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DIRECT LUMINOUS EFFICACY AND ATMOSPHERIC TURBIDITY—IMPROVING MODEL PERFORMANCE

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Abstract—Of all the atmospheric constituents, aerosol content is shown to be responsible for the greatest variations in direct luminous efficacy. Some clarity is brought to the comparison between Linke's and Ångstrom's turbidity coefficients, respectively T_L and β. Grenier's recent formulation of the optical thickness of a water and aerosol free atmosphere is presented here in a simplified expression. Based on these results and Dogniaux's illuminance turbidity factor, T_{il}, two direct luminous efficacy models are derived, one of which is tuned to our experimental data. The input parameters are optical air mass, β, and water vapour content in the tuned version. These models perform significantly better than any of twelve other models found in the literature when compared to 1 yr's measurements from each of two sites in the U.S. and Switzerland. In both sites. β was derived from horizontal visibility estimated in a nearby airport.

1. INTRODUCTION

Interest in our natural daylight resource is rising with environmental concern and improved architectural techniques enabling an efficient use of daylight for indoor lighting. Modelling illuminance values from more readily available radiation data is the essential tool in order to compensate for the scarcity of daylight measurements.

On the other hand, direct luminous efficacy may be a simple means of giving us valuable information on the state of the atmosphere above us. Direct luminous efficacy is the ratio of the visible part to net radiation in the direct solar spectrum and is therefore very sensitive to atmospheric attenuation which is proportionally important in the visible region. In a cloudless atmosphere, apart from diffusion by the permanent air molecules, scattering by the suspended solid and liquid particles (hereafter aerosols) is responsible for the majority of the depletion of the direct solar spectrum in the visible region. This becomes especially relevant in a changing urban atmosphere where daylighting models are most needed. On a larger scale, exponential increase in anthropogenic aerosol emissions may be playing a leading role in global climate change (see for example Kiehl and Briegleb, 1993) making it increasingly urgent for us to reach a better understanding of these processes.

In a cloudy atmosphere, the whole spectrum of direct radiation is rapidly attenuated and direct luminous efficacy models are of little practical interest. A physical clear sky direct luminous efficacy model is presented, making use of the relations between Angstrom's turbidity factor, β, Linke's broad band turbidity factor, T_L, and Dogniaux's illuminance turbidity factor, noted T_{il}. In our approach T_L and T_{il} are computed from b, itself computed from visibility measurements. Two expressions for determing T_L and β are used, one is adapted by Grenier *et al.* (1994) from Katz *et al.*'s (1982) experimental results, the other is empirically developed here from direct luminous efficacy measurements. State of the art direct luminous efficacy models found in the literature are also presented in comparison. The performance of the models in predicting direct illuminance in all conditions is assessed with two independent one year data banks from Albany, New York, and Geneva, Switzerland, giving a promising experimental evaluation of the turbidity equations.

2. SPECTRAL ATTENUATION OF DIRECT RADIATION AND ANGSTROM'S TURBIDITY EQUATION

Atmospheric attenuation of a monochromatic normal beam can be written as the product of five transmittances:

$$I_{n\lambda} = I_{on\lambda}\tau_{r\lambda}\tau_{a\lambda}\tau_{o\lambda}\tau_{g\lambda}\tau_{w\lambda} \quad (1)$$

where $I_{on\lambda}$ is the extraterrestrial monochromatic beam and $I_{n\lambda}$ is the corresponding attenuated normal beam irradiance of wavelength λ imping-

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ing on the earth's surface. The spectral transmittances $\tau_{i\lambda}$ ($\tau_{i\lambda} < 1$) cover the major atmospheric attenuation processes, respectively: Rayleigh scattering on air molecules (r), Mie scattering and continuous absorption by solid and liquid particles (aerosol extinction, a), selective absorption by the ozone layer (o), selective absorption by the permanent gaseous constituents other than stratospheric ozone and water vapour (g) and selective absorption by water vapour (w).

According to Middleton (1960) the law of exponential attenuation of a monochromatic beam passing through a homogeneous medium should always be attributed to Bouguer and not to Lambert or Beer as often seen in the literature. Applied to atmospheric transmittance, Bouguer's law can be written:

$$\tau_{i\lambda} = \exp(-k_{i\lambda} m_i) \tag{2}$$

where $k_{i\lambda}$ is the wavelength dependent attenuation coefficient due to a single process i and integrated over a vertical path through the atmosphere. m_i is the relative optical atmospheric mass for a single process i, defined as the ratio of the real path length (mass of the substance in a column of unit cross section in the direction of the sun's rays) to the path length in a vertical direction. As a first approximation, the total relative optical air mass can be used to approximate the relative atmospheric masses of the different constituents. Kasten and Young's (1989) update to Kasten's (1966) widely used equation is used to compute the relative optical air mass of the average atmosphere (hereafter simply called air *mass*, m_a) given here with a correction for altitude, adapted from Iqbal (1983):

$$m_a = \exp(-0.12z) \times (\sin h + 0.50572(h + 6.07995)^{-1.6364})^{-1} \tag{3}$$

where z is the altitude (km) and h is the solar height (°). In this expression, h is the apparent solar height but the difference with the calculated solar height (0.5° at sunset or sun rise due to refraction) is negligible for $h > 5°$, as was considered in this study.

Bouguer's law, although not strictly valid for the selective absorption processes in the atmosphere, is usually extended to the gaseous absorbers for which the attenuation coefficients are discrete functions of λ. These can be found in tabulated form in a number of texts, e.g. Iqbal (1983).

The scattering processes, on the other hand, can be approximated by analytical wavelength dependent expressions. Scattering of solar radiation in dry air free of aerosols was first theoretically resolved by Lord Rayleigh in 1871 and is referred to as Rayleigh scattering, yielding:

$$k_{r\lambda} = a\lambda^{-4} \tag{4}$$

where λ is in (pm) and a is a constant depending on the physical characteristics of dry air. Updates to this equation can be found for example in Leckner (1978), Bird and Riordan (1986) and Gueymard (1995). The dependence on $1/\lambda^4$ brought a successful explanation to the colour of the sky and predicts a rapid decrease in direct luminous efficacy with increasing air mass.

When the particles reach a size comparable with or larger than the wavelength of visible light, the theoretical computation of their effect on incident radiation (called Mie scattering but also covers absorption by the particles), based on the refractive index, the size and the shape of the particle, are much more laborious. Empirical results are therefore generally favoured when computing aerosol extinction. Angstrom (1929, 1930) proposed the following expression for all aerosols derived and tested during extensive experimental campaigns throughout the world (λ in pm):

$$k_{a\lambda} = \beta\lambda^{-\alpha}. \tag{5}$$

In fact, this relation has also been obtained from scattering theory in the case of a Junge size distribution of spherical particles (see Junge, 1963).

Angstrom's turbidity coefficient β (which can also be referred to as the aerosol optical depth at 1 pm) is linked to the amount of particles present in a vertical column and varies typically from 0.01 and 0.5 (whether near the south pole or in an extremely turbid atmosphere, from Angstrom, 1961). The wavelength exponent ci (sometimes referred to as the Angstrom spectral coefficient) increases as the average size of aerosols decrease and an upper limit of $a = 4$ can be deduced from eqn (4). The size of the particles are site dependent and a value of $\alpha = 1.3$ is usually quoted as a mean overall value (e.g. Angstrom, 1961). In this study, β and ci are considered constant throughout the spectrum and a value of $\alpha = 1$ gave best results, which is a plausible figure for urban aerosols according to Gueymard (1994). The size distribution of aerosols goes from approx. 10 nm (*Aitken* nuclei) to 10 μm (giant particles) and is limited at both extremes by, respectively, coagulation and precipitation.

The major drawback to Ângstrom's formalism lies in the difficulty in getting a precise evaluation of β and α. The standard practice is to measure the spectral direct beam irradiance with a sun photometer in a few wavelengths, chosen so as to minimize the influence of the other atmospheric attenuators such as water vapour. Using direct beam measurements made with cut off filters at different wavelengths. e.g. Katz et *al.* (1982), is another possible solution although correction for the other atmospheric parameters becomes much more delicate. In both cases, the need for absolutely cloud free conditions is the most limiting factor. A more debatable method which is less dependent on cloud cover, is to resort to horizontal visibility. Indeed, the distance at which objects can be observed is directly related to the aerosol loading in the lower layers of the atmosphere and β can be evaluated from vertical distribution models. Visibility is however usually estimated in airports with the unaided eye, leading to a somewhat subjective and inaccurate value of atmospheric turbidity. This is especially relevant after a large volcanic eruption when stratospheric aerosols undergo a significant but temporary increase on a global scale whereas the influence on the lower troposphere and horizontal visibility is limited to a local scale. Mt Pinatubo's eruption in the Philippines in June 1991 at 15°N, was shown to be responsible for a 30% drop in net beam irradiance observed in Geneva in the first winter after the eruption. see Michalsky et *al.* (1994). After March 1993. for latitudes above 40°N, the effect can be considered negligible and thus did not influence the Geneva data used in this study. In Albany the effect of Mt Pinatubo on the 1992 data used here did not noticeably influence the direct luminous efficacy (which is well correlated to ground visibility). A plausible explanation is that the volcanic aerosol extinction is mostly important in winter, when bad weather often obstructed the direct beam.

Below is a relation linking β to visibility, reported in King and Buckius (1979):

$$\begin{aligned}\beta &= (0.55)^{\alpha}(\ln|C|/\text{vis} - 0.01162) \\ &\times [0.02472(\text{vis} - 5) + 1.1321\end{aligned} \quad (6)$$

where vis is the horizontal visibility (km), α is the wavelength exponent in eqn (5), which has to be estimated beforehand, and C is the contrast. A value of $C = 0.02$ is generally accepted as the threshold contrast for the human eye, see for example Fleagle and Businger (1980), and was used in this study. The value of $C = 0.05$ may however be more appropriate when considering airport visibility in non ideal conditions and a revised version of eqn (6) based on updated aerosol models, published after this paper was accepted, should be used in future studies, see Gueymard (1995). In spite of the large uncertainties involved, eqn (6) was used here giving promising results in our application.

Using a model for β's seasonal variation, was also attempted. The following model was chosen based on a value of $\beta = 0.1 \pm 0.05$ (realistic values for both Geneva and Albany) with a maximum in spring and minimum in autumn:

$$\beta = 0.1 + 0.05 \sin\left((\text{nday} - 16)\frac{2\pi}{365}\right). \quad (7)$$

The variations of direct luminous efficacy with atmospheric conditions were estimated from the clear sky spectral transmission model SPCTRAL2 (Bird and Riordan, 1986) and the V_λ curve for photopic vision (CIE, 1983). Figure 1 illustrates the results obtained for four parameters, showing that apart from air mass, variations in atmospheric turbidity have a marked effect on direct luminous efficacy. Seasonal variations in ozone content at mid latitudes. 0.27–0.34cm at normalized temperature and pressure (from Van Heuklon, 1979), did not induce more than 1% variations in direct luminous efficacy, except for large values of air mass. when the sun is low over the horizon.

3. LINKE'S TURBIDITY EQUATION FOR INTEGRATED BEAM IRRADIANCE

Linke (1922), proposed to express the total integral optical thickness of a cloudless atmosphere, 6, as the product of two terms, δ_{CDA}, the optical thickness of a water and aerosol free atmosphere and Linke's turbidity factor, T_L, as discussed below:

$$I_n = I_0 \exp(-\delta m_a) = I_0 \exp(-\delta_{CDA} T_L m_a) \quad (8)$$

where I_0 is the integral extraterrestrial solar radiation (1367 W/m^2 + seasonal variations) and I_n is the attenuated normal beam irradiance impinging on the earth's surface. This definition has the great advantage of making atmospheric turbidity accessible to pyrheliometric broad

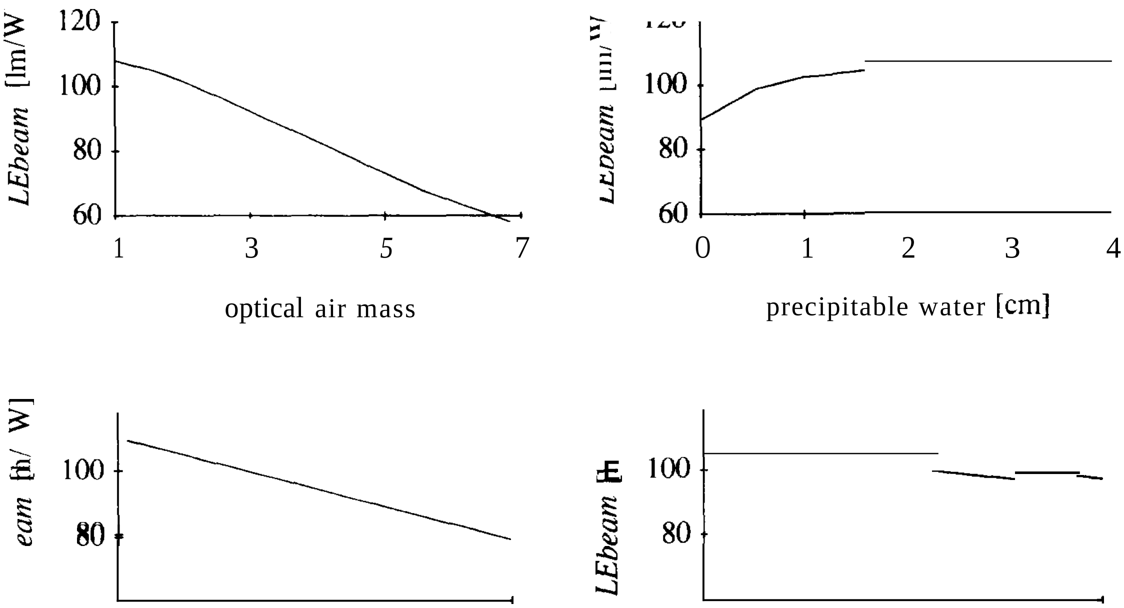

Fig. 1. Direct luminous efficacy, predicted from SPCTRALZ (Bird and Riordan, 1986) as a function of four atmospheric parameters. The constant values are: air mass = 1.5. precipitable water height = 2 cm, $\beta = 0.1$, $\alpha = 1.14$, ozone height = 0.35 cm, pressure = 1013 mb.

band measurements but depends on the theoretical value of δ_{CDA} which is used to evaluate T_L.

A careful examination of the definition of the terms δ_{CDA} and T_L is helpful in getting a clear picture of Linke's formalism and the developments made since Linke first proposed eqn (8). Linke (1922) defined δ_{CDA} as the integrated optical thickness of the terrestrial atmosphere free of clouds, water vapour and aerosols, (hereafter clean dry atmosphere. CDA) which he computed from theoretical assumptions and apparently validated in a very pure, dry mountain atmosphere. T_L thus represents the number of CDAs necessary to produce the observed attenuation, resulting from the additional and highly variable effects of water vapour and aerosols. Obviously, the minimal value of T_L should be 1. Although this definition has not changed, the theoretical value of δ_{CDA} is subject to modifications with increasing data available on atmospheric transmission. Rayleigh's theory of molecular scattering, the major contributor to the depletion of the solar beam in a clean dry atmosphere, was the first process used to compute δ_{CDA}, which is often referred to as the "Rayleigh scattering term" or "optical thickness of a Rayleigh atmosphere".

Feussner and Dubois (1930) published a series of spectral data tables enabling the calculation of δ_{CDA} where both molecular scattering and absorption by the stratospheric ozone layer are taken into account. Kasten (1980) fitted the following equation to these tables:

$$\delta_{CDA} = (9.4 + 0.9 m_a)^{-1}. \tag{9}$$

In this widely used relation, absorption by the permanent atmospheric gases such as CO_2, O_2, N_2O, CO. etc. are not taken into account. The effect of these gases will therefore be included in the term T_L, incorrectly contributing to atmospheric turbidity, as noted by Katz *et al.* (1982) and confirmed by Kasten (1994). The dependence of δ_{CDA} on air mass is a consequence of the strong dependence of Rayleigh scattering on the incident wavelength, eqn (4). As all the attenuation processes are dependant on wavelength, T_L is also dependant on air mass, although in a somewhat lesser manner than δ_{CDA}, [see Robinson (1966) for a comprehensive insight]. This variation of T_L for constant turbidity and the number of processes accounted for by T_L greatly hinders the practicality of Linke's formalism. A number of authors have tried to circumvent this difficulty by different means, the most popular method is to normalize the measured values of T_L at air mass = 2. In this respect Grenier *et al.*'s (1994) contribution is more convincing than Kasten's (1988) paper.

Linke himself (1942) recognized the variation of T_L with air mass but had little success in introducing a new extinction coefficient based on an atmosphere of pure air containing 1 cm of water.

Dogniaux (1974) derived the following relation from extensive experimental campaigns, illustrating the observed variation of T_L with solar height, h (°), atmospheric water vapour content w (cm) and Angstrom's turbidity coefficient β:

$$T_L = \left[\frac{(h+85)}{39.5e^{-w} + 47.4} + 0.1\right] + (16 + 0.22w)\beta. \tag{10}$$

Louche (1986) and Grenier *et al.* (1994) added absorption by the permanent gaseous constituents to the definition of δ_{CDA} (these gases are considered uniformly mixed and invariable in both a CDA and a turbid atmosphere). Based on updated computed spectral data. Louche (1986) fitted a polynomial in fourth order of m_a to the optical thickness of a CDA. Grenier *et al.* (1994), in the same approach, added some minor changes to the spectral absorption and scattering equations and obtained the following polynomial, yielding very similar values to Louche's (1986) relation:

$$\delta_{CDA} = (5.4729 + 3.0312m_a - 0.6329m_a^2 + 0.0910m_a^3 - 0.00512m_a^4)^{-1}. \tag{11}$$

The resulting values of δ_{CDA} are higher (and hence the resulting values of T_L will be smaller) than those obtained with eqn (9) by as much as 25% for low values of air mass, see Fig. 2. Both Louche (1986) and Grenier *et al.* (1994) attribute this difference to the updated spectral data they used and question the use of the term "Rayleigh atmosphere" instead of "clean dry atmosphere", but neither recognized the fact that, more than an update, their definition of δ_{CDA} (and hence of T_L) is actually quite different from previous formulations. In Linke's (1922) original formalism taken up by Feussner and Dubois (1930) and Kasten (1980), Rayleigh scattering was indeed the only atmospheric effect (with the exception of stratospheric ozone absorption) accounted for by δ_{CDA}. In the new definition, δ_{CDA} also accounts for absorption by the permanent atmospheric gases and should be named "optical thickness of a clean dry atmosphere".

This new definition enhances Linke's formalism, making T_L a better defined turbidity factor covering only the effects of the variable constituents of the atmosphere. T_L is now also less dependent on air mass, see Grenier *et al.* (1994). The effects of water vapour, aerosols and possible gaseous pollutants such as NO_2 or tropospheric ozone, not accounted for in eqn (11), are accounted for by T_L. Equation (11) does have a flaw however, the polynomial becomes quickly divergent for air mass > 7, see Fig. 2. Louche's (1986) polynomial, not presented here, becomes divergent for air mass > 12. This drawback was not the case with eqn (9), Kasten's original formula. In order to circumvent this drawback, the following expression was used in this study:

$$\delta_{CDA} = 0.124 - 0.0285 \ln m_a. \tag{12}$$

Equation (12) was simply obtained from a least squares fit to an artificial set of points chosen so as to respect eqn (11) in the range $1 < m_a < 6$, follow Louche's (1986) polynomial for

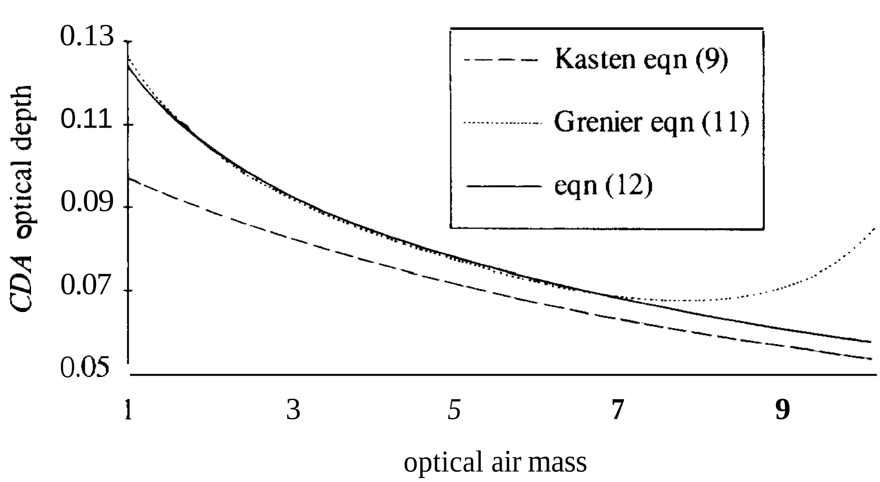

Fig. 2. Clean dry atmosphere optical depth as a function of air mass: comparison of three equations

$6 < m_a < 12$ and. finally, respect eqn (9) for $m_a > 12$. The curves of eqns (9), (11j and (12) are compared in Fig. 2 for $1 < m_a < 10$. Equation (12) does not deviate by more than 0.7% from eqn (11) in the range $1 < m_a < 6$.

Using this definition, the relation between T_L and β is now investigated. In a first approximation, T_L can be considered independent of air mass and water vapour in a temperate climate, resulting in the following expression given in Grenier *et al.* (1994) and adapted from Katz *et al.* (1982) to the new smaller values of T_L:

$$T_L = 1.74 + 15.4\beta. \tag{13}$$

The minimal value of T_L is somewhat greater than the theoretical value of 1. This means T_L accounts for a number of effects in addition to aerosol extinction. Water vapour dependence contributes to the first term of eqn (13). In a humid climate, the dependence of T_L with w, the height of precipitable water content, is reported in Grenier *et al.* (1994) but the difference with eqn (13) seldom exceeds 10%, even for $w > 3$ cm.

The advantages of using an updated definition for δ_{CDA}, the integral optical thickness of a clean dry atmosphere, are highlighted by the performance of the direct luminous efficacy models presented below. The main advantage of having a practical relation between β and T_L is the answer to the problem of T_L's dependence on air mass, as β is itself independent of air mass. In addition, β and T_L are commonly used to represent atmospheric turbidity but we have seen that their physical meaning is actually quite different, β being **a** spectral parameter and T_L representing broad band attenuation and encompassing other effects such as that of water vapour and, until recently, mixed gas absorption. In addition, these two parameters are seldom measured simultaneously and the possibility of calculating one from the other opens the field to quantitative comparisons between different turbidity data banks, whether based on *fi* or T_L. An attempt at deriving an empirical relation which accounts for the variation of T_L with both air mass, water vapour content and β, similar to eqn (10) but based on the new definition of δ_{CDA}, is discussed in Section 7.

4. ILLUMINANCE TURBIDITY FACTOR AND DIRECT LUMINOUS EFFICACY

Dogniaux (1974) was apparently the first to suggest using a formalism similar to eqn (8) for the transmission of integrated direct illuminance:

$$I_{vn} = I_{vo} \, . \exp(-\delta_{il} m_a T_{il}) \tag{14}$$

where $I_{„}$ is the extraterrestrial illuminance and T_{il},δ_{il} the corresponding illuminance turbidity and CDA optical depth. Navvab *et al.* (1984), whom incorrectly present this formalism as a new concept, derive the following expressions after multiplying theoretical attenuated spectral data with the V_λ curve for photopic vision:

$$\delta_{il} = 0.1/(1 + 0.0045 m_a) \tag{15}$$

$$T_{il} = 1 + 21.6\beta. \tag{16}$$

Direct luminous efficacy can now be computed after dividing eqn (14) by eqn (8):

$$LEbeam = \frac{I_{vn}}{I_n} = \frac{I_{vo}}{I_o} \exp[m_a(\delta_{CDA} T_L - \delta_{il} T_{il})] \tag{17}$$

which combined to eqns (9), (10), (15) and (16) will be referred to as Navvab's model giving direct luminous efficacy as a function of *fi*, ***h*** and w. If combined to eqns (12), (13), (15), and **(16)** this relation will be referred to as model A, giving *LEbeam* as a function of β and ***h.*** These equations are entirely derived from calculated spectral transmission data except for eqns (10) and (13) for which T_L was fitted to previous experimental data. Equations **(8)–**(17) are all developed for cloudless skies. The promising results obtained below in all conditions suggest however that the effect of clouds on eqn (17) is less important than on either eqn (8) or (14) taken separately.

Choosing which values of the solar constants I_o and I_{vo} should be used in eqn (17) is a delicate and sometimes disconcerting problem as these values have been revised a number of times and may bias the results. If eqns (12) and (13) are used to compute δ_{CDA} and T_L then 1367 W/m^2 should be used as the most recent value. in Navvab *et al.* (1984), a value of 1370 W/m^2 is given with eqns (9) and (10) and used with Navvab's model throughout this paper, although these equations were certainly developed from previous, lower values of the solar constant. Concerning the illuminance solar constant. the differences are more important. We suggest using a value of 127.5 klux [corresponding to Leckner's (1978) widely used spectrum] with eqns (15) and (16) as this value gave best results and was most probably used by Navvab ***et** al.* (1984). The revised value is 133 klux obtained with the CIE (1983) V_λ curve for photopic vision and Gueymard's (1995) extraterrestrial spectrum, updated from the World Radiation Centre's 1985 spectrum and in agreement with Olseth and Skartveit (1989). A revision of eqns (12), (13), (15) and (16) using SMARTS2, a simple model for the radiative transfer of clear sky irrandiance, Gueymard (1995), is the objective of a future paper.

5. EXPERIMENTAL DATA

The results presented here are limited to two independent data bases situated in two urban sites, 1 yr from Albany (42.7°N, 73.8°W, altitude: 60m, population with suburbs: 500,000, including February 1992 to January 1993) and 1 yr from Geneva (46.2°N, 6.2°E, altitude: 400m. population with suburbs: 400,000, covering March 1993 to February 1994). Global, diffuse and normal beam of both irradiance and illuminance components were measured at both sites. According to the manufacturers, the uncertainties in the measurements are $\pm 2\%$ for the Kipp & Zonen radiometers and Eppley pyrheliometers and $\pm 5\%$ for the Licor photometers used. This last figure seems somewhat overestimated when compared to our experimental results.

In this paper, direct irradiance/illuminance or normal beam irradiance/illuminance are named indifferently, referring to the totally or partially integrated solar spectrum in (W/m^2) or (klux), measured within a cone of open angle = 5.7° and impinging on a plane perpendicular to the sun's rays. The circumsolar effect (due to the fact that the sun covers only an open angle of 0.5") is not taken into account in the spectral transmission data. It is relevant to note that direct illuminance and irradiance were measured with the same sun tracker at both sites.

The quality of the measurements was rigorously controlled according to Molineaux and Ineichen (1994a). A total of 3017 hourly averaged values were thus validated for which the results cover the validated data in all sky conditions for which I, > 10 Wim', I„ > 0.1 klux and $h > 5$" (in order to eliminate perturbation from the horizon). Horizontal visibility was estimated five times a day by an observer at Geneva's airport. approx. 6 km away. In Albany visibility was estimated in much the same manner on an hourly basis at a distance of 7 km from the site of measurements. A lower limit of visibility = 14 km (corresponding to an upper limit of turbidity $\beta = 0.2$) was applied to the visibility measurements. This limit was chosen arbitrarily and was seldom exceeded in our weather conditions. It enabled elimination of exceptional conditions such as fog being present at the airport but not on the site of measurements, as sometimes observed in Albany. The height of precipitable water vapour content in the atmosphere, *w*, was estimated from on site temperature and humidity measurements using Wright ***et*** d's (1989) algorithm which was empirically developed from Albany data. In Geneva, this algorithm was also used and may be a source of error.

6. OBSERVED IMPACT OF ATMOSPHERIC PARAMETERS ON DIRECT LUMINOUS EFFICACY

increase in direct luminous efficacy with solar height. *h*, is very well demonstrated by our two data banks as illustrated in Fig. **3.** A number of models are based on this dependence, see Section 8. A reasonable approximation was also obtained with a least squares fit to our Geneva data, in terms of air mass, m_a:

$$LEbeum = 116 \cdot \exp(-0.1 m_a)\ (\mathrm{lm/W}) \tag{18a}$$

This relation, referred to as model B, was chosen to correct the measured luminous efficacies so as to illustrate the effect of atmospheric turbidity and water vapour content. Figure 4 shows the deviation of model B from the measured luminous efficacy:

$$\boldsymbol{ALE} = \boldsymbol{LEbeam} - 116 \cdot \exp(-0.1 m_a) \tag{18b}$$

where *LEbeam* is measured and ***ALE*** is repre-

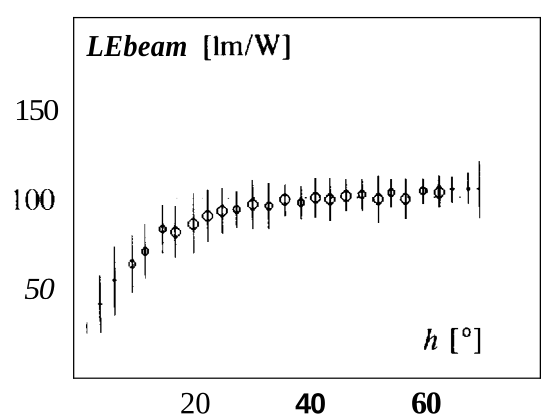

Fig. 3. Observed increase in direct luminous efficacy with solar altitude. The range of solar altitude is divided into 30 bins and the mean measured luminous efficacies are shown as a circle, the area of which is proportional to the number of observations relatively to the other bins. The means are extended by ± 1 **SD** within the considered bin.

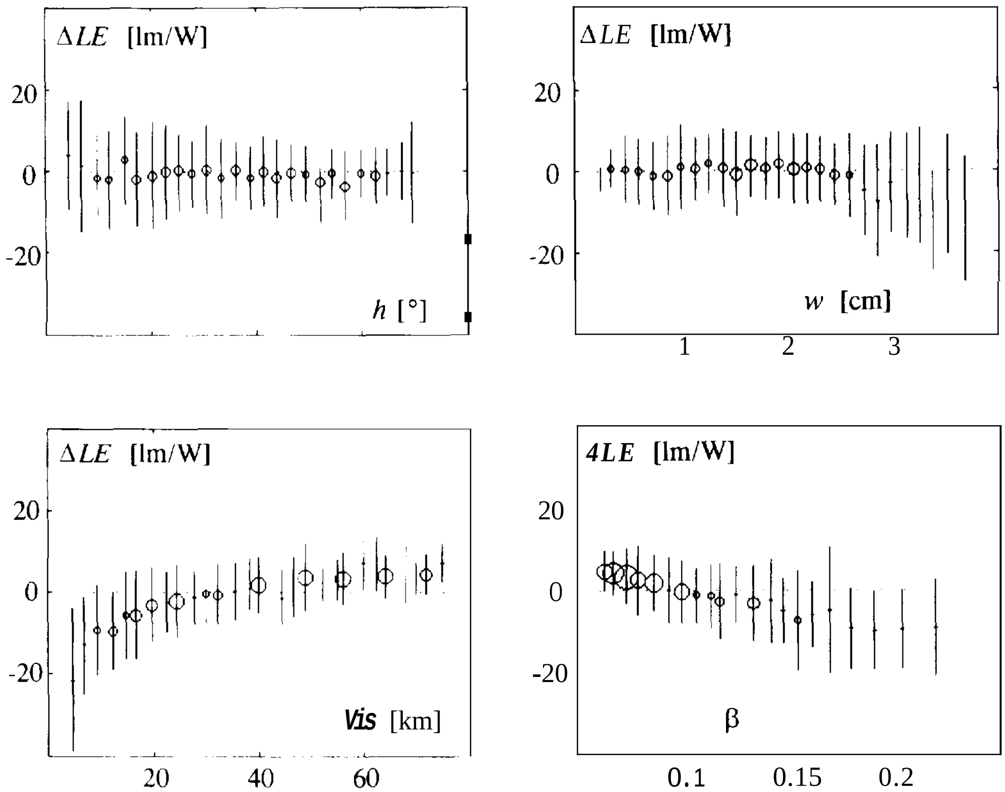

Fig 4 Measured computed (computed using model B) direct luminous efficacy as a function of four parameters.

sented in Fig. 4 as a function of four atmospheric parameters for all conditions. Dependence on solar altitude is now well accounted for. Dependence on horizontal visibility and atmospheric turbidity is significant, as expected. As in Fig. 3, the area of the circles represents the relative number of cases. showing that $1 < w < 2.5$ cm occurs in a vast majority of cases. For high values of w, it is clear that increased turbidity is more important than increased absorption in the IR region. The expected increase in direct luminous efficacy with increasing w, as predicted in Fig. 1, was only observed after selecting very clear days with low turbidity.

7. EXPERIMENTAL INVESTIGATION OF LINKE'S TURBIDITY FACTOR AS A FUNCTION OF OPTICAL AIR MASS, WATER VAPOUR CONTENT AND ÅNGSTRÖM'S TURBIDITY COEFFICIENT

An empirical approach was chosen to account for T_L's variation with air mass, m_a, water vapour content. w, and Angstrom's turbidity coefficient. β (derived here from horizontal visibility measurements) and making use of the revised definition of δ_{CDA}. Hourly values of T_L were determined from measured direct luminous efficacies. optical air mass and eqns (17), (16), (15)and (12).The observed dependence of these hourly values of T_L on β, w and m_a was then modelled in a simple relation. In order to test the model on a separate set of data, the Albany and Geneva data were divided in two data sets. The first set was used to obtain the following relation and the second set was used to test the model:

$$T_L = 1.5 + 12.4\beta + 0.5w^{1/3} + 4(\beta - 0.1) \cdot \ln m_a. \tag{19}$$

This relation was obtained by least squares fitting to 625 data points from 1 yr in Albany and 1 yr in Geneva after dividing the data banks into two equal parts, by selecting every other hour and only clear sky conditions. The range of variations of the different parameters was $0.3 < w < 3.7$ cm, $0.03 < \beta < 0.20$ and $1 < m_a < 12$. The criterion for clear sky conditions was arbitrarily chosen as $Kt' > 0.7$, where Kt' is the revised clearness index according to Perez *et al.* (1990b).

This simple model based on the revised definition of δ_{CDA} and developed on a limited set of direct luminous efficacy data is presented here as no equivalent published expression was found in the literature. The dependence on β seems somewhat underestimated when compared to eqns (10) and (13). Combined to eqns (12), (15), (16) and (17) this relation will be referred to as model **C,** for the prediction of direct illuminance.

An attempt at deriving a similar relation to eqn (19), but based on eqn (8) and the sole measurement of direct irradiance was also carried out, with little success. The reason for this discrepancy is most probably due to small clouds, which were present even in our selected clear sky data, and whose effect may be exceedingly difficult to separate from turbidity variations. Using a more restrictive criterion for clear skies had the effect of reducing our data banks to a size which was no longer statistically relevant. Thus, the use of eqn (19) for the prediction of direct irradiance via eqn (8), must be considered with extreme caution, since some clouds were present during the derivation of eqn (19). This source of error has apparently little effect when predicting direct luminous efficacy with model C, as witnessed below. The fact that β was derived from visibility estimates is also a possible source of error if eqn (19) is to be used in another context.

8. MODEL PERFORMANCE IN PREDICTING DIRECT ILLUMINANCE

Table 1 gives a list of the models tested in this study. The models' input parameters (which may be measured, calculated or estimated from tables), the basic assumptions involved, and the referred text where the algorithms can be found are also listed in Table 1. The input parameters are those used to predict direct luminous efficacy. To predict direct illuminance, as presented in Table 2, the direct luminous efficacy values are multiplied by measured direct irradiance values.

Perez *et al.*'s (1990a) model is the most extensively validated with respect to the number of sites and to the size of the data bases. Littlefair's (1988) model was fitted to a limited data set from Garston. North London. Aydinli's (1981) model is often referred to as a pioneering model, based on spectral data. Page's (1986) model uses Dogniaux's (1974) attenuation equations and a limited data set to fit T_{il} as a polynomial function of T_L. The model reported in Winkelmann and Selkowitz (1985) also borrows equations formulated by Dogniaux (1974), based on his parameterization of atmospheric extinction. Taking a constant value of 96.7 lm/W (this is the mean measured value, very close to the extraterrestrial value of 97.7 lm/W) was also attempted. Olseth and Skartveit's (1989) model is fitted to the clear **sky** spectral transmission model SPCTRAL2, (Bird and Riordan, 1986) with a seasonal term depending on day number and accounting for the seasonal variations in aerosol and water vapour content found in Bergen, Norway. Wright *et al.*'s (1989) model is empirically developed to a limited data set from Albany.

Chong's (1992) model was fitted to data from Hong Kong and appears to be climate dependent. Two other models (not presented in Table 1) predict significantly higher values of

Table 1. Direct luminous efficacy models

Model, 1st author	input parameters	Basic ingredients
Chong (1992)	h	Empirical fit to 1.5 yr's data from Hong Kong
Dogniaux (1974), see Winkelmann (1985)	h, w, β	Empirical parameterization of atmospheric extinction using extensive experimental data from Uccle, Belgium
Wright (1989)	h	Empirical fit to 3 months data from Albany
Perez (1990a)	h, I_r, G_h, w	Empirical fit to 14,000 15 min and hourly data
Olseth (1989)	h, nday	Fit to SPCTRAL? clear sky transmission model
Navvab (1984)	h, w, β	Analytical illuminance equivalent of Linke turbidity
Littlefair (1988)	h	Empirical fit to 495 hourly records of global–diffuse
Aydinli (1988)	h	Fit to theoretical spectral attenuation data
Page (1986)	h, w, I_n	Empirical illuminance equivalent of Linke turbidity with an estimated seasonal variation of turbidity
Constant	None	$LEbeam = 96.7$ lm/W, mean measured value
Model A	h, β	Same as Navvab (1984), with revised formulation of δ_{CDA} and eqn (13) for T_L
Model B	m_a	Empirical fit to 1550 h from Geneva
Model C	h, β, w	Same as model A with empirical fit to T_L, based on direct luminous efficacy measurements, eqn (19)

Table 2. Model Performance

	site	Geneva				Albany			
		MBD		RMSD		MBD		RMSD	
	Model and variations	(klux)	(%)	(klux)	(%)	(klux)	(%)	(klux)	(%)
(1)	Constant	−0.01	0.0	4.55	10.8	−0.30	−0.8	4.02	10.1
(2)	Chong (1992)	0.94	2.2	5.29	12.5	0.00	0.0	5.26	13.2
(3)	Dogniaux (1974)	1.94	4.6	5.33	12.7	2.34	5.9	4.71	11.8
(4)	Littlefair (1988)	−1.68	−6.4	4.90	11.6	−3.24	−8.1	5.16	12.9
(5)	Aydinli (1981)	−0.97	−2.1	4.04	9.6	−1.70	−4.3	4.70	10.5
(6)	Wright (1989)	1.12	5.0	4.02	9.5	1.44	3.6	3.08	7.7
(7)	Page (1986)	−0.81	−1.9	3.46	8.2	−0.79	−2.0	3.04	7.6
(8)	Model B	0.20	0.5	3.33	7.9	−0.44	−1.1	3.01	7.5
(9a)	Olseth (1989)	2.35	5.6	4.07	9.7	2.02	5.1	3.49	8.7
(9b)	Olseth, without seasonal term	2.67	6.3	4.39	10.4	2.00	5.0	3.40	8.5
(10a)	Perez (1990a)	0.03	0.1	3.14	1.4	−1.14	−2.8	2.94	7.4
(10b)	Perez, w fixed at 1.7 cm	0.00	0.0	3.01	7.1	−1.03	−2.6	2.93	7.4
(11)	Navvab (1984)	−0.23	−0.6	2.69	6.4	0.44	1.1	2.97	7.4
(12)	Model A	−0.23	−0.5	2.58	6.1	0.46	1.2	2.43	6.1
(13)	Model A, $\alpha = 1.3$	0.40	0.9	2.61	6.2	1.02	2.6	2.67	6.7
(14)	Model A, $\beta = 0.1$	0.67	1.5	3.41	8.1	0.05	0.1	2.81	7.0
(15)	Model A, seasonal β, eqn (7)	0.24	0.6	3.37	8.0	0.15	0.4	3.03	7.6
(16)	Model A, half the data	−0.24	−0.6	2.59	6.1	0.46	1.2	2.40	6.0
(17)	Model C, half the data	−0.20	−0.5	2.43	5.8	0.44	1.1	2.30	5.8

β was derived from visibility estimates unless specified. Angstrom's wavelength exponent. $\alpha = 1$, unless specified. Results refer to the complete data banks. 1518 h in Geneva and 1499 h in Albany except for comparisons 16 and 17 where half the data was used to derive model C, the other half was used to obtain these results.

the direct luminous efficacy than we observed here, Treado and Gillete (1987) suggesting a constant value of 105 lm/W or McCluney (1984), due apparently to less turbid atmospheres. The possibility of having β as model input, even on an averaged basis would make these models more universal.

The performance of the different models (with certain variations) is presented in Table 2 for the two data banks. The mean bias difference, MBD, and root mean square difference. RMSD, are obtained by subtracting the measured from the modelled value of the direct illuminance. The best model at predicting direct luminous efficacy under all conditions may not rank first in this table because a poor prediction of luminous efficacy for small values of direct illuminance will be overwhelmed by precise modelling for larger values. All models make use of direct irradiance as additional input parameter in order to predict direct illuminance. We chose this approach in the aim of obtaining the best representative values of direct illuminance.

A number of observations can be made from Table 2:

- The dispersion observed for the two data banks and the different models is comparable.
- The bias observed may differ by 3% from one data bank to the other, but there is no evidence for either of the data banks being biased by calibration errors.
- Using a constant mean measured value of 96.7 lm/W yields about a 10% RMSD on the predictions, a number of models do not show a significantly smaller dispersion.
- Accounting for variations of direct luminous efficacy with solar altitude is sufficient to reduce the RMSD to less than 8%.
- A small increase in precision is obtained with Perez *et al.'s* (1990a) empirical model which is based on Perez' sky clearness and sky brightness parameters (determined from global and direct irradiance) and on w to represent the sky conditions. Comparisons (10a) and (10b), show however that taking a fixed value of $w = 1.7$ cm (mean measured value) has little or no effect on model performance. This implies that either the effect of water vapour content is poorly estimated, or its effect is very limited.
- Making use of β computed from visibility (i.e. Navvab's model, models A and C) enables a significant increase in model precision.
- Using the new formulation of δ_{CDA} and eqn (13)for Linke's turbidity factor, models A and C, brings another remarkable increase to model performance.

- Using the new formulation of δ_{CDA} and empirical eqn (19) for Linke's turbidity factor, model C. gives the best performing model in predicting direct illuminance under all sky conditions.
- The value of α which gave best overall results is $\alpha = 1$ but taking $\alpha = 1.3$ essentially changes the bias with no effect on the dispersion, see comparisons (12) and (13).
- Littlefair's (1988) is the only model that gives a much lower luminous efficacy than was observed here. His data and subsequent empirical model plausibly suffered from the pollution caused by the city of London and its industries.
- Olseth and Skartveit's model was developed for rural aerosol conditions found in Norway and predicts a significant overestimation of direct luminous efficacy in the more polluted climates of Albany and Geneva.
- Adding a seasonal term, based on a spring maximum in aerosol actitivity, to Olseth and Skartveit's model brings little or no improvement to model precision, see comparisons (9a) and (9b).
- Comparisons (12), (14) and (15), based on model A's predictions, show the model's sensitivity to β and the importance of correctly estimating atmospheric turbidity. A seasonal variation of turbidity, also assumed in Page's and Olseth and Skartveit's models is clearly not sufficient to account for the effect of changing turbidity.

Figure 5 illustrates the results obtained with models A, B and C. Model B shows that using only the dependence on air mass in a simple expression, a reasonable estimate of direct illuminance can be obtained. This model is empirically derived from the Geneva data bank and compared here to the Albany data. An average of $\beta = 0.1$ was recorded in both Geneva and Albany, and this model may give biased results in either a very clean or very turbid climate. Model A gives remarkable results when taking into account the fact that all the functions are derived from spectral transmission models

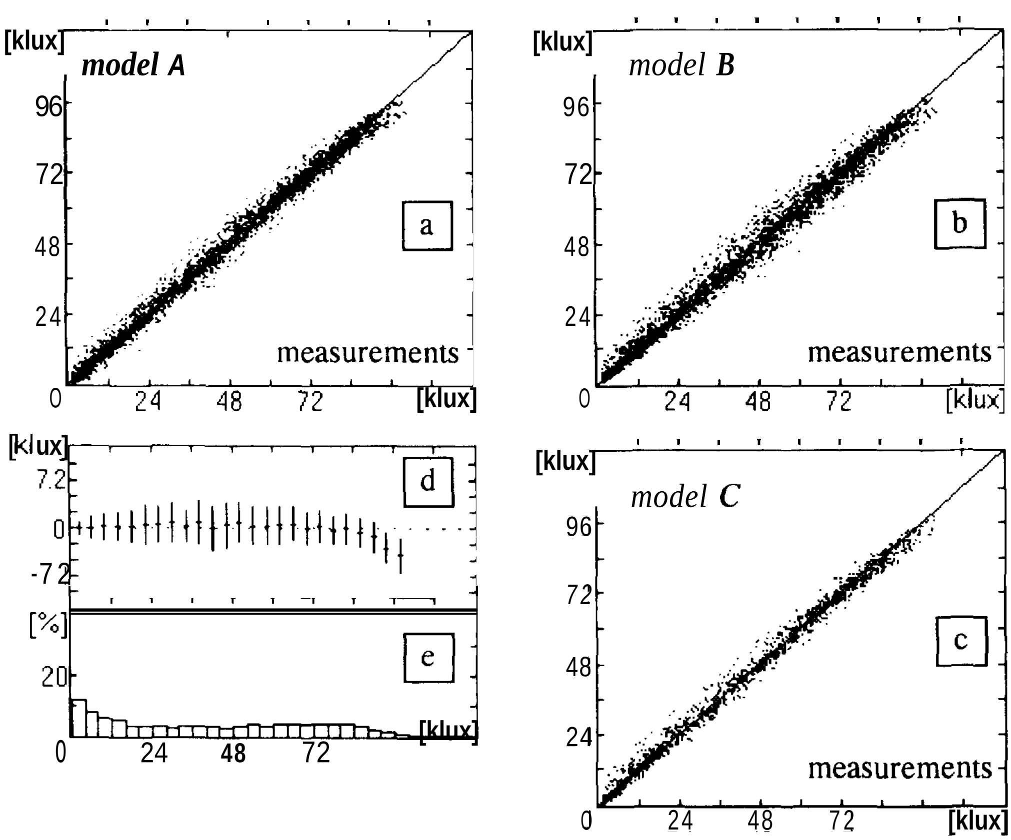

Fig. 5. Comparison of measured and modelled direct illuminance for three models. a, b, c: modelled versus measured values for models **A**, B and **C.** d: means bias difference $\pm$ 1 **SD** for model **A** and 30 bins of direct illuminance and e: relative number of events in each bin.

except the simplified expression for T_L, eqn (13), derived from independent experimental results obtained by Katz **et** *al.* (1982) and adapted by Grenier **et** *al.* (1994). Model C uses eqn (19) for T_L, which is derived from half the Albany and Geneva data and tested here on the other half. The precision obtained with this model is remarkably close to instrumentai uncertainty. The two data sets described above which were used to develop and test model *C* are far from being statistically independent. A subsequent validation has however been carried out since this paper was submitted, yielding similar results to those presented here when compared to an independent set of data from Freiburg, Germany, see Molineaux and Ineichen (1994b).

9. CONCLUSIONS

The importance of correctly assessing the turbidity of the atmosphere when predicting direct illuminance in an urban site is well demonstrated by our results. The performance of the direct luminous efficacy models developed in this paper is a promising experimental validation of the turbidity equations which were used.

The use of airport horizontal visibility estimates to determine atmospheric turbidity in a vertical direction proved to be a simple and effective method for this application. This tends to corroborate the hypothesis that the majority of the aerosol loading lies in the bottom layer of the atmosphere, at least in an urban climate. Using a seasonal model to estimate variations in atmospheric turbidity proved to be far from satisfactory, also showing the sensibility of direct luminous efficacy to rapid variations in aerosol content.

The complexity of the effect of water vapour and thin clouds on direct luminous efficacy requires a very careful study and was not properly addressed in this paper, although their impact appears to be quite limited when trying to predit direct illuminance.

Finally, these results raise one essential problem which is left greatly unsolved and is the objective of a future paper: Finding an appropriate and satisfactory model in order to estimate atmospheric turbidity from readily available pyrheliometric direct irradiance measurements.

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NOMENCLATCRE

λ	wavelength (μm)
$I_{n\lambda}$	monochromatic normal beam irradiance ($W\,m^{-2}\,\mu m^{-1}$)
$I_{o\lambda}$	monochromatic extraterrestrial beam irradiance ($W\,m^{-2}\,\mu m^{-1}$)
$\tau_{i\lambda}$	monochromatic atmospheric transmittance accounting for the following processes:
$\tau_{r\lambda}$	Rayleigh scattering by air molecules
$\tau_{a\lambda}$	Mie scattering and absorption by aerosols
$\tau_{o\lambda}$	selective absorption by the stratospheric ozone layer
$\tau_{g\lambda}$	selective absorption by the permanent atmospheric gases
$\tau_{w\lambda}$	selective absorption by water vapour
$k_{i\lambda}$	monochromatic atmospheric attenuation coefficient for the same process
h	solar height above the horizon (°)
$m_{i,a}$	relative optical atmospheric mass of a single constituent or of the averaging atmosphere
β	Angstrom's turbidity coefficient
α	Angstrom's wavelength exponent
vis	horizontal visibility as determined at airports (km)
nday	day number of the year. 1st January = 1
I_n	integrated normal beam irradiance ($W\,m^{-2}$)
I_o	integrated extraterrestrial beam irradiance ($W\,m^{-2}$)
δ	total integrated optical thickness of the atmosphere
δ_{CDA}	integrated optical thickness of a clean dry atmosphere
δ_{il}	equivalent illuminance integrated optical thickness of a clean dry atmosphere
T_L	Linke's turbidity factor
T_{il}	equivalent illuminance turbidity factor
w	height of precipitable water vapour content (cm)
I_n	integrated normal beam illuminance (klux)
I_o	integrated extraterrestrial beam illuminance (klux)
LEbeam	direct luminous efficacy (lm/W)
ALE	difference between measured and modelled direct luminous efficacy (lm/W)
MBD	mean bias difference $= \frac{1}{N}\cdot\sum_{i=1}^{N}$ (modelled value$_i$ − measured value$_i$)
RMSD	root mean square difference $= \sqrt{\frac{1}{N}\cdot\sum_{i=1}^{N}(\text{modelled value}_i - \text{measured value}_i)^2}$

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