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A MODEL FOR UPPER BOUND CLEAR SKY AVAILABILITY OF SOLAR ILLUMINANCE

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Abstract
The annual global clear sky illuminance available at points on the earth between the Arctic and Antarctic circles, at various altitudes is presented as an upper bound to available global illuminance. The analysis is based on measurements of illuminance obtained using a spectroradiometer. A simplified expression which may be used to predict the illuminance within 2% of the integrated results is presented. It is suggested that the effects of cloud cover may be included by using data readily available from NASA.

Keywords: global illuminance, spectroradiometer, NASA

1. Introduction

Increases in atmospheric concentrations of gases since the advent of the industrial revolution some 150 years ago have been well documented. For example, measurements of atmospheric concentrations of carbon dioxide in ice cores dating back over the past 420 000 years up to the start of the industrial revolution, covering four glacial and interglacial cycles, varied from lows of 180 ppm to highs of 280-300 ppm [1,2]. Detailed atmospheric carbon dioxide concentrations measured from 1958 by Earth System Research Laboratory showed that concentrations of carbon dioxide in 2007 exceeded 380 ppm and the current rate of increase is typically exponential. Increases in atmospheric concentrations of methane have shown similar trends [3].

Globally, a large percentage of electricity generated is used for interior illumination during daylight hours. In the USA, 35% of the electrical consumption is used for lighting during the day, and in some regions it may be as high as 45% [4]. Using data published by ESKOM DSM [5] in South Africa approximately 13% of the electrical power consumed in the industrial, commercial, and residential sectors of the economy is used for lighting. It may also be expected that significant amounts of electricity are used in other countries. Clearly significant reductions in the emission of greenhouse gases could be achieved if the use of electricity for day time illumination generated using carbon based fuels could be replaced using renewable energy sources.

There is a growing tendency to reduce energy consumption used for illumination by replacing lamps of low efficacy with more efficient lamps, and by the use of day lighting. Australia [6] and Canada [7] have announced their intention to ban the use of incandescent lamps in favour of more efficient light sources. The Australian Minister of the Environment noted that this could cut greenhouse gas emissions by 4 million tonnes by 2012 [6].

Problems related to the sporadic nature of solar illuminance may be counteracted by using hybrid lighting systems in which a complementary source of illumination is used to provide the difference in illumination between that required and that currently available from the sun. Advantages of using such hybrid systems include a reduced overall demand for fossil based fuels over the long term and possible improved environmental conditions for human health.

Solar illuminance at a location is generally obtained from the product of the luminous efficacy and irradiance for that location. Various descriptions of luminous efficacy, which on the surface of the earth is a function of atmospheric conditions including air mass, elevation of the sun, cloud cover, precipitable water, and atmospheric turbidity, are presented by Perez et al [8,9], Pohlen et al [10] and Tsikaloudaki [11]. Janjai [12] amongst others used a technique for mapping global illuminance using satellite data. The terrestrial efficacy used as a base reference which applies on the outskirts of the earth's atmosphere may be calculated using the terrestrial irradiance constant of 1366 W/m^2 [13] and the terrestrial solar illuminance constant of 127 500 lm/m [2,14]. The resulting terrestrial efficacy is 93.3 lm/W, which would apply at all points on the planet if there were no atmosphere. While luminous efficacy is a function of the elevation of the sun and atmospheric conditions and will vary daily, levels of the order of 100 lm/W were published by Wright et al [15], 130 lm/W by Pohlen et al [10], and 100 lm/W by Tsikaloudaki [11]. Published measured levels of global illuminance include 110 000 lm/m^2 in Athens, Greece by Tsikaloudaki [11], 110 000 lm/m^2 in Paraparauma Beach in New Zealand by Pohlen et al [10], and 120 000 lm/m^2 at an altitude of 1715 m at Johannesburg, in South Africa by Nurick [16].

Day lighting, the controlled use of solar illuminance to light the interiors of buildings through openings in walls and roofs has been used for centuries and has been widely discussed by, amongst others, Ander [17] and Philips [18]. In the Pantheon in ancient Rome, day lighting was combined with ventilation. Current developments of day lighting include: i) the concentration of luminance in a parabolic reflector directed onto a fibre optic bundle and the transmission of light to a diffuser for interior distribution [4,19,20]; ii) optical systems comprised of prisms, lenses and mirrors, for transmitting light to designated areas as discussed by Ngai [21] and Solartech [22]; and iii) light pipes, which are tubular pipes with internal walls lined with reflective materials which duct solar illuminance into buildings to provide interior lighting patented by Whitehead [23]. Zhang et al [24] present guidelines for the performance assessment of light pipes and Kocifaj [25] and the University of British Columbia [26] present analytical methods for the transmission of light in light pipes. Solar skylights, which are widely used, are short ducts used to transmit solar global illuminance through roofs into interior areas.

Typically, global illuminance will be used for day lighting through windows. Where light needs to be transmitted over longer distances, due to the collinear nature of the light required for transmission the direct component of illuminance will be transmitted with the diffuse component being dissipated before reaching the point of distribution.

Initial investigations of John Ott [27] of the physiological effects on humans have been discussed by amongst others Badia [28] and Rea [29]. Blask et al [30] documented the effects of light on cancer and Hughes [31] noted the superiority of full spectrum light sources on the physical fatigue and alertness of humans. Lewy et al [32] discuss the effects on human health of the absence of ultra violet light and the consequent lack of information provided to the human time clock, or circadian system. Light loses approximately 90% of its ultra violet component when it passes through glass and hence the design of day lighting systems using solar illuminance need to be designed to ensure that the ultra violet component is not lost. Thus, while it is necessary to quantify the amount of illuminance available for day lighting, it is also necessary to ensure that the full spectrum quality is maintained.

The objective of this work is to present an upper bound of available illuminance for the design of day lighting systems at any point on the planet between the Arctic and Antarctic circles which includes the effects of altitude.

2. Correlation of Illuminance

The analysis is based on the correlation of global illuminance measurements by Nurick [16] shown in figure 1 made using an Apogee Spectroradiometer. The data used as a basis for this work were collected on clear sky days over approximately one year at latitude -26.16^o at an altitude of 1715 m. The spectroradiometer was set to measure irradiance over a wavelength range of 274 nm to 898.5 nm which included mainly the visible portion of the irradiance spectrum. This had the advantage of not including the effects of irradiance at higher wavelengths when calculating the illuminance and the required consequent corrections for irradiance extinction in the atmosphere at wavelengths outside the visible range of wavelengths. The standard deviation of the illuminance measurements was 5.6 % of the maximum illuminance measured.

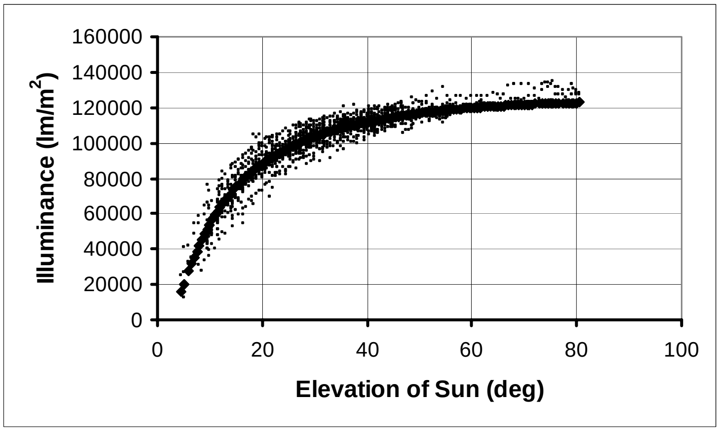

Figure 1: Variation of global solar illuminance with solar angle of elevation [16]

The correlation of illuminance with the elevation of the sun, as described in [16] is:

$$I = I_0 Exp\{\frac{-KA}{Sin(\gamma)}\} \qquad (1)$$

where $K = 2.0870 \times 10^{-5}\ m^2 / kg$ is a mean extinction function integrated over wavelengths in the visible spectrum and $I_0 = 146\,200\ lm / m^2$ is the experimentally determined terrestrial illuminance constant for the measured data set. A is the atmospheric mass based on the International Standard Atmosphere (ISA) for different altitudes h above sea level and may be approximated by:

$$A = 10220 - 1.2188\, h + 5.251 \times 10^{-5}\, h^2 \qquad (2)$$

for the altitudes considered. Equation (2) is a simplified description of A which may be expressed in terms of the atmospheric variables for an ISA [16] with a correlation coefficient of $R^2 = 1$ with the original expression.

Total daily global illuminance is given by:

$$I_d = \int_{Sunrise}^{Sunset} I\, dt \qquad (3)$$

The elevation of the sun is given by Stine [33]:

$$Sin(\lambda) = Cos(\delta)\ Cos(\omega)\ Cos(\phi) + Sin(\delta)\ Sin(\phi) \qquad (4)$$

where λ is the altitude angle of the sun above a horizontal plane at the location of interest, δ is the solar declination, ϕ is the latitude of the test location, and ω is the solar hour. The solar declination used is given by:

$$\delta = \delta_0\, Cos(\frac{J - J_0}{365.25} 2\pi) \qquad (5)$$

where $\delta_0 = 23.45^o = 0.40928$ rad, is the tilt of the earth's axis relative to the ecliptic plane, J is the Julian day of the year, and $J_0 = -11$ is the summer solstice in the southern hemisphere Julian day of the year. Other expressions for the solar declination are available (for example reference 33), but equation (5) has a useful period of one year and compares well with the expression by Stine [33] with the difference being less than 1^o.

Sunrise and sunset are taken to occur when the elevation of the sun, as expressed by equation (4) is zero, that is, when the sun's rays are tangential to the surface of the earth at the location of interest. For purposes of calculation the deflection of the sun's rays at low angles of elevation due to variations in the refractive index of the atmosphere are ignored. This is substantiated on the basis that the contribution to the total daily illuminance at low angles of elevation of the sun is small.

If sunrise and sunset correspond to solar angles of elevation of zero, then from equation (4) the solar hours at which they will occur are, for $\gamma = 0$, given by:

$$\omega_{SO} = \pm Tan(\delta)\, Tan(\phi) \qquad (6)$$

with the solar hour at sunrise being $\omega_{SO} \langle 0$ the solar hour at sunset being $\omega_{SO} \rangle 0$.

To calculate the elevation of the sun correctly, based on clock time, differences in time between solar and clock time due to the equation of time (EoT) must be included, that is, variations between clock and solar time due to the elliptic orbit of the earth around the sun, and due to the tilt of the earth's axis of rotation relative to the ecliptic plane. The EoT will, on a daily basis add a time difference which is approximately constant for the day of interest. This time variation will not affect the total length of the day, nor the maximum elevation of the sun on that day. The total illuminance for a particular day will not be affected by a constant time difference due to the EoT and hence for this analysis the EoT was not taken into account. The analyses where based solely on solar time.

Equation (3) was integrated numerically for each day in the year by using equations (1), (2), (4), and (5) to calculate the required variables. The integration was carried out by dividing the day from sunrise to sunset into twenty equal time periods, calculating I for start and end of each time period and using the Composite Simpson's Rule [34] to integrate the illuminance. The solar declination was held constant for each day period.

Integrations were carried out for latitudes from the equator to $\pm 65^o$ north and south and for altitudes varying from sea level to 3000 m. Extension of the analysis to cover a wide range of latitudes, up to the Arctic and Antarctic circles is supported based on the fact, as shown in figure 1, the variation of illuminance with elevation included data from low angles of elevation to a maximum elevation of 87.3^0 obtained at a latitude of -26.16^0. The maximum elevation of the sun at latitudes of $\pm 65^o$ is 25^0 which, as indicated in figure 1, are included in the measured data.

Results of the numerical integrations are presented in figure 2.

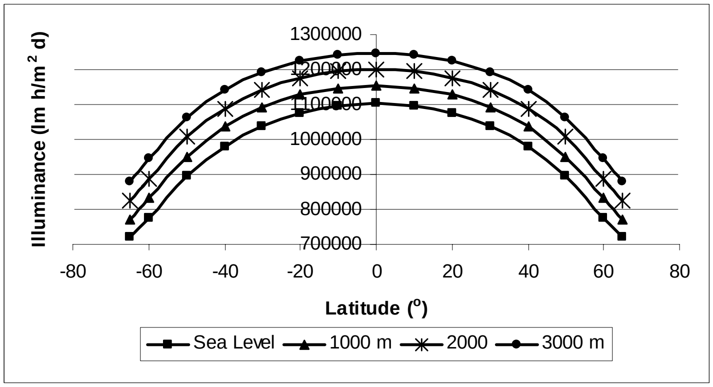

Figure 2: Variation of daily averaged illuminance (I_d) with latitude and altitude

The actual global illuminance available for day lighting and in particular the direct luminance available for transmission through a light duct may be deduced by taking the cloud cover into account. Cloud cover data are available from sites such as the NASA Atmospheric Science Data Center [35].

The daily average illuminance presented in figure 2, determined using numerical integration may be approximated to within an error bound of + 0 % to -2% over the latitude range of $-65^o \langle \phi \langle 65^o$ with a simplified expression. The expression is a product of the variation of illuminance at the equator, that is, at $\phi = 0^o$, which is in effect the first term of a Taylor series, multiplied by a function which gives the variation of daily illuminance with latitude, for a given altitude. The linear variation of illuminance at the equator with altitude is reasonable on the basis that the analysis is applied from sea level to an altitude of 3 000 m. These altitudes are the lower 10 % of the atmosphere which contains 99 % of the mass of the atmosphere and a linear variation with altitudes up to 3 000 m has a correlation coefficient of $R^2 = 0.9997$ with the analysis based on equation (3). This variation is, as indicated in figure 2, a function of the altitude as the ratios of the illuminance at $\phi = 0^o$ and at $\phi = 65^o$ are altitude dependent. This dependence on altitude is included in the exponent of a Cosine multiplier term, as indicated in equation (7).

$$I_{dc} = \left(I_{d=0,\alpha=0} + \left.\frac{\partial I_d}{\partial h}\right|_{\alpha=0} h \right) Cos^{(a+b\,h)}(\phi) \qquad (7)$$

Based on the analysis presented in figure 2, substituting the constants derived from the data gives, for equation (7):

$$I_{dc} = (1103\,800 + 47.975\ h)\, Cos^{(0.515-3.56\times10^{-5}\,h)}(\phi) \qquad (8)$$

The ratios of the calculated average daily illuminance divided by the numerically integrated average daily illuminance are presented in figure 3.

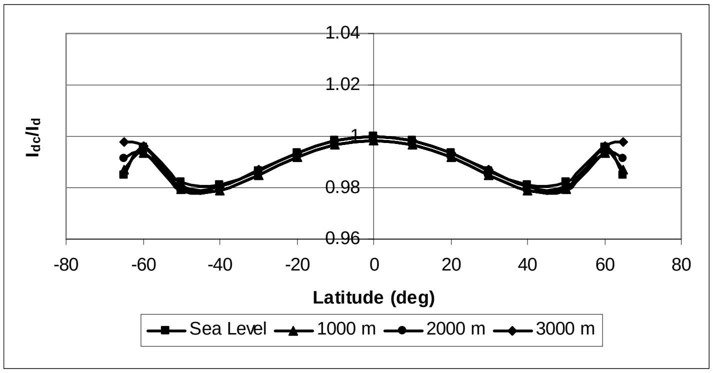

Figure 3: Ratio of average daily illuminance calculated using equation (8) and the numerically integrated values.

3. Conclusions

An upper bound for the global illuminance available at various locations between the Arctic and Antarctic circles and various altitudes on the planet has been presented. The analysis was based on data obtained using a spectroradiometer at a specified location. It was indicated that actual illuminance levels may be determined by using cloud cover data such as that available on NASA websites. A simple expression for the global illuminance is presented which agrees with the integrated results within 2%.

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