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Developing a new solar radiation estimation model based on Buckingham theorem

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ABSTRACT

While the value of solar radiation can be expressed physically in the days without clouds, this expression becomes difficult in cloudy and complicated weather conditions. In addition, solar radiation measurements are often not taken in developing countries. In such cases, solar radiation estimation models are used. Solar radiation prediction models estimate solar radiation using other measured meteorological parameters those are available in the stations.

In this study, a solar radiation estimation model was obtained using Buckingham theorem. This theory has been shown to be useful in predicting solar radiation. In this study, Buckingham theorem is used to express the solar radiation by derivation of dimensionless pi parameters. This derived model is compared with temperature based models in the literature. MPE, RMSE, MBE and NSE error analysis methods are used in this comparison. Allen, Hargreaves, Chen and Bristow-Campbell models in the literature are used for comparison. North Dakota's meteorological data were used to compare the models.

Error analysis were applied through the comparisons between the models in the literature and the model that is derived in the study. These comparisons were made using data obtained from North Dakota's agricultural climate network. In these applications, the model obtained within the scope of the study gives better results.

Especially, in terms of short-term performance, it has been found that the obtained model gives satisfactory results. It has been seen that this model gives better accuracy in comparison with other models. It is possible in RMSE analysis results. Buckingham theorem was found useful in estimating solar radiation. In terms of long term performances and percentage errors, the model has given good results.

Introduction

Solar radiation is an important variable for daily life and applications. Therefore, it is important that this value is known correctly. Estimation models are in effect when solar measurements cannot be performed [1].

In this study, Buckingham theorem based solar radiation estimation model will be established. Applications for this model will be done and error analysis will be performed. The model will be calibrated in the different regions of the world.

Main mathematical expressions about solar radiation

Main mathematical expressions about solar radiation will be given in this section.

Solar declination angle is given in Eq. (1). J is the calendar day of the year [2,3].

$$sin\delta = 0.39785 * \sin[278.97 + 0{,}9856J + 1.9165 * \sin(356.6 + 0{,}9856J)] \quad (1)$$

Sunrise hour angle is given in Eq. (2). ω_s is sunrise angle; ø is the latitude [2,3].

$$\omega_s = cos^{-1}[-\tan ø * \tan\delta] \quad (2)$$

Eccentricity correction factor is called eccentricity factor; E_o. The simple expression of the eccentricity factor is given in Eq. (3) [2,3].

$$E_0 = 1 + 0.033 * cos\left[\left(\frac{2\pi * J}{365}\right)\right] \quad (3)$$

Mathematical expression of extraterrestrial radiation is given in Eq. (4) [2,3]. I_{sc} is the solar constant; 4.921 MJ/day.m^2 [2].

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Abbreviations

H	Daily total global solar radiation, units of MJ·m^{-2}·day^{-1}	$T_{\min}$	Daily minimum temperature, units of °C
H_0	Extraterrestrial solar radiation, units of MJ·m^{-2}·day^{-1}	$T_{\max}$	Daily maximum temperature, units of °C
H_m	Measured daily total global solar radiation, units of MJ·m^{-2}·day^{-1}	RH	Relative humidity, units of %rh
H_c	Calculated daily total global solar radiation, units of MJ·m^{-2}·day^{-1}		

$$H_0 = \frac{24}{\pi} * I_{sc} * E_0 * sin\varnothing * sin\delta * \left[\left(\frac{\pi}{180}\right) * \omega_s - tan\omega_s\right] \tag{4}$$

Error analysis methods

Error analysis will be done with the help of meteorological data for the model derived using Buckingham theorem in this study. When performing these error analyzes, the percentage errors, short-term performance, long-term performance, and compatibility between the model and the meteorological data will be examined. Error analysis methods will be able to evaluate these performances.

RMSE analyzes provide information on the short-term performance of the models. MBE analyzes provide information on systematic errors and long term performance. The MPE error analysis gives the percentage error between the measured values and the values obtained from the models. As the results of this analysis approach to zero, the models become perfect [3,4]. These error analysis methods are given in Eqs. (5)–(7).

$$MPE = \frac{1}{N}\sum_{i=1}^{n}\left[\frac{H_{i,c} - H_{i,m}}{H_{i,m}}\right] \cdot 100 \tag{5}$$

$$MBE = \frac{\sum_{i=1}^{n} H_{i,c} - H_{i,m}}{N} \tag{6}$$

$$RMSE = \sqrt{\left|\frac{\sum_{i=1}^{n}(H_{i,c} - H_{i,m})^2}{N}\right|} \tag{7}$$

The Nash-Sutcliffe equation is also an error evaluation method. A model is more efficient when NSE converges to 1. NSE equation is given in Eq. (8) [10].

$$NSE = 1 - \frac{\sum_{i=1}^{n}(H_{i,m} - H_{i,c})^2}{\sum_{i=1}^{n}(H_{i,m} - \bar{H}_m)^2} \tag{8}$$

Modeling the solar radiation

According to the Buckingham theorem, all terms collected in an equation must have the same dimensions. This situation is expressed as dimensional homogeneity law. This law guarantees that all terms in an equation are in the same dimension. Unit analysis has to be performed for nondimensionalization process [5].

Dimensionless parameters are often referred to as Π. The relationship between dimensionless pi numbers that are related to each other is expressed as follows [6].

$$\prod_1 = \Phi\left(\prod_2, \prod_3, \prod_4, \ldots, \prod_{k-r}\right)$$

As the first step in the Buckingham Pi theorem, it is desirable to list the variables that affect the problem [5].

Using Buckingham's Pi theorem, it is seen that the solar radiation expression can be mathematically modeled [6]. First of all, the solar radiation will be mentioned in terms of the parameters available in the literature, in the models and in theory for the correct expression. Many models in the literature appear to have the expression of solar radiation together with extraterrestrial radiation [7–12]. It is also seen in many examples in the literature; global solar radiation can be expressed using the maximum and minimum air temperature differences, which is usually the square root of the temperature difference in mathematical formulas [9,12,13,14]. The global solar radiation value varies with meteorological factors when reaching the Earth's surface from the atmosphere. Radiation is subjected to multiple attenuation processes; the permeability of the atmosphere is related to the attenuation processes [2]. Transmittance, which is a proportional expression, will be another parameter to be considered in this theorem.

Using Buckingham theorem, models were developed using different temperature and humidity parameters (daily maximum, minimum and mean values) and error analysis were made with the station data. Mathematical expressions that are not satisfied with the results will not be shared here.

The expressions to be used in the formation of Π's are given above. It is possible to express the global solar radiation functionally as follows, in which some parameters are written for use in nondimensioning the above-mentioned parameters.

$$H = f(H_0, \tau, \Delta T, T_{min}, RH)$$

It should be noted here again; the Π parameters are without units. Both global solar radiation and extraterrestrial solar radiation expresses in energy per square meter (MJ·m^{-2}·day^{-1}). Hence, it is possible to write the first Π parameter as in Eq. (5).

$$\prod_1 = \frac{H}{H_0} \tag{5}$$

The second pi parameter is obtained by nondimensioning the difference between the maximum and minimum daily temperatures (Eq. (6)). Here, the minimum temperature will be used for the nondimensioning process.

$$\prod_2 = \left(\frac{T_{min}}{\Delta T}\right) \tag{6}$$

Finally, the atmospheric transmissivity expression will be used in the derivation of the third Π as in Eq. (7). Since atmospheric permeability is a proportional expression, the relative humidity, which is another proportional expression, will be used. The maximum, minimum, or mean value of the relative humidity will be used to modeling the solar radiation for these nondimensioning. This choice will be made in future.

$$\prod_3 = 100 * \frac{\tau}{RH} \tag{7}$$

As the result of the processes, the situation in Eq. (8) finds out according to the Buckingham Pi theorem.