Portland State University
PDXScholar

Civil and Environmental Engineering Faculty Publications and Presentations

Civil and Environmental Engineering

10-1-2007

A Comparison of Five Models for Estimating Clear-Sky Solar Radiation

Robert Leslie Annear
Portland State University

Scott A. Wells
Portland State University

Citation Details

Annear, R. L. and S. A. Wells (2007), A comparison of five models for estimating clear-sky solar radiation, Water Resour. Res., 43, W10415

A comparison of five models for estimating clear-sky solar radiation

R. L. Annear[1] and S. A. Wells[1]

Received 21 March 2006; revised 25 June 2007; accepted 27 July 2007; published 16 October 2007.

[1] Many agencies in the USA are developing management approaches to address water quality concerns and threatened and endangered species habitat requirements in water bodies. Many of these water bodies are water quality limited for temperature. Factors influencing stream temperature include: streamside vegetation, topographic shading, inflows and outflows, stream width, stream depth, light extinction and solar radiation. One of the key driving factors in estimating a water body heat budget is calculating the amount of solar radiation incident on the water surface. Even though it is preferable to measure clear-sky solar radiation, many temperature models rely on theoretical estimates of clear-sky solar radiation. The literature on estimating short-wave solar radiation by calculating the position of the sun and attenuating the radiation through the atmosphere was reviewed. As a first step in relating water temperature to solar radiation, several empirical solar radiation models were calibrated to data at seventeen sites around the United States for clear-sky days. Sensitivity analyses were conducted and differences between the models were examined. Results indicated that the more complex models for calculating solar radiation resulted in better estimates of clear-sky solar radiation once they were calibrated to data. When no data were available, models with one or no calibration parameters did reasonably well at estimating clear-sky solar radiation.

Citation: Annear, R. L., and S. A. Wells (2007), A comparison of five models for estimating clear-sky solar radiation, *Water Resour. Res.*, *43*, W10415, doi:10.1029/2006WR005055.

1. Introduction

[2] Many states in the United States are moving forward to develop Total Maximum Daily Loads (TMDLs) to address surface water quality concerns and threatened and endangered species habitat requirements in water bodies. For example, in the State of Oregon, the Oregon Department of Environmental Quality (DEQ) has approximately 940 water body segments listed as water quality limited for stream temperature [*DEQ*, 1998a]. The State temperature standards for water quality limited streams were developed to protect the most sensitive beneficial uses of Oregon streams [*DEQ*, 1998b]. In many cases the most sensitive beneficial use is protecting threatened and endangered salmonid species. The main stem of the Willamette River and its larger tributaries are currently water quality limited for temperature, and DEQ is leading a process to develop a temperature TMDL for 945 river km (587 river miles) [*DEQ*, 2001].

[3] Many agencies have been using stream temperature models to evaluate the impact of management strategies on improving stream temperatures. Recently, some models that have been used to model stream temperature include:

[4] • Heat Source, a one-dimensional steady state hydrodynamic and dynamic temperature model [*DEQ*, 1999], that accounts for the impact of riparian vegetative shading and topographic shading on stream temperature.

[5] • QUAL2E [*Brown and Barnwell*, 1987], a one-dimensional steady state hydrodynamic and diurnal temperature model.

[6] • QUAL2Kw [*Pelletier and Chapra*, 2004], a one-dimensional steady state hydrodynamic and diurnal temperature and water quality model.

[7] • CE-QUAL-RIV1 [*Environmental Laboratory*, 1995], a one-dimensional, dynamic flow and water quality model for streams.

[8] • CE-QUAL-W2 [*Cole and Wells*, 2000], a two-dimensional river/lake/reservoir hydrodynamic and dynamic temperature model with riparian shade and topographic shade [*Annear et al.*, 2004; *Berger et al.*, 2004].

[9] • SNTEMP, (Stream Network TEMPerature model), a one-dimensional, heat transport model for predicting the daily mean and maximum water temperatures. The model is based on the dynamic temperature and steady flow equations and assumes that all input data are represented by daily averages [*Theurer et al.*, 1984].

[10] • MNSTREM, a one-dimensional, dynamic flow and temperature model for streams [*Gulliver*, 1977; *Stefan et al.*, 1980].

[11] In all of these model approaches the short-wave solar radiation incident on the water surface must be determined either through measurement or through a theoretical estimate. The solar radiation is a critical component of the surface heat flux. *Pluhowski* [1970] found that solar energy was one of the most important factors affecting stream temperature and that diurnal stream temperature fluctuations

[1]Department of Civil and Environmental Engineering, Portland State University, Portland, Oregon, USA.

0043-1397/07/2006WR005055

surface is a function of the solar constant, the position of the sun, the attenuation in the atmosphere due to dust, refraction and water content and water surface albedo.

[12] This paper evaluates different theoretical methods for estimating clear-sky solar radiation and makes recommendations for models to use when solar radiation measurements are not available or limited data allow model calibration. The paper is consistent with the history of this journal publishing research on atmospheric radiation [*Brutsaert*, 1975]. This research deals with only the first step in relating water temperature to solar radiation. Additional considerations such as evaluating estimates for surface albedo and radiation attenuation in the water are outside the scope of this paper. Several solar radiation model formulations were analyzed and calibrated with data from 17 sites around the United States for clear-sky days. Clear-sky days are days with no clouds and would be represented in solar radiation versus time plots by a parabolic-shaped curve centered around solar noon with negligible fluctuations. These models required from zero to five calibration parameters such as atmospheric dust, atmospheric attenuation, the ratio of forward-scattered irradiance to the total scattered irradiance due to aerosols, and atmospheric turbidity, elevation, latitude and time of year and GMT or longitude. Input parameters for all the models included latitude, time of year, elevation (except the *EPA* [1971] model) and time zone relative to GMT or longitude.

2. Solar Radiation Formulations

[13] Five models for calculating the position of the sun and atmospheric attenuation of the radiation which are used in current temperature simulation models were reviewed. All of the models' estimates of solar radiation were compared to solar radiation data collected on clear-sky days. Additionally, the effects of ground surface reflectivity were eliminated from several models since the data collected did not account for reflectivity but did account for a smaller fraction due to backscatter. A discussion on ground surface reflectivity is included for completeness and to justify corrections made to several models before comparing model results with data.

2.1. *EPA* [1971] Model

[14] This model was used in the water quality model CE-QUAL-W2 [*Cole and Wells*, 2000]. The equations used for calculating the position of the sun have been refined based on updating the original formulation presented in *EPA* [1971].

[15] The clear-sky solar radiation at the ground surface, φ_s, was originally computed in BTU/ft^{2}day but was converted to W/m^2 below. The total clear sky solar radiation was calculated using a least squares fit polynomial regression of the solar altitude, A_o (degrees) and included direct and diffuse radiation and the influence of ground surface reflectivity (albedo):

$$\varphi_s = 24\big(2.044A_o + 0.1296A_o^2 - 1.941\times10^{-3}A_o^3 + 7.591\times10^{-6}A_o^4\big)0.1314 \quad (1)$$

where 0.1314 is used to convert the solar radiation from BTU/ft^{2}day to W/m^2. A_o was computed from the angle of inclination of the sun relative to the horizon from an observer's perspective [*Wunderlich*, 1972; *Meeus*, 1999] using

$$A_o = \arcsin[\sin(\psi)\sin(\delta) + \cos(\psi)\cos(\delta)\cos(H)] \quad (2)$$

where ψ is the latitude, δ is the solar declination, and H is the local hour angle. The local hour angle, H (radians), is the angular position of the sun for a given location at a specific time during the day and was calculated from *Ryan and Stolzenbach* [1972] using

$$H = \frac{2\pi}{24}\left[h_l - (\gamma_l - \gamma)\frac{24}{360} + h_e - 12.0\right] \quad (3)$$

where h_l is the local hour, γ is standard meridian, γ_l is the longitude, and h_e is the equation of time. The equation of time, h_e (hours), represents the difference between true solar time and mean solar time due to seasonal variations in the orbital velocity of the Earth [*Ryan and Stolzenbach*, 1972]. *DiLaura* [1984] calculated h_e as

$$h_e = 0.170\sin[4\pi(\lfloor Jday \rfloor - 80)/373] - 0.129\sin[2\pi(\lfloor Jday \rfloor - 8)/355] \quad (4)$$

where *Jday* is the Julian day, representing the local day and time since the beginning of the year based on a Julian calendar of 365 days (366 for leap years).

[16] The nearest standard meridian γ (degrees), to longitude, γ_l, was calculated using

$$\gamma = 15.0\left\lfloor \frac{\gamma_l}{15.0} \right\rfloor \quad (5)$$

where $\lfloor x \rfloor$ is the floor function (largest integer less than or equal to x). The time zones calculate a more appropriate nearest standard meridian than the longitude, so the time zone relative to Greenwich Mean Time (GMT), h_{TZ} (hours), was used to improve the calculation of the nearest standard meridian as

$$\gamma = -15.0\lfloor h_{TZ} \rfloor \quad (6)$$

[17] The solar declination angle, δ (radians), was calculated by *Spencer* [1971] as:

$$\delta = 0.006918 - 0.399912\cos(\tau_d) + 0.070257\sin(\tau_d) - 0.006758\cos(2\tau_d) + 0.000907\sin(2\tau_d) - 0.002697\cos(3\tau_d) + 0.001480\sin(3\tau_d) \quad (7)$$

where τ_d is the angular fraction of the year which *Spencer* [1971] calculated as

$$\tau_d = \frac{2\pi(\lfloor Jday \rfloor - 1)}{365} \quad (8)$$

Empirical Values for Precipitable Water Content

2.93	Mid-latitude Summer atmospheric model	*Bird and Hulstrom* [1981]
1.42	U.S. Standard atmospheric model	*Bird and Hulstrom* [1981]
1.50	Used in Qual2k model	*Pelletier and Chapra* [2004]

2.2. *Klein* [1948] Model

[18] The model by *Klein* [1948] was used in the water quality model QUAL2E [*Brown and Barnwell*, 1987] and CE-QUAL-RIV1 [*Environmental Laboratory*, 1995] and involved calculating the precipitable water content, relative optical air mass, two atmospheric transmission coefficients and dust to calculate the total clear sky radiation. After considering scattering and absorption in a moist and dusty atmosphere and ground surface reflectivity, the total clear sky solar radiation, φ_s(W/m^2), was calculated from *Klein* [1948] using

$$\varphi_s = \varphi_{ext}\left[\frac{a'' - d + 0.5(1 - a' + d)}{1 - 0.5R_g(1 - a' + d)}\right] \quad (9)$$

where φ_{ext} is the extraterrestrial solar irradiance, a' is the mean atmospheric transmission coefficient for a cloudless, dust-free, moist air after scattering, a'' is the mean atmospheric transmission coefficient for cloudless, dust-free, moist air after scattering and absorption, d is the atmospheric dust, and R_g is the ground surface reflectivity. The extraterrestrial solar irradiance, φ_{ext}(W/m^2), can be calculated from *Wunderlich* [1972], *Lee* [1978], and *Bras* [1990] as

$$\varphi_{ext} = \varphi_o E_o \sin(A_o) \quad (10)$$

where φ_o (W/m^2) is the solar constant and E_o (dimensionless) is the eccentricity correction and is calculated as

$$E_o = \left(\frac{r_o}{r}\right)^2 \quad (11)$$

where r_o (AU) is the average distance between the Earth and the sun (1 Astronomical Unit), and r (AU) is the distance between the Earth and the sun at any time. The National Aeronautics and Space Administration started monitoring solar influx in Earth orbit in the 1970s [*NASA*, 2004] using satellites. An average of all the minimum and maximum values from the data collected by *NASA* [2004] is 1367.4 W/m^2. The analyses presented in this paper use 1367 W/m^2 for the solar constant φ_o.

[19] *Spencer* [1971] and *Dingman* [2002] calculated the eccentricity correction, E_o, as

$$E_o = 1.000110 + 0.034221\cos(\tau_d) + 0.001280\sin(\tau_d) + 0.000719\cos(2\tau_d) + 0.000077\sin(2\tau_d) \quad (12)$$

[20] *Wunderlich* [1972] characterized the atmospheric transmission using the two components: a', scattering only and a'', scattering and absorption. The transmission coefficients were originally tabulated by *Kimball* [1930] and documented in figures, which were developed into equations by *Orlob and Selna* [1967]. The mean atmospheric transmission coefficient for a cloudless, dust-free, moist air after scattering, a' (dimensionless), was calculated from *Orlob and Selna* [1967] as

$$a' = \exp\left[-(0.465 + 0.134w)\{0.129 + 0.171\exp(-0.880m_p)\}m_p\right] \quad (13)$$

where m_p is the relative optical air mass and w is the precipitable water content. *Orlob and Selna* [1967] calculated the mean atmospheric transmission coefficient for cloudless, dust-free, moist air after scattering and absorption, a'' (dimensionless), as

$$a'' = \exp\left[-(0.465 + 0.134w)\{0.179 + 0.421\exp(-0.721m_p)\}m_p\right] \quad (14)$$

Wunderlich [1972] calculated the relative optical air mass, m_p (dimensionless), based on the relationship developed by *Kasten* [1964] and incorporated changes in barometric pressure with altitude from *List* [1958] as a first order approximation, such as

$$m_p = \frac{\left[\frac{(288 - 0.0065z)}{288}\right]^{5.256}}{\left[\sin(A_o) + 0.1500(A_o + 3.885)^{-1.253}\right]} \quad (15)$$

where z (meters) is the elevation of the water body, 288 (K) is the surface temperature and 0.0065 (K/m) is the temperature gradient. The precipitable water content in the atmosphere is often included in atmospheric attenuation models as an empirical coefficient. Table 1 lists several values for precipitable water content found in the literature.

[21] Several researchers developed equations to calculate the precipitable water content based on the dew point temperature. *Bolsenga* [1965] used the work by *Reitan* [1963] and developed an equation for the mean hourly precipitable water content, w (cm), such as

$$w = \exp(-0.0592 + 0.06912T_{dpt}) \quad (16)$$

where T_{dpt} (°C) is the dew point temperature.

[22] Some atmospheric attenuation models consider the effects of atmospheric dust. *Klein* [1948] divided the influence of dust into two components considering the effects of scattering d_a (dimensionless) and absorption d_a (dimensionless) of solar radiation, where the atmospheric dust coefficient d (dimensionless), was defined as

$$d = d_s + d_a \quad (17)$$

The influence of dust on attenuating solar radiation is a function of the relative optical air mass and time of year, [*Kimball*, 1930]. *Klein* [1948] and *Bolsenga* [1964] tabulated the dust attenuation values from *Kimball* [1930], as shown in Table 2. Both *Klein* [1948] and *Dingman* [2002] considered the solar radiation attenuation

d	Description	Reference
0.00 to 0.08	Remote sites	*Klein* [1948] and *Bolsenga* [1964], from *Kimball* [1930]
0.03 to 0.10	Moderate sized cities	
0.06 to 0.13	Larger metropolitan areas	

due to absorption from dust as negligible, $d_a \approx 0$ resulting in $d = d_s$.

[23] The ground surface reflectivity, R_g (dimensionless), or albedo represents the fraction of the incident radiation on the ground surface that reflects back to the atmosphere and is dependent on the surface material and the angle of the sun. The reflectivity of many surfaces has been documented in the literature. Water surface reflectivity values found in the literature varied from 0.03 to 0.60 [*Eagleson*, 1970; *Lee*, 1978; and *Muneer*, 1997].

[24] *Lee* [1978] provided a table of reflectivity values for a water surface relative to the solar altitude as shown in Table 3. *Anderson* [1954] calculated the reflectivity of the water surface, R_g, as

$$R_g = \alpha A_o^{\beta} \tag{18}$$

where coefficients α and β are dependent on the fraction of cloud cover and listed in Table 4.

2.3. *Kennedy* [1949] Model

[25] The model from *Kennedy* [1949] used a more simplified approach including the relative optical air mass and an empirical variable for the atmospheric transmission to calculate the clear-sky solar radiation. The clear-sky solar radiation, φ_s (W/m^2), was calculated using a slightly modified equation to incorporate the hourly (instead of daily) atmospheric transmission coefficient from *Kennedy* [1940] as

$$\varphi_s = \varphi_{ext} a_h^{m_p} \tag{19}$$

where a_h (dimensionless) is the hourly average atmospheric transmission coefficient defined by *Kennedy* [1949] as a function of the daily atmospheric transmission coefficient, a_t (dimensionless):

$$a_h = 1.49 a_t - 0.50 \tag{20}$$

[26] Several atmospheric attenuation models characterize all of the atmospheric attenuation variables into one empirical transmission coefficient [*Kennedy*, 1949; *Ryan and Stolzenbach*, 1972]. The atmospheric transmission coefficient a_t was often used to calibrate their models to data and represented a daily constant for a specific location [*Ryan and Stolzenbach*, 1972]. Daily atmospheric transmission coefficients found in the literature varied from 0.60 to 0.91 [*Kennedy*, 1949; *Hamon et al.*, 1954; and *Lee*, 1978].

Table 3. Water Surface Reflectivity for Varying Solar Altitude, (*Lee*, 1978)

A_o, degrees	R_g	A_o, degrees	R_g
60	0.05	10	0.35
30	0.10	5	0.60
20	0.15		

Table 4. Reflectivity Equation Coefficients Based on Cloud Cover [*Anderson*, 1954]

Cloudiness, C	Clear, 0.0	Scattered, 0.1–0.5	Broken, 0.6–0.9	Overcast, 1.0
α	1.18	2.20	0.95	0.33
β	−0.77	−0.97	−0.75	−0.45
		High Altitude Clouds		
α		2.20	1.10	0.51
β		−0.98	−0.80	−0.58
		Low Altitude Clouds		
α		2.17	0.78	0.20
β		−0.96	−0.68	−0.30

2.4. *Lee* [1978] Model

[27] The model from *Lee* [1978] used an empirical variable for the atmospheric transmission but does not include the relative optical air mass. The clear-sky solar radiation, φ_s (W/m^2), accounting for direct and diffuse radiation and the influence of reflectivity was calculated using

$$\varphi_s = \varphi_{ext} a_h^{\frac{1}{\sin(A_O)}} \tag{21}$$

[28] Equation (21) represents a modified version of the equation from *Lee* [1978] where a daily atmospheric transmission coefficient was used. The daily atmospheric transmission coefficient was a calibration parameter for the model used here.

2.5. *Meeus* [1999] and *Bird and Hulstrom* [1981] Model

[29] The *Meeus* [1999] and the *Bird and Hulstrom* [1981] models were used by *Pelletier and Chapra* [2004] in the water quality model QUAL2kw for calculating the solar position and atmospheric attenuation, respectively. The clear-sky solar radiation, φ_s (W/m^2), was calculated from *Bird and Hulstrom* [1981] using

$$\varphi_s = \frac{(\varphi_d + \varphi_l)}{(1 - R_g r_s)} \tag{22}$$

Table 5. Empirical Values for the Ratio of Forward Scatter Irradiance to the Total Irradiance

B_a	Description	Reference
0.84	Recommended	*Bird and Hulstrom* [1981]
0.85		*Pelletier and Chapra* [2004]
0.82	Rural aerosol	*Bird and Hulstrom* [1981]
0.86	Mid-latitude Summer atmosphere with Haze L aerosol model	*Dave* [1978]
1.00	All forward scattering	*Bird and Hulstrom* [1981]
0.50	Isotropic scattering	*Bird and Hulstrom* [1981]
0.00	All backward scattering	*Bird and Hulstrom* [1981]

Empirical Values of the Aerosol Absorptance Coeffi- [1981]

K_1	Description
0.0933	Rural aerosol
0.385	Urban aerosol, contains more carbon
0.1	Recommended unless aerosol data available

where φ_d is the direct solar radiation, φ_l is the scattered solar radiation, and r_s is the atmospheric albedo. *Bird and Hulstrom* [1981] calculated the direct solar radiation, φ_d (W/m^2), using

$$\varphi_d = 0.9662\varphi_{ext} T_A T_w T_{UM} T_o T_R \tag{23}$$

where T_A (dimensionless) is the transmittance of aerosol absorptance and scattering, T_w (dimensionless) is the transmittance of water vapor, T_{UM} (dimensionless) is the transmittance of uniformly mixed gases, T_o (dimensionless) is the transmittance of ozone content, and T_R (dimensionless) is the transmittance of Rayleigh scattering in the atmosphere. The solar radiation from atmospheric scattering, φ_l (W/m^2), was calculated [*Bird and Hulstrom*, 1981] using

$$\varphi_l = 0.79\varphi_{ext} T_{AA} T_w T_{UM} T_o \left(\frac{0.5(1 - T_R) + B_a\left(1 - {}^{T_A}/_{T_{AA}}\right)}{1 - m_p + m_p^{1.02}} \right) \tag{24}$$

where T_{AA} (dimensionless) is the transmittance of aerosol absorptance and B_a (dimensionless) is an empirical ratio of forward-scattered irradiance to the total scattered irradiance due to aerosols. Table 5 lists some empirical values for the ratio found in the literature. The atmospheric albedo, r_s (dimensionless), was calculated [*Bird and Hulstrom*, 1981] as

$$r_s = 0.0685 + (1 - B_a)\left(1.0 - \frac{T_A}{T_{AA}}\right) \tag{25}$$

[30] The transmittance of aerosol absorptance, T_{AA} (dimensionless), was calculated by *Bird and Hulstrom* [1981] using

$$T_{AA} = 1 - K_1\left(1 - m_p + m_p^{1.06}\right)(1 - T_A) \tag{26}$$

where K_1 is an empirical absorptance coefficient. *Bird and Hulstrom* [1981] recommended the coefficient be set to 0.1 unless information on aerosols was available. Table 6 lists the aerosol absorptance coefficients discussed in *Bird and Hulstrom* [1981].

[31] *Bird and Hulstrom* [1981] calculated the transmittance of aerosol absorptance and scattering, T_A (dimensionless), using

$$T_A = \exp\left[-\tau_A^{0.873}\left(1 + \tau_A - \tau_A^{0.7088}\right)m_p^{0.9108}\right] \tag{27}$$

where τ_A (dimensionless) is the overall atmospheric turbidity and defined as the broadband aerosol optical depth from the surface in a vertical path. The atmospheric turbidity varies from 0.02 to 0.50 and was calculated by *Bird and Hulstrom* [1981] as

$$\tau_A = 0.2758\tau_{A0.38} + 0.35\tau_{A0.50} \tag{28}$$

where $\tau_{A0.38\mu m}$ (dimensionless) is the aerosol optical depth from the surface in a vertical path at 380 nm wavelength (no molecular absorption), and $\tau_{A0.5\mu m}$ (dimensionless) is the aerosol optical depth at 500 nm wavelength (ozone absorption) [*Bird and Hulstrom*, 1981; *Muneer et al.*, 2000]. Optical depth values for the two wavelengths may be developed based on data or adjusted during model calibration. Table 7 provides a list of some optical depth values found in the literature.

[32] The transmittance of the ozone content, T_o (dimensionless), was calculated by *Bird and Hulstrom* [1981] as

$$T_o = 1 - 0.1611X_o(1 + 139.48X_o)^{-0.3035} - 0.002715X_o\left(1 + 0.044X_o + 0.0003X_o^2\right)^{-1} \tag{29}$$

where X_o (cm) is the amount of ozone in a slanted path, calculated by *Bird and Hulstrom* [1981] as

$$X_o = U_0 m_p \tag{30}$$

Table 7. Empirical Values for Atmospheric Turbidity

$\tau_{A0.5\mu m}$ (dimensionless)	$\tau_{A0.38\mu m}$ (dimensionless)	Description	Reference
0.163		Mean sea-level, Washington D.C.	*Flowers et al.* [1969]
0.093		Eastern U.S.,	*Elterman* [1964]
0.047		Mean sea-level, Washington D.C.	*Moon* [1940]
0.105		Washington D.C.	*Angstrom* [1929]
0.020–0.030		Minimum value over United States at sea level	*Flowers et al.* [1969]
0.100	0.05	Mt Vernon in Washington	*Pelletier and Chapra* [2004]
0.56	0.72	United Kingdom	*Muneer* [1997]
0.2661	0.3538	U.S. Standard Atmosphere	*Muneer* [1997]

Table 8. Empirical Values for Atmospheric Ozone

Ozone, cm	Description	Reference
0.31	Mid-latitude Summer atmospheric model	*Bird and Hulstrom* [1981]
0.34	U.S. Standard atmospheric model	*Bird and Hulstrom* [1981]
0.3 to 0.4	Average in "literature"	*Van Heuklon* [1979] (from *Elterman* [1968]; *Halpern et al.* [1974])
0.2 to 0.6	Variation in ozone globally and temporal	*Van Heuklon* [1979]
0.3	Used in Qual2k model	*Pelletier and Chapra* [2004]

Van

Parameter	Northern Hemisphere	Southern Hemisphere
A′, (atm-cm)	150.0	100.0
C′, (atm-cm)	40.0	30.0
F′, (days)	−30.0	152.625
H′, (dimensionless)	3.0	2.0
P′, (degrees)	20.0 if γ_l = + 0.0 if γ_l = −	−75.0
B′, (dimensionless)	1.28	1.50

where U_o (cm) is the ozone content in the atmosphere. *Bird and Hulstrom* [1981] incorporated the ozone content as an empirical coefficient. Table 8 lists some empirical values for ozone content found in the literature.

[33] *Van Heuklon* [1979] developed a model based on atmospheric monitoring to calculate the amount of ozone in the atmosphere, U_o (cm), as a function of location and time of year using

$$U_o = \frac{235 + \begin{bmatrix} A' + C' \sin(0.9856(\lfloor Jday \rfloor + F')) + \\ 20 \sin(H'(\gamma_l + P')) \end{bmatrix} \sin^2(B'\psi)}{1000.0} \quad (31)$$

where A', B', C', F', H', and $P'$are coefficients that are a function of hemisphere (see Table 9). The ozone model by *Van Heuklon* [1979] was used in place of an empirical value in the *Bird and Hulstrom* [1981] model.

[34] *Bird and Hulstrom* [1981] calculated the transmittance of the water vapor, T_w (dimensionless), as

$$T_w = 1 - \frac{2.4959 X_w}{(1 + 79.034 X_w)^{0.6828} + 6.385 X_w} \quad (32)$$

where X_w (cm) is the precipitable water content in a slanted path, which was calculated by *Bird and Hulstrom* [1981] using

$$X_w = w m_p \quad (33)$$

Bird and Hulstrom [1981] developed an equation for the transmittance of absorptance of uniformly mixed gases such as carbon dioxide and oxygen, T_{UM}(dimensionless), such as

$$T_{UM} = \exp\left(-0.0127 m_p^{0.26}\right) \quad (34)$$

The transmittance of Rayleigh scattering in the atmosphere, T_R (dimensionless), was calculated by *Bird and Hulstrom* [1981], using

$$T_R = \exp\left(-0.0903 m_p^2 \left(1 + m_p - m_p^{1.01}\right)\right) \quad (35)$$

The relative optical air mass, m_p (dimensionless), was calculated using Equation (15) where the solar altitude was corrected due to atmospheric refraction. The correction for the effect of atmospheric refraction on the solar altitude was presented by *NOAA* [2004]. When sunlight hits the upper atmosphere, the path of the light is bent slightly, changing the solar altitude. The corrected solar altitude, $A_{0\text{-}corrected}$ (degrees), was calculated using

$$A_{0-corrected} = A_0 + RC \quad (36)$$

where RC is the atmospheric refraction correction. Table 10 provides the equations for calculating the atmospheric refraction correction depending on the uncorrected solar altitude.

[35] The uncorrected solar altitude was calculated using Equation (2). The extraterrestrial solar irradiance φ_{ext} was calculated using Equation (10) where the eccentricity correction, E_o was calculated using Equation (11). The equations and methodology that follow were obtained from *Meeus* [1999] unless stated otherwise. An equation to calculate the distance between the Earth and the Sun at any given time, r (AU), as

$$r = \left(1.000001018\{1 - e^2\}\right) / \{(1 + e\cos\{v\}) \quad (37)$$

where e is the eccentricity of Earth's orbit, and v is the true anomaly of the sun. The true anomaly of the sun, v (degrees), was calculated using

$$v = M + c \quad (38)$$

Table 10. Atmospheric Refraction Correction for Solar Altitude, *NOAA* [2004]

A_o	Approximate Atmospheric Refraction Correction, RC
85° to 90°	0.00
5° to 85°	$\frac{1^o}{3600}\left[\frac{58.1''}{\tan(A_o)} - \frac{0.07''}{\tan^3(A_o)} + \frac{0.000086''}{\tan^5(A_o)}\right]$
−0.575° to 5°	$\frac{1^o}{3600}\left[1735'' - 518.2'' A_o + 103.4'' A_o^2 - 12.79'' A_o^3 + 0.711'' A_o^4\right]$
< −0.575	$\frac{1^o}{3600''}\left[\frac{-20.774''}{\tan(A_o)}\right]$

Equation References for Solar Radiation Models Compared

EPA [1971]	*EPA* [1971], *Spencer* [1971], *Wunderlich* [1972]	*EPA* [1971]	None
Klein [1948]		*Spencer* [1971], *Kasten* [1964], *Klein* [1948], *Bolsenga* [1965], *Wunderlich* [1972]	Dust
Kennedy [1949]		*Spencer* [1971], *Kasten* [1964], *Kennedy* [1949]	Atmospheric Transmission Coefficient
Lee [1978]		*Spencer* [1971], *Kasten* [1964], *Lee* [1978]	Atmospheric Transmission Coefficient
Meeus [1999] and *Bird and Hulstrom* [1981]	*Meeus* [1999] and *NOAA* [2004]	*Bird and Hulstrom* [1981], *Bolsenga* [1965], *Van Heuklon* [1979], *Kasten* [1964]	Ratio of Forward-Scattered Irradiance to the Total Scattered, Aerosol Absorptance and Atmospheric Turbidity

where M is the geometric mean anomaly of the sun and c is the center for the sun. The local hour angle, H (degrees), was calculated as

$$H = h_{tst}/4 - 180 \tag{39}$$

where h_{tst} (minutes) is the true solar time and was calculated as

$$h_{tst} = 60h_l + h_e - 4\gamma_l \tag{40}$$

[36] If the longitude in Equation (40) is negative, then it is multiplied by -1.0 to adjust the longitude to positive to match the time zone adjustment. The equation of time, h_e (minutes), was calculated using

$$h_e = 4\begin{bmatrix} y\sin(2\theta_{LO}) - 2e\sin(M) + 4ey\sin(M)\cos(2\theta_{LO}) \\ -0.5y^2\sin(4\theta_{LO}) - 1.25e^2\sin(2M) \end{bmatrix} \tag{41}$$

$$\text{where } y = \left(\tan\left(\varepsilon_p/2\right)\right)^2$$

where θ_{LO} is the geometric mean longitude of the sun, and ε_p is the corrected obliquity of the ecliptic. The eccentricity of Earth's orbit, e (dimensionless), was calculated using

$$e = 0.016708634 - t(0.000042037 + 0.0000001267t) \tag{42}$$

where t is the Julian centuries. The declination of the sun, δ, was calculated using

$$\delta = \arcsin\left(\sin\left(\varepsilon_p\right)\sin(\lambda)\right) \tag{43}$$

where λ is the apparent longitude of the sun. The corrected obliquity of the ecliptic, ε_p (degrees), was calculated using

$$\varepsilon_p = \varepsilon_0 + 0.00256\cos(125.04 - 1934.136t) \tag{44}$$

where ε_0 (degrees) is the mean obliquity of the ecliptic and was calculated using

$$\varepsilon_0 = 23.0 + [26.0 + ((21.448 - t\{46.8150 + t(0.00059 - 0.001813t)\})/60)]/60 \tag{45}$$

The apparent longitude of the sun, λ (degrees), was calculated using

$$\lambda = \theta_{TLO} - 0.00569 - 0.00478\sin(125.04 - 1934.136t) \tag{46}$$

Table 12. Site Locations and Details for the Seventeen Solar Radiation Monitoring Sites and Their Data Sources

Site	State	Region	Elev., m	Time zone (GMT), hrs	Years of data
Bull Run Headworks[a]	OR	Northwest	263.0	−8	1999–2004
Lower Bull Run River[b]	OR	Northwest	181.8	−8	part of 2002
Gladstone[c]	OR	Northwest	98.0	−8	1999–2003
Aurora[d]	OR	Northwest	43.0	−8	1998–2003
Eugene[c]	OR	Northwest	150.0	−8	2001–2003
H.J. Andrews[e]	OR	Northwest	430.0	−8	1990–1996
Corvallis[d]	OR	Northwest	70.1	−8	2001–2003
Parma[d]	ID	Northwest	702.6	−7	1999–2004
Seattle[f]	WA	Northwest	20.0	−8	2000–2004
Bismarck[f]	ND	Mid-West	503.0	−6	1995–2004
Madison[f]	WI	Mid-West	271.0	−6	1996–2004
Sterling[f]	VA	East Coast	85.0	−5	1995–2004
Oakridge[f]	TN	East Coast	334.0	−5	1995–2004
Tallahassee[f]	FL	East Coast	18.0	−5	1995–2002
Albuquerque[f]	NM	Southwest	1617.0	−7	1994–2004
Salt Lake City[f]	UT	Southwest	1288.0	−7	1995–2004
Hanford[f]	CA	Southwest	73.0	−8	1995–2004

[a]Water Bureau, City of Portland, Oregon (Drinking Water Headworks facility).
[b]Department of Civil and Environmental Engineering, Portland State University (Lower Bull Run River).
[c]University of Oregon Solar Radiation Monitoring Lab.
[d]AgriMet, Pacific Northwest Region, Bureau of Reclamation, U.S. Department of Interior.
[e]H.J. Andrews Experimental Forest, Oregon State University and the U.S. Forest Service.
[f]Integrated Surface Irradiance Study, Atmospheric Turbulence and Diffusion Division, Air Resources Laboratory, National Oceanic and Atmospheric Administration.

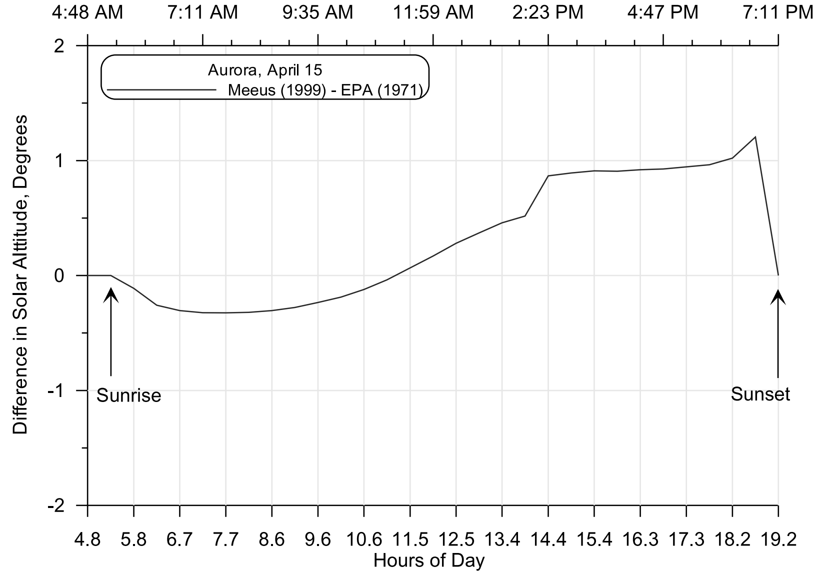

Figure 1. Difference in solar altitude for the *Meeus* [1999] and *Bird and Hulstrom* [1981] model and the *EPA* [1971] model at Aurora, Oregon.

where θ_{TLO} (degrees) is the true longitude of the sun and was calculated as

$$\theta_{TLO} = \theta_{LO} + c \tag{47}$$

The center for the sun, c (degrees), was calculated using

$$\begin{aligned} c = \; & \sin(M)(1.914602 - t(0.004817 + 0.000014t)) \\ & + \sin(2M)(0.019993 - 0.000101t) + 0.000289\sin(3M) \end{aligned} \tag{48}$$

The geometric mean anomaly of the sun, M (degrees), was calculated using

$$M = 357.52911 + t(35999.05029 - 0.0001537t) \tag{49}$$

The geometric mean longitude of the sun, θ_{LO} (degrees), was calculated as

$$\theta_{LO} = 280.46646 + t(36000.76983 + 0.0003032t) \tag{50}$$

If θ_{LO} has value outside of 0 to 360 degrees, then 360 degrees are added or subtracted until θ_{LO} is within this range. The Julian centuries since the epoch 2000 t was calculated using

$$t = (JD - 2451545.0)/36525.0 \tag{51}$$

where JD is the Julian Ephemeris Day. The Julian Ephemeris Day, JD, was calculated based on a continuous count of days since the beginning of the year −4712. The Julian Ephemeris Day begins at Greenwich mean noon and can be calculated from the Gregorian calendar. The Julian Ephemeris Day from the Gregorian calendar was calculated using

$$\begin{aligned} JD = & \lfloor 365.25(t_{yr} + 4716.0) \rfloor + \lfloor 30.6001(t_{mn} + 1) \rfloor + t_{dd} \\ & + \left(2 - \lfloor t_{yr}/100.0 \rfloor + \lfloor \lfloor t_{yr}/100.0 \rfloor /4.0 \rfloor\right) - 1524.5 \end{aligned} \tag{52}$$

where t_{yr} and t_{mn} are the year and month based on the Gregorian calendar, and t_{dd} is decimal day for the day and fraction of the day. *Meeus* [1999] adjusted the Gregorian calendar month and year to place dates in January and February in the preceding year as the 13th and 14th months. If

Table 13. Empirical Coefficients Which Provided the Smallest Model-Data Mean Error Statistics for All Sites and Clear-Sky Data

Parameter	*EPA* [1971]	*Klein* [1948]	*Kennedy* [1949]	*Lee* [1978]	*Meeus* [1999] and *Bird and Hulstrom* [1981]
Dust, d	No adjustable parameters	0.222			
Atmospheric Attenuation, a_t			0.8623	0.8693	
Ratio of Forward Scattering, B_a					0.83
Aerosol Absorptance, K_1					0.10
Atmospheric Turbidity $\tau_{A0.38}$					0.30
Atmospheric Turbidity $\tau_{A0.50}$					0.20

Model-Data Error Statistics for 2,726 Clear-Sky Days[a]

Model/Solar Radiation	ME, W/m^2	AME, W/m^2	RMS, W/m^2
EPA [1971]	−4.16	21.49	35.53
Klein [1948]	0.00	20.92	35.82
Kennedy [1949]	0.00	20.39	33.71
Lee [1978]	0.00	21.49	35.42
Meeus [1999] and *Bird and Hulstrom* [1981]	0.00	17.28	29.41

[a]ME = Mean Error; AME = Absolute Mean Error; RMS = Root Mean Square Error.

the month was less than or equal to 2, then t_{yr} and t_{mn} were adjusted as

$$\begin{aligned} t_{yr} &= t_{yr} - 1 \\ t_{mn} &= t_{mn} + 12 \end{aligned} \tag{53}$$

The decimal day of the month was calculated using

$$t_{dd} = t_{day} + h_l/24 \tag{54}$$

where t_{day} is the integer day of the month from the Gregorian calendar, and h_l is the local hour. The day, year, and month, based on the Gregorian calendar, were calculated from the Julian day, *Jday,* in the model. The Julian day corresponds to the annual Julian calendar adjusted from the local time zone to GMT using

$$Jday = Jday - h_{TZ}/24 \tag{55}$$

[37] *Meeus* [1999] made all solar calculations at Greenwich mean time (GMT) so the model input *Jday* values were adjusted to GMT for calculations and adjusted back to local standard time (LST) at the end.

3. Empirical Coefficients

[38] The solar radiation formulation models, with the exception of the *EPA* [1971] model, use empirical coefficients which can be adjusted for calibration. Table 11 lists the equation references and the calibration parameters for each model.

4. Solar Radiation Data

[39] The five models were used to calculate solar radiation over multiple years and the results from each model compared to data collected at seventeen sites in the United States. Table 12 lists the site names, states, elevation, time zone, extent of data, and the data source. Most of the data were obtained from the National Oceanic and Atmospheric Administration program, Integrated Surface Irradiance Study. Data were recorded at intervals of 10, 15, 30, or 60 minutes and compared to model predictions at these same times.

5. Solar Altitude Comparison

[40] Solar altitude was calculated using the *EPA* [1971] model (Equations (2) to (8)) and the *Meeus* [1999] and *Bird and Hulstrom* [1981] model (Equations (2), (36), (39) and (43)) and compared to investigate the differences between the solar position calculations. The mean difference in solar altitude between the two models for the seventeen sites in the U.S. was about 2.6 percent with the *EPA* [1971] model giving lower values. Based on this difference in solar altitude, the mean difference in solar radiation would be 5.8 percent lower for the *EPA* [1971] model. Figure 1 shows the results from the Aurora, Oregon site on April 15 and indicates the *Meeus* [1999] and *Bird and Hulstrom* [1981] model has higher solar altitudes after 12:00 pm and only

Table 15. Model-Data Error Statistics for the 17 Sites, 2,726 Clear-Sky Days[a]

		EPA [1971]			*Klein* [1948]			*Kennedy* [1949]			*Lee* [1978]			*Meeus* [1999] and *Bird and Hulstrom* [1981]		
Site	Clear-sky days	ME, W/m^2	AME, W/m^2	RMS, W/m^2	ME, W/m^2	AME, W/m^2	RMS, W/m^2	ME, W/m^2	AME, W/m^2	RMS, W/m^2	ME, W/m^2	AME, W/m^2	RMS, W/m^2	ME, W/m^2	AME, W/m^2	RMS, W/m^2
Bull Run Headworks	229	18.6	31.0	52.9	21.5	26.0	53.4	19.3	34.5	55.0	21.0	35.5	56.4	20.8	27.9	51.9
Lower Bull Run River	10	−6.2	14.7	22.8	−9.3	17.5	27.4	−5.8	22.3	34.5	−2.7	23.4	35.7	−8.7	15.9	24.4
Gladstone	144	1.7	11.2	19.0	4.8	14.4	24.4	0.0	13.3	21.6	3.5	14.5	23.2	3.2	9.4	16.5
Aurora	224	−6.4	15.9	25.8	−3.5	13.8	23.1	−8.6	19.3	30.8	−4.6	19.2	30.6	−5.0	11.9	18.8
Eugene	132	−3.9	10.3	16.8	−2.7	16.9	26.8	−3.7	10.4	16.6	−0.6	11.1	17.5	−3.1	10.8	17.8
H.J. Andrews	189	43.5	47.0	80.7	43.1	49.8	89.4	48.4	49.5	82.2	48.3	49.5	82.1	44.5	47.8	85.5
Corvallis	99	5.2	14.8	23.9	7.1	12.8	20.3	4.3	22.1	34.2	8.3	23.9	37.2	6.1	12.6	19.6
Parma	87	−22.3	24.2	40.1	−12.6	18.7	30.4	−17.2	19.3	34.3	−20.2	21.6	37.4	−14.2	15.8	26.2
Seattle	84	1.4	10.8	17.9	3.2	14.3	23.2	−1.9	14.0	22.7	2.7	15.4	24.7	1.5	8.4	14.4
Bismarck	139	−9.7	19.1	30.0	−6.7	20.2	32.2	−6.0	17.8	28.7	−7.0	18.2	29.4	−7.0	15.1	24.0
Madison	172	−11.8	18.1	29.8	−6.0	16.5	27.4	−10.7	18.0	29.6	−9.3	17.9	29.5	−7.5	13.9	22.8
Sterling	186	−13.4	18.7	30.9	−7.9	16.9	28.4	−12.4	18.4	30.2	−8.9	17.5	28.7	−9.0	13.9	23.2
Oakridge	181	−14.1	19.0	31.5	−6.8	16.5	27.8	−8.8	15.7	26.6	−8.0	15.6	26.7	−7.0	13.1	22.0
Tallahassee	166	−7.6	19.9	33.6	−1.2	18.3	33.4	−3.4	17.0	29.5	0.9	17.1	29.6	−1.0	14.9	26.7
Albuquerque	261	−25.5	28.0	45.2	−17.4	23.9	38.6	−6.1	14.9	25.8	−19.2	20.9	35.1	−14.3	17.7	28.5
Salt Lake City	195	−17.6	23.9	38.5	−11.5	23.5	36.9	−3.6	17.8	30.2	−13.3	19.6	34.3	−9.6	16.9	26.7
Hanford	228	−4.3	15.3	24.6	−3.3	19.0	31.3	−1.9	15.1	25.8	2.2	16.2	26.9	−2.3	13.0	21.3

[a]ME = Mean Error; AME = Absolute Mean Error; RMS = Root Mean Square Error.

Parameter	*EPA* [1971]	*Klein* [1948]	*Kennedy* [1949]	*Lee* [1978]	*Meeus* [1999] and *Bird and Hulstrom* [1981]
Dust, d	No adjustable parameters	0.1709			
Atmospheric Attenuation, a_t			0.8668	0.8737	
Ratio of Forward Scattering, B_a					0.85
Aerosol Absorptance, K_1					0.10
Atmospheric Turbidity $\tau_{A0.38}$					0.204
Atmospheric Turbidity $\tau_{A0.50}$					0.100

slightly different before 12:00 pm. These results are similar at the other sixteen sites and throughout the year. The solar altitudes from the two models were divided into two groups, before 12:00 pm and after 12:00 pm each day and analyzed separately. The difference between the two models before noon each day had a mean difference in solar altitude of −0.1 percent across the 17 sites. The difference between the two models after noon each day had a mean difference in solar altitude ranges of −5.1 percent. The *EPA* [1971] model consistently calculated a lower solar altitude in the latter half of the day compared to the *Meeus* [1999] and *Bird and Hulstrom* [1981] model.

6. Model Calibration and Testing

6.1. All Sites and Data

[41] The five models were calibrated to the clear-sky solar radiation data identified at the 17 sites. A large data set of clear-sky solar radiation days was created to allow a comprehensive comparison with the model estimates of solar radiation. The calibration process consisted of adjusting parameter values which would provide the best model-data comparison results at all of the sites. The number of clear-sky days among the 17 sites varied from 10 to 261 over a maximum of 10 years of available data (e.g., see Table 12). The result was a total of 2,726 clear-sky days that could be used for model parameter estimation and model-data comparisons. The clear-sky solar radiation data collected at the sites did not include reflected radiation so several models which included reflected radiation in their formulation were adjusted for comparison with the data. In the *Klein* [1948] model the reflectivity coefficient, R_g, was set to zero for comparison with the data. The *EPA* [1971], *Kennedy* [1949], and *Lee* [1978] models include direct, diffuse and reflected radiation, but do not parameterize a reflectivity coefficient in their model formulations like *Klein* [1948]. The calculated solar radiation values for these three models were dynamically corrected for the effects of reflectivity using Equation (18) from *Anderson* [1954] and then compared to the clear-sky solar radiation data.

[42] Table 13 shows the list of model coefficient values which provided the smallest model-data error using the mean error (ME) while trying to minimize the root mean square (RMS) error. Table 14 shows the model-data error statistics for each model. The table shows *Meeus* [1999] and *Bird and Hulstrom* [1981] model performs best, with the lowest model-data error statistics, which may be attributable to the model having more empirical coefficients which can be adjusted. The *Kennedy* [1949] model performed the second best and required one coefficient to be adjusted. Table 15 shows the model-data error statistics for all sites and models. The table indicates there is slight positive bias with the sites located in the Northwestern region of the U.S. while the remaining sites have a negative bias across the five models. The *Meeus* [1999] and *Bird and Hulstrom* [1981] model had the lowest model-data RMS error for most of the sites. The smallest model-data mean errors were from the *Klein* [1948] and *Kennedy* [1949] models. The *EPA* [1971] model has relatively consistent model-data errors across the country with no regional patterns in absolute mean error and RMS error. The negative ME for the *EPA* [1971] model is due the formulation being derived for sea level. Higher altitude sites shown in Table 15 show the under-prediction of the clear-sky solar radiation with increasing elevation with the *EPA* [1971] model. The *Klein* [1948] model performs similarly in the Western half of the U.S. and better in the East and Mid-West. The *Kennedy* [1949], *Lee* [1978] and the *Meeus* [1999] and *Bird and Hulstrom* [1981] models perform better in Southwest, East, and Mid-west than in the Northwest. The data from the Bull Run Headworks and H.J. Andrews solar radiation monitoring sites may have been influenced by vegetative or topographic shade early and late in the day as shown in the poorer model-data errors statistics.

6.2. All Sites, April Calibration

[43] The five models were calibrated to clear-sky solar radiation data at 16 sites in April only, and then used to calculate solar radiation values for the full year. The solar radiation data from the Lower Bull Run River were elim-

Table 17. Model-Data Error Statistics for 16 Sites Calibrated in April and Applied to All the Data[a]

Model/Solar Radiation	Calibration April, 209 Clear-Sky Days			Application All Data, 2,726 Clear-Sky Days		
	ME, W/m^2	AME, W/m^2	RMS, W/m^2	ME, W/m^2	AME, W/m^2	RMS, W/m^2
EPA [1971]	−12.76	24.79	39.82	−4.16	21.49	35.53
Klein [1948]	0.00	22.42	37.79	8.47	19.84	34.09
Kennedy [1949]	0.00	18.70	31.15	3.27	20.63	33.86
Lee [1978]	0.00	19.97	33.19	3.39	21.73	35.62
Meeus [1999] and *Bird and Hulstrom* [1981]	0.00	18.32	31.11	6.67	16.85	28.69

[a]ME = Mean Error; AME = Absolute Mean Error; RMS = Root Mean Square Error.

Empirical Coefficients Which Provided the Smallest

Parameter	*EPA* [1971]	*Klein* [1948]	*Kennedy* [1949]	*Lee* [1978]	*Meeus* [1999] and *Bird and Hulstrom* [1981]
Dust, d	No adjustable parameters	0.2156			
Atmospheric attenuation, a_t			0.8633	0.8690	
Ratio of forward scattering, B_a					0.84
Aerosol absorptance, K_1					0.10
Atmospheric turbidity $\tau_{A0.38}$					0.287
Atmospheric turbidity $\tau_{A0.50}$					0.200

inated from the analysis since there were collected during the summer only. The calibration process consisted of adjusting parameter values which would provide the lowest model-data mean error. The data set for comparisons consisted of 209 clear-sky days from the 16 sites.

[44] Table 16 shows the list of model coefficient values which provided the smallest model-data error using the mean error while trying to minimize the RMS error. Table 17 shows the model-data error statistics for each model for the April calibration period and the application period of the whole year. The *Meeus* [1999] and *Bird and Hulstrom* [1981] model had the lowest RMS errors for both the April calibration period and the all-year application period.

6.3. All Sites, One Year Calibration

[45] The five models were calibrated with the solar radiation data at 15 sites for clear-sky days in 2001 only, and then used to calculate solar radiation values for 2002 and then compared with data. The solar radiation data from the Lower Bull Run River and H.J. Andrews were eliminated from the analysis since there were no data in 2001 from these two sites. The calibration process consisted of adjusting parameter values which would provide the lowest model-data mean error in 2001. The data set for comparisons consisted of 395 clear-sky days from the 15 sites in 2001.

[46] Table 18 shows the list of model coefficient values which provided the smallest model-data error using the mean error while trying to minimize the RMS error in 2001. Table 19 shows the model-data error statistics for each model for the 2001 calibration period and the application period in 2002. The statistics indicate all of the models had decreased model-data root-mean square errors for 2002 when compared to 2001, but increased mean-errors. The improved RMS statistics may be due the larger number of clear-sky days in 2002 (442) than in 2001 (395). The *Meeus* [1999] and *Bird and Hulstrom* [1981] model had the lowest RMS errors for both years compared to the other models.

6.4. One Site, All Data

[47] The five models were calibrated for 13 clear-sky days in April (from multiple years) at the Aurora, Oregon site and then the calibrated coefficient values were then applied for 29 clear-sky days in September (from multiple years) to determine how well the models perform with "predicting" another time period. Table 20 shows the list of coefficient values which provided the smallest model-data error using the mean error while trying to minimize the RMS error during April. Table 21 shows the model-data error statistics for each model during both April and September. The *Meeus* [1999] and *Bird and Hulstrom* [1981] model had lower RMS errors for both April and September than the other models.

6.5. Sensitivity of Dew Point Temperature Data

[48] The second sensitivity analysis conducted evaluated the influence of dew point temperature in the *Klein* [1948] model and the *Meeus* [1999] and *Bird and Hulstrom* [1981] model. Solar radiation was calculated with the two models using dew point temperature data which were adjusted by ±10%. The sensitivity of the solar radiation due to changes in dew point temperature was calculated using

$$S = \left(\frac{\varphi_{dataset1} - \varphi_{dataset2}}{\varphi_{dataset1}}\right) / \left(\frac{T_{dpt_{dataset1}} - T_{dpt_{dataset2}}}{T_{dpt_{dataset1}}}\right) \tag{56}$$

expressed as a dimensionless percentage where φ is the calculated clear-sky solar radiation, T_{dpt} is the dew point temperature data, *data set*1 is the dew point temperature data set used, and *data set*2 corresponds to either +10% or −10% from *datset*1.

[49] The annual average of the dimensionless sensitivity coefficients was taken at each site. Table 22 shows the sensitivity coefficient for the *Klein* [1948] model and the *Meeus* [1999] and *Bird and Hulstrom* [1981] model. The table indicates the dew point temperature has limited effect on the calculated solar radiation. The sensitivity values were larger

Table 19. Model-Data Error Statistics for 15 Sites Calibrated in 2001 and Applied to 2002[a]

Model/Solar Radiation	Calibration Year 2001, 395 Clear-Sky Days			Application Year 2002, 442 Clear-Sky Days		
	ME, W/m^2	AME, W/m^2	RMS, W/m^2	ME, W/m^2	AME, W/m^2	RMS, W/m^2
EPA [1971]	−3.74	18.70	30.85	−4.86	17.27	28.18
Klein [1948]	0.00	19.01	32.08	−0.40	17.11	29.04
Kennedy [1949]	0.00	18.87	30.73	−2.13	17.31	27.70
Lee [1978]	0.00	20.28	32.92	−1.88	18.70	29.75
Meeus [1999] and *Bird and Hulstrom* [1981]	0.00	15.05	25.32	−1.17	13.72	23.19

[a]ME = Mean Error; AME = Absolute Mean Error; RMS = Root Mean Square Error.

Aurora, Oregon

Parameter	*EPA* [1971]	*Klein* [1948]	*Kennedy* [1949]	*Lee* [1978]	*Meeus* [1999] and *Bird and Hulstrom* [1981]
Dust, d	No adjustable parameters	0.1460			
Atmospheric attenuation, a_t			0.8787	0.8800	
Ratio of forward scattering, B_a					0.85
Aerosol absorptance, K_1					0.10
Atmospheric turbidity $\tau_{A0.38}$					0.07
Atmospheric turbidity $\tau_{A0.50}$					0.07

for the *Klein* [1948] model for 10% higher dew point temperature and smaller for 10% lower dew point temperature than the *Meeus* [1999] and *Bird and Hulstrom* [1981] model.

7. Summary and Discussion

[50] Several empirical models have been developed for calculating the total clear-sky solar radiation on the ground surface. Five models were presented, some with modifications, to calculate the position of the sun and the resultant solar radiation. The models used for calculating the position of the sun and solar radiation varied from having no empirical coefficients to four empirical coefficients (see Table 13) which had limited ranges based on the literature. Solar radiation data from 17 sites around the United States and up to 10 years of data at some sites were obtained to identify clear-sky solar radiation data to compare with the model results. The five models were calibrated and tested in four different ways: (1) clear-sky days (2,726) from all sites and years were used to estimate an optimal set of coefficients for each model and the models then used to predict solar radiation at all sites for all clear-sky days; (2) similarly, clear-sky days (209) from all months of April were used to estimate model coefficients and the models used to predict solar radiation for all 2,726 clear-sky days; (3) clear-sky days (395) from 2001 were used to estimate model coefficients and the models used to predict clear-sky solar radiation for 2002 (442); and (4) clear-sky days (13) from Aurora, OR from all months of April were used to estimate model coefficients and the models used to predict clear-sky solar radiation for all months of September (29) at the same site. The sensitivity of the *Klein* [1948] and *Meeus* [1999] and *Bird and Hulstrom* [1981] models, since they required dew point temperature in their models, were tested for model sensitivity to dew point temperature.

[51] The solar altitude calculated with the *EPA* [1971] model was 2 to 3 percent lower than calculated with the *Meeus* [1999] and *Bird and Hulstrom* [1981] model which resulted in a decrease in solar radiation estimates of 1 to 9 percent. The solar altitude calculated by the *Meeus* [1999] and *Bird and Hulstrom* [1981] model is preferred since it is more accurate.

[52] The *Meeus* [1999] and *Bird and Hulstrom* [1981] model resulted in the best model calibration with data from the 17 sites around the U.S and all years with the clear-sky solar radiation data identified. When the five models were calibrated to all the clear-sky data at 16 sites in April and the calibrated coefficients were applied to all the data throughout the year, the *Meeus* [1999] and *Bird and Hulstrom* [1981] model performed best at predicting solar radiation. When all of the models were calibrated to 2001 clear-sky data and then applied and compared with 2002 clear-sky data, all of the models performed better in 2002 than 2001. This may be due to the larger number of clear-sky days available for comparison in 2002 than 2001. For both years the *Meeus* [1999] and *Bird and Hulstrom* [1981] model performed best based on mean error and RMS error. When the five models were calibrated to all of the clear-sky data at Aurora, Oregon in April and then applied and compared to data in September, the *Meeus* [1999] and *Bird and Hulstrom* [1981] model had the lowest RMS error for both the application period.

[53] The dew point temperature has limited influence on the calculated solar radiation using the *Klein* [1948] and the *Meeus* [1999] and *Bird and Hulstrom* [1981] models. The *Klein* [1948] model was found to be slightly more sensitive to changes in dew point temperature than the *Meeus* [1999] and *Bird and Hulstrom* [1981] model.

[54] The *EPA* [1971] model with no calibration parameters did reasonably well in matching field data even though it was developed for solar radiation prediction at sea level and hence under predicted solar radiation at higher altitudes.

8. Conclusion

[55] The analyses showed that the more complex models for calculating solar radiation are better at estimating incident solar radiation on a water surface but require data

Table 21. Model-Data Error Statistics for April and September at Aurora, Oregon[a]

Model/Solar Radiation	Calibration 13 April Clear-Sky Days			Application 29 September Clear-Sky Days		
	ME, W/m^2	AME, W/m^2	RMS, W/m^2	ME, W/m^2	AME, W/m^2	RMS, W/m^2
EPA [1971]	−16.17	20.84	30.49	−4.47	12.48	19.33
Klein [1948]	0.00	13.47	23.12	11.66	14.22	22.75
Kennedy [1949]	0.00	14.16	22.32	6.97	17.68	29.28
Lee [1978]	0.00	14.61	22.99	6.90	18.17	29.97
Meeus [1999] and *Bird and Hulstrom* [1981]	0.00	9.00	16.34	9.69	12.06	18.70

[a]ME = Mean Error; AME = Absolute Mean Error; RMS = Root Mean Square Error.

Klein [1948] Model and *Meeus* [1999] and *Bird and Hulstrom* [1981] Model Input Dew Point Temperature Annual Sensitivity

Site	10 % Lower Dew Point Temperature		10 % Higher Dew Point Temperature	
	Klein [1948], Sensitivity	*Meeus* [1999] and *Bird and Hulstrom* [1981], Sensitivity	*Klein* [1948], Sensitivity	*Meeus* [1999] and *Bird and Hulstrom* [1981], Sensitivity
Bull Run Headworks	0.6%	3.1%	−4.6%	−5.5%
Lower Bull Run River	−0.2%	3.3%	−7.0%	−6.7%
Gladstone	0.4%	3.2%	−5.5%	−5.9%
Aurora	0.2%	3.2%	−6.0%	−6.0%
Eugene	0.4%	3.1%	−5.1%	−5.6%
H.J. Andrews	0.3%	2.7%	−4.9%	−5.2%
Corvallis	0.4%	3.0%	−5.0%	−5.4%
Parma	−0.3%	0.2%	−1.7%	−1.6%
Seattle	0.4%	3.1%	−5.3%	−5.6%
Bismarck	−1.6%	0.1%	−3.8%	−2.0%
Madison	−1.7%	0.5%	−4.6%	−2.8%
Sterling	−2.2%	1.0%	−6.7%	−4.0%
Oakridge	−2.5%	1.3%	−7.7%	−4.7%
Tallahassee	−3.8%	1.9%	−11.2%	−6.3%
Albuquerque	−0.8%	−0.9%	−0.9%	0.0%
Salt Lake City	−0.7%	−0.5%	−1.0%	−0.9%
Hanford	0.0%	3.1%	−5.7%	−5.9%

to be calibrated for a specific location and time period. If there is an on-site clear sky solar radiation data set to estimate the coefficients in a solar radiation model, then the *Meeus* [1999] and *Bird and Hulstrom* [1981] model should be used. If there are no on-site clear sky solar radiation data available then the modified *EPA* [1971] should be used to estimate incident solar radiation on the water surface at sea level.

Notation

φ_s clear-sky solar radiation (direct and diffuse) at the ground surface, W/m^2.
A_o solar altitude (uncorrected), degrees.
ψ latitude, degrees.
δ solar declination angle, radians.
H local hour angle, radians.
h_l local hour, hours.
γ standard meridian, degrees.
γ_l longitude, degrees.
h_e equation of time, hours.
$Jday$ Julian day as a floating-point value on a scale of 1 to 365 days for a year (366 for a leap year), days.
h_{TZ} time zone relative to Greenwich Mean Time, hours.
τ_d angular fraction of the year, radians.
φ_{ext} extraterrestrial solar irradiance, W/m^2.
a' mean atmospheric transmission coefficient for a cloudless, dust-free, moist air after scattering, dimensionless.
a'' mean atmospheric transmission coefficient for cloudless, dust-free, moist air after scattering and absorption, dimensionless.
d atmospheric dust, dimensionless.
R_g ground surface reflectivity (or albedo), dimensionless.
φ_o solar constant, W/m^2.
E_o eccentricity correction, dimensionless.
r_o average distance between the Earth and the sun, 1 AU, Astronomical Unit.
r distance between the Earth and the sun at any given time, AU.
m_p relative optical air mass, dimensionless.
w precipitable water content in the atmosphere, cm.
z elevation of the water body, meters.
T_{dpt} dew point temperature, degrees Celsius.
d_s atmospheric dust scattering of solar radiation, dimensionless.
d_a atmospheric dust absorption of solar radiation, dimensionless.
α coefficient dependent on the fraction of cloud cover, dimensionless.
β coefficient dependent on the fraction of cloud cover, dimensionless.
a_h hourly average atmospheric transmission coefficient, dimensionless.
a_t daily atmospheric transmission coefficient, dimensionless.
φ_d direct solar radiation on a horizontal ground surface, W/m^2.
φ_l scattered solar radiation on a horizontal ground surface, W/m^2.
r_s atmospheric albedo, dimensionless.
T_A transmittance of aerosol absorptance and scattering, dimensionless.
T_w transmittance of water vapor, dimensionless.
T_{UM} transmittance of uniformly mixed gases, dimensionless.
T_o transmittance of ozone content, dimensionless.
T_R transmittance of Rayleigh scattering in the atmosphere, dimensionless.
B_a ratio of forward-scattered irradiance to the total scattered irradiance due to aerosols, dimensionless.

transmittance of aerosol absorptance, dimensionless.
K_1 empirical absorptance coefficient, dimensionless.
τ_A overall atmospheric turbidity, dimensionless.
$\tau_{A0.38\mu m}$ aerosol optical depth from the surface in a vertical path at 380 nm wavelength (no molecular absorption), dimensionless.
$\tau_{A0.5\mu m}$ aerosol optical depth from the surface in a vertical path at 500 nm wavelength (ozone absorption), dimensionless.
X_o amount of ozone in a slanted path, cm.
U_o ozone content in the atmosphere, cm.
A' empirical coefficient for calculating the ozone content in the atmosphere, atm-cm.
C' empirical coefficient for calculating the ozone content in the atmosphere, atm-cm.
F' empirical coefficient for calculating the ozone content in the atmosphere, days.
H' empirical coefficient for calculating the ozone content in the atmosphere, dimensionless.
P' empirical coefficient for calculating the ozone content in the atmosphere, degrees.
B' empirical coefficient for calculating the ozone content in the atmosphere, dimensionless.
X_w precipitable water content in a slanted path, cm.
$A_{0\text{-}corrected}$ corrected solar altitude to account for light bending when hitting the atmosphere, degrees.
RC atmospheric refraction correction, degrees.
e eccentricity of Earth's orbit, dimensionless.
v true anomaly of the sun, degrees.
M geometric mean anomaly of the sun, degrees.
c center for the sun, degrees.
h_{tst} true solar time, minutes.
θ_{LO} geometric mean longitude of the sun, degrees.
ε_p corrected obliquity of the ecliptic, degrees.
t Julian centuries since the epoch 2000.
λ apparent longitude of the sun, degrees.
ε_0 mean obliquity of the ecliptic, degrees.
θ_{TLO} true longitude of the sun, degrees.
JD Julian Ephemeris Day (based on a continuous count of days since the beginning of the year -4712).
t_{yr} year based on the Gregorian calendar.
t_{mn} month based on the Gregorian calendar.
t_{dd} decimal day for the day and fraction of the day, days.
t_{day} integer day of the month from the Gregorian calendar, days.
S sensitivity of solar radiation, dimensionless.

[56] **Acknowledgments.** This work was partially supported by a grant from the U.S. Geological Survey Oregon Water Resources Research Institute through the Center for Water and Environmental Sustainability at Oregon State University. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the U.S. Geological Survey.

References

Anderson, E. R. (1954), Energy Budget Studies, Water Loss Investigations–Lake Hefner Studies, Technical Report, *Geological Survey Professional Paper 269*, U.S. Geological Survey, Washington, D. C.

Angstrom, A. (1929), On the atmospheric transmission of sun radiation and on dust in the air, *Geogr. Ann.*, *11*, 156–166.

Annear, R. L., M. L. McKillip, S. J. Khan, C. J. Berger, and S. A. Wells (2004), Willamette River Basin Temperature TMDL Model: Boundary Conditions and Model Setup, *Technical Report EWR-01-04*, 530 pp., Dept. of Civil and Environmental Engineering, Portland State Univ., Portland, OR.

Berger, C. J., M. L. McKillip, R. L. Annear, S. J. Khan, and S. A. Wells (2004), Willamette River Basin Temperature TMDL Model: Model Calibration, *Technical Report EWR-02-04*, 341 pp., Dept. of Civil and Environmental Engineering, Portland State Univ., Portland, OR.

Bird, R. E., and R. L. Hulstrom (1981), A Simplified Clear Sky Model for Direct and Diffuse Insolation on Horizontal Surfaces, *TR-642-761*, 33 pp., Solar Energy Research Institute, Golden, CO.

Bolsenga, S. J. (1964), Daily Sums of Global Radiation for Cloudless Skies, *Technical Report No. 160*, 124 pp., U. S. Army Material Command, Cold Regions Research and Engineering Laboratory, Hanover, NH.

Bolsenga, S. J. (1965), The relationship between total atmospheric water vapor and surface dew point on a mean daily and hourly basis, *J. Appl. Meteorol.*, *4*(3), 430–432.

Bras, R. L. (1990), *Hydrology: An Introduction to Hydrologic Science*, 643 pp., Addison-Wesley Publishing Company, Reading, MA.

Brown, L., and T. Barnwell (1987), The Enhanced Stream Water Quality Models QUAL2E and QUAL2E-UNCAS: Documentation and User Manual, *EPA/600/3-87/007*, Envir. Research Laboratory, U.S. Environmental Protection Agency, Athens, GA.

Brutsaert, W. (1975), Derivable formula for long-wave radiation from clear skies, *Water Resour. Res.*, *11*(5), 742–744.

Cole, T., and S. A. Wells (2000), CE-QUAL-W2: A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 3.0, *Instruction Report EL-00-1*, Waterways Experiments Station, U.S. Army Corps of Eng., Vicksburg, MS.

Dave, J. V. (1978), Extensive datasets of the diffuse radiation in realistic atmospheric models with aerosols and common absorbing gases, *Sol. Energy*, *21*, 361–369.

Dept. of Environmental Quality (1998a), Oregon's 1998 303 (d) List Water body Segment Summary Report, Dept. of Environmental Quality, State of Oregon, <http://www.deq.state.or.us/wq/303dlist/SegmentsSummaryReport.htm> (28 December 2002).

Dept. of Environmental Quality (1998b), Questions and Answers About DEQ's Temperature Standards, Dept. of Environmental Quality, State of Oregon, <http://www.deq.state.or.us/wq/303dlist/TempFactSheet.htm> (28 December 2002).

Dept. of Environmental Quality (1999), Heat Source Methodology Review, Dept. of Environmental Quality, State of Oregon, <http://www.deq.state.or.us/wq/HeatSource/Heat Source.htm> (28 December 2002).

Dept. of Environmental Quality (2001), *Recommended modeling options to address Willamette River temperature, aquatic growth, dissolved oxygen, and pH concerns*, 20 pp., Watershed Management Section, Dept. of Environmental Quality, State of Oregon, Portland, OR.

DiLaura, D. L. (1984), IES Calculation Procedures Committee Recommended practice for the calculation of daylight availability, *J. Illuminating Engineering Soc. of North America*, *13*(4), 381-392.

Dingman, S. L. (2002), *Physical Hydrology, Second Edition*, 646 pp., Prentice Hall, Upper Saddle River, NJ.

Eagleson, P. S. (1970), *Dynamic Hydrology*, 462 pp., McGraw-Hill, New York, NY.

Elterman, L. (1964), Atmospheric Attenuation Model, 1964, in the Ultraviolet, Visible, and Infrared Regions for Altitudes to 50 km, *Technical Report AFCRL 64-70*, 40 pp., Air Force Cambridge Research Laboratories, Bedford, MA.

Elterman, L. (1968), UV, Visible, and IR Attenuation for Altitudes to 50 km, *Technical Report AFCRL 68-0153*, Air Force Cambridge Research Laboratories, Bedford, MA.

Environmental Laboratory (1995), CE-QUAL-RIV1: A Dynamic, One-Dimensional (Longitudinal) Water Quality Model for Streams: User's Manual, *Instruction Report EL-95-2*, 290 pp., Waterways Experiments Station, U.S. Army Corps of Eng., Vicksburg, MS.

Environmental Protection Agency (1971), Effect of Geographical Location on Cooling Pond Requirements and Performance, in *Water Pollution Control Research Series*, *Report No. 16130 FDQ*, 160 pp., Water Quality Office, U.S. Environmental Protection Agency, Washington, D. C.

Flowers, E. C., R. A. McCormick, and K. R. Kurfis (1969), Atmospheric turbidity over the United States, 1961–1966, *J. Appl. Meteorol.*, *8*, 955–962.

Gulliver, J. S. (1977), Analysis of Surface Heat Exchange and Longitudinal Dispersion in a Narrow Open Field Channel with Application to Water Temperature Prediction, 187 pp., M.S. Thesis, Univ. of Minnesota, Minneapolis, MN.

Science, *186*, 1204–1208.

empirical function of daily sunshine duration, *Mon. Weather Rev.*, *82*(6), 141–146.

Kasten, F. (1964), A New Table and Approximation Formula for the Relative Optical Air Mass, *Technical Report No. 136*, 18 pp., U.S. Army Material Command, Cold Regions Research and Engineering Laboratory, Hanover, NH.

Kennedy, R. E. (1940), Average daily air mass, *Mon. Weather Rev.*, *68*(11), 301–303.

Kennedy, R. E. (1949), Computation of daily insolation energy, *Bull. Am. Meteorol. Soc.*, *30*(6), 208–213.

Kimball, H. H. (1930), Measurements of Solar Radiation Intensity and Determination of its depletion by the Atmosphere, *Mon. Weather Rev.*, *58*(2), 43–52.

Klein, W. H. (1948), Calculation of solar radiation and the solar heat load on man, *J. Meteorol.*, *5*(4), 119–129.

Lee, R. (1978), *Forest Microclimatology*, 276 pp., Columbia Univ. Press, New York, NY.

List, R. J. (1958), *Smithsonian Meteorological Tables*, *Sixth Edition*, 575 pp., Smithsonian Institution, Washington, D. C.

Meeus, J. (1999), *Astronomical Algorithms*, 2nd ed., 477 pp., Willmann-Bell, Inc., Richmond, VA.

Moon, P. (1940), Proposed standard solar radiation curves for engineering use, *J. Franklin Inst.*, *230*, 583–617.

Muneer, T. (1997), *Solar Radiation and Daylight Models for Energy Efficient Design of Buildings*, 197 pp., Architectural Press, New York, NY.

Muneer, T., M. S. Gul, and J. Kunie (2000), Models for estimating solar radiation and illuminance from meteorological parameters, *J. Sol. Energy Eng.*, *122*, 146–153.

National Aeronautics and Space Administration (2004), The Goddard Distributed Active Archive Center, Climatology Interdisciplinary Data Collection, Total Solar Irradiance, <http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/FTP_SITE/INT_DIS/readmes/sol_irrad.html> (15 June 2004).

National Oceanic and Atmospheric Administration (2004), Solar Calculation Details, Surface Radiation Research Branch, <http://www.srrb.noaa.gov/highlights/sunrise/calcdetails.html> (8 October 2004).

Orlob, G. T., and Selna (1967), Prediction of Thermal Energy Distribution in Streams and Reservoirs, 90 pp., prepared for the California Dept. of Fish and Game, Water Resources Eng., Inc., Walnut Creek, CA.

Pelletier, G., and S. Chapra (2004), QUAL2Kw, Documentation and User Manual for a Modeling Framework to Simulate River and Stream Water Quality, *Publication Number 03-03-041*, 177 pp., Washington State Dept. of Ecology, Olympia, WA.

Pluhowski, E. J. (1970), Urbanization and Its Effect on Temperature of the Streams on Long Island, New York, *Geological Survey Professional Paper 627-D*, U.S. Geological Survey, Washington, D. C.

Reitan, C. H. (1963), Surface dew point and water vapor aloft, *J. Appl. Meteorol.*, *2*(6), 776–779.

Ryan, P. J., and K. D. Stolzenbach (1972), Chapter 1: Environmental Heat Transfer, in *Engineering Aspects of Heat Disposal from Power Generation*, edited by D. R. F. Harleman, R. M. Parson Laboratory for Water Resources and Hydrodynamics, Dept. of Civil Engineering, Massachusetts Institute of Technology, Cambridge, MA.

Spencer, J. W. (1971), Fourier series representation of the position of the sun, *Search*, *2*(5), 172.

Stefan, H. G., J. Gulliver, M. G. Hahn, and A. Y. Fu (1980), Water Temperature Dynamics in Experimental Field Channels: Analysis and Modeling, St. Anthony Falls Laboratory, Univ. of Minnesota, Minneapolis, MN.

Theurer, F. D., K. A. Voos, and W. J. Miller (1984), Instream Water Temperature Model, Instream Flow Information Paper 16, *FWS/OBS-84/15*, U. S. Fish and Wildlife Service, Washington, D. C.

Van Heuklon, T. K. (1979), Estimating atmospheric ozone for solar radiation models, *Sol. Energy*, *22*, 63–68.

Wunderlich, W. (1972), Heat and Mass Transfer between a Water Surface and the Atmosphere, *Report No 14, Report Publication No. 0-6803*, Water Resources Research Laboratory, Tennessee Valley Authority, Division of Water Control Planning, Engineering Laboratory, Norris, TN.

R. L. Annear and S. A. Wells, Department of Civil and Environmental Engineering, Portland State University, PO Box 751, Portland, OR 97207-0751, USA. (annearr@cecs.pdx.edu)