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Research Article
Parameterization of the Downward Long Wave Radiation under Clear-sky Condition in Baghdad, Iraq

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Abstract
Objective: The purpose of this study is to evaluate the performance of seven downward long wave radiation models under clear-sky condition and to propose a locally modified equation. **Methodology:** The observed vapor pressure and air temperature data, downward long wave radiation and the atmospheric parameters were measured within the period, from 1st October, 2014 to 31st September, 2015 at a solar radiation station installed at the experimental site in Baghdad, Iraq. **Results:** The comparative statistics for the performance of the downward long wave radiation model calculations during day-time and night-time have shown that the parameterizations have the best results compared to the measured data. The locally proposed equation showed errors not greater than 1.1%, in comparison with the measured values, the models were used for estimating the apparent emissivity of the locally calibrated atmosphere. The percentage mean relative error and the root square errors obtained from calibrated equations were equal to 5.9 and 1.4%, 28.3 and 7.3 W m^{-2} for Idso and Jackson, Sugita and Brutsaert equations, respectively. **Conclusion:** It was found that the errors obtained basically reduced with the standardization performed and those calculations of the downward long wave radiation with the same output results are far more accurate than those made with the calibrations originally proposed. Finally, the locally examined equation can be used to estimate downward long wave energy, needed as input to most agricultural and hydrological models in some regions of Iraq, where this parameter is not measured.

Key words: Long wave, short wave, energy balance, emissivity, water vapor

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Long wave radiation is an important component of the energy balance of the earth's surface. Net radiation is a critical component of the surface energy budget[1-3]. Enhanced estimation of net radiation using reliable downward long wave radiation (DLR) values will contribute to a better understanding of the surface energy budget and will result in improved characterization of evapotranspiration for many applications in hydrology, climatology, biology and ecology[4].

Long wave radiative fluxes have generally received less attention than the short wave fluxes, partially due to difficulties and the costs associated with an accurate long wave radiation measurements and it is also due to a lack of measurable atmospheric parameters, which long wave radiation is dependent upon, such as cloud cover[5-7]. Unlike short wave radiation, incoming long wave radiation is not readily measured at automated weather stations.

Lacking the required data and measurements, DLR can be calculated using screen height measurements of air vapor pressure and temperature from weather stations via simple physical or empirical models[8-12]. More reliable DLR estimation can be obtained from the radiative transfer models, such as MODTRAN[13]. However, required input data, such as the vertical profiles of temperature and air vapor are not typically available[14,15].

Many researches have been done to develop various approaches in order to estimate atmospheric radiation. In spite of the recent advances in the area of measurement technology, there is noticeable interest in determining the DLR from the available meteorological measurements, which is emitted by the atmosphere and clouds, such as the air temperature and vapor pressure near the ground surface[2]. The research studies of the surface energy balance are often intricate, due to the various uncertainties associated with the estimation of a downward long wave radiation at the surface[3]. Accurate estimates of the surface radiation balance, which regulates the values of the surface energy balance components, depend on proper estimates of the downward long wave radiation. An instrument that measures directly the downward long wave radiation is the pyrgeometer, which is expensive and sensitive, in comparison with the pyranometer, which is used to measure the incoming short wave radiation[16]. The DLR is the surface radiation balance component that is rarely available at meteorological stations[17]. Thus, in recent years, many techniques have been developed to estimate DLR, where there are no pyrgeometers, the estimations are based only on surface observations. These methods have presented varied accuracy and new techniques are being developed on a regional scale[3,17].

The main disadvantage of previous studies on this subject is that they did not perform systematically in other locations, since they applied or made use of local empirical coefficients. This is mainly caused by the significant variation of the coefficients in those models, due to the variability of air temperature and water vapor pressure, which in turn, resulted from the spatial change in the land use pattern and from temporal changes in atmospheric circulation. At land scale, human activities affect the regional climate by changing the land use characteristics that affect the distributions of the ecosystems, energy (latent and sensible heat) and mass fluxes (for example, water vapor, trace gases and particulates). These contrasting land use patterns induce convection and circulation, which affect the cloud formation and precipitation. For example, when large areas of forest are cleared, reduced transpiration results in less cloud formation, less rainfall and increased drying of the earth's surface[17]. Previous studies carried out on the measurement of some radiation components (incoming short wave radiation or net energy balance) focused on specific land use type, such as grass, short vegetation, bare soil, forest and few crops, but disregarded the urban areas and water-covered areas[18-20].

In Iraq, there is a shortage in research studies related to analyzing and proposing an empirical equation in order to estimate the DLR. Thus, the main objective of this study is to assess the performance of DLR equations under clear-sky conditions, in order to develop an equation using the measured data at an experimental site in the Al-Mustansiriyah University solar station, for the semiarid region of the capital of Baghdad.

MATERIALS AND METHODS

Experimental site and measurements: The radiation and atmospheric parameters were measured every 15 min within the period from 1st October, 2014 to 31st September, 2015, at the solar radiation station and an automatic weather station (DAVIS VANTAGE PRO2) was installed on the roof building of the Atmospheric Sciences Department in Al-Mustansiriyah University (33°08'44"N, 44°05'53"E, altitude 56 m) as shown in Fig. 1. The sensor specifications which measure DLR and global radiation, referred to as a pyrgeometer and pyranometer[21] respectively are tabulated in Table 1.

Fig. 1: Ground-based multifunctional radiometric station at Al-Mustansiriyah site

The study region is Baghdad city. It is the capital and the main administrative center of Iraq. Baghdad is located in the central part of Iraq on both sides of the Tigris river. The climate of the Baghdad region (which is part of the plain area at the central part of Iraq and has same climatic characteristics) may be defined as a semi-arid, subtropical and continental, dry, hot and long summer, cool winters and short springs. Rainfall is very seasonal and occurs in the winter from October-May, the average annual rainfall is 120 mm. The maximum temperature recorded in summer was 51°C, while the minimum was -4°C. The average maximum temperature for the last 30 years is 30.8°C and the average minimum temperature is 15.5°C for the same period. The daily average of sunshine duration is 9.6 h and the daily incoming radiation is 4.7 k Wh m^{-2}. The total average annual sunny hour during one complete year is about 3500 h.

Table 1: Specifications of the CGR3 and CPM11 sensors

Specifications	CGR3	CMP11
Spectral range (overall)	4500-42000 nm	285-2800 nm
Sensitivity	5-15 μV W^{-1} m^2	7-14 μV W^{-1} m^{-2}
Response time	<18 sec	<5 sec
Window heating offset	<15 W m^{-2}	<7 W m^{-2}
Zero offset B	<4 W m^{-2}	<2 W m^{-2}
Temperature dependence of	<5%	<1%
sensitivity (-10 to +40°C)	-40 to +80°C	-40 to +80°C
Operational temperature range		
Net irradiance range	-250 to +250 W m^{-2}	0-4000 W m^{-2}
Field of view	150°	180°

Table 2: Emissivity of clear-sky parameterizations based on air temperature (T, K) and water vapor pressure (e_a, Pa), suggested by different researchers

Author	Equation	No. of equation
Swinbank[22]	$\varepsilon_a = 9.365\times10^{-6}T^2$	2
Idso and Jackson[9]	$\varepsilon_a = 1\text{-}0.261\exp[-7.77\times10^{-4}(273-T)^2]$	3
Brutsaert[1]	$\varepsilon_a = 0.643\left(\frac{e_a}{T_a}\right)^{\frac{1}{7}}$	4
Idso[23]	$\varepsilon_a = 0.7+5.95\times10^{-7}e_a\exp\left(\frac{1500}{T}\right)$	5
Sugita and Brutsaert[2]	$\varepsilon_a = 0.714\left(\frac{e_a}{T_a}\right)^{0.0687}$	6
Duarte *et al.*[15]	$\varepsilon_a = 0.625\left(\frac{e_a}{T_a}\right)^{0.131}$	7
Kruk *et al.*[17]	$\varepsilon_a = 0.576\left(\frac{e_a}{T_a}\right)^{0.202}$	8

Methodology: The Stefan-Boltzmann law for the radiation emission of any body at a temperature T (K), DLR (W m^{-2}), coming from the near-surface layer of the atmosphere may be written as Eq. 1:

$$DLR = \varepsilon_a \sigma T^4 \quad (1)$$

where, T is the air temperature near-surface (K), ε_a is the emissivity of the clear-sky atmosphere and $\sigma = 5.6705\times10^{-8}$ W m^{-2} K^{-4} is the Stefan-Boltzmann constant. According to Duarte *et al.*[15] and Kruk *et al.*[17], Eq. 1 is inspired by Stefan-Boltzmann's law for the radiation emitted by a grey body, at uniform temperature. All the equations analyzed in this study made the assumption that ε is a function of temperature and/or vapor pressure near the ground. Several authors have proposed different models for calculating ε_a. Seven popular ε_a formulations and those developed by Swinbank[22], Idso and Jackson[9], Brutsaert[1], Idso[23], Sugita and Brutsaert[2], Duarte *et al.*[15] and Kruk *et al.*[17] were tested against the DLR measured data on the experimental site. An analysis of the clear-sky models' consistency proposed by mentioned researchers are presented in Table 2.

A sample of 12 clear-sky days (1152 data point) was selected. These days represented the Fractional Cloud Coverage (CLF), calculated by employing Eq. 9, less than or equal to 0.05. Since the presence of clouds significantly increases the total effective emissivity of the sky, modifications must be made to the existing clear-sky formulations. Deardorff[24] used a fairly simple cloud modification, which involves introducing a cloud fraction term (CLF). In the present study, CLF was defined by:

$$CLF = 1\text{-}S \quad (9)$$

where, S is the ratio of the measured solar irradiance to the clear-sky irradiance. The clear-sky short wave irradiance I at the ground was calculated using a previously developed model based on the results of Paltridge and Platt[25], Meyers and Dale[26]. This quantity was approximated given by Eq. 10:

$$I = I_o (\cos Z)\, T_R\, T_{pg}\, T_w\, T_a \quad (10)$$

where, I_o is the effective solar constant, Z is the solar zenith angle and T_i is the transmission coefficients for Rayleigh scattering R, absorption by permanent gases pg and water vapor w and absorption and scattering by aerosols a.

The effective solar constant (W m^{-2}) is given by Eq. 11:

$$I_o = 1370 \left(\frac{\bar{r}}{r}\right)^2 \quad (11)$$

where, $\bar{r}$ and r are the average and daily distances between the sun and the earth, respectively. The cosine of the solar zenith angle is represented by Eq. 12:

$$\cos Z = \sin\gamma \sin\delta + \cos\gamma \cos\delta \cos H \quad (12)$$

where, γ represents the latitude of the station, δ is the solar declination and H is the hour angle. The hour angle Eq. 13 is:

$$H = \left(\frac{\pi}{12}\right)(t_{noon} - t) \quad (13)$$

where, t_{noon} is the local solar noon. The empirical expression for the product of the first two transmission coefficients[27] Eq. 14 is:

$$T_R\, T_{pg} = 1.021\text{-}0.084\, [m\, (0.000949p+0.051]^{0.5} \quad (14)$$

where, p represents the pressure in millibars and m is the optical air mass at p = 1013 mb, given by m = 35 cos Z (1224 cos^2 Z+1)$^{-0.5}$. The third coefficient[28] Eq. 15 is:

$$T_w = 1\text{-}0.077\, (um)^{0.3} \quad (15)$$

where, u represents the perceptible water given by:

$$u = \exp[0.113\text{-}\ln (G+1)+0.0393T_d]$$

where, T_d is the dew point (°F) and G is an empirical constant dependent upon time of the year and latitude. The fourth transmission coefficient[26,29] is given by Eq. 16:

$$T_a = 0.935^m \quad (16)$$

Once I was calculated from Eq. 10, direct observations of solar irradiance were used to calculate S and CLF in Eq. 9. Inclusion of the effects of clouds yields given in Eq. 17:

$$DLR = [CLF+(1\text{-}CLF)\varepsilon_c]\sigma T_4 = \varepsilon\sigma T_4 \quad (17)$$

Statistical indicators for evaluating the performance of the tested and proposed models are given in Table 3. For each parameterization, the calculated value of DLR, which is denoted by c was compared with the measured values, which is denoted by m. The statistical analysis includes bias (BIAS), Root Mean Square Error (RMSE), Mean Absolute Error (MAE) and Percent Mean Relative Error (PMRE)[30].

RESULTS AND DISCUSSION

The calculated DLR data was evaluated by employing the Eq. 2-8 according to the statistical criteria previously mentioned as shown in Table 3. It involves the experimentally measured downward short wave radiation S vapor pressure and temperature, in order to adjust an Eq. 18 under clear-sky

Table 3: Statistical indicators for evaluation of the parameterization performances

Statistical indicator	Symbols	Calculation formula
Bias	BIAS	$\frac{1}{n}\sum_{i=1}^{n}(c_i - m_i)$
Root mean square error	RMSE	$\sqrt{\frac{1}{n}\sum_{i=1}^{n}(c_i - m_i)^2}$
Mean absolute error	MAE	$\frac{1}{n}\sum_{i=1}^{n}\lvert c_i - m_i\rvert$
Percent mean relative error	PMRE	$\frac{100}{n}\sum_{i=1}^{n}\left\lvert\frac{c_i - m_i}{m_i}\right\rvert$
Correlation coefficient	CC	$r = \frac{\sum_{i=1}^{n}(c_i - \bar{c}_i)(m_i - \bar{m}_i)}{[(\sum_{i=1}^{n}(c_i - \bar{c}_i))(\sum_{i=1}^{n}(m_i - \bar{m}_i))]^{0.5}}$

The suffixes c, m and n denotes the mean calculated, measured and number of observations, respectively conditions, using a measured vapor pressure and temperature data from the experimental site of Al-Mustansiriyah University in Baghdad, Iraq as shown in Fig. 2.

The locally investigated Eq. 18 is:

$$\varepsilon_a = 0.492\left(\frac{e_a}{T_a}\right)^{0.3009} \quad (18)$$

The linear regression method employed in order to investigate the correlation between the calculated and measured DLR for clear-sky condition days are illustrated in Fig. 3. All tested models presented more than one slope, these results indicate overestimation, except for the model proposed by Sugita and Brutsaert[2] and Eq. 18. Whereas, the proposed models by Swinbank[22] and Idso and Jackson[9], which depend on air temperature only do not employ the vapor pressure as a measure of the humidity effect on atmospheric path length. It presented slope values of 1.19 and 1.11, respectively that point to further overestimation.

Figure 3 shows the comparisons between DLR calculated by Eq. 18, that is locally produced equation and the measured DLR on clear-sky days. The least square linear regression presented slope value of 0.98, indicating underestimation and showing similar results when compared with those presented by Brutsaert[1], Sugita and Brutsaert[2] and Prata[11] models.

Table 4 shows the comparative statistics for the performance of the eight downward long wave clear-sky computational models, compared to measured data from the experimental site in the Al-Mustansiriyah solar radiation station.

Overall, those parameterizations, which employ vapor pressure and air temperature to obtain the atmospheric emissivity have the best statistical criteria, which represented by the lowest values of BIAS, RMSE, MAE and PMRE were estimated by the Eq. 18, then the Sugita and Brutsaert[2] model came in second order, followed by Duarte *et al.*[15] and Kruk *et al.*[17]. The results with the highest BIAS, RMSE, MAE and PMRE were presented by Swinbank[22] and Idso and Jackson[9], respectively.

Table 4: Statistical criteria for the performance of the eight DLR clear-sky calculation models compared to measured data from the experimental site

Models	BAIS (W m^{-2})	RMSE (W m^{-2})	MAE (W m^{-2})	PMRE (%)	r	R^2
Swinbank[22]	16.6	26.0	14.6	5.2	0.88	0.78
Idso and Jackson[9]	18.2	28.3	17.9	5.9	0.88	0.78
Brutsaert[1]	4.7	9.9	6.6	2.4	0.92	0.84
Idso[23]	11.1	17.3	9.3	2.9	0.87	0.77
Sugita and Brutsaert[2]	0.4	7.3	5.1	1.4	0.87	0.86
Duarte *et al.*[15]	4.4	12.8	6.7	1.9	0.94	0.88
Kruk *et al.*[17]	5.1	9.3	5.9	1.8	0.93	0.84
Equation 18	0.3	5.7	3.2	1.1	0.94	0.89

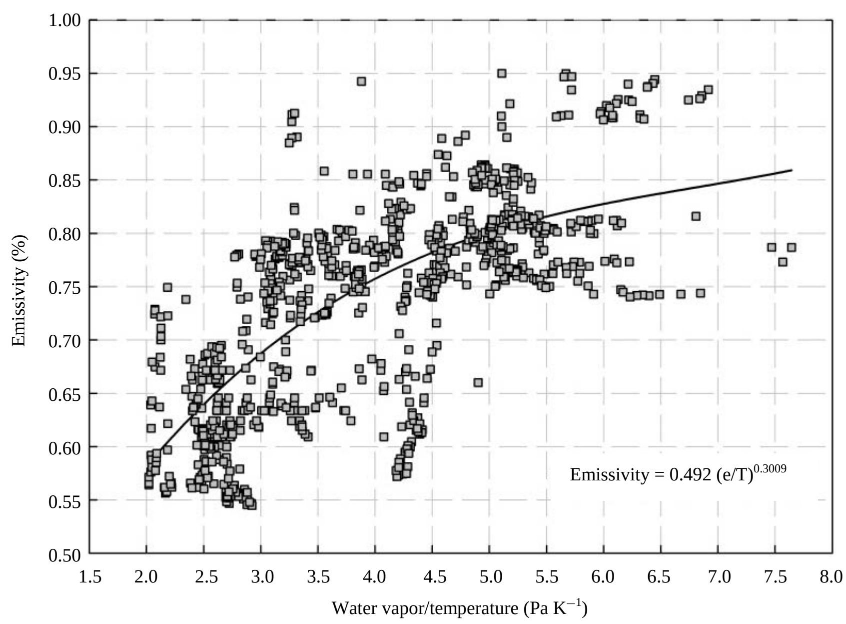

Fig. 2: Emissivity of 12 clear-sky cases of Al-Mustansiriyah station as a function of the ratio of level water vapor pressure and temperature

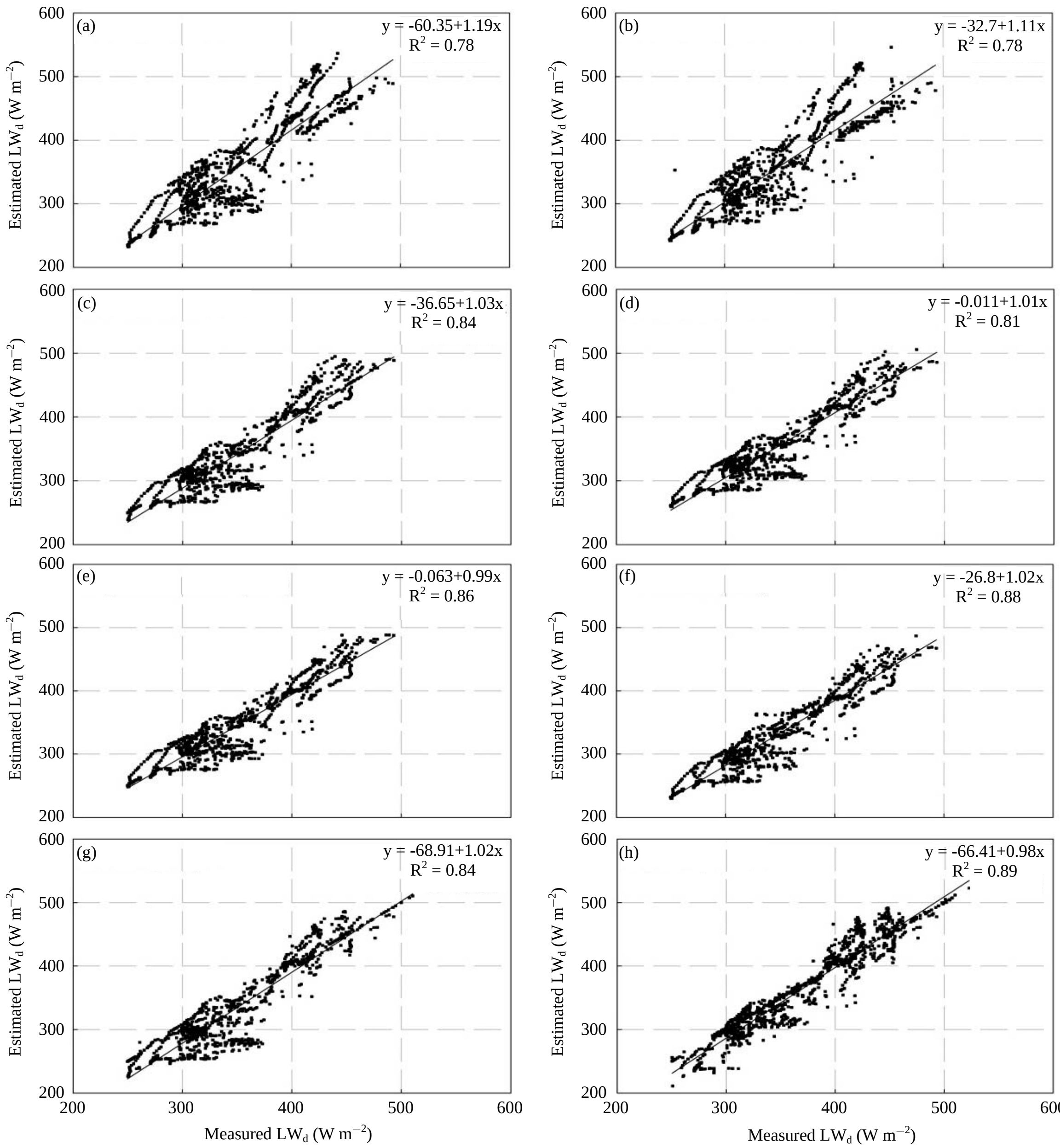

Fig. 3(a-h): Comparisons between calculated and measured downward long wave radiation in clear-sky days, (a) Swinbank[22], (b) Isdo and Jackson[9], (c) Brutsaert[1], (d) Idso[24], (e) Sugita and Brutsaert[2], (f) Duarte *et al.*[15], (g) Kruk *et al.*[17] and (h) Equation 18

Figure 4 shows the mean diurnal cycle of DLR for clear-sky days, calculated using Eq. 18 and the actual measurements. The demeanor of calculated values of DLR between midnight and early morning is smaller than the measured values. In the early hours after sunrise, the model overestimated the values. However, between 10:00 am and 17:00 pm, the calculated values are underestimated and after that time, they are overestimated until the sunset. At the same time, it can be spotted that the average of DLR calculated for clear-sky days from Eq. 18, exceedingly correspond with the average of measurements (Fig. 4), presenting a satisfactory congruence between them.

Finally, results obtained from this study will provide a deeper comprehension of the surface energy budget in the semi-arid region of Baghdad city and it can result in amending the general properties of evaporation in numerous practical applications in agriculture, environmental studies and hydrology.

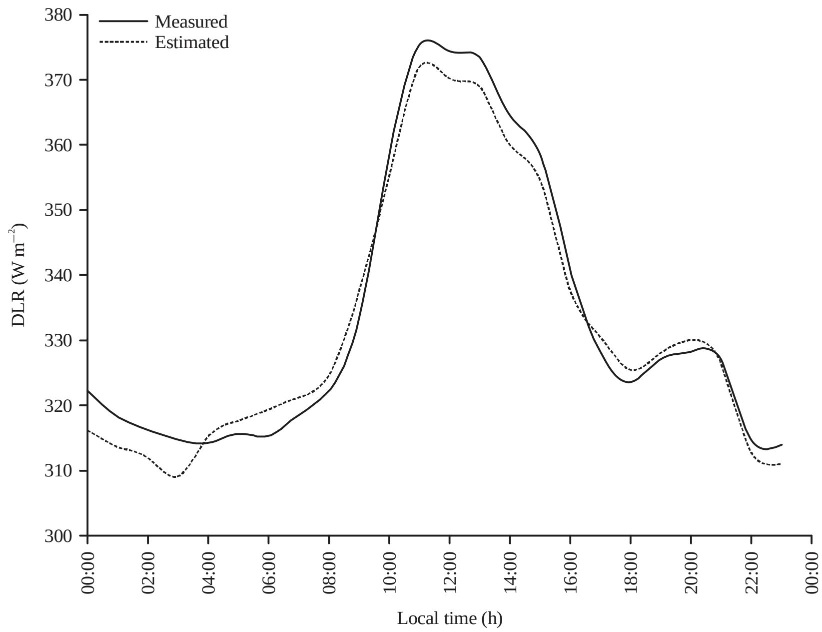

Fig. 4: Mean diurnal cycle of downward long wave radiation flux for clear-sky day estimated using the Eq. 18 and measured in the experimental site

CONCLUSION

The standardization which utilize air temperature only, such as, Swinbank model and Idso and Jackson model, shows a considerable DLR overestimation, while other parameterizations present slight DLR overestimation. The results suggest a good agreement existing between the estimated and measured values, the obtained results by the locally adjusted equation presented the smallest statistical criteria. The proposed equation can be used to estimate the downward long wave radiation with acceptable accuracy, which is required as an input parameter to most agricultural and hydrological models, in the semi-arid regions of Iraq, where this component is not measured due to the high cost of the measuring DLR devices.

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