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Calibration of the modified Angstrom global solar radiation models for different seasons in South of Iran

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Abstract

The Angstrom equation is one of the most accurate and widely used sunshine based models to estimate global solar radiation. The key in its application is the calibration of the local specific coefficients. The global solar radiation in fall and winter is affected by cloudiness conditions and the lower ratios of actual to maximum possible sunshine hours, resulted in receiving the lower global solar radiation during these seasons compared with the received radiation in spring and summer. Therefore, in this study, due to differences in sky-cloudiness, and atmosphere transmissivity in different seasons, the coefficients of the Angstrom modified models, namely Angstrom-Prescott, Modified Angstrom-Prescott and Reitveld, calibrated for the fall, winter, spring and summer seasons in Bajgah, Iran, independently. The seasonal based calibrated equations were compared based on statistical error tests such as the mean bias error (MBE), root mean square error (RMSE), coefficient of determination (R^2) and Nash–Sutcliffe equation (NSE) indexes. Good agreement was found between measured values and estimated data by the mentioned models. Statistical analysis is indicated that three seasonal based calibrated models are more accurate and recommendable to use in study region, when sunshine hours data are available in comparison with Angstrom-Prescott equation using the recommended coefficients for northern hemisphere.

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Introduction

Estimation of global solar radiation (Rs) value is essential for many applications, including architectural design, solar energy systems, crop growth models and crop water requirements determine in the design of irrigation systems. Unfortunately, for many developing countries, global solar radiation measurements are not easily available due to the cost and maintenance requirements of the measuring equipment. Therefore, it is important to develop models to estimate the global solar radiation based on available meteorological data.

Angstrom (1924) presented a relationship between the ratio of global solar radiation (Rs) to the corresponding value on a full clear sky day and the ratio of actual sunshine hour (n) to maximum possible sunshine hour (N). Prescott (1940) suggested using the extraterrestrial radiation (Ra) to replace completely clear sky day radiation value, and modified Angstrom model as follows:

$$\frac{Rs}{Ra} = a + b\frac{n}{N} \quad (1)$$

where Rs and Ra are the global and extraterrestrial solar radiation, respectively, *a* and *b* the Angstrom-Prescott model coefficients, n and N the actual and maximum possible sunshine hour duration, respectively. The Angstrom-Prescott equation is one of the accurate and widely used sunshine based models to estimate global solar radiation. The key in its application is the calibration of the local specific coefficients. Rietveld (1978) examined several published values of the *a* and *b* coefficients and noted that *a* is related linearly and *b* hyperbolically to the appropriate mean value of n/N such that:

$$a = 0.10 + 0.24\frac{n}{N} \quad (2)$$

$$b = 0.38 + 0.08\frac{n}{N} \quad (3)$$

Zand-Parsa *et al.* (2011) modified the Angstrom-Prescott equation by using effective maximum possible sunshine hour instead of maximum possible sunshine hour in an intermountain region as follows:

$$\frac{Rs}{Ra} = a + b\frac{n}{N-t} \quad (4)$$

where t is the mean difference between the values of n during clear-sky days and daily values of N. The values of Ra and N are calculated by the following methods (Allen *et al.* 1998):

$$Ra = 37.6\, d_r(\omega_s sin\varphi sin\delta + cos\varphi cos\delta sin\omega_s) \quad (5)$$

$$d_r = 1 + 0.033\cos\left(\frac{2\pi}{365}J\right) \quad (6)$$

$$\omega_s = \arccos\left(-tan\varphi\, tan\delta\right) \quad (7)$$

$$\delta = 0.4093 sin\left(\frac{2\pi}{365}J - 1.39\right) \quad (8)$$

$$N = \frac{24}{\pi}\omega_s \quad (9)$$

where d_r is the inverse relative distance between the sun and earth, ω_s, φ and δ are the angle of sun at sunset, latitude and solar declination angle, respectively. According to climate conditions, dust and solar radiation the values of *a* and *b* are changed for different areas. Allen *et al* (1998) suggested values of 0.25 and 0.5, for *a* and *b*, respectively for the northern hemisphere. Liu *et al.* (2009) calibrated Angstrom-Prescott equation at daily, monthly and annually time scales in China. Chen *et al.* (2006) determined the *a* and *b* coefficient values for different stations of China. Many empirical solar radiation models based on meteorological data such as sunshine hours, temperature, humidity etc. have been discussed in daily or monthly average daily scale (Almorox and Hontoria, 2004; Mossad, 2004), among which the most widely used is the Angstrom model and its modified model, which is based on sunshine hours. Bristow and Campbell (1984) developed a widely used, simple algorithm for estimating solar irradiance at specific locations with coefficients developed from daily measurements of air temperature, precipitation and solar radiation. Hargreaves *et al.* (1985) recommended a simple method to estimate global solar radiation, which was a function of Ra and mean monthly maximum and minimum temperatures. Castellvi (2001) reported a model based on precipitation and temperature. Majnooni-Heris *et al.* (2008) proposed a model based on several variables, such as the extraterrestrial radiation, relative humidity, ratio of actual to possible sunshine hours, air temperature, vapor pressure deficit and precipitation. Seasonal calibration of Angstrom-Prescott coefficients is one way to reduce the uncertainty related with time scale mismatch in using the Angstrom-Prescott model for prediction of global solar radiation in each day of seasons. Furthermore, the global solar radiation in fall and winter is affected by cloudiness conditions and the lower ratios of actual sunshine to maximum possible sunshine duration, resulted in receiving the lower global solar radiation during these seasons compared with the received radiation in spring and summer. Therefore, in this study, due to differences in sky-cloudiness, and atmosphere transmissivity in different seasons, the coefficients of the Angstrom modified models, namely Angstrom-Prescott, Modified Angstrom-Prescott and Reitveld, are calibrated by measured radiation data for the fall, winter, spring and summer seasons in Bajgah, located in south of Iran, independently. Additionally, predicted Rs data by mentioned seasonal calibrated equations was compared with uncalibrated Angstrom-Prescott equation, with using recommended coefficients for northern hemisphere, results.

Materials and methods

In this study, daily sunshine hours and global solar radiation were measured in the weather station of Agricultural Research Station at Shiraz University, Bajgah, located in south of Iran. The latitude, longitude and elevation above mean sea level of the station are 29° 44´ 55″N, 52° 34´ 20″E and 1810 m, respectively. Daily data of global solar radiation (Rs) and actual sunshine hours (n) were measured from 2003 to 2006. Global solar radiation was measured by solarimeter (507-250 pyranometer sensor, ELE, England) and sunshine hours were measured by Campbell–Stokes sunshine recorder (Lambrecht, Germany).

Measured global solar radiation data and actual sunshine hours during 2003- 2006 were used for seasonal scale calibration of three sunshine based models, Angstrom– Prescott, modified Angstrom–Prescott and Reitveld, coefficients, respectively.

Model constant coefficients were estimated by minimizing the sum of square errors from measured and predicted values, by Solver tool in EXCEL.

The performance of models was evaluated by statistical error tests such as coefficient of determination (R^2), mean bias error (MBE), root mean square error (RMSE) and Nash–Sutcliffe equation (NSE) (Nash and Sutcliffe, 1970) indexes as follows:

$$MBE = \frac{\sum_1^n (p_i - m_i)}{n} \quad (10)$$

$$RMSE = \sqrt{\frac{\sum_1^n (p_i - m_i)^2}{n}} \quad (11)$$

$$NSE = 1 - \frac{\sum_1^n (p_i - m)^2}{\sum_1^n (m_i - \bar{m})^2} \quad (12)$$

where p_i and m_i are the predicted and measured global solar radiation values, respectively, $\bar{m}$ is the mean measured values and n is the total number of measurements.

The mean bias error test provides information on the long term performance. A low MBE is desired. When MBE is close to zero, the predicted results are accurate. A positive or negative value gives the over-estimation or under-estimation, respectively. The root mean square error gives information on the short term performance of the correlations by allowing a term by term comparison of the actual deviation between the calculated and measured values. The smaller the value, the better is the model's performance. However, a few large errors in the sum can produce a significant increase in the RMSE (Ulgen and Hepbasli, 2002 and Menges *et al.*, 2006). A model performance is more efficient when R^2 and *NSE* calculated values are close to one (Loumagne and Chkir, 1996).

Results and discussion

Measurement of short wave radiation from the sun and atmosphere is important for quantitative ecophysiological studies as source of the energy used in photosynthesis and evapotranspiration. These measurements are especially important for determining the irrigation water requirements and potential growth and yield of crop in agriculture. Despite this importance there are few accurate measurements of global solar radiation in various areas, especially in developing countries. The shortage of the measurements has led the researchers to estimate global solar radiation from other, more widely and easily measured, climatic parameter-sunshine duration. In our study region amounts of sunshine duration and global solar radiation determined 3152 hour/year and 8619 MJ/m²/year, respectively. Sunshine duration and solar radiation showed that there are high actual sunshine duration days and high global solar radiation in south of country. Measured daily global solar radiation (Rs) and actual sunshine hours (n), and calculated extraterrestrial radiation (Ra) during study years are shown in figure 1.

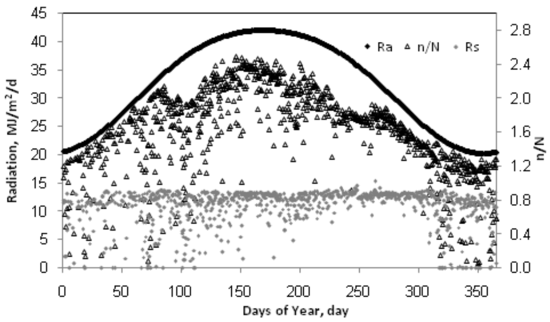

Fig. 1. Comparison between daily values of global solar radiation, actual sunshine duration (n) and extraterrestrial radiation during study years.

Figure 1 shows, the values of measured Rs in the fall and winter season are closer to the Ra. Hence, in the clear sky condition the ratios of measured daily global solar radiation to extraterrestrial radiation in fall and winter are greater than those values in spring and summer seasons. Distance variations between Rs and Ra values in clear sky condition show that global solar radiation equations should be calibrated for each season, separately.

Angstrom Prescott equation

For prediction of Rs in each season, the Angstrom Prescott equation with using parameters of *a* and *b* equal to 0.25 and 0.5, respectively [proposed by Allen *et al.* (1998)] was used as follows:

$$\frac{Rs}{Ra} = 0.25 + 0.50\frac{n}{N} \quad (14)$$

$R^2 = 0.86,\ RMSE = 5.72\left(\frac{MJ}{m^2d}\right), MBE = -5.19\left(\frac{MJ}{m^2d}\right)$ and $NSE = 0.07$ Spring

$R^2 = 0.49,\ RMSE = 4.24\left(\frac{MJ}{m^2d}\right), MBE = -3.54\left(\frac{MJ}{m^2d}\right)$ and $NSE = 0.01$ Summer

$R^2 = 0.89,\ RMSE = 4.31\left(\frac{MJ}{m^2d}\right), MBE = -3.65\left(\frac{MJ}{m^2d}\right)$ and $NSE = 0.43$ Fall

$R^2 = 0.89,\ RMSE = 6.62\left(\frac{MJ}{m^2d}\right), MBE = -7.38\left(\frac{MJ}{m^2d}\right)$ and $NSE = 0.45$ Winter

The NSE values at the spring, summer, fall and winter season are 0.07, 0.01, 0.43 and 0.45, respectively. The values of Rs by equation (14) are under-predicted with average RMSE and MBE equal to 5.22 MJ/m²/d and -4.94 MJ/m²/d, respectively. Poor statistical results showed that the mentioned model has not good accuracy by applying of uncalibrated *a* and *b* coefficients. The values of measured and predicted global solar radiation by equation (14) with the parameters of *a* and *b* equal to 0.25 and 0.5, respectively [proposed by Allen *et al.* (1998)] are compared as shown in figure 2.

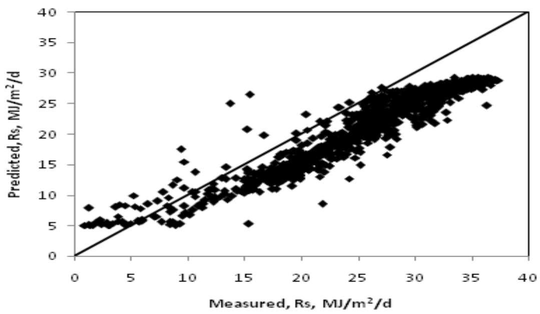

Fig. 2.

Seasonal calibration of models

1. Angstrom Prescott equation

Relationships between the ratio of measured global solar radiation to extraterrestrial radiation and ratios of $\frac{n}{N}$ for the fall, winter, spring and summer seasons are shown in figure 3. Our study region is located in the northern hemisphere and during fall and winter seasons, most of clouds come from the Mediterranean Sea and Indian Ocean. So, the received solar radiation is affected by cloudiness conditions in fall, winter and those conditions are different from summer and spring seasons. Therefore, the Angstrom-Prescott model is calibrated for the fall, winter, spring and summer seasons as follows:

$$\frac{Rs}{Ra} = 0.32 + 0.58\frac{n}{N} \quad Spring \quad (15)$$

$$R^2 = 0.83,\ RMSE = 2.21\left(\frac{MJ}{m^2d}\right), MBE = -0.00213\left(\frac{MJ}{m^2d}\right)\ and\ NSE = 0.86$$

$$\frac{Rs}{Ra} = 0.36 + 0.48\frac{n}{N} \quad Summer \quad (16)$$

$$R^2 = 0.61,\ RMSE = 2.36\left(\frac{MJ}{m^2d}\right), MBE = +0.00006\left(\frac{MJ}{m^2d}\right)\ and\ NSE = 0.59$$

$$\frac{Rs}{Ra} = 0.27 + 0.71\frac{n}{N} \quad Fall \quad (17)$$

$$R^2 = 0.83,\ RMSE = 1.42\left(\frac{MJ}{m^2d}\right), MBE = +0.00008\left(\frac{MJ}{m^2d}\right)\ and\ NSE = 0.90$$

$$\frac{Rs}{Ra} = 0.25 + 0.77\frac{n}{N} \quad Winter \quad (18)$$

$$R^2 = 0.85,\ RMSE = 2.56\left(\frac{MJ}{m^2d}\right), MBE = +0.00124\left(\frac{MJ}{m^2d}\right)\ and\ NSE = 0.88$$

The values of MBE are close to zero and the values of R^2 and NSE are close to one. The values of RMSE for summer and winter are greater than those obtained for spring and fall season. The values of *a* coefficient are 0.32, 0.36, 0.27 and 0.25 for spring, summer, fall and winter, respectively. Therefore it is showed that in cloudy days of summer and spring in comparison with fall and winter higher amounts of Rs can be received to earth from sky. The summation of *a* and *b* coefficients are 0.90, 0.84, 0.98 and 1.02 for spring, summer, fall and winter, respectively in the clear sky conditions. In the winter season, their summation is greater than one, which is not physically correct. Liu *et al.* (2009) reported average, maximum and minimum of *a* and *b* summations equal to 0.75, 0.85 and 0.62, respectively in monthly scale calibration of Angstrom Prescott equation for different provinces in China.

The average values of RMSE and NSE in equations 15-18 are equal to 2.14 and 0.81 respectively, which are very better of those predicted by equation (14). Results showed using the Angstrom Prescott model to estimate global radiation in the seasonal scale could get better results than using it for throughout the year by applying of uncalibrated *a* and *b* coefficients in this study.

2. Modified Angstrom Prescott equation

In this part of research relationships between the ratio of measured global solar radiation to extraterrestrial radiation and ratios of $\frac{n}{N-t}$ for the fall, winter, spring and summer seasons were investigated, separately. According to Zand-Parsa *et al.* (2011) recommendation, the value of t considered equal to 1.85 hr for study region. The modified Angstrom-Prescott model is calibrated for the fall, winter, spring and summer seasons as follows:

$$\frac{Rs}{Ra} = 0.32 + 0.50\frac{n}{N} \quad Spring \quad (19)$$

$$R^2 = 0.86,\ RMSE = 2.24\left(\frac{MJ}{m^2d}\right), MBE = +0.0402\left(\frac{MJ}{m^2d}\right)\ and\ NSE = 0.86$$

$$\frac{Rs}{Ra} = 0.37 + 0.40\frac{n}{N} \quad Summer \quad (20)$$

$$R^2 = 0.59,\ RMSE = 2.32\left(\frac{MJ}{m^2d}\right), MBE = -0.0149\left(\frac{MJ}{m^2d}\right)\ and\ NSE = 0.60$$

$$\frac{Rs}{Ra} = 0.27 + 0.58\frac{n}{N} \quad Fall \quad (21)$$

$$R^2 = 0.91,\ RMSE = 1.83\left(\frac{MJ}{m^2d}\right), MBE = -0.0532\left(\frac{MJ}{m^2d}\right)\ and\ NSE = 0.90$$

$$\frac{Rs}{Ra} = 0.25 + 0.62\frac{n}{N} \quad Winter \quad (22)$$

$$R^2 = 0.88,\ RMSE = 1.6\left(\frac{MJ}{m^2d}\right), MBE = -0.0761\left(\frac{MJ}{m^2d}\right)\ and\ NSE = 0.89$$

As shown in above equations in the clear-sky conditions, the sum of *a* and *b* values for spring, summer, fall and winter seasons are 0.82, 0.78, 0.85 and 0.87, respectively. These values are in agreement with reports of Liu *et al.* (2009) in China and Reietveld (1978) for anywhere of the world. The summations of *a* and *b* are lower than the values obtained from calibrated Angstrom Prescott equation (i.e. equations of 15 to 18) in study region. Allen *et al.* (1998) recommended the summation of *a* and *b* equal to 0.75 for northern hemisphere. The value of their summation is closer to Allen *et al.* (1998) report in summer season in compared with other seasons. Investigation of *a* and *b* calibrated coefficients in Angstrom Prescott (equations 15-18) and modified Angstrom Prescott (equations 19-22) equations showed that the most changes appeared in a coefficient and the values of b coefficients are close with together in all seasons. Finally, statistical analysis showed that the accuracy of summer season equation is less than the other seasons.

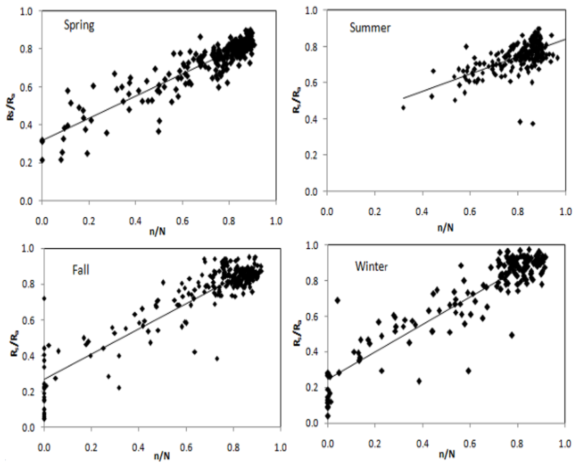

Fig. 3. Relationships between the ratio of measured global solar radiation to extraterrestrial radiation and actual sunshine to maximum possible sunshine duration.

3. Rietveld equation

Rietveld (1978) noted that *a* coefficient is related linearly and *b* hyperbolically to the appropriate means value of n/N. According to Rietveld method, the values of daily Rs are predicted based on calculated daily Ra and calibrated *a* and *b* coefficients as the following equations for spring, summer, fall and winter seasons:

$$\frac{Rs}{Ra} = \left(0.33 + 0.22\frac{n}{N}\right) + \left(0.32 + 0.031\frac{n}{N}\right)\frac{n}{N} \quad pring \quad (23)$$

$R^2 = 0.86,\ RMSE = 2.20\left(\frac{MJ}{m^2d}\right), MBE = +0.0001\left(\frac{MJ}{m^2d}\right)$ and $NSE = 0.87$

$$\frac{Rs}{Ra} = \left(0.25 + 0.35\frac{n}{N}\right) + \left(0.45 - 0.23\frac{n}{N}\right)\frac{n}{N} \quad Summer \quad (24)$$

$R^2 = 0.58,\ RMSE = 2.34\left(\frac{MJ}{m^2d}\right), MBE = -0.0011\left(\frac{MJ}{m^2d}\right)$ and $NSE = 0.57$

$$\frac{Rs}{Ra} = \left(0.23 + 0.49\frac{n}{N}\right) + \left(0.59 - 0.40\frac{n}{N}\right)\frac{n}{N} \quad Fall \quad (25)$$

$R^2 = 0.90,\ RMSE = 1.75\left(\frac{MJ}{m^2d}\right), MBE = -0.0002\left(\frac{MJ}{m^2d}\right)$ and $NSE = 0.91$

$$\frac{Rs}{Ra} = \left(0.22 + 0.45\frac{n}{N}\right) + \left(0.55 - 0.27\frac{n}{N}\right)\frac{n}{N} \quad Winter \quad (26)$$

$R^2 = 0.88,\ RMSE = 2.49\left(\frac{MJ}{m^2d}\right), MBE = -0.0002\left(\frac{MJ}{m^2d}\right)$ and $NSE = 0.89$

The RMSE values of equations 23–26 for spring, summer, fall and winter seasons are 2.20, 2.34, 1.75 and 2.49 $\frac{MJ}{m^2d}$, respectively. At all seasons, the RMSE and MBE values of equations 23-26 are less and the NSE values are higher than those of equation 14, which is the uncalibrated original Angstrom-Prescott model.

Conclusions

Present study region is located in the northern hemisphere and during fall and winter seasons, most of clouds come from the Mediterranean Sea and Indian Ocean. Therefore, the received solar radiation is affected by cloudiness conditions in fall, winter and those conditions are different from summer and spring seasons. Due to differences in sky-cloudiness, and atmosphere transmissivity in different seasons, the original and modified Angstrom-Prescott and Rietveld models have calibrated for the fall, winter, spring and summer seasons, separately. Using the calibrated original and modified Angstrom Prescott and Rietveld models to estimate global solar radiation in the seasonally scale could get better results than using them with applying of a=0.25 and b=0.50 [recommended by Allen *et al.* (1998)]. Good agreement was found between measured values and data estimated by the mentioned models. The average RMSE between measured and predicted Rs are 2.14 (i.e. average RMSE of equations 15-18), 2.0 and 2.2 MJ/m2/d for calibrated original and modified Angstrom Prescott and Rietveld model, respectively. While average RMSE of uncalibrated Angstrom Prescott model is 5.22 MJ/m2/d and this value is more than twice of mentioned calibrated models RMSE. Generally, statistical analysis (i.e. RMSE, MBE and NSE) showed, that three investigated models are recommendable to use in present study region when sunshine hours are available.

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