Training event report
Radiative transfer theory and modelling with libRadtran

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DOI: 10.19232/uv4pb.2016.2.15

The ability to model the light environment using radiative transfer theory is a vital tool for scientists studying the radiation environment. libRadtran (Emde et al. 2016; Mayer et al. 2015) allows physicists and atmospheric scientists to compute spectral irradiance in the solar and thermal regions from 120 nm–100,000 nm, and to calculate radiative forcing due to different atmospheric components. It is also a useful tool for plant scientists wishing to study the effect of changes in spectral composition on plant responses at the leaf and canopy scale.

The doctoral program in plant sciences (DPPS) from the University of Helsinki sponsored me to attend the libRadtran workshop organised by the Finnish Meteorological Institute and CanSEE research group. The workshop was given by Arve Kylling from the Norwegian Institute for Air Research, one of the early pioneers and co-creators of the program libRadtran. Arve Kylling has a strong reputation and has published extensively on the methods to accurately-measure and model UV radiation in the Earth's atmosphere, and the influence that the Earth's atmosphere has on UV radiation. The libRadtran program provides a library for radiative transfer modelling, and includes functions for the calculation of solar and thermal radiation in the Earth's atmosphere. First developed in the 1980's, it still remains as open access software, freely available for any scientists wishing to utilise it.

At the core of libRadtran is the radiative transfer model uvspec, which describes energy transfer in the form of electromagnetic radiation. Radiative transfer models calculate how extraterrestrial solar radiation is altered by its path through the atmosphere. These models use extraterrestrial solar radiation as the starting point. Radiance is a distribution function, and defines the radiation field, which is a function of position, direction, frequency and time. Radiance is expressed per unit solid angle and per unit surface, given in $W\,sr\,m^{-2}$. The propagation of electromagnetic energy is affected by processes such as absorption and scattering. Absorption implies the 'death' of a photon, whereby a field of particles removes the incident energy from the photon, and converts this energy into a different form. Scattering is a change in the direction of a photon's propagation. Both molecules (Rayleigh scattering) and particles (aerosols, clouds, Mie scattering) scatter radiation. Irradiance, as opposed to radiance, is the measure of radiation striking a defined area of surface, and changes according to the distance between the source and the target surface (Figure 9.1). Irradiance is given in the units $W\,m^{-2}$.

The Beer–Lambert–Bouguer law is incorporated into the model, and describes the absorption of radiation along the beam direction and scattering out from the beam direction. Calculation of the vertical variation in these properties is achieved by splitting the atmosphere into boundary layers, with each boundary layer having defined proper-

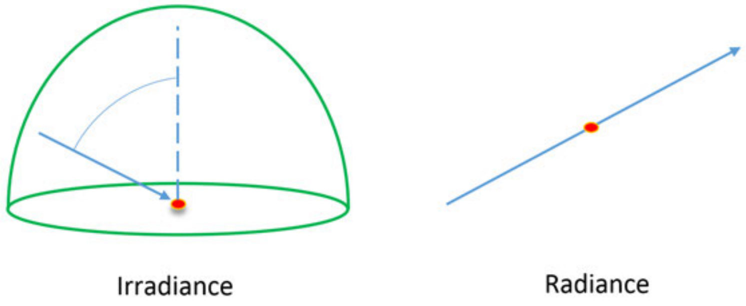

Figure 9.1: Visual representation of radiance and irradiance. The red circle represents the point at which a measurement is taken. Redrawn from (Lazarov 2011).

ties relating to its absorption and scattering. If the user wishes to model the irradiance under snow, rain, or even the ocean, then all of these can be treated as a boundary layer within libRadtran as well -- likewise under a plant canopy or horticultural greenhouse -- although these sort of boundaries were not quite what the model was envisaged for when it was developed. For instance, plant canopies can be considered a heterogeneous layer and thus the Beer-Lambert equation has often been modified to overcome this problem when modelling the light in forest understories. Modelling of within-canopy radiation transfer is commonly based on the Monsi-Saeki equation, which provides a simplified assumption that the canopy is composed of small horizontal leaves with a random distribution (Monsi et al. 1973). Using this method, empirical parameters such as the transmissibility of a leaf can be included in the model. For plant scientists using manipulative filter material to monitor the effects of UV or other regions of spectral composition, then the material can also be included as a boundary layer, and its attenuation properties can be defined to produce an accurate model of light below the filter. The final product of the uvspec model in libRadtran is the irradiance for every wavelength defined in the model.

There are some assumptions made in the model, which include that the atmosphere is one-dimensional and bounded at the top and bottom by horizontal plane surfaces (known as a plane-parallel atmosphere), the medium (e.g. atmospheric layer) does not change with time as the photon passes through it, that the frequency of the photon does not change as it interacts with the matter, and that the photons move in straight lines.

Once downloaded, the model can either be used through systems such as Cygwin (which allows a Linux-like interface to be operated from within Windows), and called from a Python or shell script, or via a graphical user interface. As mentioned, the core function in libRadtran is the uvspec radiative transfer model. This can be characterised into four different parts (Figure 9.2). Firstly, the atmospheric state or description is provided. The user then selects parameterisation values to convert the atmospheric state into optical properties, such as an extinction coefficient that describes the optical properties of a water cloud. These optical properties are then passed on to a radiative transfer equation (RTE) solver, which then produces an unprocessed spectral irradiance value.

A working directory has to be defined in Cygwin (or whatever operating system is being used to run libRadtran), and an input file is created which contains the parameter values and names of functions to use in the simulation for the uvspec model to read. This input file must be a text file format with a name tag '.inp'. Allowed input values are doc-

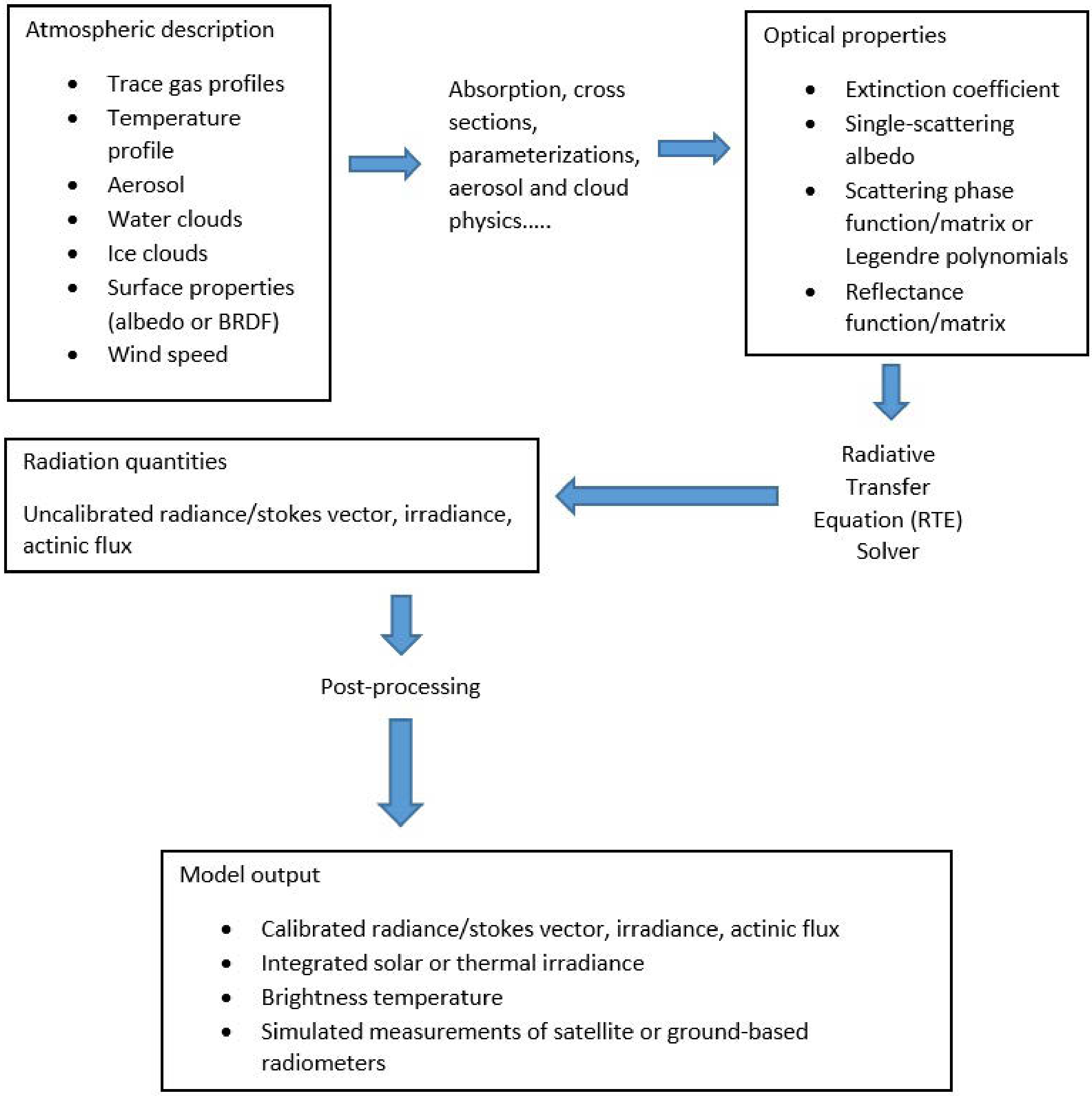

Figure 9.2: Structure of the uvspec radiative transfer model. Redrawn from (Emde et al. 2016).

umented in the functions, as well as example '.inp' files for different types of calculations which are available from the libRadtran website. There are several key features that allow the user to simulate the irradiance at any location on the Earth's surface, for any day of the year. The user can do this by referring to and editing the input file for the model. The surface type, altitude, zenith angle, day of the year, thickness of ozone column in Dobson units and the wavelength range can all be defined here within the input file. In addition, there are more advanced features for those wishing to adjust the number of beam directions used (a compromise between computation speed and accuracy), as well as clouds and their optical depth.

An output file is then saved into the same working directory. There are typically seven columns in the file describing irradiances and actinic fluxes (Figure 9.3). The first column lists the wavelength (nm) of light and the following six columns give the direct irradiance, diffuse downwards irradiance, diffuse upwards irradiance, and direct actinic flux (the total number of photons, or radiation, incident at any point from all directions), diffuse downward actinic flux and lastly diffuse upward actinic flux.

In this way, one can produce useful figures, such as Figure 9.4, which display the simulated spectral irradiance (calculated here as the sum of downward direct irradiance and downward diffuse irradiance) for a particular location on the Earth's surface at a particular point in time, or those such as 9.5, which display the modelled radiation components from Figure 9.3 for the same location and time. Following the steps provided for in uvspec, users are able to manipulate the conditions and input requirements to suit the scientific question at hand. As with most models, it is used most effectively alongside measured spectra to ensure accuracy. Usually the most difficult input to obtain is a good description of local cloud cover, which is crucial for any instantaneous or short term estimate.There are currently over 400 publications citing libRadtran, demonstrating its strong reputation amongst the scientific community.

libRadtran is but one of many radiative transfer models available for scientists to use. Another popular model with free access is the Tropospheric Ultraviolet and Visible (TUV) radiation model, which was developed by Sasha Madronich at the National Centre of Atmospheric Research, USA (Madronich et al. 1997). There are of course differences in how to use these different models. One advantage of the TUV model is that it provides a simplified "Quick TUV calculator" which one can access to obtain data simply through a web page online (http://cprm.acom.ucar.edu/Models/TUV/Interactive_TUV/). However, the TUV model operates over a shorter wavelength range: TUV can calculate between wavelengths of 150 nm--750 nm, whereas libRadtran can calculate any wavelength from 120 nm–100 000 nm.

There are still novel questions to be explored using the libRadtran model, particularly with regards to the response of plants to UV and other regions of light, and the possibility to model the spectral irradiance beneath forest and crop canopies, or even inside greenhouses. The libRadtran program provides an impressive toolbox allowing plant scientists to model the light environment in situations where measurements are not possible, or to be used as a predictive tool to model the light environment under future circumstances.

For more information on libRadtran, please visit www.libradtran.org

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Figure 9.3: Example rows from an output file from the uvspec model in libRadtran.

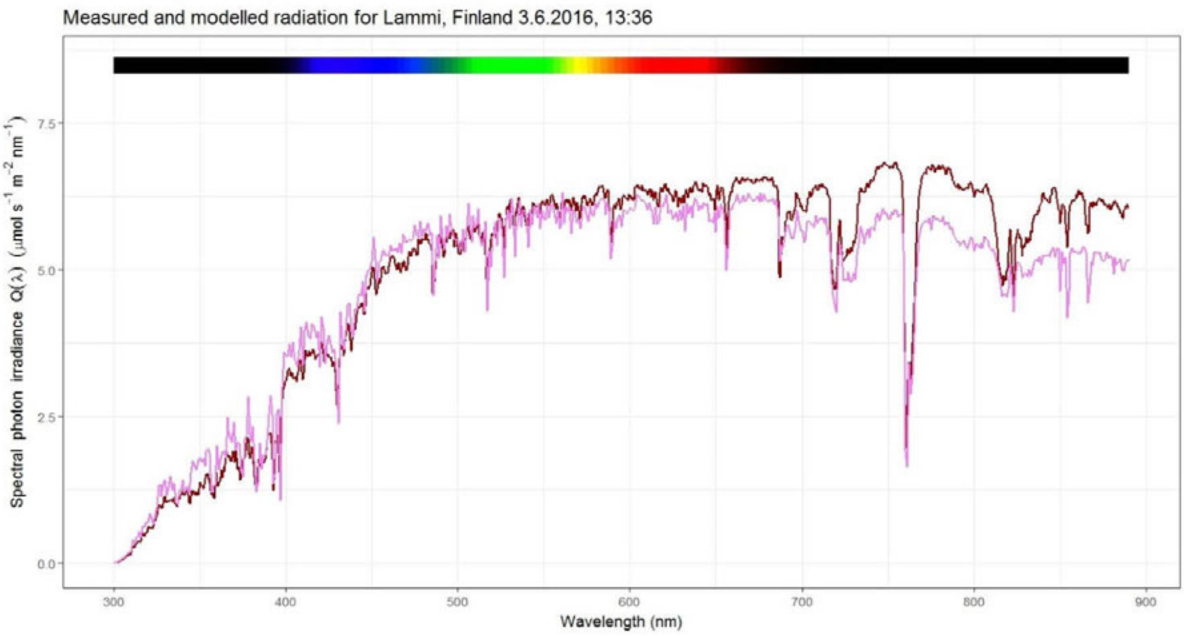

Figure 9.4: Plot of the spectral photon irradiance measured with a Maya2000 Pro array spectroradiometer on 4 June 2016 at solar noon (13:36) in an unshaded grass meadow adjacent to Lammi Biological Station (130 masl, 61°03'14.3"N 25°02'14.2"E). Measured solar irradiance (dark red) is compared with modelled solar irradiance (violet) using the uvspec model in libRadtran. Differences in the far-red region are likely due to nearby vegetation on the edge of the meadow, which whilst not shading, may have increased the amount of far-red light by selective reflection. The difference in blue and UV regions may have been the result of partial occlusion of the sky by adjacent vegetation or buidings.

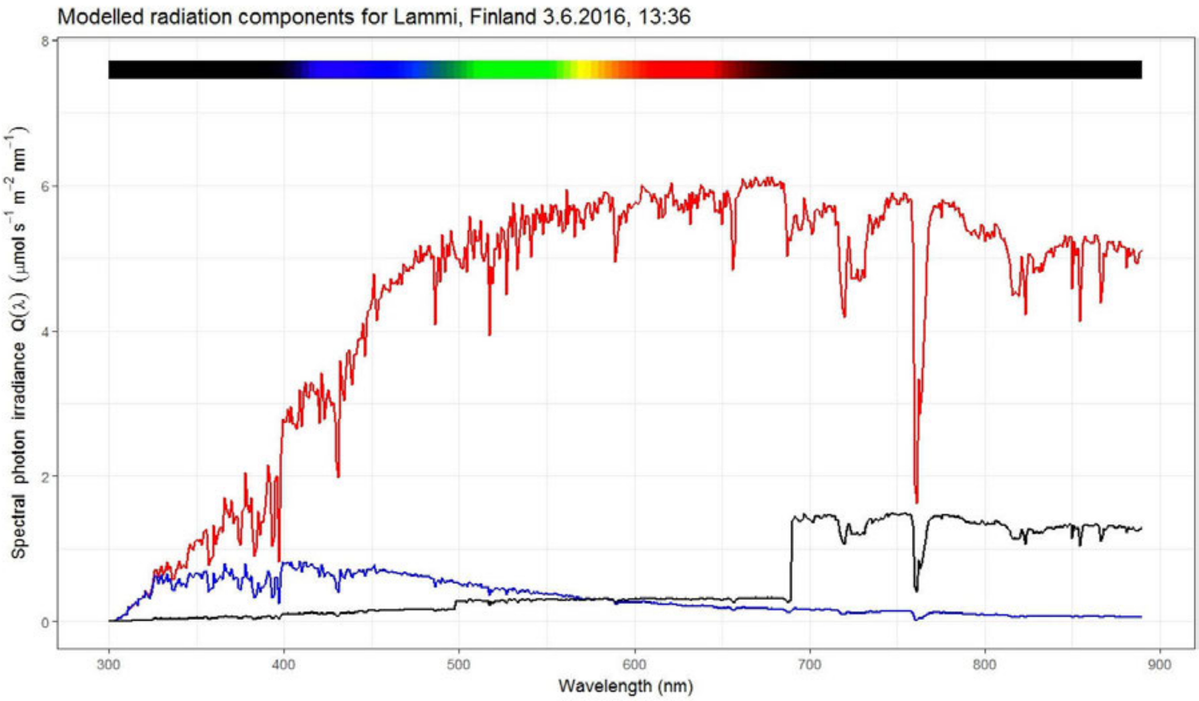

Figure 9.5: Plot of modelled direct spectral irradiance (red line), diffuse downward spectral irradiance (blue line), and diffuse upward spectral irradiance (black line) using the uvspec model in libRadtran. Modelled for the 4th June 2016 at solar noon (13:36) at Lammi Biological Station, Finland (130 masl, 61°03'14.3"N 25°02'14.2"E). The increase in diffuse upwards irradiance at 680nm is due to reflection by plant leaves in the far-red region.

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Editorial-board-reviewed article.
Published on-line on 2017-02-01.
Edited by: P. J. Aphalo and P. Barnes.