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# THE ATMOSPHERIC INTEGRAL TRANSPARENCY COEFFICIENT AND THE FORBES EFFECT

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**Abstract**—The Forbes effect (known from 1842) expresses the fact that a total (broadband) direct solar beam becomes increasingly penetrating on its way through the atmosphere – because of changes in its spectral content and loss of less penetrating spectral components. The effect restricts the use of the Bouguer-Lambert law for calculating the characteristics of transparency (or turbidity) of the air. Efforts to overcome this effect and to transform the coefficients of transparency to a given solar elevation have finally met with success, and in this study one of such methods (developed by Mürk and Ohvril) is presented in detail. This method is compared with those of Evnevich and Savikovskij. For solar elevations $20° \leq h \leq 80°$ all three techniques are compatible, securing accuracy with an uncertainty below 2.5% with regard to standard values of the coefficient of transparency. Simple transition to the Linke turbidity factor is available. Time courses of mean annual values of the coefficient of atmospheric transparency at solar elevation $h = 30°$ and the Linke factor for the last 40 years at an Estonian station at Tiirikoja are given as examples. In the average the multiannual time courses demonstrate an increase of atmospheric turbidity as well as bear evidence of sensitivity to great volcanic eruptions. 

## 1. INTRODUCTION

Transparency is one of the primary measures indicating the state of the atmosphere. Long-term time series of transparency allow one to assess quantitatively the variability of turbidity of air and to make **climatological conclusions** with regard to contamination, radiative exchange, humidity, cloud formation, greenhouse effect, global warming/cooling.

Transparency can be determined in several ways and in different directions – by visibility of remote objects, by brightness of calibrated lamps or known natural or artificial sources of light, etc.

In meteorological practice the sun – despite its rotation, sunspot cycles and faculae activities – is considered as a fairly stable source of light. The amount of total (integral) solar energy at all wavelengths, incident on unit area at the **T**op **O**f the **A**tmosphere (**TOA**) may be easily calculated with an error of only a few tenths of a percent.

According to the well known Bouguer-Lambert law, the ratio of the intensity of the direct solar beam which reaches the earth's surface after attenuation in the air (total direct solar irradiance or simply direct solar radiation) and to that at the TOA serves as the basic quantity for further calculation of various characteristics of atmospheric transparency/turbidity. The effect of Forbes, caused by selective attenuation of the total direct solar beam, places an interesting but serious barrier on the calculation of broadband characteristics of atmospheric transparency/turbidity.

Some historical remarks. There is a difference in terms used in western countries and in the territory of the former USSR. The term, *Forbes effect,* has been widely used by Russian actinometrists (Sivkov, 1968, Sivkov, 1971; Evnevich and Savikovskij, 1989). In western countries the same effect is better known as the *virtual diurnal variation* of atmospheric broadband transmission characteristics. It means that even in the case of a stationary and azimuthally homogeneous atmosphere, broadband characteristics of transparency/turbidity depend on solar elevation. Solar rays, due to the change of their spectral content, become more penetrating at the lower sun. This effect was first explained by Scottish physicist James David Forbes (1809–1868): *the tendency to absorption* (of light) *through increasing thickness of air is a diminishing one ... the physical cause of this law of absorption appears to be the nonhomogeneity of the incident rays which by parting with their more absorbable elements*

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*become more persistent in their character* (Forbes, 1842). Making this important conclusion, Forbes was guided by an earlier remarkable experiment of the German scientist Johann Heinrich Lambert (1728–1777). In his monograph ‘‘Pyrometrie’’ Lambert (1779), studying thermometers, described in detail his experiment with a set of three glassplates. He measured the intensity of solar radiation after it passed through each plate and thus found that the facility of transmission of solar radiation through successive plates increased with the number already traversed.

To eliminate the Forbes effect, the generally accepted practice is to reduce broadband characteristics of transparency/turbidity from the actual optical air mass $m$ to the air mass $m = 2$ (solar elevation angle $h = 30°$). Historically, different final values of $m$ were used, from $m = 1$ to $m = 3$. The value $m = 2$ is considered the most convenient because, for the majority of observation stations, direct solar irradiance can be directly measured at this mass. The case $m = 1$ (the sun at zenith) is not available for most radiometric stations, while $m = 3$ corresponds to a solar elevation (19.3°) which is too low, as the sun is often screened by clouds, trees, constructions, etc.

The present paper summarizes our results in the development of simple computational procedures to reduce the Forbes effect with regard to the atmospheric integral transparency coefficient, and transition to the Linke turbidity factor.

## 2. SOME CLASSIC FORMULAS

The following relation determines the extinction of a monochromatic solar beam $I_\lambda$ along its path d$s$:

$$dI_\lambda = -k_\lambda I_\lambda \rho \, ds, \tag{2.1}$$

where $k_\lambda$ is the mass extinction coefficient and $\rho$ denotes the air density.

Designating by $I_{0\lambda}$ the monochromatic solar radiant flux at the TOA, and integrating the above relation over the entire beam’s geometrical path in the atmosphere, we obtain the monochromatic beam irradiance $I_\lambda$ at the earth’s surface:

$$I_\lambda = I_{0\lambda} \exp(-m\theta_0) = I_{0\lambda} p_\lambda^m, \tag{2.2}$$

where $\theta_0$ represents the optical thickness (depth) of the atmosphere in the vertical direction, and $p_\lambda = \exp(-\theta_0)$ is the atmospheric monochromatic transparency coefficient in the vertical direction when the optical mass $m = 1$.

Integrating both sides of (2.2) over all wavelengths $\lambda$, we find:

$$I_m = \int_0^\infty I_\lambda \, d\lambda = \int_0^\infty I_{0\lambda} p_\lambda^m \, d\lambda = p_m^m \int_0^\infty I_{0\lambda} \, d\lambda = p_m^m I_0, \tag{2.3}$$

where $I_0$ is the extraterrestrial irradiance determined by the earth–sun distance in astronomical units $d$ and by the solar constant $I_0^* = 1.367$ kW/m$^2$:

$$I_0 = I_0^* \frac{1}{d^2}, \tag{2.4}$$

the coefficient $p_m$ may be interpreted as the **A**tmospheric **I**ntegral **T**ransparency **C**oefficient (AITC) averaged over the whole spectrum. This is the main quantity of the present paper. The result

$$I_m = I_0 p_m^m \tag{2.5}$$

expresses the Bouguer-Lambert law for the total (integral) solar beam $I_m$ when the atmospheric optical mass is $m$. The above abbreviated derivation of this formula followed the classic monograph of Kondratyev (1969).

The AITC $p_m$ is one of the simplest characteristics of the transparency of the atmosphere. For its determination it is necessary to measure the direct solar beam $I_m$ and to use the formula

$$p_m = \left(\frac{I_m}{I_o}\right)^{1/m}. \tag{2.6}$$

Dependence of $p_m$ on the optical air mass $m$ seems to us as the prime reason why characteristics based on direct solar irradiance are not widely used (a second reason is vulnerability of high quality pyrheliometers to precipitations and lack of cheap operational actinometers for everyday measurements of the direct solar beam, while a third reason lies in the difficulty of automatic detection of clouds in the direction of the sun). Therefore development of algorithms to convert the $p_m$ values into standard quantities $p_2$ (corresponding to air mass $m = 2$) stimulates new measurements of direct solar irradiance $I_m$ as an energetically and climatologically important parameter. On the other hand, long time series of $I_m$ have already been recorded by various well equipped meteorological or radiometric stations in connection with routine measurements and calibrations. The possibility of converting and standardizing the $p_m$ values gives new life to already measured data.

## 3. PARAMETERIZATION FORMULAS FOR THE ATMOSPHERIC INTEGRAL TRANSPARENCY COEFFICIENT

Elaboration of computational procedures for the reduction of the Forbes effect should start from compilation of tables of values of the direct solar beam $I_m$ at different solar elevations and different rates of atmospheric transparency/turbidity. The greatest work in the generalization of theory and measurements of the direct solar irradiance $I_m$ has been done by Russian actinometrists, especially by Sergei Sivkov (1965, 1968, 1971). Using databases from eight meteorological stations on the territory of the former 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 transparencies, he compiled a table of mean values of the direct solar irradiance, $I_m$. He found the values for $I_m$ at solar elevations, $h > 42°$, using mathematical extrapolation and the Kastrov formula

$$I_m = \frac{I_0}{1 + cm}, \tag{3.1}$$

where the coefficient $c$ unfortunately depends on the atmospheric transparency/turbidity and on the mass $m$. This coefficient was usually tabulated in the form $c = c\ (p_2,\ m)$, i.e. as a function of the transparency $p_2$ and mass $m$.

In connection with the introduction of new radiation units, the new solar constant, and changes in the pyrheliometric scale, Evnevich (1986) published a new version of the table for $I_m$ and then, together with Savikovskij, the newest version (Evnevich and Savikovskij, 1989), which we shall consider as standard (Table 1).

The table presents mean values of $I_m$ corresponding to 10 different cases of atmospheric transparency – from the very low ($p_2 = 0.410$) to the ideal (clean and dry) atmosphere ($p_2 = 0.905$).

It should be stressed that Table 1 contains only the mean values of the direct irradiance $I_m$ averaged over all seasons at moderate latitudes. Estimation of individual rates of contribution of water vapor or aerosols to the total attenuation of the direct solar beam is not available.

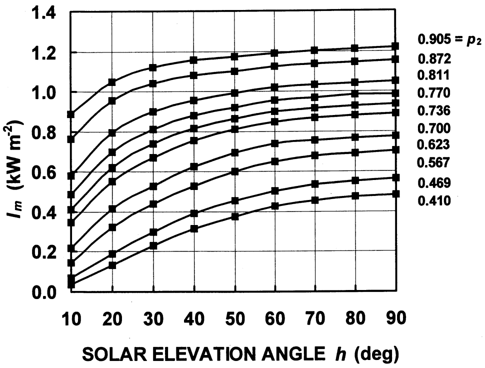


Fig. 1. Standard values of direct solar beam, $I_m$, as functions of solar elevation angle, $h$, corresponding to 10 different values of atmospheric transparency, $p_2$, according to Evnevich and Savikovskij (1989).

In order to visualize the variation of the standard values of $I_m$ as functions of the solar elevation angle $h$, Fig. 1 contains 10 different plots in accordance with Table 1.

Until Evnevich and Savikovskij (1989) developed formulas to calculate $p_2$ directly from values of the measured direct solar beam $I_m$, this kind of tables were used in the actinometric net of the former USSR for determination of reduced values of transparency.

Evnevich and Savikovskij developed two formulas. Their *first formula* (which we shall call *method ES-1*):

$$p_2 = 0.978\left(\frac{I_m}{1.307}\right)^{(\sin h + 0.15)/1.3}, \tag{3.2}$$

and the *second formula* (*method ES-2)*:

$$p_2 = \left(\frac{I_m}{1.367}\right)^{(\sin h + 0.205)/1.41}, \tag{3.3}$$

Table 1. Standard values of direct solar irradiance $I_m$ in kWm$^{-2}$ as functions of atmospheric transparency $p_2$ and solar elevation $h$ (according to Evnevich and Savikovskij, 1989)

| Transparency | | Solar elevation angle, $h$ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $p_2$ | 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 |
| | 0.700 | 0.346 | 0.551 | 0.670 | 0.756 | 0.810 | 0.846 | 0.866 | 0.879 | 0.886 |
| Normal | 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 | 0.87 | 1.050 | 1.120 | 1.156 | 1.176 | 1.190 | 1.204 | 1.212 | 1.219 |

represent handy tools for direct conversion of values of the direct beam $I_m$ to standard values of transparency $p_2$.

An Estonian actinometrist, Herman Mürk (1908–1988), used the Bouguer law in differential form:

$$dI_m = -\alpha_m I_m \, dm, \tag{3.4}$$

where $\alpha_m$ is the attenuation coefficient for direct solar radiation. In order to consider the effect of Forbes, he proceeded from the assumption that $\alpha_m$ is not a constant but decreases when the optical mass $m$ increases:

$$d\alpha_m = -B\frac{dm}{m}. \tag{3.5}$$

Here $B$ is an additional parameter of atmospheric transparency introduced by Mürk (1959a). In the present paper this parameter is used only temporarily and will not appear in final formulas. It is seen from (3.4) and (3.5) that the direct solar beam $I_m$ is now described by two parameters, $p_1$ and $B$:

$$I_m = I_0 p_1^m m^{mB}, \tag{3.6}$$

where $p_1$ is the AITC at $m=1$.

From (3.6) follows a linear dependence between log $p_m$ and log $m$:

$$\underbrace{\log p_m}_{y} = \underbrace{\log p_1}_{A} + B\underbrace{\log m}_{x}, \tag{3.7}$$

$$y = A + Bx, \tag{3.8}$$

where the initial ordinate of the straight line (3.8) is log $p_1$ and the inclination is determined by parameter $B$.

Further, generalizing measurements made in the former USSR by Sivkov, Tshaidze and Averkiev, Mürk found an interesting experimental fact, namely that all possible lines (3.7) intersect at approximately the same point $O^*$, with co-ordinates (Mürk, 1959b):

$x(O^*) = \log m = 1.848$,

which corresponds to $m = 70.47$,

$y(O^*) = \log p_m = -0.009$,

which corresponds to $p_m = 0.979$.

Of course, this value of $x$ is not available in reality because the maximal optical air mass, $m=39.7$, occurs when the sun is at the horizon. Each member of the family of straight lines

$$y = \log p_m = B \log m - 1.848\,B - 0.009 \tag{3.9}$$

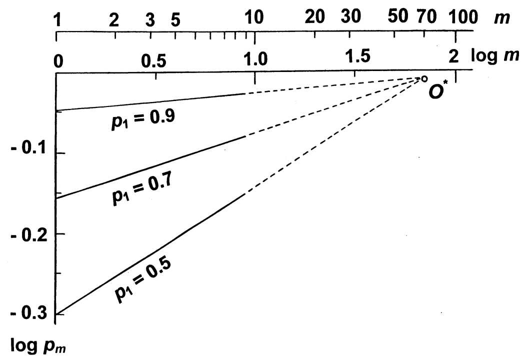


Fig. 2. Family of lines $y=\log p_m = B \log m - 1.848\,B - 0.009$.

is determined by Mürk's new parameter of transparency $B$ and by the point $O^*$ (Fig. 2).

The case $m=1$ gives a link between the parameters of transparency $p_1$ and $B$:

$$\log p_1 = -1.848\,B - 0.009, \tag{3.10}$$

which allowed Mürk to construct a nomogram, thus enabling in the 1960s, before computers and electronic calculators, easy determination of various characteristics of atmospheric transparency/turbidity – the AITC, the coefficient $B$, the Linke turbidity factor $T$ – according to the given air mass $m$ and measured direct solar beam $I_m$ (Mürk, 1959b). The nomogram also enabled to reduce the AITC $p_m$ from the actual air mass $m$ to another air mass $i$. The nomogram of Mürk was widely used in Estonia until the early 1990s. As an example of this use, diurnal course of AITC $p_m$, measured in Tartu, Estonia, on March 22, 1956 is given in Fig. 3 (redrawn from Aruksaar et al., 1964).

After creation of Mürk's nomogram, only one step remained to the derivation of a formula

$$p_i = f(p_m, i), \tag{3.11}$$

which would enable to transform the AITC $p_m$ corresponding to an air mass $m$ to $p_i$ corresponding to another air mass $i$ at the same state of transparency/turbidity of the air.

This step was taken by Mürk and Ohvril (1988), Mürk and Ohvril (1990) who proved that, proceeding from the Bouguer-Lambert law (2.5) and Mürk's formulas (3.6), (3.10), one may obtain a general relation for going from coefficient $p_m$ to $p_i$ (from mass $m$ to mass $i$):

$$p_i = p_m\left(\frac{i}{m}\right)^{(\log p_m + 0.009)/(\log m - 1.848)}. \tag{3.12}$$

For the most important particular case $i=2$ ($h=30°$):

$$p_2 = p_m\left(\frac{2}{m}\right)^{(\log p_m + 0.009)/(\log m - 1.848)}, \tag{3.13}$$

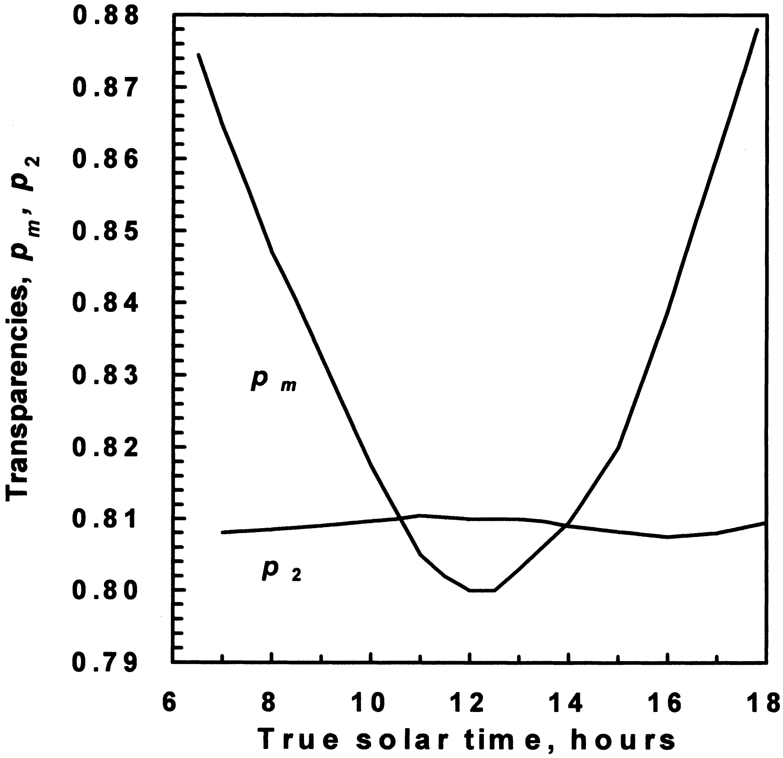


Fig. 3. Measured diurnal courses of $p_m$ and $p_2$ during a clear day in Tartu, Estonia, on March 22, 1956 (redrawn from Aruksaar *et al.,* 1964).

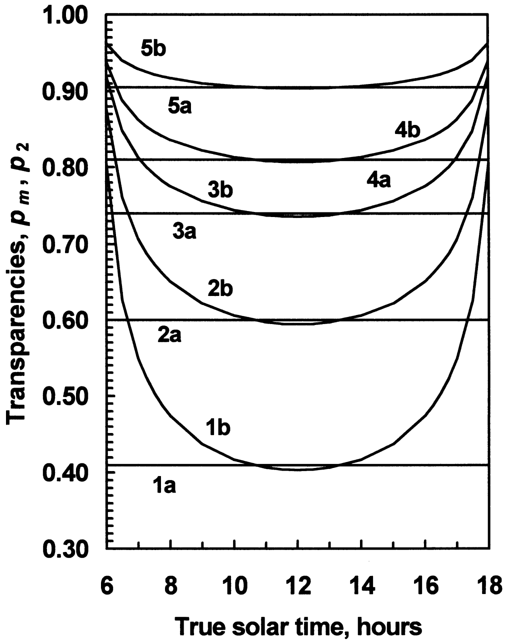


Fig. 4. Possible diurnal courses of AITC at the Tartu actinometric station (58.35 N, 26.68 E), Estonia, on March 22, 1956: (1a) $p_2 = 0.410$, very low transparency; (2a) $p_2 = 0.600$, low transparency; (3a) $p_2 = 0.740$, normal transparency; (4a) $p_2 = 0.810$, high transparency; (5a) $p_2 = 0.905$, ideal transparency; (1b), (2b), (3b), (4b), (5b) – corresponding diurnal courses of $p_m$.

$$p_m = p_2\left(\frac{m}{2}\right)^{-(\log p_2 + 0.009)/1.547}. \tag{3.14}$$

Detailed derivation of these formulas is given by Mürk and Ohvril (1990). Formula (3.14) allows one to model possible diurnal courses of the AITC $p_m$ for given values of $p_2$. Fig. 4 shows results of such calculations for the same place and date as in Fig. 3. The Forbes effect is especially strong in the case of low values of transparency (e.g. line 1b).

## 4. COMPARISON OF METHODS OF REDUCTION

In order to compare the accuracy of the three presented methods (ES-1, ES-2, MO-1) in reducing the values of atmospheric transparency we have proceeded from Table 1 and have calculated, for each standard value of direct solar beam $I_m$ in this table, by formula (2.6), a standard value of the AITC – $p_m$(*standard*). Then, using the values of $p_2$ given in Table 1 (and corresponding to each of 10 levels of transparency), we have calculated $p_m$ in three different ways (Ohvril and Okulov, 1996):

1. according to method ES-1; solving (3.2) for $I_m$ and applying (2.6), we find

$$p_m = \left[ 0.9561 \left( \frac{p_2}{0.978} \right)^{1.3/(\sin h + 0.15)} \right]^{1/m}; \tag{4.1}$$

2. according to ES-2; solving (3.3) for $I_m$ and using again (2.6), we obtain

$$p_m = (p_2)^{1.41/(\sin h + 0.205)m}; \tag{4.2}$$

3. according to MO-1, using (3.14).

The accuracy of the values of $p_m$ found by each method (ES-1, ES-2, MO-1) in comparison with the standard values, $p_m$ (*standard*), was estimated by the relative errors, $\delta$:

$$\delta = \frac{p_m - p_m(standard)}{p_m(standard)} 100\%. \tag{4.3}$$

For all three methods the greatest errors occur in the case of very low transparency, when $p_2 = 0.410$ (Figs. 5–7). The greatest of all errors, 6.4%, arises with the use of method ES-2 at solar elevation $h = 10°$. The maximum error in method ES-1 is only 2.31% ($h = 10°$) and in method MO-1, $-2.65\%$ ($h = 90°$).

Thus we can conclude that methods ES-1 and MO-1 give almost the same accuracy, they may both be recommended for practical calculations of the AITC $p_2$.

The advantage of the method ES-1 lies in the simplicity of formula (3.2), which allows easy and immediate (without the intermediate calculation of mass $m$) finding of standardized coefficients $p_2$ from raw values of the direct solar irradiance, $I_m$.

Method MO-1 is the most general, as Eq. (3.12) provides a transition between any values of optical masses $m$ and $i$. The method is not connected with the pyrheliometric scale and the solar constant. But it is a little more clumsy because of the need for intermediate calculation of the atmospheric mass $m$ when measurements or simulations have been made versus the solar elevation.

It is important to stress that for solar elevations $20° \leq h \leq 80°$, all three methods secure accuracy of transition of the AITC from $p_2$ to $p_m$ with an error smaller than 2.5% in comparison with standard values of $p_m$. This accuracy is usually enough for actinometric calculations (uncertainty of a single measurement of direct solar beam by actinometer is about $\pm 4\%$ and global solar beam by pyranometer $\pm 10\%$).

About limitations of use of the above three methods for calculation of coefficients of transparency $p_m$ and transitions (from $m_1$ to $m_2$) between them. Development of the methods is based on Table 1, which represents the average intensity of the direct solar radiation at given solar elevation and given transparency conditions.

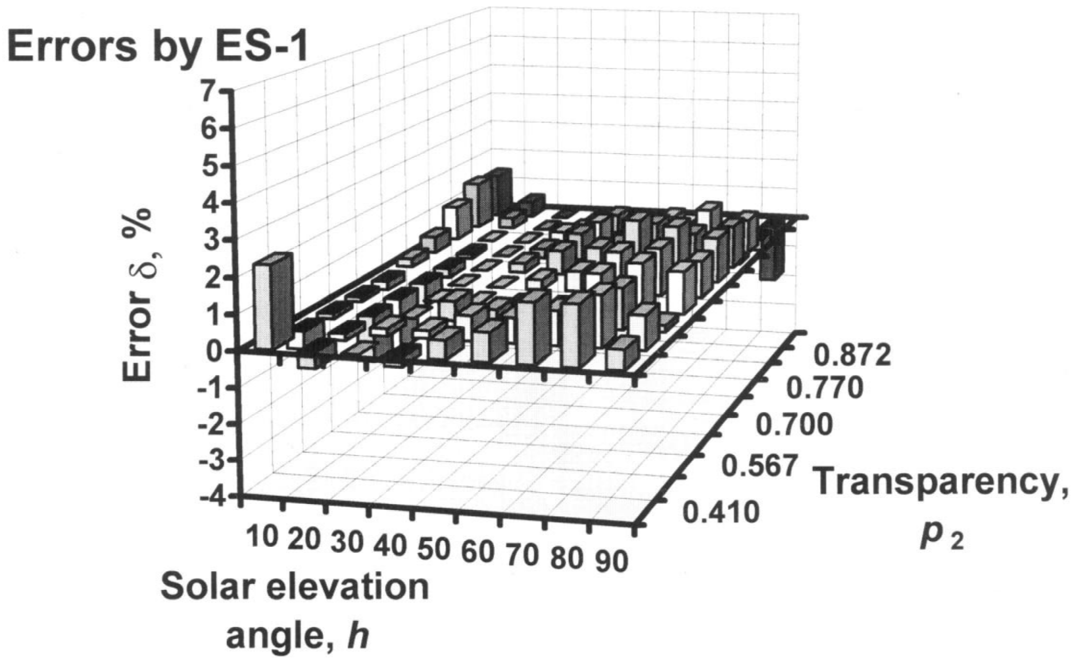


Fig. 5. Relative errors, $\delta$ (in %), of calculation of the AITC $p_m$, using method ES-1. The greatest error, $\delta = 2.31\%$, corresponds to solar elevation $h = 10°$ and to very low transparency (AITC $p_2 = 0.410$).

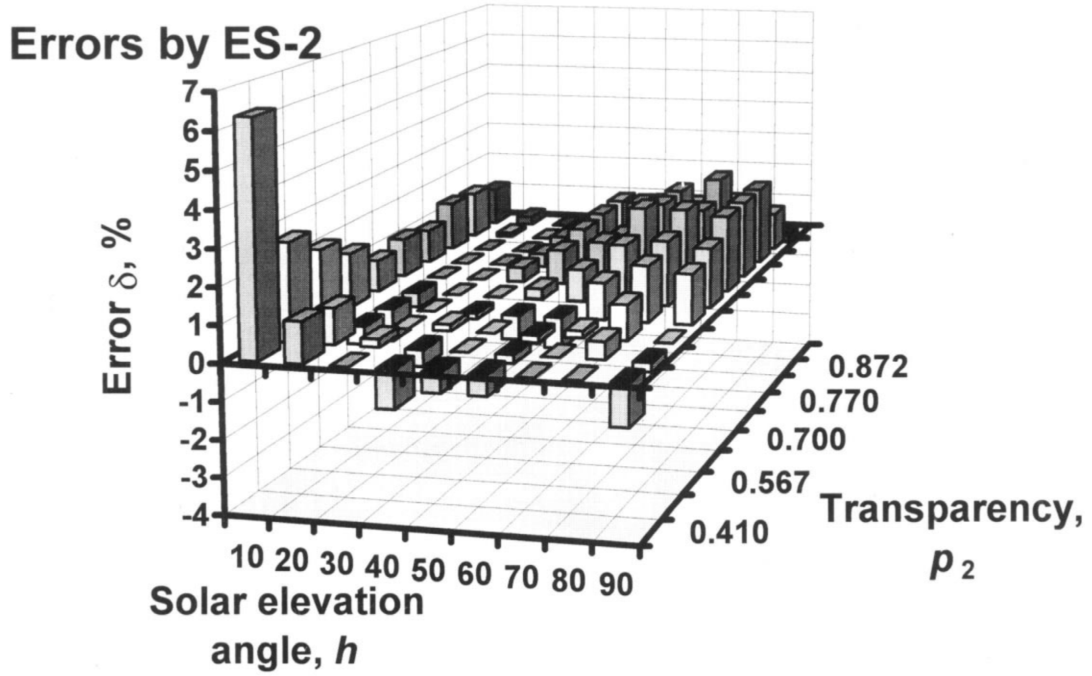


Fig. 6. Relative errors, $\delta$ (in %), of calculation of the AITC $p_m$, using method ES-2. The greatest error, $\delta = 6.4\%$, corresponds to solar elevation $h = 10°$ and to very low transparency (AITC $p_2 = 0.410$).

Table 1 was compiled on the basis of measurements of the direct solar radiation in several meteorological stations. The southernmost of these stations was Ashabad (38°N) and the northernmost Yakutsk (62° N). Thus, proceeding from formalistic considerations, use of the described methods is justified within the geographical latitudes 38°–62°.

There is also a second limitation connected with Table 1, seeing that it is confined to solar elevations from 10° (corresponds to $m = 5.60$) to 90° ($m = 1.00$). Unfortunately we do not have at

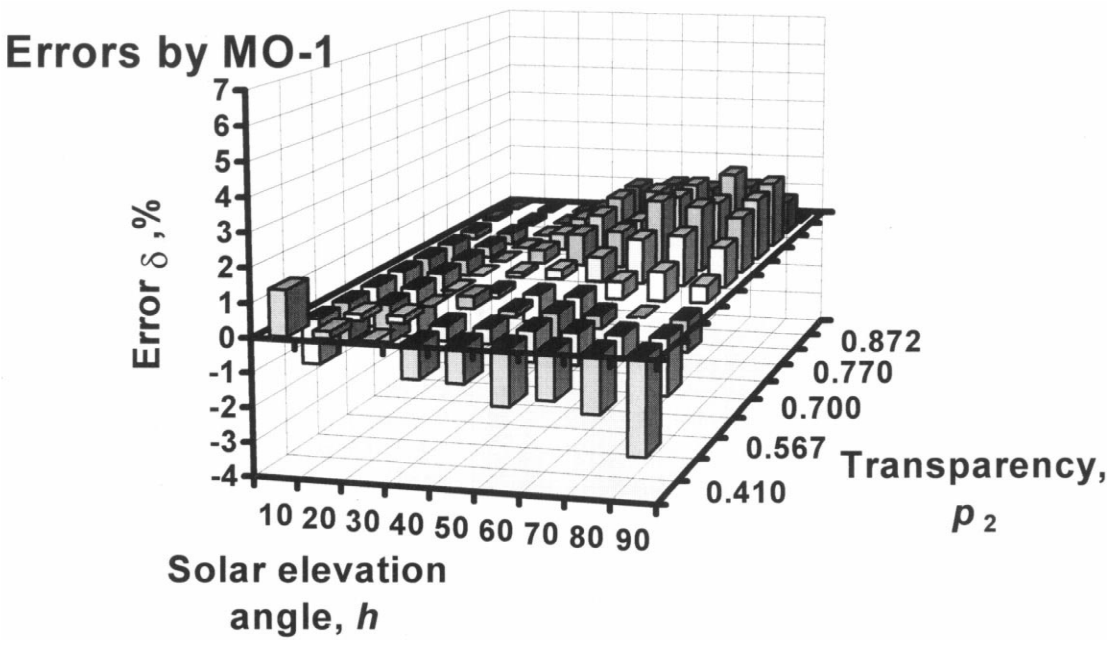


Fig. 7. Relative errors, $\delta$ (in %), of calculation of the AITC $p_m$, using method MO-1. The greatest error, $\delta = -2.65\%$, corresponds to solar elevation $h = 90°$ and to very low transparency (AITC $p_2 = 0.410$).

our disposal data on the direct solar beam outside the range of optical masses $m = 1.00–5.60$ to evaluate the quality of above methods.

## 5. EXAMPLE OF CALCULATIONS OF $p_2$ – MEAN ANNUAL VALUES OF TRANSPARENCY IN ESTONIA DURING THE PAST 40 YEARS

The observational program of the Tiirikoja Lake Station (58.87 N, 26.97 E, 32 m above sea-level), located on the western lakeside of Peipsi, includes broadband instantaneous measurements of direct solar radiation at 3-h intervals, if only the solar disk is free of clouds. Actinometers AT50 (developed at the main Geophysical Observatory in Leningrad (St. Petersburg)) have been operated manually or by solar tracker. A description of this durable device could be found in the monograph of Kondratyev (1969). Uncertainty of the transformation coefficient of the actinometers was estimated to be less than $\pm 1\%$ (Ross, 1957). Uncertainty of a single measurement of the direct solar beam is guaranteed by the Estonian Meteorological and Hydrological Institute to be less than $\pm 4\%$.

The available Tiirikoja data cover the period from 1956 until 1995. The initial data set contains 7200 raw values of $I_m$ (about 180 single measurements each year). We have composed a multiannual time course of the coefficient of transparency $p_2$ for the above four decades. It is evident from Fig. 8 that transparency has decreased during 20 years – from the end of the 1950s until the end of the 1970s. This decrease may be caused by the increased load of industrial and agricultural (i.e. man-made) aerosols. Data from another Estonian station, Tartu, proves that the AITC in the 1930s was even higher, exceeding the level $p_2 = 0.80$ (Ohvril *et al.,* 1998).

Although the influence of volcanoes also accompanied this period, their remote role on Estonia's atmosphere is not entirely clear. However, from the end of the 1970s decrease of the temporal course deepens. Obviously this may be linked with the series of volcanic eruptions since 1979 which ended with the explosion of the El Chichón in Mexico in the spring of 1982. The decrease pulse of transparency after the eruption of the Pinatubo (Philippines, June 1991) is also impressive. Fig. 9 shows the locations of Tiirikoja, Pinatubo and El Chichón.

Although the effective clearing of the atmosphere after eruptions of the El Chichón and Pinatubo is surprising, the linear trend of the AITC $p_2$ at Tiirikoja for 1956–1995 remains negative:

$$p_2 = 3.26 - 0.001264y, \tag{5.1}$$

where $y$ is the year number. By extrapolation of this trend to $y = 1950$ and $y = 2000$, we find the relative decrease of the AITC during the 50 years

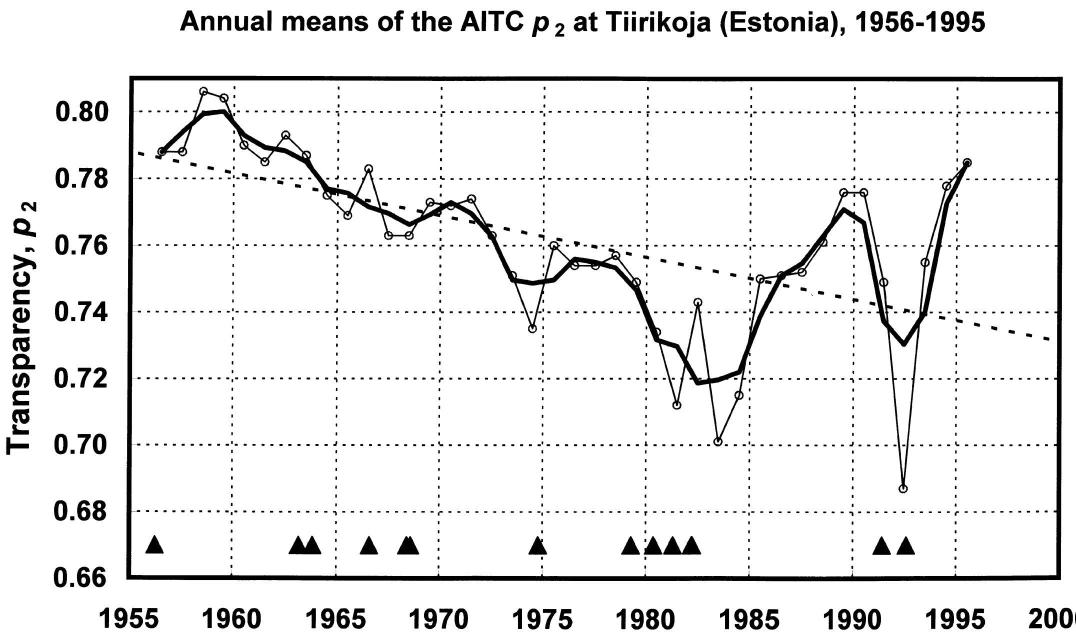


Fig. 8. Mean annual values, 3-year running average, and linear trend of the AITC $p_2$ at Tiirikoja, Estonia; ▲ – dates of the greatest volcanic eruptions (see list in Appendix).

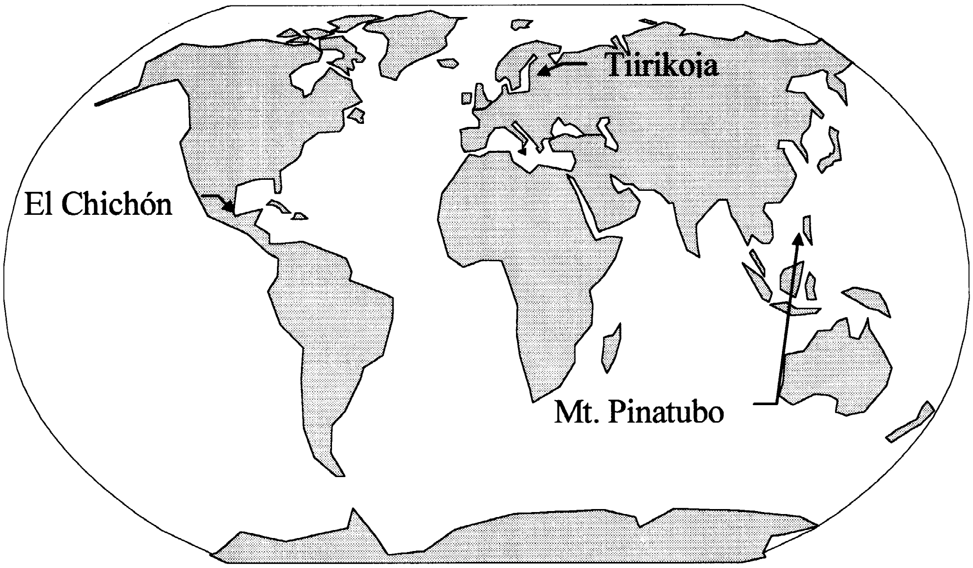


Fig. 9. Locations of the Tiirikoja Lake (Radiometric) Station and two volcanoes.

to be for 8%. The latter would cause a relative decrease of intensity of the direct solar beam by 16% (at solar elevation $h=30°$). Although this decrease should be partly compensated by increase of the diffuse component of the solar radiation, and perhaps cloudiness, it would mean changes in the light and energy regime of the atmosphere and of the underlying surface.

In greater detail, variability of the atmospheric transparency $p_2$ in the Baltic region has been discussed by Heikinheimo *et al.* (1996), by Ohvril *et al.* (1998), and parallelism with the variability of transparency in Spain by Alados-Arboledas *et al.* (1997). It was noticed that since the transparency at Tiirikoja before and after the Pinatubo's minimum (1991–1993) was at the same level as 20–30 years earlier, it is possible that the drop in atmospheric transparency has ceased for the present and may even reveal an increasing trend. Heikinheimo *et al.* (1996) therefore concluded that the recovery of atmospheric transparency in this corner of Northern Europe is most likely caused by improvements in the prevention of anthropogenic sulphur and nitrous compound emissions.

As an additional check, we have compared multiannual time courses of transparency, $p_2$, at Tiirikoja with time courses for $p_2$ at Tõravere (Estonia, 80 km from Tiirikoja) and in Moscow (1000 km from Tiirikoja) (Abakumova *et al.,* 1996). Parallelism in the behaviour of these three multiannual time courses is evidence which attests to the conclusions reached regarding trends in the atmospheric transparency.

## 6. CONNECTION OF THE TRANSPARENCY COEFFICIENT WITH THE *LINKE TURBIDITY FACTOR*

The second parameter commonly used to describe the clarity of the atmosphere, the *Linke turbidity factor* $T_{L,m}$, is defined as the number of ideal (clean and dry) atmospheres that it would be necessary to pile up in order to obtain the same attenuation of solar radiation as that produced by the actual atmosphere (Linke, 1922; Kasten, 1988; Grenier *et al.,* 1994; Jacovides, 1997):

$$T_{L,m} = \frac{\alpha_m}{\alpha_{id,m}} = \frac{\log p_m}{\log p_{id,m}}, \qquad (6.1)$$

where $\alpha_{id,m}$ and $p_{id,m}$ are the total (broadband) optical thickness and the integral transparency coefficient of the ideal (clean and dry) atmosphere.

The Forbes effect on $T_{L,\,m}$ is considerably less pronounced than on $p_m$ because the wavelength-dependence of the numerators in (6.1) is partially compensated by wavelength-dependence of the denominators (Kasten, 1988). This is one of the advantages of the Linke turbidity factor.

On the other hand, calculation of the Linke turbidity factor requires information on the ideal atmosphere, as expressed by $\alpha_{id,\,m}$ or $p_{id,\,m}$. Unfortunately these parameters are not permanent values, they change with development of our knowledge. Here is an uncertainty which seems to represent the main difficulty in the use of $T_{L,m}$.

To obtain the Linke turbidity factors from broadband irradiance measurements after calculation of the transparency coefficients $p_m$, it is convenient to change Eq. (6.1) to the form (Sivkov, 1968; Sivkov, 1971):

$$T_{L,m} = k(m) \log \frac{1}{p_m^m} = -mk(m) \log p_m \quad (6.2)$$

In the most important particular case, $m=2$:

$$T_{L,2} = -2k(2) \log p_2 \quad (6.3)$$

Here $k(m)$ is a coefficient which remains constant for a given $m$:

$$k(m) = \frac{1}{\log I_0 - \log I_{id,m}} = \frac{-1}{m \log p_{id,m}} \quad (6.4)$$

but it depends on values of the direct solar beam $I_{id,m}$, i.e. on the model used of the ideal atmosphere. Table 2 gives a short historical review of developments of some parameters related to the ideal atmosphere.

It seems to us that the most detailed calculations of transmittance of the ideal atmosphere have been made by Gueymard (1998). Row 9 in Table 2 has been obtained using Gueymard's parameterizations and assuming the amounts of $O_3$ and $NO_2$ to be 0.3 atm cm and 0.204 matm cm respectively (absorption by $NO_2$ is usually neglected by other authors). Row 10 has been added to express transparency of the ideal atmosphere in round numbers: $p_{id,2}=0.905$.

Keeping in mind the uncertainty of broadband direct solar irradiance measurements ($\pm$4%), one can estimate $T_{L,2}$ with acceptable accuracy by using Sivkov (1968), Sivkov (1971) simple expression (row 3):

$$T_{L,2} = -23 \log p_2, \quad (6.5)$$

which, corresponding to $p_{id,2}=0.9047$, is in very good concordance with Gueymard's parameterization (row 9) given 30 years later.

As an illustration, Fig. 10 represents the multiannual time course of the Linke turbidity factor $T_{L,2}$ at Tiirikoja, Estonia, during 1956–1995. The following sequence of calculations was used:

1. Determination of the raw instantaneous $p_m$ values by Eq. (2.6).
2. Conversion of the raw $p_m$ values into standardized instantaneous values $p_2$ by Eq. (3.13).
3. Computation of the instantaneous $T_{L,2}$ values by Eq. (6.5).
4. Averaging of the instantaneous $T_{L,2}$ values over days, months and the corresponding year.

As expected, Fig. 10 verifies an increase of the Linke turbidity factor in Estonia after great volcanic eruptions (1979–1982, 1991). The multiannual trend of $T_{L,2}$ was evidently increasing until the middle of 1980s when the atmosphere began to restore its clarity. Influence of the Pinatubo eruption (on June 15, 1991) lasted for 2 years, the low level of turbidity of 1989–1990 was recovered in 1994.

In order to examine possible diurnal variations of the turbidity factor, the values of $T_{L,m}$ were computed against the solar zenith angle $z$ by means of Eq. (6.1). The necessary AITC values of the ideal atmosphere, $p_{id,m}$, were given according to the calculations of: (1) Sivkov (1968, 1971), (2) Evnevich (1994), and (3) Gueymard's parameterization (1998), respectively. The amount of $O_3$ was assumed to be 0.3 atm cm, $NO_2$ was considered only in Gueymard's formulas – 0.204 matm cm. Values of the AITC of the real atmosphere, $p_m$, were obtained by means of Eq. (3.14) for four different levels of atmospheric transparency: $p_2=0.41$ (corresponds to very low transparency), $p_2=0.6$ (low transparency), $p_2=0.74$ (normal transparency), $p_2=0.81$ (high transparency).

Plots in Fig. 11 exhibit the stability of factor $T_{L,m}$ for solar zenith angles less than 70° ($m\approx3$). However, more complicated models, based on spectral calculations (Grenier *et al.,* 1994; Gueymard, 1998) show that at low values of turbidity ($T_{L,m}<3$, $p_m>0.74$, $m<3$, precipitable

Table 2. Short historical review of parameters characterizing passage of direct solar beam through the ideal atmosphere at $m=2$

| Coefficient of transparency $p_{id,2}$ | Transmittance $\tau_{id,2}=I_{id,2}/I_0$ | Coefficient $k(2)$ | Formula (6.3) $T_{L,2}=$ | Reference |
|---|---|---|---|---|
| 1. 0.8940 | 0.7993 | 10.28 | $-20.56 \log p_2$ | Linke, 1922 |
| 2. 0.9144 | 0.8361 | 12.86 | $-25.72 \log p_2$ | Feussner and Dubois, 1930 |
| 3. 0.9047 | 0.8185 | 11.50 | $-23.00 \log p_2$ | Sivkov, 1968; Sivkov, 1971 |
| 4. 0.9014 | 0.8124 | 11.08 | $-22.17 \log p_2$ | Louche *et al.,* 1986 |
| 5. 0.9146 | 0.8365 | 12.89 | $-25.79 \log p_2$ | Kasten, 1988 |
| 6. 0.9052 | 0.8193 | 11.55 | $-23.11 \log p_2$ | Evnevich and Savikovskij, 1989 |
| 7. 0.9092 | 0.8266 | 12.09 | $-24.19 \log p_2$ | Evnevich, 1994 |
| 8. 0.9020 | 0.8137 | 11.17 | $-22.33 \log p_2$ | Kasten, 1996 |
| 9. 0.9049 | 0.8188 | 11.52 | $-23.04 \log p_2$ | Gueymard, 1998 |
| 10. 0.9050 | 0.8190 | 11.53 | $-23.07 \log p_2$ | – |

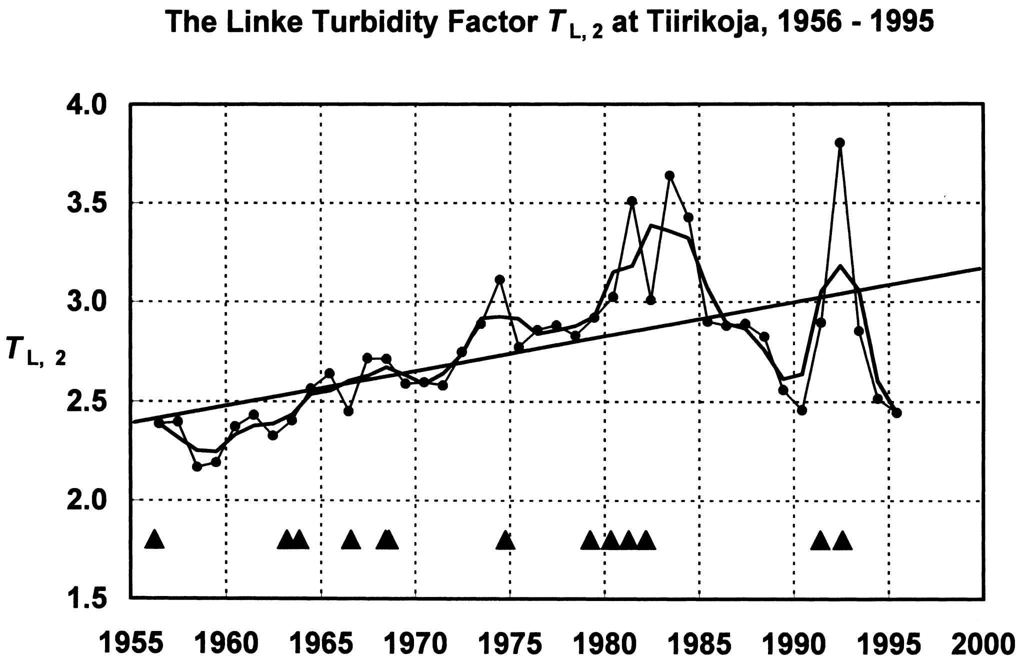


Fig. 10. Mean annual values, 3-year running average, and linear trend of the Linke turbidity factor $T_{L,\,2}$ at Tiirikoja, Estonia; ▲ – dates of the greatest volcanic eruptions (see list in Appendix).

water $w=2$ cm), the Linke turbidity factor has a tendency to decrease with increase of the optical path $m$. At higher turbidity, the factor $T_{L,\,m}$ is an increasing function of $m$. The above-mentioned spectral calculations show that $T_{L,\,m}$ exhibits changes with $m$, according to: (1) the aerosol content of the atmosphere as expressed by the Ångström turbidity coefficient $\beta$, (2) the amount of precipitable water $w$.

Explaining this discrepancy we should stress that our method for transformation of broadband coefficients of transparency $p_m$ from one solar elevation to another submitted in this work is based on the average values of the direct solar irradiance $I_m$ (Table 1) at different states of atmospheric transparency (turbidity). Stability of the 'our' Linke factor for zenith angles $z<70°$ may therefore be interpreted as an average state of aerosol and water vapor content in the atmosphere in middle latitudes. This average dependence of $T_{L,\,m}$ on $m$ may be recommended for use in cases where neither the aerosol nor water vapor content in the atmosphere have been estimated.

## 7. CONCLUSIONS

Broadband instantaneous values of the direct solar beam $I_m$ have not found a wide use. One reason of this seems to be a selective spectral attenuation of the direct solar radiation in the atmosphere (another couple of reasons are the vulnerability of pyrheliometers for daily measurements, and difficulties in automatic detection of clouds screening the solar disc). Spectral attenuation of the direct solar beam causes the so-called Forbes effect – diurnal trend of broadband parameters of transparency and turbidity of the air.

Algorithms proposed by Evnevich and Savikovskij (1989), and Mürk and Ohvril (1988), Mürk and Ohvril (1990) allow for easy reduction of the Forbes effect in diurnal courses of the Atmospheric Integral Transparency Coefficient (AITC) $p_m$ and computation of standardized values of the AITC $p_2$ or the Linke turbidity factors $T_{L,\,2}$ corresponding to a relative optical air mass $m=2$ and solar elevation 30°.

It should be stressed that the described simple reduction schemes are easy to implement (e.g. using only a scientific pocket calculator), but they are also limited in their scope. The point is that the algorithms are based on mean values of the direct irradiance $I_m$ (Table 1) averaged over all seasons in moderate latitudes (38°–62°). Estimation of individual rates of contribution of water vapor or aerosols to total attenuation of the direct solar beam is not available.

Despite this limitation, the possibility for conversion of databases of the direct irradiance $I_m$ into time series of standardized values of $p_2$ and $T_{L,\,2}$ allows one to draw climatological conclu-

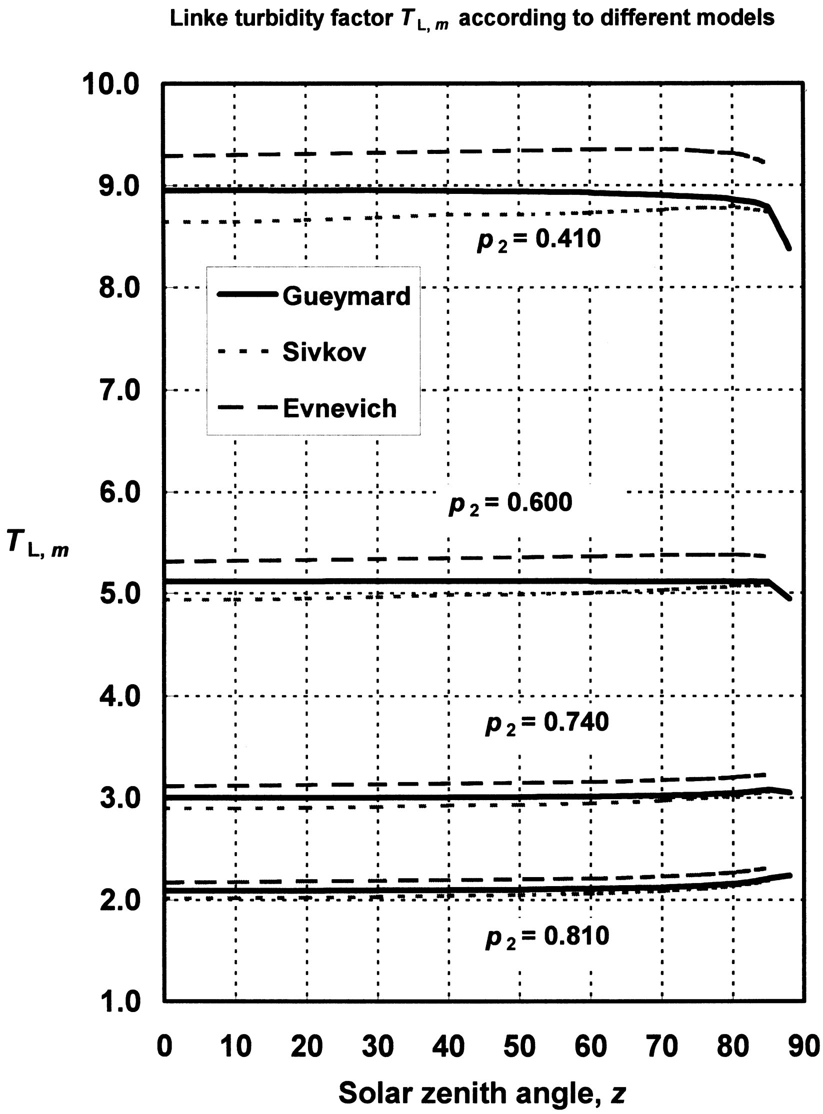


Fig. 11. Linke turbidity factor $T_{L,\ m}$ determined by different models of the ideal atmosphere as a function of solar zenith angle $z$ and transparency $p_2$.

sions with regard to multiannual trends of atmospheric transparency and turbidity. This possibility should lead to a renewed interest in the instantaneous values of $I_m$ as an energetically important quantity.

40-year time series of $p_2$ and $T_{L,\ 2}$ calculated as examples from the measurements at the Estonian Tiirikoja station during 1956–1995 demonstrate an obvious sensitivity of atmospheric transparency (turbidity) to great volcanic eruptions. Although the linear trend of transparency for the entire period was decreasing, transparency at Tiirikoja before and after the Pinatubo's minimum (1991–1993) reached the level of 1960s. Therefore, it is possible that the multiannual drop in atmospheric transparency has ceased for the present in this corner of Northern Europe and may even reveal an increasing trend.

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## APPENDIX A. LIST OF THE GREATEST VOLCANOES (FIG. 8, FIG. 10)

(1) Sopka Bezymiannaya, 30.03.1956; (2) Agung, 17.03.1963; (3) Surtsay, 14.11.1963; (4) Avu, 12.08.1966; (5) Fernandina, 11.06.1968; (6) Arenal, 14.08.1968; (7) Fuego, 17.10.1974; (8) Soufriere, 15.04.1979; (9) Saint Helens, 18.05.1980; (10) Alaid, 27.04.1981; (11) El Chichón, 04.04.1982; (12) Pinatubo, 15.06.1991; (13) Spurr, 18.08.1992.

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