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LUMINOUS EFFICACY OF DIRECT IRRADIANCE: VARIATIONS WITH INSOLATION AND MOISTURE CONDITIONS

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Abstract—The present work is an experimental study of the relationship between the luminous efficacy of direct solar radiation and the following quantities: global and direct solar radiation, total water vapor content (as estimated from surface dew point), and solar zenith angle. This work will contribute to the development of a model to derive direct illuminance, a critical component in daylighting applications, from more commonly available direct irradiance.

Direct luminous efficacy is defined as the ratio between the direct illuminance and direct irradiance. This varies with turbidity, water vapor content, cloud cover, and solar geometry. Insolation conditions were parameterized by global and diffuse irradiance and solar geometry in earlier work. We attempt here to account for atmospheric water content as an additional descriptor. This has an impact on luminous efficacy directly because of spectrally selective absorption and indirectly because of spectrally selective aerosol scattering.

An important step of this work includes the determination of instantaneous total precipitable water (as a measure of water vapor absorption) from surface dew point temperature. The latter quantity is routinely measured, the former is not.

The utilization of surface dew point temperature as an estimator of atmospheric water vapor content improves the determination of the visible radiation from solar radiation data. Experimental observations presented in this work are consistent with expected atmospheric physical processes.

1. INTRODUCTION

Luminous efficacy provides a link between the two important quantities of daylight and solar radiation. Both quantities are increasingly important to building design optimization in terms of lighting and energy consumption; luminous efficacy, therefore, appears likely to be increasingly employed in simulations, especially in the calculation of daylight illuminance for places where measured data do not exist. Also, luminous efficacy may provide valuable insight on the spectral quality of incoming radiation. This is useful information for photovoltaic and photosynthetic studies. It is therefore important to have a good understanding of luminous efficacy and its variations with meteorological conditions.

Luminous efficacy, K, is defined as the ratio between daylight illuminance E and solar irradiance Ee. It is expressed in lumens per watt and is defined by the following expression:

$$K = E/Ee = Km \frac{\int_{380}^{760} V(\lambda)\, Ee(\lambda)\, d\lambda}{\int_{0}^{\infty} Ee(\lambda)\, d\lambda} \qquad (1)$$

where E is the illuminance, that is, the visible—eye sensitive—radiation, Ee is the irradiance, that is, the total radiation, λ is the wavelength, and $Ee(\lambda)$ is the spectral irradiance. Km (683) is a normalizing factor representing the number of lumens of light stimulus produced by one watt of electromagnetic radiation at a wavelength of 555 nm. $V(\lambda)$ is the value of C.I.E. (Commission Internationale de l'Eclairage[1] photopic spectral sensitivity of the eye. This sensitivity has a maximum value of 1.0 at 555 nm and drops to zero at 380 and 760 nm. The C.I.E. photopic curve is compared to a direct irradiance spectrum in Fig. 1. The spectra in this manuscript are produced using the model SPCTRAL2 of Bird and Riordan[2].

Little work has been attempted in the past to systematically analyze luminous efficacy, primarily because of the lack of coincident energy and daylight availability data. Littlefair[3] reviewed literature reporting luminous efficacy observed in various parts of the world for the past 50 years. He concluded that (1) luminous efficacy generally falls in the range 90–130 lm/w; (2) substantial variation can occur, depending on solar altitude, atmospheric aerosol and water vapor content, type and amount of cloud, and whether direct sun or diffuse sky radiation is being considered. Navvab *et al.*[4] analyzed solar radiation and daylight measurements collected during a four-year period in San Francisco, California. They observed that the luminous efficacy of global, direct and diffuse solar radiation depends upon solar altitude and turbidity. Perez *et al.*[5] used a parameterization method based on direct and global irradiance to study the variations of global and diffuse illuminance and

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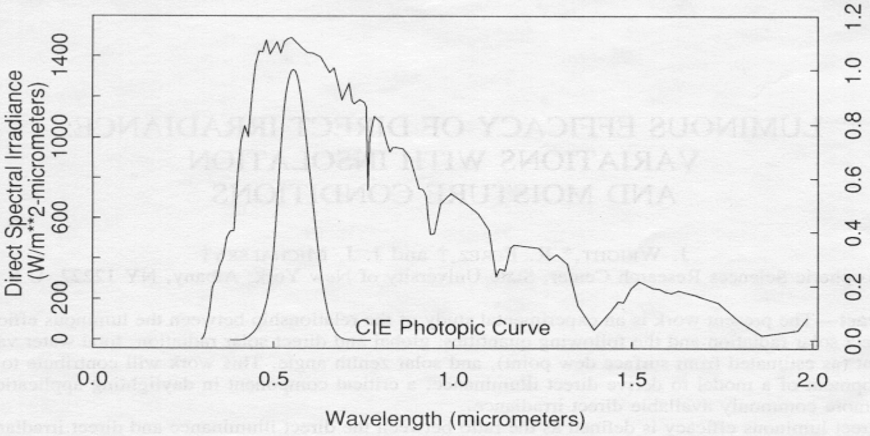

Fig. 1. Comparison of the direct normal irradiance spectrum and the CIE photopic curve.

concluded that much of the observed variation can be explained by these two quantities and solar geometry. The work presented here expands Perez's parameterization in an attempt to include the effect of water vapor on the direct beam luminous efficacy.

This paper is divided into five sections. The following section includes a review of the insolation parameterization method previously used by Perez *et al.*[5]. Methods to estimate precipitable water from surface dew point temperature are then reviewed and validated for Albany, New York. The next section describes the solar and meteorological measurements used for the present work, and the final section focuses on the combined effect of water vapor and insolation conditions on the measurement of luminous efficacy.

2. PARAMETERIZATION OF INSOLATION CONDITIONS

Three coordinates were proposed to describe all sky conditions from completely clear to heavily overcast including all intermediate situations. These coordinates are (a) the solar zenith angle; (b) the clearness of the sky; and (c) the brightness of the sky. These are shown in Fig. 2.

The clearness of the sky, ϵ, is given by:

$$\epsilon = (B + Dh)/Dh, \tag{2}$$

where B is the direct normal irradiance and Dh the diffuse horizontal irradiance. A high value represents clear conditions, and a value of 1 represents complete overcast.

Atmospheric brightness, Δ, is given by:

$$\Delta = Dh * m/ETR, \tag{3}$$

where m is the air mass and ETR the extraterrestrial solar irradiance. This variable is proportional to the diffuse horizontal irradiance. When the sky is completely overcast ($\epsilon = 1$), Δ may vary by a factor of 10. This illustrates the need for a third variable to adequately describe sky conditions.

Incorporation of water vapor into parameterization

Perez *et al.*[5] used the above parameterization of sky condition to model luminous efficacy. However, they did not determine the effect of water vapor which should have a strong impact on luminous efficacy because of spectrally selective water vapor absorption and aerosol scattering.

Figure 3 illustrates the effect of water vapor on the solar spectrum. The two spectra are presented for $W = 0.4$ cm and 4.0 cm of precipitable water. The infrared region of the spectrum containing absorption bands is noticeably affected by water vapor variations while the visible region is not.

Precipitable water (W) is used to assess the effect of water vapor on the extinction of the direct beam radiation. This is defined as the amount of water in an air column. Since W is not routinely measured, it will be estimated from surface dew point temperature which is measured at many weather stations.

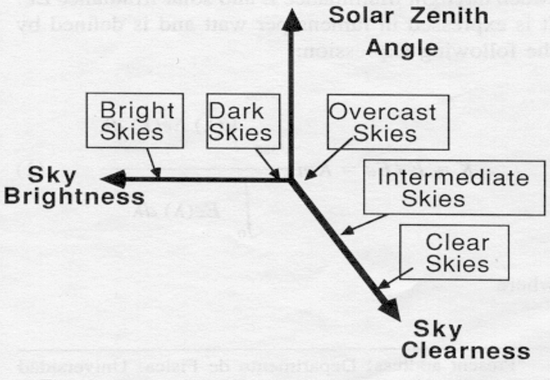

Fig. 2. Three-dimensional parameterization of sky conditions.

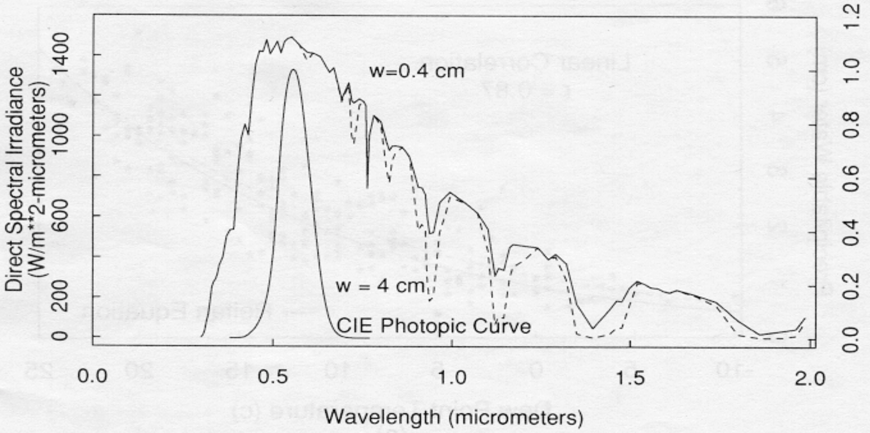

Fig. 3. Direct normal spectral irradiance with different amounts of water vapor.

In summary, the proposed parameterization will use surface dew point as a fourth dimension, besides ϵ, Δ and solar zenith angle Z.

3. ESTIMATION OF TOTAL PRECIPITABLE WATER

Reitan[6] reported a correlation of 0.98 between mean monthly values of liquid equivalent (precipitable water) and mean monthly surface dew point temperature for 15 stations in the United States. He obtained a relationship between the dew point temperature (Td) and the total precipitable water (W) in the form

$$W = \exp[a + m*Td], \qquad (4)$$

where a and m are constants.

Mixing ratio tends to be conserved with height. Water vapor content is greatest at the surface and decreases exponentially with height just as does pressure. To first order, the dew point is related to the natural logarithm of the precipitable water[7] which suggests the plausibility of Reitan's[6] functional form.

Bolsenga[8] found a correlation coefficient of 0.80 for 97 pairs of dew point temperatures made just before radiosonde launch and the integrated water values from these launches in New Hampshire.

In contrast to Bolsenga[8], Reber and Swope[9] concluded that the estimation of precipitable water from single point surface measurements are not sufficiently reliable.

Reber and Swope's[9] objection may not be valid for Albany, where a reasonable correlation is found between integrated values of total precipitable water and surface dew point temperature. In the present study for Albany NY, two daily values (0000 GMT and 1200 GMT) of precipitable water and few point temperature are compared for the period April to July 1987. Precipitable water data are obtained from moisture maps provided by the National Weather Service[10], and the corresponding surface dew point temperatures are from the Local Climatological Data of the National Climatic Center[11].

All sky conditions

Figure 4a presents the plot between total precipitable water and surface dew point temperature for all sky conditions in Albany. An expression identical in form to eqn (4) is derived empirically and plotted in this same figure. By taking the natural log of both sides of eqn (4) the coefficients a and m may be derived by linear least square fitting. Reitan's[6] equation is also plotted in this figure. Both curves nearly coincide indicating that Reitan's method, based on average monthly data, is valid for instantaneous values in Albany.

The following regression equation will be used to compute the instantaneous total precipitable water in Albany:

$$\ln W = -0.0756 + 0.0693*Td, \qquad (5)$$

where W is the total precipitable water in cm and Td is the surface dew point temperature in degrees C. The correlation coefficient (r) between ln W and Td is 0.87. The standard error of estimate (Δ ln W) is 0.28 which is higher than Reitan's[6] standard error of estimate for mean monthly values (0.18), but lower than Bolsenga's[8] value for instantaneous data (0.43). Since the standard error is a measure of the general reliability of estimates calculated from regression equations, it follows that the surface dew point temperature is an adequate estimator of the total precipitable water for all possible insolation conditions in Albany.

Clear sky conditions

Some of the scatter in Fig. 4a is due to the presence of clouds or precipitation when the soundings were obtained, which produces an error in the calculation of W. Figure 4b is a plot of total precipitable water against the surface dew point temperature for

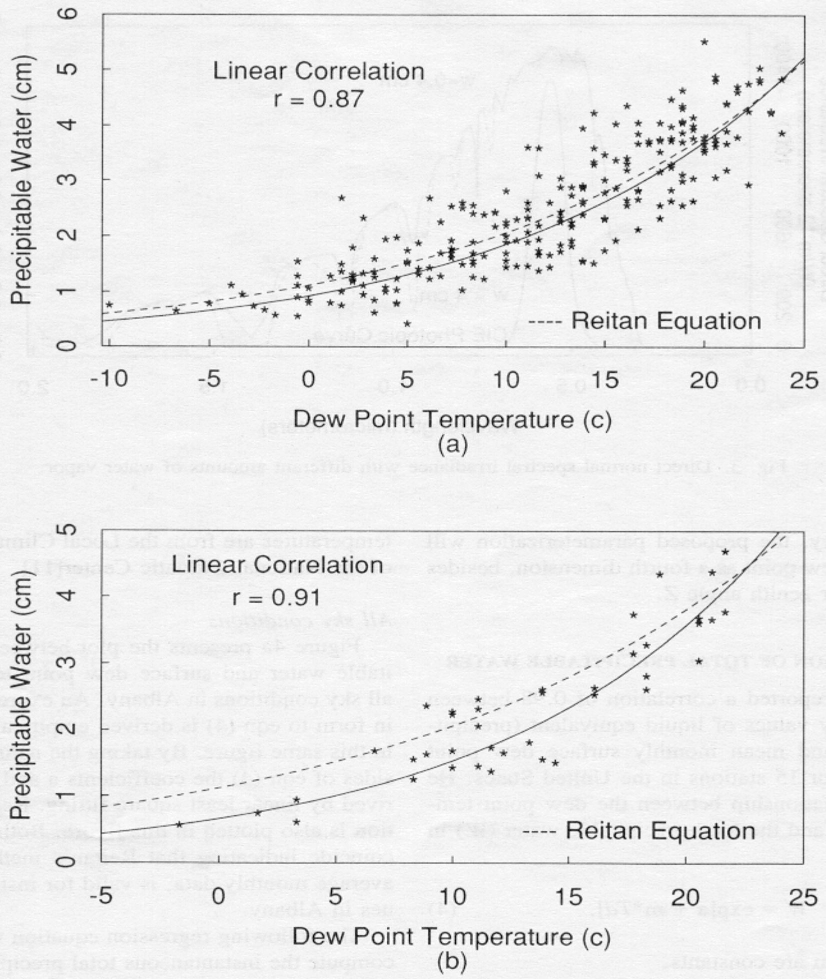

Fig. 4. Instantaneous precipitable water versus dew point temperature in Albany, NY for (a) all sky conditions, (b) clear sky conditions.

clear sky conditions defined as $\epsilon > 6$. The correlation coefficient obtained is 0.91, and the standard error of estimate between these two variables, is lower than for all sky conditions. The improved accuracy is likely due to the absence of condensed water for these clear conditions.

Equation (5) is adequate for computing instantaneous total precipitable water from surface dew point temperature at Albany. This method should be verified for climatologically different locations.

4. EXPERIMENTAL IRRADIANCE AND ILLUMINANCE DATA

The approach used here to observe weather conditions effect on luminous efficacy is experimentally based. A first-principles analytical approach could be used, but is thought to be too complex to fully describe real atmospheric effects.

The experimental data used for this study were measured at the Atmospheric Science Research Center of the State University of New York at Albany. The following instrumentation was used:

Measurement	*Instrument*
Global Irradiance	Eppley PSP
Direct Irradiance	Eppley NIP
Direct illuminance	Li-Cor Photometer + Baffled Tube

Solar radiation data were recorded with a 15-minute time step. Besides daily instrument cleaning and tracking checks every three hours, data were subjected to a rigorous automatic quality control. Data are from April 1, 1987 to July 31, 1987.

Three-hourly values of dew point temperature for the period of study were measured at the Albany airport by the National Weather Service[11]. They are merged with the 15-minute time step of the radiation data.

5. RESULTS

Variation of direct luminous efficacy with solar zenith angle

The direct luminous efficacy varies with solar zenith angle. As the solar zenith angle increases, the sun rays have to pass through more air before reaching the ground increasing the attenuation due to Rayleigh scattering, aerosol scattering and water vapor absorption. Rayleigh scattering is caused by the molecules of the air and occurs under all weather conditions. It preferentially removes radiation of wavelengths in the ultraviolet and visible regions. The infrared portion of the solar spectrum is relatively unaffected. Hence, increasing Rayleigh scattering tends to reduce direct luminous efficacy. Aerosol scattering is caused by small particles (e.g., smoke or dust) in the air. It generally scatters short wavelength radiation more effectively, lowering the direct luminous efficacy. Water vapor absorption occurs in certain wavelength bands mainly in the infrared region. The visible direct spectral irradiance is virtually unaffected. Thus water vapor tends to increase the direct luminous efficacy.

The variation of direct luminous efficacy with solar altitude has been noted in previous work (e.g., Navvab *et al.*[4]; Perez *et al.*[5]). However, no model to estimate the direct illuminance from the direct irradiance for all insolations conditions has been derived.

Figure 5 is a plot of clear day (i.e., $\epsilon > 6$) direct luminous efficacy versus solar zenith angle for the Albany experimental data. A non-parametric estimate, known as robust, locally weighted regression or lowess[12] is plotted as a best estimate of the data. A parametric fit is derived from that data as well. This is plotted in Fig. 5. The equation is

$$Kb' = b/B = 105.4 - 0.94 * \exp(0.1087 * Z - 5.130), \quad (6)$$

where Kb' is the luminous efficacy of direct solar radiation, Z is the solar zenith angle, b is the direct illuminance, and B is the direct irradiance. The strong effect of solar zenith angle on the direct luminous efficacy is clearly demonstrated in Fig. 5. For high zenith angles Rayleigh scattering, aerosol scattering, and water vapor absorption become more important. Luminous efficacy drops because the two scattering processes, which preferentially remove radiation in the visible region, dominate. This is illustrated in Fig. 6 where modeled direct beam spectra have been plotted for two different air masses.

Normalization of the direct luminous efficacy with solar zenith angle

To eliminate the first order effect of solar zenith angle, direct luminous efficacy is normalized by

$$Kbn = Kb^* (Ko'/Kb') \quad (7)$$

Where Ko' is the direct luminous efficacy when $Z = 0$, Kb' was obtained from eqn (6), Kb is the measured direct luminous efficacy and Kbn is the normalized direct luminous efficacy. The normalized values of the direct luminous efficacy versus the solar zenith angle are plotted in Fig. 7. There is an increased dispersion of the direct normalized luminous efficacy for large zenith angles because the normalizing process increases errors at low values. For the rest of the study, zenith angles below 70 degrees are eliminated in order to focus on other parametric effects.

Combined effects of insolation conditions and water vapor

Insolation conditions are parameterized by the two quantities ϵ and Δ, clearness and sky brightness. Insolation conditions are described here by ϵ only. Δ is not used because it is redundant information for the domain studied. For values of ϵ greater than 2, that is when direct beam becomes significant and di-

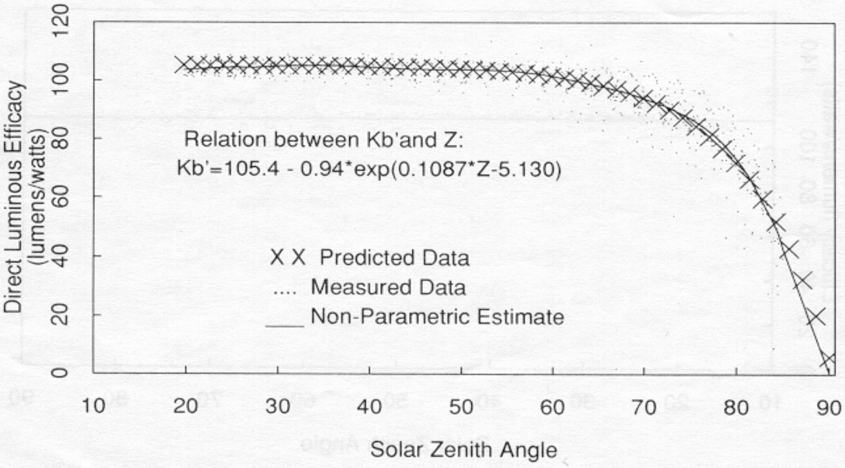

Fig. 5. Measured and estimated luminous efficacy of direct solar radiation as a function of solar zenith angle.

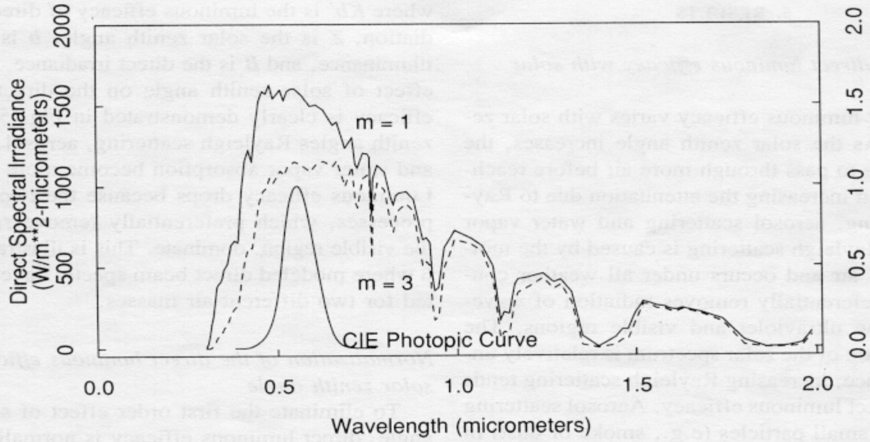

Fig. 6. Direct normal spectral irradiance for different air masses.

rect luminous efficacy is of concern, ϵ is well correlated with Δ. This is shown in Fig. 8 where solar events observed for one year in several locations worldwide have been plotted[13]. Direct radiation is not considered when there is little or no contribution from this component.

With elimination of Z and Δ, the analysis will now focus on the dependence of luminous efficacy on total precipitable water and sky clearness.

For this purpose four domains of insolation conditions are investigated. These are very clear ($\epsilon > 7$), intermediate skies ($1.5 < \epsilon < 2$), as well as two domains between the above extremes ($5 < \epsilon > 6$) and ($4 < \epsilon < 5$). Figure 9 (a,b,c,d) illustrates these conditions, where, in each case, the normalized direct luminous efficacy is plotted against total precipitable water.

The plot of the direct normalized luminous efficacy versus the computed precipitable water (from eqn (5)) for very clear sky conditions in Albany is given in Fig. 9(a). The luminous efficacy of direct solar radiation increases with precipitable water in the atmosphere. This is caused by the increased attenuation of the beam solar radiation in the infrared region of the solar spectrum due to water vapor. The intensity of beam solar radiation in the visible would be affected only slightly (as can be seen in Fig. 3). As a result, there is a decrease of the intensity of the direct irradiance but the direct illuminance remains practically constant with increasing moisture.

The plot of the normalized direct luminous efficacy versus the computed precipitable water for intermediate sky conditions ($1.5 < \epsilon < 2$) is given in Fig. 9(d). The luminous efficacy of the direct solar radiation decreases with water vapor content for these conditions: in this case aerosol scattering effects are greater than water vapor absorption effects. Aerosol concentration and size increase with available water and, as the scattering efficiency is more important at lower wavelengths, luminous efficacy decreases.

Intermediate conditions between the extremes described above are illustrated in Figs. 9(b) and 9(c); they show a smooth transition of the water vapor effect between very clear and intermediate skies.

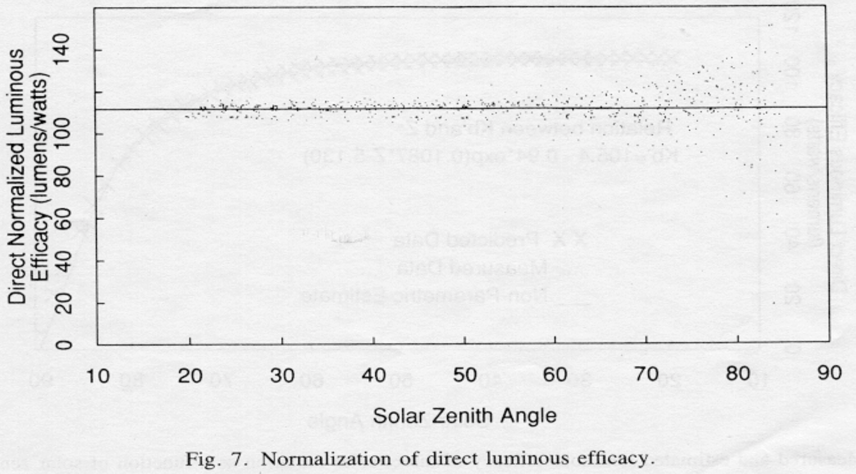

Fig. 7. Normalization of direct luminous efficacy.

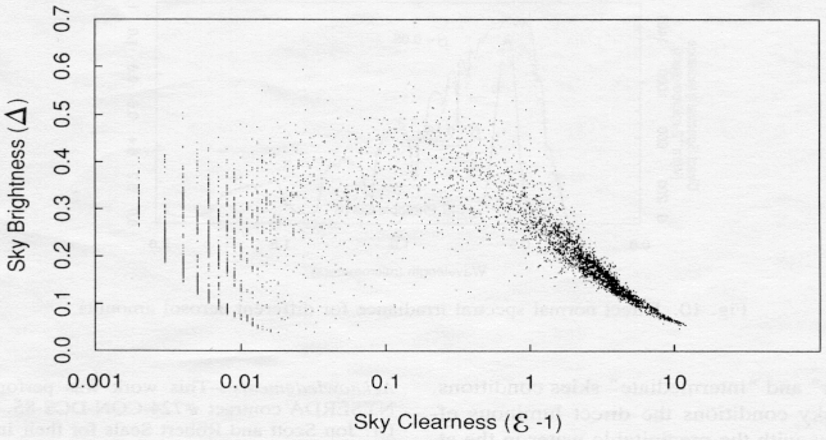

Fig. 8. Distribution of all observed events for 6 locations worldwide as a function of sky clearness and sky brightness.

Discussion of results

When solar radiation enters the atmosphere in a cloudless sky a part of the energy is removed by scattering and a part by absorption. These processes affect the spectral distribution, and hence the luminous efficacy of direct radiation. Figure 9 illustrates the combined effect of these processes on luminous efficacy for different insolation conditions. Aerosol scattering is caused by small particles (e.g., dust, haze, smoke, condensed water vapor) in the air. Like the Rayleigh scattering it preferentially removes shortwave radiation, lowering the direct luminous efficacy. Aerosol produced in high humidity conditions are effective scatterers. Absorption of direct solar radiation is caused mainly by water vapor and occurs mainly in the infrared region.

Based on experimental data and the findings of this study, the variation of the direct luminous efficacy with the precipitable water can be divided into two regimes of insolation conditions. These are de-

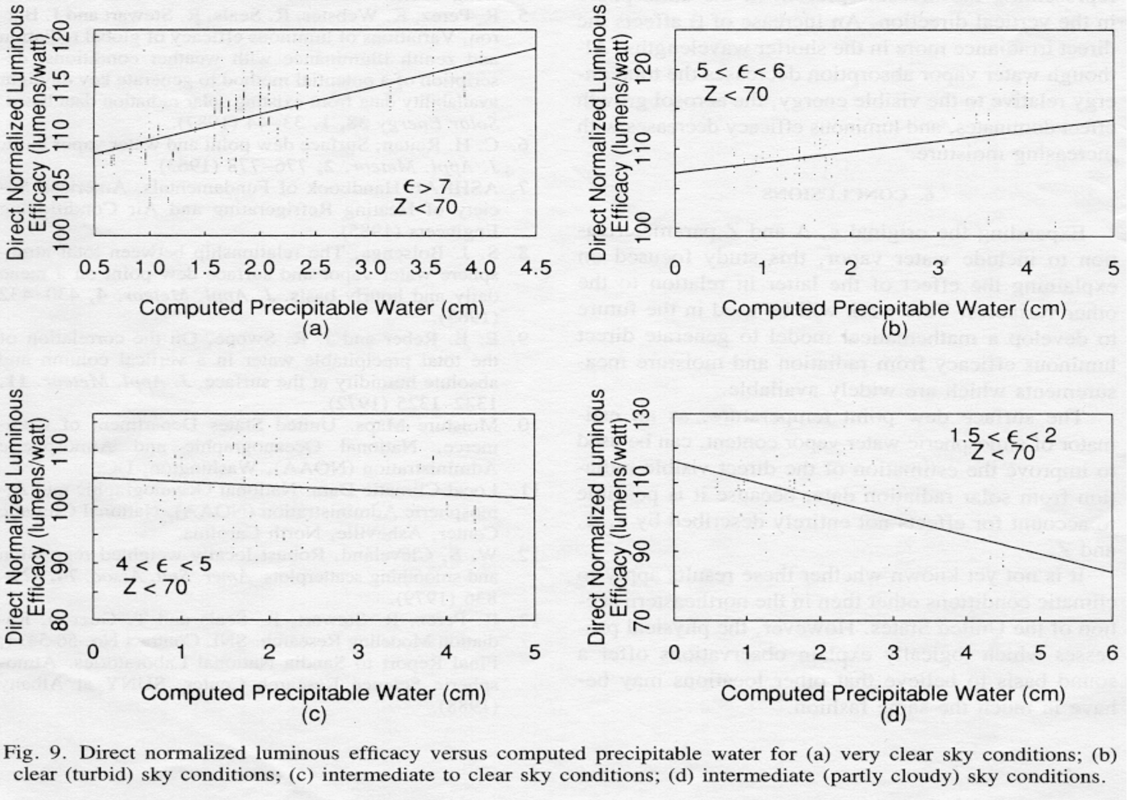

Fig. 9. Direct normalized luminous efficacy versus computed precipitable water for (a) very clear sky conditions; (b) clear (turbid) sky conditions; (c) intermediate to clear sky conditions; (d) intermediate (partly cloudy) sky conditions.

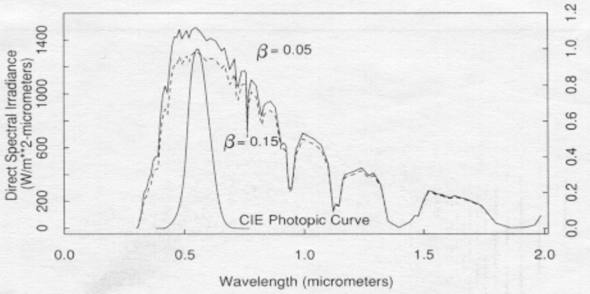

Fig. 10. Direct normal spectral irradiance for different aerosol amounts.

fined as "clear" and "intermediate" skies conditions.

For clear sky conditions the direct luminous efficacy increases with the precipitable water in the atmosphere. The direct solar radiation is attenuated mainly by the absorption of water in the infrared region. The effect due to growing aerosol is not significant under clear to very clear sky conditions.

For intermediate sky conditions the direct luminous efficacy decreases with the precipitable water in the atmosphere. In these conditions, there are more aerosol particles to serve as nuclei upon which water vapor may condense. Hence, as size and number of the aerosol particles increases with increasing water vapor, scattering increases primarily in the visible. The effect of aerosols on the direct spectral irradiance is illustrated in Fig. 10. The parameter β is an index representing the aerosols present in the atmosphere in the vertical direction. An increase of β affects the direct irradiance more in the shorter wavelengths. Although water vapor absorption decreases the total energy relative to the visible energy, the aerosol growth effect dominates, and luminous efficacy decreases with increasing moisture.

6. CONCLUSIONS

Expanding the original ϵ, Δ and Z parameterization to include water vapor, this study focused on explaining the effect of the latter in relation to the other variables. This work will be used in the future to develop a mathematical model to generate direct luminous efficacy from radiation and moisture measurements which are widely available.

The surface dew point temperature, as an estimator of atmospheric water vapor content, can be used to improve the estimation of the direct visible radiation from solar radiation data, because it is possible to account for effects not entirely described by ϵ, Δ, and Z.

It is not yet known whether these results apply to climatic conditions other then in the northeastern section of the United States. However, the physical processes which logically explain observations offer a sound basis to believe that other locations may behave in much the same fashion.

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