Proc. Estonian Acad. Sci. Ecol., 1996, 6, 3/4, 167–175
https://doi.org/10.3176/ecol.1996.3/4.07

COMPARISON OF TWO METHODS FOR THE CALCULATION OF THE ATMOSPHERIC INTEGRAL TRANSPARENCY COEFFICIENT

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Presented by J. Ross

Received 8 January 1996, accepted 6 June 1996

Abstract. Accuracy of the transformation (reduction) of the atmospheric integral transparency coefficient from the actual air mass m to air mass $m = 2$ (solar elevation $h = 30°$) was studied using two different methods – the method proposed by Evnevich–Savikovskij, and the method proposed by Mürk–Ohvril. The table of average values of direct solar radiation versus solar elevation angle and rate of atmospheric turbidity, compiled by Sivkov and updated by Evnevich–Savikovskij, was considered as the basic one. The results show that both methods give almost the same uncertainty (2%) and they may be recommended for practical calculations of the atmospheric integral transparency coefficient.

Key words: direct solar radiation, atmospheric integral transparency coefficient, Forbes' effect.

INTRODUCTION

The *Atmospheric Integral Transparency Coefficient* (AITC), p_m, is easily calculated, according to the well-known Bouguer law, from the measured integral (broadband) direct solar irradiance on a plane perpendicular to the beam, S_m :

$$p_m = \left(\frac{S_m}{S_o}\right)^{\frac{1}{m}}. \quad (1)$$

Here m is the number of (relative optical) air masses in the direction of the sun and S_o is the extraterrestrial irradiance determined by the earth–sun distance in astronomical units ρ and the solar constant $S_o^* = 1.367$ kW m^{-2} :

$$S_o = S_o^* \frac{1}{\rho^2}. \quad (2)$$

The coefficient p_m is one of the simplest characteristics of the turbidity of the atmosphere. This is not a new parameter. Numerous actinometrists, mainly in the former USSR (FSU), have used it since the 1920s (Kondratyev, 1969). A large amount of measured and archived data on direct solar radiation in various meteorological stations over the world would be a rich database for the retrieval of long-term time series of AITC and the creation of an extremely useful climatological material of the local and global climate changes. Unfortunately, outside the FSU this parameter was almost unknown. Even in the FSU the number of meteorological stations where direct solar irradiance, S_m, was in the daily program of measurements was considerably reduced in the 1960s.

Mainly two kinds of difficulties are encountered in using S_m and p_m:

(1) high quality pyrheliometers used in measuring direct solar radiation are expensive but vulnerable instruments, their application in automatized measurements always contains risk of damage by precipitation; unfortunately cheap and more robust Actinometers AT50 (developed at the Main Geophysical Observatory in Leningrad), considered to provide acceptable accuracy, are hardly available now;

(2) because of the Forbes' effect (caused by the selective spectral attenuation of direct solar radiation in the atmosphere) the AITC depends on solar elevation even in the case of stationary and azimuthally homogeneous atmosphere.

The problem of vulnerability of pyrheliometers needs to be solved by the development of instruments of more reliable design. Until new instruments are available, the solutions might be: (1) manual use of pyrheliometers, or (2) measurement of S_m by pyranometers as the difference of global and diffuse solar radiation.

To eliminate the Forbes' effect, the generally accepted practice is to reduce the AITC p_m from the actual air mass m to p_2 corresponding to the air mass $m = 2$ (solar elevation angle $h = 30°$). The complicated problem of reducing the Forbes' effect was in principle solved in the 1960s by Sergei Sivkov (who compiled tables for the transformation of AITC) and Herman Mürk (who created a nomogram for the same purpose).

Unfortunately both methods were quite clumsy, needing a certain amount of "manual work", which seems to be one of the reasons for their limited use. However, both methods have been considerably upgraded to simple analytical forms. Sivkov's method was developed to be more user-friendly by Evnevich & Savikovskij (Евневич & Савиковский, 1989) and Mürk's method by Mürk & Ohvril (Мюрк & Охвриль, 1988, 1990).

The method of Evnevich & Savikovskij allows one to calculate p_2 directly from measured values of S_m using one of the two formulas presented below. The *first formula* (which we further call *model ES-1*):

$$p_2 = 0.978 \left(\frac{S_m}{1.307} \right)^{\frac{\sin h + 0.15}{1.3}}, \qquad (3)$$

or the *second formula* (*model ES-2*):

$$p_2 = \left(\frac{S_m}{1.367} \right)^{\frac{\sin h + 0.205}{1.41}} . \quad (4)$$

Mürk & Ohvril proposed a *general formula* to go from the transparency coefficient p_m to p_i (*model MO-1*):

$$p_i = p_m \left(\frac{i}{m} \right)^{\frac{\log p_m + 0.009}{\log m - 1.848}} , \quad (5)$$

which in the most important particular case $i = 2$ ($h = 30°$) takes the form:

$$p_2 = p_m \left(\frac{2}{m} \right)^{\frac{\log p_m + 0.009}{\log m - 1.848}} . \quad (6)$$

The aim of the present paper is to compare the accuracy of these different methods for the calculation of AITC p_2.

STANDARD VALUES OF DIRECT SOLAR IRRADIANCE

The greatest work in the generalization of measurements of direct solar irradiance, S_m, was done by Sivkov (Сивков, 1965). Using databases from eight meteorological stations on the territory of the USSR containing more than 13 000 measurements at different solar elevations ($7° \leq h \leq 42°$ or $8 \geq m \geq 1.5$) and a wide range of atmospheric turbidity, he compiled a table of mean values of direct solar irradiance, S_m . He found the values for S_m at solar elevations $h > 42°$ using mathematical extrapolation.

In connection with the introduction of new radiation units, a new solar constant, and changes in the pyrheliometric scale, Evnevich published a new version of tables for S_m (Евневич, 1986) and then, together with Savikovskij, the newest version (Евневич & Савиковский, 1989), which we consider as standard (see Table 1). This table presents mean values of S_m corresponding to 10 different situations of atmospheric turbidity – from very low transparency ($p_2 = 0.410$) to the ideal atmosphere ($p_2 = 0.905$). All values are original except the value $S_m = 1.082$ in the second row from bottom ($p_2 = 0.872$, $h = 40°$), written in bold. In the original this value was 1.032, which is evidently a typographical error.

Table 1

Standard values of direct solar irradiance, S_m, in kW/m^2 according Evnevich & Savikovskij (Евневич & Савиковский, 1989)

Transparency, p_2		Solar elevation angle, h								
		10	20	30	40	50	60	70	80	90
Very	0.410	0.035	0.133	0.230	0.316	0.377	0.426	0.456	0.475	0.486
low	0.469	0.070	0.188	0.300	0.391	0.456	0.506	0.537	0.554	0.564
Low	0.567	0.147	0.321	0.440	0.530	0.600	0.649	0.677	0.691	0.704
	0.623	0.216	0.416	0.530	0.624	0.694	0.740	0.755	0.768	0.775
Normal	0.700	0.346	0.551	0.670	0.756	0.810	0.846	0.866	0.879	0.886
	0.736	0.412	0.621	0.740	0.817	0.865	0.900	0.914	0.928	0.935
	0.770	0.489	0.698	0.810	0.879	0.921	0.956	0.970	0.984	0.986
High	0.811	0.579	0.796	0.900	0.956	0.991	1.019	1.033	1.040	1.047
	0.872	0.761	0.956	1.040	**1.082**	1.103	1.124	1.138	1.145	1.152
Ideal	0.905	0.887	1.050	1.120	1.156	1.176	1.190	1.204	1.212	1.219

In order to visualise the variation of standard values of S_m as functions of solar elevation angle, h, we have inserted Fig. 1, which contains 10 different plots according to Table 1.

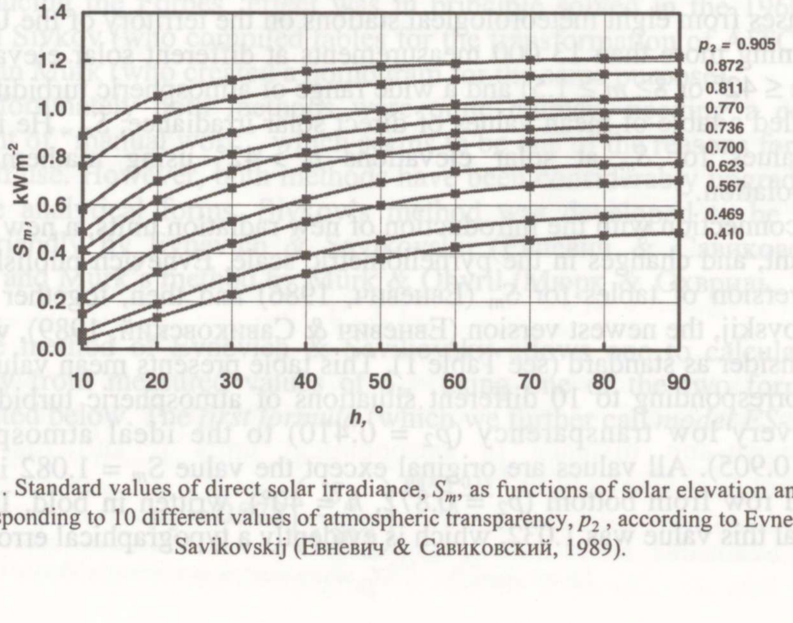

Fig. 1. Standard values of direct solar irradiance, S_m, as functions of solar elevation angle, h, corresponding to 10 different values of atmospheric transparency, p_2 , according to Evnevich & Savikovskij (Евневич & Савиковский, 1989).

Comparison of methods

In order to compare the accuracy of the use of the three models discussed (ES-1, ES-2, and MO-1) we have proceeded from Table 1 and calculated for each standard S_m a standard value of AITC p_m according to formula (1). Then, proceeding from these models and the given AITC p_2, we calculated AITC p_m in three different ways:

(1) according to ES-1; revealing S_m from (3) and applying (1), we easily obtain

$$p_m = \left[0.9561 \left(\frac{p_2}{0.978} \right)^{\frac{1.3}{\sin h + 0.15}} \right]^{\frac{1}{m}}, \tag{7}$$

(2) according to ES-2; revealing S_m from (4) and using again (1), we obtain

$$p_m = (p_2)^{\frac{1.41}{(\sin h + 0.205)m}}, \tag{8}$$

(3) according to MO-1; from the general formula (5) follows a special one

$$p_m = p_2 \left(\frac{m}{2} \right)^{-\frac{\log p_2 + 0.009}{1.547}}. \tag{9}$$

The accuracy of the values of p_m, found by each model (ES-1, ES-2, MO-1) with regard to standard values, p_m (standard), was estimated by calculating the relative errors, δ:

$$\delta = \frac{p_m - p_m(\text{standard})}{p_m(\text{standard})} 100\%. \tag{10}$$

For three selected cases of atmospheric turbidity (p_2 = 0.410, 0.700, 0.872) the results of the calculation of p_m and δ are presented in Table 2.

To economize the space of this paper, the remaining seven cases of turbidity given in Table 1 are not presented. The greatest errors caused by each considered model occur in the case of very low transparency, when $p_2 = 0.410$.

The greatest of all errors, equal to 6.4%, is in the use of model ES-2 at solar elevation $h = 10°$. The maximum error caused by model ES-1 is only 2.31% ($h = 10°$) and by model MO-1, 2.65% ($h = 90°$). In Table 2 the maximum errors in the case of $p_2 = 0.410$ are written in bold.

It is important to stress that for solar elevations $20° \leq h \leq 80°$, all three models secure accuracy of reduction of AITC p_2 to p_m with an error smaller than 2.5% in regard to standard values of p_m.

Table 2

Standard and modelled values of AITC p_m with relative errors δ

h	m	S_m (standard)	p_m (standard)	ES-1		ES-2		MO-1	
				p_m	δ, %	p_m	δ, %	p_m	δ, %
				Very low transparency, $p_2 = 410$					
10	5.60	0.035	0.520	0.532	**2.31**	0.553	**6.40**	0.527	1.47
20	2.90	0.133	0.448	0.446	–0.44	0.453	1.17	0.449	0.27
30	2.00	0.230	0.410	0.410	0.00	0.410	0.00	0.410	0.00
40	1.556	0.316	0.390	0.389	–0.41	0.386	–1.06	0.386	–1.16
50	1.305	0.377	0.373	0.375	0.69	0.371	–0.45	0.369	–0.89
60	1.155	0.426	0.364	0.367	0.72	0.362	–0.66	0.358	–1.62
70	1.064	0.456	0.356	0.362	1.47	0.356	0.00	0.351	–1.40
80	1.015	0.475	0.353	0.359	1.59	0.353	0.02	0.347	–1.59
90	1.00	0.486	0.356	0.358	0.64	0.352	–0.99	0.346	**–2.65**
				Normal transparency, $p_2 = 0.700$					
10	5.60	0.346	0.782	0.780	–0.26	0.789	0.90	0.771	–1.41
20	2.90	0.551	0.731	0.726	–0.68	0.728	–0.41	0.725	–0.82
30	2.00	0.670	0.700	0.700	0.00	0.700	0.00	0.700	0.00
40	1.556	0.756	0.683	0.683	0.00	0.683	0.00	0.684	0.15
50	1.305	0.810	0.670	0.672	0.30	0.672	0.30	0.672	0.30
60	1.155	0.846	0.660	0.664	0.61	0.666	0.91	0.665	0.76
70	1.064	0.866	0.651	0.659	1.23	0.662	1.69	0.660	1.38
80	1.015	0.879	0.647	0.656	1.39	0.659	1.85	0.657	1.55
90	1.00	0.886	0.648	0.655	1.08	0.659	1.70	0.656	1.23
				Very high transparency, $p_2 = 0.872$					
10	5.60	0.761	0.901	0.914	1.44	0.913	1.37	0.902	0.12
20	2.90	0.956	0.884	0.887	0.32	0.885	0.11	0.883	–0.15
30	2.00	1.040	0.872	0.872	0.00	0.872	0.00	0.872	0.00
40	1.556	1.082	0.860	0.861	0.04	0.864	0.41	0.865	0.51
50	1.305	1.103	0.848	0.853	0.52	0.859	1.25	0.860	1.36
60	1.155	1.124	0.844	0.847	0.34	0.855	1.29	0.857	1.47
70	1.064	1.138	0.842	0.843	0.14	0.853	1.34	0.854	1.49
80	1.015	1.145	0.840	0.840	0.00	0.852	1.45	0.853	1.56
90	1.00	1.152	0.843	0.840	–0.36	0.852	1.10	0.852	1.16

Figure 2 contains eight plots of reduced coefficients of p_m calculated by the three models considered, and plots of standard values of p_m (continuous line). It is obvious from the physical content of the Forbes' effect that the course of p_m as a function of diminishing solar elevation angles, h (or increasing optical masses, m), should form an increasing sequence

$$p_m\,(h=90°) < p_m\,(h=80°) < p_m\,(h=70°) < ... < p_m\,(h=10°)\,. \qquad (11)$$

All models used fulfil this demand except standard values of p_m at high solar elevations ($h > 60°$).

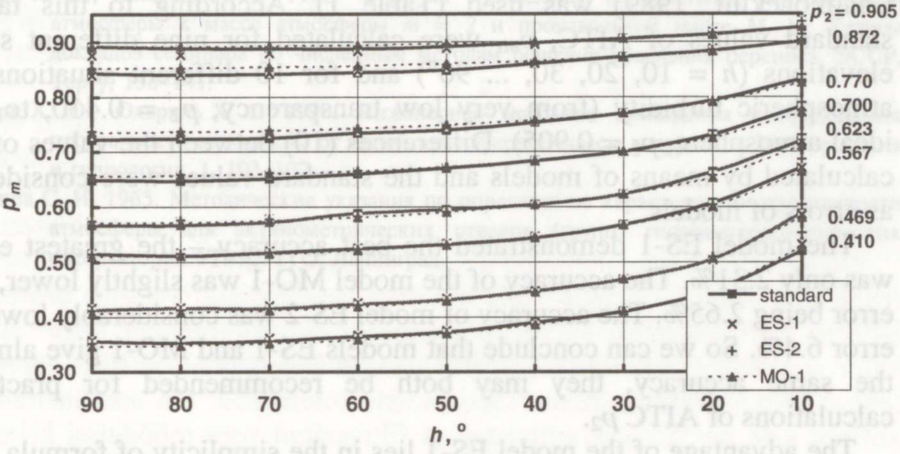

Fig. 2. Values of AITC p_m as functions of diminishing solar elevation angle, h.

For example, in the case of very low transparency ($p_2 = 0.410$), standard values of p_m are

$$p_m\,(h=90°) = 0.356 > p_m\,(h=80°) = 0.353, \qquad (12)$$

and in the case of the ideal atmosphere ($p_2 = 0.905$) even:

$$p_m\,(h=90°) > p_m\,(h=60°)\,. \qquad (13)$$

Neither inequality (12) nor (13) is physically based.

Irregularities in the courses of standard values of p_m may be corrected by correcting standard values of direct solar irradiance, S_m, in Table 1. As mentioned above, Sivkov (Сивков, 1965) found standard values for S_m at solar elevations $h > 42°$ using mathematical extrapolation. Evidently, to correct Table 1, special measurements of daily courses of S_m for solar elevations $h > 42°$ would be necessary.

CONCLUSIONS

Two user-friendly, simple methods for the calculation of the *Atmospheric Integral Transparency Coefficient* (AITC), p_2, were proposed in the end of the 1980s:

1) the method of Evnevich–Savikovskij, which may be considered consisting of two models, ES-1 and ES-2, and expressed by formulas (3) and (4) respectively, and

2) the method of Mürk–Ohvril, model MO-1, expressed by formula (6).

In order to compare the accuracy of the above-mentioned models for the calculation of AITC, a table of standard values of direct solar irradiance, S_m, proposed by Evnevich & Savikovskij (Евневич & Савиковский, 1989) was used (Table 1). According to this table, standard values of AITC, p_m, were calculated for nine different solar elevations (h = 10, 20, 30, ... 90°) and for 10 different situations of atmospheric turbidity (from very low transparency, $p_2 = 0.410$, to the ideal atmosphere, $p_2 = 0.905$). Differences (10) between the values of p_m calculated by means of models and the standard values were considered as errors of models.

The model ES-1 demonstrated the best accuracy – the greatest error was only 2.31%. The accuracy of the model MO-1 was slightly lower, the error being 2.65%. The accuracy of model ES-2 was considerably lower – error 6.4%. So we can conclude that models ES-1 and MO-1 give almost the same accuracy, they may both be recommended for practical calculations of AITC p_2.

The advantage of the model ES-1 lies in the simplicity of formula (3), which allows easy calculation of the coefficients p_2 from the results of measurements of direct solar irradiance, S_m. The advantage of the model MO-1 is that formula (6) does not contain a solar constant and is not connected with the pyrheliometric scale.

Uneven, rough angular courses of the calculated standard values of the AITC p_m (Fig. 2) prove the necessity to update the initial table of standard values of direct solar irradiance, S_m (Table 1).

ACKNOWLEDGEMENTS

The authors wish to thank the Central European University and G. Soros foundation for supporting this research in the very beginning through the contract CEU\RSS\ No: 357\93. We would like to thank IBM Finland and Mr. P. Lönnfors for the donation of a PS/2 computer and Mr. S. Sipola, who suggested this donation. Many thanks to our Finnish colleagues R. Lemmelä, J. Virta, and M. Leppäranta for their friendly help during visits to Helsinki.

From the Estonian side this research was sufficiently supported during 1994–96 by grant No. 446 of the Estonian Science Foundation.

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