

Gap Light Analyzer (GLA):

Imaging software to extract canopy structure and gap light transmission indices from true-colour fisheye photographs.

Users Manual and Program Documentation, Version 2.0



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Copies of this document and the Gap Light Analyzer (Version 2.0) software may be obtained from the authors, or downloaded via the Internet at:

<http://www.rem.sfu.ca/forestry/index.htm>

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CONTENTS

ACKNOWLEDGEMENTS.....	iii
1.0 INTRODUCTION.....	1
2.0 APPLICATION OVERVIEW.....	2
2.1 Hardware Requirements.....	3
2.2 Software Design.....	4
3.0 GETTING STARTED.....	4
Step 1: Open an Image.....	4
Step 2: Image Registration.....	4
Step 3: Edit, Save, or Load a Configuration.....	6
Step 4: Image Classification.....	6
Step 5: Compute Results.....	7
4.0 NAVIGATING THE MAIN MENU.....	7
4.1 File Menu.....	7
4.2 Edit Menu.....	9
4.3 View Menu.....	9
4.4 Configure Menu.....	10
4.5 Image Menu.....	11
4.6 Calculate Menu.....	13
4.7 Utilities Menu.....	14
5.0 UNDERSTANDING THE CONFIGURATION SETTINGS.....	15
5.1 Image Tab.....	15
5.2 Site Tab.....	16
5.3 Resolution Tab.....	17
5.4 Radiation Tab.....	18
6.0 HOW TO GENERATE AND INTERPRET OUTPUT RESULTS.....	21
6.1 Calculation Report (Summary).....	21
6.2 Calculation Report (Detailed).....	22
7.0 HOW DOES THE GLA COMPARE TO GLI/C?.....	26
8.0 HOW TO COMPUTE REGION-SPECIFIC MODEL PARMETERS.....	27
8.1 Cloudiness Index.....	27
8.2 Spectral Fraction.....	29
8.3 Beam Fraction.....	32
REFERENCES.....	33

1.0 INTRODUCTION

The number, size, and location of gaps in a forest canopy have a direct influence on the availability and distribution of understory light. The quantity and spectral quality of this incident solar energy, in turn, plays a significant role in determining the abundance and diversity of understory plants, the growth and mortality of seedlings, and the development, structure, and species composition of the canopy trees (Canham et al. 1994, Gray and Spies 1996, Wright et al. 1998, Nicotra et al. *in press*). Species, site, and age-related differences in the architecture of canopies create a patterning of gaps that is highly variable across space and through time, leaving a complex mosaic of forest structure and light environments at many scales across the landscape (Lertzman et al. 1996, Frazer et al. 1998, Trichon et al. 1998).

Interest in documenting the relationships between forest structure and the understory light regime has converged from two distinct lines of research. On the one hand, community and population ecologists studying successional processes associated with canopy gaps formed by patchy tree-mortality needed to quantify the environmental conditions associated with those gaps (Rich et al. 1993, Canham et al. 1994, Easter and Spies 1994). On the other, microclimatologists and production ecologists required easily replicated and non-destructive methods for quantifying the leaf area borne by forest stands (Chen et al. 1997). In both cases, the challenges and constraints of direct measurement of the variables of interest (for instance, multiple light sensors running over several seasons or direct destructive sampling of tree crowns) led to the development of faster, less direct methods, which lend themselves more easily to spatial and temporal replication (Welles and Cohen 1996).

Hemispherical canopy photography is one indirect optical technique that has been widely used in studies of canopy structure and forest light transmission. Photographs taken skyward from the forest floor with a 180° hemispherical (fisheye) lens produce circular images that record the size, shape, and location of gaps in the forest overstory. Digital scanners or cameras convert these hemispherical images into bitmaps, which are then analyzed using specialized image analysis software. Image processing involves the transformation of image pixel positions into angular coordinates, the division of pixel intensities into sky and non-sky classes, and the computation of sky-brightness distributions. These data are subsequently combined to produce estimates of growing-season light transmission, as well as other measures more directly related to canopy structure, such as openness, leaf area, and sunfleck frequency (Chazdon and Field 1987, Becker et al. 1989, Rich 1990, ter Steege 1993, Canham 1995).

2.0 APPLICATION OVERVIEW

The Gap Light Analyzer (GLA) is a Windows-based software application designed to import, display, and analyze digital hemispherical (fisheye) canopy photographs. GLA was developed from an earlier true-colour imaging program, GLI/C, created by Dr. Charles Canham at the Institute of Ecosystem Studies (IES), Millbrook, New York (Canham 1995). GLI/C (now called GLA) has been completely re-engineered to include 1) a new Multiple Document Interface (MDI), 2) a solar radiation model that takes into account the influences of topography and seasonal patterns of cloudiness, 3) new spatial methods to extract beam transmission and sunfleck-frequency distribution data, 4) a variety of stand-alone utilities that allow the user to explore, extract, and display gap fraction, canopy openness, and gap light transmission information, 5) TWAIN compliance to acquire digital data directly from scanners and cameras, and 6) a suite of image processing tools for image modification.

GLA will compute canopy and site openness, effective leaf area index (L_e), sunfleck-frequency distribution and daily duration, and the amount of above- and below-canopy (transmitted) direct, diffuse, and total solar radiation incident on a horizontal or arbitrarily inclined receiving surface. Images can be imported in a variety of graphics formats or directly from a scanner or digital camera. GLA includes a number of tools and image-processing functions to register and manipulate these imported images. Image processing functions, such as image threshold, brightness, contrast, etc., can be used to affect the entire image or only a select portion of it. Results from the GLA calculations are displayed on a separate form with an option to append these data to a spreadsheet. There are a number of stand-alone utilities that will compute and display mean daily extraterrestrial radiation, sunfleck duration and frequency, solar positions and intensities, and sky-region brightness. Other utilities can be used to display both canopy openness (as equal intervals of zenith or area) and the amount of above- and below-canopy solar radiation as a function of zenith angle.

GLA was designed to process large numbers of photographs taken from numerous sites. Individual configurations settings can be created for different camera lenses and orientations, regional climatic patterns and growing seasons, and topographic settings. These configuration data can be saved to disk for later use, or loaded directly into the Windows system registry so that each time the program is executed the configuration settings are already initialized. GLA supports import, export, and editing of all configuration settings.

2.1 Hardware Requirements

Operating System, Processor, and Display Device

GLA is 32-bit application compiled to run under Microsoft Windows 95 or later, or Windows NT 4.0 or later. The software was developed on a Dell Dimension XPS 266 with 64 Mb of RAM and 4 Mb of video RAM, and has been tested on a Dell Dimension XPS 90 (48 Mb of RAM, 2 Mb VRAM, Windows 95) and a Dell Dimension XPS R400 (64 Mb of RAM, 8 Mb VRAM, Windows 98).

For optimum performance, we would recommend that GLA be installed on a recent Pentium machine (266 MHz or faster) with at least 64 MB of RAM. The computer should also have a graphics display device (video card) that has 4 MB of video memory or better, and is capable of true colour display at screen resolutions of 600 x 800 or better (application will display best at 1024 x 768 or higher). GLA will support large or small display font sizes, but it will not support any of the custom fonts.

Scanner

GLA should work with any TWAIN-compliant scanner or digital camera that uses a 32-bit TWAIN driver. The software however, has only been tested with a Polaroid Sprint 35 film scanner using the manufacturer's 32-bit TWAIN driver.

Camera Lens Formats and Projections

GLA can be used to analyze any circular fisheye image that has been captured using a short focal length (8 mm or less) hemispherical lens with a full 180° field of view (FOV) and a known projection distortion. Fisheye lenses that have longer focal lengths (e.g., 16 mm) and a full 180° FOV create non-circular images that are cropped in either one or both dimensions of the image. These images cannot be analyzed using GLA. Four standard projections (e.g., polar, orthographic, stereographic, Lambert's Equal Area) and any number of user-defined custom lens distortions are supported by GLA.

2.2 Software Design

GLA consists of a graphical user interface (GUI) written in MS Visual Basic, and an ActiveX module (CGACalc) developed in MS Visual C++. The GUI utilizes a single third-party ActiveX component (LeadTools) to handle image scanning, import, display, and basic image processing. Commercial chart (VCI First Impression) and data grid (VCI Formula One) objects were also used for tabular and graphical display. The CGACalc ActiveX module is responsible for receiving and processing numerical and image data input from the GUI, and computing each of the various canopy structure and light transmission models. CGACalc passes all of the processed data back to the GUI for final display.

3.0 GETTING STARTED

Five simple steps are necessary to analyze a fisheye photograph. The first step is to open an existing image or scan in a new one. Second, register the image so that both the orientation and circular extent of the exposure are known. Third, if necessary, edit the configuration settings to reflect the site position and orientation, growing-season length, and atmospheric conditions. Fourth, threshold the image so that the each pixel is accurately classified as either a sky (white) or non-sky (black) pixel. Last, run the calculations to compute the canopy structure and/or gap light transmission results.

Step 1: Open an Image

Image data can be imported directly from an existing graphics file or via a TWAIN-compliant scanner or digital camera. Most common graphics formats (e.g., BMP, JPG, PCX, etc.) are supported by GLA. Those formats that are not supported by the application are compressed TIFF, GIF and some of the more recent graphics formats (e.g., FlashPix). Use the **Open** option under the **File** menu or on the toolbar to import an existing image file. To obtain digital data directly from a TWAIN-compliant device, first select the appropriate driver from the **Select TWAIN Source...** option under the **File Menu** and then click **Scan Image...** under the same menu or on the toolbar.

Step 2: Image Registration

Image registration is the process by which the user identifies the geographic orientation and circular extent of the hemispherical image. To register an image, the user must identify two

known points on the image. The first point is termed the initial point in GLA and it determines the geographic orientation of the image. The second point is located at an opposing azimuth (e.g., if the initial point is 0° north the second point will be 180° south) and marks the circular extent of the image (Figure 1).

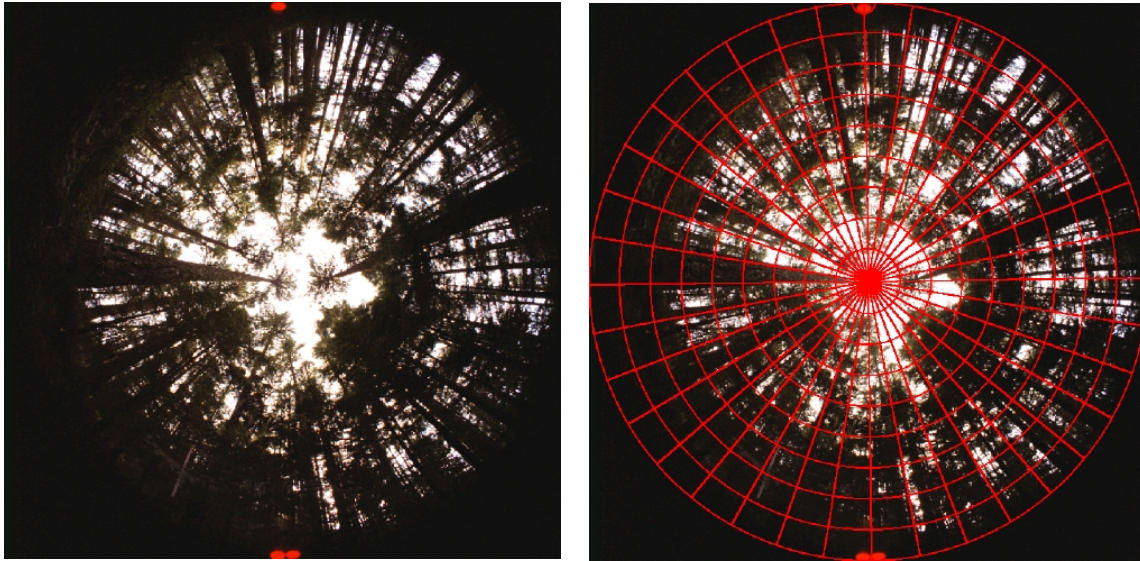


FIGURE 1. The single red dot at the top of the images identifies geographic north (0°), and the two red dots at the bottom define south (180°). The photo on the right has been accurately registered. The photograph was marked at the time of exposure using fibre optics mounted at the edge of the fisheye lens.

To register an image in GLA, select **Register Image** from the **Configure** main menu or the toolbar. Two techniques may be used to identify the two required registration points. First, points may be identified graphically by dragging the mouse from the initial point (left mouse button down) to the last point (left mouse button up). Second, if the pixel coordinates of the registration points are already known, then the two positions may be keyed in directly. If you have keyed in the data points, click the **Apply** button on the **Registration** form to view the outer ring and centre of the registration circle. Click on the **OK** button on the **Registration** form to accept the registration. If you except the registration then the photo will be cropped and two identical images will be posted side by side on the MDI form. The picture on the left is the **Registered Image** and the one on the right is the **Working Image**.

Step 3: Edit, Save, or Load a Configuration

A configuration file contains the input data necessary to run the various models contained in the CGACalc module. These input data include information on image orientation, projection distortion, site location, growing-season length, sky-region brightness, and atmospheric conditions. The configuration settings can be accessed from the **Configure** option on the main menu or toolbar. Options exist to save, load or edit these configuration data. Since the application is installed with default configuration settings, choose the **Edit Configuration...** option from the main menu or toolbar to view the default settings.

The configuration form is displayed as a tab notebook composed of four separate tabs including the **Image**, **Site**, **Resolution**, and **Radiation** tabs. The **Image** tab contains all of the input that describes the geometric distortion and spatial orientation of the digital photograph. All of the input related to the physical location where the photograph was taken (i.e., geographic location, slope and aspect, and topographic shading) are found in the **Site** tab. Input parameters stored under the **Resolution** tab are used to determine the detail with which gap fraction and light transmission data are extracted from the images. Lastly, the **Radiation** tab contains all of the numeric input required to compute the amount of above-canopy solar radiation received at the site over the course of a growing season.

Once you have made changes to some or all of the configuration settings, click **OK** on the **Configuration Settings** form to update all of the input data. If you want to save these settings for future use, click **Save As** on the form and enter an appropriate filename (*.SCF) when the common dialogue box appears. Choose **Load Configuration...** on the **Configure** menu to reload a configuration file that had been previously saved.

Step 4: Image Classification

Image classification involves the separation of pixels within the image array into sky and non-sky classes using the **Threshold...** function found under **Image** on the main menu or on the toolbar. Image classification is relatively easy when the original photograph has a reasonable degree of colour contrast between the sky and canopy. Often, however, there is an inadequate amount of image contrast in certain portions of the photograph. For example, light scattering around the zenith will sometimes blur the boundary between sky and foliage, and near the horizon the low light tends to under-represent the number and size of gaps.

Two approaches can be used to improve the classification during image analysis. First, by splitting a 24-bit colour image into separate RGB planes, it is possible to improve colour contrast in at least one of the planes. For example, colour contrast sometimes improves in the blue plane, because a clear sky tends to scatter blue light while a canopy absorbs it. To split a colour image into its component parts, click on **Choose a Colour Plane...** under the **Image** menu or on the toolbar. A second method is to use the “region of interest” capabilities (inside or outside) and apply separate threshold values to sensitive regions within the image. To apply a threshold to only a selected region of the image, click on **Select Region** under **Edit** on the main menu or **Freehand** on the toolbar. Next, outline the region of interest on the **Working Image** and then apply an appropriate threshold value for that selected area.

Step 5: Compute Results

The final step in the image analysis process is to generate output results. There are two basic ways to do this. First, the user can compute canopy structure data alone (e.g., canopy openness and effective LAI), or canopy structure and gap light transmission data together using the **Calculate** option found on the main menu and toolbar. Results computed using either of these two settings are displayed on a single form with options available to append the results into a separate spreadsheet. To append these data to a default spreadsheet, click on the command button labeled **Append**. Use the maximize button on the **Calculation** form (located in the bottom left-hand corner of the MDI form) to view all of the appended data records. A second way to generate output is to run any of the seven functions organized under **Utilities** on the main menu. These are all stand-alone utilities that may be used to generate bitmaps, graphs, and tabular data.

4.0 NAVIGATING THE MAIN MENU

The main menu in the GLA application is composed of eight separate menu items: File, Edit, View, Configure, Image, Calculate, Utilities, and Help. Contained within each of these menu items is another list of program functions. The following information describes all of the program functions found within the GLA application.

4.1 File Menu

The eleven functions found under the **File Menu** item are used for file management tasks such as, opening, saving, and printing files, or exiting the program:

- **Open Image...** allows the user to open an existing graphics file.
- **Save Image...** is used to save either the original, registered, or working images. The application will only save the image from the highlighted image form. Images will be saved in the default graphics format.
- **Save Image As...** will save an image to another filename, image format, or colour resolution. Note: the LEADTools common dialogue has its default colour depth set to 1 bit (2 colours). To save your image as true colour (24 bit) you must first select this in the **Save As Type** box found towards the bottom of the dialogue form.
- **New Summary Data...** loads an empty spreadsheet into the **Calculation Summary Output Data** form, which is found minimized in the lower left-hand corner of the MDI at run time. An empty spreadsheet is automatically loaded when you first start the program.
- **Open Summary Data...** is used to reload an existing summary output file (*.SUM), which contains output data that was previously saved from an earlier session.
- **File Info...** displays filename, format, and file size information for any one of the highlighted images. Note: file information will not be returned if the image data only resides in memory.
- **Select TWAIN Source...** is used to select an appropriate TWAIN-compliant peripheral (e.g., film scanner) and TWAIN driver. Once the **Select Source** dialogue appears, highlight the required driver and then click on the **Select** button. Note: this only tells GLA the appropriate driver to call when you want to scan another photograph. A TWAIN driver must be identified before you can scan an image.
- **Scan Image...** can be used to transfer an image directly from a TWAIN-compliant scanner to the GLA software. This function will only work if the scanner is turned on and connected, and the appropriate 32-bit TWAIN driver has been identified using the **Select TWAIN Source...** function.
- **Print Setup...** displays the standard Windows print setup options.
- **Print...** allows the user to scale the size of the image before printing. Clicking **OK** will send the print job off to the selected printer.
- **Exit** is used to terminate the program. You will be prompted to save any unsaved data before the application closes.

4.2 Edit Menu

Four separate edit functions can be found in the **Edit Menu**:

- **Undo** can only be used with the **Working Image** to undo the last change made. Note: if you have made a number of changes to the working image and want to get back to the original unmodified one, the easiest and fastest way is to click on the **Register Image** in the **Configure** menu or on the toolbar.
- **Copy** will make a bitmap copy of the **Registered** or **Working Image** onto the Windows clipboard.
- **Turn Off Region** will turn off the region of interest selection on the **Working Image**.
- **Select Region (Free Hand, Ellipse, and Rectangle)** can be used to identify a “region of interest” on the **Working Image**. Image modification functions (e.g., threshold, colour fill, etc.) will only work within the selected region. Three different methods can be used to identify a region: freehand, ellipse, or rectangle.

4.3 View Menu

The eleven program functions located under the **View Menu** are used to alter the image display (zooming), overlay a sky-region grid or topographic mask, and return image information (e.g., pixel position, colour, sky position, etc.):

- **Zoom to Point** is used to zoom into a selected point on any of the images. To zoom in, click on the left mouse button. To zoom out click on the right mouse button. Note: the image must repaint each time the mouse is clicked. Therefore the zoom function will not keep pace with mouse clicks that are repeated quickly.
- **Zoom to Rectangle** will zoom the image to a selected rectangular region on the image. To use this function, select an initial corner of the rectangle by pressing down on the left mouse, then drag the mouse cursor to the last corner and release.
- **Actual Size** will set the zoom factor to one and display the **Original**, **Registered**, or **Working Image** in its true dimensions. When the **Original Image** is first opened, the display size of the image is set according to the size of the MDI form. To view an image in its full size, highlight the image of interest and click on **Actual Size**.
- **Normal** will return the **Original**, **Registered**, or **Working Image** to a size relative to the MDI form. Use this function to return a zoomed or actual size image back to its original display settings.

- **Chain** is used to lock the image containers of the **Registered** and **Working Images** together, so that any time you zoom in on one image, the other follows and will display in the exact same manner. Note: use the scroll bars to pan around the zoomed images. With an MS IntelliMouse and IntelliPoint software, you can pan around the image by clicking the wheel button and moving the mouse in the direction of interest.
- **Return Projection Coordinates** will display the angular coordinates (angle of zenith, angle of azimuth) of any pixel when the mouse cursor is over the **Registered Image**. These coordinate data are displayed in the two left-most panels of the status bar located at the bottom of the MDI form. When the mouse falls outside the registration circle a value of -1 is returned for both the angles of zenith and azimuth.
- **Overlay Mask** allows the user to overlay the topographic mask on the **Registered Image**. If a mask has not been specified in the configuration settings, then the **Overlay Mask** function will appear disabled in the main menu and on the toolbar. Note: turning the Overlay Mask function off does not remove the mask from the calculations. To remove the mask from the calculations, you must turn the mask off in the configuration settings.
- **Overlay Sky-Region Grid** will let the user overlay a vector grid, which divides the hemispherical image into discrete azimuth-by-zenith regions based on equal-angular divisions of the sky. Note: the numbers of azimuth and zenith divisions are defined in the configuration settings under the **Resolution** tab.
- **Return Pixel Value** will return RGB (i.e., red plane, blue plane, and green plane) colour values for any pixel within the **Original, Registered, or Working Images**.
- **View Histogram** will display a two-dimensional graph (number of pixels on the y-axis and pixel intensity on the x-axis) showing the number of pixels that have a specific intensity value in any or all of the RGB planes. Note: this function is sometimes useful to help find the best intensity value that divides the sky and non-sky pixels during the threshold process.
- **Count Unique Colours** is used to return the number of unique colours contained in the **Original, Registered, or Working Images**.

4.4 Configure Menu

Program functions contained within the **Configure Menu** allow the user to define how each image will be processed. Two tasks are required before the user can analyze an image. First, the image must be registered, and second, the configuration settings must be altered before the final calculations are run. The following functions allow the user to do both:

- **Register Image** sets the application into registration mode, so that the user can identify two points on the circular image that define its extent and geographic orientation. These two points are then used to help convert each pixel contained in the image array into real world coordinates based on a specific projection transformation (e.g., polar, orthographic, etc.). These points may be entered graphically using the mouse (press left mouse button down and drag), or keyed in directly on the **Image Registration** form found next to the **Original Image**. The check box labeled **Fix Registration for Next Image**, which is located at the bottom of the **Image Registration** form, should be checked if you wish to reuse the same registration points for each image that is opened. Note: check the registration results using the **Overlay Sky-Region Grid** and **Return Projection Coordinates** functions in the **View Menu**. The **Fix Registration for Next Image** option should only be used with images that have fixed resolutions and registration points (e.g., images captured with a digital camera).
- **Load Configuration** allows the user to load in a configuration file (*.SCF) that has been previously saved. The configuration file contains all of the input necessary to run an analysis.
- **Edit Configuration** displays all of the configuration settings organized into a tab notebook. There are four individual tabs: **Image**, **Site**, **Resolution**, and **Radiation**. Click on each of the individual tabs to view the input organized under each of the headings. If you wish to include any of your changes in the current analysis, click on the **OK** button, or choose **Cancel** to ignore any changes. To save your configuration settings to a file, click on the **Save As** button.
- **Define Default** will write your current configuration settings into the Windows System Registry, so that each time you load the application those same settings will appear. Note: you should choose a default that reflects your current methods of image capture (e.g., camera orientation, and lens projection) and the atmospheric conditions for your region.
- **Configuration Summary** displays a form summarizing all of the current settings in the configuration. This form is automatically updated every time a change is made to the configuration settings. Note: you should keep this form minimized on the screen when you are analyzing a large number images that require many different configuration settings.

4.5 Image Menu

The **Image Menu** provides a number of image-processing functions, which are similar to the ones found in most standard graphics application. These functions are used to alter the **Working Image**, and are only available after the **Original Image** has been registered:

- **Threshold...** will convert the **Working Image** into a two-colour bitmap composed of black and white pixels. The “threshold” is a pixel intensity between 0 and 255 that defines the boundary at which image pixels will become white (represents sky) or black (represents foliage). For example, at a threshold value of 200, pixel intensities less than or equal to 200 will convert to black, while the remaining pixels become white. Move the slide bar on the **Threshold** form to change the intensity value interactively. Note: the image must have a threshold value assigned before the final calculations can be run. Use the **Select Region** function in the **Edit Menu** to threshold one region of the image different from another.
- **Brightness...** changes the intensity of the bitmap based on a flat scale.
- **Contrast...** modifies the contrast of a bitmap by brightening and darkening pixels with intensity values above and below 128, respectively.
- **Hue...** changes the hue of colours in the bitmap by rotating the color wheel. This method can rotate the colour wheel in either direction. A 180-degree rotation in either direction changes each colour to its complement. Positive rotation changes red toward green, green toward blue, and blue toward red. Negative rotation has the opposite effect.
- **Saturation...** increases or decreases the saturation of colours in the bitmap. Negative values decrease the saturation of colours, while positive values increase them. The saturation level is increased or decreased by a percentage of its present saturation level. This process is carried out for every pixel.
- **Histogram Contrast...** increases or decreases the contrast of the pixels in a bitmap, using a histogram to determine the median brightness. Pixel intensities above the median brightness value are increased, while those below the median are darkened.
- **Gamma Correct...** adjusts the intensity of colours in the bitmap by changing the gamma constant that is used to map the intensities.
- **Sharpen...** increases or decreases the sharpness of the image in the bitmap. Negative values decrease the sharpness of the image, while positive values increase the sharpness.
- **Emboss...** is purely an aesthetic effect that allows you to better see the spatial arrangement and size of the canopy gaps.
- **Choose a Colour Plane...** will allow the user to split a true colour (24-bit) bitmap into individual RGB planes. Certain colour planes will improve image contrast depending on the film type, species composition of the canopy, and sky conditions at the time of exposure.
- **Colour Fill** will fill the entire **Working Image** or a select region of it with the current default colour defined in the **Colour Palette**.

- **Draw** sets the application into draw mode, and the mouse cursor will change to a pen icon when the cursor is placed over the **Working Image**. Note: the fill colour will be white or black on an image that has been modified using the **Threshold** function.
- **Colour Palette...** displays a standard colour palette. Click on any colour to change the default colour settings.
- **Fill Area** allows the user to define whether the area **Inside** or **Outside** the “region of interest” is affected by any of the image modification functions. Note: the default is set to the **Inside** option.
- **Draw Width** is used to set the thickness of the **Draw** function to **Thin**, **Medium**, or **Thick**.

4.6 Calculate Menu

There is only one program function contained under the **Calculate Menu**:

- **Run Calculations...** allows the user to run two separate combinations of calculations. These combinations are labeled **Canopy Structure** and **Canopy Structure and Transmitted Gap Light**. The first option, **Canopy Structure**, will compute six different attributes: **% Sky Area**, **% Mask Area**, **% Canopy Openness**, **% Site Openness**, **LAI (4 Ring)**, and **LAI (5 Ring)**. The second option, **Canopy Structure and Transmitted Gap Light**, will compute each of the six attributes above, as well as 15 others that describe the amount of radiation transmitted by a forest canopy. These are: the Beam Radiation Tilt Factor (**RB**), Diffuse Radiation Tilt Factor (**RD**), Total Shortwave Extraterrestrial Radiation (**Extra**), the amount of direct (**Above Direct**), diffuse (**Above Diffuse**), and total (**Above Total**) radiation incident on a tilted or horizontal surface without any obstruction from the surrounding topography or canopy foliage; the amount of transmitted direct (**Above Direct Mask**), diffuse (**Above Diffuse Mask**), and total (**Above Total Mask**) radiation incident on a tilted or horizontal surface when there is blockage of light from the surrounding topography; the amount of transmitted direct (**Transmitted Direct**), diffuse (**Transmitted Diffuse**), and total (**Transmitted Total**) radiation incident on a tilted or horizontal surface when there is blockage of light from the surrounding topography and overlying forest canopy; **% Transmitted Direct**, **% Transmitted Diffuse**, and **% Transmitted Total**. An option at the bottom of the **Calculations** form labeled **Log Details to File** allows the user to create a text file (semi-colon delimited) containing all of these attribute data for each sky region, for each month (if input data are specified monthly), and for the growing season.

4.7 Utilities Menu

Within the **Utilities Menu** are seven program functions that allow the user to run a number of utilities. Although these utilities are considered stand alone, each function relies on selected input data stored in the configuration settings (e.g., site location, sky-region distribution, etc.):

- **Compute Extraterrestrial Radiation...** lets the user compute daily or monthly mean daily extraterrestrial solar radiation data in W/m^2 or $\text{MJ/m}^2/\text{d}$ for the period of the growing season. These data are output graphically, but may be saved into a delimited text file by clicking on the **Save As** button. Note: this utility is useful for computing mean daily Cloudiness Index (Kt) data when empirical global (total shortwave) radiation data are available for a given region.
- **Plot Sunpath...** is a utility used to plot the position of the sun for each solar time step (in minutes) during the growing season. The intensity of the dot marking each solar position is a function of the sun's brightness. Note: the image is a resized copy of the **Registered Image**. If you want to add more spatial information to the sunpath bitmap, overlay the sky-region grid and topographic mask before you click on the **Plot Sunpath**.
- **Display Sky-Region Brightness...** allows the user to create a bitmap that describes the direct and diffuse brightness weightings assigned to each sky region. The brightness or intensity of each sky region is a function of the geometrical relationships between the earth and sun, and the diffuse skylight distribution, relative area, and incidence angle for each sky region.
- **Plot Gap Fractions...** extracts gap fraction (unweighted pixel counts) and openness (sine weighted) data and plots them as a function of zenith angle. Both the gap fraction (ratio of sky pixels to total pixels per sky-region segment) and openness data are expressed as fractions, so that they can be plotted on the same graph. Openness however, is most often expressed as a percentage (i.e., % canopy openness). Note: if you export a delimited file from this utility you should convert the openness data to percentage openness by multiplying by 100 percent.
- **Plot Solar Irradiance...** will compute the amount of total (default), direct, and diffuse solar radiation incident above and below the forest canopy as a function of zenith angle. After you have run the function using the **Calculate** button, click on the three radio buttons at the top of the **Plot Solar Irradiance** form to toggle between the different data sets. The **Save As** button can be used to export the data as a delimited text file. Note: to change the resolution of the graphical output, use the **Edit Configuration (Resolution Tab)** function to increase the number of zenith regions.

- **Plot Sunfleck Distribution...** may be used to plot either sunfleck-frequency or daily sunfleck-duration data. A sunfleck may be defined as the brief period for which a point on the forest floor experiences direct sunlight. Over the course of a day, a site may experience numerous sunflecks of variable length and intensity depending on the distribution and size of canopy gaps. Sunfleck-frequency distribution, therefore, describes the frequency (number) of sunflecks of a specific duration (measured in minutes) that a site could potentially experience between the beginning and end dates of the growing season. Sunfleck duration, on the other hand, describes the number of minutes of potential direct sun that a site could see over the course of a day for each day of the growing season. Use the radio buttons at the top of the form to toggle between these two different data sets. Note: to change the resolution of the sunfleck data, use the **Solar Time Step (in Minutes)** setting under the **Resolution** tab of the configuration notebook.
- **Calculate Equal-Area Gap Fractions...** will extract gap fraction and openness data from images based on equal intervals of the cosine of the zenith angle. This method produces sky-regions that have equal sky-area weightings.

5.0 UNDERSTANDING THE CONFIGURATION SETTINGS

All of the configuration settings necessary to successfully run the GLA application were loaded into the Windows System Registry when the software was installed. These default settings can be viewed by clicking on the **Edit Configuration** function located in the **Configure Menu** or on the toolbar. However, before new images may be processed, the user must modify these configuration settings to reflect the photographic equipment, field methods, location, and atmospheric conditions associated with these new images. Although many of the settings are straightforward and require very little explanation, some are more difficult to understand and require some guidance. The following is a description of the input data found within the **Image**, **Site**, **Resolution**, and **Radiation** tabs of the configuration notebook.

5.1 Image Tab

- **Initial Cursor Point** is the first point that the user identifies on the image during the registration phase. This point is defined as one of four cardinal directions (e.g., north (default), south, east, or west). Use the two radio buttons labeled **Geographic North** and **Magnetic North** to identify whether the **Initial Cursor Point** corresponds to a geographic meridian or a local magnetic meridian. For example, if the camera was aligned using a

compass that was not corrected for the local magnetic declination, then the radio button marked **Magnetic North** should be checked and the appropriate magnetic declination entered into the text boxes located next to it. Note: to determine the local magnetic declination for any position on the globe, see http://www.geolab.nrcan.gc.ca/geomag/e_magdec.html.

- **Projection Distortion** settings define the way in which objects located in the hemispherical object region are projected to points on the image plane. Four standard lens projections are available in GLA: **Polar**, **Orthographic**, **Lambert's**, and **Stereographic** (see Herbert 1987 for definitions). Note: check the manufacturer's specifications to determine which projection the camera lens should conform too.
- **User-Defined** projections are custom fisheye lens distortions that are manufacturer specific. For example, the Nikkor 8-mm f/2.8 fisheye lens is manufactured to produce a standard polar projection, but calibration data show that this lens deviates slightly from this geometric pattern (Herbert 1987, Frazer et al. 1997). To define a custom lens distortion, first, click on the **Custom** command button. Second, when the **Custom Projection Transformation** form displays, click on the **New** button. Third, enter the name of the new lens in the **Current Lens Name** text box. Fourth, enter your calibration points in the data grid (i.e., angular position in the hemispherical object region versus the corresponding radial measure on the image plane – see Nikkor data as an example). A linear interpolation is used to estimate the location of objects between known points. Therefore, you must make sure that you enter an adequate number of calibration points. Make sure also, that the last point entered is 90 degrees. Fifth, press the **View** button at the bottom of the form to display the projection. Finally, press **OK** to save the custom projection to the Windows system registry. Note: the **Import** and **Export** buttons allow GLA users to exchange custom lens projection files (*.LNS) electronically.

5.2 Site Tab

- **Location** represents the position where the hemispherical photograph was taken, and is entered as geographic coordinates in degrees, minutes, and seconds. The suffix north/south for **Latitude** and east/west for **Longitude** defines the appropriate hemisphere in which the geographic coordinates are found. The **Elevation** of the site is entered as metres above mean sea level. Currently, GLA only makes use of the **Latitude** and **Elevation**, and therefore **Longitude** is an optional input.
- **Orientation** is used to define the general slope and aspect of the site. **Horizontal** surfaces are flat lying and typically found at valley bottoms or on plateaus in mountainous terrain.

Inclined sites have a **Slope** (degree of tilt) and **Aspect** (direction of tilt), measured in degrees, and are generally found on mountain- and valley-side slopes. Micro-topography should be ignored when considering these measurements in the field.

- **Topographic Shading** occurs when the surrounding terrain obstructs sun- and skylight radiating from selected regions of the sky. In mountainous areas, incident solar radiation is influenced not only by surface orientation but also by a reduced view of the sky hemisphere. Ridgelines will therefore create an “effective” horizon that is reduced from the 90 degrees characteristic of a flat site. In GLA, we call this **topographic shading**, and the angular coordinates describing the position of the surrounding topography are called the **topographic mask**. These data can be acquired manually in the field using a compass and clinometer, or automatically from a digital elevation model (DEM) using a geographic information system (GIS). To enter, edit, or view a **topographic mask**, click on the checkbox labeled **Use Topographic Mask Data** and then click on the **Edit...** command button. To create a new mask, click on **Add Row** as many times as there are points in your dataset. Once you have enough rows, begin to enter your data. **Azimuth** is the geographic bearing of the data point, and **Zenith** is the angular distance between the local zenith and the top of the ridgeline. A bearing of 0° is valid but the duplicate azimuth of 360° is not. Click **View** to display the data and **OK** to use the mask only for the session that you have GLA running. To save the mask data, choose **Export** and save these data to a file. Use **Import** to load already existing mask data.

5.3 Resolution Tab

- **Solar Time Step** (measured in minutes) describes the time interval for which the sun’s position will be measured between sunrise and sunset for the full length of the growing season. For example, a 2-minute time step causes the CGACalc module to compute the solar position every 2 minutes between sunrise and sunset. Note: because GLA computes the amount of beam radiation transmitted at each time step, it is best to use a smaller (< 5 minutes) time step value. Also, the resolution of the sunfleck data is affected by the solar time step, so make sure that this input parameter is properly set before running the **Plot Sunfleck Distribution** utility.
- **Growing Season Start** and **Growing Season End** define the starting and ending dates of the growing season. These dates affect the range in the solar declination for the period of interest. Note: to compute data for a single day, set the end date equal to the start date.

- **Sky Regions** are discrete areas of the sky hemisphere separated by equal-interval divisions of azimuth and zenith. In an effort to model diffuse-light transmission, GLA breaks the sky hemisphere into a finite number of discrete sky regions. Increasing the number of these sky regions should, in theory, improve the quality of the gap light transmission results. Note: when you increase the sky regions to a very large number, data generated by the **Calculate Equal-Area Gap Fractions** utility takes a very long time to load due to limitations with the control.

5.4 Radiation Tab

- **Data Source** tells the application how to derive monthly or growing season above-canopy solar radiation data. Two possible sources may be specified: **Modelled**, or **User-Defined**. The **Modelled** option tells the application that it should compute the appropriate above-canopy estimates using the region-specific parameters displayed in the **Model Parameters** frame. If the above-canopy solar radiation data are already known, then the user can choose the **User-Defined** option instead, and enter these data directly within the **User Defined** frame.
- **Modelled** data are calculated using five different input parameters. The first parameter is the **Solar Constant**, which is measured in W/m^2 . The solar constant is the total radiant flux of the sun on a perpendicular surface located outside the earth's atmosphere at a mean distance of 1 astronomical unit (see Gates 1980, Iqbal 1983). This value is anything but constant in the research literature, and will vary from 1350 to 1370 W/m^2 . The default solar constant is set to 1367 W/m^2 and should not require modification.
- **Cloudiness Index** (also known as **Kt**) is a site-specific measure of cloudiness. **Kt** can be estimated for any time period (e.g., hourly, daily, or monthly, etc.) as the fraction of extraterrestrial radiation that reaches the ground surface as total solar radiation (0.25 μm to 25.0 μm) for the specified period. For example, a **Kt** value of 0.5 tells us that exactly one-half of the extraterrestrial radiation incident on a horizontal surface outside the earth's atmosphere would reach the ground as total solar radiation over the specified period. The default Kt value has been set to 0.5, which is adequate to describe the annual cloudiness index for many parts of North America. Keep in mind however, that certain regions, such as coastal British Columbia, have significant seasonal shifts in cloudiness. **Kt** data constructed for southern Vancouver Island, for example, indicate that mean monthly **Kt** values generally range from 0.55 to 0.65 during the clear months of July through September to a low of 0.25 to 0.35 in the rainy period that stretches from mid-October to mid-March. Interestingly enough, these

maximum **Kt** values occur when the solar path is coincident with the greatest amount of openness in coastal forests of southern Vancouver Island (i.e., 25 to 40° from the zenith). In these situations, it is important to specify **Kt** by the month, otherwise the transmitted irradiance values will be under- or overestimated for regions with distinct seasonal differences in cloudiness (see section on **How to Compute Region-Specific Model Parameters** for more information).

- **Spectral Fraction** is the fraction of global solar radiation (0.25 μm to 25.0 μm) incident on a horizontal surface at the ground that falls within a limited range of the electromagnetic spectrum. For example, the photosynthetically active (PAR) or visible wavelengths (400 to 700 nm) will, over the course of a year, account for approximately 45 percent of total shortwave radiation incident on a horizontal surface (see Papaioannou et al. 1996). The default setting for the growing-season spectral fraction has therefore been set to 0.45. Keep in mind however, that the spectral fraction is also a function of cloud cover (**Kt**). Mean daily PAR and total shortwave radiation data collected at a site on southern Vancouver Island indicate that the ratio of PAR to total shortwave radiation (R_p/R_s) tends to remain relatively stable for **Kt** values greater than 0.5 (Spectral Fraction = 0.43); however, as the cloud cover increases and **Kt** falls below 0.5, there is an exponential increase in the R_p/R_s ratio (i.e., Spectral Fraction = 0.70 at **Kt** = 0.05), (see section on **How to Compute Region-Specific Model Parameters** for more information).
- **Units** refers to the units of measure used to compute the incident radiant flux density data output by the application. The default **Units** has been set for the incident photon flux density of PAR (**mols/m²/d**). Note: if you are interested in transmitted PAR, set the growing-season **Spectral Fraction** to 0.45 and the output **Units** to **mols/m²/d**. If you are interested in transmitted total shortwave radiation, set the **Spectral Fraction** to 1.0 and the **Units** of measure to **MJ/m²/d**.
- **Beam Fraction** is the ratio of direct (beam) to total (global) spectral radiation incident on a horizontal surface at the ground over a specified period (e.g., hourly, daily, monthly, etc.). This ratio is largely a function of cloud cover when the beam fraction is computed for periods longer than a day. For example, when the sky is perfectly clear (no clouds) between sunrise and sunset, approximately 85 to 90 percent of the incident total daily solar radiation is received as direct or beam radiation. In contrast, under heavy cloud cover, all of the incident total daily solar radiation will be in the form of diffuse radiation. For most regions of North America, the beam fraction will be approximately 0.5, when computed for the entire year. In climatic regions that experience significant seasonal shifts in cloud cover (e.g., coastal BC),

the beam fraction should be approximated for each month (see section on **How to Compute Region-Specific Model Parameters** for more information).

- **Use Input Data Specified by Month (Model Parameters)** is a data grid used to enter the monthly model parameters (i.e., **Cloudiness Index (Kt)**, **Beam Fraction**, **Spectral Fraction**). Note: input data are only required for the months that comprise the growing season. Input data related to months outside the growing season are ignored.
- **User Defined** are above-canopy solar radiation data entered by the user. These data may be obtained from solar radiation sensors (e.g., pyranometers or quantum sensors) or other more sophisticated predictive models. Both **Above-Canopy Direct** and **Below-Canopy Diffuse** data are required. Note: the application will assume that the user-defined data entered are unaffected by topographic shading effects (i.e., the data have been collected at the tops of ridges and not within narrow valley bottoms). If the empirical solar radiation data are strongly influenced by topography, do not use a **Topographic Mask** in the analyses, since the transmitted portions will be further underestimated. Also, enter a tilted site orientation only if the above-canopy data reflects a similar alignment.
- **Use Input Data Specified by Month (User Defined)** allows the user to enter **Above-Canopy Direct** and **Above-Canopy Diffuse** user-defined data for individual months of the growing season. Note: input data are only required for the months that comprise the growing season. Input data related to months outside the growing season are ignored.
- **Sky-Region Brightness** settings are used to describe the intensity of the solar disk and the diffuse sky. Two standard models are used in this application to describe the intensity of a diffuse sky: the Universal Overcast Sky (**UOC**), and the Standard Overcast Sky (**SOC**) (see Hutchison et al. 1980). The **UOC** model considers all regions of the sky hemisphere to be equally as bright, while the **SOC** assumes that the zenith is three times as bright as the horizon. Note: the bitmap displayed on the form shows the spatial distribution of sky-region intensity or brightness as a function of sky-region area and incidence angle. Use the **Display Sky-Region Brightness** utility to look at the distribution when the receiving surface has been tilted.
- **Clear-Sky Transmission Coefficient** is a factor that describes the regional clarity of the atmosphere with respect to the instantaneous transmission of direct (beam) radiation. This clear-sky coefficient will vary with geographic location and elevation, and will range from 0.4 to 0.8 (see Gates 1980). For most dust-free regions, including North America, this coefficient will typically fall somewhere between 0.6 and 0.7. Black et al. (1991) estimated the **Clear-Sky Transmission Coefficient** to be 0.65 on Vancouver Island, British Columbia.

6.0 HOW TO GENERATE AND INTERPRET OUTPUT RESULTS

A user may generate output from the application using either the **Calculate Menu** or the **Utilities Menu**. The **Calculate Menu** allows the user to compute canopy openness, effective LAI, and percentage light transmission. The **Utilities Menu** offers seven different program functions, which are used to graph, plot, and display openness and solar radiation data (see **Utilities Menu** under the **Navigating the Main Menu** section).

6.1 Calculation Report (Summary)

As many as twenty-two attributes will be displayed on the **Calculation Report Summary** form when the **Run Calculations** command under the **Calculate Menu** is selected by the user. Only the first 6 of these 22 attributes are displayed if the **Canopy Structure** option on the **Run Calculations** form is checked. The report is divided into three sections: openness, effective LAI (4 and 5 ring integrations), and above- and below-canopy irradiances. The following is a description of each computed parameter:

- **% Sky Area** is the percent area of the sky hemisphere found above the effective horizon. If the effective horizon is at 90° (i.e., no topographic mask), then **% Sky Area** will equal 100 percent. However, if the effective horizon is less than 90°, then the area of visible sky will be less than 100 percent.
- **% Mask Area** is the percent area of the sky hemisphere that is obstructed by the surrounding topography.
- **% Canopy Openness** is the percentage of open sky seen from beneath a forest canopy. This measure is computed from the hemispherical photograph only, and does not take into account the influence of the surrounding topography.
- **% Site Openness** is the percentage of open sky seen from beneath a forest canopy given the influence of an effective horizon that is less than 90° (topographic shading).
- **LAI 4 Ring** is the effective leaf area index integrated over the zenith angles 0 to 60° (see Stenberg et al. 1994).
- **LAI 5 Ring** is the effective leaf area index integrated over the zenith angle 0 to 75° (see Welles and Norman 1991).
- **Units** is the unit of measure used to represent solar irradiance estimates for above and below the forest canopy.
- **RB** is the beam tilt factor computed for an arbitrarily tilted surface (Iqbal 1983).
- **RD** is the diffuse tilt factor computed for an arbitrarily tilted surface (Iqbal 1983).

- **Above Direct** is the amount of direct (beam) radiation incident on a horizontal or tilted surface located at the earth surface without any effect of topography or forest canopy.
- **Above Diffuse** is the amount of diffuse radiation incident on a horizontal or tilted surface located at the earth surface without any effect of topography or forest canopy.
- **Above Total** is the sum of the **Above Direct** and **Above Diffuse**.
- **Above Direct Mask** is the amount of direct radiation incident on a horizontal or tilted surface taking into account the effect of a topographic mask.
- **Above Diffuse Mask** is the amount of diffuse radiation incident on a horizontal or tilted surface taking into account the effect of a topographic mask.
- **Above Total Mask** is the sum of **Above Direct Mask** and **Above Diffuse Mask**.
- **Trans Direct** is the amount of direct solar radiation transmitted by the canopy and topographic mask (if one has been defined).
- **Trans Diffuse** is the amount of diffuse solar radiation transmitted by the canopy and topographic mask (if one has been defined).
- **Trans Total** is the sum of **Trans Direct** and **Trans Diffuse**.
- **% Trans Direct** is the ratio of **Trans Direct** to **Above Direct Mask** multiplied by 100%.
- **% Trans Diffuse** is the ratio of **Trans Diffuse** to **Above Diffuse Mask** multiplied by 100%.
- **% Trans Total** is the ratio of **Trans Total** to **Above Total Mask** multiplied by 100%.

6.2 Calculation Report (Detailed)

The application can also generate a detailed report that shows much of the same information displayed in the **Calculation Report Summary**; however, the information in the detailed report is output on a sky region basis. This report will also include monthly information per sky region if monthly input data are used in the configuration settings. To output a detailed report, place a check in the box labeled **Log Details to File...** found at the bottom of the **Run Calculations** form. The following is a list of the column definitions for the detailed output file:

- **Month** (Column 1) is the month number ranging from 1 to 12. The month number **All** refers to the entire growing-season. If monthly input data were not provided in the configuration settings, then individual month data will not be presented in the detailed output file.
- **Alt Bin** (Column 2) identifies the index value of the sky-region altitude bin. The index increases as the angle of altitude increases from a minimum at 0° and a maximum at 90°.

- **Azi Bin** (Column 3) identifies the index value of sky-region azimuth bin. The index increases as the angle of azimuth increases from a minimum at 0° and a maximum at 360° .
- **Altitude** (Column 4) is the mid-point angle of the sky-region. Altitude angle is the angular distance measured from the horizon (zenith is the angular distance measured from the zenith).
- **Azimuth** (Column 5) is the mid-point angle of the sky region. Azimuth is the angular distance measured clockwise from geographic north. Note: remember that east and west are reversed on the fisheye photograph since the camera is looking skyward.
- **Sky Sky Pixels** (Column 6) is the number of overlapping pixels within a sky region, which are open on the photograph and open on the topographic mask.
- **Sky Top Pixels** (Column 7) is the number of overlapping pixels within a sky region, which are open on the photograph but closed on the topographic mask. Note: this field will always be equal to 0 if a mask has not been used in the analysis.
- **Fol Top Pixels** (Column 8) is the number of overlapping pixels within a sky region, which are closed on the photograph and closed on the topographic mask. Note: this field will always be equal to 0 if a mask has not been used in the analysis.
- **Fol Sky Pixels** (Column 9) is the number of overlapping pixels within a sky region, which are closed on the photograph but open on the topographic mask.
- **Total Pixels** (Column 10) is the total number of pixels contained in a sky region.
- **Sky Area** (Column 11) is the fraction of sky contained in each sky region that is not blocked by the surrounding topography. Note: this measure is not to be confused with canopy openness.
- **Mask Area** (Column 12) is the fraction of sky contained in each sky region that is blocked by the surrounding topography. Note: if the **Mask Area** is greater than 0, **Sky Area** will be less than 1.
- **Total Area** (Column 13) is the fraction of the sky hemisphere contained in each sky region.
- **Gap Can Diffuse** (Column 14) is the fraction of pixels in each sky region that are open (white) on the fisheye photograph.
- **Gap Topo Diffuse** (Column 15) is the fraction of pixels in each sky region that are open (white) on the topographic mask.
- **Gap Both Diffuse** (Column 16) is the fraction of overlapping pixels in each sky region that is open (white) on both the topographic mask and the fisheye photograph.
- **Gap Can Direct** (Column 17) is the fraction of the total monthly or growing-season relative beam intensity weightings found within canopy gaps in each sky region. Note: some sky

regions will have a **Gap Can Direct** value equal 1 even though the sun's path does not pass through that part of the sky. This happens because the variable array holding these data have been initialize using a value of 1 to avoid division by zero.

- **Gap Topo Direct** (Column 18) is the fraction of the total monthly or growing-season relative beam intensity weightings, which is not blocked by the topographic mask in each sky region. Note: some sky regions will have a **Gap Topo Direct** value equal 1 even though the sun's path does not pass through that part of the sky. This happens because the variable array holding these data have been initialize using a value of 1 to avoid division by zero.
- **Gap Both Direct** (Column 19) is the fraction of the total monthly or growing-season relative beam intensity weightings found within overlapping gaps in the canopy and topographic mask for each sky region. Note: some sky regions will have a **Gap Both Direct** value equal 1 even though the sun's path does not pass through that part of the sky. This happens because the variable array holding these data have been initialize using a value of 1 to avoid division by zero.
- **Canopy Openness** (Column 20) is the percentage of the total sky area that is found in canopy gaps for each sky region. Note: These are the **Gap Can Diffuse** data weighted by hemispherical area and multiplied by 100%. Summing the **All** month data across all sky regions is the percentage canopy openness for the site.
- **Site Openness** (Column 21) is the percentage of the total sky area that is found in overlapping gaps in the canopy and mask for each sky region. Note: These are the **Gap Both Diffuse** data weighted by hemispherical area and multiplied by 100%. Summing the **All** month data across all sky regions is the percentage site openness for the site.
- **Id_UOC** (Column 22) is the monthly and or growing-season diffuse intensity weightings for each sky region calculated according to the Universal Overcast Sky model (UOC). Note: individual month weightings summed across all sky regions must equal 1.
- **Id_SOC** (Column 23) is the monthly and or growing-season diffuse intensity weightings for each sky region calculated according to the Standard Overcast Sky model (SOC). Note: individual month weightings summed across all sky regions must equal 1.
- **Above Direct** (Column 24) is the absolute amount (in $\text{mol/m}^2/\text{d}$ or $\text{MJ/m}^2/\text{d}$) of monthly and/or growing-season direct (beam) radiation found above the canopy that is contributed by each sky region. This measure excludes the effect of topography and assumes that the effective horizon is equal to 90° .
- **Above Diffuse** (Column 25) is the absolute amount (in $\text{mol/m}^2/\text{d}$ or $\text{MJ/m}^2/\text{d}$) of monthly and/or growing-season diffuse radiation found above the canopy that is contributed by each

sky region. This measure excludes the effect of topography and assumes that the effective horizon is equal to 90°.

- **Above Total** (Column 26) is the absolute amount (in mol/m²/d or MJ/m²/d) of monthly and/or growing-season total (direct plus diffuse) radiation found above the canopy that is contributed by each sky region. This measure excludes the effect of topography and assumes that the effective horizon is equal to 90°.
- **Mask Direct** (Column 27) is the absolute amount (in mol/m²/d or MJ/m²/d) of monthly and/or growing-season direct (beam) radiation found above the canopy that is contributed by each sky region. This measure includes the effect of topography if a mask has been introduced. If a mask has not been defined, then **Mask Direct** will equal **Above Direct**.
- **Mask Diffuse** (Column 28) is the absolute amount (in mol/m²/d or MJ/m²/d) of monthly and/or growing-season diffuse radiation found above the canopy that is contributed by each sky region. This measure includes the effect of topography if a mask has been introduced. If a mask has not been defined, then **Mask Diffuse** will equal **Above Diffuse**.
- **Mask Total** (Column 29) is the absolute amount (in mol/m²/d or MJ/m²/d) of monthly and/or growing-season total (direct plus diffuse) radiation found above the canopy that is contributed by each sky region. This measure includes the effect of topography if a mask has been introduced. If a mask has not been defined, then **Mask Total** will equal **Above Total**.
- **Trans Direct** (Column 30) is the absolute amount (in mol/m²/d or MJ/m²/d) of monthly and/or growing-season direct (beam) radiation found below the canopy and topographic mask that is contributed by each sky region. Note: **Trans Direct** is equal to **Mask Direct** multiplied by **Gap Both Direct**.
- **Trans Diffuse** is the absolute amount (in mol/m²/d or MJ/m²/d) of monthly and/or growing-season diffuse radiation found below the canopy and topographic mask that is contributed by each sky region. Note: **Trans Diffuse** is equal to **Mask Diffuse** multiplied by **Gap Both Diffuse**.
- **Trans Total** is the absolute amount (in mol/m²/d or MJ/m²/d) of monthly and/or growing-season total (direct plus diffuse) radiation found below the canopy and topographic mask that is contributed by each sky region.

7.0 HOW DOES GLA COMPARE TO GLI/C?

The basic gap light transmission model in GLA is very similar to the gap light index (GLI) used in GLI/C (see Canham 1988). There are, however, a few differences that should be identified. First, the user should remember that there are many ways to alter the way in which GLA will compute the percentage of incident direct and diffuse radiation transmitted through gaps. For example, a user may change the solar time step, the sky-brightness model, the inclination angle of the receiving surface, or they may add a different projection distortion model, or introduce a topographic mask. Any or all of these changes will impact on the degree of similarity between the estimates produced by these two applications. For the nearest approximation of GLI, set the GLA configurations settings to: 1) polar projection distortion, 2) horizontal site orientation, 3) no topographic mask, 4) 2- or 3-minute solar time step, 5) use the modelled data source with growing-season parameters, 6) use a UOC sky-brightness model, and 7) make sure that the beam fraction, clear-sky transmission coefficient, and number of sky regions are set the same in both applications.

A second difference between GLA and GLI is the way in which each of these two models computes transmitted direct (beam) radiation. Both programs use the same basic algorithm to compute the relative intensity of the sun at any instance of time (see Spencer 1971, Gates 1980, Iqbal 1983, Michalsky 1988). Although, a more recent approximation of the relative optical air mass has been introduced in GLA (see Kasten and Young 1989). More significant, however, is the way in which GLA estimates beam transmission through gaps. In GLA, the program computes a solar position and relative intensity weighting for each solar time step, and at each of these positions along the sun's path also checks to see if the underlying pixel is opened or closed. The ratio of the sum of the relative beam weightings found in gaps to the total relative beam weightings for the entire sky hemisphere is used as a measure of percentage beam transmission. GLI works in much the same way, except that the sum of the relative beam weighting found in gaps is estimated as the sum of the relative beam weightings per sky region multiplied by the gap fraction per sky region. This solution works well in all sky regions where the sun moves across all parts of it. An exception to this rule however, can occur at the minimum and maximum solar declinations when the sun may visit only a limited portion of a sky region. In this case, the GLI percentage beam transmission estimates might be slightly greater than ones produced by GLA. Increasing the number of sky regions in GLI should minimize any of this difference.

A third difference between the two programs is a change in the gap light index nomenclature. In GLA, the relative gap light index is composed of percent-transmitted direct, diffuse, and total solar radiation. These three output variables correspond directly to the %Beam, %Diffuse, and %Global calculated by GLI. We changed the name from global to total, largely because in mountainous areas, canopy gaps may transmit a significant amount solar radiation reflected from the surrounding hillslopes. Since this form of gap light is completely ignored by GLA, we have used the term “total” to denote the sum of the direct and diffuse components of gap light.

8.0 HOW TO COMPUTE REGION-SPECIFIC MODEL PARAMETERS

GLA requires three different input parameters to estimate monthly or growing-season estimates of above-canopy solar radiation: i.e., the Cloudiness Index (K_t), Spectral Fraction, and the Beam Fraction. All of these parameters are region specific and can be estimated from empirical meteorological data. In Canada, meteorological stations that monitor incoming solar radiation are particularly sparse, both in their years of recorded data and geographic distribution. Even more rare is the measurement of diffuse and photosynthetically active radiation (400 to 700 nm). Deriving reliable parameter estimates for certain parts of British Columbia and Canada may therefore be a difficult task. The following is a guideline for constructing daily, monthly, and growing-season input parameters.

8.1 Cloudiness Index (K_t)

For any given time period, K_t can be computed as the ratio of global radiation incident on a horizontal surface at the ground to the amount of extraterrestrial radiation incident on a horizontal surface outside the earth’s atmosphere (Lui and Jordan 1960, Iqbal 1983):

$$K_t = H/H_o$$

Where H is the amount of global radiation incident at the ground, and H_o is amount of extraterrestrial radiation incident on a horizontal surface outside the earth’s atmosphere. Both estimates must share the same units of measure and integration period (e.g., daily, monthly, etc.). Global radiation data can be obtained directly from available solar radiation measurements or estimated indirectly using the number of sunshine hours per day (Iqbal 1983). Mean daily or

monthly mean daily extraterrestrial data (in W/m^2 or $\text{MJ/m}^2/\text{d}$) can be calculated using the **Compute Extraterrestrial Radiation** in the **Utilities Menu** of GLA.

Total daily global radiation data collected at the Sooke Lake Dam on southern Vancouver Island by the Greater Victoria Capital Regional District (CRD) and total daily extraterrestrial insolation data estimated by GLA were used to construct daily Kt estimates for the period of February 1998 to December 1998 (Figure 2). These data show two interesting patterns. First, Kt varies significantly from day to day. For example, on clear days Kt reaches a maximum of approximately 0.8, indicating that 80% of the mean daily extraterrestrial radiation incident on a horizontal surface outside the atmosphere arrived at the ground as global solar radiation. In contrast, daily Kt will be less than 0.1 on extremely overcast days. Second, there is a significant seasonal pattern within the daily Kt data, which indicates that summers on the coast tend to be mostly sunny and clear (monthly Kt averages 0.55 to 0.65), while winters are cloudy and rainy (monthly Kt averages 0.25 to 0.35) (Figure 3).

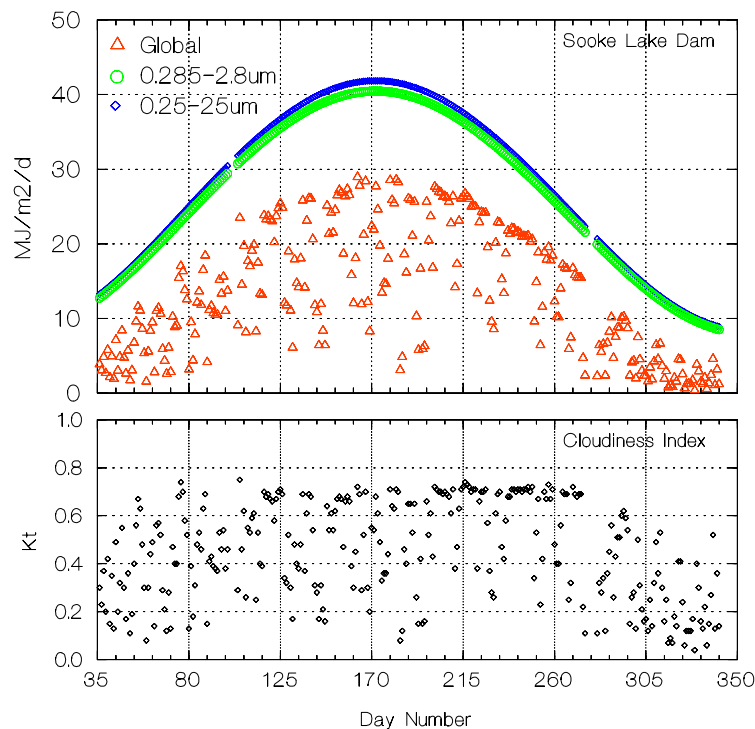


Figure 2. Daily Kt data calculated for a site located at Sooke Lake, Vancouver Island, British Columbia. Daily global solar radiation data were collected at a permanent meteorological station operated by the Greater Victoria Capital Regional District (CRD). Extraterrestrial insolation data were predicted using the GLA software program.

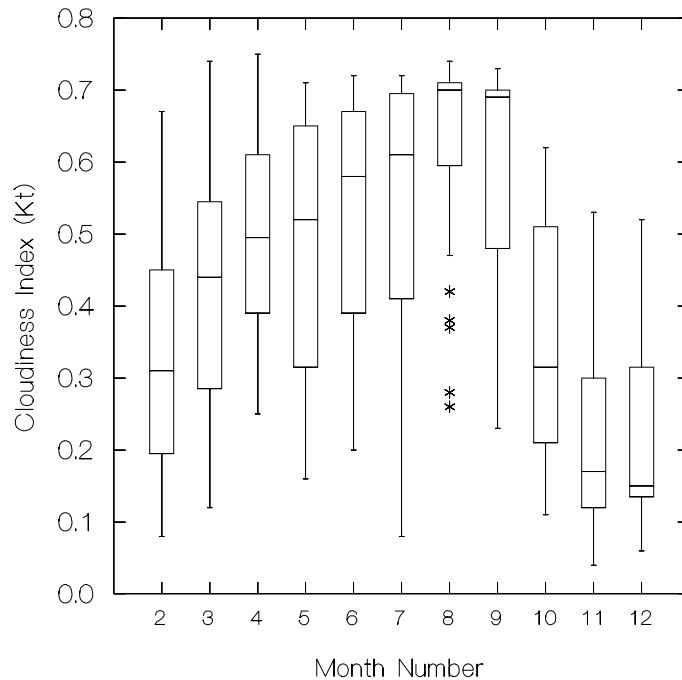


Figure 3. Box-and-whisker plot showing the distribution of daily Kt estimates (collected at the Sooke Lake, BC) aggregated by individual months. Mean monthly Kt estimates reach their maximum by late summer (July to September) when sky conditions are generally clear, while cloudy late-fall and early-winter months (October to February) show a significant decrease in Kt.

For regions that do not show significant shifts in seasonal cloudiness, it is unnecessary to enter monthly Kt estimates into the GLA gap light model. However, for regions such as Vancouver Island that do experience distinct seasonal differences in cloudiness, it is advisable to compute Kt on a monthly basis. To calculate monthly Kt values, divide the mean daily global radiation for the month of interest by the mean daily extraterrestrial insolation for that same month.

8.2 Spectral Fraction (R_p/R_s)

The spectral fraction is the ratio of solar energy found in a limited part of the electromagnetic spectrum to the total shortwave (broadband) radiation (R_s) contributed by all wavelengths (0.25 μm to 25 μm). Photosynthetically active radiation (PAR), for example, is part of the visible waveband between 400 and 700 nm (R_p). The ratio R_p/R_s computed for a single day, tells us the fraction of daily global radiation incident on a horizontal surface that will be received as PAR. The R_p/R_s ratio can be measured directly using a pyranometer and quantum sensor mounted side

by side. PAR and total shortwave radiation data collected at a meteorological station located at Sooke Lake on southern Vancouver Island, indicate that the daily R_p/R_s ratio remains fairly stable throughout most of the year averaging approximately 0.45 (Figure 4). A summary of published R_p/R_s data compiled by Papaioannou et al. (1996) for different sites around the world indicate that this ratio averages 0.44 to 0.47 with slightly higher averages reported for cloudy day observations (i.e., 0.483 to 0.69).

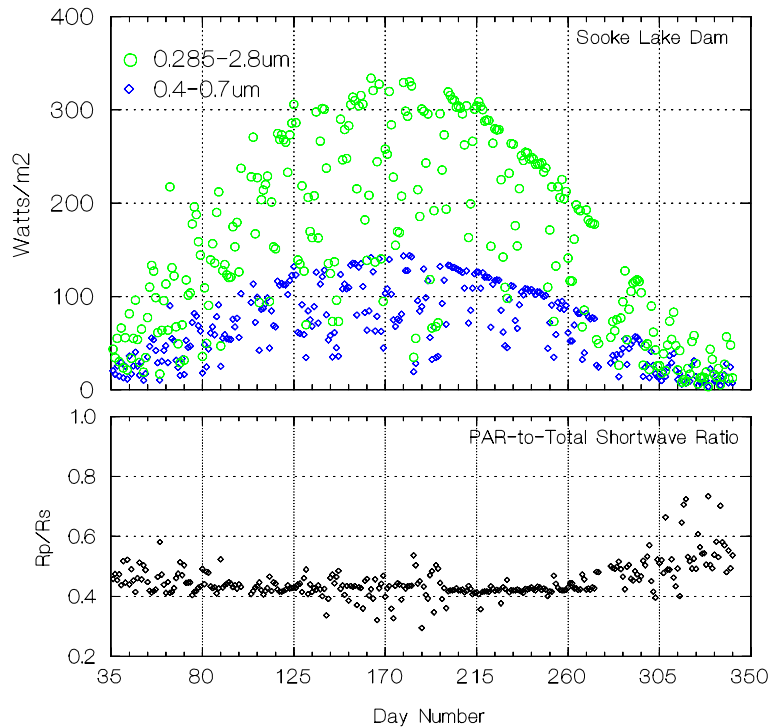


Figure 4. The ratio of PAR to total shortwave radiation (R_p/R_s) at Sooke Lake on southern Vancouver Island remains fairly stable throughout the year. R_p/R_s ranges between 0.4 and 0.72 and averages 0.45. R_p/R_s values less than 0.4 correspond to days with incomplete hourly observations.

A similar rise in the R_p/R_s ratio under cloudy-sky conditions has also been noted for total shortwave and PAR data collected at the meteorological station at Sooke Lake. The R_p/R_s ratio tends to remain stable for K_t values greater than 0.5; however, as cloud cover increases and K_t falls below 0.5, there is an exponential increase in the proportion of PAR (Figure 5). When empirical data are unavailable, the negative relationship between the R_p/R_s ratio and K_t can be reasonably predicted ($R^2 = 0.73$) using the following exponential function:

$$R_p/R_s = 1 - \exp(-0.499Kt^{-0.219})$$

Where R_p/R_s is the ratio of total daily global PAR to total daily global (total shortwave) radiation, and Kt is the fraction of total daily extraterrestrial radiation received at the ground surface as global radiation.

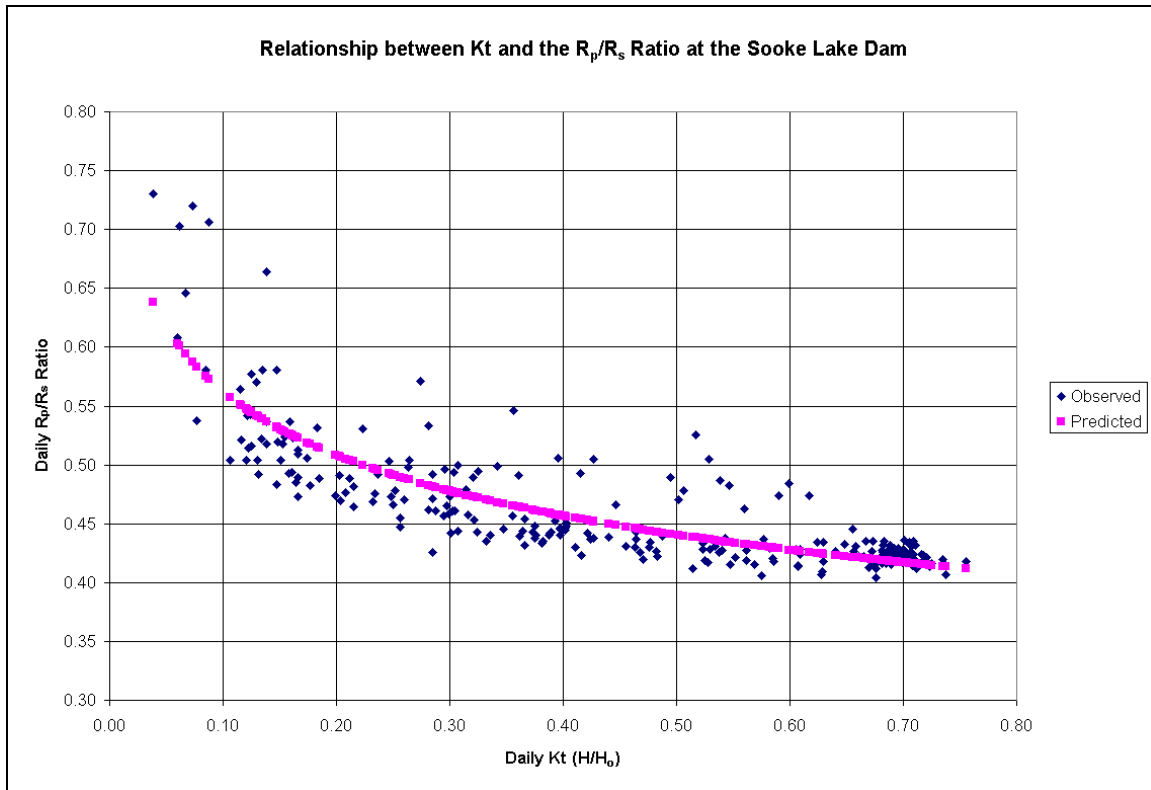


Figure 5. The relationship between Kt and the R_p/R_s at the Sooke Lake watershed on southern Vancouver Island. The R_p/R_s ratio remains relatively stable at Kt values greater than 0.5. As skies become more cloudy ($Kt < 0.5$), the R_p/R_s ratio increases exponentially. The line of points running through the observed data represents the predicted estimates produced by the exponential function shown above.

To compute a monthly mean daily R_p/R_s ratio for a site, 1) calculate a daily R_p/R_s ratio using daily Kt and the exponential function above, 2) multiply the predicted daily R_p/R_s ratio by the mean daily global (total shortwave) solar radiation, 3) calculate mean daily global PAR and mean daily global (total shortwave) solar radiation for each month, and 4) divide the monthly mean daily global PAR by the monthly mean daily global (total shortwave) solar radiation to compute monthly spectral fraction parameters.

8.3 Beam Fraction (H_b/H)

Solar radiation is composed direct (H_b) and diffuse (H_d) components. Direct (beam) radiation is the energy that streams from the solar disk and is neither absorbed nor scattered by the earth's atmosphere. Diffuse radiation is the portion that is scattered towards the earth's surface from all regions of the sky. The amount of direct and diffuse radiation that reaches the earth's surface is a function of cloudiness (K_t). For example, under heavy-cloud cover, all incident solar radiation will be in the form of diffuse radiation. When the sky is cloud free, approximately 85 to 90% of the incident solar radiation is received as direct or beam radiation (Figure 6).

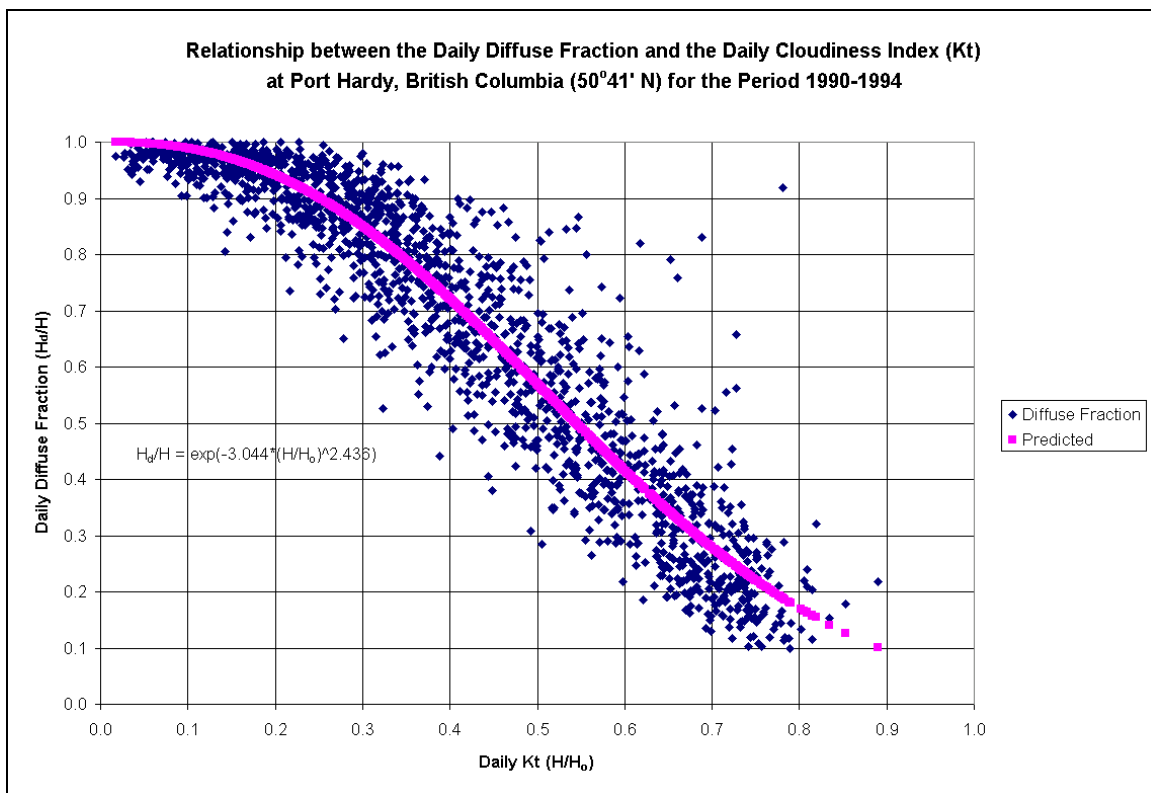


Figure 6. The relationship between K_t and the diffuse fraction at Port Hardy on northern Vancouver Island, British Columbia. The daily diffuse fraction is the ratio of diffuse radiation (H_d) to global radiation (H) incident on a horizontal surface. These data show that as skies become clearer (K_t increases), more of the incident global radiation is composed of direct (beam) radiation. The diffuse fraction reaches a minimum of approximately 0.1 when K_t reaches its maximum around 0.8. The beam fraction is equal to 1 minus the diffuse fraction. The line running through the data points represents a set of values predicted according to the exponential function given below.

A number of mathematical functions developed from empirical relationships between the beam or diffuse fractions and K_t have been used to separate global radiation into direct and diffuse components (Iqbal 1983, Spitters et al. 1986, Reindl et al. 1990). Four years of total daily diffuse and global solar radiation data published by the federal Atmospheric Environment Service (AES) for Port Hardy, British Columbia, have been used to derive an approximation function ($R^2 = 0.9$, $n = 1460$), which can be used to separate daily global solar radiation into its direct and diffuse components:

$$H_b/H = [1 - \exp(-3.044K_t^{2.436})]$$

Where H_b/H is the fraction of daily global solar radiation incident on a horizontal surface that is in the form of direct solar radiation, and K_t is the daily cloudiness index.

Ideally, the approximation function should be developed for the waveband of interest, since specific wavelengths within the solar spectrum tend to be preferentially absorbed and scattered by the earth's atmosphere. Long-term daily K_t , diffuse PAR, and global PAR data collected by the Institute of Ecosystem Studies in Millbrook, New York, indicate that the relationship between daily $H_d \text{ PAR}/H \text{ PAR}$ and daily K_t is not as easily predicted as it is for total shortwave radiation. Nevertheless, the correlation using the above approximation function is still quite good ($R^2 = 0.77$, $n = 730$). Other approximation functions for daily and monthly average daily diffuse radiation are given in Iqbal (1983).

To compute monthly beam fraction parameters, 1) use the predicted daily R_p/R_s ratio to compute daily global PAR, 2) multiple the predicted beam fraction (H_b/H) by the daily global PAR data to calculate the amount of direct and diffuse PAR, 3) compute average daily direct and global PAR for each month of the growing season, 4) divide the monthly mean direct PAR by global PAR to compute monthly mean beam fraction data.

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