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VARIATIONS OF THE LUMINOUS EFFICACY OF GLOBAL AND DIFFUSE RADIATION AND ZENITH LUMINANCE WITH WEATHER CONDITIONS—DESCRIPTION OF A POTENTIAL METHOD TO GENERATE KEY DAYLIGHT AVAILABILITY DATA FROM EXISTING SOLAR RADIATION DATA BASES

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Abstract—The Atmospheric Sciences Research Center and the New York State Energy Research and Development Authority have undertaken a comprehensive daylight resource assessment program which includes the coincident measurement of 25 radiometric and photometric quantities[1]. This paper contains selected results of the analysis performed on collected data. These include the study of the variations of global and diffuse luminous efficacy, and of zenith luminance with insolation conditions. These conditions are described using a parameterization based on two widely available radiative quantities (global and direct irradiance). Based on three 45-day monitoring periods, it appears that many of the observed variations can be accounted for from the knowledge of these two quantities.

1. INTRODUCTION

The need for specific and accurate input data for building energy simulation models has become crucial as the users' needs have become more demanding and the modeling techniques more sophisticated. This is particularly true for the simulation of solar heat gain and daylight availability.

There exists a limited amount of accurate irradiance data bases in the USA (e.g. [2]). However, with few exceptions (e.g. [3, 4]), no daylight data bases exist. The relationship between the two classes of parameters still leaves many questions unanswered, causing potentially large errors when converting one type of quantity into the other for modeling purposes.

The U.S. Working Group on Daylight Availability[5] acknowledged this lack of information and encouraged the implementation of a comprehensive measurement program throughout the contry and abroad. One of the primary aspects of this program would be to gather parallel sets of solar unfiltered and visible quantities in order to study their interrelationship as a function of weather conditions and climatic/geographic environments.

This objective prompted the New York State Energy Research and Development Authority and the ASRC at Albany to begin an extensive data acquisition/analysis program. The major focus of this research effort is to evaluate the possibility of using more widely available hourly solar data (notably global and diffuse irradiance) to extrapolate the needed daylighting parameters and to identify the key measurements to be performed in future high density low-cost resource assessment networks.

The first phase of this program consisted of measuring, on a 3-minute basis, 25 irradiance, illuminance and luminance quantities, for three seasonally distinct periods of 45 days. Measurements were performed in Albany, New York. The interrelationships among these quantities was then studied on the basis of a sky condition parameterization method which has proven successful in delineating the anisotropy of diffuse irradiance and its effects on the energy collected by sloping suraces[6]. Subsequent phases of the program will evaluate the site-dependency of relationships established in Albany by measuring a limited set of key parameters in several other locations in New York State.

2. METHODS

2.1 *Experimental data*

Table 1 described the measurements performed in Albany, NY, along with the type of instrumentation used. The choice of measured parameters was based on (1) recommendations of the U.S. daylighting community[5] concerning projected future demands from engineers, notably concerning skylight spatial distribution; (2) the existence of over 40 sites in the USA where direct and global irradiance have been measured for several years on an hourly basis[2] and (3) the existence, in Albany, NY, of a high quality four-year-one-minute data base, [7], containing notably broad band spectral irradiance records, and the possibility to extrapolate accurate and specific daylighting information as pointed out by Ref. 8. Results presented in this

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Table 1. Measurements and sensors used in Albany.

Measurement	Sensor
Global Irradiance	Eppley PSP
Filtered Global Irradiance 1	Same + RG520 filter (opaque below 530 nm)
Filtered Global Irradiance 2	Same + RG620 filter (opaque below 630 nm)
Filtered Global Irradiance 3	Same + RG695 filter (opaque below 695 nm)
Direct Irradiance	Eppley NIP
Filtered Direct Irradiance 1	Eppley NIP + RG530 filter
Filtered Direct Irradiance 2	Eppley NIP + RG630 filter
Filtered Direct Irradiance 3	Eppley NIP + RG695 filter
Vertical Irradiance S	Silicon based radiometer (Li Cor) *
Vertical Irradiance E	Silicon based radiometer (Li Cor) *
Vertical Irradiance W	Silicon based radiometer (Li Cor) *
Vertical Irradiance N	Silicon based radiometer (Li Cor) *
Diffuse Irradiance	Eppley PSP + Shadow band
Global Illuminance	Silicon-based photometer (UDT)
Diffuse Illuminance	Same + shading disk
Direct Illuminance	Same + 5° FOV Ges. tube
Vertical Illuminance S	Silicon based photometer (UDT) *
Vertical Illuminance E	Silicon based photometer (UDT) *
Vertical Illuminance W	Silicon based photometer (UDT) *
Vertical Illuminance N	Silicon based photometer (UDT) *
Zenith Luminance	Same + 15° FOV lens + 15° FOV Ges. Tube
45° South Luminance	Same + 15° FOV lens + 15° FOV Ges. Tube
45° East Luminance	Same + 15° FOV lens + 15° FOV Ges. Tube
45° West Luminance	Same + 15° FOV lens + 15° FOV Ges. Tube
45° North Luminance	Same + 15° FOV lens + 15° FOV Ges. Tube

*Sensors equipped w/artificial horizons

paper are based on three measurement periods: from March 15, 1985 to April 30, 1985, from May 15, 1985 to June 30, 1985 and from July 24, 1985 to August 31, 1985.

Data was recorded with a 3-minute time step. Besides daily instrument cleaning and 3-hour tracking checks, data was subjected to a rigorous automatic quality control developed for the U.S. working group on daylight availability[5], and extrapolated from Solar Energy Research Institute original guidelines[9].

Most of the data rejected by quality control were found among daylight parameters and could be traced to minor instrument problems. Unlike irradiance instrumentation, the daylight measuring instruments selected for this program have had a shorter history of outdoor operation measurements and are still prone to minor developmental problems. Among the problems encountered with this otherwise very accurate instrumentation ($\pm 2\%$) are moisture and rain water tightness of the sensors as well as questionable cosine response of diffusers at high incidence angles. This second point prompted the building of an additional instrument to measure beam illuminance directly, as it was impossible to retrieve this component accurately from global and diffuse at low solar altitudes. This new instrument became operational for the second monitoring period.

2.2 *Parameterization of the sky condition*

A vital key consideration when observing the relationship between two quantities, such as zenith luminance and diffuse irradiance for a wide range of possible weather conditions, is to parameterize these conditions so as to describe adequately the majority of events. It is also important that the key inputs selected for this purpose be easily available so as to facilitate applications.

The approach used here is to postulate that the insolation conditions at a given time, and hence, the value of any radiative quantity of interest to the user, may be described by three basic inputs: global irradiance, diffuse (or direct) irradiance and solar zenith angle. This approach was used successfully to explain the effects of diffuse irradiance anisotropy on nonhorizontal surfaces. The resulting irradiance conversion model[10] is now increasingly used, notably in the recent photovoltaic simulation program, PVFORM, developed at Sandia National Laboratories[11]. Combinations of the three input parameters are used to build a three-dimensional space representing all possible sky conditions from very clear to overcast, including all intermediate events.

The three coordinates of this space were originally selected to be (1) the solar zenith angle, Z, (2) the horizontal diffuse irradiance, Dh, (3), and ϵ, defined as the sum of the latter and normal incidence

Table 2. Sky condition parameterization intervals.

	Δ (W/m²)					
Int. #	A	B	C	D	E	F
Lo-bound	0	150	250	350	450	550
Up-bound	150	250	350	450	550	---

	ε (dimensionless)							
Int. #	1	2	3	4	5	6	7	8
Lo-bound	1	1.003	1.03	1.1	1.5	2.5	5	9
Up-bound	1.003	1.03	1.1	1.5	2.5	5	9	-

	Z (degrees)				
Int. #	I	II	III	IV	V
Lo-bound	0	35	50	65	75
Up-bound	35	50	65	75	90

direct irradiance divided by Dh. These three quantities describe, respectively, the position of the sun, the brightness of the sky and the relative contribution of direct irradiance at the earth's surface. The second and third quantities are indeed not totally independent from each other, or from the solar zenith angle; however, they do vary quasi-independently from one another due to other factors affecting the sky condition such as cloud cover, cloud type altitude and thickness. Hence, in order to account at least partially for these factors it is assumed that Z, Dh and ϵ are three linearly independent quantities. It will be noted that other more widely used combinations of the same inputs could have been selected to describe the sky condition space, such as for example the clearness index and the ratio of diffuse to global irradiance. The choice was based on the more visual description of the sky conditions offered by the proposed method.

At this stage of analysis the space has been divided into 240 discrete categories based on 5, 6 and 8 intervals on the Z, Dh and ϵ axes. This partition greatly facilitates observational analysis.

For the present study, an attempt was made to modify these dimensions in order to make the second and third components less dependent on Z and to obtain a better distribution of observed events in the discrete categories. To that effect, Dh was weighed by the air mass and the direct normal irradiance in ϵ was weighed using a standard transmission function[12] for a moderately turbid atmosphere. The second and third dimensions, Δ and ϵ, are now given by

$$\Delta = Dh * m,$$

where m is the air mass and

$$\epsilon = \{I \exp(+ 3m/(9.4 + 0.9m)) + \Delta\}/\Delta,$$

where I is the normal direct irradiance.

Table 2 describes the boundaries of each (Z, Δ, ϵ) categories. An example of this parameterization is shown in Fig. 1. The distribution of hourly events observed in Trappes, France during a 3-year period [13] has been plotted against Δ and ϵ. A similar type

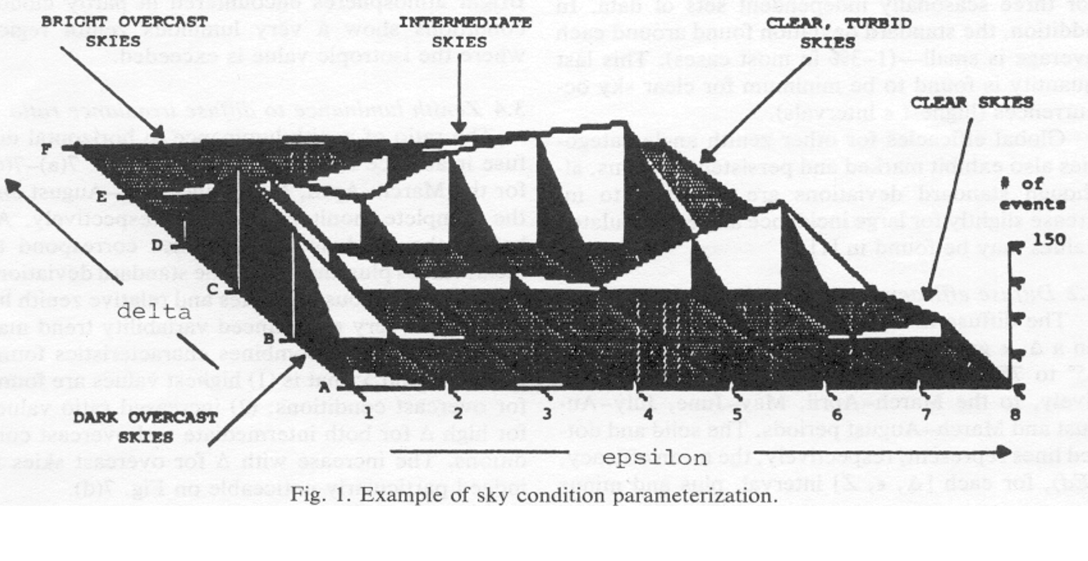

Fig. 1. Example of sky condition parameterization.

of presentation will be used to display this study's findings.

3. RESULTS

The 3-minute data sets from each of the three periods have been analyzed independently. Their results are compared and discussed below. The four relationships analyzed include (1) the global luminous efficacy, defined as the ratio of global illuminance and global irradiance, (2) the diffuse luminous efficacy, ratio of diffuse illuminance and diffuse irradiance, (3) the relative zenith luminance defined here as the ratio of zenith luminance and diffuse illuminance and (4) the zenith luminance-diffuse irradiance ratio.

3.1 *Global efficacy*

The global luminous efficacy has been plotted against the parameters Δ and ϵ for solar zenith angles ranging from 35° to 50°. This appears in Fig. 2(a) for the March–April period, in Fig. 2(b) for the May–June period, in Fig. 2(c) for the July–August period and in Fig. 2(d) for the complete monitoring period. The solid line represents the mean efficacy, $\langle Eg \rangle$, obtained for each (Δ, ϵ, Z) category, plus one standard deviation, while the dotted line represents $\langle Eg \rangle$ minus one standard deviation.

The statistical distribution of events encountered during the monitoring periods has been plotted on Figs. 3(a)–3(d) for March–April, May–June, July–August and March–August, respectively. Two very important points can be made. These are the following: (1) global efficacy exhibits a predictable variability when expressed according to the proposed parameterization: Eg is found to decrease with Δ when ϵ equals a constant. This is very noticeable for the first ϵ interval (no direct beam), showing dark overcast events having a higher luminous efficacy than bright overcast events. Eg is also found to decrease while the relative contribution of direct radiation increases. (2) The variation pattern persists qualitatively and quantitatively for three seasonally independent sets of data. In addition, the standard deviation found around each average is small—(1–3% in most cases). This last quantity is found to be minimum for clear sky occurrences (highest ϵ intervals).

Global efficacies for other zenith angle categories also exhibit marked and persistent patterns, although standard deviations are observed to increase slightly for large incidence angles. Tabulated values may be found in [1].

3.2 *Diffuse efficacy*

The diffuse luminous efficacy has been plotted on a Δ, ϵ grid for solar zenith angles ranging from 65° to 75°. Figures 4(a)–4(d) correspond, respectively, to the March–April, May–June, July–August and March–August periods. The solid and dotted lines represent, respectively, the mean efficacy, $\langle Ed \rangle$, for each $[\Delta, \epsilon, Z]$ interval, plus and minus one standard deviation. As previously, two obvious observations can be made: (1) existence of a marked variation pattern, (2) persistence of this trend for three independent sets of events.

The efficacy is found to be maximum for clear sky conditions (blue sky) which is consistent with numerous past observations (e.g. [14]). However, the most interesting point is the persistence of a seemingly predictable variability with Δ and ϵ in the center portion of the graphs (intermediate ϵ categories). These categories, which include a wide range of possible partly cloudy conditions, appear to exhibit a consistent pattern of a long term spectral split between visible and total energy. A similar observation has been reported by Perez[6] concerning the long term distribution of radiance through the sky dome for these intermediate conditions.

3.3 *Relative zenith luminance*

The ratio of zenith luminance to diffuse illuminance has been plotted against Δ and ϵ on Figs. 5(a)–5(d) for the same four time periods, for solar zenith angles ranging from 35° to 50°. The variations of the same quantity with the solar altitude, Z and Δ have been plotted on Figs. 6(a)–6(d) for the same periods for $\epsilon > 5$ (clear skies). It will be noted that the Δ axis has been reversed on Fig. 5 and that Fig. 6 does not include standard deviations around mean values.

Once again the same observation can be made. Existence and persistence of a strongly marked variation pattern when the quantity is expressed according to the proposed insolation parameterization.

Points of interest include the following: (1) Higher ratios for overcast conditions, where the isotropic value ($1/\pi$) is exceeded. (2) Lower ratios for clear skies and low solar altitude and noticeable increase with solar altitude. This is consistent with numerous past observations (e.g. [14, 15]). (3) Increasing ratio with Δ for intermediate conditions. Bright atmospheres encountered in partly cloudy conditions show a very luminous zenith region where the isotropic value is exceeded.

3.4 *Zenith luminance to diffuse irradiance ratio*

The ratio of zenith luminance to horizontal diffuse irradiance has been plotted in Figs. 7(a)–7(d) for the March–April, May–June, July–August and the complete monitoring period, respectively. As before the solid and dotted lines correspond to mean values plus and minus one standard deviation.

As for luminous efficacies and relative zenith luminance, a very pronounced variability trend may be observed. This combines characteristics found in Figs. 4 and 5; that is (1) highest values are found for overcast conditions; (2) increased ratio values for high Δ for both intermediate and overcast conditions. The increase with Δ for overcast skies is indeed particularly noticeable on Fig. 7(d).

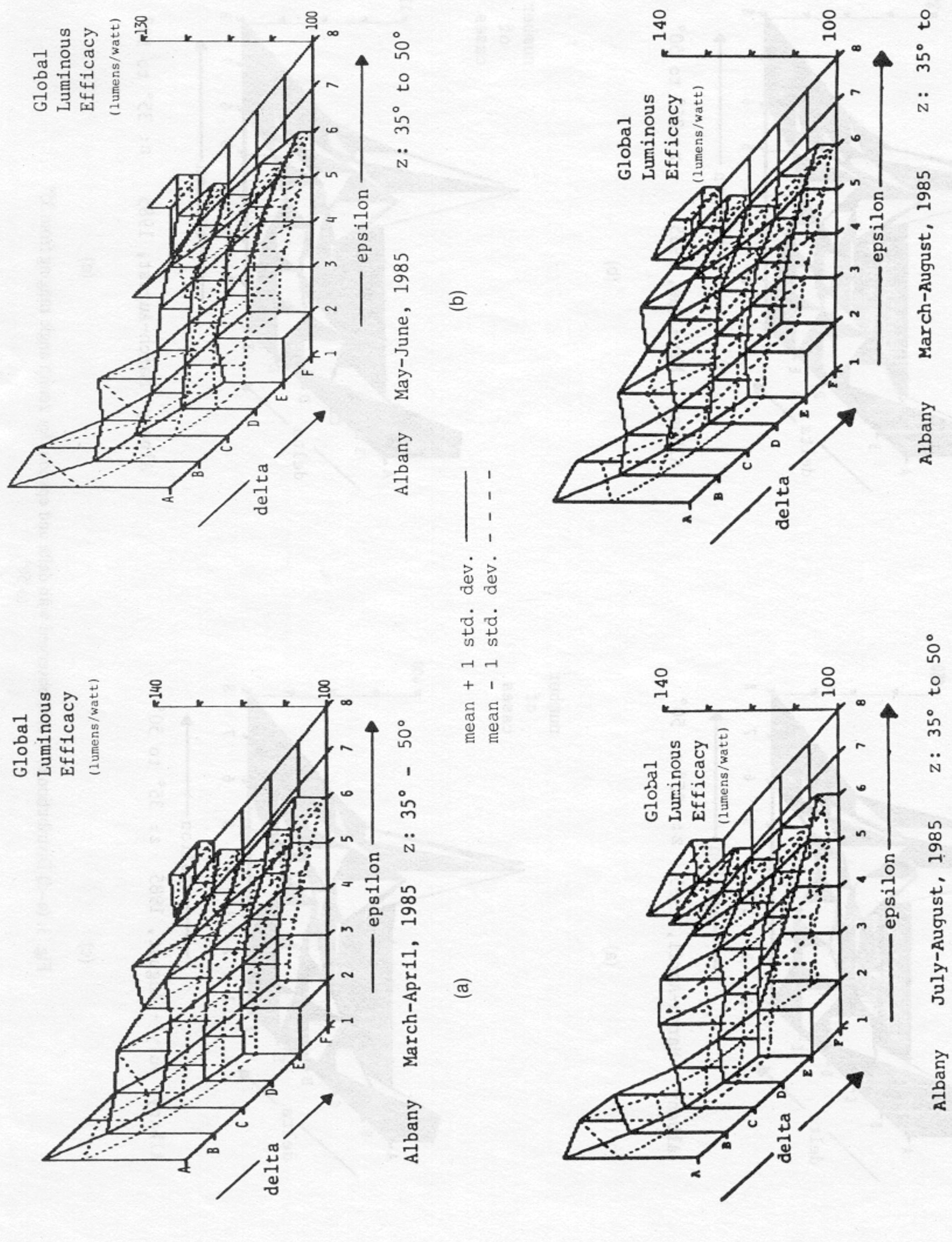

Fig. 2. (a–d) Variation of global luminous efficacy with delta and epsilon, for zenith angle ranging from 35° to 50°.

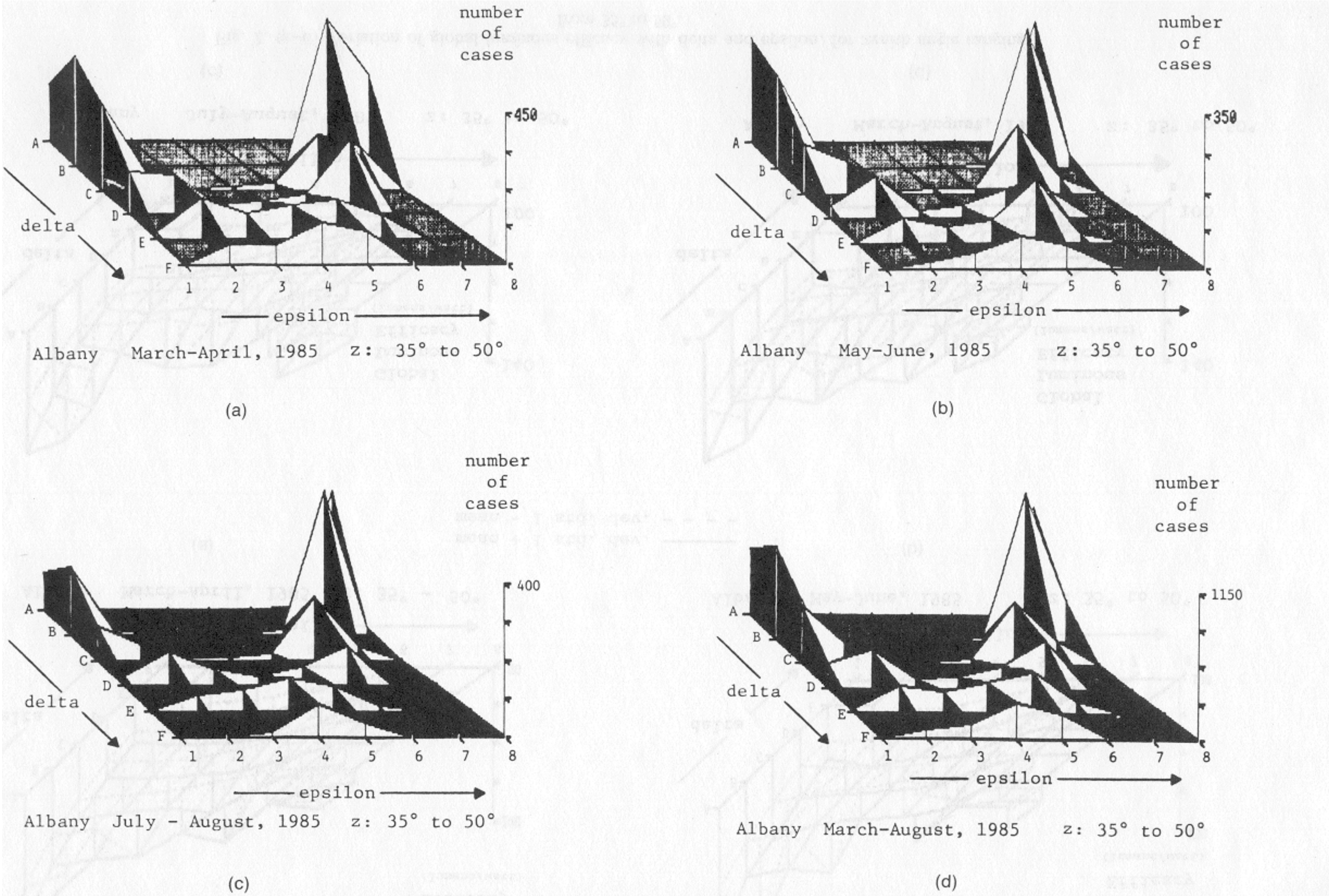

Fig. 3. (a–d) Distribution of events observed with delta and epsilon, for zenith angle ranging from 35° to 50°.

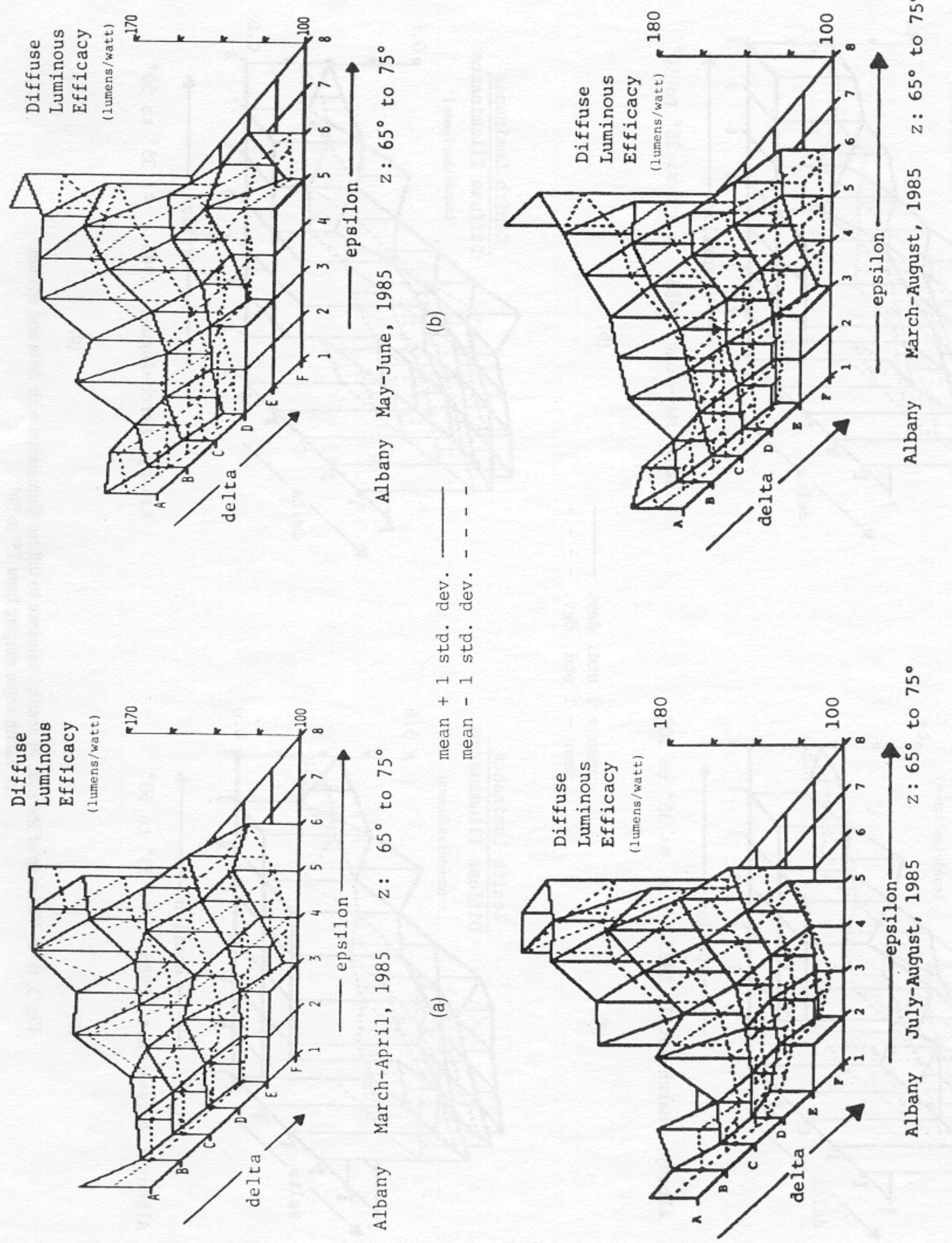

Fig. 4. (a–d) Variation of diffuse luminous efficacy with delta and epsilon, for zenith angle ranging from 65° to 75°.

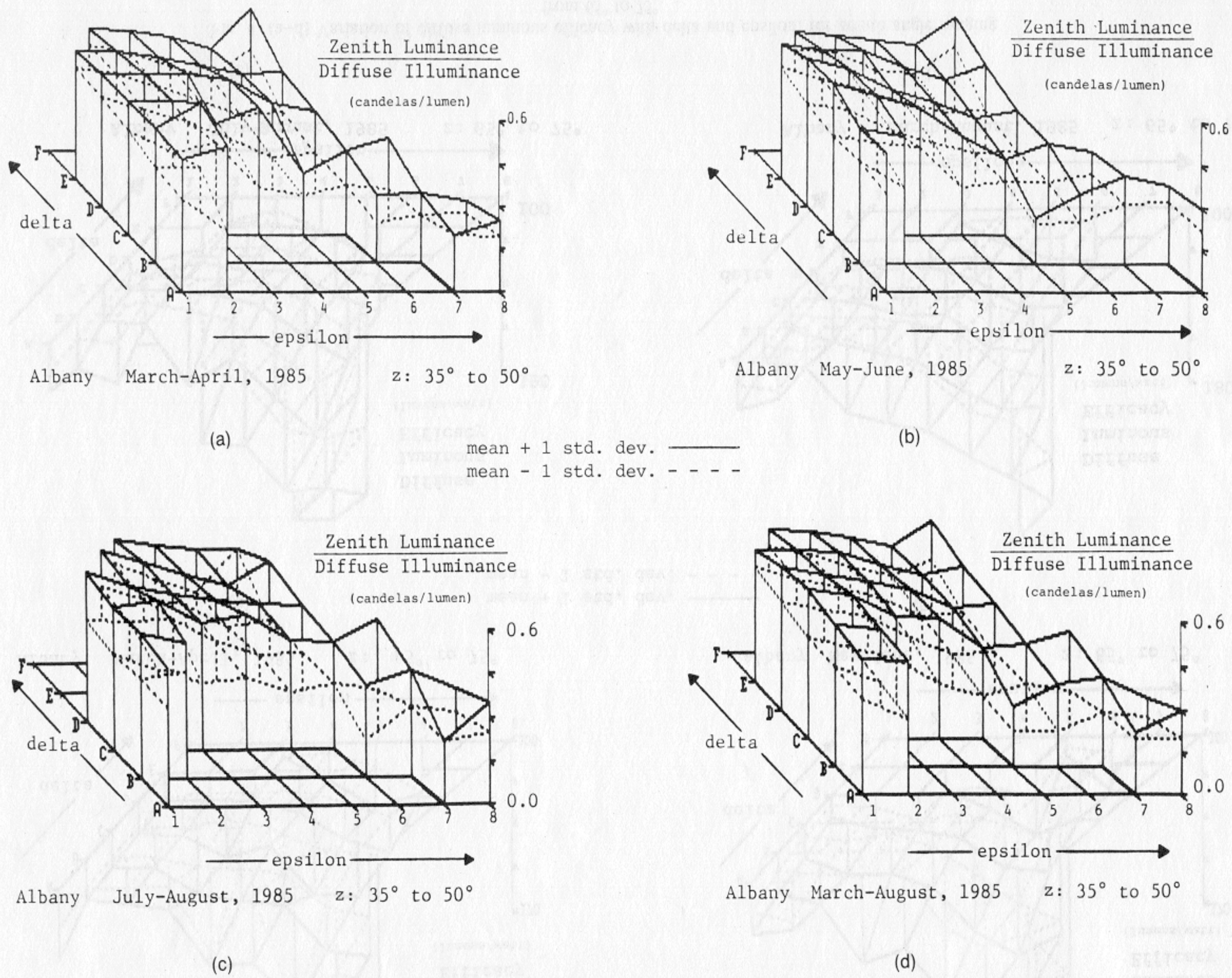

Fig. 5. (a–d) Variation of the ratio of zenith luminance to diffuse illuminance with delta and epsilon, for zenith angle ranging from 35° to 50°.

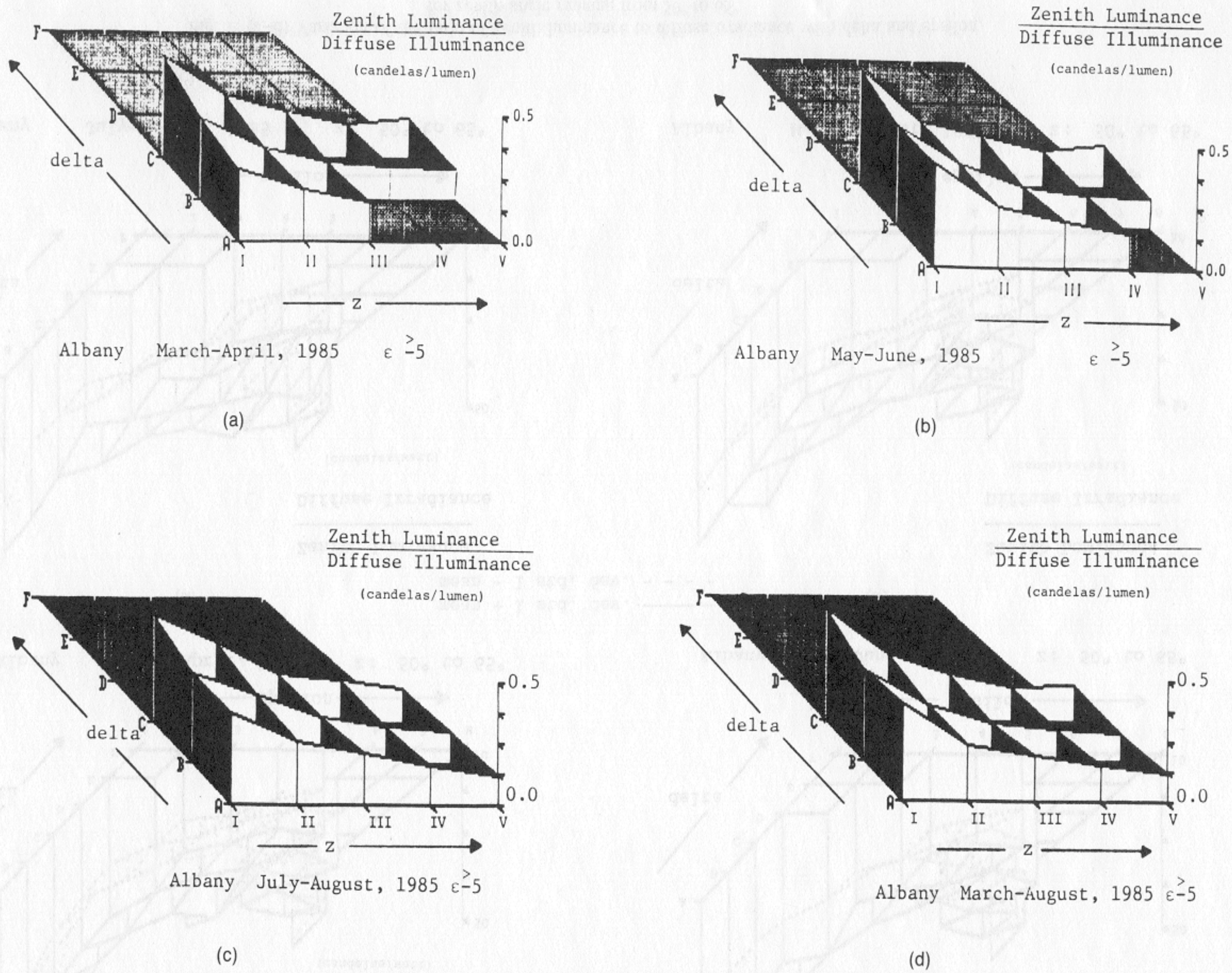

Fig. 6 (a–d) Variation of the ratio of zenith luminance to diffuse illuminance with delta and zenith angle, for epsilon ≥ 5.

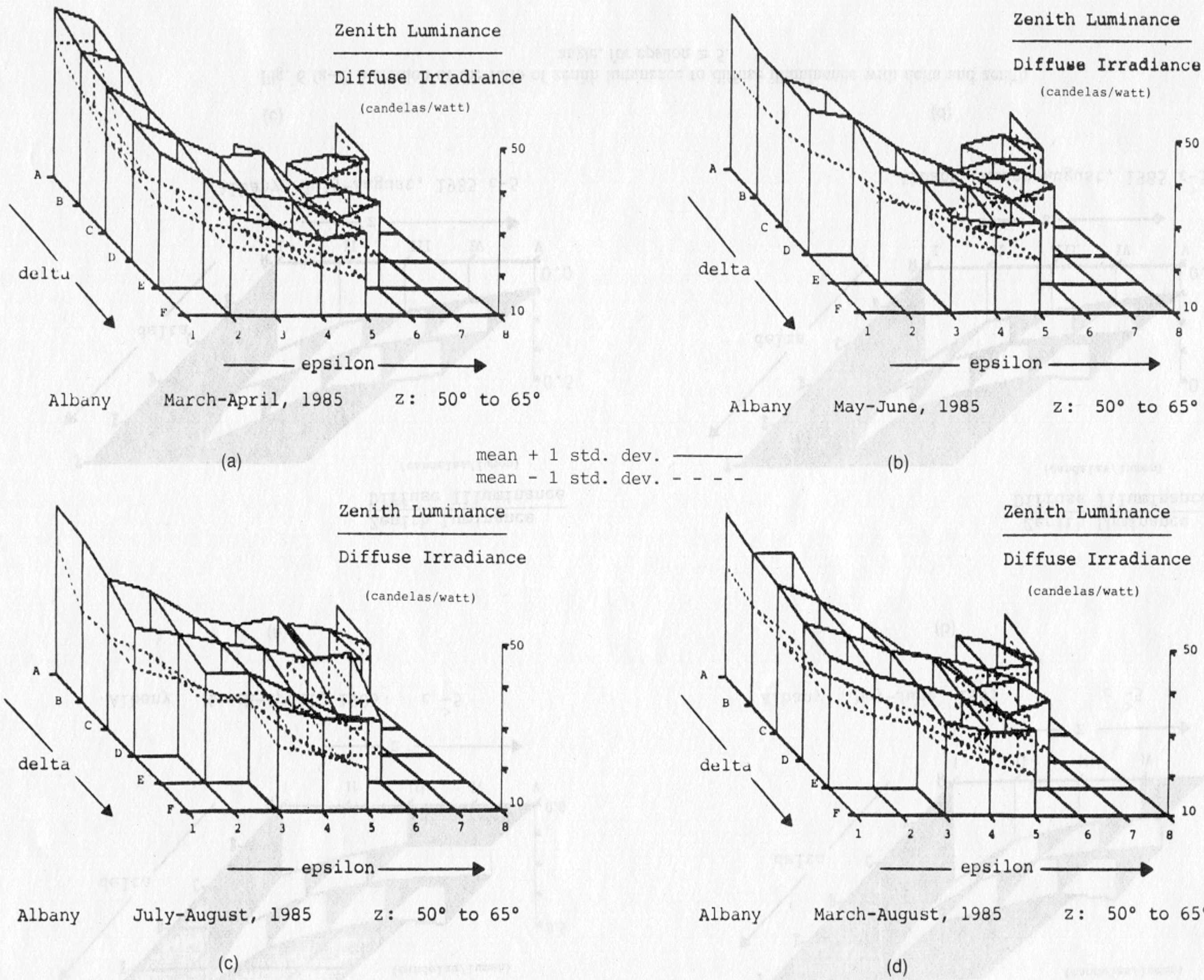

Fig. 7. (a–d) Variation of the ratio of zenith luminance to diffuse irradiance with delta and epsilon, for zenith angle ranging from 50° to 65°.

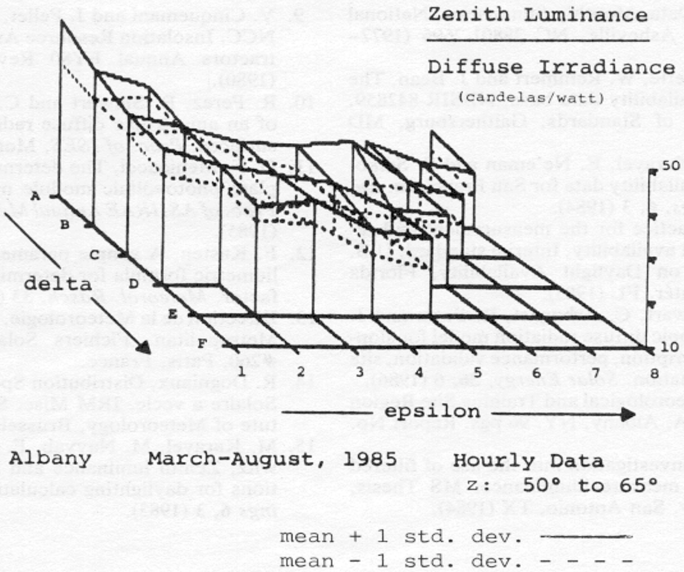

Fig. 8. Variation of the ratio of zenith luminance to diffuse irradiance with delta and epsilon, for zenith angle ranging from 50° to 65°, based on hourly average data.

Standard deviations around mean values are small in most instances, which indicates that zenith luminance may be retrieved with a good degree of precision from diffuse irradiance when using the present weather parameterization method. It will be noted that standard deviations are further reduced for all relationships when hourly instead of 3-minute data are analyzed. This can be assessed by comparing Figs. 8 and 7(d).

4. CONCLUSIONS

The main fact presented in this paper is that, based on three seasonally independent monitoring periods in a given location, the variations of three key daylighting quantities may be inferred with reasonable precision for all weather conditions from the knowledge of two radiative quantities and the position of the sun. The three key daylighting quantities are the global and diffuse illuminance and the zenith luminance, while the two radiative quantities are the global and diffuse irradiance. This point is made because the variability of these quantities appear to be predictable and that reasonably low dispersion has been observed after the analysis of about 15,000 3-minute events, and because the observed variation patterns persist when independent data sets are compared. This is most interesting for partly cloudy cases, considering the wide range of possible cloud types, height and distribution throughout the sky dome. It will, of course, be necessary to repeat this study over longer time periods and to investigate site dependency before any final conclusions regarding the applicability of this work can be drawn.

Finally, an interesting aspect of this approach is its possible extension to the retrieval of spectral quantities useful for other users, notably the photovoltaic community, which is now interested in the modeling of various spectral response cells such as thin film A-Si. For the reader's information the spectral response of such a cell has been plotted along with the CIE (eye response) curve on Fig. 9.

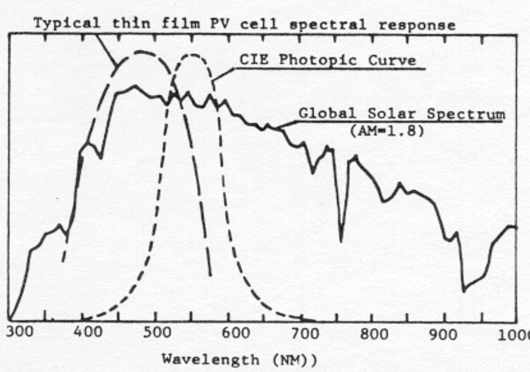

Fig. 9. Typical thin film PV cell spectral response and CIE eye response curve.

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REFERENCES

1. R. Perez, K. Webster, R. Stewart and J. Barron, Daylight resource availability, Final Report 724-CON-BCS-85, NYSERDA, Albany, NY (1986).

2. Solar Radiation Data, Monthly Summaries. National Climatic Center, Asheville, NC 28801-2696 (1977–1980).
3. S. Treado, G. Gilette, W. Remmert and J. Bean, The NBS daylight availability data base, NBSIR-842859, National Bureau of Standards, Gaithersburg, MD (1984).
4. M. Navvab, M. Karayel, E. Ne'eman and S. Selkowitz, Daylight availability data for San Francisco. *Energy and Buildings,* **6,** 3 (1984).
5. U.S. standard practice for the measurement and reporting of daylight availability, Interim standard. U.S. Working Group on Daylight Availability, Florida Solar Energy Center, FL (1985).
6. R. Perez, R. Stewart, C. Arbogast, R. Seals and J. Scott, An anisotropic diffuse radiation model for sloping surfaces: Description, performance validation, site dependency evaluation. *Solar Energy,* **36,** 6 (1986).
7. Solar Energy Meteorological and Training Site Region II. ASRC-SUNYA, Albany, NY. 96 pgs. Report No. 840 (1979–1982).
8. B. Yozwiak, An investigation into the use of filtered pyranometers to measure illuminance. MS Thesis, Trinity University, San Antonio, TX (1984).
9. V. Cinquemani and J. Pellet, Solar data processing at NCC. Insolation Resource Assessment Program Contractors Annual FY80 Review. SERI/CP-G42-977 (1980).
10. R. Perez, R. Stewart and C. Arbogast, Climatology of an anisotropic diffuse radiation model for sloping surfaces. *Proc. of ISES,* Montreal, Canada (1985).
11. D. F. Menicucci, The determination of optimum flat-plate photovoltaic module mounting configurations. *Proc. of ASHRAE Annual Meeting,* Honolulu, Hawaii (1985).
12. F. Kasten, A simple parameterization of the pyeheliometric formula for determining the Linke turbidity factor. *Meteorol. Rdsch.* **33** (1980).
13. Direction de la Meteorologie, Service Meteorologique Metropolitan. Fichiers Solaires Horaires, Station #260, Paris, France.
14. R. Dogniaux, Distribution Spectrale du Rayannement Solaire a vccle. IRM Misc. Serie B#52, Royal Institute of Meteorology, Brussels, Belgium (1981).
15. M. Karayel, M. Navvab, E. Ne'eman and S. Selkowitz, Zenith luminance and sky luminance distributions for daylighting calculations. *Energy and Buildings* **6,** 3 (1983).