Modelling global radiation for the Portofino area in Italy

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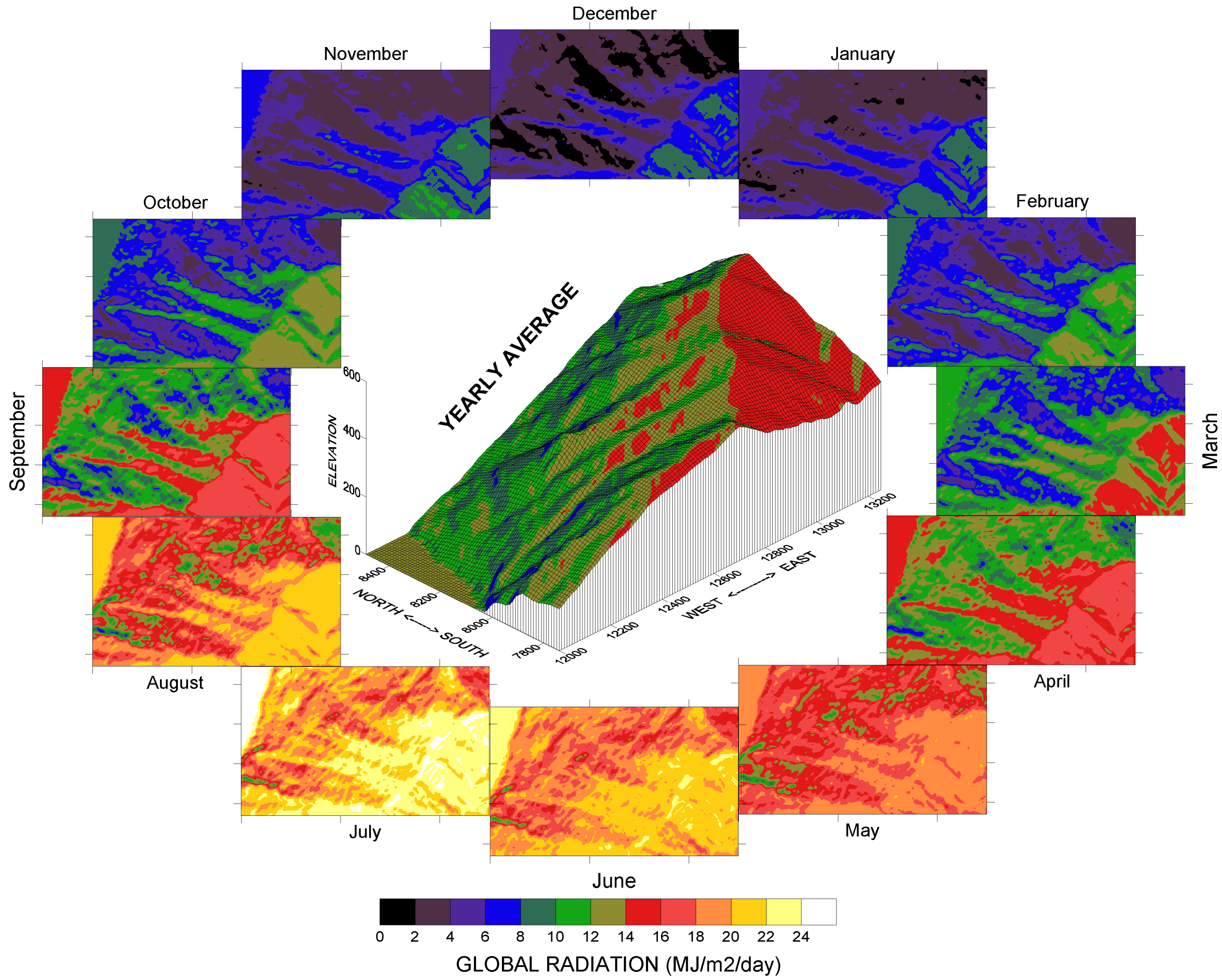

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SUMMARY

Solar radiation is an important parameter affecting many meteorological and biological processes. In hilly or mountainous terrain global radiation (the total amount of solar radiation arriving at the surface) varies from place to place, as a result of the slope and orientation of the slope. Modelling is the only practical way to assess the detailed distribution of global radiation in such terrain.

The model described here calculates global radiation as the sum of direct and diffuse radiation, taking into account cloud cover information. In order to obtain direct radiation the clear sky transmission was calculated using Linke's approach. Diffuse radiation was determined by a method that closely resembles Erbs' approximation. For diffuse radiation under a clouded sky an average cloud transmissivity was used for all cloud types, because no information is available about cloud cover percentages of different cloud types.

The model is optimised in such a way that the calculations for 500.000 grid points for an entire month take no more than a few minutes on a modern PC. The main input and output files are in Surfer ™ ASCII format and can be transformed to ArcInfo ASCII files. The model was thoroughly tested and debugged. There are some restrictions to using the model, in other locations, since some parameters are tuned to the Portofino area (e.g. elevation close to sea level and Linke's turbidity factor equal to 2.7).

Modelled annual mean global radiation for horizontal surfaces in the Portofino area was 13.8 MJ/m^2/day, when adequate data are used to estimate relative duration of sunshine. This is within 1% of values published for meteorological stations in the area. It seems the model slightly underestimates global radiation in spring and overestimates in summer. If raw cloud cover data are used the model underestimates annual mean global radiation by about 5%.

The maps of modelled monthly mean global radiation provide a good insight in the yearly course and the difference between various slopes. Monthly mean global radiation varies from less than 2 MJ/m^2/day for north-facing slopes in December to 25 MJ/m^2/day for horizontal surfaces in July.

Annual mean global radiation is highest (15 MJ/m^2/day) on south-facing slopes with a slope angle of about 30°. The lowest values (7 MJ/m^2/day) occur on steep north-facing slopes.

FRONT PAGE:
Yearly course of global radiation calculated for a small fraction of the Portofino Area.

Contents

1. Introduction

Solar radiation is an important climate parameter driving many processes. The energy present in the solar radiation is absorbed at the surface and can be used to heat the soil and the air near the surface. For evaporation the input of solar energy also is a crucial factor since the energy needed for evaporation is mainly obtained in the form of solar radiation. As long as enough water is available, a major part of the energy in solar radiation will be used for evaporation, thereby limiting the daily amplitude of temperature.

Also for plants solar radiation is vital, since they use the energy for the photosynthesis process. This might lead to the hypothesis that the more solar radiation is available, the better plants will grow. This is however only true is water availability is not a limiting factor. In order to get one of the resources for photosynthesis, namely carbon dioxide, they have to open their stomata. If they do so, they will also loose water. If not enough water is available plants will have to keep their stomata closed, resulting in lesser growth. North facing slopes generally receive less radiation, resulting in lower evaporation losses. Therefore the soil-plant system can retain the available amount of water for a longer time. If water is a limiting factor, then the plants on north-facing slopes can therefore make more use of the solar radiation for photosynthesis during a longer time, resulting in better plant growth. The north-facing slopes generally have less problems with drought stress.

In hilly and mountainous areas the input of solar radiation varies from place to place, depending on slope angle and slope orientation (aspect angle). Since it is practically impossible to install a pyranometer (an instrument measuring the intensity of solar radiation) at each point in the area, modelling of solar radiation is a good alternative.

This report describes a model that is used to model the monthly mean global radiation (intensity of solar radiation) in a hilly or mountainous area. Important input data to the model are slope angle and aspect at each point in the area, which are derived from a DEM (Digital Elevation Model). Also needed are latitude and information on cloud cover. Output of the model is monthly maps for the global radiation in the area. The model is applied to the Portofino area (near Genoa in Italy). In principle the model applicable to any area, but there are some restriction in this, since some of the parameters specially apply to the Portofino area.

This report first gives an overview of the theory needed, the implementation of the theory in the model, a short model description and than concentrates on the results for the Portofino area.

2. Theory

Calculating ***extraterrestrial radiation*** (intensity of solar radiation on a horizontal surface outside the atmosphere) is relatively straightforward and needs only astronomical data. Part of this radiation is reflected at the tops of clouds and part is absorbed or scattered in the atmosphere by the air molecules, aerosols and clouds. The amount of radiation that can reach the surface without being reflected, absorbed or scattered is called ***direct radiation***. On a sloping surface the direct radiation also depends on slope angle and slope aspect. Part of the radiation that is scattered can still reach the surface as ***diffuse radiation***. In the case of a clouded sky all radiation penetrating through the clouds is considered to be diffuse radiation. The sum of direct and diffuse radiation is called ***global radiation***; that is all solar radiation reaching the surface. Much of the theory needed is discussed in Van Boxel 2000.

The next sections contain the mathematical description of the calculation of global radiation for a sloping surface, following more or less the definition is the previous paragraph.

2.1 Extraterrestrial radiation.

The extraterrestrial radiation (intensity of solar radiation on a horizontal surface outside the atmosphere) can be calculated as a function of the solar constant (I_0 = 1367 W/m^2), the zenith angle (Z) and a correction factor (F):

$$I_p = I_0 \; F \cos(Z)$$ **(W/m2) (1)**

The correction factor (F) which describes the effect of the fact that the track of the earth around the sun is not exactly circular, but slightly elliptical, is approximated as a function of Julian day number (D: 1 Jan: D=1; 2 Jan: D=2; ……… 1 Feb D=32; etc.):

$$F = 1 + 0.033 \; \cos\left(\frac{2\pi}{366} D\right)$$ **(-) (2)**

The zenith angle, Z, is the angle between the incoming solar radiation and a line that connects the surface with the zenith (the point exactly vertically above the surface). The zenith angle can be calculated as a function of latitude (φ), solar declination (δ) and true solar time (t):

$$\cos(Z) = \sin(\varphi)\sin(\delta) - \cos(\varphi)\cos(\delta)\cos(\omega t)$$ **(-) (3)**

Where the true solar time t=12 hours when the sun is exactly in the south and ω is the speed of rotation of the earth around its axis ω = 2π/24 rad/hour.

The solar declination (δ) is the latitude on earth where the sun is exactly in the zenith (vertically above the surface). It varies with the season and is approximated as a function of Julian day number (D):

$$\delta = -23.45 \cos\left(\frac{2\pi}{366}(D+10)\right)$$ **(°) (4)**

2.2 Direct radiation on a horizontal surface

Direct radiation is only calculated for those cases in which clouds do not obscure the sun, since under a clouded sky all radiation reaching the earth surface is considered to be diffuse radiation. Direct radiation on a horizontal plane (K_{bH}) is equal to the extraterrestrial radiation, multiplied with the transmission coefficient of the unclouded atmosphere (Tr_0):

$$K_{bH} = Tr_0 \, I_p = Tr_0 \, I_0 \, F \cos(Z) \qquad \textbf{(W/m}^2\textbf{)} \quad \textbf{(5)}$$

The transmission of the atmosphere depends on the mass of the atmosphere vertically above the point of observation (this mass is proportional to the atmospheric pressure), the angle of the solar rays through the atmosphere (zenith angle) and the composition of the atmosphere. We have applied Linke's method, in which transmission is modelled as a function of the transmission of a Rayleigh atmosphere (Tr_R) and Linke's turbidity factor (T):

$$Tr_0 = Tr_R^T \qquad \textbf{(-)} \quad \textbf{(6)}$$

Since the Portofino area is located at the coast we have used Linke's turbidity factor for clean air (T = 2.7).

The transmission of a Rayleigh atmosphere is the theoretical transmission that would occur in an atmosphere containing only air molecules (no clouds and no aerosols) and in which Rayleigh scattering is the only process reducing the intensity of solar radiation. Often the transmission of a Rayleigh atmosphere is approximated as a fourth power polynomial of the true optical mass (M):

$$Tr_R = 0.959 - 0.0636\,M + 0.00282\,M^2 - 6*10^{-5}\,M^3 + 4*10^{-7}\,M^4 \qquad \textbf{(-)} \quad \textbf{(7)}$$

The parameters in this approximation equation have been adjusted to give better performance at high optical masses. The true optical mass is a function of atmospheric pressure and the relative optical mass (m_r). Since the Portofino area is close to sea level (all elevations below 600 m) we have taken the true optical mass equal to the relative optical mass. At first approximation the relative optical mass is equal to the reciprocal of the cosine of the zenith angle ($m_r \approx 1/\cos(Z)$), but if diffraction of the solar rays in the atmosphere is taken into account, the relative optical mass is better approximated by:

$$m_r = \left(\cos(Z) + \frac{0.08}{93° - Z} \right)^{-1} \qquad \textbf{(-)} \quad \textbf{(8)}$$

in which Z is expressed in degrees.

Summarizing: The cosine of the zenith angle (calculation described in paragraph 2.1) can be used to calculate relative optical mass, which goes into (7) to obtain Rayleigh transmission, which is used to calculate direct solar radiation on a horizontal surface using (6) and (5) and the assumption that Linke's turbidity factor is equal to 2.7.

2.3 Direct radiation on a sloping surface

For a sloping surface cos(Z) in (5) has to be replaced by cos(I), where the impact angle (I) I is the angle between the solar rays and a point perpendicular (not vertical) above the surface. The impact angle (I) is determined by the zenith angle, the slope (β) and aspect (Ψ_p) of the sloping surface and the azimuth of the sun (Ψ_s):

$$\cos(I) = \cos(\beta)\cos(Z) + \sin(\beta)\sin(Z)\cos(\Psi_s - \Psi_p) \quad \textbf{(-)} \quad \textbf{(9)}$$

We use $\cos(\Psi_s\text{-}\Psi_p) = \sin(\Psi_s)\sin(\Psi_p)+\cos(\Psi_s)\cos(\Psi_p)$ and calculate the sine and cosine of the solar azimuth as:

$$\sin(\Psi_s) = -\frac{\cos(\delta)\sin(\omega t)}{\sin(Z)} \quad and \quad \cos(\Psi_s) = \frac{\sin(\delta) - \sin(\varphi)\cos(Z)}{\cos(\varphi)\sin(Z)} \quad \textbf{(-)} \quad \textbf{(10)}$$

Combining these equations with (5), remembering that we have to use cos(I) instead of cos(Z) and a little bit of calculus shows that the direct radiation on a sloping surface $K_{b\beta}$ is equal to:

$$K_{b\beta} = Tr_0 I_0 F \left\langle \begin{array}{l} \cos(\beta)\{\sin(\varphi)\sin(\delta) - \cos(\varphi)\cos(\delta)\cos(\omega t)\} + \\ + \sin(\beta)\left\{ \begin{array}{l} \cos(\Psi_p)[\cos(\varphi)\sin(\delta) + \sin(\varphi)\cos(\delta)\cos(\omega t)] + \\ + \cos(\delta)\sin(\Psi_p)\sin(\omega t) \end{array} \right\} \end{array} \right\rangle \quad \textbf{(W/m}^2\textbf{)} \quad \textbf{(11)}$$

If the transmission of the atmosphere (Tr_0) would be constant it would be easy to integrate (11) analytically to get the direct radiation for one day. However since the transmission is a complicated function of the zenith angle analytical integration is out of the question and the integration has to be done numerically. However, numerical integration with let us say time steps of 15 minutes every grid point (500.000 grid points) would require (11) to be calculated ca 1400 million calculations of (11) for each month. Even for today's powerful PC's this is a considerable task. We have therefore used a slightly different approach.

We have calculated the direct radiation on a sloping surface ($K_{b\beta}$) as a function of the slope angle (β), the direct radiation on a horizontal surface (K_{bH}) and the direct radiation on a vertical surface (K_{bV}), where vertical surface has the same aspect as the sloping surface:

$$K_{b\beta} = K_{bH}\cos(\beta) + K_{bV}\sin(\beta) \quad \textbf{(W/m}^2\textbf{)} \quad \textbf{(12)}$$

Direct radiation on a vertical surface with aspect (Ψ_p) is calculated from Ψ_p, direct radiation on an east facing vertical plane (K_{bE}) and direct radiation on a south facing vertical plane (K_{bS}):

$$K_{bV} = K_{bE}\sin(\psi_p) - K_{bS}\cos(\psi_p) \quad \textbf{(W/m}^2\textbf{)} \quad \textbf{(13)}$$

Here direct radiation on an east facing vertical plane (K_{bE}) and direct radiation on a south facing vertical plane (K_{bS}) are calculated as:

$$K_{bE} = Tr_0 I_0 F\sin(Z)\sin(\Psi_s) \quad and \quad K_{bS} = -Tr_0 I_0 F\sin(Z)\cos(\Psi_s) \quad \textbf{(W/m}^2\textbf{)} \quad \textbf{(14)}$$

After some mathematical conversions it can be shown that this second approach is exactly equivalent to using (11). However this second approach provides more opportunities for optimising the calculations (see the chapter on implementation).

2.4 Diffuse radiation under a clear sky

For a horizontal surface the method of Erbs describes the ratio of diffuse radiation over global radiation (K_{d0H}/K_G) as a function of the Erbs coefficient (C_E), which is defined as the ratio of global radiation over extraterrestrial radiation (K_G/I_p):

$$\frac{K_{D0H}}{K_G} = \begin{vmatrix} 1.0 - 0.09C_E & For\ C_E \leq 0.22 \\ 0.9511 - 0.1604C_E + 4.39C_E^2 - 16.6C_E^3 + 12.34C_E^4 & For\ 0.22 < C_E < 0.80 \\ 0.165 & For\ C_E \geq 0.80 \end{vmatrix} \qquad \textbf{(15)}$$

This approximation assumes that global radiation is measured and can be used to calculate the Erbs coefficient. However global radiation will be the final result for which we need to calculate diffuse radiation. We have therefore taken a somewhat different approach. We have first calculated a turbidity coefficient, defined as the ratio of direct radiation on a horizontal plane and extraterrestrial radiation to a certain power: $C_T \equiv (K_{b0}/I_p)^P$, with P=0.363. This coefficient has been used to approximate diffuse on a horizontal surface according to:

$$K_{D0H} = K_{bH}\left(-0.035 + 2.236C_T - 4.000C_T^2 + 2.134C_T^3 - 0.272C_T^4\right) \qquad \textbf{(W/m}^2\textbf{)} \quad \textbf{(16)}$$

Figure 1 shows that the difference between the original Erbs equations and our approximation is small.

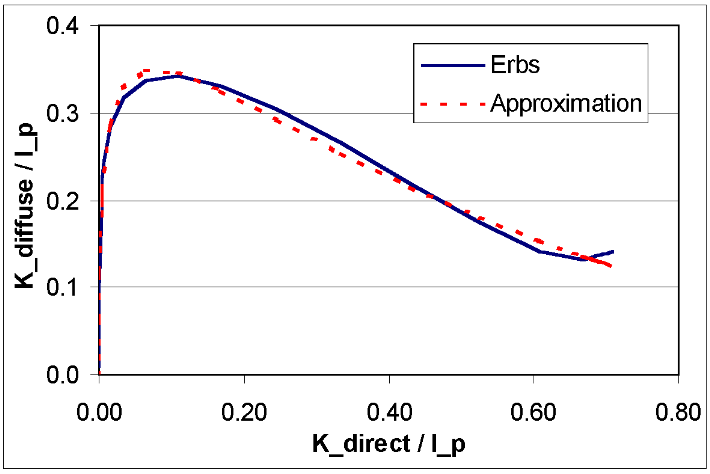

Figure 1: *Ratio of Diffuse radiation over extraterrestrial radiation according to Erbs and our approximation.*

For sloping a surface part of the sky is obscured. When calculating clear sky diffuse radiation over a sloping surface it was assumed that the sources of diffuse radiation were distributed uniformly over the sky and diffuse radiation from nearby slopes was ignored, since this is only important at high surface albedo's (e.g. snow covered slopes). Using these simplifications the clear sky diffuse radiation over a sloping surface (K_{D0}) is given as a function of slope angle by:

$$K_{D0} = K_{D0H}\cos^2(\beta/2) \qquad \textbf{(W/m}^2\textbf{)} \quad \textbf{(17)}$$

Strictly spoken the assumption that diffuse radiation is evenly distributed over the sky is not valid for clear skies. However we aim at calculating monthly mean global radiation. Under clear sky conditions generally diffuse radiation is much less then direct radiation, so global radiation is mainly determined by direct radiation and errors in diffuse radiation will not have a large influence on the calculated global radiation. The exception is when the solar elevation is very low. In this case (just after sunrise or just before sunset) diffuse radiation can be of the same order of magnitude or even larger the direct radiation. However in these cases the intensity of solar radiation is low anyway and will not provide a large contribution to the monthly mean global radiation. Since a more precise calculation would require much more calculation time and would not greatly improve the accuracy of the results we have chosen to use the simplification above.

2.5 Diffuse radiation under a clouded sky

Diffuse radiation under clouded conditions depends on cloud type and cloud thickness, since these determine the transmissivity of the clouds for solar radiation. However since such detailed information on cloud cover is rarely available we have used an average transmissivity, which is a function of relative optical mass (Tr_{cl} = 0.37-0.01m_r). Taking in account multiple reflections between surface and cloud base and again assuming that the sources of diffuse radiation are uniformly distributed over the sky we arrive at:

$$K_{D1} = (0.40 - 0.01 m_r)\ K_{bH}\ \cos^2(\beta / 2) \qquad \textbf{(W/m}^2\textbf{)} \quad \textbf{(18)}$$

The relative optical mass (m_r) is given by equation (8)and direct radiation on a horizontal surface (K_{bH}) by (5). Under clouded skies the assumption that, on average, the sources of diffuse radiation are evenly distributed over the sky is much stronger than under clear skies. Here the weak point is the use of an average transmissivity for all cloud types. However as long as no information about the percentage of cover by different cloud types is available, there is no other solution.

2.6 Global radiation

Once direct and diffuse radiation have been calculated the calculation of Global radiation is simple. For a clear sky global radiation is equal to the sum of direct radiation $K_{b\beta}$, given by equations (12) trough (14) and diffuse radiation for a clear sky given by (17). If the sun is obscured by clouds there is no direct radiation and the global radiation is equal to the diffuse radiation penetrating though the clouds (K_{D1}) given by equation (18). The global radiation weighted for The relative duration of sunshine (N_t) is than given by:

$$K_G = N_t\ \left(K_{b\beta} + K_{D0}\right) + (1 - N_t)\ K_{D1} \qquad \textbf{(W/m}^2\textbf{)} \quad \textbf{(19)}$$

Relative duration of sunshine is often estimated as N_t=1-CC (with CC equal to cloud cover fraction), but this is not exactly the same.

The global radiation calculated by (19) will be integrated over the entire month in order to calculate mean monthly global radiation.

3. IMPLEMENTATION

The model will calculate monthly mean global radiation for each grid point in a given DEM by means of numerical integration. The numerical integration is performed by calculating global radiation over the entire month at preset time intervals (e.g. 15 minutes), averaging the results and converting the results to units of MJ/m2/day. As was already discussed in section 2.3 a straightforward numerical integration for each grid point separately is impractical, because of the large number of calculations required.

The approach taken in the model was as follows. First for each time interval in the month the variables that do not depend on slope and aspect were calculated and stored in arrays. These variables are cosine of the zenith angle (cos(Z)), extraterrestrial radiation (I_p), direct radiation on a horizontal plane (K_{bH}), direct radiation on an east-facing vertical plane (K_{bE}), direct radiation on a south-facing vertical plane (K_{bS}), diffuse radiation on a horizontal surface for the case of a clear sky (K_{D0H}) and diffuse radiation on a horizontal surface for the case of a clouded sky (K_{D1H}) (see table 1).

<table>
<tr><th>Cos(z)</th><th>Tr_0</th><th>Aspect</th><th>Slope</th><th>Cloud cover</th></tr>
<tr><td>$\mathbf{I_p}$</td><td colspan="2">$\mathbf{K_{bH}}$</td><td rowspan="3">$K_{b\beta}$</td><td rowspan="5">K_G</td></tr>
<tr><td></td><td>$\mathbf{K_{bE}}$</td><td rowspan="2">K_{bV}</td></tr>
<tr><td></td><td>$\mathbf{K_{bS}}$</td></tr>
<tr><td>Erbs</td><td colspan="2">$\mathbf{K_{D0H}}$</td><td>K_{D0}</td></tr>
<tr><td>Clouds</td><td colspan="2">$\mathbf{K_{D1H}}$</td><td>K_{D1}</td></tr>
</table>

Table 1: *Calculation scheme (for symbols see text). Top row lists the main parameter required. The variables in bold are also witten to file for debuggin purposes.*

After these values have been calculated slope and aspect for one point are read from the input files. Then for each time interval direct, diffuse and global radiation are calculated using equations (12) through (14), (17) and (18), averaging is performed and the value of global radiation is written to the output file. This procedure is repeated for each grid point.

The user of the model can set the time interval to values between 5 and 60 minutes. The user can further more choose not to do the calculations for every day in the month, but for every second, third up till tenth day, thereby reducing the calculation time by a factor of two, three, up to ten. In the slowest mode (every day and 5 minute time intervals) the calculations for 10.000 grid points take about 13 seconds on a 800 MHz Pentium. When using 500.000 grid points in the slowest mode, the calculations for one month will take about nine minutes. In the standard mode (3 days; 30 minutes) the calculations for one month took about 30 seconds and for the entire year about 6 minutes.

In order to evaluate the effect of enlarging the time interval and day increment, a test calculation was performed for a DEM with 10.000 point for the month of June (Table 2). For all cases tested the error was less then or equal to 0.06 $MJ/m^2/day$ at an average global radiation of 20 $MJ/m^2/day$. A time interval of 30 minutes and calculating every third day gave a maximum relative error of about 0.1%.

Days \ dt	**5**	**10**	**15**	**30**	**60**
1	-	0.01	0.01	0.02	0.05
2	0.02	0.02	0.02	0.02	0.05
3	0.01	0.02	0.01	0.02	0.04
5	0.01	0.02	0.01	0.03	0.05
7	0.06	0.06	0.06	0.05	0.05
9	0.05	0.05	0.05	0.05	0.05

Table 2: *Influence of time interval (dt) and day interval on accuracy of calculation. The errors listed in the table are in $MJ/m^2/day$ relative to dt=5 minutes and days=1.*

4. Program description

This chapter does not contain a detailed explanation of the algorithm used, but is a user-oriented description of the program. It describes the user interface, the format of input and output files and restrictions and/or shortcomings of the model.

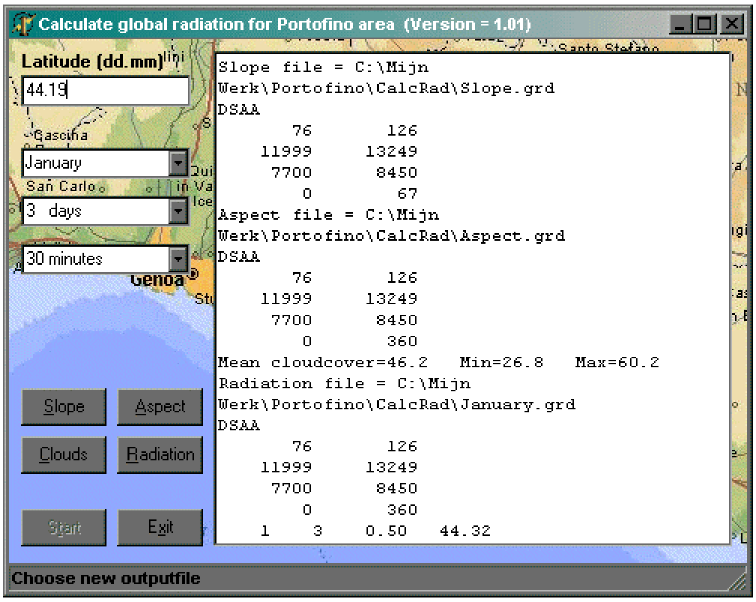

Figure 2: *User interface of the model*

4.1 User interface

The user interface (Figure 2) gives the user of the model the possibility to change the latitude, to choose the month, the increment in days, the time interval and to choose input and output files. The window to the right gives information on these choices. The statusbar at the bottom gives information on what the next step should be and on the progress of the calculations.

Latitude: In the edit field at the upper left of the user interface the user can specify the latitude of the area for which the calculations have to be performed. The latitude is specified in degrees and minutes separated by a decimal point. Latitudes south of the equator should be preceded by a minus sign. The latitude of Portofino (44°19’N) is the default and is preset in the edit field.

Month: By clicking on the small triangle to the right of the word January the user can also choose any other month. The option “Whole year” will calculate for all months. In this case the program will choose the output file names.

Day-increment: The user can choose to calculate for every day in the month (increment = 1 day), every second day (2 days), up to every tenth day (10 days).

Time interval: This options set the time interval for the numerical integration. Possible choices are: 5, 10, 15, 30 and 60 minutes.

Slope and Aspect: The buttons titled “Slope” and “Aspect” are used to choose the input files containing the slope and aspect data. These files are in Surfer ™ ASCII grid file format.

Clouds: This button is used to choose the input file containing cloud cover information.

Radiation: This button is used to choose the output file in which the calculated global radiation data are to be stored. The file will be in Surfer ™ ASCII grid file format.

Start and Exit Buttons: The start button is used to start the calculations. Initially it is disabled. It will only be enabled after all input and output files have been defined. Changing the month will disable the start button again, since it is assumed that this means that also a new output file should be chosen.

The statusbar at the bottom gives information on what the acton is that is expected from the user and it informs on the progress of the calculations.

The text window to the right will show the headers of input and output files and some additional information. This window only appears after the first file is opened.

4.2 Input files

Slope and Aspect file should be in Surfer ™ ASCII grid file format. The file contains a five-line header. The first line contains the text “DSAA”. The second line contains two integers: the number of rows and the number of columns. The next three lines contain the minimum and maximum value of respectively X, Y and Z. The rest of the file contains the Z (either slope or aspect) data, ten numbers per line. A new line starts after each row of data. All numbers in the file are space separated.

Cloud cover: The first four lines of the cloud cover file are ignored and can be used to include information like name of the station, location etc. The rest of the lines should contain at least three numbers: *Month*, *Hour* and *Cloud-cover-percentage*. If a line contains more information after these numbers, this is ignored. Empty lines are ignored. Numbers should be space or tab separated. For each month the file should contain at least one line with data. Cloud cover for the hours not mentioned in the file is interpolated.

4.3 Output files

Global radiation file is in Surfer ™ ASCII grid file format. See section 4.2 for a description of this file format.

Diagnostics: Diagnostic files are generated for extraterrestrial radiation (_I_Pot.dat), direct radiation on a horizontal surface (_KdirH.dat), direct radiation on a south-facing vertical plane (_KdirS.dat), direct radiation on an east-facing vertical plane (_KdirE.dat), clear sky diffuse radiation on a horizontal surface (_Kdif0.dat) and diffuse radiation on a horizontal surface under clouded conditions (_Kdif1.dat). These files will contain radiation data (W/m^2) on each time interval selected in the month. Columns contain data on the various days; lines represent the different times on each day. The first column shows the time (in decimal hours). The last line contains the daily total radiation ($MJ/m^2/day$). The direct radiation on an east-facing vertical slope can be negative (in the afternoon, if the west-facing slope is exposed). For reasons of symmetry the daily total should be zero for the east-facing slope.

4.4 Restrictions

File format of the input files should be as specified in section 4.2.

Slope and aspect file should refer to the same area. The program does not check this (it could be checked by comparing the header information). It is assumed that the user is smart enough to verify this carefully before starting the calculations.

Parameters: Linke's turbidity factor for a clean atmosphere (a value of 2.7) is embedded in the program as a constant. The user cannot change it. The same is true for the parameters in the equation determining the cloud transmissivity for diffuse radiation (see eq. 18). If appropriate radiation data were available these parameters could maybe be used for calibrating the model. Also the parameters in equation 7 (Rayleigh transmission), 8 (relative optical mass) and 16 (approximation of Erbs formula) are embedded in the program source code, but there is less discussion about these parameters, since they closely resemble published data (see for example figure 1).

4.5 Calibration

No attempt was made to calibrate the model since at the time of the writing of this report no adequate radiation data on the Portofino area were available.

A validation was performed using radiation data from Malpensa (see section 6.1). These data were however not used to calibrate the model since Malpensa is located 150 km to the NNW of Portofino and is located inland and not in a coastal region like Portofino.

When the writing of this report was almost finished radiation data for Genova, Genova-Sestri and Chiavari (all within 25 km of Portofino and close to the coast) became available. These were also only used for validation purposes. First of all when these data arrived it was to late to do the calibration. Secondly the fit of the model to the data was rather good, so there was no reason for further calibration. In the third place it seemed that the radiation data in the tables was not directly measured at the location, but was interpolated data. Despite differences in cloud cover monthly mean global radiation for Genova and for Genova-Sestri was identical and global radiation of Chiavari differed only slightly (see table 3).

	Genova		Genova-Sestri		Chiavari	
Month	CC	Rad	CC	Rad	CC	Rad
Jan	60	5.4	60	5.4	60	5.5
Feb	60	8.0	60	8.0	60	7.9
Mar	50	13.6	60	13.6	60	13.5
Apr	50	17.4	60	17.4	50	17.3
May	50	20.7	60	20.7	60	20.7
June	50	22.9	50	22.9	50	22.8
July	30	22.9	40	22.9	30	22.9
Aug	30	19.7	40	19.7	40	19.7
Sep	40	14.6	50	14.6	40	14.7
Oct	50	10.0	50	10.0	50	10.1
Nov	60	6.2	60	6.2	60	6.2
Dec	50	4.4	60	4.4	60	4.4

Table 3: *Cloud cover (%) and global radiation data (MJ/m2/day) for three nearby stations (from Petrarca et al.)*

5. Area description

Figure 3: *Portofino and surroundings (made with Microsoft Encarta 97 World Atlas).*

The Portofino area is located on a peninsula at the Gulf of Genoa (44°19'N; 9°11'E), 25 km ESE of the city of Genoa. It is a mountainous area with elevations up to a little over 600 m. Slopes are often steep: 29% of the area consists of slopes steeper than 30° and 2.4% of the area has slopes even steeper than 45%. Figure 4 shows the elevation map of the Portofino area and the derived slope and aspect maps.

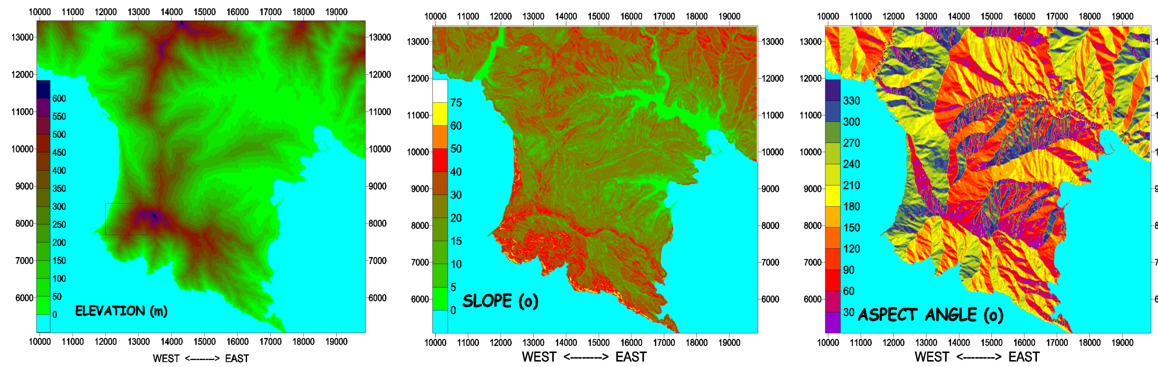

Figure 4: *Elevation, slope and aspect maps for the Portofino area. Rectangle on elevation map indicates area used for front page.*

The area has a Mediterranean climate. Yearly mean temperature is 15.6°C. The warmest months are July and August with a mean maximum temperature of 27.2°C and a mean minimum temperature of 20.5°C. Wettest month is October (153 mm) and the driest month July (27 mm). Yearly precipitation is about 1073 mm, but probably depending on topography. On the basis of data from ISMCS cloudiness was estimated as a function of month and hour of the day (Figure 5). Yearly mean cloud cover is about 46%. July and August are the sunniest months with a mean cloud cover around 35%.

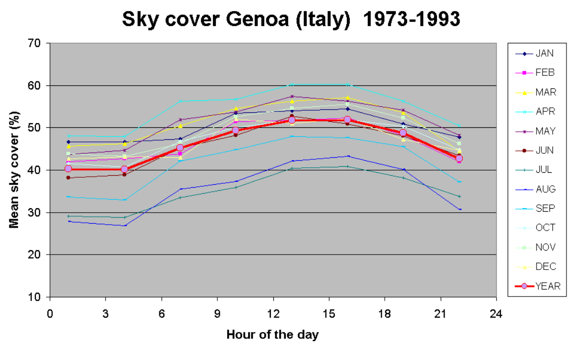

Figure 5: *Cloud cover in Genoa as a function of month and hour of the day.*

6. Results

This chapter discusses a preliminary validation of the model and the results obtained for the Portofino area. But first we will describe how we derived data for the relative duration of sunshine from the ISMCS-data (ISMCS 1995).

6.1 Relative duration of sunshine and cloud cover

For each month and for several times of the day ISMCS (1995) contains climatological data of percentage of time that the sky was clear, had scattered clouds, broken clouds or was completely clouded. It was assumed that with scattered clouds the clouds obscure the sun during 33% of the time and with broken clouds during 67% of the time. This yields the following equation for relative duration of sunshine:

$$N_t = Clear + 0.67\ Scatterd + 0.33\ Broken \qquad \textbf{(\%)} \qquad \textbf{(20)}$$

The ISMCS cloud cover shown in figure 6 is 100%-N_t, which is not exactly identical to cloud cover. Since generally cloud cover information is more readily available than data on relative duration of sunshine the model was designed to work with cloud cover data. In the model relative duration of sunshine is estimated as N_t=100%-CC (where CC is percentage of cloud cover).

Figure 6 shows that estimated ISMCS cloud cover generally is less that cloud cover obtained from the meteorological stations (Petrarca et al.). As explained before, this was to be expected. A disadvantage of the Petrarca data is that they are rather course. The ISMCS data show more detail and also contain information on the differences in cloud cover over the day.

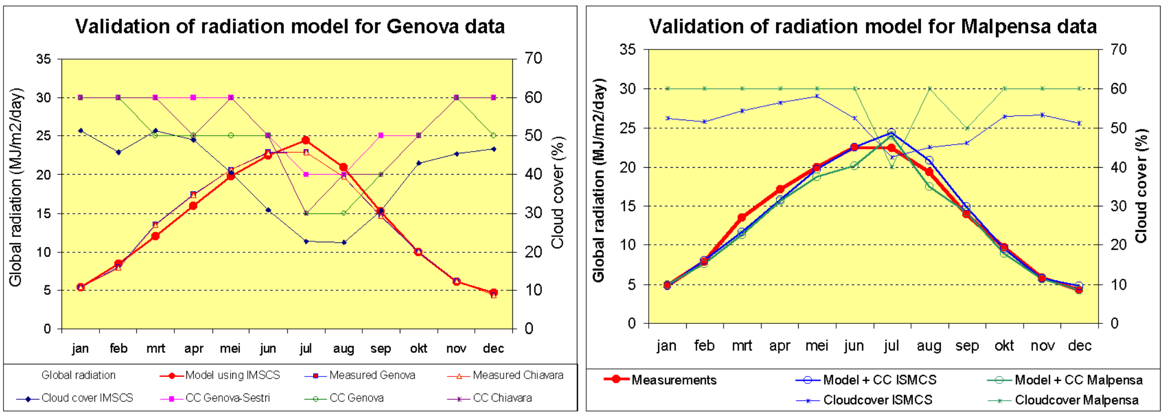

Figure 6: *Cloud cover (%), global radiation from meteorological stations (Petrarca et al.) and modeled global radiation (MJ/m^2/day) for horizontal surfaces for Genova and Malpensa. The ISMCS cloud cover in the graphs is in fact 100%-N_t as calculated by (20).*

6.2 Validation

The Petrarca dataset also contained information on mean monthly global radiation. Data form Genova, Chiavari and Malpensa were use to check the accuracy of the model (see figure 6).

When using the ISMCS cloud cover data to model the global radiation on a horizontal surface for Genova the result very closely resemble the values reported by Petrarca for Genova and Chiavari. In spring modelled global radiation is slightly less than the values reported by Petrarca and in summer they are slightly higher. The annual mean is very accurate:13.78 $MJ/m^2/day$ modelled against 13.82 $MJ/m^2/day$ measured, a difference of 0.3%. The Genova and Chiavari "measured" global radiation can hardly be distinguished visually, because they are so close (for the values see table 6). This seems strange because reported cloud cover percentages do differ between the locations. Considering these doubts on whether global radiation is measured separately on the three stations, the small differences in the seasonal behaviour between the model and the measurements are no reason to make any changes in the model.

Global radiation was also available for Malpensa, 150 km to the NNW (45°37'N; 8°44'E) and located inland, whereas Portofino is located at the coast (44°19'N; 9°11'E). If the model is applied to this location using ISMCS cloud cover data we see the same behaviour as in the validation for Genova, a light underestimation in spring and a slight overestimation in summer. Annual mean global radiation is overestimated by 0.7%, which is considered very accurate. One could doubt that a value for Linke's turbidity factor of 2.7 is applicable to this area, but it seems that nevertheless the model seems very capable of calculating global radiation. If the cloud cover data reported by Petrarca are used annual mean global radiation is underestimated by 5.2%. Of course cloud cover data in Petrarca is rather course: In entities of 10% and no information on the distribution over the day. However this probably is not the only reason. Probably the direct translation of cloud cover to relative duration of sunshine as N_t=100%-CC is not accurate enough.

From the tests above it seems that the model is very capable of calculating global radiation for horizontal surfaces. The translation to sloping surface was very thoroughly checked so it is believed that the model is also capable of calculating global radiation for sloping surfaces. One restriction has to be made however. If there is another mountain or hill in the neighbourhood, that will cast a shadow over the terrain for which the radiation is calculated, the effect of the shadow is not taken into account. Especially in deep valleys this could lead to an overestimation of global radiation.

6.3 Monthly global radiation maps

The appendix shows the calculated maps of global radiation for each month of the year. On the front page the yearly course of global radiation is shown for a small fraction of the area.

Because the mean monthly global radiation is influenced by slope angle, as well as aspect angle the maps often show large differences on relatively small distances, so there is a lot of detail.

The yearly course is obvious. In December and January the area receives less then 10 MJ/m^2/day and north-facing slopes even less then 4 MJ/m^2/day, whereas south-facing slopes get 6 to 10 MJ/m^2/day. In June and July almost the entire area receives more than 16 MJ/m^2/day with extremes up to 25 MJ/m^2/day. Of course this is because the higher solar elevation and the longer duration of daylight in summer, in combination with the lower cloud cover in July and August. In May and August solar elevation and duration of daylight do not differ very much. In fact in May solar elevation is higher than in August and duration of daylight longer. Nevertheless insolation is stronger in August because of the lower cloud cover. This is especially true for south-facing slopes and gentle slopes. Steep north-facing slopes receive less global radiation in August that in May, because they get less direct radiation.

In general south-facing slopes receive most radiation and north-facing slopes the least. However in June and July horizontal surfaces (on the front page the sea and the crest of the mountain ridge) receive more global radiation than south-facing slopes. In these months solar elevation at noon is so high that a horizontal plane receives almost as much direct radiation as a south-facing slope. In fact a steep south-facing slope might receive less radiation than a horizontal plane. In the summer, however, the sun rises in the ENE and sets in the WSW. So the first hour(s) after sunrise and before sunset south-facing slopes will receive no direct radiation, but the horizontal surface does. Furthermore for sloping surfaces a part of the sky is obscured, so they will receive less diffuse radiation.

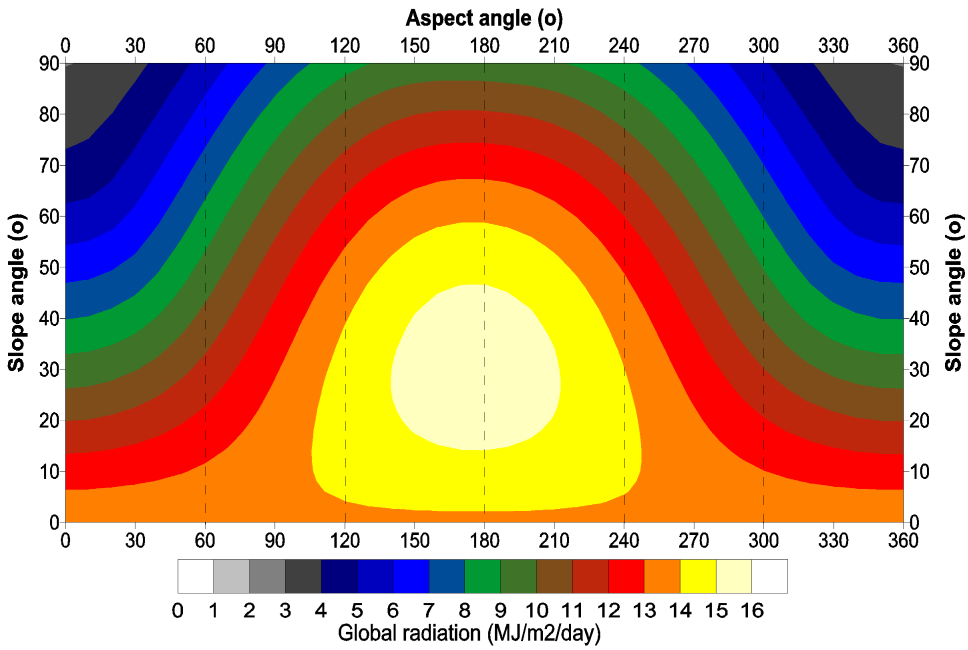

Figure 7: *Annual mean global radiation for the Portofino area as a function of slope and aspect angle. Due to a cloud cover that is on average less in the morning than in the afternoon east-facing slopes receive slightly more radiation than comparable west-facing slopes.*

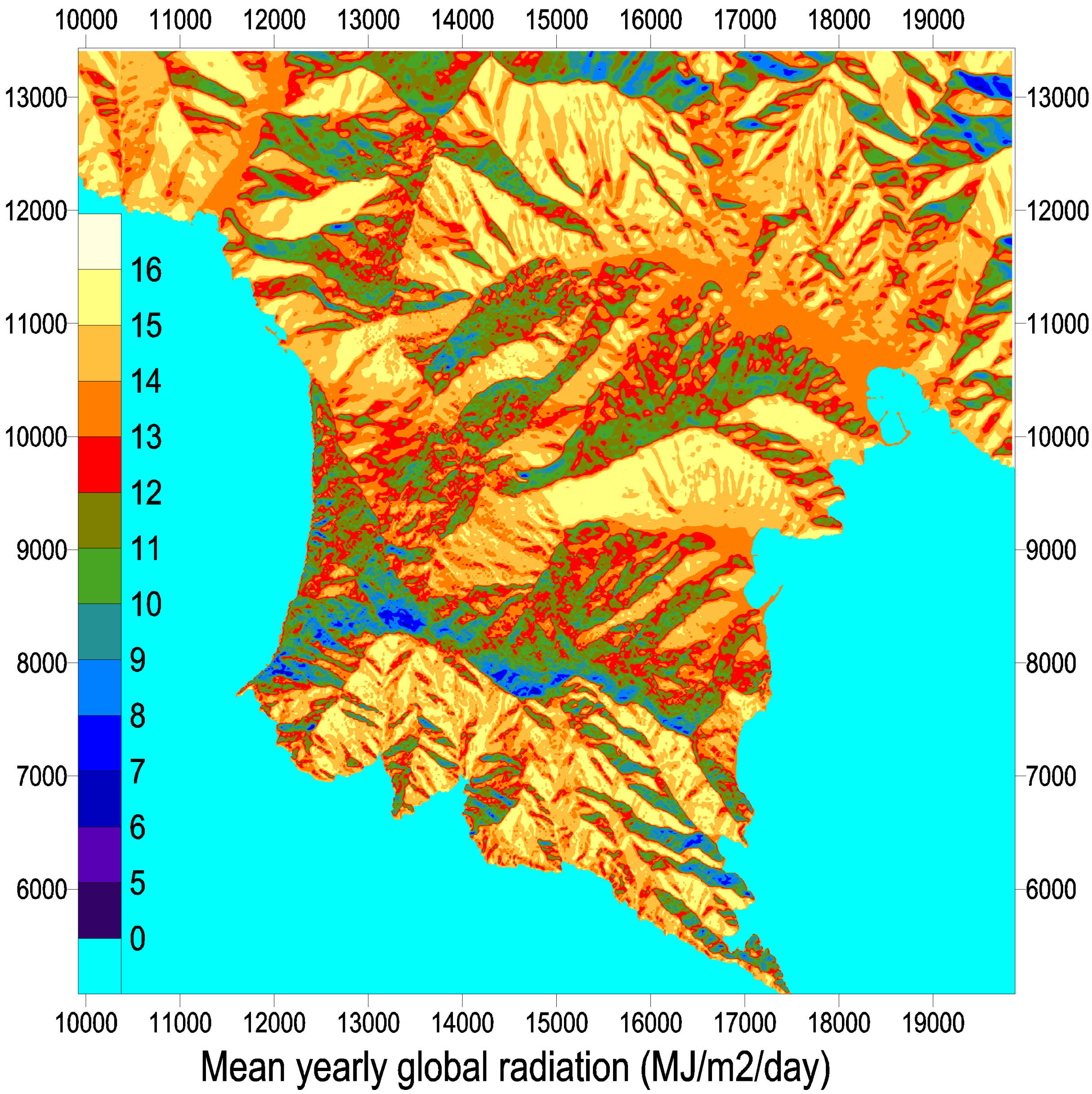

Figure 8: *Modeled mean annual global radiation (MJ/m²/day) for the Portofino area*

6.4 Yearly mean global radiation

Figure 8 shows the distribution of the modelled global radiation averaged over the entire year. Comparison with figure 4 shows that slope orientation is an important factor determining yearly mean global radiation. Horizontal surfaces receive an annual mean global radiation of 13.8 MJ/m^2/day. South-facing slopes receive a little more; the values vary from 14 to 16 MJ/m^2/day. The steepest north-facing slopes receive 7 to 9 MJ/m^2/day, whereas more gentle north-facing sloping obtain 9 to 12 MJ/m^2/day. There is also a difference between east-facing slopes and west-facing slopes, partly because of small differences in orientation. However east-facing slopes will also receive more radiation than west-facing slopes because on average cloud cover is higher in the afternoon (about 52%) than in the morning (about 47%). This is illustrated by a small asymmetry in figure 7.

7. Conclusions

Due to the optimisations applied the model, that calculates the global radiation for hilly or mountainous terrain, is very fast. Even for 500.000 grid points the numerical integration of global radiation over one month takes 30 seconds, up to a few minutes, depending on the time interval etc. chosen by the user.

The model results compare very well with published data of global radiation for four meteorological stations (Petrarca et al.). For all cases that were tested the difference between model results of annual mean global radiation and published data was less than 1 %, provided detailed cloud cover data from ISMCS (1995) were used. When the courser data of Petrarca et al. were used for cloud cover the model underestimated annual mean global radiation by about 5%. Possibly also because of the inaccurate conversion of cloud cover to relative duration of sunshine.

The model results give a good insight in the annual course of global radiation and the differences between the various slopes angles and slope orientations.

Annual mean global radiation for horizontal surface was calculated to be 13.8 MJ/m^2/day. South-facing slopes received 14 to 16 MJ/m^2/day and north-facing slopes 7 to 12 MJ/m^2/day. So the difference between a south-facing slope and a horizontal surface is less than the difference between north-facing slopes and horizontal surfaces.

Monthly mean global radiation varies from less than 2 MJ/m^2/day for north facing slopes in December to 25 MJ/m^2/day for horizontal surfaces in July. In June and July south-facing slopes receive less global radiation than horizontal surface, because they are shaded just after sunrise and just before sunset. Also the slopes receive less diffuse radiation.

8. References

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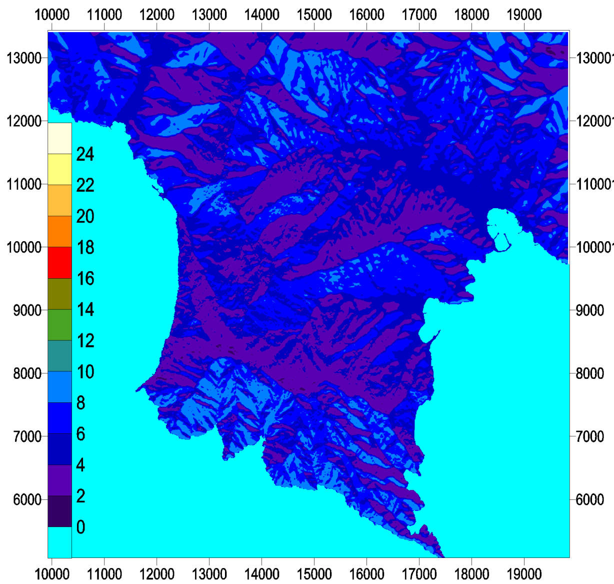
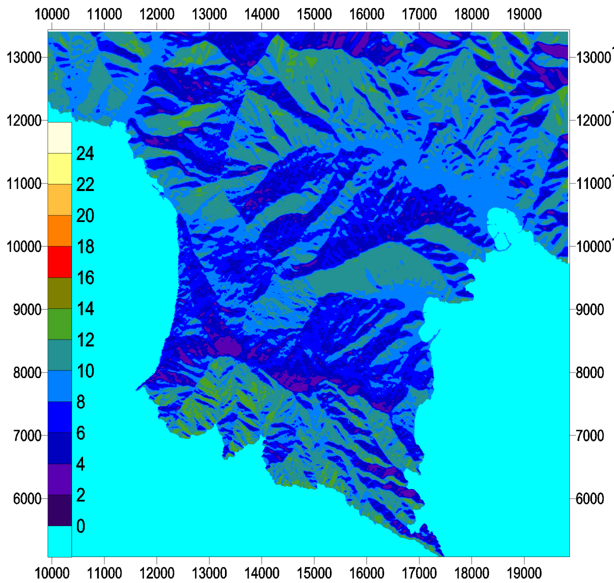
Petrarca, S., F. Spinelle, E. Cogliani & M. Mancini. Profilo climatico dell'Italia; Volume 1: Valle d'Aosta, Piemonte, Ligura. ENEA (Ente per le Nuove tecnologie, l'Energia e l'Ambiente).

Van Boxel, J.H. van, 2000. Warmtebalans van het aardoppervlak en straling (Heat balance of the earth surface and radiation), Faculty of Science, University of Amsterdam, The Netherlands (138 pp).

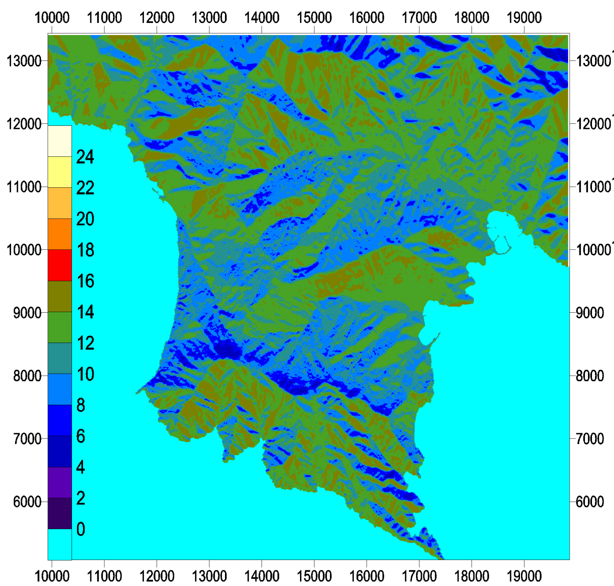
Appendix: Global radiation maps for each month



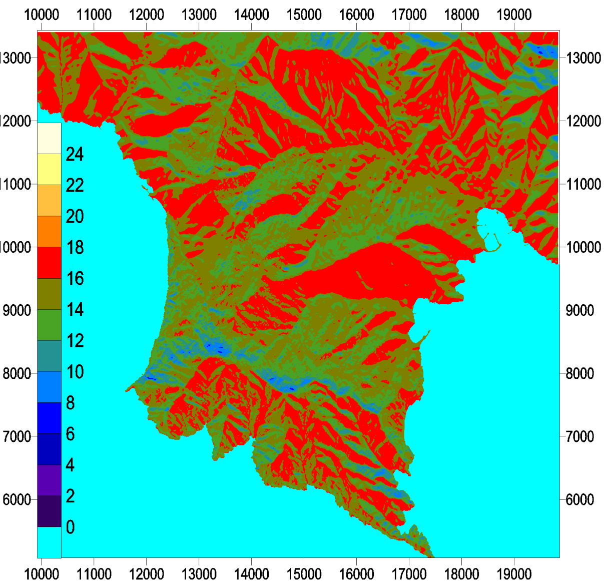
Global Radiation (MJ/m2/day) JANUARY



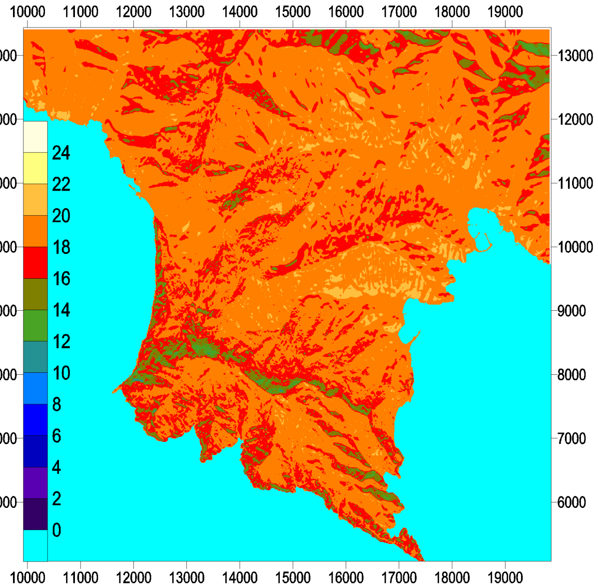
Global Radiation (MJ/m2/day) FEBRUARY



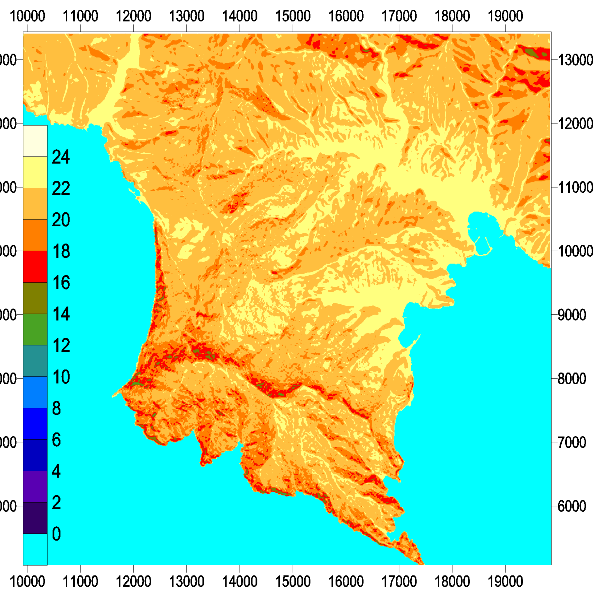
Global Radiation (MJ/m2/day) MARCH



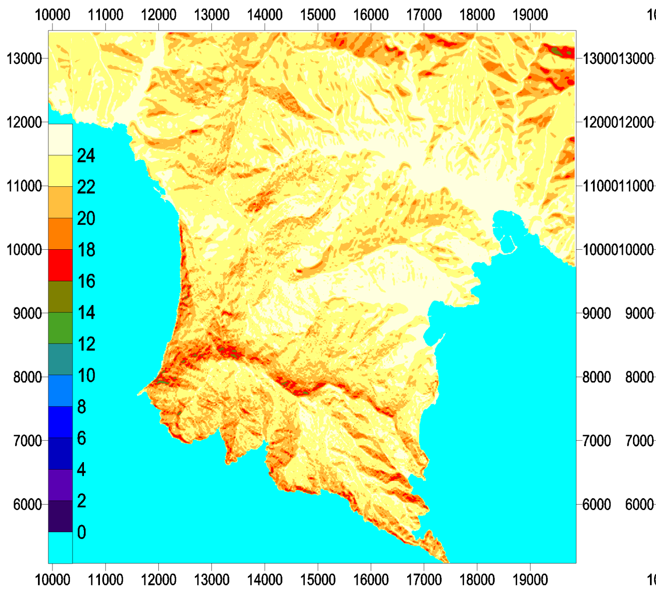
Global Radiation (MJ/m2/day) APRIL



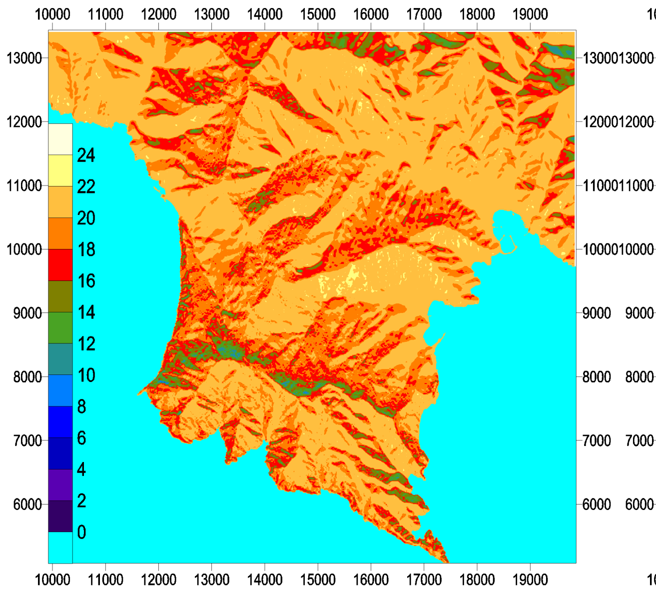
Global Radiation (MJ/m2/day) MAY



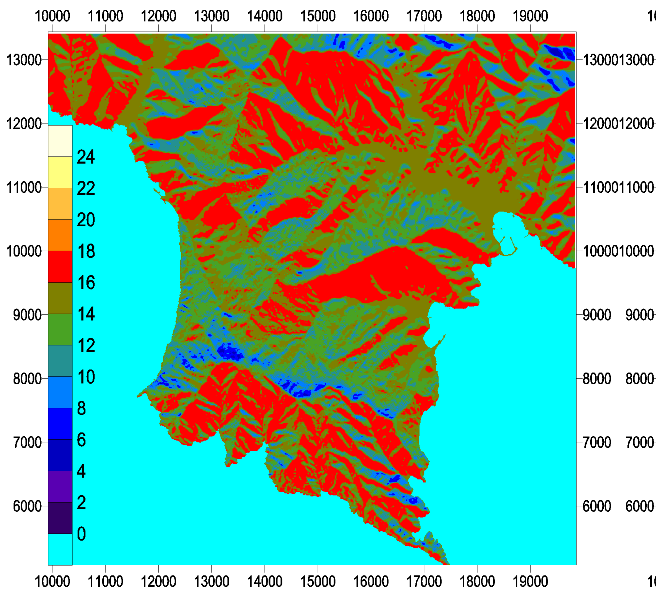
Global Radiation (MJ/m2/day) JUNE



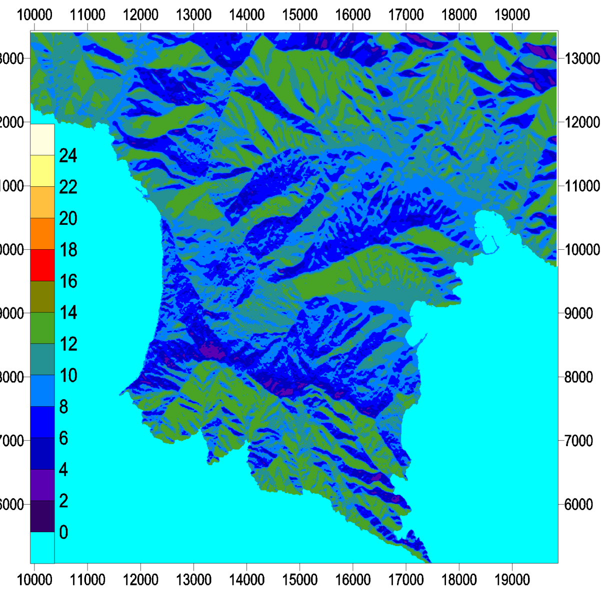
Global Radiation (MJ/m2/day) JULY



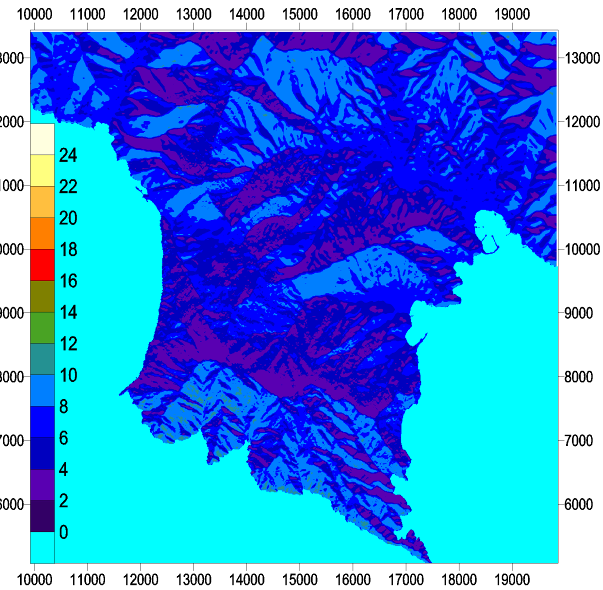
Global Radiation (MJ/m2/day) AUGUST



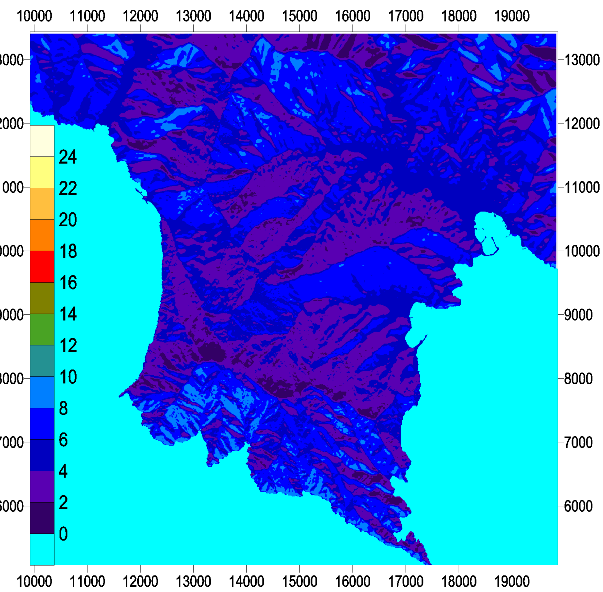
Global Radiation (MJ/m2/day) SEPTEMBER



Global Radiation (MJ/m2/day) OCTOBER



Global Radiation (MJ/m2/day) NOVEMBER



Global Radiation (MJ/m2/day) DECEMBER