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A Simplified Clear Sky Model for Direct and Diffuse Insolation on Horizontal Surfaces

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A SIMPLIFIED CLEAR SKY MODEL FOR DIRECT AND DIFFUSE INSOLATION ON HORIZONTAL SURFACES

RICHARD E. BIRD
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PREPARED UNDER TASK NO. 1093.00

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PREFACE

The work documented here was performed by the SERI Renewable Resource Assessment Branch for the U.S. Department of Energy under Task No. 1093.00. The report compares several simple global horizontal insolation models with several rigorous radiative transfer models and describes an improved, simple, global insolation model. We would like to thank J. V. Dave of IBM for providing data sets from his Spherical Harmonics code.

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SUMMARY

OBJECTIVE

This report presents the Bird model, a simple broadband model for direct and diffuse insolation under clear sky conditions. The model is based on comparisons with results from rigorous radiative transfer codes. The model is composed of simple algebraic expressions, and the inputs to the model are from readily available meteorological data. This enables the model to be implemented very easily.

DISCUSSION

The results of a detailed comparison of five simple broadband models for clear sky global insolation are presented here. These five models have appeared recently in publications, and many of them are widely used in the solar community. A sixth simple model, the Bird model, has been formulated that uses parts of the formalisms of these five models. This model is expected to provide greater accuracy and is still easy to implement and use.

CONCLUSIONS

All of the simple models compared here provide results that agree within < 10% with the results from three rigorous radiative transfer codes when the sun is in the zenith position. The Bird and Hoyt models agree within 3% with each other and with the results from the rigorous codes. However, the Bird model is the easier of the two models to implement. Future work will include comparisons with carefully taken insolation and meteorological data and the inclusion of the effects of clouds in the model.

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NOMENCLATURE

a_i	Absorptance parameters defined by Hoyt
a_{co}	Carbon dioxide absorptance
a_{ox}	Oxygen absorptance
a_w	Water vapor absorptance
B_a	Ratio of the forward-scattered irradiance to the total scattered irradiance due to aerosols
F_{zj}	A parameter used by Watt in air mass calculations
I_{as}	Solar irradiance on a horizontal surface from atmospheric scattering (W/m^2)
I_d	Direct solar irradiance on a horizontal surface (W/m^2)
I_G	Solar irradiance on a horizontal surface from multiple reflections between the ground and sky (W/m^2)
I_s	Solar irradiance on a horizontal surface from scattered light ($I_{as} + I_G$)
I_T	Total (global) solar irradiance on a horizontal surface (W/m^2)
I_o	Extraterrestrial solar irradiance (1353 W/m^2)
K	Aerosol transmittance for Davies and Hay
K_1	Constant used in Bird model associated with aerosol absorptance
M	Air mass
M'	Pressure-corrected air mass
M_i	Watt's path length modifier (similar to air mass)
P	Surface pressure (millibars)
r_g	Ground albedo
r_s	Sky, or atmospheric, albedo
T	Surface temperature (K)
T_A	Transmittance of aerosol absorptance and scattering
T_{AA}	Transmittance of aerosol absorptance

T_{AS}	Transmittance of aerosol scattering
T_{as}	Transmittance of dry air absorptance and scattering for Watt
T_L	Transmittance of lower layer aerosol for Watt
T_M	Global transmittance of all molecular effects except water vapor for Atwater
T_{Md}	Direct transmittance of all molecular effects except water vapor for Atwater
T_o	Transmittance of ozone absorptance
T_R	Transmittance of Rayleigh scattering
T_U	Transmittance of upper layer aerosol for Watt
T_{UM}	Transmittance of absorptance of uniformly mixed gases (carbon dioxide and oxygen)
T_w	Transmittance of water vapor absorptance $(1 - a_w)$
T_{ws}	Transmittance of water vapor scattering
U_o	Amount of ozone in a vertical column from surface (cm)
U_w	Amount of precipitable water in a vertical column from surface (cm)
X_o	Total amount of ozone in a slanted path (cm)
X_w	Total amount of precipitable water in a slanted path (cm)
Z	Angle between a line to the sun and the local zenith (zenith angle in degrees)
α_{cs}	An attenuation multiplier used by Watt
τ_A	Broadband aerosol optical depth from surface in a vertical path (broadband turbidity)
$\tau_{0.5}$	Aerosol optical depth from surface in a vertical path at 0.5-μm wavelength
$\tau_{0.38}$	Aerosol optical depth from surface in a vertical path at 0.38-μm wavelength
τ_L	Lower layer aerosol optical depth in a vertical path for Watt
τ_u	Upper layer aerosol optical depth in a vertical path for Watt
W_o	Single scattering albedo--the fraction of the light lost from an incident pencil of radiation that is due to scattering

SECTION 1.0

INTRODUCTION

To properly design a solar energy system for a location lacking an insolation data base, insolation models are required. This need for insolation models has been recognized for many years. One early and widely used insolation model was published in 1940 by Moon [1]. This model is still used today in its original or modified forms [2,3].

Insolation models have proliferated to the point where it is difficult for a solar user to decide which model to adopt. The purpose of this paper is to provide a detailed comparison of several simple, broadband insolation models that are currently in use and, based on this comparison and comparisons with more rigorous radiative transfer models, to formulate a simple clear sky model for direct and diffuse insolation. This type of comparison should be helpful in evaluating the relative accuracy of various models and give direction for formulating a model that uses the best of each existing model. The criteria used for evaluating and formulating models have been simplicity, accuracy, and the ability to use readily available meteorological data.

It should be noted that the use of the word "rigorous" does not necessarily mean that the "rigorous" results truly represent reality. Even though these "rigorous" codes are very detailed in the methods used to solve the radiative transfer problem, the representativeness of the results depends upon how well the atmospheric model, the measured atmospheric parameters, the mathematical methods, and other assumptions made in the codes relate to a real situation. However, in the absence of well-documented data, this approach of using "rigorous" codes as a basis of comparison was used.

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SECTION 2.0

DESCRIPTION OF MODELS

A brief description of the several models that have been compared is presented here. Further details of this comparison can be found in Ref. 4 and in the original publications of each author. Most of the models include the effect of clouds, but this aspect of the models is not included here. Comparisons of cloud-cover global insolation models will follow (in a subsequent report) the clear sky model comparisons reported here. Such comparisons have also been performed by Davies and Hay [5].

2.1 ATWATER AND BALL MODEL

Direct and global insolation models were published by Atwater and Ball [6,7]. The direct insolation model was taken from Kastrov as discussed by Kondratyev [8]. The equations of transfer and the transmission functions for this insolation model are given in Table 2-1. (The symbols in Tables 2-1 through 2-6 are defined in the Nomenclature.)

Table 2-1. EQUATIONS FOR TOTAL DOWNWARD IRRADIANCE FOR ATWATER AND BALL MODEL

Basic Equations

$$I_d = I_o (\cos Z) (T_{Md} - a_w) T_A$$

$$I_T = I_o (\cos Z) (T_M - a_w) T_A/(1 - r_g r_s)$$

Transmission Functions

$$T_{Md} = 1.041 - 0.16 [M(949 \times 10^{-6} P + 0.051)]^{0.5}$$

$$T_M = 1.021 - 0.0824 [M(949 \times 10^{-6} P + 0.051)]^{0.5}$$

$$a_w = 0.077 (U_w M)^{0.3}$$

$$T_A = \exp (-\tau_A M')$$

$$M = 35/[(1224 \cos^2 Z) + 1]^{0.5}$$

$$M' = PM/1013$$

The form of the equation for water vapor absorption was published by McDonald [9]. The value of $r_s = 0.0685$ for a molecular atmosphere, as reported by Lacis and Hansen [10], was used with this model. Atwater and Ball used MIE calculations to obtain τ_A, which is much too rigorous for a simple model. Therefore, a value of τ_A that will be described later in the Bird model was used here.

2.2 DAVIES AND HAY MODEL

A model for solar insolation (direct and diffuse) was published by Davies and Hay [5]. The equations used in this model were partially the result of comparing several existing models, and they are presented in Table 2-2.

Table 2-2. EQUATIONS FOR TOTAL DOWNWARD IRRADIANCE FOR DAVIES AND HAY MODEL

Basic Equations

$$I_d = I_o (\cos Z)(T_o T_R \quad a_w) T_A$$

$$I_{as} = I_o (\cos Z)[T_o(1 - T_R)T_A (0.5) + (T_o T_R - a_w)(1 - T_A)W_o B_a]$$

$$I_G = r_g r_s (I_d + I_{as})/(1 - r_g r_s)$$

$$I_T = I_d + I_{as} + I_G$$

Transmission Functions

$$T_o = 1 - 0.02118X_o/(1 + 0.042X_o + 0.000323X_o^2) - 1.082X_o/(1 + 138.6X_o)^{0.805} - 0.0658X_o/[1 + (103.6X_o)^3]$$

$$X_o = U_o M$$

$$a_w = 2.9X_w/[(1 + 141.5X_w)^{0.635} + 5.925X_w]$$

$$X_w = U_w M$$

$$T_A = K^M$$

$$r_s = 0.0685 + (1 - B_a)(1 - T_A)W_o$$

The expressions for ozone transmittance, T_o, and water vapor absorption, a_w, were taken from Lacis and Hansen [10]. The transmission due to Rayleigh scattering, T_R, was presented in tabular form, and so we used the Bird model expression for T_R in this model. The value K = 0.91 was used for data generated here and is representative of aerosol conditions in southern Ontario. W_o = 0.98 and B_a = 0.85 were used here also.

2.3 WATT MODEL

Another direct and diffuse insolation model has been constructed by Watt [3], based partially on the work of Moon [1]. The equations for this model are shown in Table 2-3.

Table 2-3. EQUATIONS FOR TOTAL DOWNWARD IRRADIANCE FOR WATT MODEL

Basic Equations

$$I_d = I_o(\cos Z)\, T_{wa} T_{as} T_o T_{ws} T_L T_U$$

$$I_s = I_o[0.8\, r_s(1 + r_g r_s)(1 + \cos Z)^{0.5} + 0.5\, \alpha_{cs} r_g r_s \cos Z + 0.5\, r_s \cos Z]$$

$$I_T = I_d + I_s$$

Transmission Functions

$$T_w = 0.93 - 0.033 \log (U_w M_2)$$

$$T_{as} = 10^{-0.045[(P/P_o)\, M_1]^{0.7}}$$

$$T_o = 10^{-(0.0071 + 0.01\, U_o M_4)}$$

$$T_{ws} = 10^{-(0.0095\, U_w M_2)}$$

$$T_L = 10^{\tau_L M_2 0.7}$$

$$T_U = 10^{-\tau_u M_3}$$

$$\tau_L = 0.6\, (\tau_{0.5} - 0.01\, U_w - 0.03)$$

$$\alpha_{cs} = (0.93 - 0.033 \log U_w)\, 10^{-[0.006\, P/1013 + 0.4\, (T_L + T_u)]}$$

$$r_s = \alpha_{cs} \{1 - 10^{-[0.003\, P/1013 + 0.01\, U_w + 0.4\, (T_L + T_U)]}\}$$

$$M_i = \sec Z \text{ for } Z \leq 70° \quad (i = 1,2,3,4)$$

$$M_i = (h_2 F_{z2} - h_1 F_{z1})/(h_2 - h_1) \text{ for } Z > 70° \quad (i = 1,2,3,4)$$

$$F_{zj} = \{[(r/h_j) \cos Z]^2 + 2\, r/h_j + 1\}^{0.5} - (r/h_j) \cos Z \quad (j = 1,2)$$

for $i = 1$, $h_1 = 0$ km and $h_2 = 30$ km
$i = 2$, $h_1 = 0$ km and $h_2 = 3$ km
$i = 3$, $h_1 = 15$ km and $h_2 = 25$ km
$i = 4$, $h_1 = 20$ km and $h_2 = 40$ km

The upper layer broadband turbidity, τ_u, was not well defined by Watt. A value of $\tau_u = 0.02$ was used in the calculations performed here, which appears to be an average value for locations in the United States. The parameter r is the earth's radius (6.4×10^6 m).

2.4 HOYT MODEL

The equations used in the model by Hoyt [11] are shown in Table 2-4.

Table 2-4. EQUATIONS FOR TOTAL DOWNWARD IRRADIANCE FOR HOYT MODEL

Basic Equations

$$I_d = I_o (\cos Z)\left(1 - \sum_{i=1}^{5} a_i\right) T_{AS} T_R$$

$$I_{as} = I_o (\cos Z)\left(1 - \sum_{i=1}^{5} a_i\right)[(1 - T_R)0.5 + (1 - T_{AS})0.75]$$

$$I_G = (I_d + I_{as}) r_g \left(1 - \sum_{i=1}^{5} a_i'\right)[(1 - T_R')0.5 + (1 - T_{AS}')0.25]$$

$$I_T = I_d + I_{as} + I_G$$

Transmission Functions

$$a_1 = a_w = 0.110\,(0.75\,U_w M + 6.31 \times 10^{-4})^{0.3} - 0.0121$$

$$a_2 = a_{co} = 0.00235\,(126\,M' + 0.0129)^{0.26} - 7.5 \times 10^{-4}$$

$$a_3 = (1 - T_o) = 0.045\,(U_o M + 8.34 \times 10^{-4})^{0.38} - 3.1 \times 10^{-3}$$

$$a_4 = a_{ox} = 7.5 \times 10^{-3}\,(M')^{0.875}$$

$$a_5 = 0.05\,T_{AS}$$

$$M' = MP/1013.25$$

Hoyt obtained air mass values, M, from Bemporad's [12] tables. The expression for air mass of Kasten [13] was used here instead. The values of T_{AS} and T_R are calculated from tables furnished by Hoyt [11]. The a_i' values are calculated using air mass values of $M' + 1.66\,P/1013.25$ in the a_i expressions.

T_{AS}' and T_R' are evaluated for air mass values of 1.66 P/1013.25 in T_{AS} and T_R. The table values from which T_{AS} is calculated are limited so that large optical depths cannot be considered. Large optical depths can occur from high turbidity or from large zenith angles. In the data presented later for Z = 80°, an approximate value of T_{AS} was used to complete the plotted results.

2.5 LACIS AND HANSEN MODEL

The equations for the model developed by Lacis and Hansen [10] are shown in Table 2-5.

Table 2-5. EQUATIONS FOR TOTAL DOWNWARD IRRADIANCE FOR LACIS AND HANSEN MODEL

Basic Equation

$$I_T = I_o (\cos Z) [(0.647 - r_s' - a_o)/(1 - 0.0685\ r_g) + 0.353 - a_w]$$

Transmission Functions

$$r_s' = 0.28/(1 + 6.43 \cos Z)$$

$$a_o = 1 - T_o \text{ as shown in Table 2-2}$$

a_w = Shown in Table 2-2 with the following correction:

$$X_w = X_w(P/1013)^{0.75}(273/T)^{0.5}$$

2.6 BIRD MODEL

A model has been constructed that is based on comparisons with the SOLTRAN 3 and SOLTRAN 4 [4] direct insolation models and the BRITE Monte Carlo global model [14]. Formalisms in the previous models that were considered to be optimum were adopted here. The equations for this model are shown in Table 2-6.

The atmospheric turbidity values, $\tau_{A,0.38}$ and $\tau_{A,0.5}$, have been measured on a regular basis by the National Weather Service [15] at 0.38- and 0.5-μm wavelengths, respectively. If one of the turbidity values is not available, its value can be entered as a zero in the expression for τ_A. The expression for τ_A is based on the Air Force Geophysics Laboratory (AFGL) rural aerosol model [16]. The expression used here for T_{AA} was found by fitting the expression to the results of the SOLTRAN 4 [4] code. The value of K_1 = 0.0933 for the rural aerosol was used here for all calculations. For the urban aerosol model, which contains more carbon, the value of K_1 = 0.385 was found to be appropriate. From a theoretical standpoint, K_1 should be nearly equal to $1 - W_o$, where W_o is the single scattering albedo. The forward-scattering

Table 2-6. EQUATIONS FOR TOTAL DOWNWARD IRRADIANCE FOR THE BIRD MODEL

Basic Equations

$$I_d = I_o \, (\cos Z) \, (0.9662) \, T_R T_o T_{UM} T_w T_A$$

$$I_{as} = I_o \, (\cos Z) \, (0.79) \, T_o T_w T_{UM} T_{AA} \, [0.5 \, (1 - T_R) + B_a \, (1 - T_{AS})]/[1 - M + (M)^{1.02}]$$

$$I_T = (I_d + I_{as})/(1 - r_g r_s)$$

Transmission Equations

$$T_R = \exp \{- 0.0903 \, (M')^{0.84} [1 + M' - (M')^{1.01}]\}$$

$$T_o = 1 - 0.1611 \, X_o \, (1 + 139.48 \, X_o)^{-0.3035} - 0.002715 \, X_o \, (1 + 0.044 \, X_o + 0.0003 \, X_o{}^2)^{-1}$$

$$X_o = U_o M$$

$$T_{UM} = \exp \, [-0.0127 \, (M')^{0.26}]$$

$$T_w = 1 - 2.4959 \, X_w \, [(1 + 79.034 \, X_w)^{0.6828} + 6.385 \, X_w]^{-1}$$

$$X_w = U_w M$$

$$T_A = \exp \, [\, \tau_A{}^{0.873} \, (1 + \tau_A - \tau_A{}^{0.7088}) \, M^{0.9108}]$$

$$\tau_A = 0.2758 \, \tau_{A,0.38} + 0.35 \, \tau_{A,0.5}$$

$$T_{AA} = 1 - K_1 (1 - M + M^{1.06})(1 - T_A)$$

$$T_{AS} = T_A / T_{AA}$$

$$r_s = 0.0685 + (1 - B_a)(1.0 - T_{as})$$

$$M = [\cos Z + 0.15(93.885 - Z)^{-1.25}]^{-1}$$

$$M' = MP/1013$$

ratio, B_a, is related through MIE theory to a parameter $\langle \cos \theta \rangle$, called the asymmetry factor, by

$$B_a = 0.5(1 + \langle \cos \theta \rangle)$$

The asymmetry factor is the mean of the cosine of the scattering angle, θ, with the angular intensity as the weighting function. The extreme values of B_a are

$$B_a = \begin{cases} 1 \text{ for all forward scattering;} \\ 0.5 \text{ for isotropic scattering;} \\ 0 \text{ for all backward scattering.} \end{cases}$$

Table 2-7 contains values of the asymmetry factor at various wavelengths for the rural aerosol model and the haze L aerosol model used by Dave [17]. Two differences in these aerosol models are: (1) the rural aerosol model is bimodal, whereas Dave's model has a single mode; and (2) the rural aerosol model varies the complex index of refraction with wavelength, and the Dave model holds it constant. The values of the asymmetry factors for the two models are in reasonably good agreement, and our calculations indicate that the Bird model is relatively insensitive to small changes in this parameter. A value of B_a = 0.82 was used for the rural aerosol, and B_a = 0.86 for Dave's aerosol in calculations shown later.

Table 2-7. VALUES OF THE ASYMMETRY FACTOR FOR THE RURAL AND THE DAVE HAZE L AEROSOL

Rural		Dave Haze L	
λ	⟨cos θ⟩	λ	⟨cos θ⟩
0.325	0.66	--	--
0.35	0.66	0.35	0.73
0.4	0.65	--	--
0.5	0.64	0.455	0.72
0.63	0.64	0.635	0.71
0.7525	0.63	0.7525	0.71
0.86	0.63	--	--
0.9935	0.63	0.994	0.70
1.235	0.64	1.235	0.69
1.497	0.65	1.61	0.67
1.8	0.68	2.1	0.63
2.198	0.71	2.198	0.62

It is suggested that values of B_a = 0.84 and K_1 = 0.1 be used with this model unless good information on the aerosol is available. All other data required by the model comes from meteorological measurements near the site of interest.

Ozone measurements are sometimes difficult to obtain. Since ozone has a minor effect on broadband solar insolation, it is suggested that the method of Van Heuklon [18] could be used in lieu of real data.

The expression used for air mass in the Bird model comes from Kasten [13] and was used for all of the calculations reported here except for the Atwater and Ball model and the Watt model.

For the convenience of the reader, Table 2-8 itemizes the input parameters required for each of the simple models.

Table 2-8. INPUT PARAMETERS REQUIRED FOR SIMPLE MODELS

Model	Input
Atwater and Ball	Solar constant, zenith angle, surface pressure, ground albedo, precipitable water vapor, total ozone, broadband turbidity
Davies and Hay	Solar constant, zenith angle, surface pressure, ground albedo, precipitable water vapor, total ozone, aerosol single scattering albedo (0.98 suggested), aerosol forward scattering ratio (0.85 suggested), broadband aerosol transmittance
Watt	Solar constant, zenith angle, surface pressure, ground albedo, precipitable water vapor, total ozone, turbidity at 0.5-µm wavelength, upper layer turbidity
Hoyt	Solar constant, zenith angle, surface pressure, ground albedo, precipitable water vapor, total ozone, turbidity at one wavelength
Lacis and Hansen	Solar constant, zenith angle, surface pressure, surface temperature, ground albedo, precipitable water vapor, total ozone
Bird	Solar constant, zenith angle, surface pressure, ground albedo, precipitable water vapor, total ozone, turbidity at 0.5- and/or 0.38-µm wavelength, aerosol forward scattering ratio (0.84 recommended)

2.7 RIGOROUS CODES

Three rigorous codes have been used in this study as a basis for formulating the Bird model. One code is for direct normal irradiance and is called SOLTRAN 4 [4]. Two other codes, which include both the direct normal and the diffuse irradiance, are the BRITE [14] Monte Carlo code and the Dave [17] Spherical Harmonics code. In each of these codes, a multilayered atmospheric model can be constructed, where important atmospheric parameters are defined at each layer. In this way, a fairly detailed atmosphere can be constructed that closely resembles the real atmosphere at a given time and specific location. Each code then uses its own technique to solve the radiative transfer problem.

These rigorous codes calculate the irradiance at a specified altitude, sun angle, and for an atmospheric model at discrete wavelengths. For comparison with the simple broadband models described previously, the spectral irradiance from the rigorous codes has to be integrated over wavelength.

The SOLTRAN 3 code, an earlier version of SOLTRAN 4, was used to formulate most of the transmittance functions found in the Bird model. This was accomplished by performing a least-square fit of each transmittance function to transmittance data from SOLTRAN 3 for each atmospheric constituent. Further details of this operation can be found in Ref. 4. SOLTRAN 3 was used because it was the only version available to us when this portion of the work was performed. The only difference in the two models that would be apparent in the results would be caused by a slight difference in the "continental" and "rural" aerosol models that are used in the two codes.

A comparison was made between data from the BRITE code and several of the simple clear sky global models. Based on this comparison and the author's judgment of the best expressions used in the simple models, a model for the diffuse irradiance was formulated. This simple model of the diffuse irradiance was then fine-tuned to provide good agreement with the BRITE code as well as results from the Dave Spherical Harmonics code.

It is appropriate to comment here that there are problems with the expressions used for the diffuse irradiance model. The general formalism for the diffuse transfer equation of some of the simple models was adopted even though it may not be as acceptable, based on the physics of the problem, as one would like. For example, a cosine of the solar zenith angle is included in the diffuse transfer equation. This implies that all of the diffuse radiation behaves just like the direct normal component. The cosine is used to calculate the irradiance falling on a horizontal surface. However, it is well known that the diffuse irradiance is much more complex than this. An example of a more rigorous but fairly simple formalism for the diffuse irradiance is found in Ref. 19, in which the diffuse radiation is divided into three components: an isotropic term, a term resulting from horizon brightening, and a circumsolar term. The circumsolar term is the only one that behaves very much like the direct normal radiation. For tilted surfaces, a ground reflection should be added to this diffuse model. Another problem with this formalism is associated with using transmittance expressions for diffuse radiation that were derived for direct radiation.

SECTION 3.0

MODEL COMPARISONS

Each of the simple models described in Section 2.0 was programmed on a computer to produce data for comparison. A comparison of the aerosol transmittance, the transmittance after molecular (Rayleigh) scattering, the water vapor (H_2O) transmittance, and the ozone (O_3) transmittance will be presented first. Then, a comparison between the direct, the diffuse sky, the diffuse sky/ground, and the global radiation for three different atmospheric models will be shown. Comparisons are made, where possible, between each of the simple model results as well as the results from the rigorous models.

3.1 TRANSMITTANCE COMPARISONS

To become oriented as to the relative importance of each atmospheric constituent in atmospheric transmittance, the broadband transmittance versus the secant of the solar zenith angle (approximate air mass) for each constituent was plotted in Fig. 3-1. This figure was generated with output from the SOLTRAN 3 code for a Midlatitude Summer (MLS) atmospheric model. Table 3-1 shows the amounts of H_2O and O_3 from sea level to the top of the atmosphere in a vertical column for the two atmospheric models--MLS and USS (U.S. Standard)--used in this comparison.

Table 3-1. AMOUNTS OF H_2O AND O_3 IN A VERTICAL COLUMN FOR THE MLS AND USS ATMOSPHERES

	H_2O (cm)	O_3 (cm)
MLS	2.93	0.31
USS	1.42	0.34

An examination of Fig. 3-1 shows that CO_2 and O_2 are the least important attenuators, and this is why they are not included in some models. The next element exhibiting increased attenuation is O_3, followed by H_2O. Molecular scattering dominates the total molecular absorption at large zenith angles and has a greater effect than most individual molecular species at all zenith angles. The most significant attenuator at all zenith angles is the aerosol. The aerosol modeled here was the continental aerosol model [16] with a sea level meteorological range of 23 km. A 23-km meteorological range is considered to be a moderately clear atmosphere. This aerosol produces an optical depth of 0.27 (base e) at 0.5-μm wavelength.

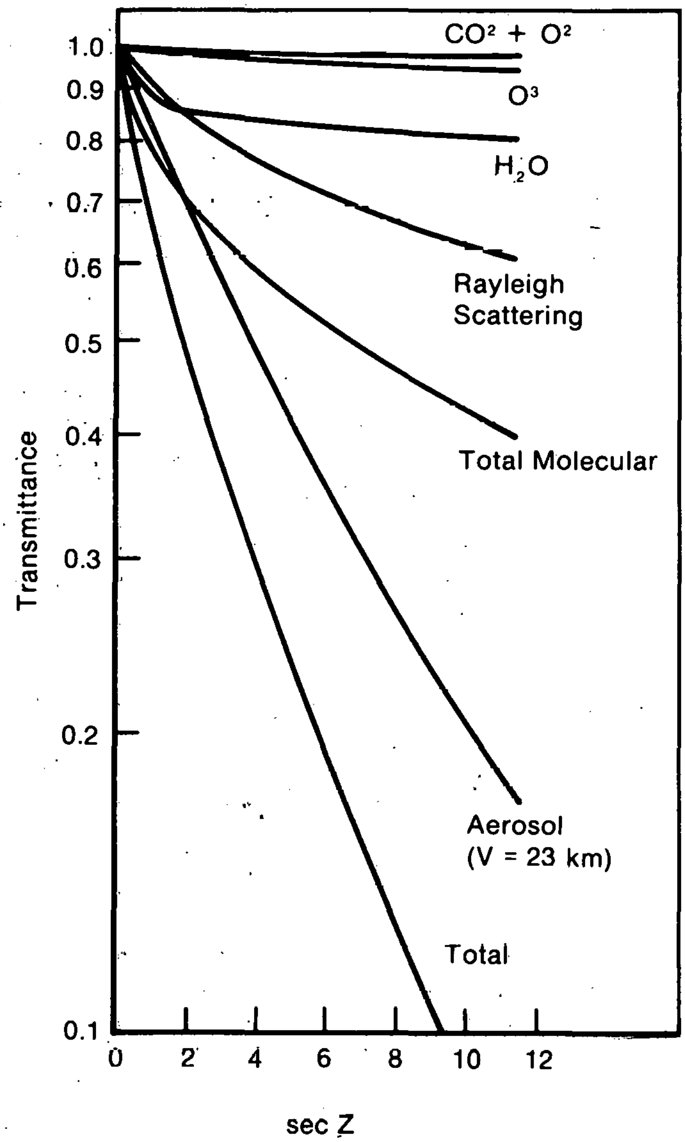

Figure 3-1. Transmittance versus Secant of Solar Zenith Angle for Midlatitude Summer Model

The data in Fig. 3-1 indicate the relative effect that the atmospheric constituents have on the direct irradiance. However, when global irradiance is being considered these results can be misleading. A large fraction of the radiation lost in the direct beam by molecular and aerosol scattering is regained in the diffuse component. As a result of this, changes in aerosol optical depth through the atmosphere have less effect on the total global irradiance than on the direct irradiance.

Figures 3-2 and 3-5 present transmittance data for the USS atmosphere from several of the models. It should be pointed out that the broadband turbidity expression from the Bird model was used in the Atwater and Ball model. A similar effort could have been made with the aerosol transmittance term in the Davies and Hay model to produce identical results. One of the strengths of the Bird model is that it is based entirely on algebraic expressions for transmittance calculations rather than tabulated data. This makes the use of the model considerably easier and provides more flexibility.

The comparison made here for one model atmosphere is not really indicative of the accuracy of each model. Since a wide range of values of turbidity, H_2O amount, and O_3 amount are required for real atmospheric conditions, the model must be able to accommodate these changes. Additional comparisons are presented in Ref. 4 for a range of these parameters. As was stated earlier, the transmittance expressions in the Bird model were derived from comparisons with SOLTRAN 3 results, but the comparisons made here are with SOLTRAN 4 results. This should have an effect only on the aerosol transmittance shown in Fig. 3-2. The transmittance comparisons shown in Figs. 3-2 through 3-5 are rather self-explanatory, and so no further discussions are presented.

3.2 IRRADIANCE COMPARISONS

The global solar irradiance has been divided into three components: the direct irradiance on a horizontal surface, the diffuse sky irradiance on a horizontal surface, and the diffuse ground/sky irradiance on a horizontal surface. The diffuse sky irradiance is the total diffuse radiation present when the ground has zero albedo (completely absorbing ground), and the diffuse ground/sky irradiance is that amount added to the total diffuse irradiance when the ground albedo is not zero.

Figures 3-6 through 3-9 present comparisons of the global irradiance at sea level in the USS atmosphere from all of the models as well as comparisons of the three components of the global irradiance. For this atmospheric model, the Bird, Hoyt, and Monte Carlo models produce very similar results. The model of Atwater and Ball significantly underestimates the diffuse sky irradiance, and the Watt model overestimates the diffuse sky irradiance. The results of the Davies and Hay model would have shown much better agreement with the Monte Carlo results if a more reasonable value of the aerosol transmittance had been used. The Bird model Rayleigh transmittance was used in the Davies and Hay model.

It is instructive to examine the relative magnitude of each component. For a solar zenith angle of zero (the sun directly overhead), the direct component provides approximately 81% of the total, the diffuse sky approximately 17%,

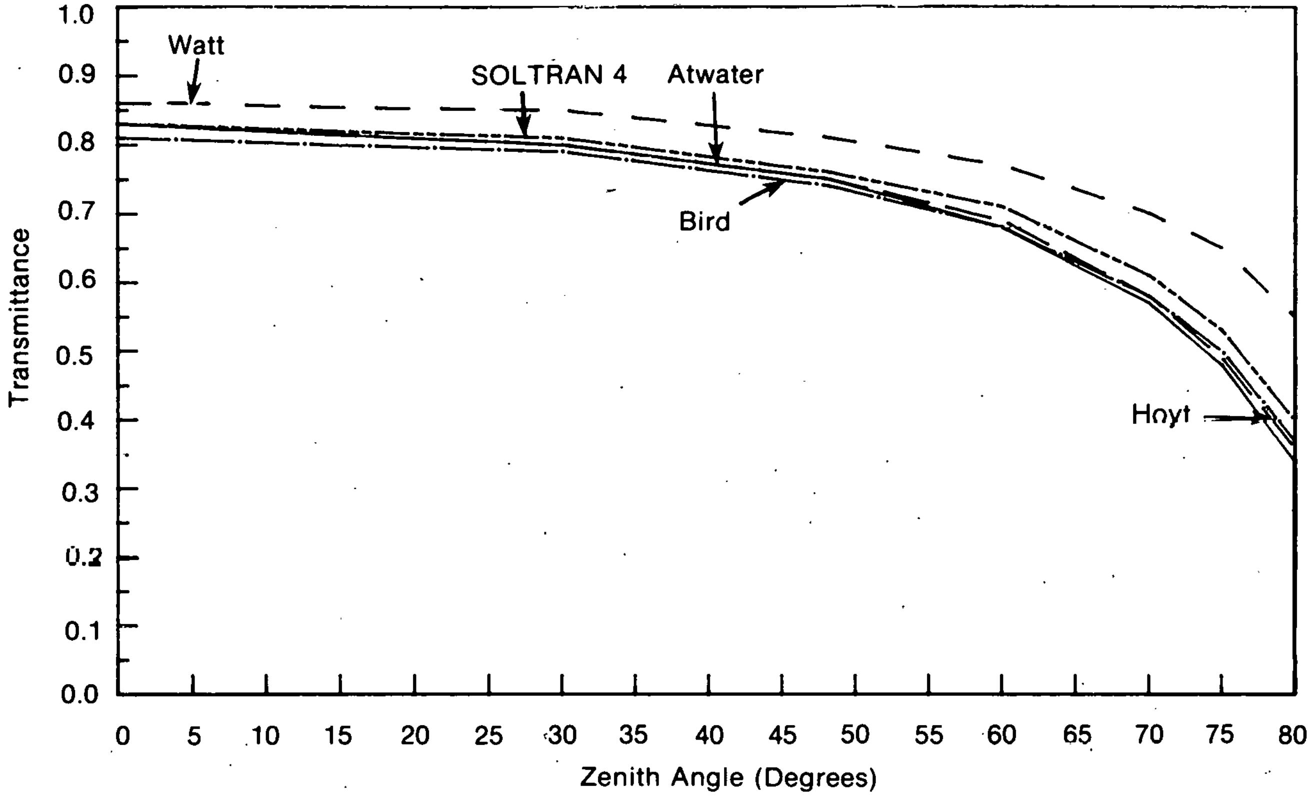

Figure 3-2. Aerosol Transmittance – USS Atmosphere (23-km-Visibility Aerosol)

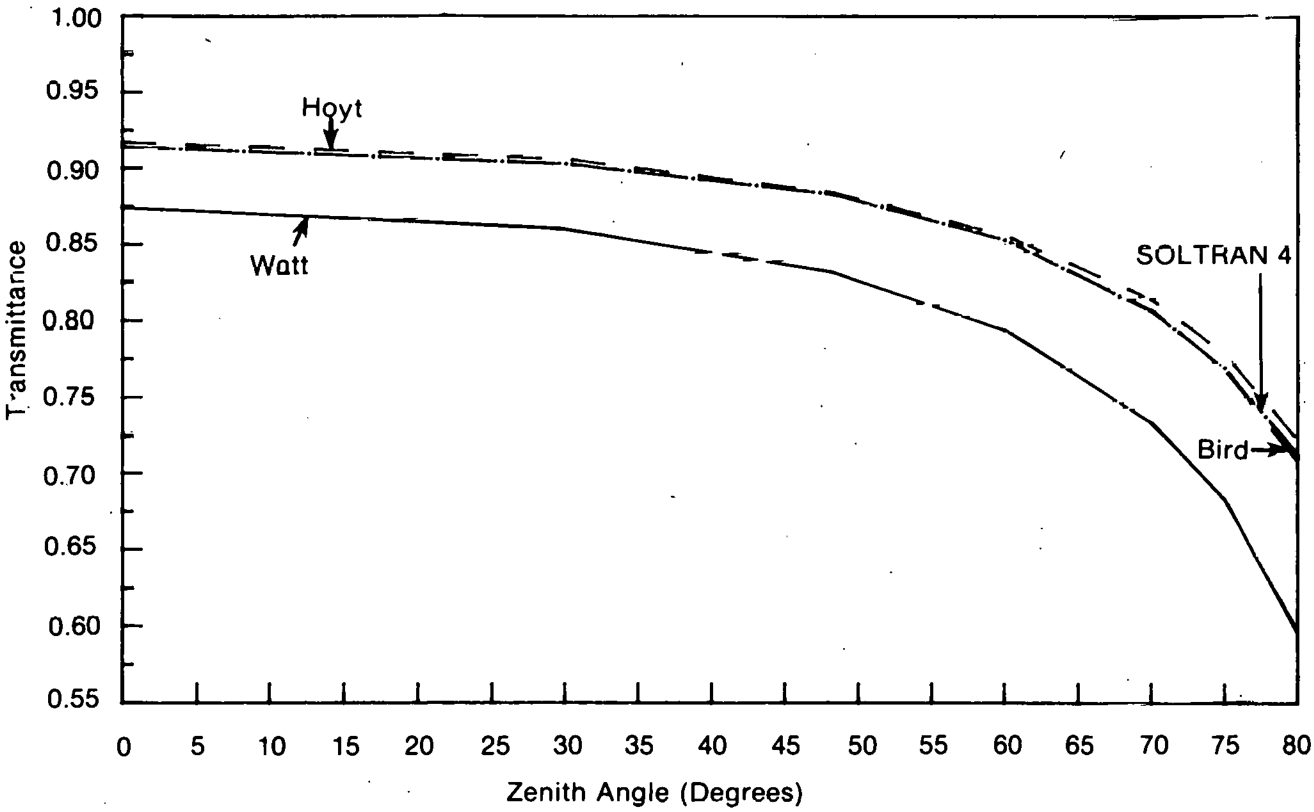

Figure 3-3. Rayleigh Transmittance

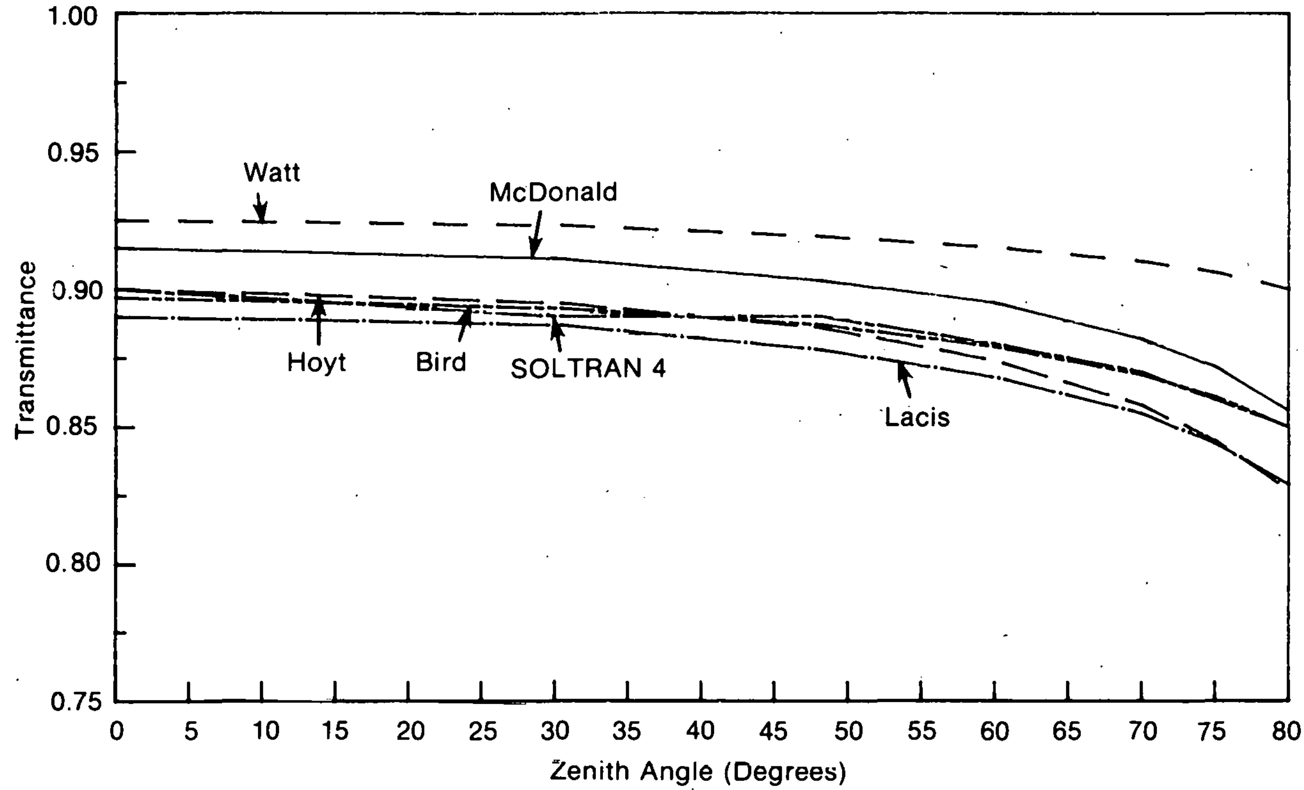

Figure 3-4. Water Vapor Transmittance – USS Atmosphere (1.42-cm H_2O in Vertical Column)

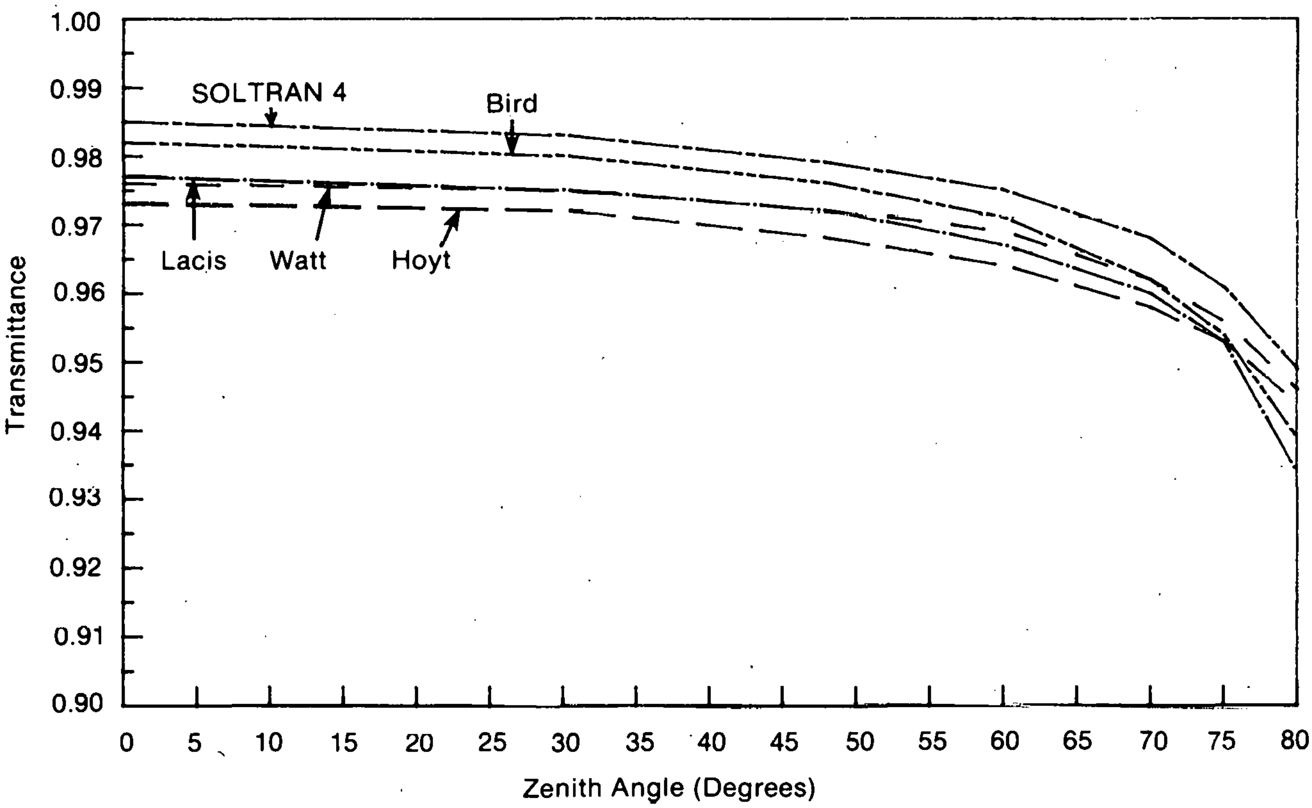

Figure 3-5. Ozone Transmittance — USS Atmosphere

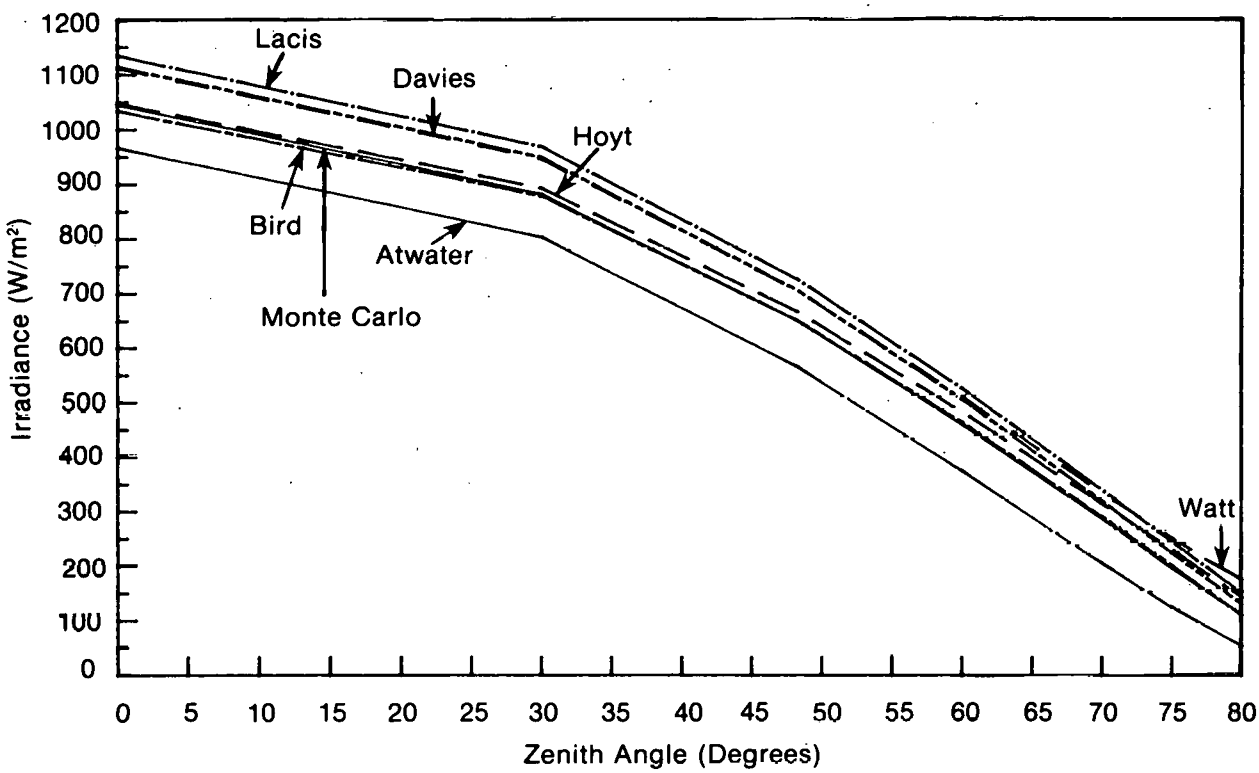

Figure 3-6. Total Insolation – USS Atmosphere (23-km-Visibility Rural Aerosol, Albedo = 0.2)

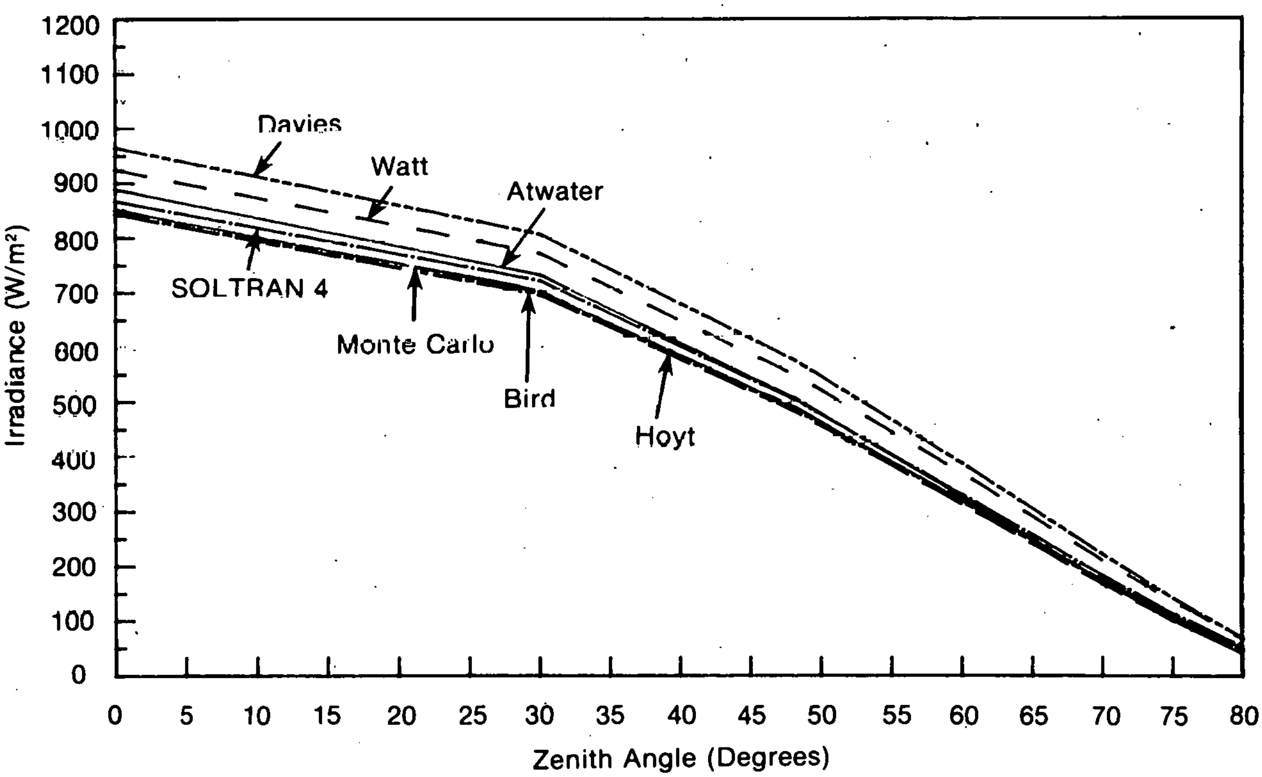

Figure 3-7. Direct Horizontal Insolation – USS Atmosphere (V = 23 km; U_W = 1.42 cm; U_O = 0.34 cm)

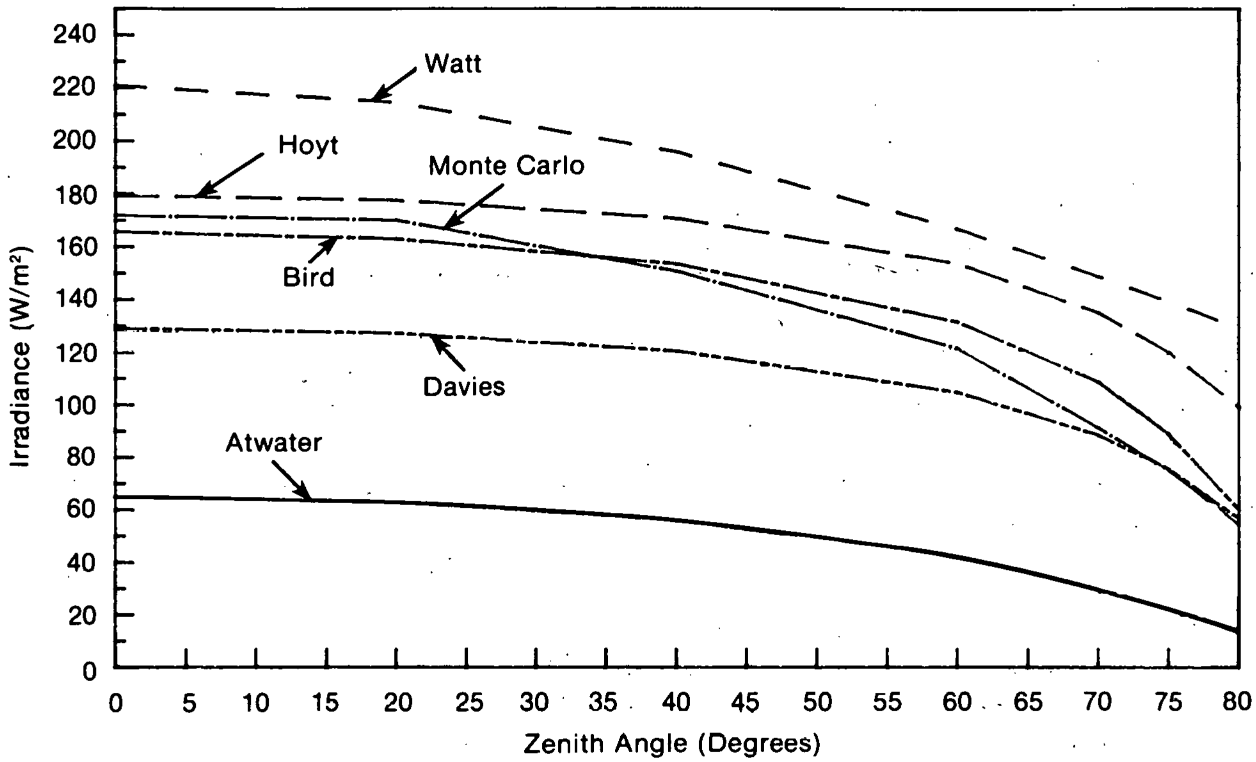

Figure 3-8. Diffuse Sky Insolation – USS Atmosphere (V = 23 km; U_W = 1.42 cm; U_O = 0.34 cm)

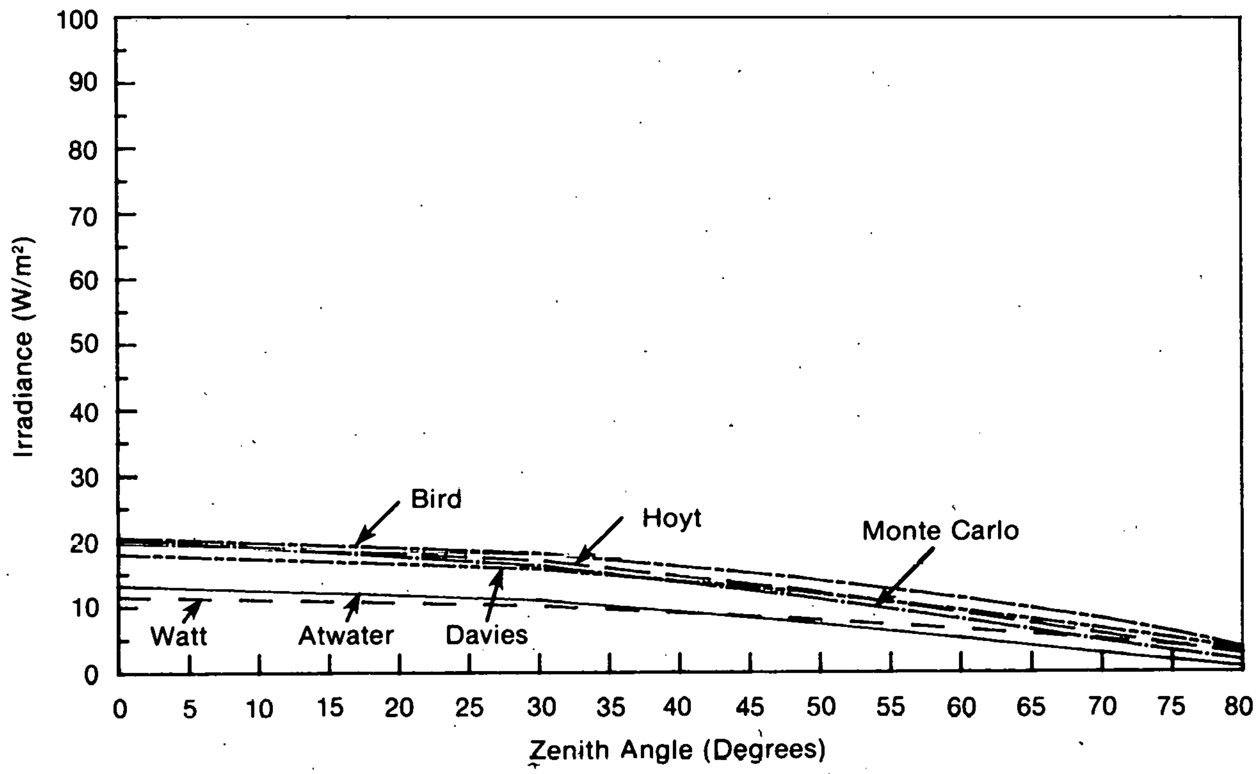

Figure 3-9. Diffuse Ground/Sky Insolation – USS Atmosphere (23-km-Visibility Rural Aerosol, Albedo = 0.2)

and the diffuse ground/sky approximately 2%. The calculations are for a turbidity of 0.27 at 0.5-μm wavelength and a ground albedo of 0.2.

In Figures 3-10 through 3-13, a similar set of plots is presented for the MLS atmospheric model with an atmospheric turbidity of 0.27 at 0.5-μm wavelength and a ground albedo of 0.8. The larger ground albedo increases the diffuse ground/sky component by a factor of four. It is evident that the simple models begin to deviate from the Monte Carlo result for the diffuse ground/sky component. However, since this component is so small, the global result is still in close agreement. The relative agreement of the results from the different models is nearly the same as with the USS atmosphere. This is principally because the aerosol model is identical in both models.

Finally, a comparison is made of the models for the MLS atmosphere with the Haze L aerosol model of Dave [17]. The Dave atmosphere modeled here consists of 15 homogeneous layers instead of the 32 exponentially varying layers that were used in the previous MLS atmosphere. In addition, the Haze L aerosol model is significantly different from the rural aerosol model used previously. Not only are the particle size distributions and complex indices of refraction different, but most importantly the number density of the aerosol as a function of altitude is very different. The turbidity of this model is 0.0996 instead of the 0.266 used previously in the vicinity of 0.5-μm wavelength. Calculations with SOLTRAN 4 show that a turbidity of 0.0996 in the rural aerosol model corresponds to a sea level visibility of nearly 250 km. This is an extremely clear atmosphere. Figures 3-14 through 3-17 illustrate the comparison results for this atmospheric model.

It is readily apparent from the results shown in Figs. 3-14 through 3-17 that the Atwater and Ball model is based on a very clear atmosphere, since it agrees much better with the Dave data. Similarly, the aerosol parameter, K = 0.91, used in the Davies and Hay model is for a very clear atmosphere. The Lacis and Hansen model appears to be in slightly closer agreement with this clear atmosphere also, but it does not have provisions for changes in turbidity.

The clear sky diffuse irradiance of the Atwater and Ball model as shown in the figures presented here may be slightly lower than the model intended because of the way the calculations were performed. This model is really composed of two separate models: one for the direct irradiance and one for the global irradiance. The clear sky diffuse irradiance was obtained by running the model for a ground albedo of zero and then subtracting the direct horizontal from the global. If the direct horizontal irradiance is slightly high, as it appears to be, then the diffuse term would be slightly lower than expected. The real evaluation of this model should be made on the global horizontal irradiance.

It will be noted in Fig. 3-14 that there is a slight difference between the Monte Carlo global and the spherical harmonic global results of Dave (~3.6% at a zenith angle of 0). Figure 3-15 shows that a large fraction of this difference is in the direct component. Since the direct component of the Monte Carlo code is deterministic in nature rather than statistical, these differences are most likely due to differences in the molecular absorption coefficients used and the band absorption models used. Dave used an older set

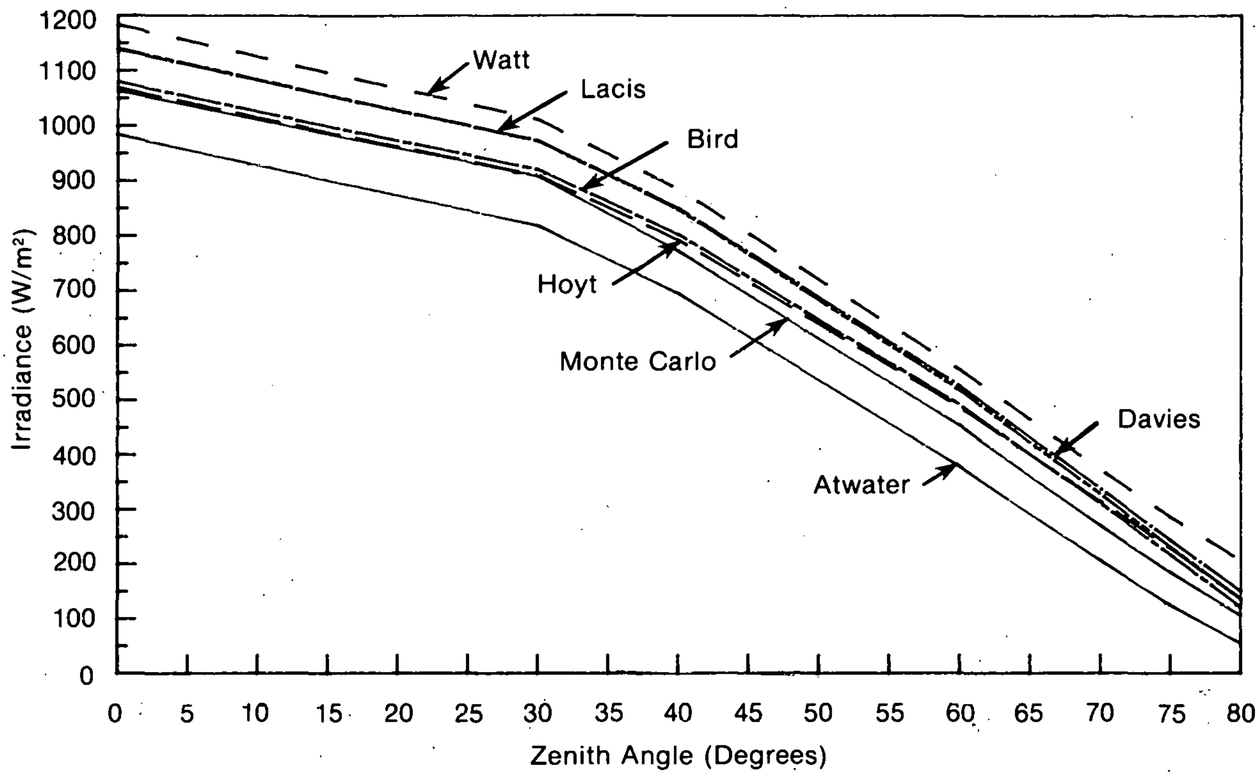

Figure 3-10. Total Insolation – MLS Atmosphere (23-km-Visibility Rural Aerosol, Albedo = 0.8)

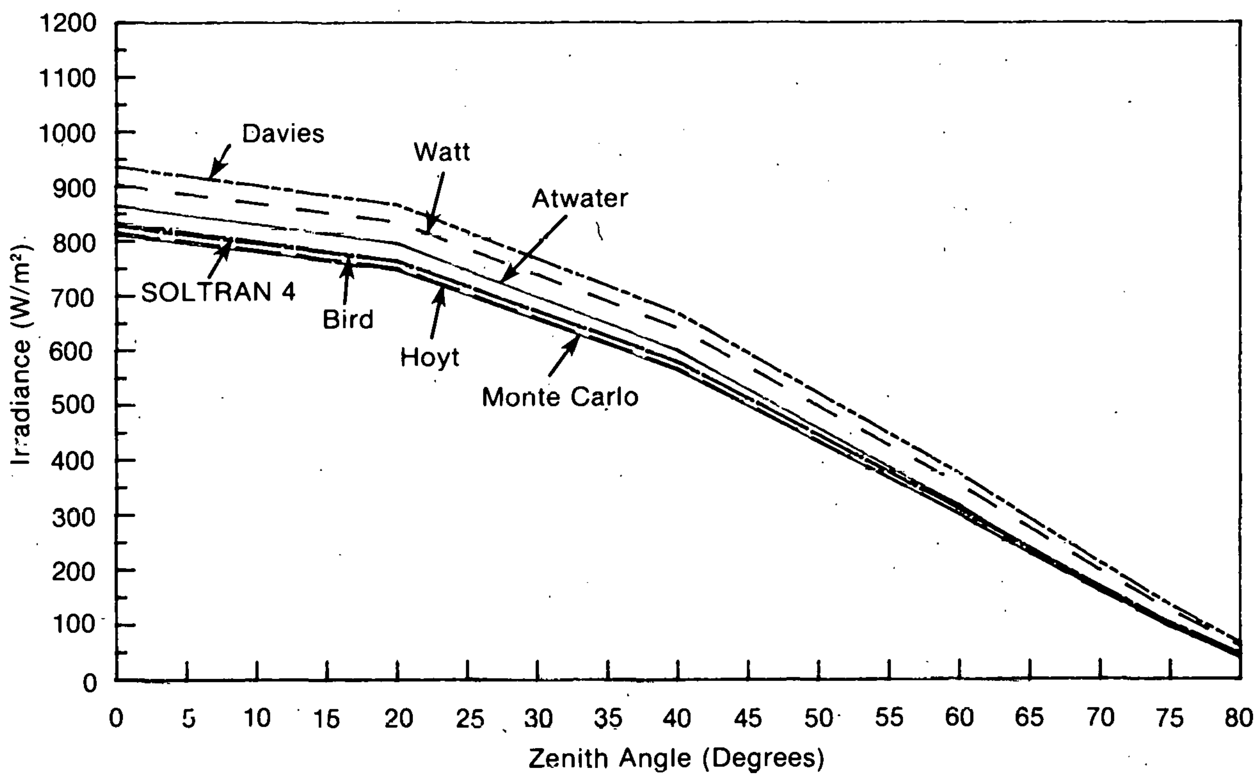

Figure 3-11. Direct Horizontal Insolation – MLS Atmosphere (V = 23 km, U_W = 2.93 cm, U_O = 0.31 cm)

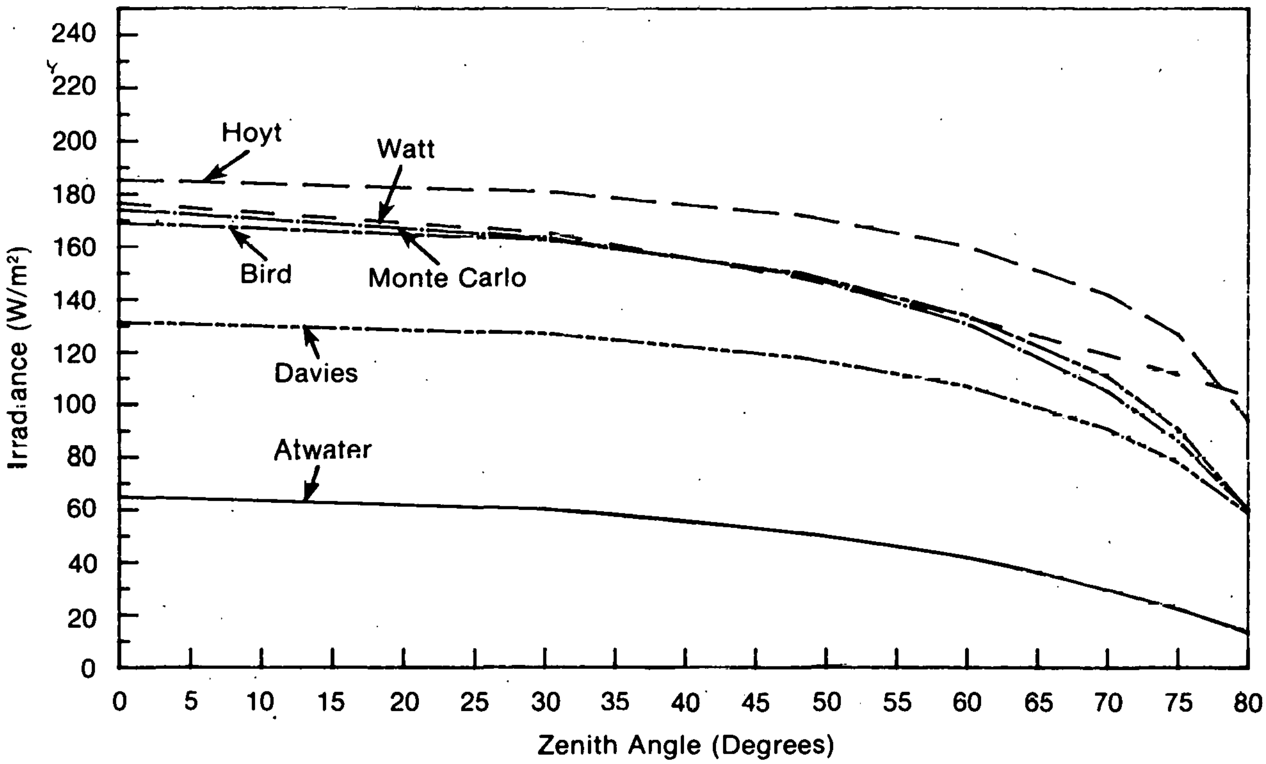

Figure 3-12. Diffuse Sky Insolation — MLS Atmosphere (V = 23 km, U_W = 2.93 cm, U_O = 0.31 cm)

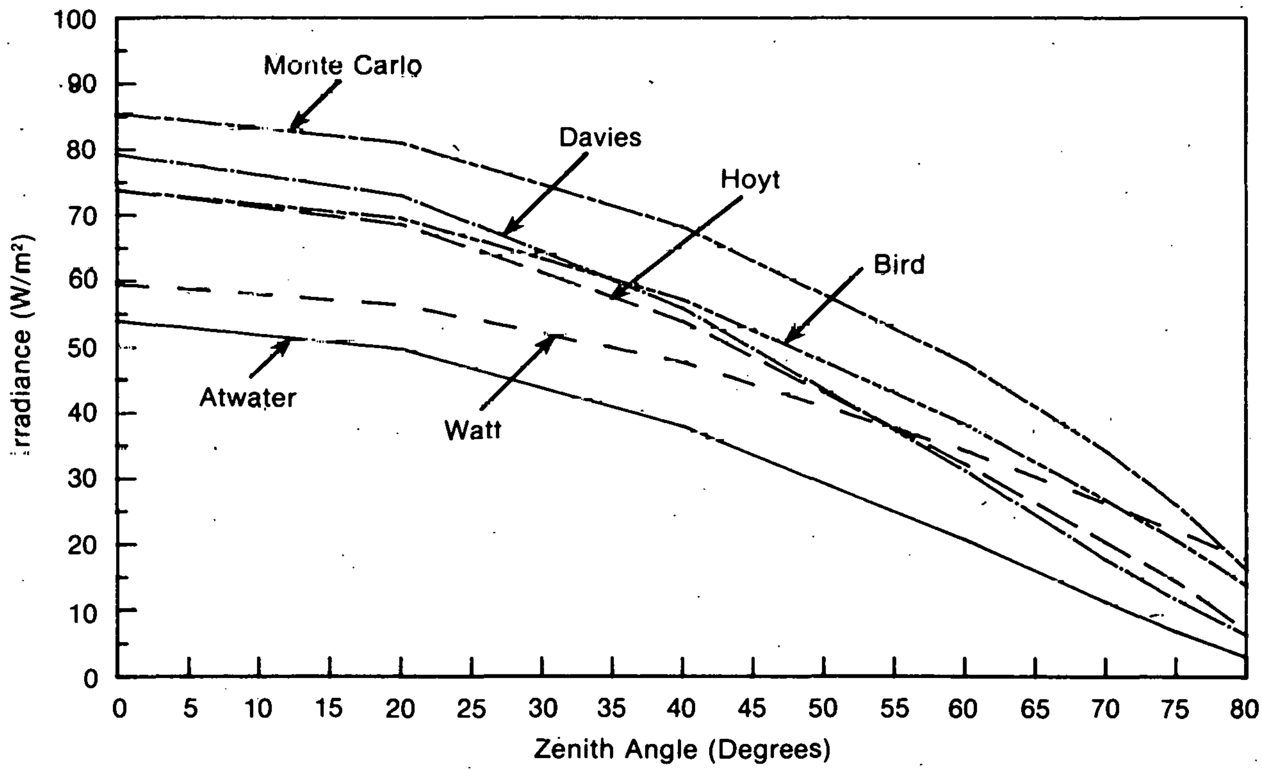

Figure 3-13. Diffuse Ground/Sky Insolation – MLS Atmosphere (23-km-Visibility Rural Aerosol, Albedo = 0.8)

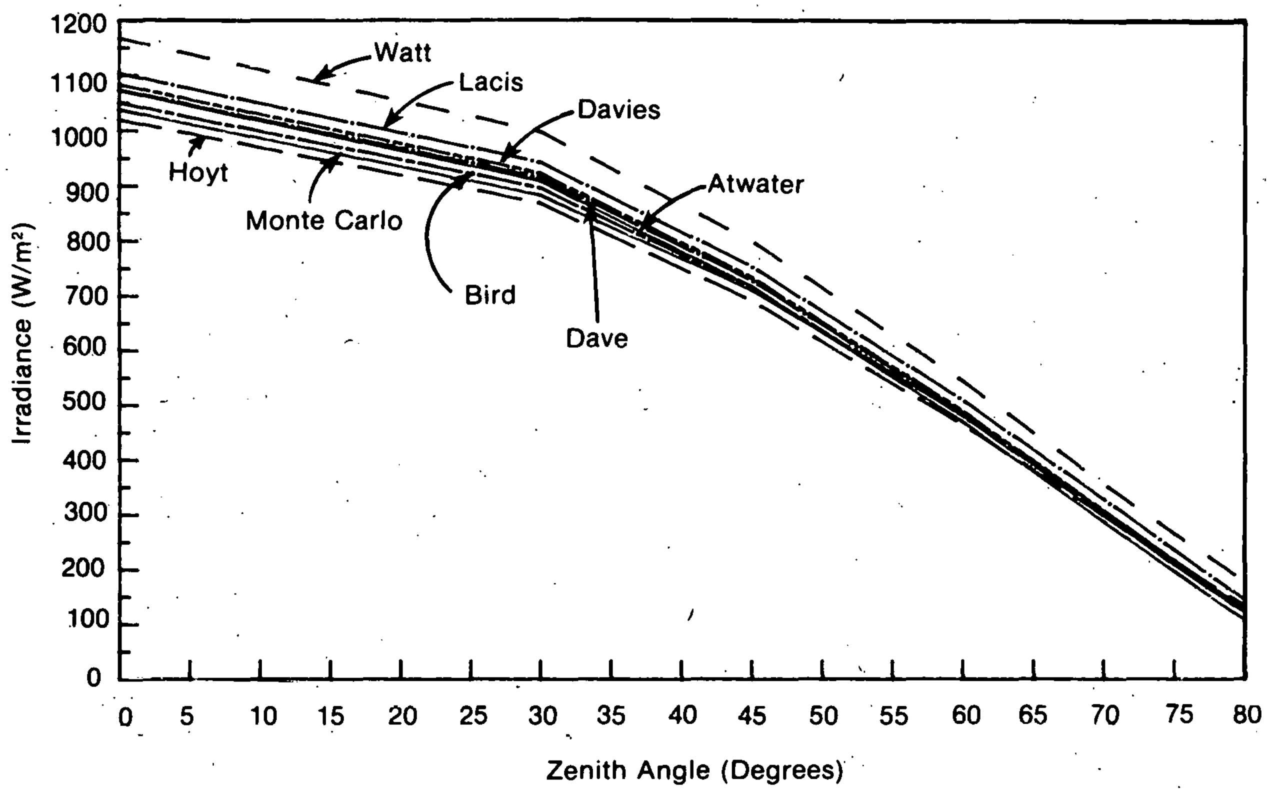

Figure 3-14. Total Insolation—Dave Model 3 (Albedo = 0.2)

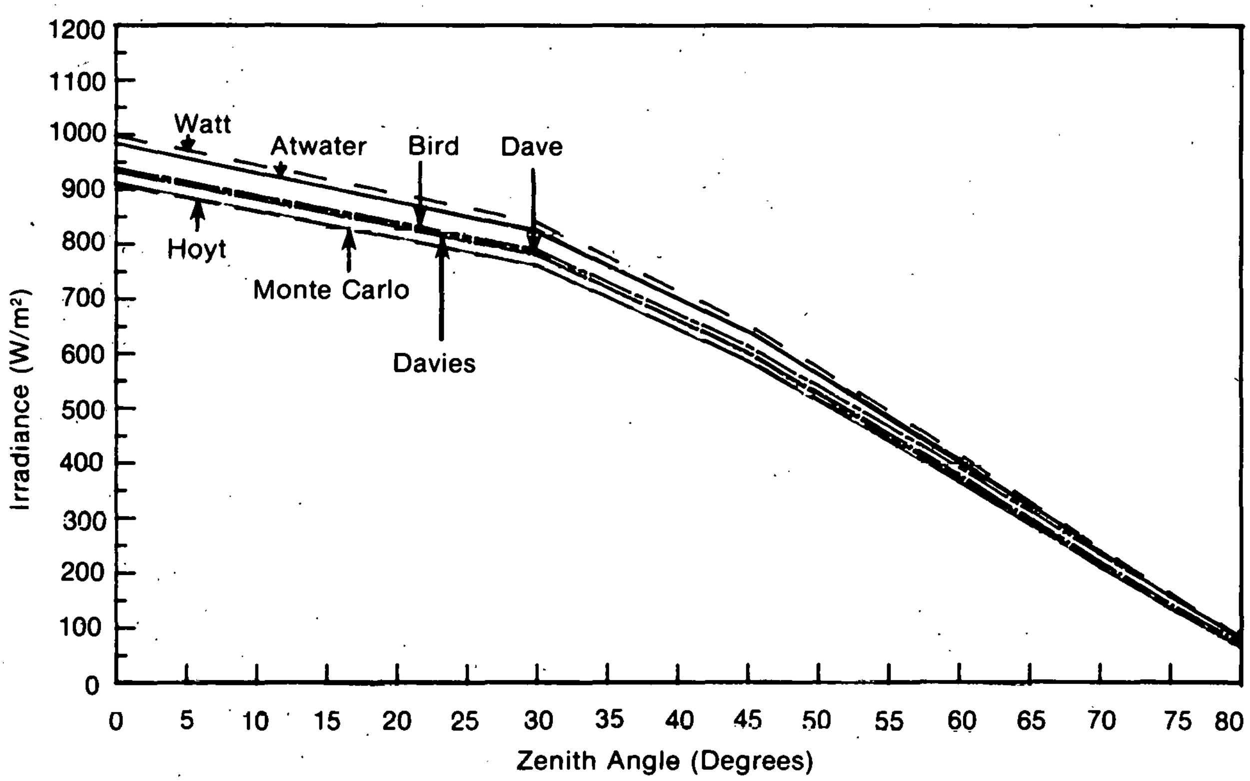

Figure 3-15. Direct Horizontal Insolation—Dave Model 3 (U_W = 2.93 cm, U_O = 0.31 cm)

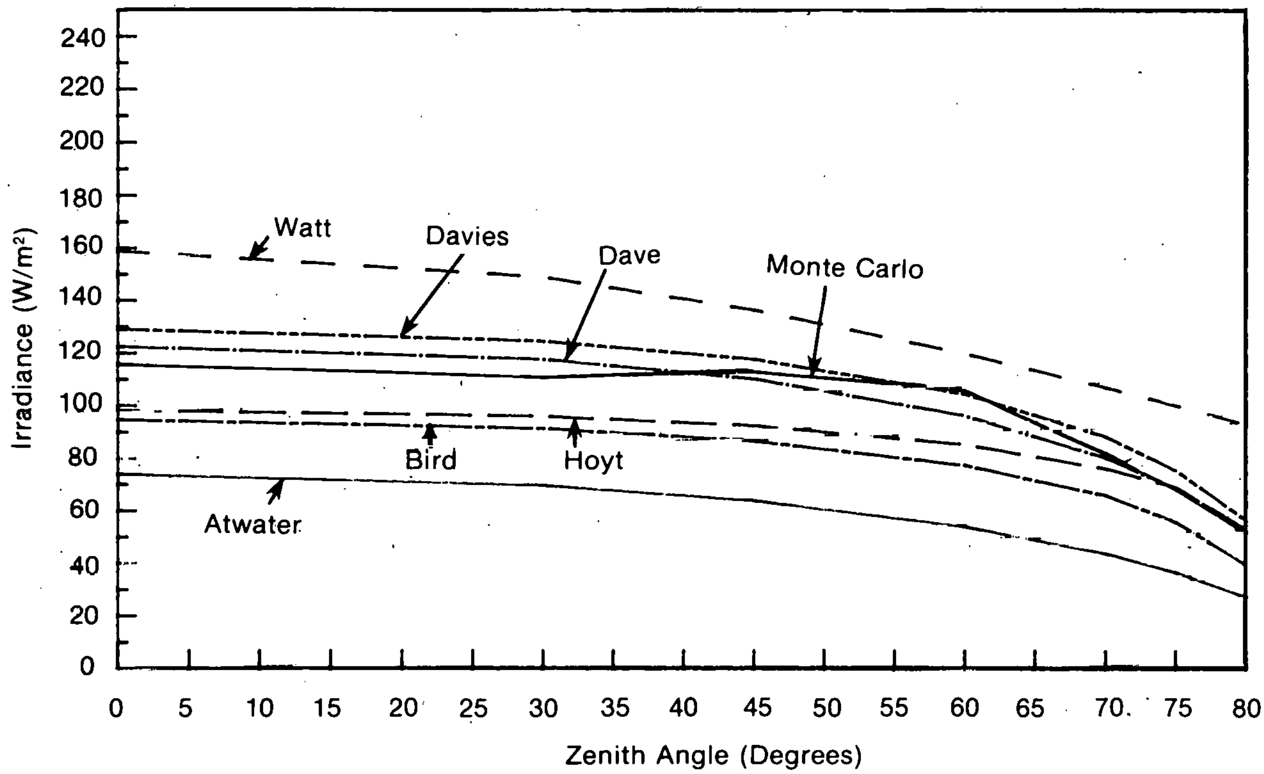

Figure 3-16. Diffuse Sky Insolation—Dave Model 3 (U_W = 2.93 cm, U_O = 0.31 cm)

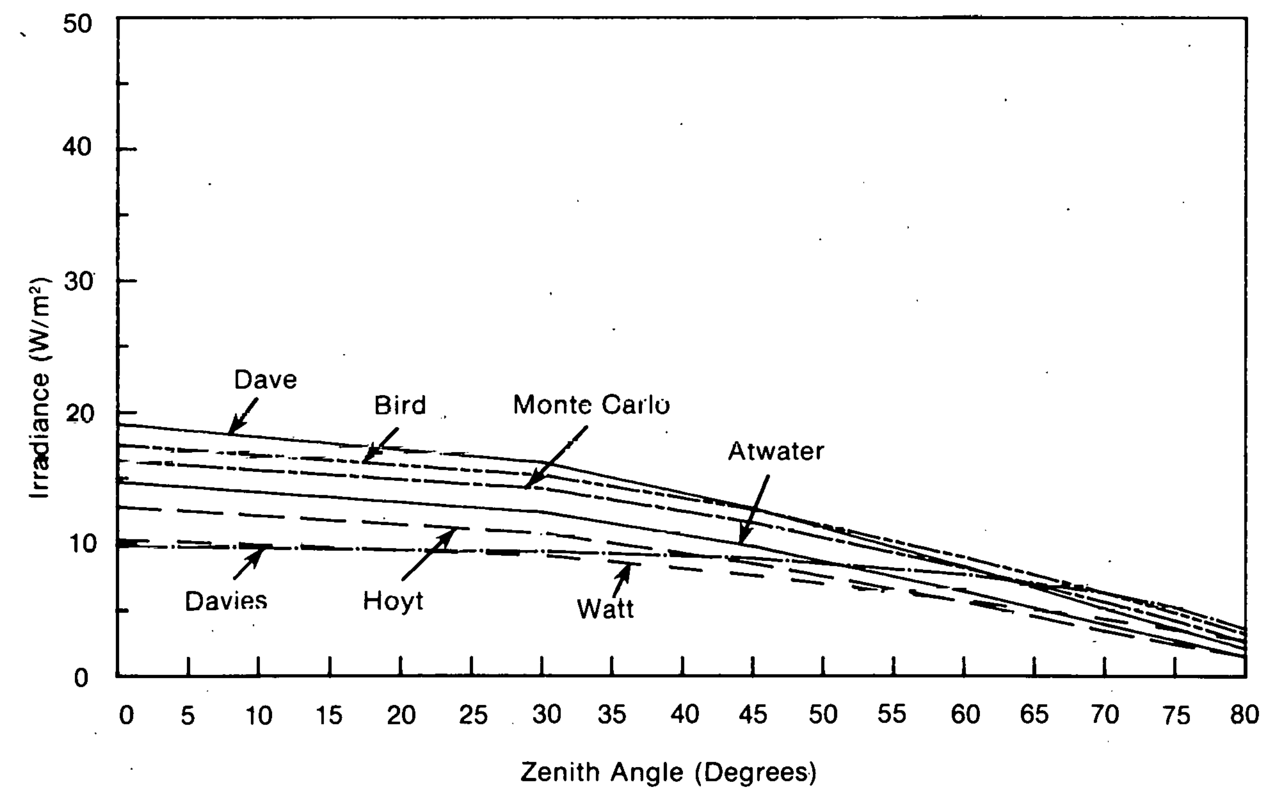

Figure 3-17. Diffuse Ground/Sky Insolation—Dave Model 3 (Albedo = 0.2)

of molecular absorption coefficients from AFGL than was used in the Monte Carlo code [20]. Figure 3-18 is a comparison of the spectral direct irradiance for these two codes. It is evident that there are some weak absorption bands present in the Monte Carlo code that are not present in the spherical harmonics code, and the shape of some of the bands is significantly different for the two codes. SOLTRAN 4 is based on the same absorption data that Dave used, and similar differences in the direct normal irradiance occur between SOLTRAN 4 and the Monte Carlo code. These differences are shown in Fig. 3-19, which has 31 more data points in the Monte Carlo results than in Fig. 3-18. This increase in the number of data points increases the apparent spectral resolution. The SOLTRAN 4 code provided approximately 600 data points in this figure. Our conclusion is that most of the differences in the results from the rigorous codes are due to differences in the molecular absorption coefficients used.

A final observation is that many of the simple models have been based on actual measured data rather than comparison to rigorous models. This fact can make a difference in the direct normal irradiance or the diffuse irradiance but should not affect the total irradiance. The reason for this is that pyrheliometers measure the irradiance in a 5.8-degree field-of-view, which includes some diffuse or circumsolar irradiance. The rigorous codes include only the direct normal irradiance with no circumsolar. This means that the direct normal irradiance calculated with the Bird model will slightly underestimate the irradiance measured by a pyrheliometer. On a normal clear day, one is talking about less than a 1% underestimation. Let us reiterate that the total insolation should agree.

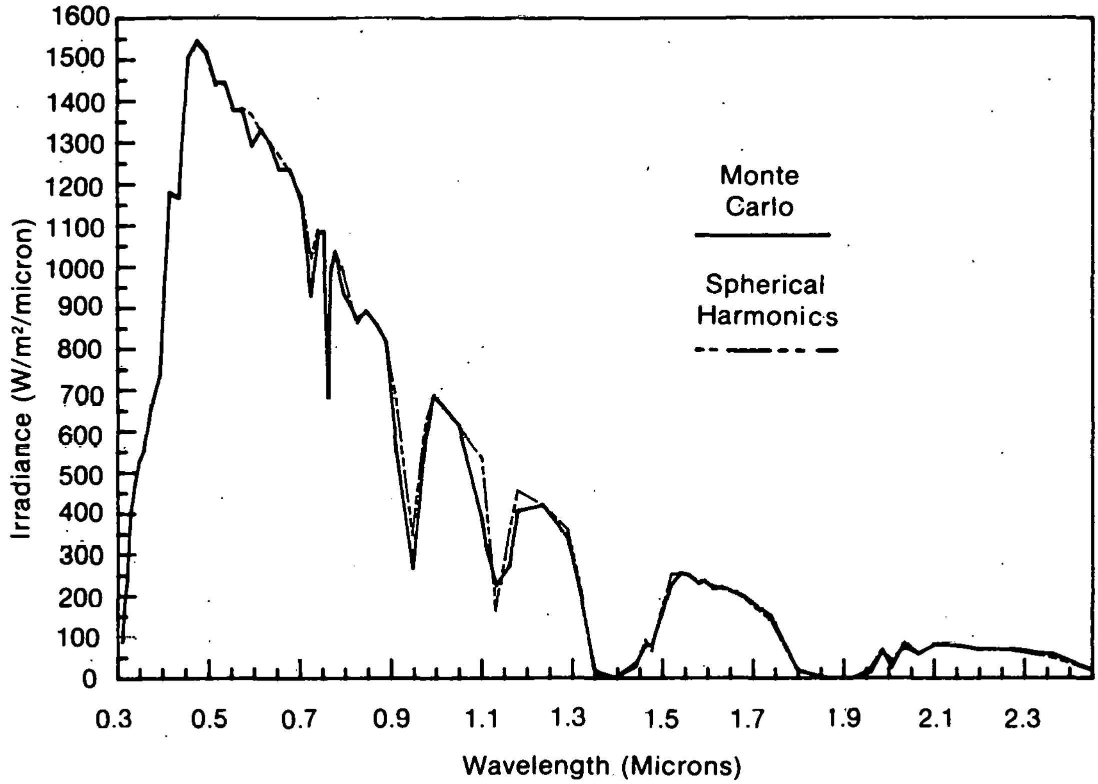

Figure 3-18. Direct Normal Insolation — Dave Model 3 (AM1)

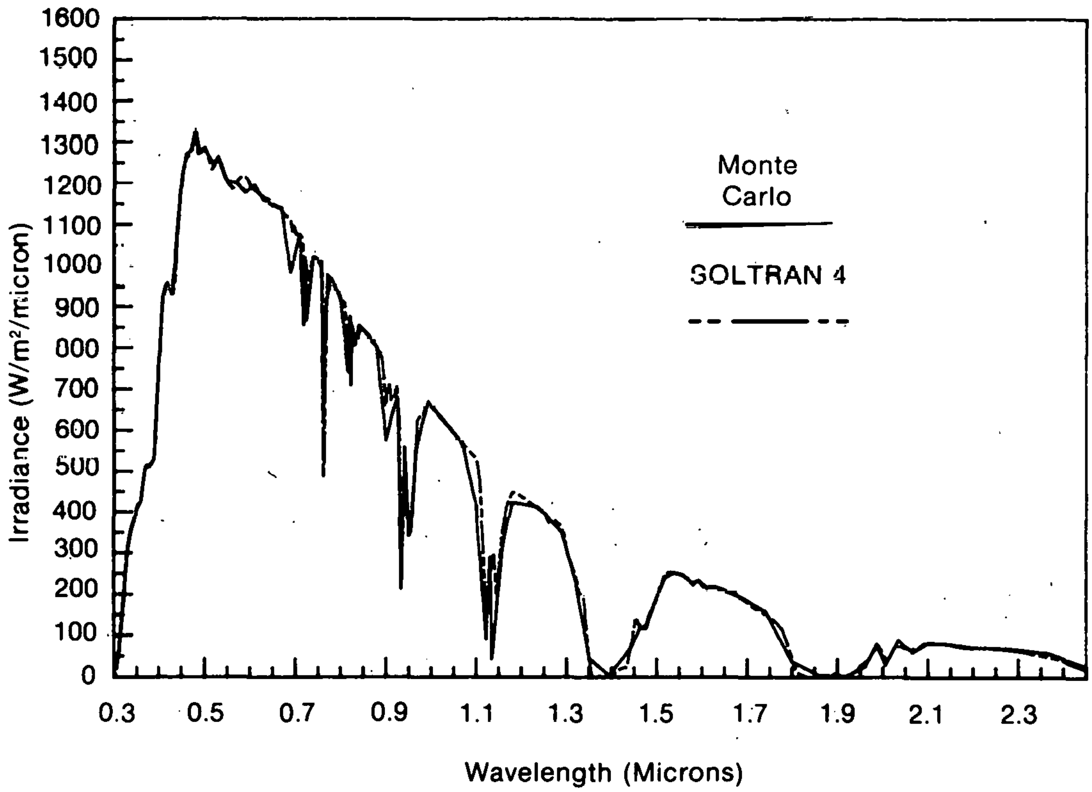

Figure 3-19. Direct Normal Insolation—USS Atmosphere (23-km-Visibility Rural Aerosol, AM1)

SECTION 4.0

SUMMARY AND CONCLUSIONS

Five simple broadband models for clear sky global horizontal insolation have been compared with the spectrally integrated results from three rigorous spectral codes. As a part of this comparison, a sixth simple broadband model has been formulated. This sixth model, designated the Bird model, uses parts of the formalisms from the other simple models and has been fine-tuned to provide good agreement with the rigorous codes. The Bird model was constructed so that readily available meteorological data could be used in it. It is based entirely on algebraic expressions rather than look-up tables, which greatly simplifies the use of the model.

The comparison of the results from each of the simple models with the results of the rigorous codes indicates the following:

- The Atwater and Ball model is applicable to extremely clear atmospheric conditions with an atmospheric turbidity (base e) near 0.1- at 0.5-μm wavelength. For turbidities near 0.27, this model underestimated the global irradiance by approximately 8% for air mass 1 (AM1). This model is extremely simple but does not have a good method of treating aerosol transmittance.
- The Watt model is relatively complicated and appears to overestimate the global insolation for AM1 conditions by approximately 7%. This is a complete model based on meteorological parameters. However, the upper air turbidity required in this model is not readily available.
- The Hoyt model provides excellent agreement with the rigorous codes. However, its use of look-up tables and the requirement to recalculate transmittance and absorptance parameters for modified air mass values causes this model to be relatively difficult to use.
- The Lacis and Hansen model is extremely simple. It tends to overestimate the global irradiance by approximately 8% at AM1, and it has no provisions for calculating direct irradiance.
- The Davies and Hay model could possibly provide good agreement with the rigorous codes. However, it uses a look-up table for the Rayleigh scattering transmittance term and does not have a good method for treating aerosol transmittance. The aerosol transmittance through a vertical path used by Davies and Hay for southern Ontario (K = 0.91) is for an extremely clear atmosphere.
- It is hoped that the rigorous codes and accurate simple models will provide results that will agree within ± 5% with quality experimental data on clear days. Cloudy days are much more difficult to model accurately, and clouds can have the greatest effect on the total irradiance. Models that address cloud influences for irradiance will be examined at a later date.

- It should be recalled that the basis of comparison/evaluation of the simple models is the much more rigorous radiative transfer codes--as opposed to a comparison with actual data. Because of a lack of suitable, high-quality data, comparisons with actual data are impossible at this time. The greatest deficiency has been the lack of meteorological measurements accompanying good insolation data. However, efforts* are currently underway at SERI and several universities to provide such data. As this data becomes available, comparisons and improvements will be made. Until then, it appears that both the Hoyt and Bird simplified models yield results in good agreement with the rigorous techniques. However, the Bird model is more flexible and easily used.

*As part of the U.S. Department of Energy's Insolation Resource Assessment Program.

SECTION 5.0

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APPENDIX A

TABULATED MODEL DATA

Three sets of tabulated data from each simple model are presented here, and each set represents one of the atmospheric models discussed in the main text. The parameters listed at the top of each table are:

I_o	=	Solar constant (W/m^2)
UW	=	Precipitable water vapor in vertical path (cm)
UO	=	Ozone amount in vertical path (cm)
PR	=	Surface pressure (mb)
TAU5	=	Turbidity at 0.5-μm wavelength
TAU38	=	Turbidity at 0.38-μm wavelength
RS	=	Ground albedo
TEMP	=	Surface temperature (K)
CONST	=	Constant K used in BIRD model
BA	=	Forward to total scattered irradiance ratio
TAUB	=	Broadband turbidity

The parameters at the top of each column of data are self-explanatory for the transmittance and absorptance terms. The remaining parameters are:

DIRH	=	Direct horizontal irradiance (W/m^2)
DIFSH	=	Diffuse sky horizontal irradiance (W/m^2)
DIFGH	=	Diffuse ground horizontal irradiance (W/m^2)
DTOT	=	Total or global horizontal irradiance (W/m^2)

Table A-1. TABULATED DATA FROM SEVERAL MODELS FOR THE USS ATMOSPHERE

IO	=	1353.0000
UW	=	1.4200
UO	=	.3400
PR	=	1013.0000
TAUS	=	.2661
TAU38	=	.3538
RS	=	.2000
TEMP	=	288.1000
CONST	=	.0933
BA	=	.8200
TAUB	=	.1907

ZENITH	AIRMASS
0.0000	.9995
20.0000	1.0634
30.0000	1.1536
48.1900	1.4972
50.0000	1.5525
60.0000	1.9927
70.0000	2.8997
75.0000	3.8076
80.0000	5.5790
85.0000	10.3163

ATWATER MODEL

ZEN	TA	AW	TMD	DIRH	DIFSH	DIFGH	DTOT
0.0	.8264	.0855	.9381	888.2846	64.9349	13.2405	966.4600
20.0	.8163	.0872	.9356	817.6250	62.8348	12.2298	892.6897
30.0	.8024	.0893	.9319	732.1165	60.0704	11.0037	803.1906
48.2	.7513	.0966	.9195	506.4300	51.2334	7.7461	565.4095
50.0	.7434	.0977	.9176	480.1187	50.0130	7.3637	537.4954
60.0	.6832	.1053	.9038	327.3209	41.7589	5.1266	374.2064
70.0	.5736	.1179	.8795	172.0532	30.0717	2.8076	204.9324
75.0	.4806	.1281	.8585	100.5358	22.3903	1.7075	124.6335
80.0	.3382	.1441	.8233	40.7697	13.2023	.7497	54.7216
85.0	.1249	.1752	.7472	4.9225	3.5038	.1170	8.5433

WATT MODEL

ZEN	TA	TH2OA	TH2OS	TO3	TAIR	DIRH	DIFSH	DIFGH	DTOT
0.0	.8653	.9250	.9694	.9761	.9016	923.885	176.483	11.272	1111.639
20.0	.8590	.9241	.9675	.9756	.8974	854.888	171.361	10.680	1036.929
30.0	.8503	.9229	.9648	.9749	.8917	771.205	165.065	9.957	946.227
48.2	.8187	.9192	.9545	.9723	.8714	548.932	147.788	7.996	704.717
50.0	.8138	.9186	.9528	.9719	.8683	522.831	145.694	7.761	676.286
60.0	.7770	.9150	.9398	.9685	.8451	369.969	133.040	6.352	509.361
70.0	.7092	.9096	.9132	.9615	.8029	210.444	118.758	4.789	333.991
75.0	.6544	.9056	.8873	.9562	.7702	135.596	111.100	3.963	250.659
80.0	.5620	.9000	.8373	.9456	.7142	67.205	103.151	3.117	173.473
85.0	.3961	.8904	.7074	.9259	.6123	16.682	94.951	2.255	113.888

HOYT MODEL

ZEN	TAS	AA	AW	ACO2	AO3	AO2	TR
0.0	.8317	.0416	.1000	.0075	.0268	.0075	.9170
20.0	.8220	.0411	.1021	.0076	.0275	.0079	.9125
30.0	.8084	.0404	.1049	.0078	.0285	.0085	.9063
48.2	.7588	.0379	.1144	.0084	.0317	.0107	.8840
50.0	.7511	.0376	.1158	.0085	.0322	.0110	.8807
60.0	.6926	.0346	.1258	.0091	.0357	.0137	.0560
70.0	.5859	.0293	.1422	.0101	.0417	.0190	.8138
75.0	.4956	.0248	.1553	.0109	.0466	.0242	.7781

ZEN	DIRH	DIFSH	DIFGH	DTOT
0.0	842.7127	185.2787	19.8473	1047.8387
20.0	776.0145	183.3879	18.4825	977.8849
30.0	695.2566	180.8148	16.8257	892.8972
48.2	482.1123	171.6728	12.4167	666.2018
50.0	457.2772	170.2822	11.8978	639.4573
60.0	313.2352	159.8604	8.8496	481.9533
70.0	167.1730	141.5303	5.6278	314.3311
75.0	99.6955	126.4744	4.0258	230.1957

Table A-1. TABULATED DATA FROM SEVERAL MODELS FOR THE USS ATMOSPHERE (concluded)

LACIC MODEL

ZEN	AW	AO3	DTOT
0.0	.1089	.0234	1134.0234
20.0	.1109	.0240	1059.6338
30.0	.1135	.0249	969.0372
48.2	.1220	.0283	725.7510
50.0	.1233	.0288	696.0444
60.0	[illegible]	.0327	525.3496
70.0	.1455	.0403	339.5933
75.0	.1559	.0474	244.5878
80.0	.1711	.0602	150.9857
85.0	.1969	.0906	63.4795

DAVIES MODEL

ZEN	DIRH	DIFSH	DIFGH	DTOT
0.0	964.6041	131.3193	18.2102	1114.1335
20.0	893.1822	129.3610	17.1608	1039.7040
30.0	806.4406	126.7305	15.8783	949.0494
48.2	575.4248	117.7340	12.3977	705.5564
50.0	548.2303	116.4077	11.9791	676.6171
60.0	388.6384	106.7716	9.4598	504.8698
70.0	221.5297	90.5812	6.6085	318.7193
75.0	140.8761	77.6703	5.0465	223.5929
80.0	68.5779	58.6164	3.3589	130.5533
85.0	16.1786	29.9684	1.5249	47.6719

BIRD MODEL

ZEN	TA	TO3	TU	TR	TAS	AW	TAA
0.0	.8127	.9822	.9874	.9137	.8271	.1032	.9825
20.0	.8029	.9814	.9872	.9094	.8100	.1048	.9815
30.0	.7695	.9803	.9869	.9033	.8055	.1068	.9801
48.2	.7410	.9763	.9860	.8816	.7603	.1134	.9746
50.0	.7336	.9756	.9859	.8783	.7541	.1144	.9728
60.0	.6778	.9709	.9849	.8531	.7029	.1209	.9643
70.0	.5785	.9619	.9834	.8074	.6126	.1312	.9444
75.0	.4959	.9537	.9822	.7684	.5435	.1389	.9124
80.0	.3704	.9391	.9803	.7078	.4494	.1499	.8242
85.0	.1757	.9056	.9770	.6157	.4256	.1684	.4130

ZEN	DIRH	DIFSH	DIFGH	DTOT
0.0	844.2037	168.9023	20.5954	1033.7014
20.0	777.9391	166.1341	19.5137	963.5869
30.0	697.7136	162.3802	18.1816	878.2754
48.2	485.8908	149.7404	14.5168	650.1480
50.0	461.1879	147.4221	14.0423	622.6523
60.0	317.6805	133.6742	11.2868	462.6415
70.0	171.6204	110.5682	0.0237	[illegible]
75.0	103.9955	90.4421	6.0411	200.4786
80.0	46.5685	59.8652	3.6917	110.1254
85.0	9.0703	12.5752	.7707	22.4162

Table A-2. TABULATED DATA FROM SEVERAL MODELS FOR THE MLS ATMOSPHERE

```
IO     =  1353.0000
UW     =     2.9300
UO     =      .3100
PR     =  1013.0000
TAUS   =      .2661
TAU38=        .3538
RS     =      .8000
TEMP   =   294.0000
CONST=        .0933
BA     =      .8200
TAUB   =      .1907
```

ZENITH	AIRMASS
0.0000	.9995
20.0000	1.0634
30.0000	1.1536
48.1900	1.4972
50.0000	1.5525
60.0000	1.9927
70.0000	2.8997
75.0000	3.8076
80.0000	5.5790
85.0000	10.3163

ATWATER MODEL

ZEN	TA	AW	TMD	DIRH	DIFSH	DIFGH	DTOT
0 0	.8264	.1063	.9381	865.0702	64.9349	53.9190	983.9241
20.0	.8163	.1083	.9355	795.6702	62.8348	49.7737	908.2787
30.0	.8024	.1110	.9319	711.7362	60.0704	44.7471	816.5538
48.2	.7513	.1200	.9195	490.5418	51.2334	31.4106	573.1858
50.0	.7434	.1214	.9176	464.7946	50.0130	29.8471	544.6547
60.0	.6832	.1308	.9038	315.5108	41.7589	20.7135	377.9832
70.0	.5736	.1465	.8795	164.4570	30.0717	11.2782	205.8069
75.0	.4806	.1592	.8585	95.3030	22.3903	6.8235	124.5168
80.0	.3382	.1790	.8233	37.9910	13.2023	2.9680	54.1614
85.0	.1249	.2177	.7472	4.2961	3.5038	.4522	8.2521

WATT MODEL

ZEN	TA	TH2OA	TH2OS	TO3	TAIR	DIRH	DIFSH	DIFGH	DTOT
0.0	.8836	.9146	.9379	.9768	.9016	903.091	220.790	58.727	1182.608
20.0	.8779	.9137	.9341	.9763	.8974	834.679	214.383	55.738	1104.800
30.0	.8701	.9125	.9287	.9757	.8917	751.725	206.506	52.083	1010.315
48.2	.8417	.9088	.9083	.9733	.8714	531.559	184.892	42.168	758.619
50.0	.8373	.9083	.9051	.9729	.8683	505.732	182.271	40.978	728.982
60.0	.8038	.9047	.8797	.9698	.8451	354.681	166.441	33.849	554.970
70.0	.7413	.8992	.8291	.9635	.8029	197.827	148.573	25.932	372.332
75.0	.6904	.8953	.7813	.9586	.7702	124.044	138.992	21.750	285.586
80.0	.6032	.8896	.6933	.9489	.7142	59.236	129.047	17.457	205.740
85.0	.4434	.8800	.4896	.9309	.6123	12.842	118.790	13.085	144.716

HOYT MODEL

ZEN	TAS	AA	AW	ACO2	AO3	AO2	TR
0.0	.8317	.0416	.1272	.0075	.0258	.0075	.9170
20.0	.8220	.0411	.1298	.0076	.0264	.0079	.9125
30.0	.8084	.0404	.1333	.0078	.0274	.0085	.9063
48.2	.7588	.0379	.1451	.0084	.0305	.0107	.8840
50.0	.7511	.0376	.1469	.0085	.0310	.0110	.8807
60.0	.6926	.0346	.1592	.0091	.0344	.0137	.8560
70.0	.5859	.0293	.1796	.0101	.0401	.0190	.8138
75.0	4956	.0248	.1960	.0109	.0448	.0242	.7781

ZEN	DIRH	DIFSH	DIFGH	DTOT
0.0	815.7084	179.3415	72.9219	1067.9718
20.0	750.5957	177.3810	67.8237	995.8004
30.0	671.8142	174.7181	61.6398	908.1721
48.2	464.2596	165.3157	45.2155	674.7908
50.0	440.1194	163.8930	43.2865	647.2989
60.0	300.3540	153.2941	31.9775	485.6256
70.0	159.2519	134.8242	20.0839	314.1600
75.0	94.4394	119.8065	14.2080	228.4540

Table A-2. TABULATED DATA FROM SEVERAL MODELS FOR THE MLS ATMOSPHERE (concluded)

LACIS MODEL

ZEN	AW	AO3	DTOT
0.0	.1327	.0274	1138.0919
20.0	.1350	.0231	1063.0223
30.0	.1379	.0239	971.6311
48.2	.1475	.0270	726.4310
50.0	.1489	.0275	697.3221
60.0	.1585	.0312	524.7679
70.0	.1736	.0382	338.2250
75.0	.1849	.0448	243.0373
80.0	.2012	.0568	149.4940
85.0	2282	.0051	62.4267

DAVIES MODEL

ZEN	DIRH	DIFSH	DIFGH	DTOT
0.0	936.3331	129.0411	74.5253	1139.8995
20.0	866.5097	127.0680	70.2349	1063.8126
30.0	781.7525	124.4193	64.9933	971.1651
48.2	556.3066	115.3767	50.7790	722.4623
50.0	529.8009	114.0456	49.0708	692.9173
60.0	374.4382	104.3899	38.7949	517.6231
70.0	212.2479	88.2198	27.1739	327.6415
75.0	134.2798	75.3692	20.8053	230.4543
80.0	64.7464	56.4768	13.9067	135.1298
85.0	14.9323	28.3066	6.3442	49.5832

BIRD MODEL

ZEN	TA	TO3	TU	TR	TAS	AW	TAA
0.0	.8127	.9834	9874	.9139	.8271	.1219	.9826
20.0	.8029	.9826	.7072	.9094	.8180	.1235	.9815
30.0	.7895	.9816	.9869	.9033	.8055	.1257	.9801
48.2	.7410	.9778	.9860	.0816	.7603	.1330	.9746
50.0	.7336	.9772	.9859	.8783	.7541	.1340	.9728
60.0	.6778	.9727	.9849	.8531	.7029	.1411	.9643
70.0	.5785	.9643	.9834	.8074	.6126	.1520	.9444
75.0	.4959	.9566	.9822	.7684	.5435	.1601	.9124
80.0	.3704	.9430	.9803	.7078	.4494	.1717	.8242
85.0	.1757	.9116	.9770	.6157	.4256	.1907	.4130

ZEN	DIRH	DIFSH	DIFGH	DTOT
0.0	827.6234	165.5850	86.0091	1079.2176
20.0	762.5502	162.8477	81.5689	1006.9668
30.0	603.7850	159.1305	76.1007	919.0243
48.2	475.9279	146.6700	61.0603	683.6583
50.0	451.6994	144.3891	59.1048	655.1932
60.0	311.0063	130.8658	47.7834	489.6554
70.0	167.9332	108.1927	34.3338	310.4597
75.0	101.7433	88.4834	26.0710	216.2770
00.0	45.5637	58.5735	16.1263	120.2635
85.0	8.8855	12.3191	3.3810	24.5857

Table A-3. TABULATED DATA FROM SEVERAL MODELS FOR THE DAVE MODEL 3 ATMOSPHERE

IO	=	1353.0000
UW	=	2.9300
UO	=	.3100
PR	=	1013.0000
TAUS	=	.0999
TAU38	=	.0979
RS	=	.0200
TEMP	=	294.0000
CONST	=	.0933
BA	=	.8600
TAUB	=	.0620

ZENITH	AIRMASS
0.0000	.9995
20.0000	1.0634
30.0000	1.1536
48.1900	1.4972
50.0000	1.5525
60.0000	1.9927
70.0000	2.8997
75.0000	3.8076
80.0000	5.5790
85.0000	10.3163

ATWATER MODEL

ZEN	TA	AW	TMD	DIRH	DIFSH	DIFGH	DTOT
0.0	.9399	.1063	.9381	983.9331	73.8571	1.4512	1059.2413
20.0	.9362	.1083	.9355	912.4993	72.0609	1.3507	985.9109
30.0	.9310	.1110	.9319	825.7991	69.6973	1.2285	896.7250
48.2	.9113	.1200	.9195	594.9837	62.1416	.9015	658.0268
50.0	.9081	.1214	.9176	567.8031	61.0969	.8628	629.7628
60.0	.8836	.1308	.9038	408.0431	54.0058	.6339	462.6827
70.0	.8348	.1465	.8795	239.3498	43.7662	.3884	283.5044
75.0	.7881	.1592	.8585	156.2876	36.7179	.2648	193.2703
80.0	.7031	.1790	.8233	78.9828	27.4474	.1460	106.5762
85.0	.5087	.2177	.7472	17.4954	14.2687	.0436	31.8077

WATT MODEL

ZEN	TA	TH2OA	TH2OS	TO3	TAIR	DIRH	DIFSH	DIFGH	DTOT
0.0	.9762	.9146	.9379	.9768	.9016	997.790	158.878	1.029	1157.697
20.0	.9743	.9137	.9341	.9763	.8974	926.307	154.267	.974	1081.548
30.0	.9716	.9125	.9287	.9757	.8917	839.372	148.600	.907	988.879
48.2	.9609	.9088	.9083	.9733	.8714	606.839	133.046	.725	740.610
50.0	.9592	.9083	.9051	.9729	.8683	579.335	131.160	.703	711.198
60.0	.9452	.9047	.8797	.9698	.8451	417.053	119.769	.572	537.395
70.0	.9157	.8992	.8291	.9635	.8029	244.378	106.911	.428	351.717
75.0	.8921	.8963	7813	.9586	.7702	161.311	100.017	.351	261.680
80.0	.8457	.8896	.6933	.9489	.7142	83.046	92.061	.273	176.179
85.0	.7602	.8800	.4896	.9309	.6123	22.017	85.480	.193	107.689

HOYT MODEL

ZEN	TAS	AA	AW	ACO2	AO3	AO2	TR
0.0	.9321	.0466	.1272	.0075	.0258	.0075	.9170
20.0	.9279	.0464	.1298	.0076	.0264	.0079	.9125
30.0	.9220	.0461	.1333	.0078	.0274	.0085	.9063
48.2	.9000	.0450	.1451	.0084	.0305	.0107	.8840
50.0	8965	.0448	.1469	.0085	.0310	.0110	.8807
60.0	.8692	.0435	.1592	.0091	0344	.0137	.8560
70.0	.8155	.0408	.1796	.0101	.0401	.0190	.8138
75.0	.7650	.0383	.1960	.0109	.0448	.0242	.7781

ZEN	DIRH	DIFSH	DIFGH	DTOT
0.0	908.3464	98.2025	1.2750	1007.8240
20.0	841.6283	97.2154	1.1857	940.0295
30.0	760.6718	95.8785	1.0773	857.6276
48.2	545.5922	91.1694	.7888	637.5504
50.0	520.3379	90.4580	.7548	611.5508
60.0	372.5084	85.1641	.5554	458.2279
70.0	218.1138	76.0972	.3449	294.5559
75.0	142.9609	68.9767	.2407	212.1782

Table A-3. TABULATED DATA FROM SEVERAL MODELS FOR THE DAVE MODEL 3 ATMOSPHERE (concluded)

LACIS MODEL

ZEN	AW	AO3	DTOT
0.0	.1327	.0224	1093.1443
20.0	.1350	.0231	1020.9793
30.0	.1379	.0239	933.1311
48.2	.1475	.0270	697.4798
50.0	.1489	.0275	669.5094
60.0	.1585	.0312	503.7295
70.0	.1736	.0382	324.5709
75.0	.1849	.0448	233.1836
80.0	.2012	.0568	143.4038
85.0	.2282	.0851	59.8739

DAVIES MODEL

ZEN	DIRH	DIFSH	DIFGH	DTOT
0.0	936.3331	129.0411	1.7442	1067.1183
20.0	866.5097	127.0680	1.6427	995.2204
30.0	781.7525	124.4193	1.5186	907.6905
48.2	556.3066	115.3767	1.1823	672.8657
50.0	529.8009	114.0456	1.1419	644.9885
60.0	374.4382	104.3899	.8989	479.7270
70.0	212.2479	88.2198	.6243	301.0919
75.0	134.2798	75.3692	.4742	210.1232
80.0	64.7464	56.4768	.3127	121.5359
85.0	14.9323	28.3066	.1388	43.3777

BIRD MODEL

ZEN	TA	TO3	TU	TR	TAS	AW	TAA
0.0	.9219	.9834	.9874	.9137	.9286	.1219	.9927
20.0	.9175	.9826	.9872	.9094	.9247	.1235	.9923
30.0	.9115	.9816	.9869	.9033	.9192	.1257	.9916
48.2	.0091	.9778	.9860	.8816	.8989	.1330	.9891
50.0	.8856	.9772	.9859	.8783	.8961	.1340	.9883
60.0	.8585	.9727	.9849	.8531	.8722	.1411	.9843
70.0	.8068	.9643	.9834	.8074	.8279	.1520	.9745
75.0	.7595	.9566	.9822	.7684	.7926	.1601	.9582
80.0	.6774	.9430	.9003	.7078	.7444	.1717	.9099
85.0	.5057	.9116	.9770	.6157	.7004	.1907	.6479

ZEN	DIRH	DIFSH	DIFGH	DTOT
0.0	930.0407	94.5702	1.6248	1035.0359
20.0	871.3803	93.1824	1.5273	966.0901
30.0	789.4391	91.3142	1.4082	882.1616
48.2	571.0358	85.0776	1.0865	657.1999
50.0	545.2946	83.9642	1.0470	630.3058
60.0	393.9366	77.2467	.8155	471.9707
70.0	[illegible].2077	65.8789	.5567	300.6456
75.0	155.8315	55.7656	.4135	212.0107
80.0	83.3321	39.5922	.2569	123.1812
85.0	25.5650	11.1038	.0729	36.7417

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A detailed comparison was made between five simple broadband models for clear sky global insolation. Compared models were those of Atwater and Ball, Davies and Hay, Watt, Hoyt, and Lacis and Hansen. A sixth simple model, called the Bird model, has been formulated by using parts of these five models and by comparison with the results from three rigorous radiative transfer codes. All of the simple models provide results that agree within <10% with the three rigorous codes when the sun is in the zenith position. The Bird and Hoyt models agree within 3% with each other and with the results of the rigorous codes. However, the Bird model is easier to implement and has broader application than the Hoyt model.

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