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Developing regional calibration coefficients for estimation of hourly global solar radiation in Ireland

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ABSTRACT

This study proposed regional coefficients for estimating hourly global solar radiation through the adaptation of some empirical models that relate radiation to climatological and geographical variables. A total of 10 models were adapted over 7 stations in Ireland. The performance of the models was evaluated using some selected error indicators including the global performance index which combines all other error indices. The results indicated that the sunshine based regional calibration coefficients generated through a polynomial approach was most superior over other models with the lowest RMSE (0.2–0.3 $MJm^{-2}\,hr^{-1}$), MAE (0.1–0.2 $MJm^{-2}\,hr^{-1}$) and Pbias (0–7.0%) and highest R^2 and KGE (>0.85). The study found no local effect such as instrumental siting, observational uncertainty and climate on the variations of these coefficients. This outcome will therefore facilitate the design of various local and/or regional solar energy applications at microscale in a temperate region.

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1. Introduction

Solar radiation is an important component that drives the earth-atmosphere systems. It could be measured in form of global solar radiation, diffused solar radiation or beam solar radiation. The global solar radiation is the most important parameter for many solar energy applications (Muzathik et al. 2011; Despotovic et al. 2015) including in agriculture, hydrology, meteorology and climatology. The amount of this energy received at the surface depends on a number of factors such as the altitude of the sun, the clarity of the sky and the slope and aspect and the latitudinal position of an area. Global solar radiation therefore varies in space and time due to these factors and the design to optimise the energy receipt for different applications depends highly on the ability to measure and understand its spatial-temporal distribution. At different local regions around the world, information about this solar radiation component is limited in space and time due to the costs of instrumental requirements. Measured data from the distant stations are extrapolated to obtain values for stations with no data. This method is however uncertain and with low precision due to local variations in the aforementioned factors. In a bid to overcome the challenge of missing global radiation data, several empirical models have been developed at a given local region using available climatological and/or geographical data (Ertekin and Yaldiz 2000; Karakoti, Pande, and Pandey 2011; Yao et al. 2014). Some of these studies used parameters such as sunshine hours (Almorox, Benito, and Hontoria 2005; Al-mostafa,

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Maghrabi, and Al-shehri 2014), air temperature (Dos Santos et al. 2014; Yacef et al. 2014), precipitation (Liu and Scott 2001; Wu, Liu, and Wang 2007), sky cover (Tasdemiroglu and Sever 1991; Muneer and Gul 2000; Badescu and Dumitrescu 2013), and relative humidity (Yang and Koike 2002; Adaramola 2012). Sunshine duration is the widely used parameter for estimating global radiation. Angstrom (1924) proposed the first empirical global radiation model by establishing a linear relationship between the ratio of mean daily global radiation to clear day radiation and the ratio of sunshine hours to the maximum possible sunshine duration. This model was modified by Prescott (1940) by optimising the clear sky radiation to extraterrestrial radiation. Several other global radiation models around the world have been built and adapted from this optimised Angstrom–Prescott model for global radiation estimation at local scale. Some of these adapted models found that the relationship between the parameters are not simply linear thus different non-linear such as the cubic, quadratic, polynomial and exponential relationships ensued (Yang and Kioke 2005; Yorukoglu and Celik 2006; Besharat, Dehghan, and Faghih 2013). The possibilities of integrating meteorological variables into the global radiation models have also been tested (Hargreaves 1994; Allen 1997; Chen et al. 2004). Moreover, the present situations of solar radiation estimation across the world have adopted artificial intelligence techniques as an alternative hybrid soft-computing process to the traditional statistical methods (Iqdour and Zeroual 2007; Olatomiwa et al. 2015; Kassem et al. 2016; Wang et al. 2016, 2017; Zou et al. 2017; Qin et al. 2018). Some of these soft-computing methodologies include the Adaptive Neuro-Fuzzy Inference Systems (ANFIS), Bristow-Campbell Model (BCM), Yang Hybrid Model (YHM), M5 model Tree (M5Tree) and Artificial Neural Network (ANN) methods. The development and application of different ANFIS amongst the artificial intelligence techniques at different regions have been well documented. For instance, Olatomiwa et al. (2015) investigated the accuracy of ANFIS to simulate solar radiation in Iseyin, Nigeria. With three neurons in the input layer of ANFIS network and using the monthly mean maximum and minimum temperatures and sunshine duration as the inputs, the study found the proposed model efficient for predicting global solar radiation. Similar results have also been replicated in Kassem et al. (2016) using ANFIS model over Alexandria city in Egypt. Two different optimised ANFIS with grid partition (ANFIS-GP) and subtractive clustering (ANFIS-SC) in comparison with M5Tree and empirical Angstrom methods for modelling daily global solar radiation have been tested in China (Wang et al. 2017). The study reported ANFIS models to provide the best accuracy than the later two models. In another development, hybrid parameters were used to test and compare the validity of three different ANN methods, Multilayer Perceptron (MLP), Generalised Regression Neural Network (GRNN) and Radial Basis Neural Network (RBNN) with BCM model to predicting the daily global solar radiation. The study attributed the underestimation of few high radiation values by ANN methods at some stations to the differences in training and testing data ranges and distribution of the stations. A comparative study of four shortwave solar radiation models, Yang's Hybrid Model (YHM), an efficient physically based model (EPP), an hourly solar radiation model (HSRM) and ANN models has been carried out in China (Qin et al. 2018). The paper reported the superiority of YHM over other models and found cloud fraction and solar zenith angle to be the major parameters influencing the model accuracies. Although, the expanded and improved BCM and YHM models provided better accuracies than the original models, ANFIS was yet found to be the most superior to all the models in daily global solar radiation predictions (Zou et al. 2017). The merits of artificial intelligence techniques are in their abilities to; track complexities between different parameters where conventional methods are limited; and merge the learning power of ANN methods with the knowledge representation of fuzzy logic hence, computational efficiency and adaptability (Kassem et al. 2016).

In Ireland, fewer studies have attempted to develop global radiation models for different stations (Connaughton 1967; Morton 1968; McEntee 1980; Fealy and Sweeney 2008) even-though hourly observations about this parameter are limited in the region. It is important to note that the findings reported in these studies were basically on the linear relation between daily global radiation and sunshine duration. Recently, total global radiation models based on daily extremes air temperature and relative humidity were proposed in Dublin, Ireland (Ekici and Teke 2017). The models were found to be in good agreement with the observed and thus could be used to estimate daily global radiation at the local region. Although, McEntee (1980) proposed general empirical coefficients for estimating global radiation based on daily observations in Ireland, the study suggested the possibility of improving their models using a high temporal resolution datasets. Furthermore, one important challenge of these models is the uncertainty of using the empirical coefficients for hourly and regional estimation of global radiation. The Irish Meteorological Service provides hourly meteorological information of different meteorological parameters including air temperature, relative humidity and cloud amount at virtually all the synoptic stations. However, only few of these stations measure global radiation and sunshine hours at the time scale. The hourly global radiation data is important for atmospheric boundary layers studies and the understanding of the physical process driving the earth-atmosphere systems which occurs at microscale and principally depends on the solar radiation component. Besides, the local dependency of the calibration coefficients developed in the earlier studies, poses a major constraint on the reliability of the models to estimating the regional distribution of hourly global solar radiation (Besharat, Dehghan, and Faghih 2013).

Therefore, this study proposed regional empirical coefficients of global solar radiation models based on an integration of climatological and extraterrestrial radiation data obtained from the few available synoptic stations which will enhance regional estimation of global solar radiation on an hourly basis in Ireland. The choice of the traditional statistical approaches over the soft-computing techniques in this study lies in their computational simplicities which could be satisfactorily applied to a region like Ireland where there is little/no difference in the local/regional global solar radiation values reflected by local climate effect, instrumental siting and operational characteristics (McEntee 1980); and also due to poor observational network. A total of 10 empirical linear and nonlinear models were developed and tested following the procedures in the literatures, 4 of these models basically depend on sunshine duration, 3 of the models depend on air temperature and relative humidity and the last 3 depend on the combination of the parameters. The idea is to propose a model that is capable of estimating global solar radiation regionally with or without any of these parameters and consequently reduce the challenge of missing hourly global radiation data at various locations in Ireland. Four synoptic stations cut across the country were used to develop and calibrate the models and three independent stations were used to test the validity of the developed models. The best performed model was further evaluated against the recommended non-linear globally calibrated Angstrom model (Yang and Kioke 2005) and the linear locally calibrated Angstrom model for Ireland (McEntee 1980) over the three independent stations. The detailed descriptions of the observational data, study locations and the concepts of the empirical procedures used in this study are given in the next section. In Section 3, the description of the selected statistical error indicators used to evaluate the model performance is presented.

2. Observational data

The Island of Ireland is geographically located in the North Atlantic between latitude 51°N and 55°N, and longitude from 9°W to 6°W. The average hours of sunshine in this region range between 1100 and 1600 hr per year with the sunniest month in May and June averaging 5–6.5 hr per day (met.ie). The average solar energy received by a horizontal surface at the top of the atmosphere in the latitude of Birr for instance, ranges from about 4170 J/cm^2 a day in late June (4187 J would raise the temperature of 1 l of water 1°C) to less than 600 J/cm^2 in late December. On days without sun, the surface receives averagely 20–25% of the energy arriving at the top of the atmosphere. The percentage top of the atmosphere radiation which reaches the surface has a mean value of 40–47% during the months March to September and 30–37% during the months October to February (met.ie). The lowest duration of sunshine occur in December with average values between 1 and 2 hr per day. Due to its location, the Minimum air temperature in the region falls below zero averagely 40 days per year at the inland stations, but less than 10 days each year in most coastal areas. Average air temperatures inland reach 18–20°C during summer days, and about 8°C during winter. The current observations were obtained from seven synoptic stations (Figure 1) of Met Eireann, an Irish Meteorological Service. These stations were selected because of their capacities to provide long-term hourly data used for calibration and validation, and are good representatives of their geographical locations. The synoptic stations used for calibration consist of Malin-head to the North, Belmullet to the west, Dublin-airport to the east and Valentia-observatory to the south of the country (Figure 1). The other in-land stations Birr, Clones and Kilkenny were used for validation.

Hourly observations of air temperature, relative humidity, sunshine duration and global solar radiation were obtained from the periods 2000 to 2007 over the selected stations. The data over the stations used for calibration were divided into sub-datasets with the first six years (2000–2005) used for the development of regional calibration coefficients of global solar radiation models and the last two years (2006–2007) for validation. The calibrated coefficients were tested using two years (2006–2007) data over the independent in-land stations. Furthermore, extraterrestrial radiation (R_e) data for each hour and location were obtained from the estimation of geographical parameters including solar declination, solar constant and the time of the year as shown in the procedure below (Allen et al. 1998):

$$R_e = \frac{12(60)}{\pi} S_c d_r[(\omega_2 - \omega_1)\sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)(\sin(\omega_2) - \sin(\omega_1))] \tag{1}$$

where R_e extraterrestrial radiation in hour ($\text{MJm}^{-2}\ \text{hr}^{-1}$); S_c solar constant (0.082 $\text{MJm}^{-2}\ \text{min}^{-1}$); d_r inverse relative distance earth-sun; δ solar declination (rad); ϕ station latitude (rad); ω_1 solar time angle at the beginning of period (rad); ω_2 solar time angle at the end of period (rad).

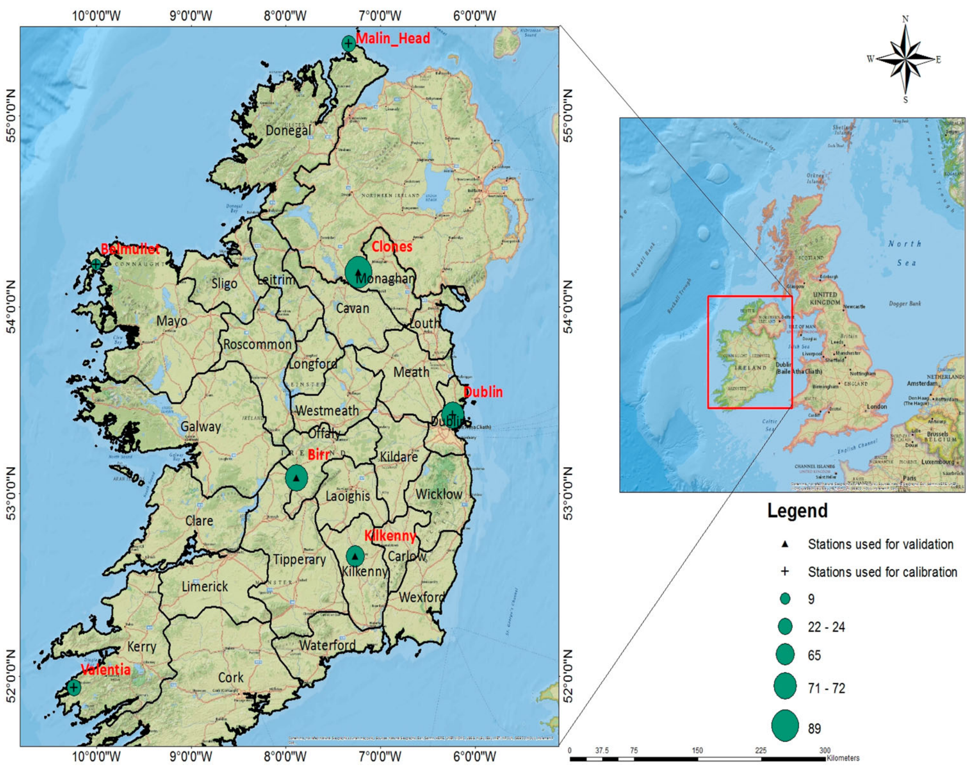

Figure 1. Map of the study area showing the geographical locations and elevations (m) of the local stations.

The inverse relative distance earth-sun and solar declination are given by;

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

$$\delta = 0.409\sin\left(\frac{2\pi}{365}J - 1.39\right) \tag{3}$$

where J is the Julian day.

The solar time angles at the beginning and end of periods are given by;

$$\omega_1 = \omega - \frac{\pi t_1}{24} \tag{4}$$

$$\omega_2 = \omega + \frac{\pi t_1}{24} \tag{5}$$

where ω solar time angle at mid-point of hourly (rad); t_1 length of calculation period (1 for hourly and 0.5 for 30 min).

The solar time angle at mid-point is presented as;

$$\omega = \frac{\pi}{12}[(t + 0.06667(L_z - L_m) + I_c) - 12] \tag{6}$$

t standard clock time at the mid-point of the period i.e. between 1300 and 1400 hr, $t = 13.5$; L_z longitude of the centre of the local time zone (degrees west of Greenwich); L_m longitude of the station (degrees west of Greenwich); I_c Seasonal correction for solar time (hr)

The seasonal correction for solar time is given as;

$$I_c = 0.1645\sin(2B) - 0.1255\cos(B) - 0.025\sin(B) \tag{7}$$

$$B = \frac{2\pi(J - 81)}{364} \tag{8}$$

J is the Julian day of the year.

The above procedure can also be applied for time period shorter than an hour (Allen et al. 1998). Moreover, the concepts of the adapted empirical models used in this paper are described in Table 1.

Table 1. Descriptions of the adapted empirical global solar radiation models.

Model	Description	Author(s)	Category
1	$R_g = \left(a + b\frac{n}{N}\right)R_e$	Angstrom (1924); Prescott (1940); Page (1961); Connaughton (1967); McEntee (1980)	Sunshine duration
2	$R_g = \left(a + b\frac{n}{N} + c\left(\frac{n}{N}\right)^2\right)R_e$	Ogelman, Ecevit, and Tasdemiroglu (1984); Rietveld (1978); Almorox and Hontoria (2004)	
3	$R_g = \left(a + b\exp\left(\frac{n}{N}\right)\right)R_e$	Almorox and Hontoria (2004); Togrul and Togrul (2002)	
4	$R_g = \left(a + b(R_e) + c\frac{n}{N}\right)$	Togrul and Onat (1999)	
5	$R_g = (a + b(T) + c(Rh))R_e$	El-Sebaii et al. (2009); Tabari et al. (2016)	Air temperature and relative humidity
6	$R_g = (a + b(R_e) + c(T))$	Ertekin and Yaldiz (1999); Tabari et al. (2016)	
7	$R_g = (a + b(T))R_e$	Proposed	
8	$R_g = \left(a + b\frac{n}{N} + c(T)\right)R_e$	El-Sebaii et al. (2009)	Hybrid
9	$R_g = \left(a + b(T) + c\exp\left(\frac{n}{N}\right)\right)R_e$	Proposed	
10	$R_g = \left(a + b(T) + c(Rh) + d\exp\left(\frac{n}{N}\right)\right)R_e$	Abdalla (1994); Maghrabi (2009); Gopinathan (1988)	

Notes: a, b, c and d are empirical calibration coefficients which depends of the prevailing atmospheric condition at a particular local region, Rg – global solar radiation (MJm^{-2} hr^{-1}), n – sunshine duration (hours), T – air temperature (°C) and Rh – relative humidity (%).

The maximum possible duration of sunshine N is computed using the sunset hour angle ω_s in radians;

$$N = \frac{24}{\pi}\,\omega_s \tag{9}$$

$$\omega_s = cos^{-1}[-\tan(\phi)\tan(\delta)] \tag{10}$$

3. Comparisons and evaluation of models

The performance of the proposed models were quantified based on few selected statistical error indicators root mean square error (RMSE), percent bias (pbias), mean absolute error (MAE) and coefficient of determination (R^2), Kling-Gupta efficiency (KGE), t-statistical test (t-stat) and global performance indicator (GPI). The modified KGE adopted in this study ensures that the bias and variability ratios are not cross-correlated (Gupta et al. 2009; Kling, Fuchs, and Paulin 2012). The t-stat indicator was obtained from RMSE and MAE and used to determine the statistical significance of the developed models (Stone 1993; Behar, Khellaf, and Mohammedi 2015; Okundamiya, Emagbetere, and Ogujor 2016). In addition, a new index GPI suggested by Behar, Khellaf, and Mohammedi (2015) was adapted to avoid erroneous selection of the best prediction models. The index was computed by multiplying all the six error indicators and further used for model ranking. We also compared the best model with the recommended FAO model, the non-linear globally calibrated Angstrom model (Yang and Kioke 2005; hereafter, GAM) and the linear locally calibrated Angstrom model for Ireland (McEntee 1980; hereafter, LAM) over the three selected independent stations. All analyses, model set-up, calibration and evaluation were carried out on R statistical software.

4. Results and discussion

4.1. Development and calibration of hourly global radiation models

This study has evaluated different categories of global solar radiation models (Table 1) to developing regional empirical coefficients for estimation over Ireland. The subdatasets from 2000 to 2005 over Belmullet, Malin-head, Valentia and Dublin were used to develop the different coefficients and calibration was performed using data from 2006 to 2007. The statistical outputs of local and regional calibrations are presented in Tables 2 and 3 respectively. The performance of the local and regional coefficients of the adapted models was independently investigated based on KGE, t-stat and GPI statistical indicators. The local calibration outputs revealed that there are variations in the values of the performance indicators from one station to another. This could be due to the varying degree of cloud cover and atmospheric constituents such as water vapour from one local region to another which brings about seasonal variations of solar radiation. Across different models and over the stations, the values of KGE ranged between 0.5 and 0.9, t-stat ranged between 0.0 and 11.5 and GPI between 0.0 and 0.05 (Table 2). It was observed that models 1, 2, 4, 8, 9, and 10 had higher KGE and lower GPI values compared to models 3, 5, 6, and 7 in all stations. This indicates that the linear and polynomial models based on sunshine hours and as well as the hybrid parameter based models are more accurate than temperature and/or relative humidity based predictive models. These results coincide with Okundamiya, Emagbetere, and Ogujor (2016) which reported a better accuracy of hybrid parameter based global radiation models than single-parameter models. The t-sat outputs across models and stations revealed that only few models such as model 2, 4, 5 and 6 at different local stations showed statistical significance with values below the chosen critical t-value ($t_c = 2.201$ at 95% confidence level). This could be attributed to the over/under-estimations of global solar radiation as quantified by the MAE and RMSE used in t-stat computations. Comparatively, model 2 which is a polynomial relation of Angstrom–Prescott model (Rietveld 1978; Ogelman, Ecevit, and Tasdemiroglu 1984;

Table 2. Local calibration outputs of the adapted models using hourly sub-data from 2006 to 2007.

		Error indicators			Calibration coefficients			
Model	Station	KGE	*t*-stat	GPI	*a*	*b*	*c*	*d*
1	Belmullet	0.77	7.1	0.00129	0.38	3.28	–	–
	Dublin	0.78	9.4	0.00256	0.37	3.10	–	–
	Malin-head	0.78	6.5	0.00095	0.36	3.38	–	–
	Valentia	0.74	9.4	0.00212	0.36	3.50	–	–
2	Belmullet	0.84	2.0	$2.29 * 10^{-5}$	0.28	8.12	−43.2	–
	Dublin	0.86	4.0	$7.53 * 10^{-5}$	0.27	7.67	−38.8	–
	Malin-head	0.86	0.6	$1.68 * 10^{-6}$	0.26	8.48	−44.3	–
	Valentia	0.81	3.0	$4.19 * 10^{-6}$	0.26	8.26	−43.2	–
3	Belmullet	0.76	7.4	0.00171	−2.68	3.07	–	–
	Dublin	0.77	9.9	0.00319	−2.52	2.89	–	–
	Malin-head	0.77	6.8	0.00127	−2.78	3.16	–	–
	Valentia	0.73	9.7	0.00235	−2.92	3.28	–	–
4	Belmullet	0.83	2.4	0.00045	−0.53	0.65	6.96	–
	Dublin	0.81	3.8	0.00126	−0.47	0.60	6.89	–
	Malin-head	0.83	0.7	$4.06 * 10^{-5}$	−0.51	0.62	7.28	–
	Valentia	0.85	5.3	0.00109	−0.59	0.64	7.78	–
5	Belmullet	0.77	3.9	0.00082	1.29	−0.005	−0.011	–
	Dublin	0.76	2.2	0.00038	1.08	−0.003	−0.008	–
	Malin-head	0.68	4.7	0.00308	1.10	−0.006	−0.009	–
	Valentia	0.73	0.4	0.00015	1.00	−0.010	−0.009	–
6	Belmullet	0.70	2.3	0.00117	−0.26	0.49	0.011	–
	Dublin	0.69	0.1	$5.89 * 10^{-6}$	−0.17	0.45	0.008	–
	Malin-head	0.69	4.0	0.00366	−0.14	0.49	0.0003	–
	Valentia	0.64	0.3	0.00041	−0.27	0.48	0.01	–
7	Belmullet	0.59	7.0	0.01452	0.26	0.010	–	–
	Dublin	0.62	4.4	0.00498	0.32	0.005	–	–
	Malin-head	0.55	9.4	0.02891	0.31	0.005	–	–
	Valentia	0.52	5.9	0.02699	0.25	0.009	–	–
8	Belmullet	0.81	9.1	0.00164	0.22	3.45	0.01	–
	Dublin	0.81	9.8	0.00180	0.26	3.42	0.008	–
	Malin-head	0.81	7.6	0.00122	0.24	3.61	0.01	–
	Valentia	0.79	11.1	0.00229	0.19	3.66	0.012	–
9	Belmullet	0.81	9.3	0.00189	−3.02	0.012	3.24	–
	Dublin	0.81	10.2	0.00227	−2.94	0.007	3.21	–
	Malin-head	0.81	8.0	0.00136	−3.13	0.011	3.37	–
	Valentia	0.79	10.3	0.00192	−3.25	0.012	3.45	–
10	Belmullet	0.83	8.7	0.00103	0.46	0.011	−0.003	3.23
	Dublin	0.83	9.1	0.00115	0.39	0.006	−0.002	3.31
	Malin-head	0.82	7.5	0.00096	0.34	0.010	−0.001	3.51
	Valentia	0.80	10.6	0.00152	0.32	0.012	−0.002	3.48

Note: KGE – Kling-Gupta Efficiency; *t*-stat – *T* statistic test; GPI – Global Performance Indicator; *a*, *b*, *c*, *d* are empirical coefficients.

Almorox and Hontoria 2004) was ranked the best global solar radiation model with the highest KGE (>0.85), lowest values of *t*-stat and GPI of the order of 10^{-6} (Despotovic et al. 2015; Behar et al. 2015) over all the stations. However, model 7 was observed to show the poorest performance with the lowest KGE (<0.60), high *t*-stat and GPI values across the stations (Table 2). It is important to also note in Table 2 that the local calibration coefficients of each adapted model showed similar values with little difference in magnitude of the order of ±0.01–±0.1 over the four stations, which suggests that the relationships between the selected predictors and global radiation are the same over all the stations, and the variation of global radiation is independent of site conditions. Hence, the local coefficients were averaged over all the stations to obtain regional coefficients that are capable of estimating hourly global solar radiation at different locations in Ireland (Table 3).Applying the regional calibration coefficients at the different local stations, the outputs showed similar range of values as local calibration outputs, with models 1, 2, 4, 8, 9, and 10 having higher and lower KGE and GPI values respectively. Model 2 was again identified as the best model and model 7 as the worst based on the GPI values (Table 3). The regional coefficients produced outputs which were in agreement with the outputs at different local stations. Although, the statistical test outline in

Table 3. Regional calibration outputs of the adapted models using hourly sub-data from 2006 to 2007.

		Error indicators			Calibration coefficients			
Model	Station	KGE	*t*-stat	GPI	*a*	*b*	*c*	*d*
1	Belmullet	0.77	5.6	0.00074				
	Dublin	0.77	10.3	0.00288	0.37	3.32	–	–
	Malin-head	0.77	6.6	0.00107				
	Valentia	0.75	6.5	0.00154				
2	Belmullet	0.84	0.5	$1.02 * 10^{-5}$				
	Dublin	0.88	4.4	$7.85 * 10^{-5}$	0.27	8.14	−42.4	–
	Malin-head	0.85	1.2	$7.07 * 10^{-6}$				
	Valentia	0.82	0.5	$1.72 * 10^{-6}$				
3	Belmullet	0.76	5.8	0.00095				
	Dublin	0.78	10.5	0.00323	−2.72	3.10	–	–
	Malin-head	0.77	6.9	0.00129				
	Valentia	0.75	6.8	0.00186				
4	Belmullet	0.85	0.01	$3.31 * 10^{-8}$				
	Dublin	0.76	5.2	0.00343	−0.52	0.63	7.23	–
	Malin-head	0.82	0.1	$1.49 * 10^{-6}$				
	Valentia	0.84	1.9	0.00034				
5	Belmullet	0.30	40.0	0.82598				
	Dublin	0.53	24.0	0.12365	1.12	−0.006	−0.01	–
	Malin-head	0.32	35.1	0.71341				
	Valentia	0.30	31.1	0.43199				
6	Belmullet	0.68	4.1	0.00413				
	Dublin	0.72	1.0	0.00021	−0.21	0.48	0.008	–
	Malin-head	0.69	3.5	0.00275				
	Valentia	0.65	2.2	0.00167				
7	Belmullet	0.57	8.7	0.02139				
	Dublin	0.62	5.7	0.00817	029	0.007	–	–
	Malin-head	0.56	8.6	0.02358				
	Valentia	0.55	7.4	0.02218				
8	Belmullet	0.82	7.8	0.00105				
	Dublin	0.81	12.1	0.00304	0.23	3.54	0.01	–
	Malin-head	0.81	7.0	0.00104				
	Valentia	0.79	8.8	0.00198				
9	Belmullet	0.81	8.0	0.00139				
	Dublin	0.80	12.4	0.00391	−3.08	0.01	3.32	–
	Malin-head	0.80	7.4	0.00131				
	Valentia	0.79	9.0	0.00243				
10	Belmullet	0.83	6.7	0.00057				
	Dublin	0.81	12.6	0.00301	0.38	0.009	−0.002	3.38
	Malin-head	0.81	6.5	0.00076				
	Valentia	0.81	8.7	0.00150				

Note: KGE – Kling-Gupta Efficiency; *t*-stat – *T* statistic test; GPI – Global Performance Indicator; *a*, *b*, *c*, *d* are empirical coefficients.

Table 2 show that the observed similarities between the models 2, 4, 5 and 6 are significant over each station, the assumption of the regional calibration coefficients obtained from these models is generally applicable. Generally, there is no peculiar change (which could be attributed to the factors such as the local climate or geographical location) in the trend of the models at individual stations (McEntee 1980). McEntee (1980) has argued that the effect of local climate, instrument siting or operational characteristics on the local calibration coefficients is only apparent if the coefficients of a particular station differ from the nearest station, and therefore concluded that the locally generated global radiation models might not necessarily be the most accurate to determine the local or regional relationship between sunshine hours and radiation. In other words, observational or instrumental error or climate factors are not significant in the variation of the coefficients generated for individual locations in this study. Overall, the sunshine based predictive models performed reasonably well than other categories of the adapted models used in this study thus, the relation of global solar radiation to the relative sunshine duration and extraterrestrial radiation cannot be over-emphasized in this temperate region.

4.2. Comparative analysis and accuracy assessment

The regional calibration coefficients were further tested over independent stations (Birr, Clones and Kilkenny) to evaluate the validity and potential of the models to estimating global solar radiation at areas where there are no available data. The comparative patterns of the estimated and observed hourly global radiation for a typical day in winter (6th December) and summer (9th June) are given in Figure 2. These periods were selected because they correspond to the periods with lowest and highest average daily sunshine hours respectively (met.ie). It was observed that the models replicated the diurnal variations of global solar radiation in the two examined dates and over all the stations when compared with the observed. However, the magnitudes of variation and lengths of day differ for different seasons due to the variations in earth's tilt about the sun and thickness of the atmosphere. The highest observed global solar radiation values during a typical day in winter were 0.54, 0.38 and 0.79 $MJm^{-2}\,hr^{-1}$ occurring at between 1200 and 1400 hr in Birr, Clones and Kilkenny respectively. Moreover, a typical summer day in June showed maximum observed global solar radiation values of 3.2 $MJm^{-2}\,hr^{-1}$ for Birr, 3.09 $MJm^{-2}\,hr^{-1}$ for Clones and 3.29 $MJm^{-2}\,hr^{-1}$ for Kilkenny at between 1300 and 1500 hr. Generally over the stations, the magnitude of global solar radiation ranged between −0.5 and 1.2 $MJm^{-2}\,hr^{-1}$ with 8 hr (between 1000 and 1700h and peak at between 1300 and 1400 hr) day length in winter, and to about 3.5 $MJm^{-2}\,hr^{-1}$ with day length of 18 hr (between 0500 and 2200 hr and peak at between 1300 and 1400 hr) in summer. In a typical winter day, all the models but models 4 and 5 showed good agreement with the distributions of magnitudes of global radiation. Models 4 and 5 underestimated global radiation especially during the early and latter hours of daylight in Birr and Clones. While models 5 and 6 underestimated in Kilkenny, model 4 overestimated the magnitudes of global radiation in winter. The variations in the performance of these models could be explained by the influence of external mechanisms such as the varying degrees of cloud

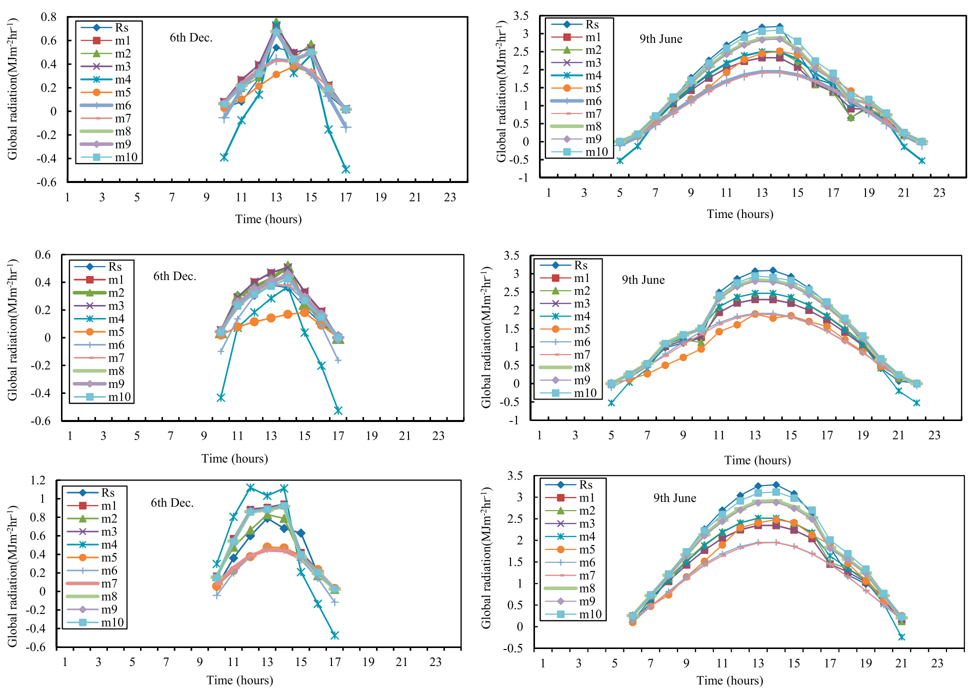

Figure 2. Comparative patterns of observed and estimated diurnal global solar radiation for typical winter and summer days over Birr (top), Clones(middle) and Kilkenny(bottom).

Note: The letter m denotes model and Rs is the observed global radiation.

cover typical of the study area which was not accounted for in the models. These disparities could also be due to the local difference in atmospheric thickness over the stations in this period. Similarly, all modelled global radiation values in summer have shown good agreement with the observed in magnitude and time. Quantitatively, the sunshine duration and hybrid models 2 and 10 seemed to be the closest to the observed in all the stations, while other models slightly underestimated the magnitudes of global radiation during the overhead hours.

To ascertain the reliability of the models over this region, statistical error indicators were used to quantify the relationship between the estimated and observed global radiation. The outputs all showed good linear relationships between the observed and estimated data in all the stations with the magnitude of R^2 ranging between 0.60 and 0.95 (Figures 3–5). Generally, the adapted models estimated the global solar radiation reasonably well over the selected independent stations with Pbias less than 30%, RMSE between 0.2 and 0.5 MJm^{-2} hr^{-1}, MAE between 0.15 and 0.35 MJm^{-2} hr^{-1} and KGE between 0.55 and 0.90. However, negative Pbias values with varying magnitudes were observed especially in models 5 and 7 in all the stations which imply underestimation of global solar radiation by these models as discussed earlier (Despotovic et al. 2015).

As reported in earlier stations used for calibration, the estimated global solar radiation by model 2 was in best agreement with the observed over all the stations with the lowest magnitudes Pbias, RMSE, and MAE and highest values of R^2 and KGE over the three stations (Table 4). Interestingly, the hybrid model 10 which was observed to show less performance in the calibration stations, performed excellently over the independent stations which reflects the effect of other climate factors on the distribution of global solar radiation in summer period as indicated in Figure 2. The best performed model, Model 2 was further compared with other recommended models (GAM and LAM; Figure 6) in the literatures (McEntee 1980; Yang and Kioke 2005). Figure (6) revealed that the proposed nonlinear hourly global solar radiation model (Model 2) in this study outperformed the recommended GAM and LAM models with the highest KGE between 0.8 and 0.9, and lowest RMSE and MAE between 0.21–0.3 and 0.15–0.22 MJm^{-2} hr^{-1} respectively over all the independent stations. Although LAM has been calibrated for Ireland, the nonlinear globally calibrated model GAM was found to be closer to the observed than the LAM as quantified by the error indicators in Figure 6. This confirms that the nonlinear relation of global solar radiation is better than the linear relation in humid areas as suggested by Yang and

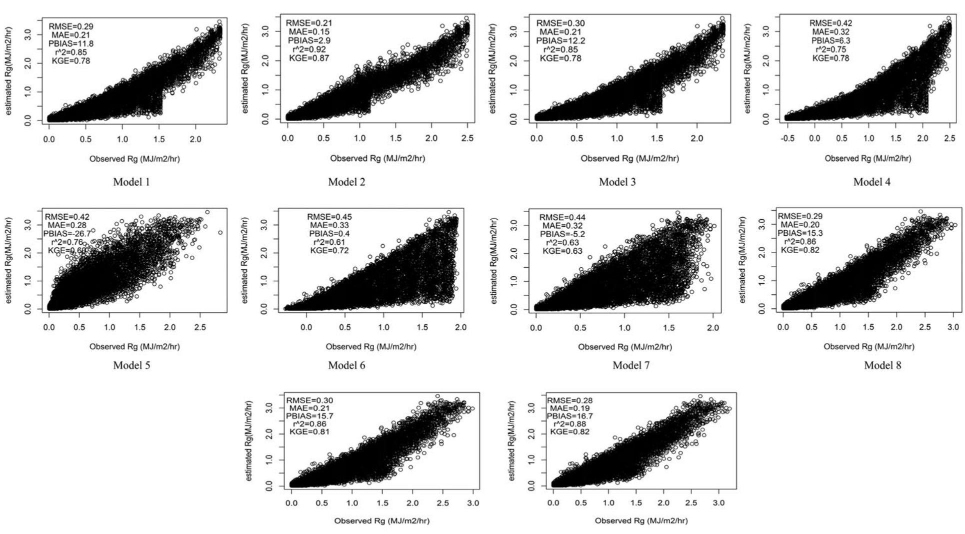

Figure 3. Relationships between the observed and estimated hourly global solar radiation for the periods between 2006 and 2007 for all models over Birr.

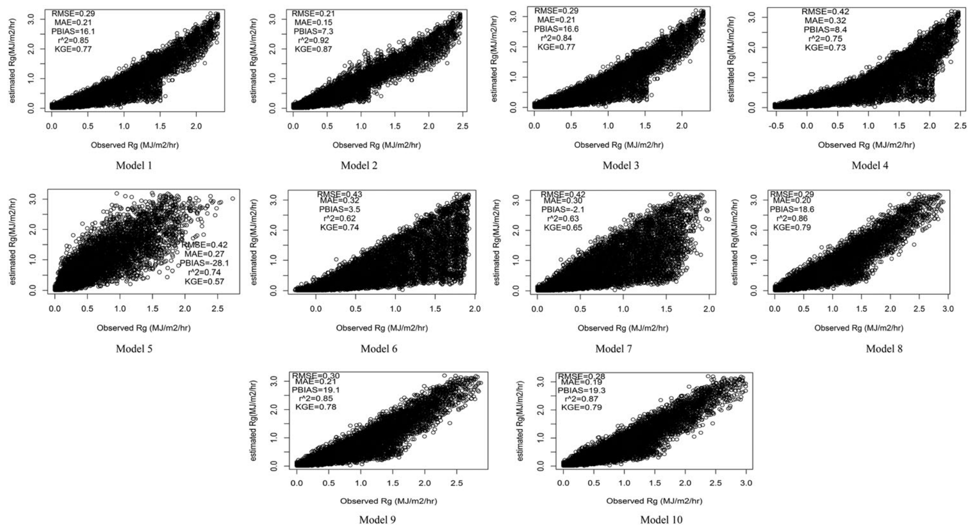

Figure 4. Relationships between the observed and estimated hourly global solar radiation for the periods between 2006 and 2007 for all models over Clones.

Kioke (2005).The underperformance of these models (GAM and LAM) in the sequel could be attributed to not only the linear relation (as in the case of LAM) but also, the bias in the empirical coefficients which were separately calibrated from hourly and daily observations; and the conditions under which they were developed.

Therefore, the generated regional calibration coefficients based on the polynomial approach of sunshine duration is recommended in this study for local or regional estimation of hourly global solar radiation. Furthermore, the coefficients generated based on the hybrid approach could also be adopted in summer to account for the effect of air temperature and relative humidity if available and inturn optimise hourly global solar radiation in a local station or the region.

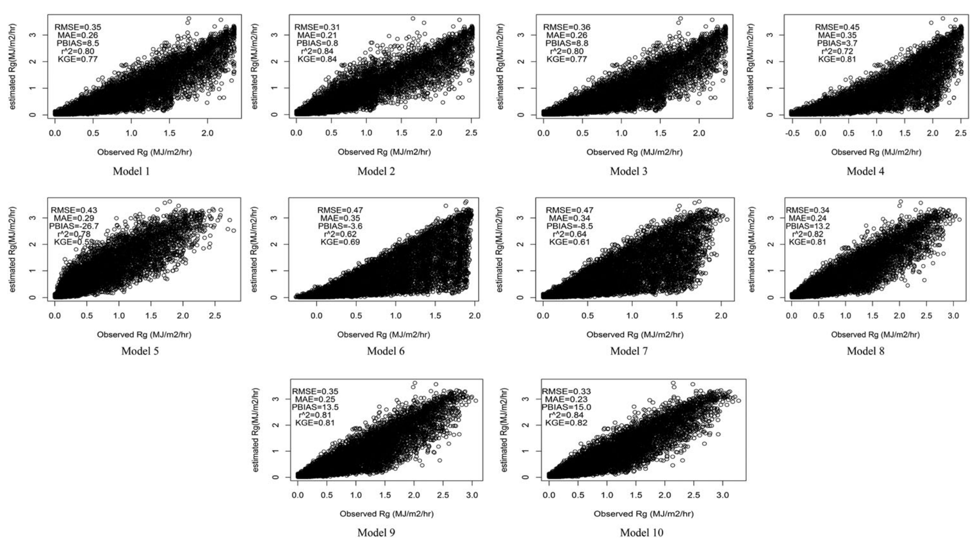

Figure 5. Relationships between the observed and estimated hourly global solar radiation for the periods between 2006 and 2007 for all models over Kilkenny.

Table 4. Validation outputs of adapted models using hourly data from 2006 to 2007 over independent stations.

		Statistical indicators				
Station	Model	R^2	Pbias (%)	RMSE	MAE	KGE
Birr	1	0.85	11.8	0.29	0.21	0.78
	2	**0.92**	**2.9**	**0.21**	**0.15**	**0.87**
	3	0.85	12.2	0.3	0.21	0.78
	4	0.75	6.3	0.42	0.32	0.78
	5	0.76	−26.7	0.42	0.28	0.6
	6	0.61	0.4	0.45	0.33	0.72
	7	0.63	−5.2	0.44	0.32	0.63
	8	0.86	15.3	0.29	0.2	0.82
	9	0.86	15.7	0.3	0.21	0.81
	10	0.88	16.7	0.28	0.19	0.82
Clones	1	0.85	16.1	0.29	0.21	0.77
	2	**0.92**	**7.3**	**0.21**	**0.15**	**0.87**
	3	0.84	16.6	0.29	0.21	0.77
	4	0.75	8.4	0.42	0.32	0.73
	5	0.74	−28.1	0.42	0.27	0.57
	6	0.62	3.5	0.43	0.32	0.74
	7	0.63	−2.1	0.42	0.3	0.65
	8	0.86	18.6	0.29	0.2	0.79
	9	0.85	19.1	0.3	0.21	0.78
	10	0.87	19.3	0.28	0.19	0.79
Kilkenny	1	0.8	8.5	0.35	0.26	0.77
	2	**0.84**	**0.8**	**0.31**	**0.21**	**0.84**
	3	0.8	8.8	0.36	0.26	0.77
	4	0.72	3.7	0.45	0.35	0.81
	5	0.78	−26.7	0.43	0.29	0.59
	6	0.62	−3.6	0.47	0.35	0.69
	7	0.64	−8.5	0.47	0.34	0.61
	8	0.82	13.2	0.34	0.24	0.81
	9	0.81	13.5	0.35	0.25	0.81
	10	0.84	15	0.33	0.23	0.82

Note: R^2 – Coefficient of determination; Pbias – Percent bias; RMSE – Root Mean Square Error; MAE – Mean Absolute Error. (RMSE and MAE are in MJm^{-2} hr^{-1}).

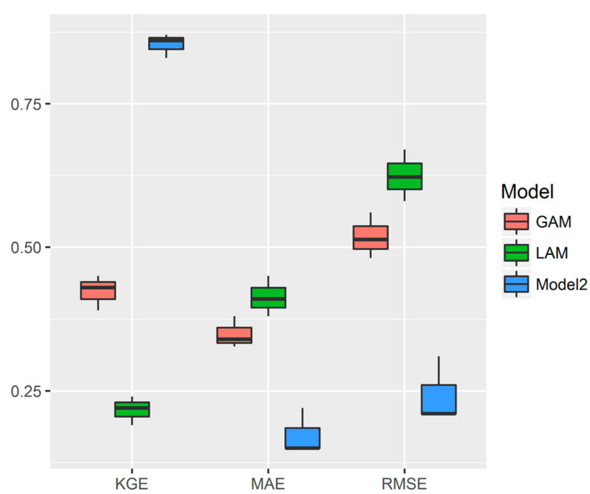

Figure 6. Boxplot of the estimated error indicators for the examined models over Birr, Clones and Kilkenny synoptic stations.
Note: RMSE and MAE are in MJm^{-2} hr^{-1}.

5. Conclusion

Attempts have been made in this study to propose empirical coefficients based on hourly climatological and extraterrestrial radiation which could be applied for local and/or regional estimation of hourly global solar radiation especially in locations where there are no available data over Ireland. A total of 10 empirical models, which were based on three categories – sunshine duration, air temperature and relative humidity, and combinations of the parameters, were adapted over 7 synoptic stations (4 stations for development and calibration, and the other 3 for validation) in Ireland. The performance of the models was evaluated using some selected error indicators including the global performance indicator which combines all other error indices for computation to avoid erroneous selection of the best model. The study found the polynomial relation of Angstrom–Prescott model (model 2) to be the most accurate predictive model for local/regional estimation of hourly global solar radiation in Ireland. Moreover, the performance of the exponential relation of Angstrom–Prescott model (model 3) was improved when the model was represented by more than a single parameter (model 10) especially in summer period, which reflects additional contribution of other climate factors to the variations of global solar radiation over the selected validation sites. Thus, the general distribution of hourly global radiation is best described by the variation of sunshine duration in this region. The performance of the adapted models was not necessarily a function of the number of input parameters that is, high number of models with various input parameters did not outperform other simpler models. Moreover, relationship between the hourly radiation and sunshine duration is not simple linear as proposed in earlier literatures thus, the generated regional calibration coefficients using polynomial approach are suggested for estimation of hourly global solar radiation in any local area in Ireland. Furthermore, the possibility of accounting for the effect of other climate variables in global radiation models cannot be totally ruled out in summer. However, the best performed hybrid model introduces various input parameters which might not be readily available in most locations in Ireland, hence the limitation of regional application of this model. Therefore, the outcome of this study will enhance the design of various solar energy applications and hydrological studies at microscale in Ireland and other temperate regions with similar atmospheric conditions. Due to its maritime environment, the distribution of global solar radiation over Island of Ireland could be influenced by a number of external factors such as amount of sky cover, airmasses and orography. The independent local/regional contributions of these factors need further investigation to improve the performance of the predictive models. The potential of artificial intelligence approaches for estimating global solar radiation over the study location also need further investigation.

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