



SCIREA Journal of Chemistry

<http://www.scirea.org/journal/Chemistry>

June 4, 2019

Volume 4, Issue 2, April 2019

Daily Variation Law of Solar Radiation Incident on the Horizontal Surface near the Ground

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Abstract:

It is important to understand the daily variation law of solar radiation flux density incident on the horizontal surface for such research and application fields as architecture, industry, agriculture, environment, hydrology, agrology, meteorology, limnology, oceanography and ecology.

However, there is not a model or theory to better explain the daily variation of solar radiation near the ground. In this study, the daily variation of solar radiation flux density incident on the horizontal surface is developed and the data investigated in Automatic meteorological station, Changwu ecoexperimental station, China is used to test the theory. The results showed that generally sky conditions is stable, and the daily dynamic of the solar radiation flux density incident on the horizontal surface near the ground is the function of time, which can be described by a normal distribution model in a day. The main parameters of the model change with date and the meteorological conditions in a day.

Keywords: Horizontal surface; Solar radiation Flux density; time; sky conditions; Daily variation model; Diurnal total solar energy; Ecological environment

Introduction

As is known to all, the amount of sunlight incident on a horizontal surface just outside the earth's atmosphere (S_i) is given by Lee(1978) and Gates (1980)

$$S_i = s_o \left(\frac{d_1}{d}\right)^2 \cos z = s_o \left(\frac{d_1}{d}\right)^2 (\sin \Phi \sin \delta + \cos \Phi \cos \delta \cosh) \dots (1)$$

$$h = \omega \times t$$

Here, S_0 is the solar constant, the ratio $(d_1 / d)^2$ is varies throughout the year, from 1.0344 on 3 Jan. to 0.9674 on 5 Jul., but is never more than 3.5% away from 1.0, and d_1 is the mean distance from the earth to the sun, which is a constant in a given place and d is the instantaneous distance at time, t , from the earth to the sun, which changes with time (day) in a year. z is solar zenith angle, and δ is the declination of the sun, and h is the hour angle of sun (angular distance from meridian of observer) . ω is angle rate of the earth moving in its orbit around the sun , and the value of ω is equal to $\pi/12$ (radian) per hour, t is time. Φ is the latitude of observer.

When the solar radiation passes through the earth's atmosphere, the solar energy is dramatically reduced and dissipated in many ways. Part of the energy is reflected and part absorbed by the atmosphere, by clouds and other masses of solid particles in the atmosphere, then by the vegetation, and finally by the earth itself. The greater the distance of atmosphere through which the sun's radiation must pass, the higher the percentage of the solar radiation that is absorbed or scattered by the atmosphere particals and not received on the Earth's surface. As the solar energy is dissipated, the radiation wavelengths are changed. The shorter ultraviolet rays are almost completely absorbed by the atmosphere. The radiation with wavelengths ranging from approximately 0.4-0.7 μ (photosynthetic active radiation) is visible to the unaided human eye and is termed light and accounts for approximately one-half of the total solar energy reaching the Earth's surface. When the sun is low on the horizon, therefore, very little ultraviolet radiation reaches the surface, and more infrared radiation reaches the earth than light. The solar radiation reaching the horizontal surface is composed of three terms, direct radiation, scattered radiation, and infrared radiation or long-wave radiation. The direct

radiation and scattered radiation only exist in the day, and the long-wave radiation exists 24 hours period of a day(Lee,1978) .

Solar radiation influences air, leaf, and soil temperature, therefore affect the life processes of plants and animals. Recently many daily changes in solar radiation reaching horizontal surfaces of the earth have been measured(Hong et al,1963; Gates G.1980; Zu, 1990;Guo and Zhang 2015). Many resources indicated that the daily changing curve of solar radiation with time is a single peaked curve with symmetry about solar noon. However, few models have been put forward to describe quantitatively the daily change of solar radiation(Hong et al,1963; Guo et al,1991; Guo 1998; Guo, Zhang, 2015;). The objective of this study is to continuously measure the total solar radiation flux density incident on the ground with high-precise equipment to obtain the quantitative characteristics of the diurnal solar radiation distribution and develop an equation to describe daily variation law of solar radiation flux density and estimate the total solar energy.

Materials and methods

Study Area and Station

The current study site is located on Hilly and gully region of Loess Plateau in the north region of China. There are fragile environment and long-term drought on the Loess Plateau.

The data used in this work was measured at Changwu Experimental Station under the China Academy of Sciences and Ministry of water Resources. It located at the juncture of Shaanxi Province and Gansu Province in the south part of Loess Plateau, China and launched in 1984. The geographic coordinate is N35°12', E107° 40', with 1200 m altitude above sea level. The soil is Helou soil and the parent material of the soil is deep mediumloam Malan Loess.The weather is warm temperate semihumid continental monsoon climate with an mean air temperature of 9.1°C and an annual mean rainfall of 584 mm, 60 % of which is from Jul. to Sep.. Frost free season is 171 days, and the water table ranges from 50 to 80 meters.

Data Collection

Daily solar radiation data came from ground measurements fixed in the experimental station. The software of MiLOS520 automatic weather station was installed in the farm land at the Changwu eco-experimental station on Loess Plateau. The data was measured with the high-

precious equipment and collected in 2005-2013. Diurnal instantaneous solar irradiance flux density (W/m^2), the stability of the diurnal cloud cover (daily variation in cloud cover), the actual measured total solar radiation are used in this study. Instantaneous solar irradiance flux density automatically was recorded once an hour from 0:00, the beginning of a day, to 24:00, the end of the day. The condition of the daily cloudy cover is observed.

Mathematical Model

In this study, the Gaussian curve is used for simulating the dynamic changes of hourly instantaneous solar irradiance flux density (W/m^2) over time (24 hours a day). General Gauss model is:

$$f(t) = \frac{dy}{dt} = ae^{-\left(\frac{t-t_0}{c}\right)^2} = ae^{-b(t-t_0)^2} \dots\dots(2)$$

- Here $f(t)$ is instantaneous solar irradiance flux density ($W/m^2.s$), t is time and t_0 is the solar noon. the value of a is the peak of daily solar irradiance flux density when time t is equal to t_0 , and c is the steepness of the curve, the curve change rate of instantaneous solar irradiance flux density. The

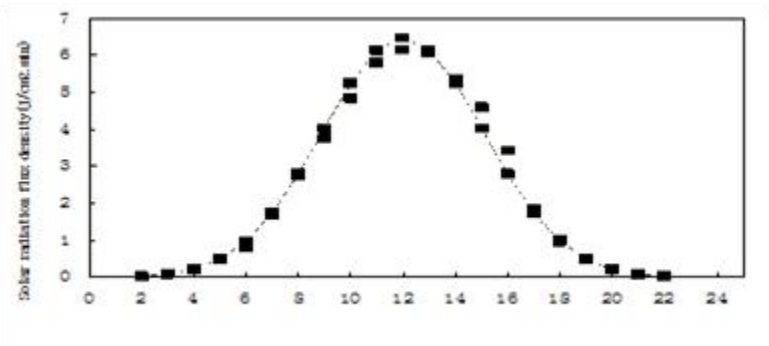


Fig.1 Diurnal change model of solar radiation flux density incident on the forest canopy in a fine day

more the c is, the smaller the b is, and the smaller the steepness of the curve is because $b = \frac{1}{c^2}$.

Because coefficient of determination reflects the weight of regression square sum in sum of squares of deviations and the more the coefficient of determination is, the higher the accuracy is, and the smaller root mean square error (RMSE) is, and the more the accuracy is. So we chose coefficient of determination, R^2 and root mean square error (RMSE) to express the fitting accuracy of equation (2).

RESULT

Daily variation law of the solar irradiances flux density

As the earth moves in its orbit, the total solar radiation flux density incident on the ground surface or the canopy of a forest takes on the daily change phenomenon, consisting of a symmetrical shape.

The amount of sunlight incident upon the Earth's surface at any point in space and time is a function of many variables. Those factors can be divided into two groups, one is based on the sky conditions, including the atmospheric and meteorological factors, while another is based on the geometric relationship between the fixed horizontal forest canopy or the ground surface and the sun. The factors are functions of time, t . When the sky conditions are constant, the solar radiation reaching a horizontal surface is the function of the geometric position between the fixed level plane and the sun, and solar radiation flux density is the only function of time, t ^{4,19}. The solar radiation flux increases nonlinearly with time t ($0 \leq t < t_0$). When time, t , is equal to time, t_0 , solar radiation flux reaches its peak. When time, t , exceeds time, t_0 , ($24 \geq t > t_0$), the solar radiation flux reduces nonlinearly with time, t , see figure 1.

The relationship between solar radiation flux density, $\frac{dw}{dt}$, and time, t , then be expressed as following

$$\frac{dw}{dt} = ae^{-bt^2} \dots\dots\dots(3)$$
$$t = t_i - t_0$$

Table 1 The change of main parameters with date in Diurnal change model of the Instantaneous Solar Radiation Incident on the Horizontal Surface in Changwu, China

The value of main parameters a , b , t_0 , R^2 and RMSE changed with time(date) and atmospheric and meteorological factors in Changwu Station is shown in Table 1 on 1-31, March, 2013. The coefficient of determination, R^2 , is more than 0.87, and RMSE is quiet smaller, showing that the equation 3 can well describe the daily change of the solar radiation flux density in a day.

The equation of the daily solar energy

Because the instantaneous solar flux density received on the horizontal surface is a successive function of time, t , throughout the day, equation 3 is integrated over a 24 hour period from 0 to 24 hour in a day. The daily total solar energy therefore can be obtained by

$$\begin{aligned} dw &= ae^{-bt^2} dt \\ w &= \int ae^{-bt^2} dt \\ w &= \int_{-12}^{12} a.e^{-bt^2} dt \dots\dots\dots(4) \end{aligned}$$

The equation is evaluated from -12 to 12 to account for the 24 hours in a day with the average $t_0 = 12$ because the value of t_0 varies from 11. 00 a. m. to 14.00 p.m, see table 1 apart from some special day in which the sky condition change dramatically. The units of a and t in the right side of equation are not unite, so a constant K is needed to unite the unit of a and t .

$$W = \int_{-12}^{12} ae^{-bt^2} dt = ak \int_{-12}^{12} e^{-bt^2} dt \dots\dots\dots(5)$$

When the unit of a is w/m^2 or J/cm^2 . min, and the unit of time is hour, then unit transformation coefficient, K , is equal to 60, so equation 3 can be rewritten as following:

$$W = \frac{2aK}{\sqrt{b}} \int_0^{12} e^{-\xi^2} d\xi = \frac{2aK}{\sqrt{b}} \int_0^{\infty} e^{-\xi^2} d\xi \dots\dots\dots(6)$$

Let bt^2 equal ξ^2 . When the time, t , tends to $\pm \infty$, ξ tends to $\pm \infty$ respectively. Then when time t is equal to 12 or -12, the value of solar radiation flux density, $\frac{D_w}{D_t}$, is so small that it can be neglected.

$$W = \frac{2aK}{\sqrt{b}} \int_0^{12} e^{-\xi^2} d\xi = \frac{2aK}{\sqrt{b}} \int_0^{\infty} e^{-\xi^2} d\xi \dots\dots\dots(7)$$

Generally, on calculating the daily solar energy, we consider the value of $\frac{D_w}{D_t}$ to be zero because when time, t , is less than -12 or greater than 12, $\frac{D_w}{D_t}$ is very smaler and approach to zero. So, Let ξ^2 equal x ,

$$d\xi = \frac{1}{2\sqrt{x}} dx$$

Because

$$\int_0^{\infty} e^{-\xi^2} d\xi = \int_0^{\infty} e^{-x} x^{-\frac{1}{2}} dx = \int_0^{\infty} e^{-x} x^{-\frac{1}{2}} dx = \frac{1}{2} \Gamma\left(\frac{1}{2}\right) = \frac{\sqrt{\pi}}{2} \dots\dots\dots(8)$$

Inserting the equation (8) into the equation (7) yields

$$W = \frac{2aK}{\sqrt{b}} \int_0^{\infty} e^{-\xi^2} d\xi = \frac{2aK}{\sqrt{b}} \times \frac{\sqrt{\pi}}{2} = aK \sqrt{\frac{\pi}{b}} \dots\dots\dots(9)$$

Here, W is the total solar energy incident on the horizontal surface or the canopy of a forest per square meter (J/m²), a and b are the same as equation 3, π is the ratio of the circumference of a circle to its diameter, and K is the unit's conversion coefficient. When time, t, expressed in hour, K is 60.

If the value of solar radiation flux density, dw/dt at time t >12 or t < -12 is so big that it can't be neglected, then Equation 10 can be used to calculate daily solar energy with progression method:

$$\int_0^x e^{-t^2} dt = x - \frac{x^3}{1 \times 3} + \frac{x^5}{2 \times 5} - \frac{x^7}{3 \times 7} + \frac{x^9}{4 \times 9} \dots\dots\dots (10)$$

It can be seen from Table 1 that the smaller the change of weather conditions in a day is, the larger the value of R is. In a fixed investigated position at the three time scales such as a year, a month, and a day, the smaller the time scale is, the more stable the sky conditions are, this is the reason why the diurnal solar radiation change with time, t, in most of days investigated in the growing seasons or a year can be described by equation 3.

Discussion

When the solar radiation flux density passes through the earth's atmosphere, the solar energy is dramatically reduced and dissipated in many ways. Part of the energy is reflected and part absorbed by the atmosphere, by clouds and other masses of solid particles in the atmosphere, then by the vegetation, and finally by the earth itself. The greater the amount of atmosphere through which the sun's radiation must pass is, the higher the percentage of the solar radiation flux density that absorbed or scattered and not received on the Earth's surface is. As the solar energy is dissipated, the radiation wavelengths are changed. The shorter ultraviolet rays are almost completely absorbed by the atmosphere. The solar radiation with wavelengths ranging from approximately 0.4-0.7 μ (photosynthetic active radiation) is visible to the unaided human eye and is termed light and accounts for approximately one-half of the total solar radiation flux density reaching the Earth's surface. When the sun is low on the horizon, therefore, very little ultraviolet radiation reaches the land surface, and more infrared radiation reaches the earth than light. The solar radiation flux density reaching the horizontal surface is composed of three terms, direct radiation, scattered radiation, and infrared radiation or long-

wave radiation. The direct radiation and scattered radiation only exist in the day, and the long-wave radiation exists 24 hours period of a day (Lee 1978) .

When author first study the change of solar radiation with time in a day, solar radiation data from the sunrise to the sunset were measured by ZD-III luxmeter, made in China, expressed in illuminance because the only measured light and recorded every two hours a day in Guyuan county in the Ningxia Hui Autonomous Region of China. Because coefficient of determination, R^2 , is a good index to reflect the degree a model describe the daily change of the total solar radiation. Although the cosine equations can be used to describe this daily change of the total solar radiation flux density, but the normal distribution equation has a higher coefficient of determination, R^2 , than that of the cosine equation. According to the analysis of the map of the diurnal change of the total solar radiation flux density incident on the ground surface, there are two possible model to describe the solar radiation flux density: the cosine equation and the normal distribution equation. Because the cosine equation can only express the solar radiation flux density from sunrise to sunset, so we decided to use the normal distribution equation to describe the diurnal change of the total solar radiation flux density incident on the ground surface and found the daily change of the total solar radiation flux density well related with and explain the diurnal change of temperature, humidity, the rate of plant photosynthesis, transpiration and evapotranspiration(Guo et al,1991) .

The luminometer has a higher response value to the solar radiation, it therefore can not be used to measure the smaller solar radiation flux density throughout the day, especially solar radiation flux density during the periods from 0:00 to the sunrise and the sunset to 24:00 in a day. Total solar radiation flux density and illuminance are related, however, approximate conversions are possible (Spurr SH and Barnes 1980; Guo et al,1991) and equation 3 can be used to describe solar radiation data from different places with different radiometer(Guo 1998).

In order to prove this, the data of the diurnal change of the solar radiation flux density measured from 5 a.m. to 18 p.m., once every hour on 18, August 1983, a fine day in Changling (44°20' N, 123° 50'E), Jilin province of China reported by Zu³ was used to prove the hypothesis. The result showed that the relationship between solar radiation flux density and time t can be described with Eq. 3 with an R value of -0.966966 (sample number, $n=14$). The solar radiation flux density was again measured from 6 a.m. to 18 p.m. once every hour on 11 July 1959, this time on a cloudy day. The daily total solar energy is 2249.7 (J/cm^2) and on 12 July, 1959, a fine day, the daily total energy is 2892.4 (J/cm^2) in Zijin mountain,

Nanjing city of China (32°05'N,118°52'E) reported by Hong and others (1963 et al.1963) and so on in different location in China, the expected results were obtained, and the values of R were -0.986369 on a cloudy day and -0.990669 on a fine day (n=13).

The amount of the instantaneous global solar radiation flux density incident on the horizontal

$$\frac{dw}{dt} = 6.476026 e^{-0.052586 t^2}$$

$$W = aK \sqrt{\frac{\pi}{b}} = 6.476026 \times 60 \times \sqrt{\frac{\pi}{0.052586}} = 3003 .3$$

surface, coming directly or indirectly from the sun, is composed of three parts, direct radiation, scattered radiation, and thermal radiation streaming downward from the atmospheric hemisphere. The former two terms exist in the daytime, but thermal radiation exists throughout a day, so the amount of the instantaneous global solar flux density always is bigger than zero in a 24-hour period.

Generally, the sky conditions are stable throughout a day, the global solar radiation flux density received on the horizontal surface is only a function of time t of a day and equation 3 can be formally described.

There are three inflection points in the daily change model of solar radiation flux density, one

$$\frac{dw}{dt} = 5.332115 e^{-0.058574 t^2}$$

$$W = 5.332115 \times 60 \times \sqrt{\frac{\pi}{0.058574}} = 2343$$

is the solar radiation flux density when the time, t , equals the solar noon, t₀, and the other two are the solar radiation flux densities at the two sides of the model. If we observed the solar radiation flux densities at the three inflection points of the daily solar radiation flux density, we can get the daily change model of the solar radiation flux density

According to Hong et al.'s report¹⁸, on a fine day, the relative error is 3.8%.

On a cloudy day, the relative error is 4.1%.

This showed that the equation 3 can be used to better describe the daily change of the amount of the instantaneous global solar flux incident on the horizontal surface and the equation 9 can be used to evaluate the the daily solar energy. The equation 9 is easy to use and has high accurate. If the equation 9 can not meet the error range, one can use equation 4 and is integrated over a 24 hour period from 0 to 24 to evaluate the daily solar energy.

Conclusion

Generally, the sky conditions are stable throughout a day, the solar radiation is the function of time t , and the daily variation law of solar radiation, the relationship between solar radiation flux density and time, t , can be described with Eq. 3, which can almost completely explain the daily change of temperature, humidity, the rate of plant photosynthesis, transpiration and evapotranspiration and the total solar energy per square centimeter is equation 9.

In fact, the sky conditions vary with time, t , in a day because of atmospheric motion, and does not completely satisfy the stable sky conditions. For this reason, the value of R always approaches to 1.0, but it does not equal 1.0. In a fixed level position or the canopy of a forest, the smaller the time scale from a year to a month or a day is, the more stable the sky conditions is, so daily solar radiation flux density change in most of the days in growing season or a year can be described by equation 3 and the total solar energy per square centimeter can be estimated by equation 9. There are three inflection points in the daily change model of solar radiation flux density. If we observed the solar radiation flux density at the three inflection points of the daily solar radiation flux density, we can get the daily change model of the solar radiation flux density. If weather conditions in a day changed dramatically, which may influence the daily change model and need to be improved. Whether the model adapt to region else is need to be further confirmed.

Acknowledgement

The author thank Professor Horton for their helps to edit the paper. This study was supported by National key R & D plan (Project No. 2016YFC0501702) and the National Science Fund of China (Project No. 41071193, 41271539).

Additional Information

The authors declare no competing financial interests

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