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DETERMINATION OF AVAILABLE SUBSURFACE LIGHT FOR PHOTOCHEMICAL AND PHOTOBIOLOGICAL ACTIVITY

by

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ABSTRACT

Appropriate determinations of available subsurface light for photochemical and photobiological processes requires accurate estimates of the subsurface scalar irradiation. Quite often only values of downwelling irradiation are available. Therefore, two sets of multiplicative factors are derived. The first set (F_θ) converts a daily irradiation just above the surface into a daily scalar irradiation just below the surface. The second set ($F_{Z\theta}$) converts an "effective" (i.e. depth-averaged) daily irradiation for a specific photic zone into an "effective" daily scalar irradiation for that photic zone. These multiplicative factors are presented as functions of the subsurface volume reflectance of the water for the volume reflectance range 0.0 to 0.14. For a latitude range appropriate to the Great Lakes, these multiplicative factors vary between 1.1 and 2.1.

RÉSUMÉ

Pour déterminer de façon appropriée la quantité de lumière au-dessous de la surface qui peut être utilisée pour les processus photochimiques et photobiologiques, il faut évaluer avec précision l'irradiation scalaire sous la surface. Bien souvent, seules les valeurs de l'irradiation vers le bas sont disponibles. On établit donc deux ensembles de facteurs de multiplication. Le premier ensemble (F_θ) permet de convertir l'irradiation quotidienne juste au-dessus de la surface en irradiation scalaire quotidienne juste au-dessous de la surface. Le deuxième ensemble ($F_{Z\theta}$) permet de convertir l'irradiation quotidienne "efficace" (c.-à-d. la valeur moyenne sur la profondeur) pour une zone euphotique spécifique en irradiation scalaire quotidienne "efficace" pour cette même zone. Ces facteurs de multiplication sont présentés comme des fonctions du facteur de réflexion volumique au-dessous de la surface de l'eau pour la plage de facteurs de réflexion volumiques de 0,0 - 0,14. Pour la plage de latitudes correspondant au Grands Lacs, ces facteurs de multiplication varient de 1,1 à 2,1.

MANAGEMENT PERSPECTIVE

In order to realistically evaluate the photochemical and/or photobiological reactions occurring in natural waters, a precise knowledge is required of the actual energy density to which the chemical or biological component is exposed. This work utilizes optical models, which we have previously devised, to convert readily measurable daily irradiation above the water surface into the appropriate available daily irradiation just below the surface.

PERSPECTIVE-GESTION

Il faut, pour évaluer de façon réaliste les réactions photochimiques et/ou photobiologiques se produisant dans les eaux naturelles, connaître avec précision la densité énergétique réelle à laquelle le constituant chimique ou biologique est exposé. Dans cette étude, nous avons utilisé des modèles optiques, élaborés précédemment, pour obtenir à partir de l'irradiation quotidienne au-dessus de la surface de l'eau, qui est un paramètre facilement mesurable, la valeur appropriée de l'irradiation quotidienne disponible juste au-dessous de la surface.

INTRODUCTION

A realistic evaluation and understanding of the photolysis (photochemical and photobiological reactions) occurring in natural waters requires precise knowledge of the actual energy density to which the chemical or biological aquatic component is exposed. Such energy density information is crucial to any estimation of the rates at which these reactions occur. The standard meteorological measurement (or meteorological model prediction) is the incident global radiation either with or without the differentiation between its direct and diffuse components. Global radiation, however, is a measure of the downwelling irradiance, and therefore, possesses inherent geometric properties. These geometric features, related to the arrival directions of the impinging radiation, are incorporated into the directly measured or inferred values of the global radiation. Consequently, subsurface downwelling irradiances determined from such global radiation values contain corresponding directional biases. As such, subsurface downwelling irradiance is not the appropriate parameter to consider in the study of photochemical or photobiological processes. Rather, the appropriate parameter for photolysis is the scalar irradiance which does not incorporate directional biases into its definition. The scalar irradiance is the total energy per unit area arriving at a point from all directions when all directions are equally weighted, and, when divided by the speed of light in water, readily yields the actual energy density at that point.

Jerome et al. (1988) provides relationships between the scalar irradiance E_0 and the downwelling irradiance E_d in natural waters as a function of subsurface volume reflectance R, solar zenith angle θ, and depth Z [i.e. relationships between $E_0(Z,\theta,R)$ and E_d (Z,θ,R). Despite the awareness that the scalar and downwelling irradiances are also functions of wavelength λ, this wavelength dependency will not be specifically designated beyond this point in the text]. It was found that the scalar irradiance at a given depth, under certain conditions, could be greater than double the downwelling irradiance at that depth. Similar analyses by Madronich (1987) indicated that scalar irradiance (actinic flux) in the atmosphere can also be much greater than the downwelling irradiance for cloudy conditions and/or high ground albedos. Clearly, therefore, the use of downwelling irradiances can result in significant underestimations of the rates of photochemical and photobiological processes occurring in both the atmosphere and natural waters.

This manuscript presents a means of obtaining values of subsurface scalar irradiation (i.e. time integrated irradiance) appropriate for photochemical and photobiological reactions. In order to obtain such irradiation values two sets of multiplicative factors will be derived. The first factor F_θ $(0^-,R)$ may be directly used to convert values of above-surface daily irradiation into values of daily scalar irradiation just below the surface. Values of above-surface daily irradiation may be obtained from either direct measurements or solar irradiance models such as described in Zepp and Cline (1977).

The second factor $F_{Z\theta}(R)$ may be directly used to convert values of depth-averaged daily irradiation for a specified photic zone into the corresponding values of depth-averaged daily scalar irradiation for that photic zone.

For the analyses described herein, the only hydro-optical parameter required is the water's subsurface volume reflectance R(0°) (ratio of upwelling to downwelling irradiance just below the surface for a solar zenith angle of zero degrees). Both photobiological and photochemical activity are strongly wavelength dependent. Since subsurface volume reflectance and incident radiation are also wavelength dependent, it is tacitly assumed that the R(0°) and radiation values utilized in the ensuing methodology possess a spectral consistency and adhere to the spectral requirements of the biological and/or chemical processes under consideration.

The methodology by which the multiplicative factors are determined is outlined in Figure 1. The inter-related activities depicted therein may be described as follows:

a) For a chosen water type [defined by its subsurface volume reflectance R(0°)] and an incident above-surface radiation (defined by the solar zenith angle θ), a Monte Carlo photon propagation simulation was utilized to determine as a function of Z, θ, and R, the ratio $E_o(Z,\theta,R)/E_d(Z,\theta,R)$ [designated as $D(Z,\theta,R)$].

b) An air/water interface transmission analysis was used to obtain the ratio of the downwelling irradiance just below the surface $E_d(0^-,\theta,R)$ to the downwelling irradiance just above the surface $E_d(0^+,\theta,R)$. (0^- and 0^+ symbolize the Z values infinitesimally below and above the air/water interface).

c) A global radiation model was used to provide an appropriate expression for $E_d(0^+,\theta,R)$. This value was used in conjunction with the ratio from step b) to yield $E_d(0^-,\theta,R)$.

d) The expressions obtained from steps a), b), and c), were then mathematically synthesized and integrated either over time (expressed as θ) or over both depth Z and time θ, to obtain the multiplicative factors $F_\theta(0^-,R)$ and $F_{Z\theta}(R)$

Expressed mathematically, these multiplicative factors may be written

$$F_\theta(0^-,R) = \frac{\int E_0(0^-,\theta,R)d\theta}{\int E_d(0^+,\theta,R)d\theta} \tag{1}$$

and

$$F_{Z\theta}(R) = \frac{\iint E_0\,(Z,\theta,R)dZd\theta}{\iint E_d(Z,\theta,R)dZd\theta} \tag{2}$$

where equation (1) indicates an integration over time (i.e. θ) and equation (2) indicates an integration over both time and depth.

These multiplicative factors will be displayed as a function of the volume reflectance of the natural water mass for both direct and diffuse incident radiation distributions for specific seasons and latitudes.

DEPTH INTEGRATION OF THE RATIO OF SCALAR IRRADIANCE TO DOWNWELLING IRRADIANCE

From the Monte Carlo simulation of photon propagation in natural waters as described in Jerome et al. (1988), the ratio of the subsurface scalar irradiance to the subsurface downwelling irradiance was determined at depths Z where the downwelling irradiance was equal to 1.0, 0.8, 0.5, 0.25, 0.1, and 0.01 of its value just below the surface. These values of $D(Z,\theta,R)$ were obtained for direct beams incident at solar zenith angles θ of 0°, 30°, 60°, and 89°, as well as for a diffuse cardioidal distribution. Fifteen distinct water types characterized by volume reflectances between 0.0 and 0.14 were considered.

Curve-fitting was performed on the six depth values of $D(Z,\theta,R)$ to obtain the depth dependencies [as shown in Figure 2 for $R(0°) = 0.08$] for each of the possible θ and R combinations. Each curve was then integrated over depth according to

$$F_Z(\theta,R) = \frac{\int_{Z_1}^{Z_2} D(Z,\theta,R)\, E_d(Z,\theta,R)dZ}{\int_{Z_1}^{Z_2} E_d(Z,\theta,R)dZ} \tag{3}$$

where

Z_1 = depth of the 100% downwelling irradiance level

Z_2 = depth of the 1% downwelling irradiance level

$F_Z(\theta,R)$ is the ratio of the depth-averaged scalar irradiance to the depth-averaged downwelling irradiance for a particular θ,R, and photic depth. That is, over the photic zone the "effective" (i.e. depth-averaged) scalar irradiance is the product of the factor $F_Z(\theta,R)$ and the "effective" downwelling irradiance. Discrete values of $F_Z(\theta,R)$ resulting from equation (3) are shown as a function of $R(0°)$ in Figure 3 for the five incident radiation distributions considered.

In order to obtain explicit mathematical relationships among $F_Z(\theta,R)$, θ, and R, the values of $F_Z(\theta,R)$ for each incident radiation distribution were curve fitted to a polynomial expansion series of the form

$$F_Z(\theta,R) = \frac{1}{\mu_o}\left[1 + c_1R(0°) + c_2R(0°)^2 + c_3R(0°)^3\right] \qquad (4)$$

where $\mu_o = \cos\left[\sin^{-1}(n \sin\theta)\right]$

n = relative refractive index of water

c_1, c_2, and c_3 = constants

Values of the constants c_1, c_2, and c_3 resulting from the curve fitting are listed in Table 1 for θ values of 0°, 30°, 60°, and 89°. Prieur and Sathyendranath (1981) have shown that an incident diffuse cardioidal distribution produces subsurface irradiances similar to those for a direct beam incident at a solar zenith angle of 43°. Consequently, Table 1 also includes c_1, c_2 and c_3 values for a solar zenith angle $\theta \doteq 43°$ which are taken to be equivalent to those for an incident diffuse cardioidal distribution. The continuous curves of

Figure 3 illustrate the relationships of equation (4) superimposed upon the discrete $F_Z(\theta,R)$ values obtained from equation (3). The maximum difference between the discrete values of $F_Z(\theta,R)$ and the predictions of equation (4) for all incident radiation distributions considered is less than 1.0%.

Thus, equation (4) readily provides the R dependence of $F_Z(\theta,R)$ for five distinct solar zenith angles. To obtain the θ dependence for those intermediate θ values not specifically shown in Figure 3, an interpolation equation may be established. Jerome et al. (1988) have shown that the variation of $D(Z,\theta,R)$ with θ is proportional to the change in μ_0^{-1}. Similarly, the interpolation equation for $F_Z(\theta,R)$ may be expressed in the form

$$F_Z(\theta,R) = F_Z(\theta_1,R) + \left(\frac{\mu_1-\mu_0}{\mu_0}\right)\left(\frac{\mu_2}{\mu_1-\mu_2}\right) [F_Z(\theta_2,R)-F_Z(\theta_1,R)] \qquad (5)$$

where θ = any solar zenith angle between 0° and 89°

θ_1 and θ_2 = those values of the five solar zenith angles considered in Figure 3 which are immediately less than and greater than the value of θ, respectively (ie., $\theta_1 < \theta < \theta_2$)

$\mu_0 = \cos[\sin^{-1}(n \sin\theta)]$

$\mu_1 = \cos[\sin^{-1}(n \sin\theta_1)]$

$\mu_2 = \cos[\sin^{-1}(n \sin\theta_2)]$

n = relative refractive index of the water

Equations (4) and (5) provide the volume reflectance and solar zenith angle dependencies of $F_Z(\theta,R)$. These parametric relationships enable integration over a complete daylight period. Such daylight period integration, however, requires either directly-measured or model-inferred expressions for incident radiation fields.

INCIDENT RADIATION MODEL

A global radiation model was taken from Kondratyev (1969) wherein the downwelling irradiance incident at the earth's surface for clear sky conditions is given by

$$E_d(0^+,\theta,R) = \frac{(2 - \sec\theta)\, E_{ext} \cos\theta}{2(1-A) - (\sec\theta - 2A)e^{f(\sec\theta - 2)}} \qquad (6)$$

where E_{ext} = extraterrestral irradiance
A = albedo $A(\theta,R)$ as defined in equation (8) below
f = an atmospheric variable

Monthly values of f are provided in Kondratyev (1969) as a function of latitude. Subsequent analysis in this communication were performed for 4 days (the spring and fall equinoxes and the winter and summer solstices) and 2 latitudes (40°N and 50°N, a latitude range appropriate to the Great Lakes).

Figure 4 illustrates these relationships resulting from equation (6). The $E_d(0^+,\theta,R)$ values for the equinoxes were identical and are labelled spring/fall in the figure. The differences between the results for 40°N and 50°N were small, (<4.5% difference between the averaged value and either unaveraged value) and consequently the results for the two latitudes were averaged. Having obtained $E_d(0^+,\theta,R)$, it remains to transfer this value through the air/water interface to obtain the downwelling irradiance just beneath the surface, $E_d(0^-,\theta,R)$.

DETERMINATION OF THE DOWNWELLING IRRADIANCE JUST BELOW THE SURFACE

By applying appropriate boundary conditions to the air/water interface it may be readily shown that

$$E_d(0^-,\theta,R) = [1 + \frac{R(\theta)\rho_u(\theta)}{1 - R(\theta)\rho_u(\theta)}] [1 - \rho_d(\theta)] E_d(0^+,\theta,R) \tag{7}$$

and

$$A(\theta,R) = \rho_d(\theta) + [1 - \rho_u(\theta)] [\frac{R(\theta)(1-\rho_d(\theta))}{1 - R(\theta)\rho_u(\theta)}] \tag{8}$$

where $A(\theta,R)$ = albedo of the water

$\rho_d(\theta)$ = above-surface reflection of downwelling irradiance

$\rho_u(\theta)$ = subsurface reflection of upwelling irradiance

Jerome _et al_. (1988) have shown that

$$\rho_u(\theta) = 0.271 + 0.249/\mu_o \tag{9}$$

for direct incident radiation, and

$$\rho_u = 0.561 \tag{10}$$

for an incident diffuse cardioidal distribution.

Values of $\rho_d(\theta)$ may be determined from Fresnel's equation, while the ρ_d value for an incident diffuse cardioidal distribution may be taken as 0.066 (Jerlov, 1976).

Further, [Jerome et al. (1988)]

$$R(\theta) = \frac{R(0^\circ)}{\mu_o} \tag{11}$$

for direct incident radiation, and

$$R = 1.165\ R(0^\circ) \tag{12}$$

for an incident diffuse cardioidal distribution.

Using equations (9), (10), (11), and (12) in conjunction with equations (7) and (8), the albedo and the ratio of the downwelling irradiance just below the surface to the downwelling irradiance just above the surface, may be obtained for any given volume reflectance $R(0^\circ)$.

DETERMINATION OF MULTIPLICATIVE FACTORS

(a) For the Case of Direct Incident Radiation

Two multiplicative factors will now be determined. The first factor $F_\theta(0^-,R)$ is designed to convert a daily irradiation immediately above the surface into a daily scalar irradiation immediately below the surface and, as such, incorporates the impact of the air/water interface. Such conversion is essential to those photolytic models requiring the value of the irradiation just below the surface. The second factor $F_{Z\theta}(R)$ is designed to convert "effective" daily irradiation for a specifically-defined photic zone into the corresponding "effective" daily scalar irradiation for that particular photic zone. The photic zone considered within the current work is defined by the irradiance level limits of 100% and 1% of the downwelling irradiance just below the air/water interface. Such limits on the photic zone are somewhat arbitrary, and the impact of alternate irradiance level definitions of the photic zone will be dicussed later and shown to be of minimal consequence. This second factor is intended for those biological models requiring values of "effective" daily scalar irradiation for natural waters to a specified depth.

The factor $F_\theta(0^-,R)$ was determined by integrating the ratio of the scalar irradiance to downwelling irradiance just beneath the air/water interface [i.e. $D(0^-,\theta,R)$] over the entire daylight period according to the equation:

$$F_\theta(0^-,R) = \frac{\int_{\theta_1}^{\theta_2} D(0^-,\theta,R)\, E_d(0^-,\theta,R)d\theta}{\int_{\theta_1}^{\theta_2} E_d(0^+,\theta,R)d\theta} \qquad (13)$$

where θ_1 = solar zenith angle at sunrise

θ_2 = solar zenith angle at sunset

Appropriate time-dependent values of $E_d(0^+,\theta,R)$ were obtained from equation (6). Corresponding values of $E_d(0^-,\theta,R)$ were then obtained from equation (7).

The multiplicative factor $F_\theta(0^-,R)$ from equation (13) is shown in Figure 5 as a function of water type for the solstices and spring/fall equinoxes. Also shown is the $F_\theta(0^-,R)$ factor for the condition of an incident cardioidal distribution. This curve, labelled "diffuse" in Figure 5, will be discussed later.

For any layer of a water body, the "effective" downwelling irradiance may be determined from

$$\frac{\int_{Z_1}^{Z_2} E_d\,(0^-,\theta,R)\; e^{-kZ}\, dZ}{\int_{Z_1}^{Z_2} dZ}$$

where Z_1 and Z_2 define the depth limits of the water layer and k is the irradiance attenuation coefficient for this layer. For a photic zone defined by the 100% and 1% irradiance levels the "effective" downwelling irradiance is ~0.215 $E_d\,(0^-,\theta,R)$.

The factor $F_{Z\theta}(R)$ was determined in the following manner. Again, an appropriate time-dependent $E_d(0^+,\theta,R)$ was obtained from equation (6), and equation (7) enabled the obtaining of a corresponding time-dependent $E_d(0^-,\theta,R)$. The depth integrated value of

$D(Z,\theta,R)$ [i.e. $F_Z(\theta,R)$] was integrated over the daylight period according to the equation:

$$F_{Z\theta}(R) = \frac{\int_{\theta_1}^{\theta_2} F_Z(\theta,R)[0.215E_d(0^-,\theta,R)]d\theta}{\int_{\theta_1}^{\theta_2} 0.215\, E_d(0^-,\theta,R)\, d\theta} \qquad (14)$$

Equation (14) then yields the multiplicative factor by which the "effective" daily irradiation for a photic zone (defined by the 100% and 1% irradiance levels) may be converted into the "effective" daily scalar irradiation. Notice that the "effective" downwelling irradiance contribution to the factor $F_{Z\theta}(R)$ is independent of the irradiance level limits of the selected photic zone. The only term dependent upon the depth definition of the photic zone is $F_Z(\theta,R)$ which is the depth integration of $D(Z,\theta,R)$.

Figure 6 illustrates the results of equation (14). Herein is plotted the multiplicative factor $F_{Z\theta}(R)$ as a function of R for the solstices and the spring/fall equinoxes. The multiplicative factor for the case of an incident cardioidal distribution (labelled "diffuse") is also shown.

(b) <u>For the Case of Diffuse Incident Radiation</u>

For the condition of the incident radiation being appropriately defined throughout the entire daylight period by a diffuse cardioidal distribution, the solar zenith angle dependence is eliminated from all the parameters except $E_d(0^-,\theta,R)$ and $E_d(0^+,\theta,R)$. Thus, the governing equations (13) and (14) for a diffuse cardioidal incident distribution become, respectively:

$$F_\theta(0^-,R) = 1.177[1.0+3.13R(0°)] \left[0.934 + \frac{0.610R(0°)}{1-0.654R(0°)}\right] \qquad (15)$$

and

$$F_{Z\theta}(R) = 1.164\ [1+c_1R(0°) + c_2R(0°)^2 + c_3R(0°)^3] \qquad (16)$$

where the constants c_1, c_2 and c_3 are appropriately chosen from Table 1. The curves resulting from equations (15) and (16) are labelled "diffuse" in Figures 5 and 6, respectively.

DISCUSSION

The conversion factors discussed in this work have been determined for Great Lakes latitudes (40°N - 50°N) and for volume reflectance values generally prevalent in the Great Lakes waters. The multiplicative factors $F_\theta(0^-,R)$ and $F_{Z\theta}(R)$ are presented as a function of volume reflectance R which is, of course, a function of wavelength λ. It is essential, therefore, that a wavelength consistency exists between the above-surface downwelling radiation and the subsurface volume reflectance. The accuracy in scalar irradiation determinations using Figures 5 or 6 decreases as the width of the selected wavelength interval increases.

The most readily applicable multiplicative factor is, perhaps, $F_\theta(0^-,R)$, since it converts an easily obtainable above-surface irradiation into a scalar irradiation value just beneath the air/water interface. It therefore provides the subsurface irradiation values required in photochemical models. The multiplicative factor $F_{Z\theta}(R)$, however, is dependent upon a depth definition of a photic zone since it converts an "effective" subsurface irradiation into an "effective" scalar irradiation. The curves of Figure 6 were constructed on the basis of a photic zone defined by the irradiance level limits 100% and 1% of the downwelling irradiance just below the air/water interface. As mentioned earlier, changing the depth-limits of integration of equation (14) impacts only the $F_Z(\theta,R)$ term, i.e., the depth integration of the $D(Z,\theta,R)$ curves of Figure 2. As seen from equation (3) such depth integration essentially weights the local value of $D(Z,\theta,R)$ according to the corresponding local value of $E_d(Z,\theta,R)$, i.e., near-surface values of $D(Z,\theta,R)$ are weighted two orders of magnitude greater than values of $D(Z,\theta,R)$ at the 1% downwelling irradiance level. Consequently, changing the depth-limit of integration of equation (14) should produce a non-dramatic impact on $F_{Z\theta}(R)$ for most applications. For example, changing the integration limit from the 1% to the 0% irradiance level results in an infinitesimal change in the value of $F_{Z\theta}(R)$. Changing the integration limit from 1% to 10% results in a change of 1.5% in the value of $F_{Z\theta}(R)$. Changing the integration limit from 1% to 30% results in a change of 10% in the value of $F_{Z\theta}(R)$. Changes in depth-limits of integration would be considered in such cases as a) the need to determine an "effective" daily irradiation for a mixed layer whose maximum depth lies either above or below the 1% downwelling irradiance level or b) the need to incorporate the wavelength dependence of the depth of a particular downwelling irradiance level into a spectral integration of the equations presented herein. Errors introduced by ignoring these changes in depth-limits of integration and directly utilizing Figure 6, as shown above, are generally not significant.

The multiplicative factors $F_\theta(0^-,R)$ and $F_{Z\theta}(R)$ as shown in Figures 5 and 6 can be quite substantial. Even for water bodies displaying a volume reflectance R = 0, the daily scalar irradiation just below the surface is (10-20)% higher than the daily irradiation measured above the surface despite the significant loss of incident radiation due to surface reflection. This figure increases to (75-95)% for waters characterized by R = 0.14. Similarly, "effective" daily scalar irradiation within the photic zone of waters displaying R = 0 is (15-45)% higher than the "effective" daily irradiation within that photic zone. This figure increases to (85-110)% for waters characterized by R = 0.14.

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FIGURE CAPTIONS

Figure 1 Flow diagram of the methodologies employed to convert incident radiation into scalar irradiation available for photolysis.

Figure 2 Depth dependencies of the ratio of downwelling irradiance to scalar irradiance $D(Z,\theta,R)$ for volume reflectance $R(0°) = 0.08$.

Figure 3 $F_Z(\theta,R)$ as a function of $R(0°)$ for five distinct configurations of incident radiation distributions.

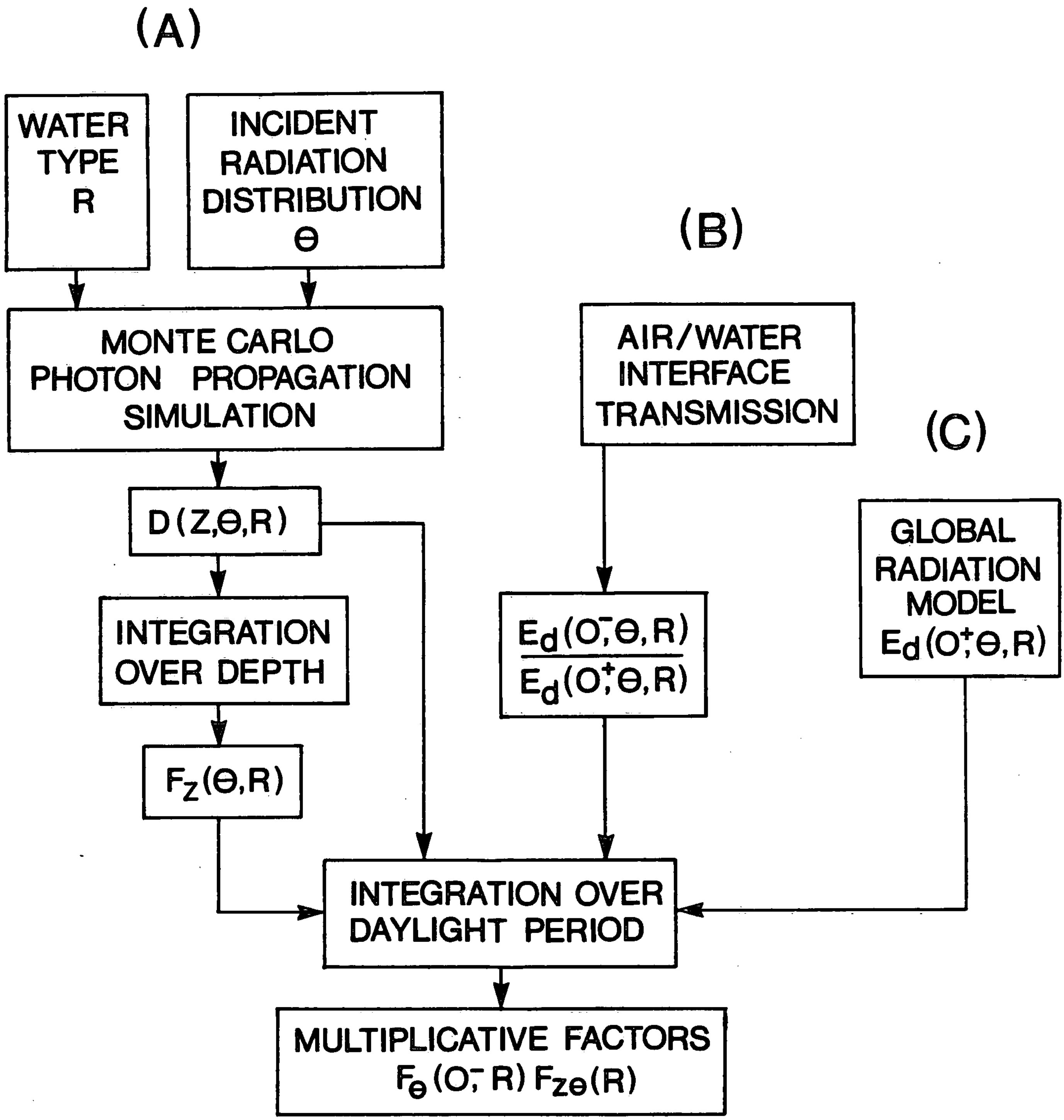
Figure 4 Relationships between the downwelling irradiance just above the air/water interface $E_d(0^+,\theta,R)$ and local time for the equinoxes and solstices.

Figure 5 $F_\theta(0^-,R)$ as a function of $R(0°)$ for the equinoxes and solstices for direct and diffuse incident radiation distributions . These are the multiplicative factors to convert the incident above surface daily irradiation into the daily scalar irradiation, just below the air/water interface.

Figure 6 $F_{Z\theta}(R)$ as a function of $R(0°)$ for the equinoxes and solstices for direct and diffuse incident radiation distributions. These are the multiplicative factors to convert the "effective" daily irradiation into the "effective" daily scalar irradiation.

Table 1. Constants for the Polynomial Expansion of Equation (4)

Solar Zenith Angle, θ	c_1	c_2	c_3
0°	6.076	-13.32	35.11
30°	5.927	-14.67	43.79
43°	6.244	-25.82	86.12
60°	6.237	-28.28	79.76
89°	5.866	-27.73	76.51
Cardioidal distribution	6.244	-25.82	86.12



(A)
WATER TYPE R
INCIDENT RADIATION DISTRIBUTION Θ
MONTE CARLO PHOTON PROPAGATION SIMULATION
D(Z,Θ,R)
INTEGRATION OVER DEPTH
F_Z(Θ,R)
(B)
AIR/WATER INTERFACE TRANSMISSION
E_d(O⁻,Θ,R) / E_d(O⁺,Θ,R)
(C)
GLOBAL RADIATION MODEL E_d(O⁺,Θ,R)
INTEGRATION OVER DAYLIGHT PERIOD
MULTIPLICATIVE FACTORS
F_Θ(O⁻,R) F_ZΘ(R)

FIGURE 1

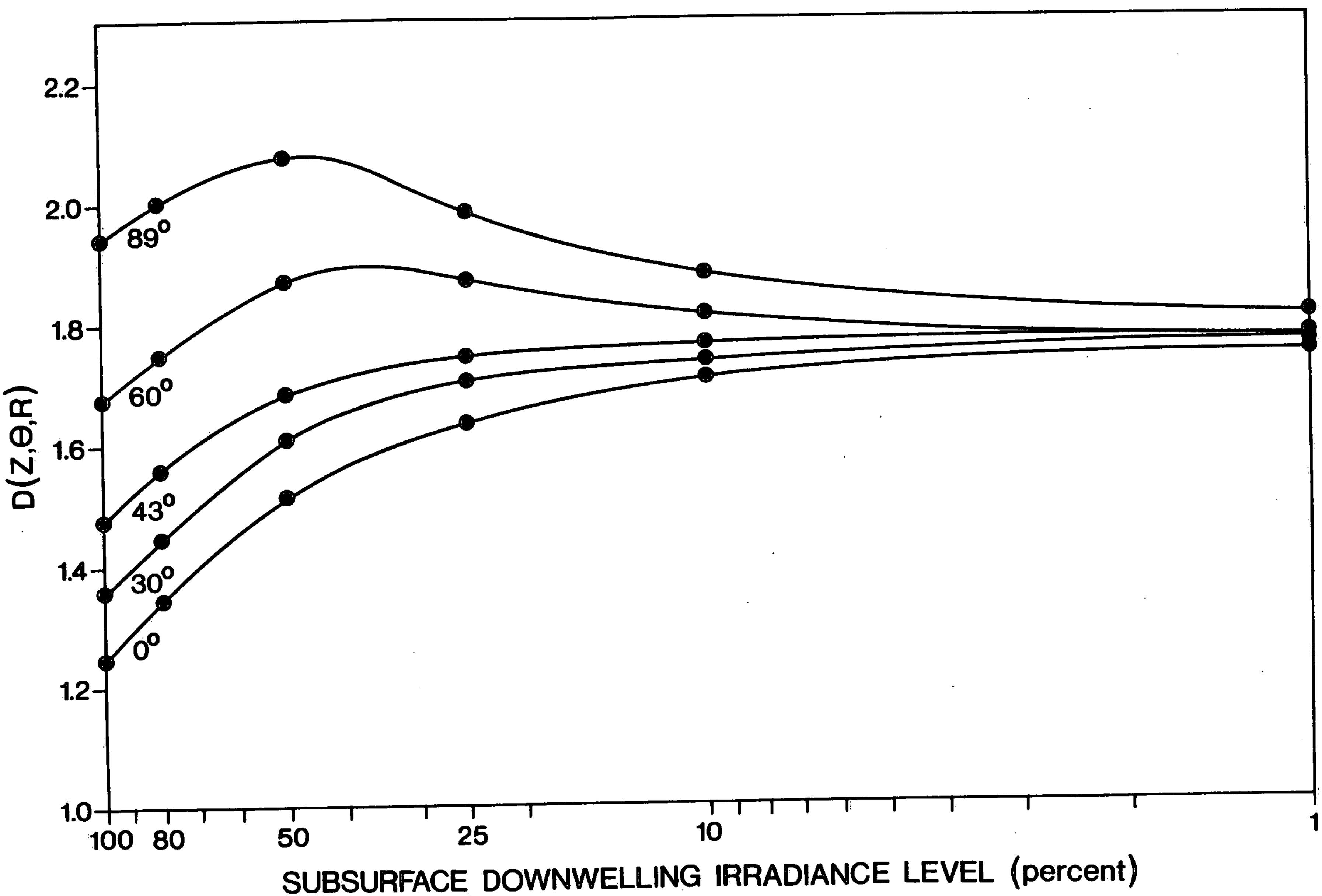
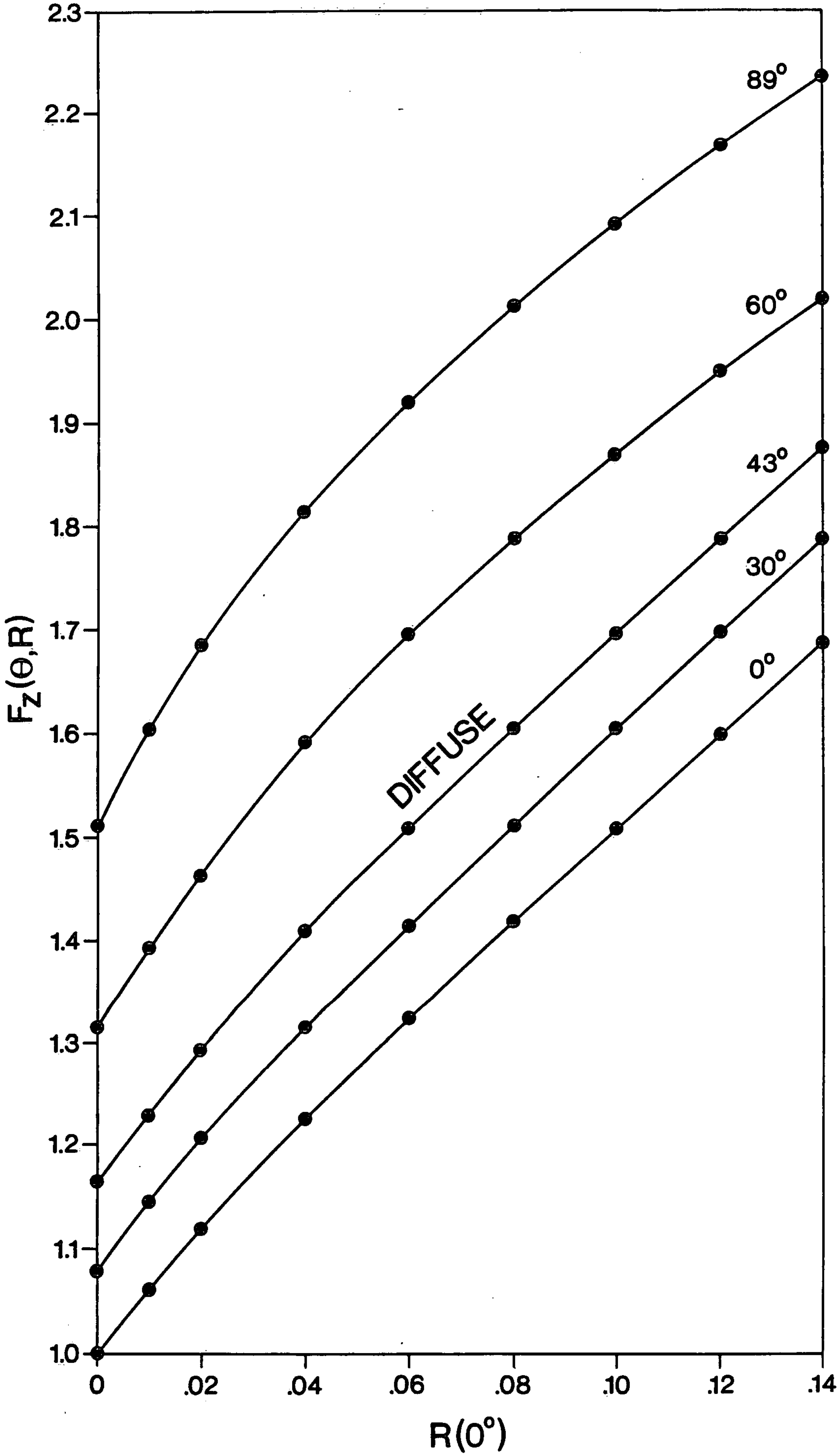

2.2
2.0
1.8
1.6
1.4
1.2
1.0
D(z,θ,R)
89°
60°
43°
30°
0°
100
80
50
25
10
1
SUBSURFACE DOWNWELLING IRRADIANCE LEVEL (percent)

FIGURE 2



2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0
.02
.04
.06
.08
.10
.12
.14
$F_Z(\theta,R)$
$R(0^{\circ})$
89°
60°
43°
30°
0°
DIFFUSE

FIGURE 3

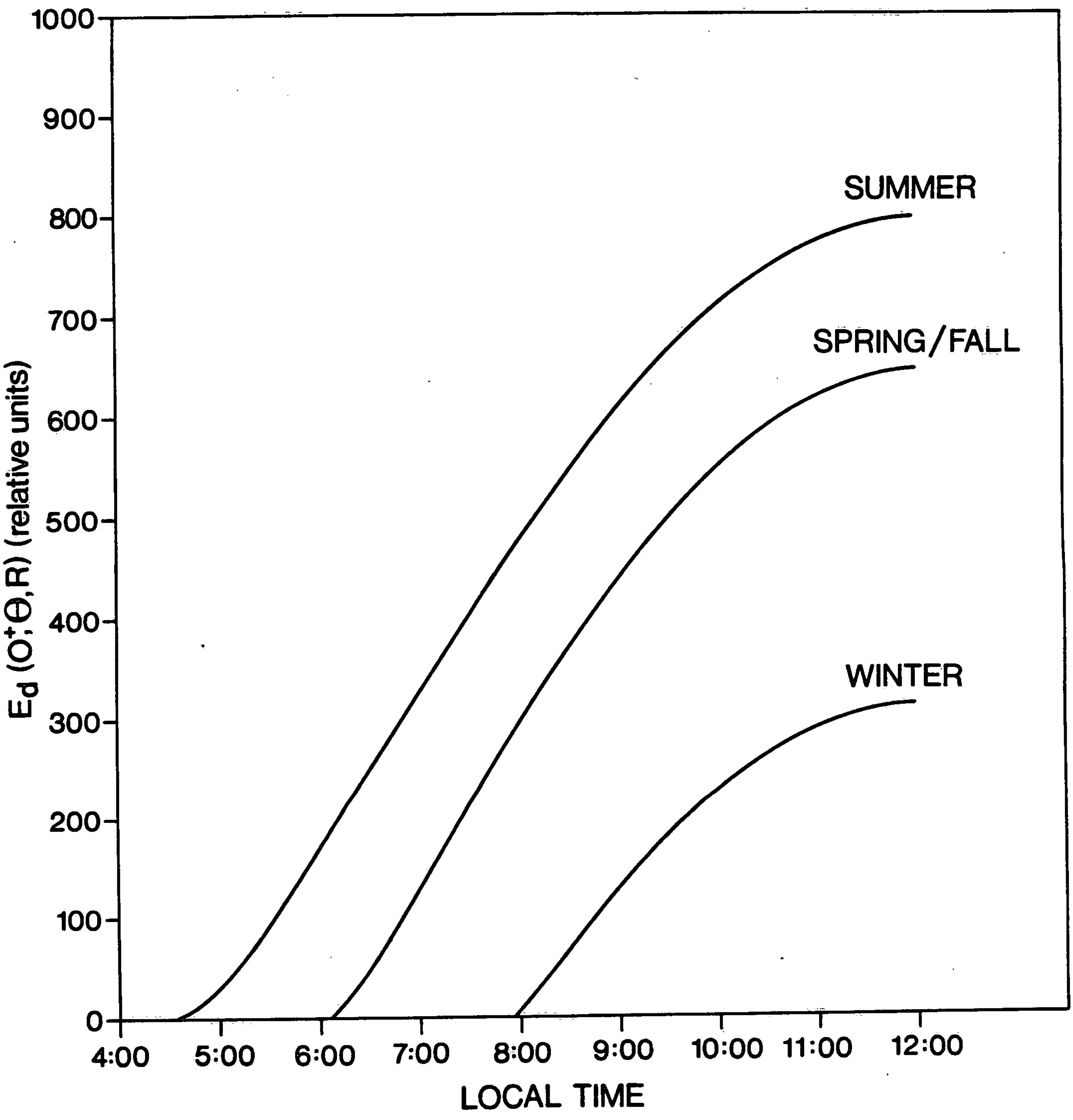

SUMMER
SPRING/FALL
WINTER
$E_d(O^+,\Theta,R)$ (relative units)
1000
900
800
700
600
500
400
300
200
100
0
4:00
5:00
6:00
7:00
8:00
9:00
10:00
11:00
12:00
LOCAL TIME

FIGURE 4

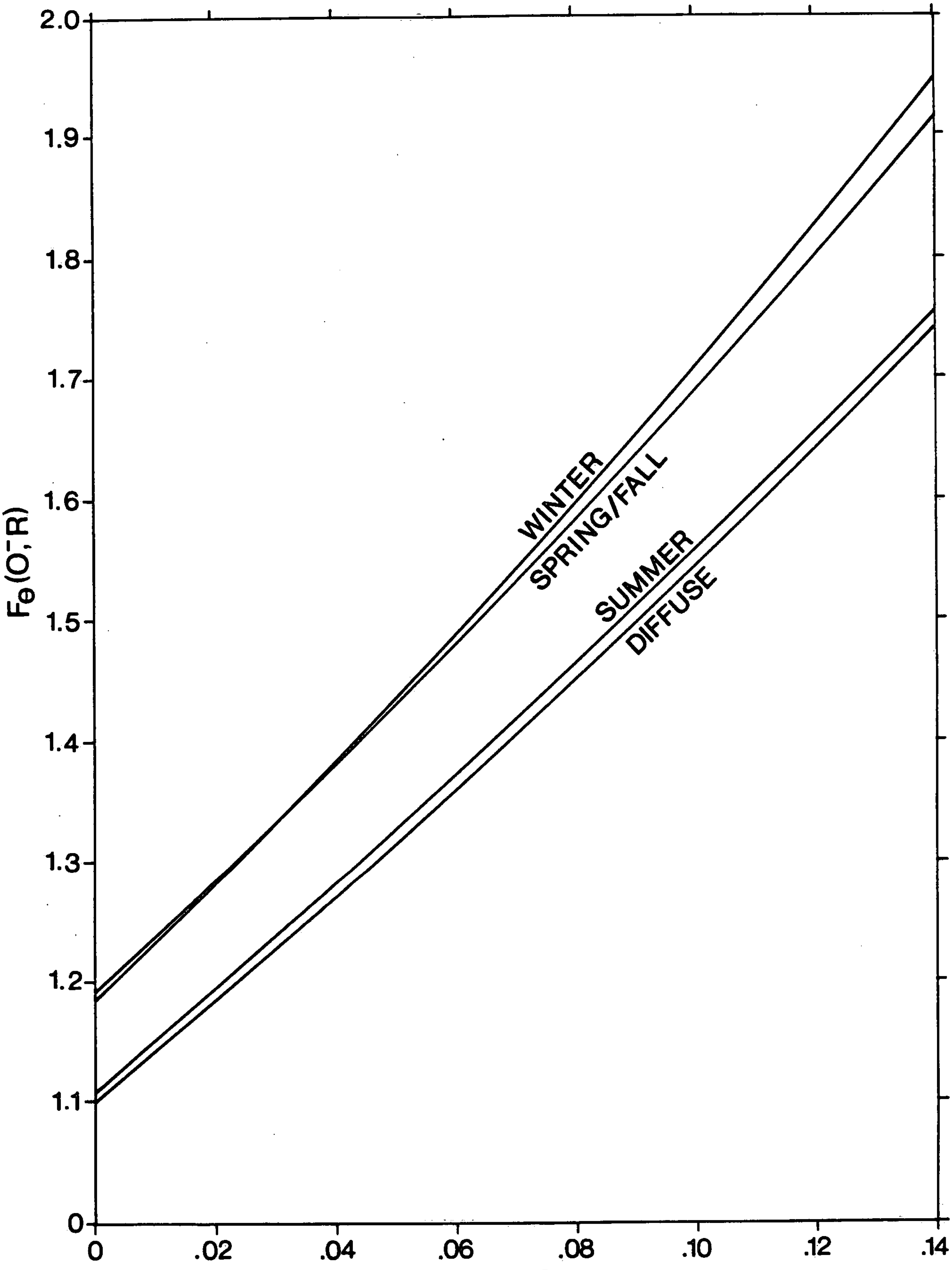
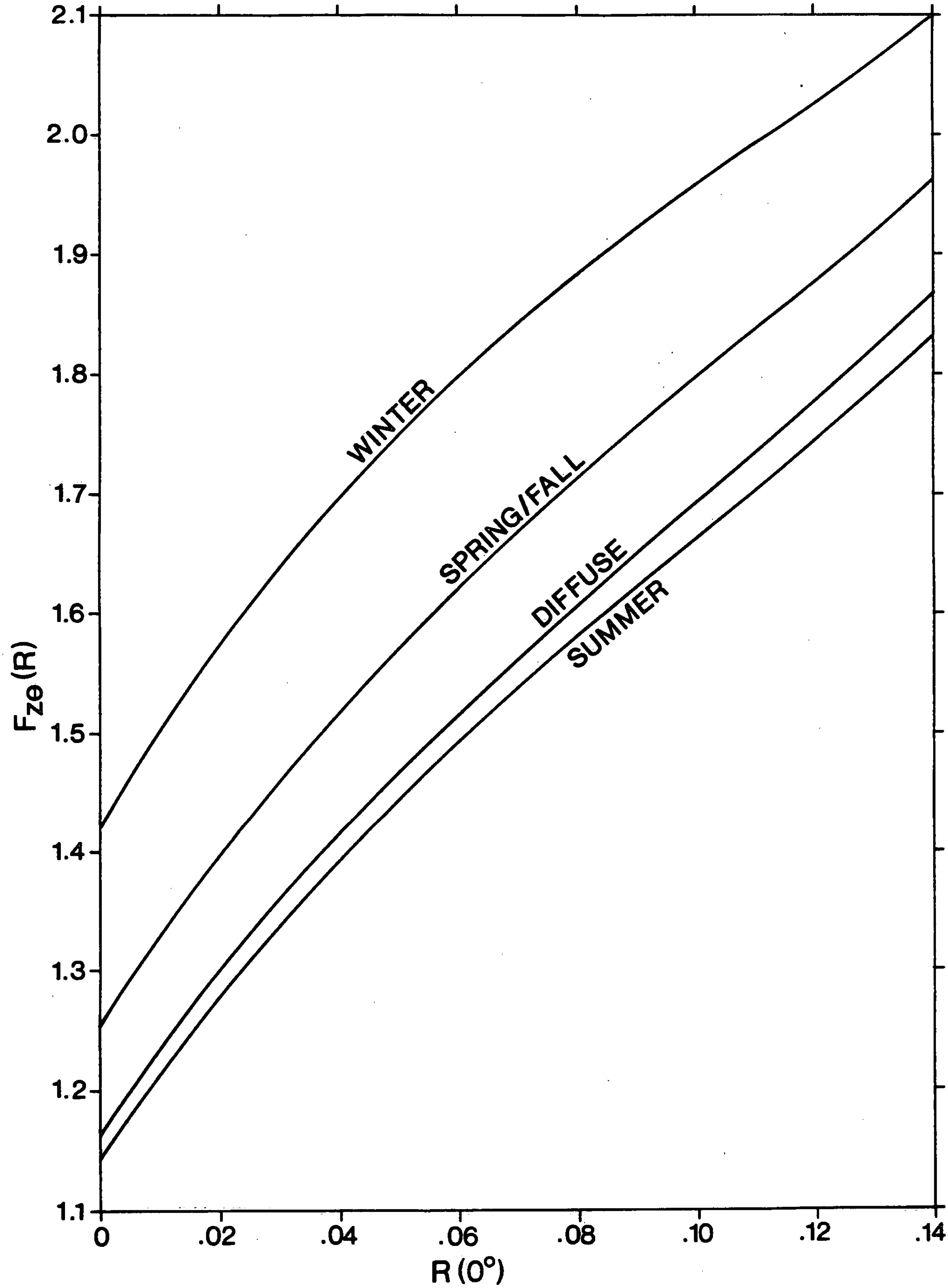

2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
0
.02
.04
.06
.08
.10
.12
.14
$F_e(0^-,R)$
$R(0^\circ)$
WINTER
SPRING/FALL
SUMMER
DIFFUSE

FIGURE 5



2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
$F_{ze}(R)$
WINTER
SPRING/FALL
DIFFUSE
SUMMER
0
.02
.04
.06
.08
.10
.12
.14
R (0°)

FIGURE 6