LINKE TURBIDITY FACTOR FOR BRAŞOV URBAN AREA

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Abstract: *Atmospheric turbidity is an important parameter for assessing the air pollution in local areas, as well as being the main parameter controlling the attenuation of solar radiation reaching the Earth's surface under cloudless sky conditions. The paper proposes a study of the Linke's turbidity factor, calculated on the basis of the meteorological data recorded during three years, in Braşov urban area. The obtained results are presented as comparative diagrams (variation of the monthly mean values depending on time).*

Key words: *Atmospheric Turbidity, Linke Factor.*

1. Introduction

Attenuation of solar irradiance is strongly dependent on conditions of the sky, cleanliness of the atmosphere, and composition of gaseous constituents. In a clean and dry atmospheric condition, solar irradiance is attenuated by permanent atmospheric constituents of air molecules, gases and ozone, whose contents are nearly invariable. Two additional attenuation processes, which are the absorption by water vapour and scattering by aerosol particles, take place in a real atmosphere. The additional attenuation caused by these two processes is known as being due to the turbidity of the atmosphere.

The complexity of phenomena involved in the attenuation processes causes difficulty in computation of solar irradiance reaching the earth's surface, especially in certain climatic conditions.

The study of atmospheric turbidity is important in meteorology, climatology and for atmospheric pollution monitoring. Information on solar irradiance on the earth's surface is necessary for application of solar energy, for the determination of the amount of spectral global irradiance for the photovoltaic cells designing and for the selective absorbers for spectral thermal collectors.

The proposed study of the turbidity factor is carried out in order to develop a possible method for estimating solar radiation. In this paper, the turbidity factor is calculated for solar radiation data from Braşov with the intention of finding a variation model of this; all the conclusions are very useful in the development of a mathematical model of the solar radiation for the urban area of Braşov.

2. Experimental Meteorological Data

The meteorological data measurement was carried out for Braşov area, altitude: 790 m, longitude: 25.35^o and latitude 45.39^o. The local weather station Delta-T is positioned on the roof of the *Transilvania* University of Braşov (Romania). A series of data have been collected since October

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2005 up to the present; they comprise:

- global solar radiation [W/m^2],
- diffuse solar radiation [W/m^2],
- air temperature [^{o}C],
- wind speed [m/s],
- wind direction [degrees],
- relative humidity [%],
- rainfall [pluviometric mm],
- sunshine.

The horizontal global radiation G, diffuse radiation D, as well as all recorded data is related to 10 minutes range, in a continuous way.

3. Linke Turbidity Factor - General Considerations

The Linke turbidity factor is an index that represents the depth of clean and dry atmosphere that would be necessary to produce attenuation of the extraterrestrial irradiance that is produced by real atmosphere. Note that, in a pure Rayleigh atmosphere the turbidity factor $T_L = 1$. The value closest to this ideal is achieved in extremely clear, cold air at high latitudes, $T_L = 2$. For a polluted atmosphere the turbidity factor can increase to 8 [1].

The values of the Linke turbidity factor will be calculated from beam measurements (the relation of the direct irradiance on a horizontal surface is re-written) [4]:

$$T_{LAM2} = -\frac{\ln\left(\frac{I_0\,\varepsilon\sin(\alpha)}{B_h}\right)}{0.8662\delta_r\,m}, \tag{1}$$

where:

- $I_0\varepsilon$ is the solar constant (1367 W/m^2) corrected by the eccentricity factor;
- B_h is the beam horizontal irradiance;
- α is the solar altitude angle;
- δ_r is the integrated Rayleigh optical thickness, due to pure molecular scattering (clear and dry atmosphere);
- m is the relative optical air mass (the ratio of the optical path length of the solar beam through the atmosphere to the optical path through a standard atmosphere at sea level with the sun at the zenith).

It can be seen from equation (1) that the turbidity factor T_L has a definite value only when the direct beam component exists [2]. 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 using equation (1) for the direct radiation is no longer reliable. Consequently, the intervals with overcast sky must be ignored during the study.

In this way, in the next step of the study we must select from the entire three-year database only the records suitable for a clear sky model (daily integration).

4. Conditions for Selecting Clear-Sky Records

The determination of the Linke factor only for clear-sky conditions assumes meeting several conditions so that clouds do not influence beam values [3]:

1. The normal incident direct irradiance exceeds 200 W/m^2:

$$B_n \geq 200\,[\text{W/m}^2]. \tag{2}$$

2. Mention should be made of the meteorological data for which conditions of clear sky were ambiguous, such as thin haze in early morning or in late afternoon - they could have sometimes been wrongly selected as clear-sky data. This is another reason to consider only the data records for solar elevation greater than 10^o:

$$\alpha \geq 10^0. \tag{3}$$

3. The clearness index, k_t is defined as the ratio of the global radiation at ground level on a horizontal surface G_h to the horizontal radiation outside the atmosphere:

$$k_t = \frac{G_h}{I_0 \varepsilon \sin(\alpha)}. \tag{4}$$

With regard to this parameter, only hourly values with a corrected clearness value of at least 0.7 are taken into consideration:

$$k_t^{'} = \frac{k_t}{1.031 \exp\left(\frac{-1.4}{0.9+9.4m}\right) + 0.1}, \tag{5}$$

$$k_t^{'} \geq 0.7. \tag{6}$$

Also, only days with a daily clearness (it is defined from daily irradiations) of at least 0.4 are taken into consideration:

$$K_t = \frac{\overline{G_h}}{I_0 \varepsilon \sin(\alpha)}, \tag{7}$$

$$K_t \geq 0.4. \tag{8}$$

Furthermore, the selection will only include the hours of days with at least 40% clear sky.

Note: For this study, all the records with a corrected clearness values $\geq$0.7 were considered. It must be mentioned that usually the hourly values of the normalised clearness index are calculated; but this method applied for Braşov will be the subject of a future paper.

5. The Selection of Clear-Sky Records from the Three-Year Meteorological Database of Braşov

Applying the above conditions for the three-year meteorological database of Braşov, 207 clear-sky days resulted. The algorithm stages are the following:

1. All the records with a solar angle $\alpha \geq 10^{o}$ were selected;

2. The daily clearness indexes were calculated; all the days with a daily clear index $\geq$0.4 were retained; **596 days** resulted;

3. From the resulted days only records with a corrected clearness value of at least 0.7 were extracted; **594 days** resulted;

4. Of the records resulted, the clear sky percentage per day was calculated; only days with a percentage of at least 40% were retained; finally, **207 days** met all three conditions above;

5. For all the days resulted (and only for the records that accomplish the three conditions) the Linke turbidity factor was calculated.

6. Linke Turbidity Factor for Braşov Urban Area

The Linke turbidity factor was determined using two models:

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):

$$m = \frac{p}{p_0} \frac{1}{\sin(\alpha^c) + 0.50572(\alpha^c + 6.07995)^{-1.6364}}, \tag{9}$$

$$\alpha_c = \alpha + 0.61359 \frac{0.1594 + 1.123\alpha + 0.065656\alpha^2}{1 + 28.9344\alpha + 277.3971\alpha^2}, \tag{10}$$

$$\begin{cases} \delta_r = \dfrac{1}{6.6296 + 1.7513m - 0.1202m^2 + 0.0065m^3 - 0.00013m^4}, & m \leq 20, \\ \delta_r = \dfrac{1}{10.4 + 0.718m}, & m > 20. \end{cases} \tag{11}$$

The relative optical air mass (9) is dependent on the corrected solar altitude given by the relation (10) and the correction for a given elevation z (relation (12)),

$$\frac{p}{p_0} = \exp\left(-\frac{z}{8435.2}\right). \tag{12}$$

The Rayleigh optical depth is given by the relation (11). 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. The relative optical air mass is determined with the relation (13), written in terms of the optical air mass at the sea level, m_0.

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

Relation (15) expresses the correction pressure level obtained for Braşov:

$$m = \frac{p}{p_0} m_0 = \exp\left(-\frac{z}{8435.2}\right)\frac{1}{\sin(\alpha) + 0.50572(\alpha + 6.07995)^{-1.6364}}, \tag{13}$$

$$\delta_r = \frac{1}{p_c}\frac{1}{6.625928 + 1.92969 m_0 - 0.170073 m_0^2 + 0.011517 m_0^3 - 0.000285 m_0^4}, \tag{14}$$

$$p_c = 1.08879307 - 0.004282756 m_0 + 0.000132327 m_0^2. \tag{15}$$

The annual variation of the Linke's turbidity factor was analysed over a three-year period: January 2006 - December 2008.

The turbidity factor diagrams were plotted considering the variation of the monthly mean values. The turbidity factor was calculated using the two models presented above.

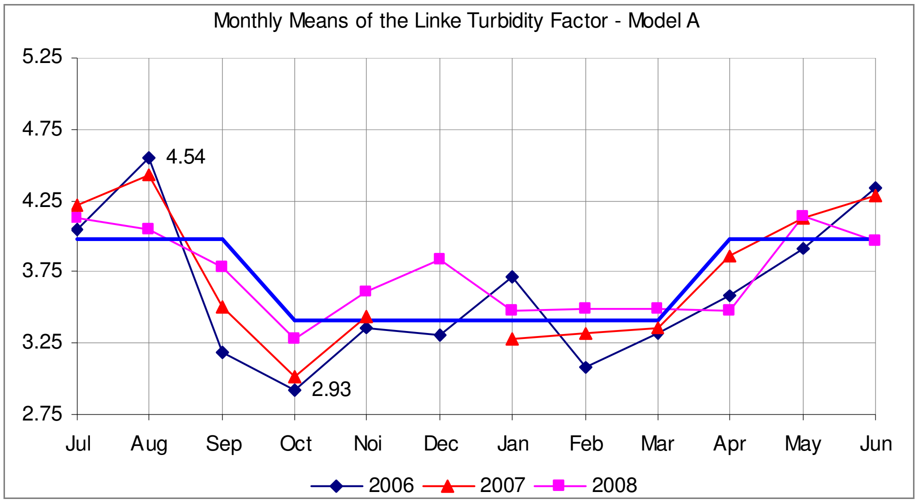
Figure 1 presents two diagrams for the monthly means values of the turbidity factor using Model **A** and Model **B**; the diagrams presented are plotted for every year considered. Figure 2 presents the monthly means values for the turbidity factor, these values representing the monthly mean for all three years analysed.

The main feature of the turbidity factor variations is a seasonal cycle divided into two half-an-year periods. The first one (from October to March) is characterised by low values of turbidity and the second one (from April to September) is characterised by high values of turbidity. April and September can be regarded as transition months between the two periods.

The calculation of the T_L factor required the calculation of the optical thickness of the clean, dry atmosphere δ_r. The two formulas (models) proposed led to different δ_r values, and consequently to different values of T_L. The optical depth calculated with the equation (14) (Remund-Page formula) led to smaller values, i.e. to significantly higher values for the turbidity factor. The two diagrams in Figure 1 emphasise the significant differences between the values of the turbidity factor calculated with the two proposed equations (11) and (14).

By analysing Figure 1 and Figure 2, it can be seen that the mean values of the turbidity factor vary:

- for the October-March period, around the value of 3.85, if the Remund-Page formula for optical thickness is used, and around 3.41 with the Kasten-Young formula;



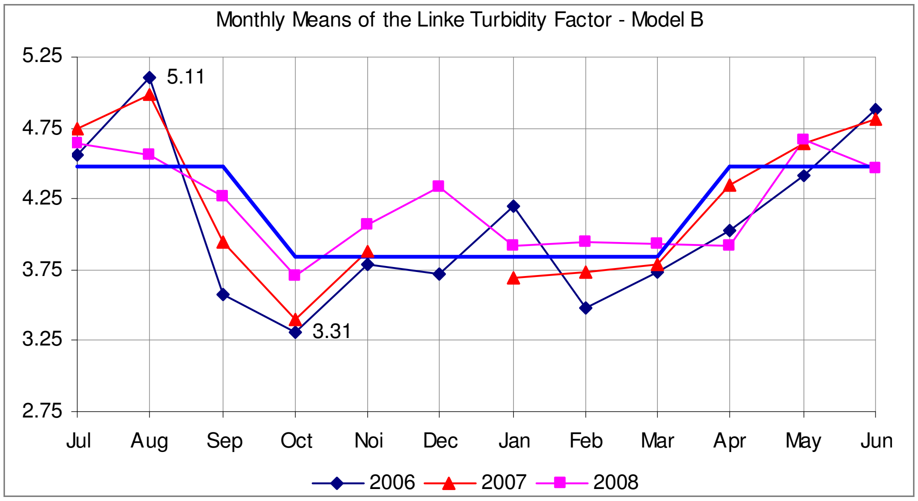


Fig. 1. *Linke turbidity factor calculated with the 2 models*

- for the periods April-June and July-September around the value of 4.48, if the Remund-Page formula for Rayleigh optical thickness is used, and around 3.98 for the Kasten-Young formula.

The smallest values of the T_L turbidity factor were obtained for October. During the three years, the smallest value was recorded in October 2006.

The higher values of the turbidity factor for the Braşov urban area were registered for August and June. The highest value of the monthly mean was obtained in August 2006.

The use of the monthly mean values of the turbidity factor for the radiation simulation could not lead to a very accurate approximation of this. For those records with higher values of the turbidity factor, it is obvious that the real radiation has higher values than the theoretical one. For these situations, it is considered that it might be necessary to recalculate the turbidity factor in order to bring the theoretical radiation variation closer to the real one.

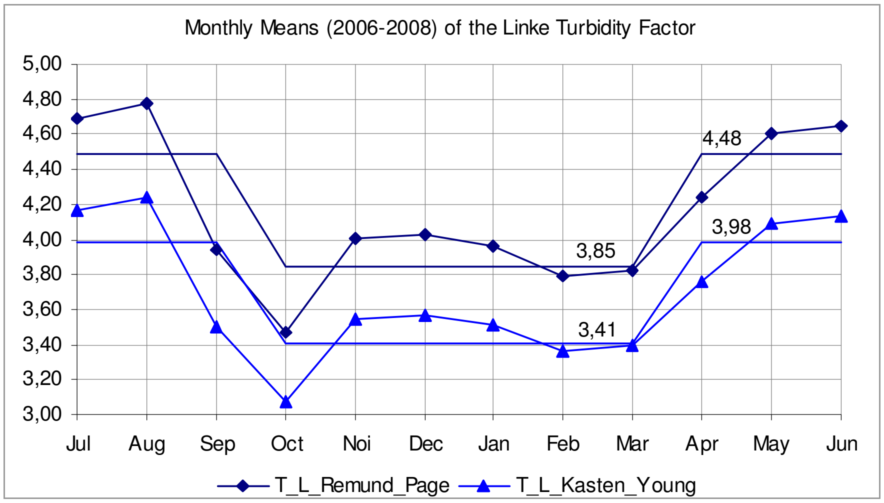


Fig. 2. *Monthly means of the Linke turbidity factor (three- year period)*

Consequently, the determination of the monthly mean of the hourly minimum values for the turbidity factor is proposed.

Figure 3 presents the two diagrams for the turbidity factor calculated with the two models, considering the monthly mean of the hourly minimum values. Diagrams in Figure 4 synthesises the turbidity factor for all three analysed years.

The monthly mean of the minimum turbidity factor values, recorded for the urban area of Braşov, are (see Figure 4):

- for the period October-March around the value of 3.54 using the Remund-Page formula for Rayleigh optical thickness (compared to 3.85, see Figure 2), and around 3.14 if the Kasten-Young formula is used (compared to 3.41, see Figure 2);
- for the periods April-June and July-September around the value of 4.18, if the Remund-Page formula for Rayleigh optical thickness is used (compared to 4.48, see Figure 2), and around 3.72 for the Kasten-Young formula (compared to 3.98, see Figure 2).

The smallest values of the T_L turbidity factor were obtained for October. During the three years, the smallest value was recorded in October 2006; the monthly mean value of hourly minimum values was 3.13 when the Remund-Page formula was used and 2.77 for Kasten and Young formula. The highest values of the turbidity factor for the Braşov urban area were registered in August. The highest value of the monthly mean of the hourly minimum values was obtained in August 2007 (4.87 for Remund-Page formula and 4.32 for Kasten-Young formula).

7. Conclusions

The measurement was carried out in Braşov, a medium-sized town located in a basin region. This region exhibits some typical features with respect to topology, climatology and the environment. The built-up area is low in comparison with that of the neighbouring mountains, which circle the basin area. Even in the sunny days the “visible” sky is delineated by the surrounding heights and the possible duration of direct sunshine and the amount of diffuse radiation are diminished. All these considered, the turbidity factor values calculated for Braşov are specific to an urban

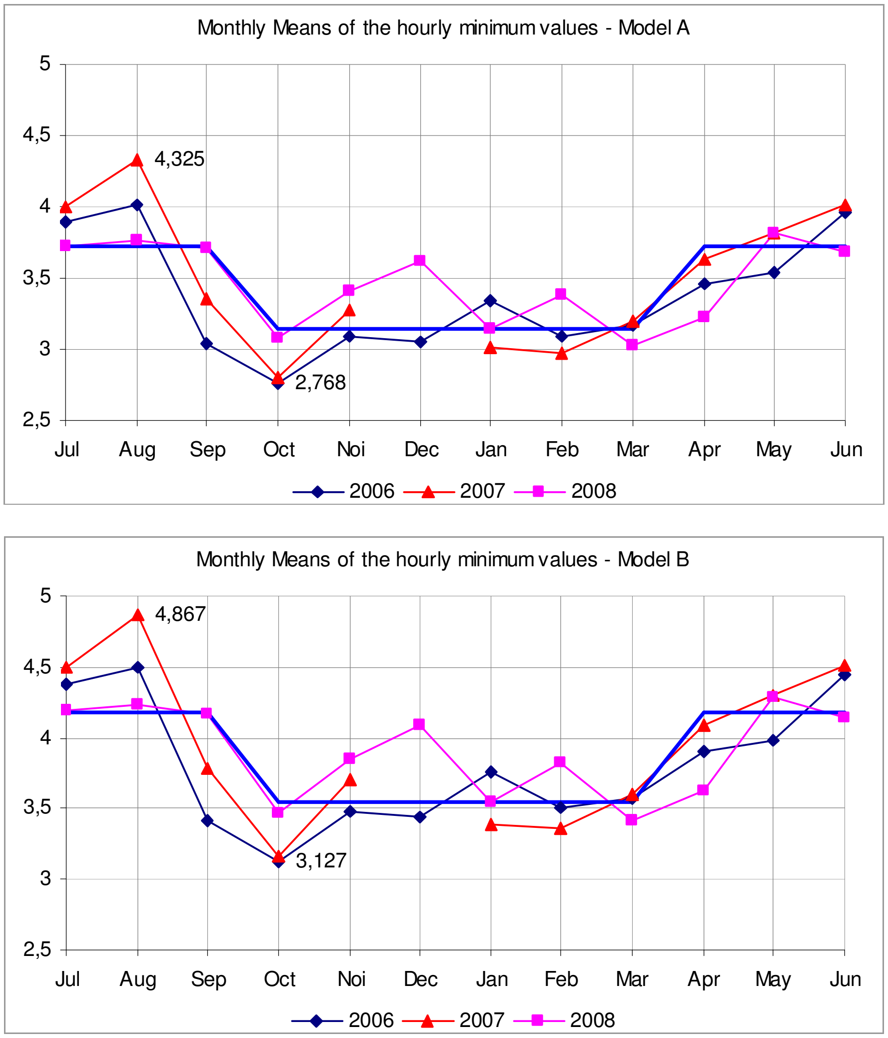


Fig. 3. *Linke turbidity factor - monthly means of the hourly minimum values*

area. Thus, the registered values of the turbidity factor characterize a moist and polluted atmosphere.

It must be mentioned that the technical literature does not offer very accurate values of this factor; besides, it does not take into consideration the geographical, climatic and urban conditions specific to Braşov area [5] (according to specialised literature, the monthly mean values of the turbidity factor varies between 1.9 and 3.5).

The future research will aim at determining the variation in solar radiation for Braşov urban area. Thus, the accurate knowledge of the turbidity factor variation will make it possible to determine a relation for the variation in solar radiation, so as to approximate reality to a great extent. Noteworthy is the fact that the only unknown parameter (in the expression of solar radiation) is the turbidity factor. Therefore, the determination of solar radiation

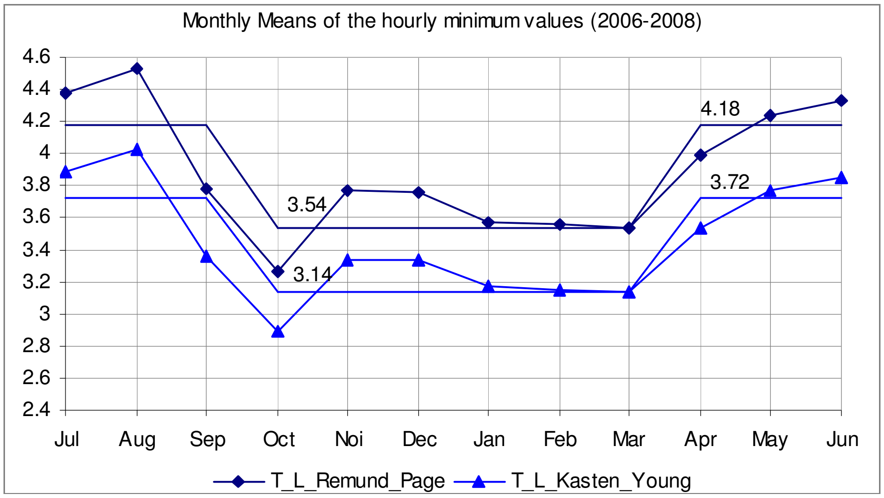


Fig. 4. *Monthly mean values of the hourly minimum values of Linke factor (three-year period)*

requires the adjustment of the turbidity factor according to all geographic and climatic conditions, as well as the pollution of a built-up area.

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