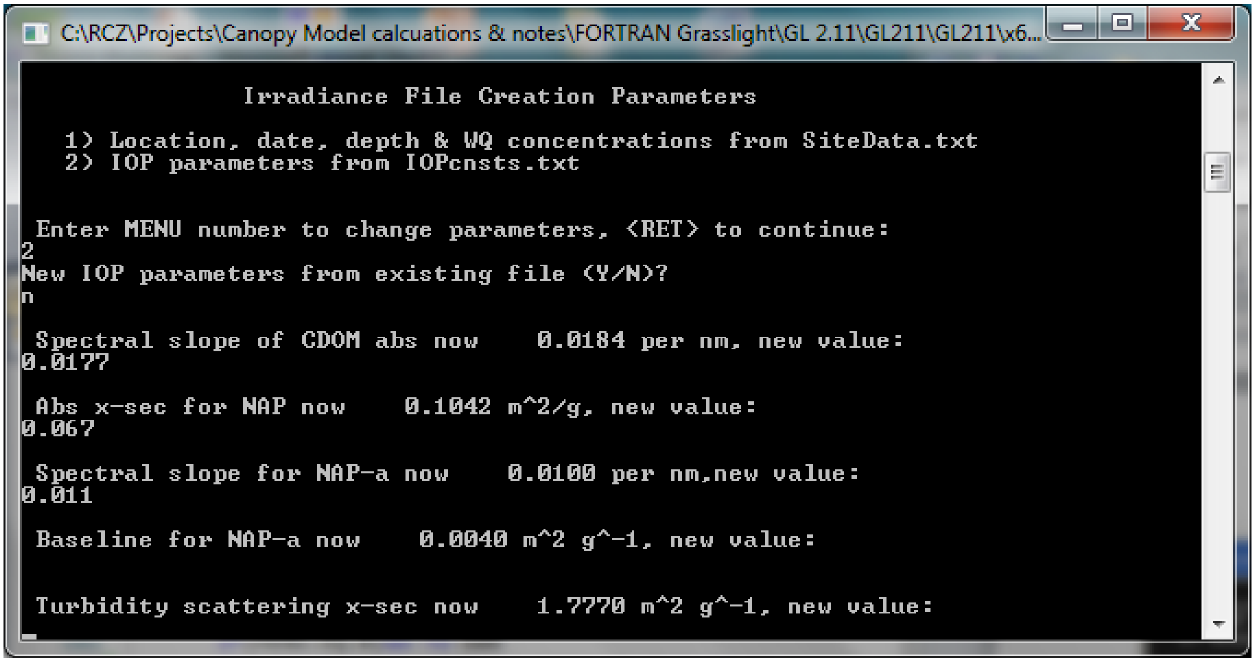


The spectral slope for NAP absorption, s_{NAP}, is generally smaller than that for CDOM, and is the least variable of all the parameters in Equation (7) (Bowers and Binding 2006). The mean of s_{NAP} for all regions compiled by Bowers and Binding (2006) was 0.012 nm^{-1}, and that for Chesapeake Bay was 0.011 nm^{-1} (Tzortziou et al. 2006). For most situations the default value in *GL 2.14* can be accepted. Entry of a new value for s_{NAP} or <RET> to keep the current value brings the query for long-wave base line absorption by NAP, c_1.



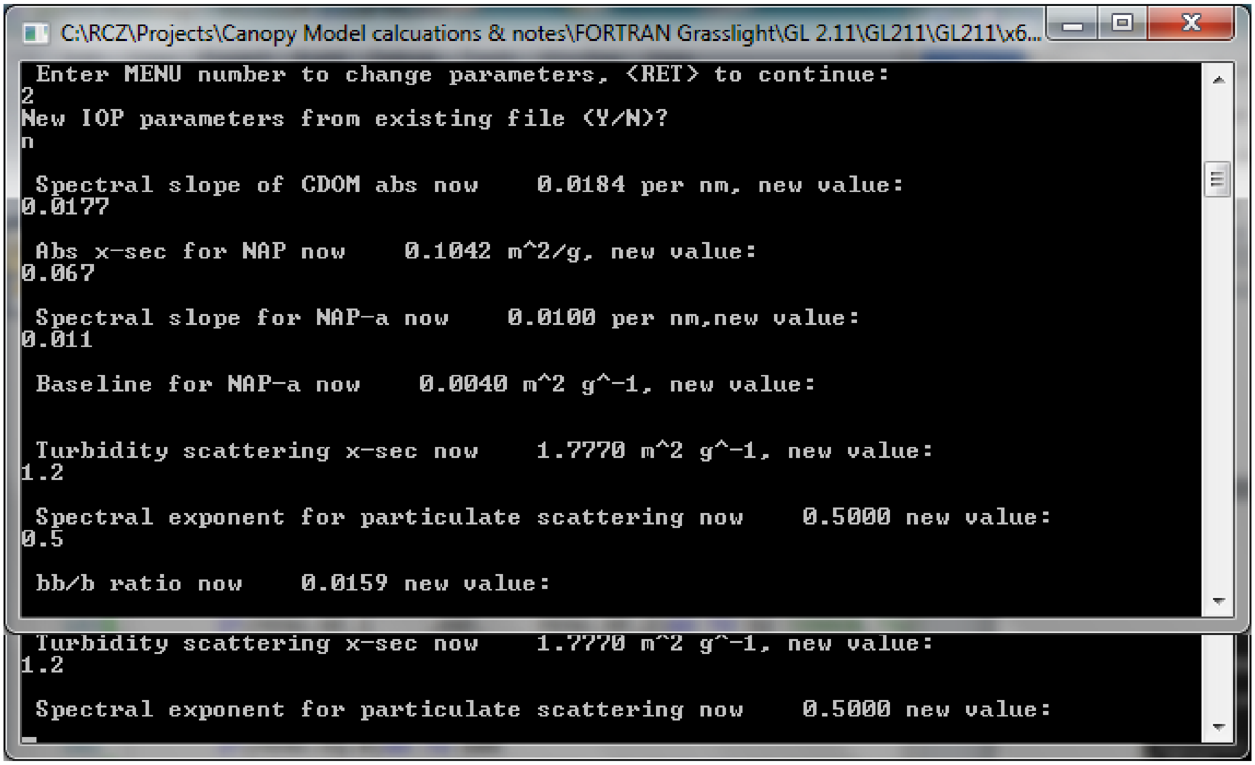
The existence of long wave absorption by NAP (c_1>0) is controversial, some authors claiming to have eliminated it by appropriate correction of the measurements for scattering error (Babin and Stramski 2004), and others claiming that it is real (Tassan and Ferrari 1995, Bowers and Binding 2006). Retention of long wave absorption was necessary to attain radiative transfer closure in Chesapeake Bay (Tzortziou et al. 2006). The average value of this parameter among studies that allowed non-zero values was 0.020 (s.d. 0.004) $m^2\ g^{-1}$ (Bowers and Binding 2006). This parameter can have a disproportionately large effect on calculated K_d(PAR), because it allows for additional absorption by particulate matter in the region of the spectrum where light absorption by other materials is minimal. It should only be adjusted if the user has specific knowledge of its local value, or to remove bias in calculations with respect to measurements when all other parameters are fixed at their known, measured values.

The next parameter for entry is the mass- or turbidity-specific scattering cross-section, parameter $b_p^*(555)$ in Equation (11). The value of the mass-specific scattering cross section



depends on the particle size and composition (i.e. index of refraction and specific gravity, Babin et al. 2003b). In an extensive data set from coastal and offshore Europe, individual observations ranged from about 0.1 to 2 m^2 g^{-1}, with regional means ranging from about 0.4 m^2 g^{-1} in the coastal Mediterranean to 1 m^2 g^{-1} offshore (Babin et al. 2003b). In general, small particles scatter more light than larger particles of similar composition; and the mass-specific scattering of organic particles is generally larger than that of similarly sized inorganic particles, because the lower specific gravity of organic particles offsets the higher refractive index of inorganic particles (Babin et al. 2003b). The range of the specific-scattering coefficient normalized to turbidity (NTU) is generally narrower than that normalized to TSS because turbidity is a scattering-based measurement that responds to particle size and composition at least in the same direction as the true scattering coefficient. Additionally, turbidity is frequently better correlated with NAP absorption and scattering than TSS (Biber et al. 2008).

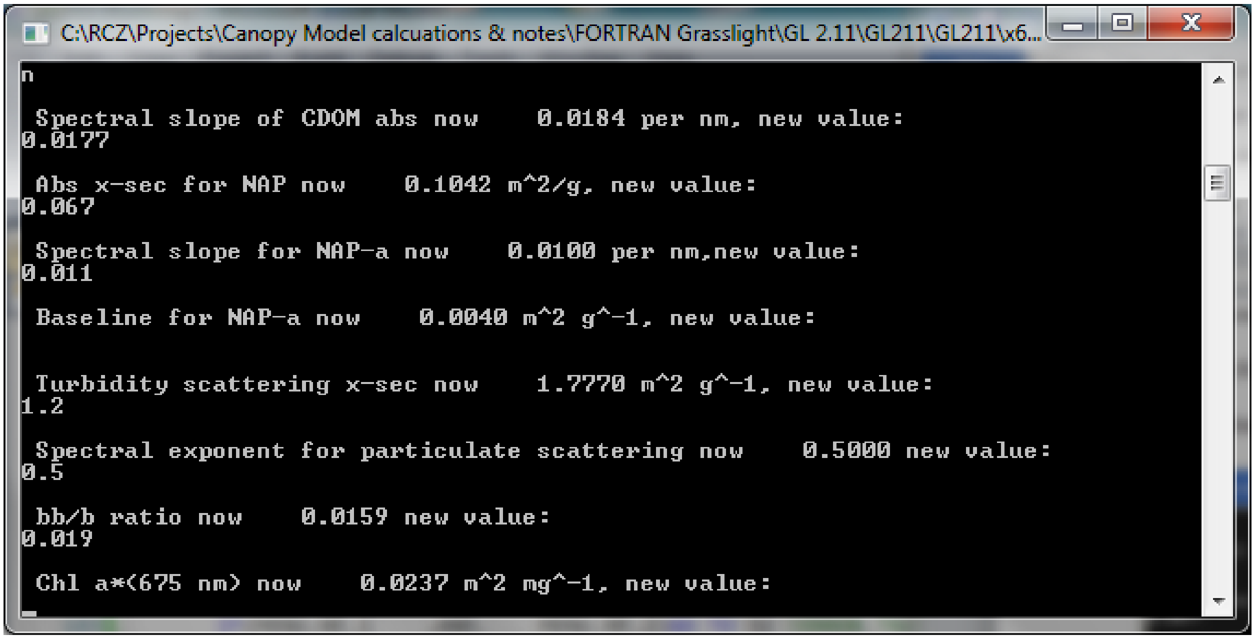
The next parameter available for modification is the spectral exponent for scattering, coefficient η in Equation (10). This parameter ranges from 0 to 2 (dimensionless) and is



dependent on the particle-size distribution (Boss et al. 2001). The sensitivity of K_d(PAR) to the spectral exponent of scattering is only a few percent over the whole range of expected values from 0 to 2.

The backscattering ratio, b_b/b, is the next parameter available to alter. The backscatter ratio is used to convert the total scattering coefficient (Equation 11) into the backscattering coefficient, which is needed to calculate $K_d(\lambda)$ in Equation (4). The backscattering ratio ranges from $<10^{-2}$ (dimensionless) for micro-phytoplankton to about 0.06 for fine grained inorganic particles (Stramski et al. 2001). Values ranged from 0.005 to 0.06 in 6000 samples from various U.S. coastal waters (Snyder et al. 2008). The value is often taken to be 0.019, the so-called Petzold average particle value, when specific information is lacking. The average backscattering ratio was 0.0123 in the mesohaline zone of main stem of Chesapeake Bay (Tzortziou et al. 2006), reflecting a greater influence of phytoplankton and organic detritus than the Petzold average particle assemblage. The default value of 0.0159 in *GL* 2.14 indicates a greater influence of inorganic solids in the shallow waters of Goodwin Islands compared with mesohaline Chesapeake Bay.

The next parameter to specify is the chlorophyll-specific absorption by phytoplankton at 675 nm, which scales $a_\phi^*(\lambda)$ in Equation (9). Values are expected to range from 0.01 m^2 (mg Chl*a*)$^{-1}$ in eutrophic systems to 0.03 in oligotrophic waters (Bricaud et al. 1995). Magnuson et al. (2004) found values ranging from 0.018 to 0.026 m^2 (mg Chl*a*)$^{-1}$ with some seasonality in lower and middle Chesapeake Bay. Given the dominant influence of absorption and scattering



NAP on K_d(PAR), simulations by *GL* 2.14 are not expected to be very sensitive to the value of $a_{\phi}^{*}(675)$ within normally observed values.

After entry of a value for $a_{\phi}^{*}(675)$ (or <RET> to keep the same value), *GL* provides the opportunity to save the current values in a file, `Save IOP constants to file (Y/N)?`. Entering "Y" or "y" prompts the user for a file name. Standard *GL* file naming conventions and restrictions apply. Entering "N", "n", or <RET> returns to the `Irradiance File Creation Parameters` menu, from which the user may alter other parameters by entering 1 through 3, or return to the *GL* main menu by entering <RET>.

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