

COMPUTER PROGRAM FOR THE SOLAR RADIATION EVALUATION

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Abstract: The paper proposes a computer program (*SimClim*) for the calculation and simulation of some important climatological parameters (Linke turbidity factor, the solar radiation, and so on), for the urban area of Braşov. The computer program also allows the display of the sun-charts for the desired day and the display of the diagrams for the optimum inclination angle of the solar system in view of the energy maximization. The program is based on original relations, conceived for Braşov area; these relations were determined as a result of the meteorological data modelling. The meteorological data are recorded by a local weather station positioned on the roof of the Transilvania University.

1. INTRODUCTION

The computer program is based on original procedures and original relations for the used climatological parameters; these relations are conceived so that to model in an accurate manner the specific geographical and climatological conditions of the urban area of Braşov.

The necessity of the determination of some specific relations concerning the radiation modelling for the Braşov urban area was assessed by the following aspects:

- the available empirical relations used for the radiation modelling (Hottel model for the direct component of the radiation; Bugler model for the diffuse component; Haurwitz, Kasten and Adnot models for the global radiation) do not approximate in a satisfactory manner the recorded real variation of the solar radiation for Braşov area;
- the extant empirical models are specific to a single location due to their derived method (these are empirical models obtained on the basis of measurements);
- the available models, although easy to apply due to their simplicity, have as a main input parameter the solar elevation; this dependence leads to radiation curves that are symmetrical to 12 solar time; it is mentioned that the real variation curves, the most of times, are not symmetrical curves;
- generally speaking, the solar radiation variation is specific to every geographical area; for its determination the entire geographical and climatological factors specific to the site must be taken into consideration.

2. THEORETICAL CONSIDERATIONS

Taking into consideration all the disadvantages of the empirical models presented above and also considering the fact that the interest area is a basin urban area characterized by a series of geographical and climatological features, the relations used for all the climatological parameters modelling (Linke turbidity factor and radiation) are original relations specific to the urban area of Braşov.

There must be mentioned, all the simulations were made on the basis of the meteorological data measurement, recorded with a local weather station Delta-T, positioned on the building roof of the Transilvania University of Braşov (Romania). The Delta-T weather station is a complete system of instrumentation for automatically measuring and recording the weather. All sensors are mounted on a 2 meters mast, except for the rain gauge. An environmental data logger (Delta-T Logger) initiates readings, controls the sensors and stores data. The data set measurements have been recorded since October 2005 until now, and they comprise: global solar radiation [W/m^2], diffuse solar radiation [W/m^2], sunshine, air temperature [$^{\circ}C$], wind speed [m/s], wind

direction [degrees], relative humidity [%], rainfall [pluviometric mm]. All recorded data are related to 10 minutes range, in a continuous way.

Considering the large number of the relations concerning the relative air mass and the optical thickness, the conceived computer program proposes two models [1, 2, 3]:

A. *The first model is based on the Kasten and Young formula for the optical air mass (1989) and the improved Kasten formula for the Rayleigh optical depth (1996) [1, 2]:*

$$m = p/p_0 \left(\sin(\alpha^c) + 0.50572(\alpha^c + 6.07995)^{-1.6364} \right)^{-1}, \quad (1)$$

$$\alpha^c = \alpha + 0.61359 \frac{0.1594 + 1.123\alpha + 0.065656\alpha^2}{1 + 28.9344\alpha + 277.3971\alpha^2}, \quad (2)$$

$$\begin{cases} \delta_r = \left(6.6296 + 1.7513m - 0.1202m^2 + 0.0065m^3 - 0.00013m^4 \right)^{-1}, m \leq 20, \\ \delta_r = (10.4 + 0.718m)^{-1}, m > 20. \end{cases} \quad (3)$$

The relative optical air mass (1) is dependent on the corrected solar altitude given by the Eq. (2) and the correction for a given elevation z (Eq. (4)),

$$\frac{p}{p_0} = \exp\left(-\frac{z}{8435.2}\right). \quad (4)$$

The Rayleigh optical depth is given by the Eq. (3). As it can be seen, the optical depth depends only on the relative optical air mass values.

B. *The second model is based on the Remund-Page corrections (2002) for the relative optical air mass and the Rayleigh optical depth [3]. The relative optical air mass is determined with the Eq. (5), written in terms of the optical air mass at the sea level, m_0 ,*

$$m = \frac{p}{p_0} m_0 = \exp\left(-\frac{z}{8435.2}\right) \frac{1}{\sin(\alpha) + 0.50572(\alpha + 6.07995)^{-1.6364}}. \quad (5)$$

The Rayleigh optical depth, Eq. (6), depends on the optical air mass at the sea level, m_0 , and the p_c factor, representing the pressure level correction,

$$\delta_r = \frac{1}{p_c} \cdot \left(6.625928 + 1.92969m_0 - 0.170073m_0^2 + 0.011517m_0^3 - 0.000285m_0^4 \right)^{-1}. \quad (6)$$

It must be mentioned, for the Rayleigh optical depth calculation, it was necessary to determine the pressure level correction (p_c) specific to our local area:

$$p_c = 1.08879307 - 0.004282756m_0 + 0.000132327m_0^2, \quad (7)$$

where: m_0 represents the optical air mass at the sea level.

The horizontal beam is modelled by the Eq. (8):

$$B_h = I_0 \varepsilon \sin(\alpha) \exp(-T_L \delta_r m), \quad (8)$$

where: $I_0 \varepsilon$ is the solar constant ($1367W/m^2$) corrected by the eccentricity factor (ε); α is the solar altitude angle; δ_r is the integrated Rayleigh optical thickness, due to pure molecular scattering (clear and dry atmosphere), calculated depending on the adopted model with Eq. (3) or Eq. (6); m is the relative optical air mass calculated with the Eq. (1) or Eq. (5) depending on the used model.

Considering a cloudless sky, for the diffuse radiation simulation, the computer program uses the following relation:

$$R_{dif} = I_0 \varepsilon T_{rd}(T_L) F_d(\alpha, T_L), \quad (9)$$

where: the $T_{rd}(T_L)$ represents the atmospheric transmission function (when the sun at the zenith), (Eq. (10)) [2]:

$$T_{rd}(T_L) = -0.015843 + 0.030543 T_L + 0.00033797 T_L^2, \quad (10)$$

and $F_d(\alpha, T_L)$ is the solar altitude correction, (Eq. (11)):

$$F_d(\alpha) = A_0 + A_1 \sin(\alpha) + A_2 (\sin(\alpha))^2, \quad (11)$$

$$A_0 = 0.26463 - 0.061581 T_L + 0.0031408 T_L^2, \quad (12)$$

if $A_0 T_{rd} < 0.0022$ then

$$A_0 = 0.0022 / T_{rd} \quad (13)$$

$$A_1 = 2.04020 + 0.018945 T_L - 0.011161 T_L^2, \quad (14)$$

$$A_2 = -1.3025 + 0.039231 T_L - 0.0085079 T_L^2. \quad (15)$$

For the diffuse radiation simulation, using Remund and Page model, the pressure variation with the site altitude (z) is taken into consideration [3]. Thus, the T_L factor will be replaced by T_L^* :

$$T_L^* = \frac{p}{p_0} T_L = \exp\left(-\frac{z}{8435.2}\right) T_L, \quad (16)$$

and the atmospheric transmission function at the zenith will be calculated with Eq. (17):

$$T_{rd}(T_L^*) = -0.015843 + 0.030543 T_L^* - 0.0031408 (T_L^*)^2. \quad (17)$$

The expression of the transmittance correction depending on the solar altitude angle (and the expressions of all its coefficients, A_0 , A_1 , A_2) is the same with that of the previous model, but T_L^* must be used instead of T_L .

3. LINKE TURBIDITY FACTOR

For the determination of some theoretical relations that to approximate in a great extend the real variation of the horizontal beam and the diffuse radiation it was necessary the accurate determination of all climatological parameters that intervene in their expressions; one of these parameters is represented by the Linke turbidity factor. In this way, for each model proposed before, and using a 3 years data base (2006-2008), the Linke turbidity factor was determined on the basis of the real horizontal beam measurements.

It must be mentioned that the turbidity factor calculus supposed as a first stage the selection, from the entire three-year database, only of the records suitable for a clear sky model (daily integration). The turbidity factor can be calculated during periods with clouds partially covering the sun, but in this case it will reflect more the variability of the clouds in position and intensity than the intrinsic turbidity of the atmosphere. The presence of the clouds alters the diffuse irradiance component, and the determination of Linke turbidity from the direct radiation is no longer reliable. Consequently, the intervals with overcast sky were ignored during the study.

In the next stage, there were calculated the monthly mean values of the Linke factor but, also the monthly means of the hourly minimum values recorded during a month. These values, for the two models proposed, are presented in Table 1.

The use of a monthly constant value for the Linke turbidity factor (the monthly mean values or the monthly means of the hourly minimum values) for the radiation calculation, does not lead to a very accurate simulation of this.

Considering the aspect above mentioned, the study of the Linke turbidity variation during a day (depending on the solar time) was also achieved. The mathematical modelling was applied for both mentioned models. All the obtained functions of the Linke factor specific to Braşov urban area are systematized in Table 2.

Table 1. Linke Factor for Braşov Urban Area

| Month | Monthly means | | Monthly means of the hourly minimum values | |
|-----------|------------------------------|-----------------------------|--|-----------------------------|
| | $T_{L \text{ Kasten Young}}$ | $T_{L \text{ Remund Page}}$ | $T_{L \text{ Kasten Young}}$ | $T_{L \text{ Remund Page}}$ |
| January | 3.11 | 3.51 | 2.75 | 3.10 |
| February | 3.18 | 3.59 | 2.73 | 3.08 |
| March | 3.44 | 3.88 | 2.72 | 3.06 |
| April | 3.62 | 4.08 | 3.07 | 3.45 |
| May | 3.79 | 4.26 | 3.26 | 3.67 |
| June | 3.79 | 4.26 | 3.33 | 3.75 |
| July | 3.82 | 4.30 | 3.37 | 3.79 |
| August | 3.81 | 4.29 | 3.48 | 3.92 |
| September | 3.53 | 3.97 | 2.91 | 3.28 |
| October | 3.00 | 3.38 | 2.50 | 2.82 |
| November | 3.14 | 3.54 | 2.90 | 3.27 |
| December | 3.44 | 3.88 | 2.89 | 3.26 |

Table 2. Linke Factor Functions for Braşov Urban Area

| Month | $T_{L \text{ Kasten Young}}$ | $T_{L \text{ Remund Page}}$ |
|-----------|--|--|
| January | $T_L = -5.185 \ln(T_{solar}) + 15.386$ | $T_L = -5.895 \ln(T_{solar}) + 17.471$ |
| February | $T_L = -5.504 \ln(T_{solar}) + 16.104$ | $T_L = -6.296 \ln(T_{solar}) + 18.393$ |
| March | $T_L = -6.255 \ln(T_{solar}) + 18.499$ | $T_L = -7.080 \ln(T_{solar}) + 20.928$ |
| April | $T_L = -5.398 \ln(T_{solar}) + 16.328$ | $T_L = -6.119 \ln(T_{solar}) + 18.407$ |
| May | $T_L = -4.234 \ln(T_{solar}) + 13.584$ | $T_L = -4.744 \ln(T_{solar}) + 15.237$ |
| June | $T_L = -4.811 \ln(T_{solar}) + 14.997$ | $T_L = -5.409 \ln(T_{solar}) + 16.861$ |
| July | $T_L = -5.689 \ln(T_{solar}) + 17.204$ | $T_L = -6.573 \ln(T_{solar}) + 19.879$ |
| August | $T_L = -5.605 \ln(T_{solar}) + 17.457$ | $T_L = -6.448 \ln(T_{solar}) + 19.871$ |
| September | $T_L = -6.840 \ln(T_{solar}) + 20.030$ | $T_L = -7.853 \ln(T_{solar}) + 22.948$ |
| October | $T_L = -7.760 \ln(T_{solar}) + 21.954$ | $T_L = -8.776 \ln(T_{solar}) + 24.825$ |
| November | $T_L = -5.597 \ln(T_{solar}) + 16.363$ | $T_L = -6.321 \ln(T_{solar}) + 18.480$ |
| December | $T_L = -8.635 \ln(T_{solar}) + 23.911$ | $T_L = -9.784 \ln(T_{solar}) + 27.090$ |

It must be also mentioned, the program uses for the simulation of the direct radiation the functions of the turbidity factor recommended by Table 2 and for the diffuse radiation there are used the medium values from Table 1.

4. COMPUTER PROGRAM'S INTERFACE

The designed computer program takes into consideration the following objectives:

- the use of a performable soft;
- the program must have a high degree of generality and applicability;
- the program's structure must allow further developments;
- the modelling of the most important climatological radiative parameters for Braşov urban area (the clearness index, Linke turbidity factor, horizontal beam irradiance, horizontal diffuse irradiance, the irradiances on a tiled surface and also the irradiances on a horizontal or tilted surface).

The proposed program uses original procedures developed for the climatological parameters modelling; these models are specific to the urban area of Braşov.

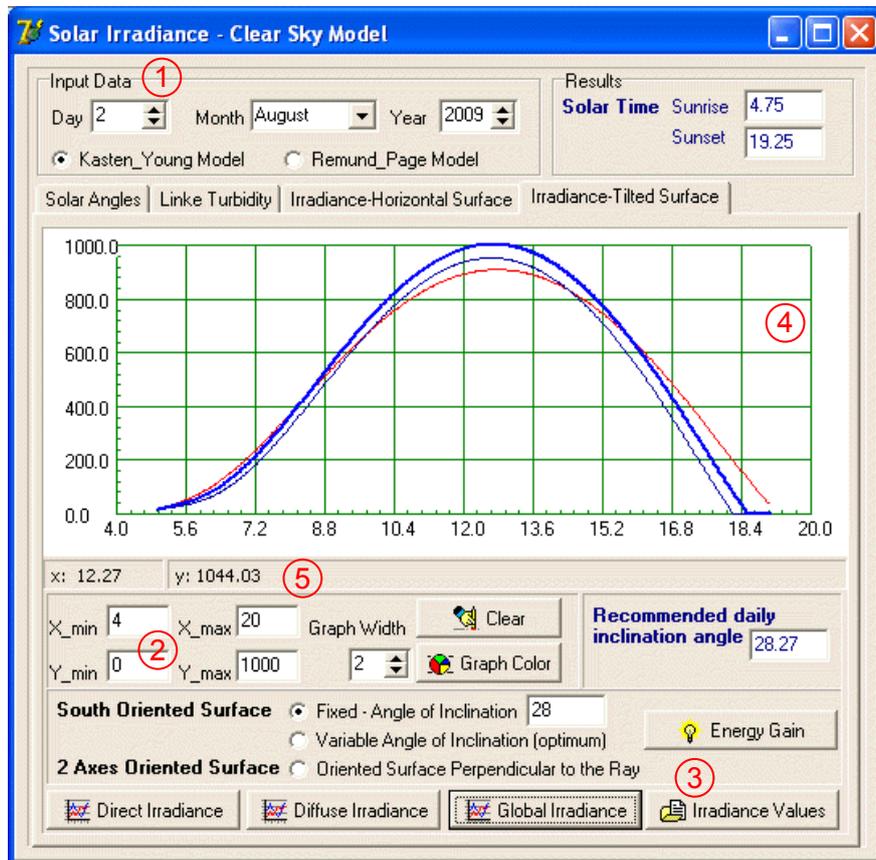


Fig. 1. Computer program's interface

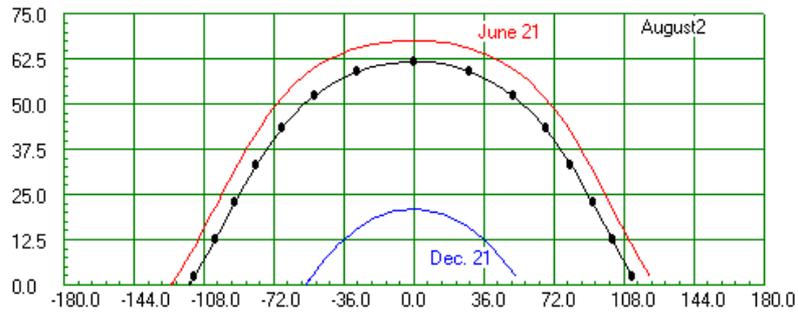
| T_solar | Extraterrestrial Irradiance | Global Irradiance | Diffuse Irradiance | Direct Irradiance |
|---------|-----------------------------|----------------------|--------------------|-------------------|
| | August 2, 2009 | Kasten - Young Model | | |
| 5.00 | 54.35 | 19.56 | 19.42 | 0.14 |
| 6.00 | 283.49 | 83.26 | 60.29 | 22.97 |
| 7.00 | 512.62 | 206.04 | 92.85 | 113.19 |
| 8.00 | 726.14 | 371.76 | 115.71 | 256.05 |
| 9.00 | 909.49 | 547.02 | 129.58 | 417.44 |
| 10.00 | 1050.19 | 703.97 | 136.61 | 567.36 |
| 11.00 | 1138.63 | 823.58 | 139.43 | 684.15 |
| 12.00 | 1168.79 | 894.22 | 140.11 | 754.11 |

a. Simulated irradiances values for the 2nd of August 2009

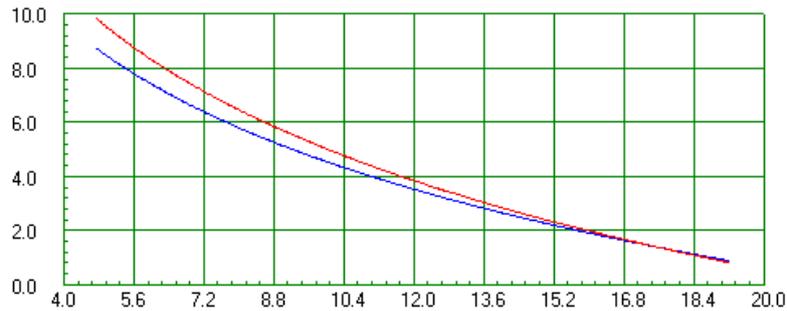
| | Horizontal | Fixed Surface 45 | 1 Axis Orientation | 2 Axes Orientation |
|------------|----------------|----------------------|--------------------|--------------------|
| | August 2, 2009 | Kasten - Young Model | | |
| | 6.03 kWh/m2 | 5.81 kWh/m2 | 6.82 kWh/m2 | 9.82 kWh/m2 |
| Percentage | | | | |
| | 0.00 % | -3.74 % | 13.04 % | 62.77 % |

b. Click on the Energy Gain button

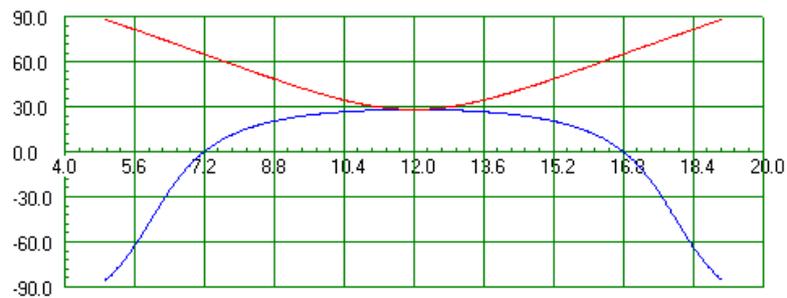
Fig. 2. Tabular displays



a. The sunchart for Braşov area, the 2nd of August 2009



b. The daily Linke turbidity factor variation for Braşov area



c. The inclination angle for Braşov area (blue curve – the inclination angle for a south oriented surface; the red curve – the inclination angle for a 2 axes tracking system)

Fig. 3. Characteristic parameters variation on the 2nd of August 2009

On the user program interface, the dialog between program and user is carried out through the *Input Data* fields: areas 1 and 2 (Figure 1). The area 1, contains input fields concerning the desired date and the adopted simulation model; the area 2, is specific to every page: *Solar Angles*, *Linke Turbidity*, *Irradiance-Horizontal Surface*, *Irradiance-Tilted Surface*, and it requires data concerning the graphical display. These last inputs set the minimum and maximum values corresponding to the desired limits for the abscissa and ordinate (the area from the diagram that presents interest can be brought in the graphic window).

The program also allows the coordinates reading for some interest points on the diagrams, by their focus with the mouse; the coordinates are displayed in the status bar, area 5. In view of a greater flexibility for the conceived program, this allows – by the activation of the buttons *Clear*, *Graph Color* and of the spinner *Graph Width* – the setting of the diagrams display manner, depending on the user request. In this way, it is possible both the setting of the widths and colours for every diagram, and the display only of the desired diagrams.

By clicking one of the buttons from the lower part of the interface, area 3, the corresponding required graph will be displayed in area 4, or if there are required tabular data, these will be displayed in a new window (Figure 2).

On every selected page, the result areas are emphasized by navy colour and bold fonts. Important parameters are calculated, namely:

- on the *Solar Angles* page: the maximum values of azimuth and solar altitude angles;
- on the *Linke Turbidity* page: the daily values of this factor;
- on the *Irradiance-Horizontal Surface*: the clearness index and the horizontal beam irradiation for the day selected;
- on the *Irradiance-Tilted Surface*: the recommended daily inclination angle.

Figure 1 presents some theoretical radiation curves, namely, the global radiation on a horizontal surface (Kasten and Young model) – the red curve, the global radiation on a tilted surface with 45 degrees – the navy curve and on a tilted surface with 28 degrees (the recommended value for the inclination angle on the 2nd of August 2009) – the blue thick curve.

The program also allows the tabular display of the horizontal irradiances, Figure 2,a and the tabular display of the daily irradiances and of the energy increase percent compared to a horizontal surface, Figure 2,b. It can be noticed that for a tilted surface with 45 degrees, the obtained energy decreases with 3.74% because of the too high value of the inclination angle (the recommended value for that day is 28.27 degrees). It is obvious that a solar renewable system equipped with a 2 axes tracker will lead to the maximum energy increase. In our case, for a clear sky day of 2nd of August (the clearness index in this day is 0.72) the energy increase, at the use of a 2 axes tracker system, can be of 62.77% compared to a horizontal surface.

For the considered day, Figure 3 presents the sun-chart, the daily Linke turbidity variation (the blue curve – Kasten and Young model, the red curve – the Remund and Page model) and the inclination angle variation – the blue curve if the surface is south oriented and the sun is one axis tracked – the red curve if the surface is 2 axes oriented.

4. CONCLUSIONS

The real variation of the radiation, for the Braşov urban area, presents a series of features; it is taken into consideration the fact that Braşov town is located in a basin area and the physical and geographical conditions effect the following feature: temperature inversion caused by the occurrence of radiative-orographic fogs and cloudiness. Thus, during the winter, the depression plains get cooler than the higher places and during the summer the depression lowland of Braşov gets warm more intensively than the surrounding slopes. Because of the surrounding mountains, the possible duration of the direct sunshine is diminished. Tacking into considerations all these aspects, it was necessary the development of a computer program for the climatological parameters and radiation modelling for the specific climatic and geographical conditions of Braşov.

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