Evaluation of the SolarCalc model for simulating hourly and daily incoming solar radiation in the Northern Great Plains of Canada

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*[1]Department of Biosystems Engineering, University of Manitoba, Winnipeg, MB R3T 5V6, Canada; [2]Department of Soil Science, University of Manitoba, Winnipeg, MB R3T2N2, Canada; and [3]Agriculture and Agri-Food Canada, Swift Current, SK S9H 3X2, Canada. *Email: Paul_Bullock@umanitoba.ca*

Kahimba, F.C., P.R. Bullock, R. Sri Ranjan and H.W. Cutforth. 2009. **Evaluation of the SolarCalc model for simulating hourly and daily incoming solar radiation in the Northern Great Plains of Canada.** Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **51**: 1.11–1.21. Solar radiation models have become essential tools for estimating incident solar energy reaching the earth's surface. Extensive evaluation of these models is a problem due to limited availability of measured solar radiation data. The performance of the SolarCalc model, which estimates hourly incoming solar radiation from limited daily meteorological data, was evaluated in the Northern Great Plains of Canada. The simulated hourly solar radiation was compared with observed hourly radiation from five meteorological stations operating through the growing season over a 4-yr period from 2003 to 2006. In addition, long-term year-round hourly solar radiation from one station over the period 1997 to 2007 was used to test the seasonal performance of the model. The model was also compared against the existing 1996-Liu and the FAO-56 models. The model simulated the year-round hourly solar radiation well ($R^2 = 0.85$; $d = 0.96$; $E = 0.82$; $MAE = 50.84$ W/m^2; and $RMSE = 96.92$ W/m^2). The model performance was also comparable to the existing models. However, the model over-predicted the hourly peak solar radiation during the summer and under-predicted during the winter. In addition, the model had none to a very small time-lag during all the seasons. Better model simulations were observed during the summer ($R^2 = 0.88$, $E = 0.85$) compared to the winter ($R^2 = 0.77$, $E = 0.69$). Improvements need to be done on simulation of peak radiation during winter and summer seasons. The SolarCalc model could be used as a potential tool for obtaining year-round hourly and daily solar radiation in areas with limited meteorological data. **Keywords:** Incident solar radiation, SolarCalc model, hourly solar radiation, daily maximum and minimum air temperature.

Les modèles de radiation solaire sont devenus des outils essentiels pour estimer l'énergie solaire incidente qui atteint la surface de la Terre. L'évaluation approfondie de ces modèles est compliquée en raison de la disponibilité limitée de données de radiation solaire mesurée. La performance du modèle SolarCalc qui estime, sur une base horaire, la radiation solaire incidente à partir de données météorologiques quotidiennes limitées a été évaluée dans les grandes plaines du nord du Canada. La radiation solaire horaire simulée a été comparée à la radiation solaire observée dans cinq stations météorologiques en opération durant la saison de croissance pendant une période de quatre ans comprise entre 2003 et 2006. De plus, la radiation solaire horaire enregistrée sur une base annuelle à une station entre 1997 et 2007 a été utilisée pour tester la performance saisonnière du modèle. Le modèle a aussi été comparé aux modèles existants 1996-Liu et FOA-56. Le modèle a bien simulé la radiation horaire annuelle ($R^2 = 0{,}85$; $d = 0{,}96$; $E = 0{,}82$; $MAE = 50{,}84$ W/m^2; et $RMSE = 96{,}92$ W/m^2). Lorsque comparée aux modèles existants, la performance du modèle s'est cependant traduite par une surestimation des pics horaires de radiation solaire durant l'été et leur sous-estimation durant l'hiver. De plus, le modèle ne présentait aucun ou très peu de décalage temporel durant toutes les saisons. Les meilleures performances du modèle ont été observées durant l'été ($R^2 = 0{,}88$, $E = 0{,}85$) comparativement à l'hiver ($R^2 = 0{,}77$, $E = 0{,}69$). Des améliorations doivent être apportées au niveau de la simulation des pics de radiation durant les saisons d'hiver et d'été. Le modèle SolarCalc a le potentiel de pouvoir être utilisé comme outil de prédiction de la radiation solaire horaire et quotidienne toute l'année dans des régions où les données météorologiques sont limités. **Mots clés:** radiation solaire incidente, modèle SolarCalc, radiation solaire horaire, température quotidienne moyenne maximale et minimale.

INTRODUCTION

Solar radiation is an important source of energy for many fields such as agriculture, hydrology, forestry, and solar power (Yin 1996; Kaplanis and Kaplani 2007; Batlles et al. 2008; Solanki and Sangani 2008). In the agricultural ecosystem in particular, solar energy controls processes such as seed germination (Spokas and Forcella 2006), evapotranspiration and photosynthesis (Pinker and Ewing 1985; Chen et al. 2007), and affects the distribution of profile soil temperature and soil moisture (Pinker and Ewing 1985). Solar radiation is also an important input variable in many agricultural models used for predicting evapotranspiration, soil temperatures, greenhouse thermal loads, and germination (Hargreaves and Samani 1985; Yoder et al. 2005; Al-zoheiry et al. 2006). Limited availability of directly measured solar radiation data in many weather stations has led to advances in the development of simulation models that estimate incoming solar radiation using commonly measured meteorological data (e.g., Pinker and Ewing 1985; Yin 1996; Liu 1996; Spokas and Forcella 2006). However most of these models lack extensive verification using directly measured solar radiation data (Pinker and Ewing 1985; Yin 1996; Winslow et al. 2001; Batlles et al. 2008).

The problem of limited availability of long-term solar radiation data in the regions experiencing harsh winter climates like Canada is magnified because most of the weather stations prior to introduction of automatic weather stations were handled by volunteers (ILMB 1996). Hence data collection was limited to daily observations mainly during the summer growing seasons. In 1982 for example, out of over 2500 weather stations in Canada, only 55 (2.2%) recorded direct incoming solar radiation (Yin 1996). In the United States, for the period 1961 through 1990, out of 239 weather stations under the National Solar Radiation Database (NSRDB) that record solar radiation, only 56 (23.4%) measure solar radiation directly. The remaining 183 use modeled solar radiation derived from other weather data (Marion and Urban 1995). In Europe, weather stations measuring solar radiation in 2001 were located 150 to 250 km apart (Struzik 2001). Solar radiation data in areas that did not record direct solar radiation were commonly estimated by interpolating from other nearby recording weather stations (Batlles et al. 2008), using empirical formulae (e.g., Hargreaves and Samani 1985; Liu 1996), or models that used satellite data as input parameters (Pinker et al. 1995; Rubio et al. 2003).

With the advances in automatic data acquisition and introduction of data loggers, weather data can now be available in many weather stations on an hourly basis year-round. Hence, using the commonly measured weather parameters as model inputs, solar radiation models are also being designed to simulate the solar radiation either on an hourly basis (e.g., Tarpley 1979; Chen et al. 2007; Kaplanis and Kaplani 2007), daily basis (e.g., Bruhn et al. 1980; Hansen 1984; Pinker and Ewing 1985; Batlles et al. 2008), or monthly basis (e.g., Yin 1996). The SolarCalc model developed by Spokas and Forcella (2006) is another addition to these models that simulate the hourly incoming solar radiation using limited meteorological data.

The diurnal variation in incoming solar radiation at field level can be greatly affected by factors such as topography (Chen et al. 2007; Batlles et al. 2008), rain occurring on the same day (Bruhn et al. 1980), and whether the slope is facing northwards or southwards (Chen et al. 2007). Other factors affecting incoming solar radiation are cloud cover (Pinker and Ewing 1985; Chen et al. 2007), season of the year (Batlles et al. 2008), atmospheric gases and aerosol effects, and surface albedo (Hansen 1984).

While the SolarCalc model has been tested using data from 18 different weather stations, it has not been extensively verified using observed data from high latitude areas such as the Northern Great Plains of Canada. The performance of the model has not been compared against other existing models, and for different seasons. Hence, the objective of this paper was to assess the performance of the SolarCalc model using measured solar radiation data from five weather stations with 19 station-year comparisons over the growing seasons of a 4-year period (2003–2006), and long-term hourly solar radiation data from one station over the period 1997 to 2007. All the sites are located within the Northern Great Plains of Canada. Specific objectives were: (1) to evaluate the performance of the SolarCalc model in simulating hourly incoming solar radiation in the Northern Great Plains of Canada, (2) to compare the accuracy of the model simulations during different seasons of the year, and (3) to compare the SolarCalc model with existing solar radiation models for simulating hourly and daily incoming solar radiation.

MODEL DESCRIPTION

The SolarCalc model developed by Spokas and Forcella (2006) estimates hourly incoming solar radiation from limited meteorological data. The primary purpose of the model was to develop a tool for integration with germination models for better simulation of microclimate characteristics at the field scale (Spokas and Forcella 2006). The daily solar radiation predictions are also essential in many other agro-climatic simulations that require solar radiation as an input parameter (e.g., Yoder et al. 2005; Al-zoheiry et al. 2006). The input parameters in the Solar Calc model are latitude and longitude of the location, elevation (m), daily total precipitation (mm), and daily maximum and minimum air temperatures (°C). The main output from the model is hourly incoming total solar radiation (W m^{-2}) (Spokas and Forcella 2006). The total incoming solar radiation (R_s) is divided into direct beam (S_b) and diffuse radiation (S_d). It is calculated in the model as follows (Spokas and Forcella 2006):

$$R_s = S_b + S_d \tag{1}$$

$$S_b = S_{Po}\tau^m \tag{1a}$$

$$S_d = 0.30(1-\tau^m)S_{Po}cos\psi \tag{1b}$$

Table 1. Stations geographical description and year range of the solar radiation data.

Station ID	Region description	Latitude (°N)	Longitude (°W)	Elevation (m)	Year range (year)
1	Carman, MB	49.50	98.02	268.20	2004–2006
2	Melfort, SK	52.82	104.60	483.11	2003–2006
3	Regina, SK	50.40	104.57	577.30	2003–2006
4	Swift Current, SK*	50.27	107.72	825.00	2003–2006
5	Swift Current, SK**	50.27	107.72	825.00	1997–2007
6	Winnipeg, MB	49.80	97.17	224.64	2003–2006

*Data were available during the growing season.
**Data were available year-round.

where, S_{Po} is the solar constant (1360 W m^{-2}), τ is the atmospheric transmittance, m is the optical air mass number (Eqs. 8 and 9 of Spokas and Forcella 2006), and ψ is the zenith angle (radians).

The atmospheric transmittance τ (the percentage of the direct radiation that will penetrate the atmosphere without being scattered), has been assumed to be affected by both the rainfall occurring in the current and the previous day (see Table 1 of Spokas and Forcella 2006). The reduction of the incoming solar radiation due to the previous day precipitation was based on the assumption that previous day precipitation affects the cloud cover and the amount of water vapor in the atmosphere. The model also assumes that the presence or absence of clouds is closely related to precipitation, and the daily extremes of maximum and minimum temperatures. Hence, the cloud cover is not taken as a separate input parameter in the model. More details on the physics of the SolarCalc model and the model availability are presented in Spokas and Forcella (2006).

MATERIALS and METHODS

Site locations

A total of five different weather stations having 19 station-year comparisons from 2003 to 2006 were used in the validation of the SolarCalc model (Table 1). All the stations used in this study were monitored by automatic weather stations during the growing season (approximately late April through September) as part of a research project (Finlay 2006). Air temperature and relative humidity were measured at 1.8 m height with a radiation shielded probe (CS 500, Campbell Sci., Logan, UT). Incoming solar radiation was measured at 2.3 m with a silicon pyranometer (Model SP-LITE, Kipp & Zonen, Netherlands). Wind at 2.5 m (Cup Anemometer, Model 3102, RM-Young Co. Traverse City, MI) and rainfall (Tipping Bucket Rain Gauge, Model TE-525mm, Texas Electronics, Houston, TX) were also measured. The data loggers were programmed to log each sensor every 10 s and to output both hourly and daily averages/sums. In addition, long term hourly solar radiation from the Swift Current meteorological station, monitored by the Agriculture and Agri-Food Canada research station, over the period 1997 to 2007 was used (Table 1). This provided year-round data to test the SolarCalc model for periods outside of the growing season. The long-term data also helped to evaluate the model performance for different seasons of the year. The total number of years of data was 30. The elevations of the sites range from 268.2 to 820.0 m above mean sea level (Table 1). The stations are located within the Northern Great Plains of Canada north of latitude 49°. Hence they experience seasonal sub-zero air temperatures during the winter.

The SolarCalc model validation

Comparison of the measured vs. predicted hourly solar radiation The SolarCalc model was used to simulate the total incoming hourly solar radiation. Comparisons were made between the predicted (P_i) and measured (M_i) solar radiation. During the growing season [starting from approximate day of the year (DOY) 96 to 288], the simulation was performed using input data from five different weather stations, each with 3 to 4 years of data (Table 1). Year-round simulations were also performed for 11 years (1997–2007) using long-term weather data from Swift Current meteorological station. Both the relative and absolute error measures (Section 3.4) were used to asses the performance of the model.

Seasonal model evaluations The year-round data obtained from the Swift Current station were used to assess the seasonal performance of the model. Separate simulations were performed for the winter, spring, summer, and fall seasons. To avoid the seasonal 'edge effect' the simulations were also performed without the season-transitional months. The simulations were performed for the months of January–February; April–May; July–August; and October–November to represent winter, spring, summer, and fall, respectively.

In addition, short ranges of data for each season (72 hours and 30 days) were randomly selected from different years to assess the time-lag before and after solar noon. The short range analysis was also used to compare the model accuracy in simulating the peak radiation for each season. Comparison was made between the measured and predicted hourly solar radiation to assess the seasonal accuracy of the model. The relative and absolute error measures were used to assess the performance of the model for the different seasons of the year.

Comparison of the SolarCalc model with the 1996-Liu model Comparison was made between the hourly simulations of the SolarCalc model and the model introduced by Monteith (1965) and used by Liu (1996), herein called the 1996-Liu model. Both models were correlated against the measured solar radiation data, and statistical analyses (section 3.4) were performed to compare their performance. The 1996-Liu model assumes that the hourly solar radiation for a given day depends on the solar radiation at solar noon and length of the day. It also follows a sine function pattern within each day (Liu 1996; Spokas and Forcella 2006). The representative equation for the 1996-Liu model is given as follows (Liu 1996):

$$R_s = S_{noon} Sin\left(\frac{t}{L_{day}}\right) \tag{3}$$

where, R_s is incident solar radiation at time t, S_{noon} is solar radiation at solar noon, and L_{day} is daylight hours. The daylight hours were calculated using a formula proposed by Allen et al. (2002) as follows:

$$L_{day} = \frac{24}{\pi}\omega_s \tag{4}$$

where, ω_s is sunset hour angle (radians). The ω_s was calculated from latitude of the area, φ (radians) and solar declination, δ as follows (Allen et al. 2002):

$$\omega_s = arccos(0 - tan\varphi\ tan\delta) \tag{4a}$$

where

$$\delta = 0.409\sin\left[\frac{2\pi}{365}\mathrm{DOY} - 1.39\right] \tag{4b}$$

$$\varphi = \frac{\pi}{180}(\textit{Latitude in decimal degrees}) \tag{4c}$$

The 1996-Liu model requires solar radiation at solar noon as one of its input parameters. The model cannot be used to predict solar radiation in areas where there are no radiation data for solar noon (Spokas and Forcella 2006). Therefore, the models were compared using data from Swift Current station that had year-round solar radiation data.

Model comparisons for simulating daily solar radiation The hourly solar radiation values simulated by the SolarCalc model were summed on each day to obtain daily radiation values. Hargreaves and Samani (1985) proposed a method for estimating daily incoming solar radiation from the difference in maximum and minimum air temperatures. The equation was adopted in the FAO Irrigation and Drainage Manual No. 56 (FAO-56) (Eq. 50 in Allen et al. 2002). The values from the summed daily radiation from the SolarCalc model, and the daily radiation predicted using the FAO-56 model were all compared against the measured daily solar radiation. The FAO-56 equation for determining daily solar radiation (R_s) is given as follows (Hargreaves and Samani 1985; Allen et al. 2002):

$$R_s = k[(T_{max} - T_{min})^{0.5}]R_a \tag{5}$$

where, k is an adjustment factor ($^{\circ}C^{-0.5}$) taking into account the geographical locations (ranges from 0.16 for interior regions to 0.19 for coastal areas close to water bodies); T_{max} and T_{min} are the maximum and minimum daily air temperatures (°C), respectively; and R_a is the extraterrestrial radiation (MJ m^{-2} d^{-1}). A value of $k =$ 0.16 was used for this simulation. The R_a values for each location were calculated according to Eqs. 21 to 26 in Allen et al. (2002).

Statistical methods for model validations

In this study the relative error measures used to assess the performance of the SolarCalc mode were R^2, *E, d,* and the trend line. The absolute error measures used were the *RMSE*, *MAE*, and *MBE* for reasons outlined below.

The coefficient of determination R^2 was calculated as follows:

$$R^2 = \left[\frac{\sum_{i=1}^{n}(M_i - \bar{M})(P_i - \bar{P})}{\sqrt{\left[\sum_{i=1}^{n}(M_i - \bar{M})\right]\left[\sum_{i=1}^{n}(P_i - \bar{P})^2\right]}}\right]^2 \tag{6}$$

where, M_i and P_i are the measured and predicted solar radiation values, respectively; n is the total number of observations; and $\bar{M}$ and $\bar{P}$ are the means of the measured and predicted values, respectively.

The R^2 alone can not be used to assess the model performance since it is oversensitive to outliers, and it cannot detect the proportional and additive differences between the P_i and M_i (Willmott et al. 1985; Yoder et al. 2005). Therefore, higher values of R^2 may not necessarily mean better model performance (Willmott et al. 1985; Spokas and Forcella 2006).

The coefficient of modeling efficiency (E) is defined as the ratio of *MSE* to the variance of M_i, subtracted from unity (Legates and McCabe Jr. 1999). It ranges from $-_{\infty}$ to 1.0 with better model performance when the E values are close to 1.0. The E measure differs from R^2 in that it takes into account the variations between the means and variances of the P_i and M_i. The following formula was used to calculate the coefficient of modeling efficiency:

$$E = 1.0 - \left[\frac{\sum_{i=1}^{n}(P_i - M_i)^2}{\sum_{i=1}^{n}(M_i - \bar{M})^2}\right] \tag{7}$$

where variables have the same definitions as in Eq. 6. The measure E also indicates whether P_i and M_i differences are as large as the variability in the measured data (Yoder et al. 2005). The index of agreement, (d) was calculated as follows:

$$d = 1.0 - \left[\frac{\sum_{i=1}^{n}(P_i - M_i)^2}{\sum_{i=1}^{n}(|P_i - \bar{M}| + |M_i - \bar{M}|)^2}\right] \tag{8}$$

where variables have the same definitions as in Eq. 6. The measure d takes into account the differences between means and variances of P_i and M_i. The d values range between 0.0 and 1.0, with values close to 1.0 indicating better agreement between the P_i and M_i (Legates and McCabe Jr. 1999).

A complete assessment of the model accuracy and precision requires a combination of both the relative and absolute error indices (Willmott et al. 1985; Legates and McCabe Jr. 1999). The absolute error measures used in this evaluation were the *RMSE*, *MAE*, and *MBE*. Unlike the dimensionless relative error measures, the absolute error measures can be expressed in units of the measured data. Hence they give a better indication of model accuracy in the same units (Spokas and Forcella 2006). The *RMSE* is the square root of the mean squared deviations (Steel et al. 1997). It gives the weighted variations in errors (residuals) between the measured and predicted values. The *RMSE* was calculated as shown in Eq. 9 below:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - M_i)^2} \tag{9}$$

where, n is the number of observations, M_i is the measured, and P_i is the predicted solar radiation. The *RMSE* can also be expressed in terms of percentage of the mean of measured values to give an indication of model accuracy on the scale of 0 to 100%. Studies indicate that a standard

Table 2. Statistical analysis of the SolarCalc model predicted vs. measured hourly incoming solar radiation for five stations during the growing season.

				Relative error measures*			Absolute error measures**		
Station	Year	Day of the year range	N	R^2	d	E	MAE (W m^{-2})	MBE (W m^{-2})	RMSE (W m^{-2})
Carman	2004	137–260	2920	0.74	0.91	0.62	94.76	44.42	153.83
	2005	112–236	2973	0.75	0.93	0.69	92.66	28.28	146.23
	2006	128–256	3075	0.80	0.93	0.70	92.74	43.74	149.95
Melfort	2003	107–260	3697	0.73	0.91	0.62	104.37	42.51	157.50
	2004	119–287	4028	0.74	0.92	0.65	89.32	34.44	139.34
	2005	117–278	3862	0.75	0.92	0.66	91.54	36.93	140.78
	2006	96–262	3536	0.75	0.92	0.67	100.29	36.09	147.68
Regina	2003	105–258	3677	0.78	0.95	0.69	101.59	39.07	150.87
	2004	118–288	4089	0.72	0.91	0.63	96.78	34.58	148.11
	2005	115–241	3022	0.72	0.92	0.67	104.36	26.92	158.46
	2006	114–236	2923	0.69	0.90	0.58	121.29	42.66	178.07
Swift Current	2003	107–259	3652	0.71	0.91	0.61	117.91	36.36	171.33
	2004	117–275	3802	0.86	0.95	0.80	68.67	38.69	118.81
	2005	116–228	2687	0.73	0.92	0.67	101.30	32.80	169.71
	2006	116–236	2889	0.74	0.92	0.70	105.02	37.26	167.17
Winnipeg	2003	121–223	2449	0.74	0.91	0.57	106.87	66.37	167.41
	2004	139–274	2920	0.67	0.89	0.56	92.35	35.22	157.14
	2005	123–280	2563	0.82	0.95	0.80	86.58	28.54	155.09
	2006	117–229	2690	0.68	0.90	0.56	98.62	60.88	186.66
Average			3234	0.74	0.92	0.66	98.26	39.25	156.01

*R^2 = Coefficient of determination, d = index of agreement, and E = Coefficient of model efficiency.
**MAE = mean absolute error, MBE = mean bias error, and $RMSE$ = root mean square error.

error of 10% of the mean can be taken as a sufficient accuracy for most agricultural uses (Tarpley 1979).

The MAE gives the average of the absolute difference (error) between the measured and predicted values. The MAE is a linear score that gives equal weight to both small and larger errors, and it does not consider direction of the errors. Hence if the errors have the same magnitudes, the MAE equals the $RMSE$. The MAE was calculated as shown below:

$$MAE = \frac{1}{n}\left[\sum_{i=1}^{n} |P_i - M_i|\right] \quad (10)$$

where the variables have the same definitions as in Eq. 9. The MBE was calculated as:

$$MBE = \frac{1}{n}\left[\sum_{i=1}^{n} (P_i - M_i)\right] \quad (11)$$

The MBE is an indicator of whether the model is over-predicting or under-predicting the measured values. It also gives the uniformity of error distribution. The MBE value of 0.0 indicates an equal distribution between positive and negative errors. Negative MBE value (for $P_i - M_i$) indicates under-prediction, while a positive value indicates over-prediction.

RESULTS and DISCUSSIONS

Comparison of the predicted and measured incoming hourly solar radiation

Results of statistical analysis of the SolarCalc model predicted vs. measured hourly incoming solar radiation during the growing season from April to September of each year are presented in Table 2 for five different locations. Table 3 presents the long-term year-round statistical analysis of the model for one station from 1997 to 2007.

During the growing season (combined data for late spring, summer, and early fall) the SolarCalc model simulated fairly well the hourly solar radiation (R^2 = 0.74, d = 0.92, E = 0.66, and $RMSE$ = 156.01 W m^{-2}, MAE = 98.26 W m^{-2}, Table 2). The model generally over-predicted the solar radiation for all the stations (MBE = 26.92 to 66.37 W m^{-2}) during the growing season.

The year-round hourly model simulations were better than the growing-season simulations (Table 3). The corresponding 11-year average statistical parameters for the year-round hourly simulations were (R^2 = 0.84, d = 0.96, E = 0.82, MAE = 50.84 W m^{-2}, MBE = −1.24 W m^{-2}, and $RMSE$ = 156.01 W m^{-2}, MAE = 50.84 W m^{-2}, Table 3). The results are in agreement with the results obtained by Spokas and Forcella (2006) during model

Table 3. Year-round statistical analysis of the SolarCalc model predicted vs. measured hourly incoming solar radiation at Swift Current from 1997 to 2007.

		Relative error measures*			Absolute error measures**		
Year	N	R^2	d	E	MAE (W m^{-2})	MBE (W m^{-2})	RMSE (W m^{-2})
1997	8760	0.82	0.95	0.82	54.99	−10.15	105.23
1998	8760	0.86	0.96	0.84	48.19	1.24	93.09
1999	8760	0.83	0.95	0.82	50.93	−7.76	97.06
2000	8784	0.84	0.96	0.83	50.43	−5.54	95.49
2001	8760	0.84	0.96	0.82	50.67	0.64	98.42
2002	8760	0.82	0.95	0.81	52.87	−3.70	101.37
2003	8736	0.86	0.97	0.84	49.15	0.83	90.61
2004	8784	0.84	0.96	0.82	49.49	1.22	94.35
2005	8760	0.85	0.96	0.83	47.83	3.72	91.99
2006	8760	0.85	0.96	0.83	48.61	8.57	93.11
2007	8789	0.82	0.95	0.81	56.03	−2.68	105.40
Average	8765	0.84	0.96	0.82	50.84	−1.24	96.92

*R^2 = Coefficient of determination, d = index of agreement, and E = Coefficient of model efficiency.
**MAE = mean absolute error, MBE = mean bias error, and $RMSE$ = root mean square error.

development ($R^2 = 0.85$, $d = 0.95$, $E = 0.80$, and $RMSE = 111.0$ W m^{-2}).

SolarCalc model performance during different seasons of the year

A summary of the seasonal statistical analysis of SolarCalc model hourly simulations is presented in Table 4. The table also includes the seasonal evaluation of the daily solar radiation values that were summed from the SolarCalc hourly simulations. Both the hourly and the daily simulated values were compared against the observed data. The summing of simulated hourly solar radiation to obtain the daily radiation has been done before (Tarpley 1979).

The hourly model simulations were much better ($R^2 =$ 0.77 to 0.88 vs. 0.43 to 0.62) compared to the corresponding daily simulations (Table 4). The correlation between the measured and the predicted hourly radiation was better during the summer ($R^2 = 0.88$, $d = 0.97$ and $E =$ 0.85) compared to the winter ($R^2 = 0.77$, $d = 0.88$ and $E = 0.69$). The same trend was also observed for the daily simulations (Table 4). However, the model over-predicted the spring and summer radiation ($MBE = 22.6$ and 28.67 W m^{-2}, respectively). It also under-predicted the hourly radiation during the winter ($MBE = -22.79$ W m^{-2}). Higher value of MBE during the spring and summer compared to fall and winter was due to higher numerical values of solar radiation during those times compared to fall and winter.

The accuracy of the model was evaluated seasonally and at different times of the day by examining the data for a 3-day interval (Fig. 1) during approximately the middle of each season. A 1-month range of hourly simulations is also presented to evaluate the seasonal simulation of peak solar radiation (Fig. 2).

Table 4. Seasonal evaluation of the SolarCalc model predicted vs. measured hourly and daily incoming solar radiation at Swift Current using combined four-year data from 2003 to 2006.

				Relative error measures*			Absolute error Measures**		
Simulation type	Season	Day of the year range	N	R^2	d	E	MAE (W m^{-2})	MBE (W m^{-2})	RMSE (W m^{-2})
SolarCalc Hourly	Winter	1–59	5664	0.77	0.88	0.69	31.21	−22.79	67.36
	Spring	91–151	5856	0.84	0.95	0.81	66.42	22.55	115.77
	Summer	182–243	5952	0.88	0.97	0.85	66.28	28.67	109.73
	Fall	274–334	5832	0.74	0.93	0.74	30.73	−2.15	66.47
SolarCalc Daily	Winter	1–59	236	0.43	0.68	−0.07	629.91	−547.01	796.54
	Spring	91–151	244	0.52	0.83	0.37	1060.08	541.09	1407.29
	Summer	182–243	248	0.62	0.85	0.40	1034.12	688.15	1273.82
	Fall	274–334	243	0.44	0.81	0.31	525.57	−51.66	755.67

*R^2 = Coefficient of determination, d = index of agreement, and E = Coefficient of model efficiency.
**MAE = mean absolute error, MBE = mean bias error, and $RMSE$ = root mean square error.

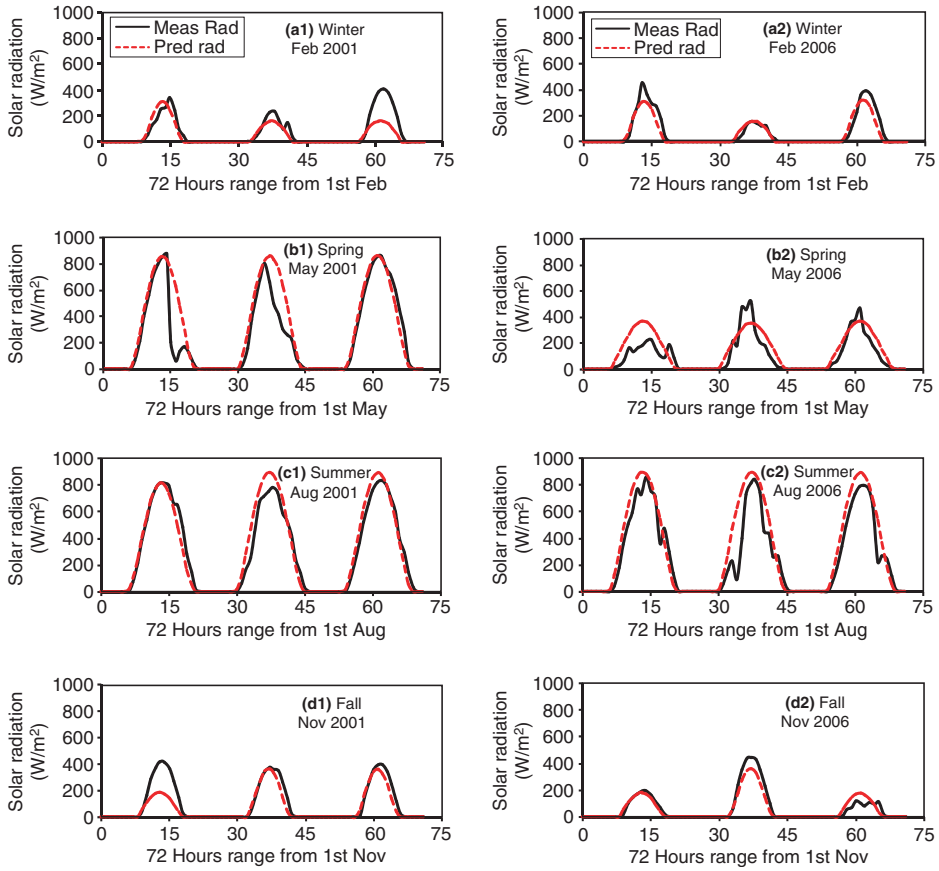

Fig. 1. Hourly simulations of the SolarCalc model showing time-lag between the predicted and measured solar radiation at Swift Current during: (a) winter, (b) spring, (c) summer, and (d) fall seasons. The range is for 72 hours in (1) 2001 and (2) 2006.

The model simulations had none to a very small (30 min) time-lag during the winter, spring, summer, and fall seasons (Fig. 1 and Fig. 2). The peak radiation matched well during the spring and fall seasons. The model over-predicted the peak radiation by approximately 100–200 W m^{-2} during the summer. The model under-predicted the peak radiation during the winter by approximately 50 to 150 W m^{-2}. Results of hourly and daily simulations indicate that the SolarCalc model predicted very well on year-round simulations of hourly solar radiation. However, on a seasonal basis, the model had better predictions during the summer compared to the winter when the temperatures are below zero.

The model tends to over-predict the peak radiation during the summer season, and under-predict the radiation during the winter (Figs. 1 and 2). Modifications of the model to correct the summer and winter peak radiation predictions will greatly enhance the accuracy of the model for areas experiencing seasonal sub zero soil temperatures, similar to the Northern Great Plains of Canada.

Comparison of the SolarCalc model with the 1996-Liu model

Hourly simulation from the SolarCalc and the 1996-Liu models (Liu 1996) were both compared against the measured solar radiation. Table 5 presents the statistical comparison of the two models for year-round simulations from the Swift Current station.

The SolarCalc model performed better ($R^2 = 0.82$ to 0.85, $E = 0.81$ to 0.83, $MAE = 48.61$ to 52.87 W m^{-2}, $RMSE = 93.11$ to 101.37 W m^{-2}) compared to the 1996-Liu model ($R^2 = 0.71$ to 0.73, $E = 0.70$ to 0.71, $MAE = 63.87$ to 68.78 W m^{-2}, $RMSE = 121.24$ to 127.84 W m^{-2}). The 1996-Liu model overestimated the year-round radiation ($MBE = 8.60$ to 13.70 W m^{-2}) compared to the SolarCalc model ($MBE = -5.43$ to 8.57 W m^{-2}). In comparison to the 1996-Liu model, better prediction by the SolarCalc model is likely due to the inclusion of the current and previous day precipitation factor that affects the cloud cover of the current day (Spokas and Forcella 2006). These factors are not accounted for in the 1996-Liu model.

Comparison of the SolarCalc model and the FAO-56 model daily simulations

The daily simulations using the SolarCalc model and the FAO-56 solar radiation model (Hargreaves and Samani 1985; Allen et al. 2002) were all compared against the measured values for 3 years from three randomly selected weather stations (Fig. 3). The daily values for the SolarCalc model were summed from the hourly simulations. Figure 3 presents the scatter plots comparing the SolarCalc model

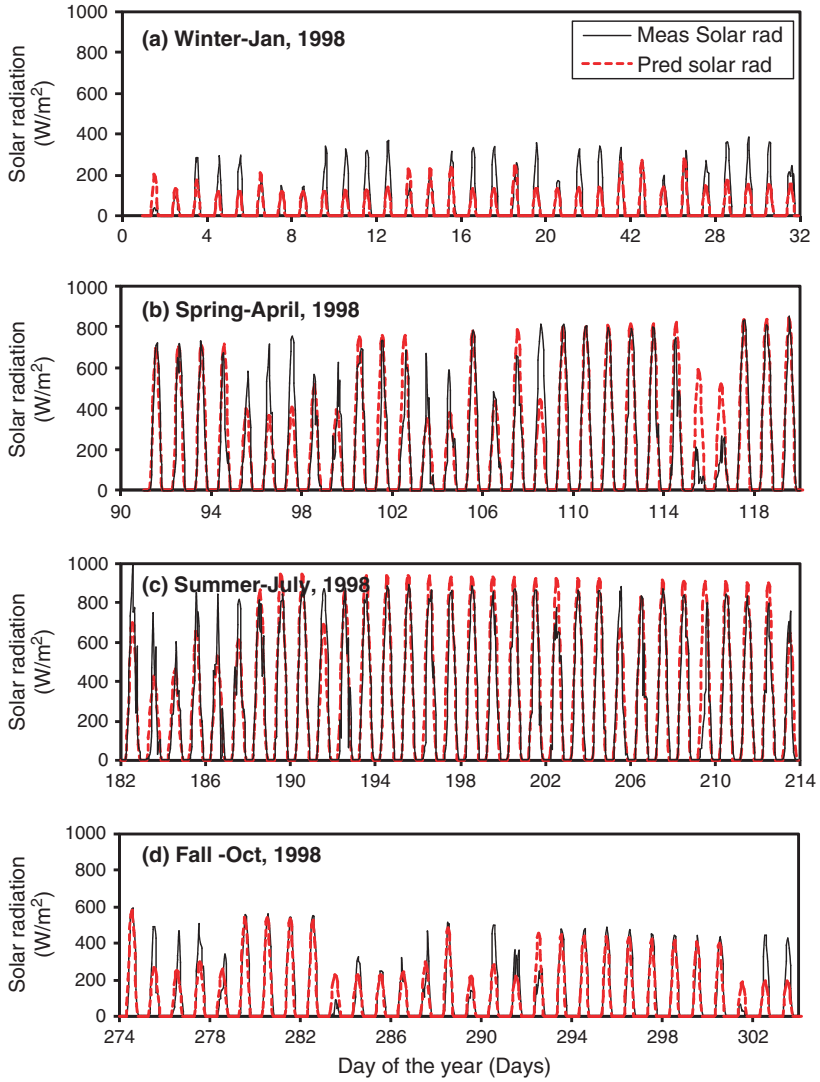

Fig. 2. Measured and predicted one-month hourly simulations showing peak solar radiation using the SolarCalc model at Swift Current during: (a) winter, (b) spring, (c) summer, and (d) fall seasons for the randomly selected year (1998).

Table 5. Comparison of the SolarCalc and the 1996-Liu models for predicting year-round hourly incoming solar radiation at Swift Current.

			Relative error measures			Absolute error measures		
Year	Model	N	R^2	d	E	MAE (W m^{-2})	MBE (W m^{-2})	RMSE (W m^{-2})
2000	SolarCalc	8784	0.84	0.96	0.83	50.43	−5.54	95.49
	1996-Liu	8784	0.71	0.92	0.70	68.78	9.91	127.84
2002	SolarCalc	8760	0.82	0.95	0.81	52.87	−3.70	101.37
	1996-Liu	8760	0.72	0.92	0.70	66.84	8.60	126.53
2004	SolarCalc	8784	0.84	0.96	0.82	49.49	1.22	94.35
	1996-Liu	8784	0.72	0.92	0.70	65.06	13.70	122.26
2006	SolarCalc	8760	0.85	0.96	0.83	48.61	8.57	93.11
	1996-Liu	8760	0.73	0.92	0.71	63.87	11.55	121.24

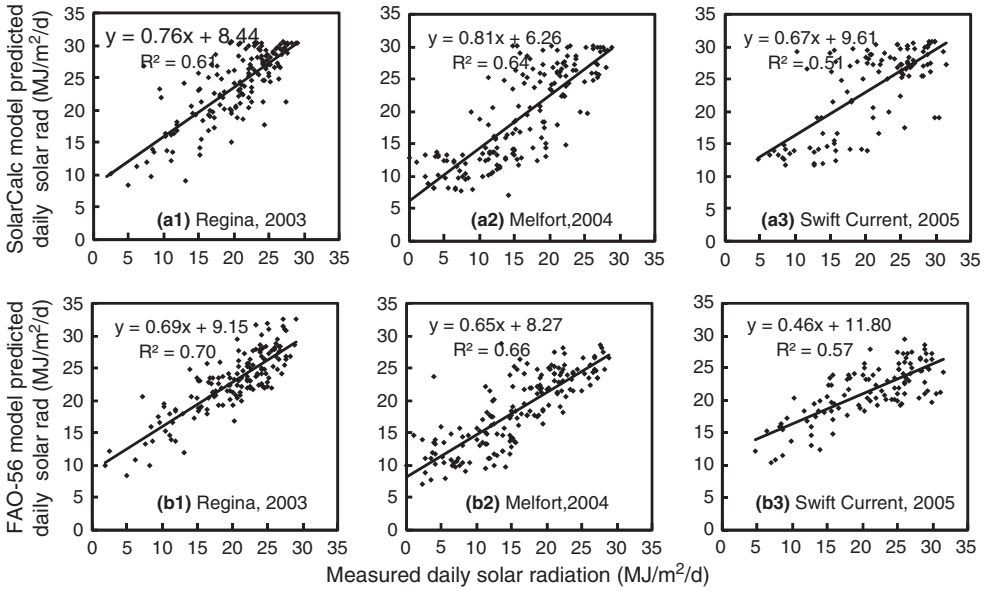

Fig. 3. Scatter plots of measured vs. predicted daily solar radiation at randomly selected locations predicted using (a) the SolarCalc model and (b) the FAO-56 model from 2003 to 2005.

against the FAO-56 model at the same location sites and years.

The daily predictions from the SolarCalc model compared favorably with the simulations from the FAO-56 model during the summer (Fig. 3, Table 6). The *MAE* and *RMSE* for the selected stations were 4.04–4.39 and 5.11–5.66 W m^{-2} for the SolarCalc model, and 3.43–4.39 and 4.27–5.66 W m^{-2} for the FA0-56, respectively (Table 6). Intercepts >6.0 MJ m^{-2} d^{-1} indicated that both models over-predicted solar radiation during the growing season. The over prediction is also revealed by the *MBE* (2.68–3.54 W m^{-2} for SolarCalc, and 0.52–2.88 W m^{-2} for the FAO-56) (Table 6). The regression analysis comparison of the models returned intercepts close to 0.0 and slopes close to 1.0 (Fig. 4). Hence, with further improvements to the model as explained earlier, apart from the hourly simulation capability of the SolarCalc model, the model could also be used to predict daily incoming solar radiation. Daily incoming solar radiation is an important weather parameter for input into hydrologic and soil models. The model also accounts for diurnal change in solar radiation making it suitable for monitoring of microclimate. It is also applicable to field scale making it suitable for agricultural research.

The SolarCalc model uses daily meteorological data commonly measured at most meteorological stations to simulate the hourly radiation for the whole year, which minimizes data constraints for most model applications.

CONCLUSION

The performance of the SolarCalc model for simulating hourly and daily incoming solar radiation was evaluated using daily meteorological data from the Northern Great Plains of Canada. The evaluation was performed using data from five meteorological stations having 19 station-year comparisons during the growing season. In addition, long-term year-round weather data (1997–2007) available from one station was used to assess the seasonal performance of the model. The hourly and daily model predictions were also compared against the existing 1996-Liu and the FAO-56 solar radiation models.

The SolarCalc model simulated the year-round hourly incoming solar radiation well ($R^2=0.84$, $d=0.96$, $E=$

Table 6. Comparison of the SolarCalc and the FAO-56 models for predicting daily incoming solar radiation.

			Relative error measures			Absolute error measures		
Station	Model	N	R^2	d	E	MAE (W m^{-2})	MBE (W m^{-2})	RMSE (W m^{-2})
Regina 2003	SolarCalc	152	0.61	0.80	0.19	4.04	3.54	5.11
	FAO-56	152	0.69	0.84	0.43	3.43	2.88	4.27
Melfort 2004	SolarCalc	167	0.64	0.85	0.39	4.39	3.27	5.56
	FAO-56	167	0.69	0.86	0.55	3.70	2.67	4.75
Swift 2005	SolarCalc	111	0.51	0.82	0.31	4.28	2.68	5.66
	FAO-56	111	0.57	0.81	0.54	3.81	0.52	4.61

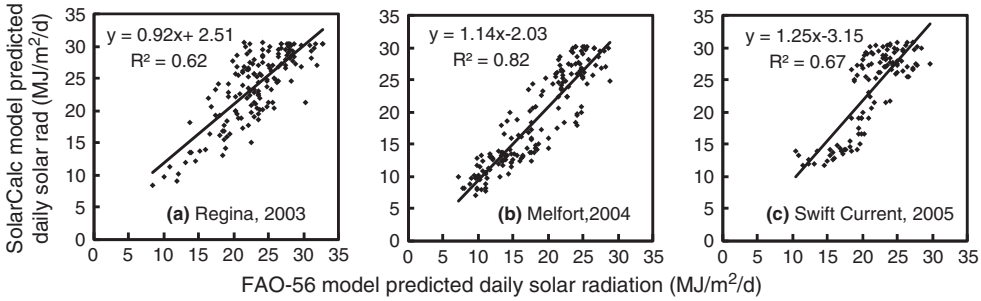

Fig. 4. Scatter plots of the SolarCalc vs. FAO-56 predicted daily solar radiation at randomly selected locations from 2003 to 2005.

0.82, $MAE = 50.84$ W m^{-2}, $MBE = -1.24$ W m^{-2}, and $RMSE = 96.92$ W m^{-2}). Evaluation of the seasonal performance of the model indicated that the model simulated hourly radiation better during the spring and summer ($R^2 = 0.84$ to 0.88, $d = 0.95$ to 0.97, and $E = 0.81$ to 0.85) compared to the fall and winter seasons ($R^2 = 0.74$ to 0.77, $d = 0.88$ to 0.93, and $E = 0.69$ to 0.74). The model overestimated the hourly peak radiation during the summer and under-estimated during the winter. The model also had none to a very small (30 min) time-lag during all the seasons. Better simulations of peak radiation were observed during the spring and fall compared to summer and winter seasons.

The year-round hourly simulations using the SolarCalc model were much better ($R^2 = 0.82$ to 0.85, $E = 0.81$ to 0.83, $RMSE = 93.11$ to 101.37 W m^{-2}) than the 1996-Liu model ($R^2 = 0.71$ to 0.73, $E = 0.67$ to 0.69, $RMSE = 126.37$ to 132.26 W m^{-2}). The 1996-Liu model overestimated the year-round hourly solar radiation ($MBE = 13.97$ to 20.65 W m^{-2}) compared to the SolarCalc model ($MBE = -5.43$ to 8.57 W m^{-2}). When the hourly radiation values were converted to daily radiation, poor simulations were observed in the daily values compared to the hourly values. However, daily solar radiation predictions from the SolarCalc model were in good agreement with that of the FAO-56 daily solar radiation model. Both of the models over-predicted solar radiation during the spring to fall growing season.

Modifications to the model to more accurately simulate peak radiation during summer and winter will improve the prediction of hourly radiation. However, even without the modifications, the SolarCalc model could be used as a useful tool for simulating both hourly and daily incoming solar radiation in areas with limited meteorological data.

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