Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

An improved technique for global daily sunshine duration estimation using satellite imagery

Muhammad Ali SHAMIM†[1], Renji REMESAN[2], Da-wei HAN[3], Naeem EJAZ[1], Ayub ELAHI[1]

(*[1]Department of Civil Engineering, University of Engineering and Technology, Taxila 47050, Pakistan*)
(*[2]Department of Geography, University of Hull, HU6 7RX, UK)*
(*[3]Department of Civil Engineering, University of Bristol, BS8 1TR, UK*)
†E-mail: ali.shamim@uettaxila.edu.pk

Received Oct. 28, 2011; Revision accepted Feb. 28, 2012; Crosschecked July 11, 2012

Abstract: This paper presents an improved model for global sunshine duration estimation. The methodology incorporates geostationary satellite images by including snow cover information, sun and satellite angles and a trend correction factor for seasons, for the determination of cloud cover index. The effectiveness of the proposed methodology has been tested using Meteosat geostationary satellite images in the visible band with a temporal resolution of 1 h and spatial resolution of 2.5 km×2.5 km, for the Brue Catchment in the southwest of England. Validation results show a significant improvement in the estimation of global sunshine duration by the proposed method as compared to its predecessor (R^2 is improved from 0.68 to 0.83, root mean squared error (RMSE) from 2.37 h/d to 1.19 h/d and the mean biased error (MBE) from 0.21 h/d to 0.08 h/d). Further studies are needed to test this method in other parts of the world with different climate and geographical conditions.

Key words: Sunshine duration, Geostationary satellite, Evapotranspiration, Solar radiation, Remote sensing
doi:10.1631/jzus.A1100292 **Document code:** A **CLC number:** TP79; TK51

1 Introduction

Due to the limited availability of relevant datasets needed to build an accurate model, hydrological modelling in data sparse catchments has always been a complicated issue. Consequently, researchers all over the world have to rely on indirect approaches for the estimation of relevant weather variables such as solar radiation. Solar radiation is a significant force not only for the hydrological cycle, but also for solar energy systems, architectural designs and the design of irrigation systems (Almorox and Hontoria, 2004). In almost all applications of solar radiation information, sunshine duration is a crucial factor (Sahin, 2007). With respect to the hydrological cycle, sunshine duration directly affects the rate of evapotranspiration, which accelerates under bright sunshine compared to no sunshine/cloud cover. Some researchers also argue that the use of sunshine duration data as a predictor helps achieving the highest degree of precision in solar radiation estimation for agricultural and hydrological studies (Trnka *et al.*, 2005), signifying its importance among other climatological variables (Kandirmaz, 2006). This fact is also illustrated by Akapabio and Etuk (2003) who used bright sunshine duration for global solar radiation estimation in Nigeria. Li *et al.* (2011) also estimated the global solar radiation for various sites in China using sunshine duration data. Sunshine duration can be used for the quality control of the global solar radiation estimation as shown by Moradi (2009). The history of the relationship developed between daily bright sunshine duration and solar radiation dates back to the early 20th Century when Kimball (1919) presented a graphical relationship between the two using data from several locations in the USA. Alternatively, Angstrom (1924) was also one of the pioneers in the development of a linear statistical formulation that was subsequently modified.

Normally, meteorological stations continuously record bright sunshine duration data despite of the continuity, and the data lacks spatial coverage as these stations are limited in number (Kandirmaz, 2006). Therefore, one has to rely upon alternative techniques for the estimation at un-gauged sites. Jervase *et al.* (2003) used the artificial neural network model for the generation of contour maps representing sunshine hours in Sultanate of Oman while El-Metwally (2005) used maximum and minimum temperatures and cloud cover fractions. Another approach that can be used for rugged terrains was also presented using a digital elevation model (DEM) to estimate the duration of sunshine (Zeng *et al.*, 2003). Kandirmaz (2006) proposed a methodology for estimating the duration of global sunshine over a number of sites in Turkey using geostationary satellite images, received at four times a day, which were then used to generate spatially continuous daily bright sunshine duration map. In this study, an improved version of the model developed by Kandirmaz (2006) was presented, incorporating a recently improved methodology developed by Perez *et al.* (2002), for the estimation of cloud cover index. It used the pixel dynamic range, external information about snow cover and effects of sun and satellite angles that were individualised for each pixel together with a time series of hourly geostationary satellites images. The results show a great improvement in sunshine duration estimation with root mean squared error (RMSE) decreasing from 2.37 h/d to 1.19 h/d as compared to the previous model.

2 Materials and methods

Geostationary satellite images are of high importance in the field of solar radiation and other illumination processes (Ineichen and Perez, 2002), since they are continuous in time and provide a spatial coverage that the ground networks cannot easily achieve. This in turn signifies their importance for predictions in un-gauged and data sparse catchments. An improved technique is hereby presented, for daily sunshine duration estimation in un-gauged catchments using geostationary satellite images, originally developed by Kandirmaz (2006).

2.1 Study area and dataset

The study is primarily focused on the Brue Catchment (51.16° N and −2.47° W), a small catchment (135 km^2) located in the southwest of England (Fig. 1). It was part of the Hydrology Radar Experiment (HYREX) project from 1993 to 2000 funded by the Natural Environment Research Council (NERC), UK. The area has a dense rain gauge network of 49, 0.2 mm Tipping Bucket type rain gauges, an automatic weather station, a Campbell-Stokes type sunshine recorder and an automatic soil water station for recording meteorological data including bright sunshine duration. In this study, the sunshine duration data for 1994 was used for training and 1995 data was used for validation. Also, hourly Meteosat geostationary images in visible band (0.6 μm), jpeg (grayscale) format and a spatial resolution of 2.5 km× 2.5 km were obtained for the same two years for the whole of UK from European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) data facility.

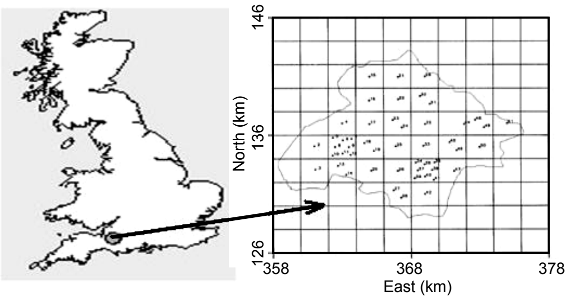

Fig. 1 The Brue Catchment, southwest of England

Key statistics for Brue Catchment are given in Table 1. The overall and seasonal variation of meteorological variables can be observed. Specifically, sunshine duration at the catchment varies from a minimum of 0.20 h to a maximum of 14.30 h, and temperature ranges from −7.88 °C to 32.47 °C. The wind speed varies from no wind to a maximum of 11.52 m/s, while the net radiation at the catchment varies from −68.96 W/m^2 to 570.52 W/m^2.

2.2 Cloud index determination

Perez *et al.* (2002) presented an evolved form of the Cano *et al.* (1986) model, whereby pixels of the image are treated as 'raw' pixels that are relative to the radiance of the earth that the satellite senses.

Table 1 Key statistics for Brue Catchment, UK*

Season	Sunshine duration (h)	Temperature (°C)	Wind speed (m/s)	Net solar radiation (W/m^2)
Spring	6.03±4.13 (0.26–14.00)	8.52±5.25 (−4.76–27.95)	1.89±1.51 (0.00075–11.52)	85.65±146.26 (−63.16–570.25)
Summer	7.14±4.61 (0.35–14.30)	16.91±8.28 (2.50–32.47)	1.22±0.94 (0–5.54)	119.86±175.74 (−57.15–561.45)
Autumn	3.80±3.12 (0.28–11.00)	11.03±4.36 (−5.48–22.89)	1.13±1.01 (0–4.76)	37.86±94.35 (−59.40–471.80)
Winter	2.17±3.42 (0.20–7.60)	5.22±6.68 (−7.88–14.00)	2.04±1.54 (0.00065–9.94)	6.69±72.61 (−68.96–332.00)
Average	4.78±3.85 (0.20–14.30)	10.43±6.34 (−7.88–32.47)	1.55±1.27 (0–11.52)	59.46±126.16 (−68.96–570.52)

* Data are expressed as mean±standard deviation (range)

Firstly, solar zenith angle cosine was used for the normalisation of raw pixels to cater for the solar geometry effect of the first order (Perez *et al.*, 2002):

$$\text{norpix} = \text{pix(am)(soldist)}, \qquad (1)$$

where ‘raw’ image pixel is represented by pix, air mass (optical) is represented by am, and soldist represents square of the normalised distance between earth and sun.

A secondary normalisation is then carried out to account for the high air mass effects leading to a fully normalised pixel ‘npix’ (Perez *et al.*, 2002)

$$\text{npix} = \text{norpix} / (2.283h^{-0.26}\,\mathrm{e}^{0.004h}), \qquad (2)$$

where h is the solar elevation in degree and is set at a minimum value of 1.5° and maximum of 65° for solar elevations outside this interval.

This fully normalised pixel was then gauged against the satellite pixel’s dynamic range (Fig. 2). The dynamic range actually represents the range of values that a normalised pixel can assume at a given location from its lowest (darkest pixel, i.e., clearest conditions) to highest value (brightest pixel, i.e., cloudiest conditions) (Perez *et al.*, 2002). Cloud index was calculated as

$$\text{CI} = (\text{npix} - \text{low}) / (\text{up} - \text{low}), \qquad (3)$$

where up and low are the upper and lower bounds of the dynamic range after reversing the secondary normalisation (Perez *et al.*, 2002). Seasonal trend correction and sun-satellite angle effect were also applied to the lower bound before the determination of cloud index. Further details can be found in (Perez *et al.*, 2002).

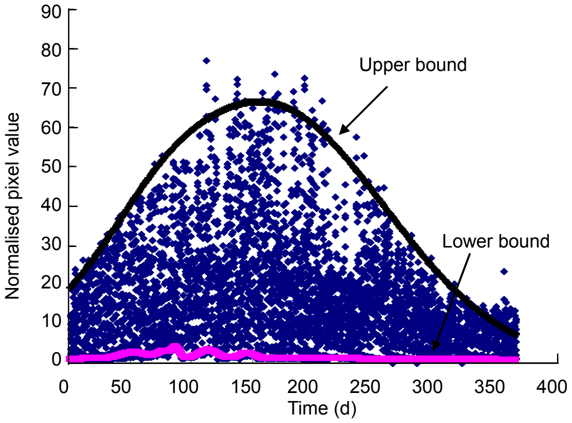

Fig. 2 Satellite pixel dynamic range

Subsequently, the mean daily cloud cover index was calculated by taking average of all cloud indices for a day using the relation (Kandirmaz *et al.*, 2004)

$$\text{CI}_\text{m} = (1/z)\sum_{k=1}^{k=z}\text{CI}_k, \qquad (4)$$

where z is the number of images per day, and CI_k is the cloud cover index for the kth image.

Kandirmaz (2006) elaborated that the cloud cover index was the amount of cloud cover per pixel and normally ranged between 0 and 1. The same applies for the mean daily cloud cover index gives information about daily cloudiness. The closer the value is to 1, the higher the cloud cover, and the more the pixel intensity with the opposite being true for values closer to zero.

2.3 Sunshine duration estimation

After the calculation of the mean daily cloud index and mean daily atmospheric transmission factor, a ratio of global solar radiation at ground to extraterrestrial radiation was calculated. To achieve that, one needs to develop a relationship between atmospheric transmission factor and cloud index. In this study, we adopted the same approach as described by Kandirmaz (2006):

$$T_\mathrm{t} = T_\mathrm{c} + \mathrm{CI}_\mathrm{t}(T_\mathrm{o} - T_\mathrm{c}), \tag{5}$$

where T_c and T_o are the clear and overcast sky transmission factors, respectively. Eq. (5) can also be written as (Kandirmaz, 2006)

$$T_\mathrm{t} = b - \mathrm{CI}_\mathrm{t} a, \tag{6}$$

where a and b give measures of cloudiness and clear sky atmospheric transmissivity, respectively, and can be derived from the regression equations. Kandirmaz *et al.* (2004) obtained a similar linear equation that relates the daily transmission factor T_d with the mean daily cloud index (CI_m) which is given by

$$T_\mathrm{d} = b - \mathrm{CI}_\mathrm{m} a. \tag{7}$$

Also, in a manner similar to cloud index, Angström (1924) related the daily transmission factor with fractional bright sunshine hours s/S by

$$T_\mathrm{d} = d + (s / S)c, \tag{8}$$

where s and S are actual daily sunshine hours and maximum possible sunshine hours (day length) respectively as estimated by the FAO (1998) procedure for the estimation of day length. c and d are the functions of seasons of the year and climate type and estimated through regression equations. Daily bright sunshine duration can therefore be estimated by relating Eqs. (7) and (8) (Kandirmaz, 2006).

The present study differs from the Kandirmaz (2006) approach in which satellite images of a finer resolution have been used for cloud index determination. Apart from this, it also utilizes external snow cover information and accounts for the sun-satellite angle effects individually for each pixel. A comparison of the two models has also been made to observe the improvement in the result.

3 Results and discussion

As mentioned above, two year hourly datasets of 1994 and 1995 were used for training and validating of the model, respectively. Using Eq. (7), a linear relationship was established between the mean daily atmospheric transmissivity and mean daily cloud index for each month using the ground measurements. Correlation coefficients for all months were greater than 0.75 and the regression coefficients (a and b) were pretty stable. A similar kind of procedure was adopted for sunshine fraction and mean daily atmospheric transmission factor. As mentioned by Kandirmaz (2006), the relationship was found to be linear. The results of the correlation and regression coefficients for both cases are given in Table 2.

Table 2 Regression coefficients for model training

Month	a	b	R^2	c	d	R^2
Jan.	−1.34	1.20	0.86	0.81	0.22	0.89
Feb.	−1.86	1.42	0.87	0.88	0.20	0.95
Mar.	−1.92	1.46	0.93	0.70	0.29	0.85
Apr.	−1.62	1.21	0.86	0.70	0.28	0.92
May	−1.62	1.27	0.91	0.70	0.32	0.92
June	−1.64	1.27	0.89	0.73	0.31	0.96
July	−1.48	1.19	0.82	0.72	0.28	0.90
Aug.	−1.44	1.13	0.79	0.88	0.24	0.92
Sept.	−1.44	1.07	0.79	0.79	0.27	0.91
Oct.	−1.84	1.21	0.82	0.80	0.24	0.90
Nov.	−1.91	1.18	0.79	0.99	0.22	0.76
Dec.	−1.82	1.18	0.90	0.79	0.24	0.78

3.1 Model validation

Model validation was carried out on 1995 dataset using the regression coefficients estimated for 1994 dataset. Sunshine duration values for all 12 months of 1995 were estimated along with statistical parameters including mean biased error (MBE), root mean squared error (RMSE) and R^2 as shown in Table 3.

It can be seen that RMSE values range from 0.66 h/d (December) to 2.31 h/d (March) while MBE values vary between −0.90 h/d (August) and 1.65 h/d (March), respectively. Also, MBE values for January to July were found to be positive, depicting overestimation for these months. Conversely, MBE values are negative from August to December showing underestimation in sunshine duration values.

Table 3 Summary of validation results of all 12 months in 1995

Month	MBE (h/d)	RMSE (h/d)	R^2
Jan.	0.40	0.87	0.85
Feb.	0.98	1.33	0.86
Mar.	1.65	2.31	0.86
Apr.	0.34	1.52	0.87
May	0.16	1.60	0.86
June	0.28	1.57	0.89
July	0.23	1.29	0.90
Aug.	−0.90	1.44	0.87
Sept.	−0.78	1.41	0.87
Oct.	−0.65	1.32	0.89
Nov.	−0.36	1.06	0.90
Dec.	−0.22	0.66	0.92

Finally, the model was compared with the Kandirmaz (2006) model that used only four images per day and did not consider snow cover information, individualised sun-satellite angle effects or seasonal trend correction for the calculation of cloud index. Note that contrary to the 7 km×7 km spatial resolution of satellite images used in (Kandirmaz, 2006), this study uses a higher spatial resolution of 2.5 km× 2.5 km for cloud index calculation. Results for this comparison for the whole year are shown in Table 4 and Fig. 3.

Both Fig. 3 and Table 4 clearly show a improvement in the estimate of sunshine duration using the proposed approach with R^2 going up from 0.68 (Kandirmaz, 2006) to 0.83, and RMSE and MBE coming down to 1.19 h/d and −0.081 h/d from 2.37 h/d and −0.21 h/d. Negative MBE values show that the model is underestimating.

Note that the aim of this study is to propose and demonstrate an improved technique for daily sunshine duration estimation. Although the results from the Brue Catchment are very positive, more sites should be explored to check how well the present technique would work in different geographic and climatic conditions.

Table 4 Result comparisons

	R^2	RMSE (h/d)	MBE (h/d)
Kandirmaz (2006)'s model	0.68	2.37	−0.21
Proposed model	0.83	1.19	−0.08

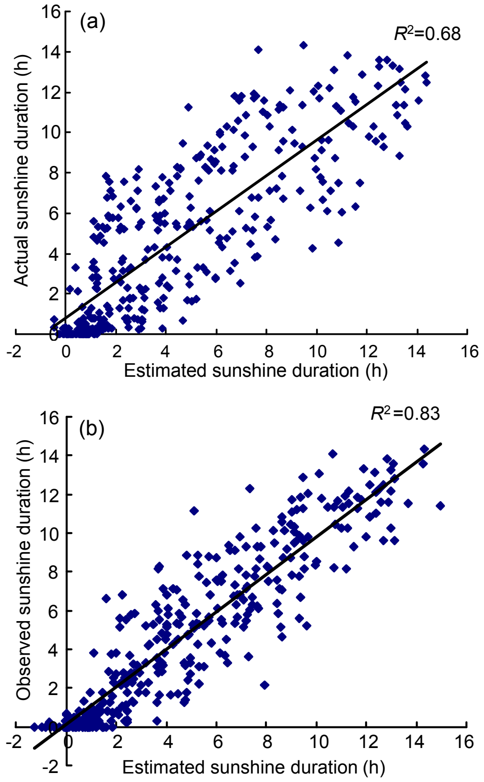

Fig. 3 Comparisons of results between Kandirmaz (2006) model (a) and proposed model (b)

4 Conclusions

An improved technique for sunshine duration estimation in un-gauged catchments is presented that takes into account snow cover information, sun-satellite angle effects and seasonal trend for cloud index calculation using geostationary satellite images, none of which were included in the previous studies. It also reiterates the fact that a linear statistical relationship between daily atmospheric transmission factor and the mean daily cloud index can be effectively used in sunshine duration estimation, which is an important factor in the regionalisation of regression parameters. In addition, the use of geostationary satellite images of a higher spatial and temporal resolution results in a further significant improvement in the estimation. This study demonstrates the effectiveness of this methodology for sunshine duration estimation in the Brue Catchment of southwest England. Further studies in other parts of UK and the world should be explored.

References

Almorox, J., Hontoria, C., 2004. Global solar radiation estimation using sunshine duration in Spain. *Energy Conversion and Management*, **45**(9-10):1529-1535. [doi:10.1016/j.enconman.2003.08.022]

Angström, A., 1924. Solar and terrestrial radiation. *Quarterly Journal of the Royal Meteorological Society*, **50**(210): 121-125. [doi:10.1002/qj.49705021008]

Cano, D., Monget, J.M., Albuissan, M., Guillard, H., Regas, N., Wald, L., 1986. A method for the determination of the global solar radiation from meteorological satellite data. *Solar Energy*, **37**(1):31-39. [doi:10.1016/0038-092X(86)90104-0]

El-Metwally, M., 2005. Sunshine and global solar radiation estimation at different sites in Egypt. *Journal of Atmospheric and Solar Terrestrial Physics*, **67**(14):1331-1342.

FAO (United Nations Food and Agriculture Organization), 1998. Crop Evapotranspiration—Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56.

Ineichen, P., Perez, R., 2002. A new air mass independent formulation for the Linke turbidity coefficient. *Solar Energy*, **73**(3):151-157.

Jervase, J.A., Al-Lawati, A., Dorvlo, A.S.S., 2003. Contour maps for sunshine ratio for Oman using radial basis function generated data. *Renewable Energy*, **28**(3):487-497. [doi:10.1016/S0960-1481(02)00035-6]

Kandirmaz, H.M., 2006. A model for the estimation of daily global sunshine duration from meteorological geostationary satellite data. *International Journal of Remote Sensing*, **27**(22):5061-5071. [doi:10.1080/01431160600840960]

Kandirmaz, H.M., Yengi Ngil, L., Pestemalci, V., Emrahoglu, N., 2004. Daily global solar radiation mapping of Turkey using Meteosat satellite data. *International Journal of Remote Sensing*, **25**(11):2159-2168.

Kimball, H.H., 1919. Variations in the total and luminous solar radiation with geographical position in the United States. *Monthly Weather Review*, **47**(11):769-793. [doi:10.1175/1520-0493(1919)47<769:VITTAL>2.0.CO;2]

Li, H., Ma, W., Lian, Y., Wang, X., Zhao, L., 2011. Global solar radiation estimation with sunshine duration in Tibet China. *Renewable Energy*, **36**(11):3141-3145. [doi:10.1016/j.renene.2011.03.019]

Moradi, I., 2009. Quality control of global solar radiation using sunshine duration hours. *Energy*, **34**(1):1-6. [doi:10.1016/j.energy.2008.09.006]

Perez, R., Ineichen, P., Moore, K., Kmiecik, M., Chain, C., George, R., Vigonla, F., 2002. A new operational model for satellite derived irradiances: description and validation. *Solar Energy*, **73**(5):307-317. [doi:10.1016/S0038-092X(02)00122-6]

Sahin, A.D., 2007. A new formulation for solar irradiation and sunshine duration estimation. *International Journal of Energy Research*, **31**(2):109-118. [doi:10.1002/er.1229]

Trnka, T., Žalud, Z., Eitzenger, J., Dubrovskŷ, M., 2005. Global solar radiation in Central European lowlands estimated by various empirical formulae. *Agricultural and Forest Meteorology*, **131**(1-2):54-76. [doi:10.1016/j.agrformet.2005.05.002]

Zeng, Y., Qiu, X.F., Miao, O.L., Liu, C.M., 2003. Distribution of possible sunshine durations over rugged terrains of China. *Progress in Natural Science*, **13**(10):761-764. [doi:10.1080/10020070312331344380]