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PRELIMINARY STUDY ON AN ESTIMATION METHOD FOR ANNUAL SOLAR IRRADIANCE AT VARIOUS GEOGRAPHIAL ALTUTUDES

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ABSTRACT

A preliminary investigation is made into the global variation in irradiance under the Clear, the Intermediate (partly cloudy) and the Overcast sky conditions (Nakamura et. al., 1986, 1987). A formula for global irradiance is proposed as a function of solar altitude and geographical altitude (height above the sea level) under each of the conditions based on measured data. These formulae can be used to estimate the cumulative global irradiance over a year for any location given the daily sky conditions.

INTRODUCTION

The authors are involved in research on predicting solar irradiance in various locations around the world as a means of simulating the cumulative global solar energy input over a year. As solar energy is expected to become a more viable energy source in the future, methods for accurately predicting solar radiation strength and quantity are needed in order to make effective use of solar energy. One of the basic parameters for determining solar radiation is global irradiance. Although an equation for global irradiance has been proposed by other researchers, it has been proposed as a parameter of mainly only solar altitude (Duffie et al., 1991) and not geographical altitude..

Since 1991, the International Commission on Illumination (CIE) has been promoting International Daylight Measurement Programs (IDMP) for collection of basic data related to solar energy on a worldwide scale. The measurement station at the Ashikaga Institute of Technology in central Japan is one station of the IDMP. The data collected by the IDMP station in Ashikaga has proven to be useful for establishing a simulation method for anual solar irradiance.

EQUATIONS OF GLOBAL IRRADIANCE

Data measured at a fixed point of geographical altitude 59 m over a long period of time is used as a reference for the prediction formula based on geographical altitude. Eeg_{CL}, Eeg_{IN} and Eeg_{OV} are global irradiance of the Clear, the Intermediate and the Overcast sky conditions respectively. Figure 1 shows the value calculated by the following equations.

$$Eeg_{CL} = 650(\sin\frac{4}{3}h - 30) + 325 \ \ (W/m^2) \qquad (1)$$

$$Eeg_{IN} = 460(\sin\frac{4}{3}h - 30) + 230 \ \ (W/m^2) \qquad (2)$$

$$Eeg_{OV} = 110(\sin\frac{4}{3}h - 30) + 55 \ \ (W/m^2) \qquad (3)$$

h : *Solar altitude* (deg .)

The higher the solar altitude, the greater the global irradiance under the Clear and the Intermediate sky conditions. Under the Overcast sky conditions, the radiance values are significantly lower than under the Clear sky conditions, and there is little correlation with solar altitude.

Although the prediction formulae were created based on limited data and may need to be revised in the future, the formulae at the very least provide some rough trends.

This paper reports only measurement results and the proposed equation for global irradiance, but the authors are currently conducting a similar study of global illuminance, as well as solar ultraviolet radiation A and B (UV-A and UV-B).

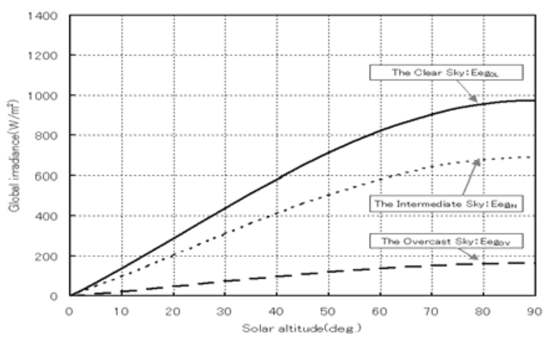

Figure 1. Calculation using Eqs. (1) to (3)

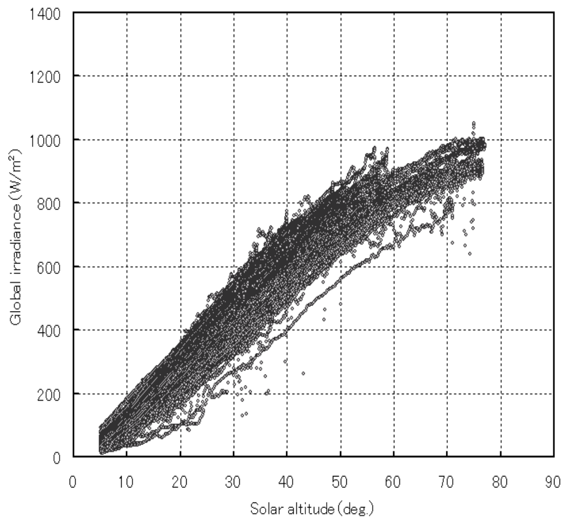

Figure 2. Measured data for the Clear sky conditions

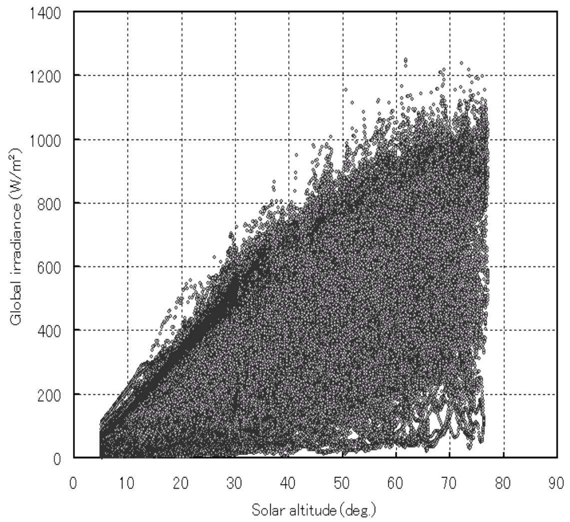

Figure 3. Measured data for the Intermediate (partly cloud) sky conditions

Table 1. Error of calculated values

	Clear sky	Intermediate sky	Overcast sky
R	0.9747	0.7056	0.5719
MBE	- 0.0419	- 0.0117	- 0.1071

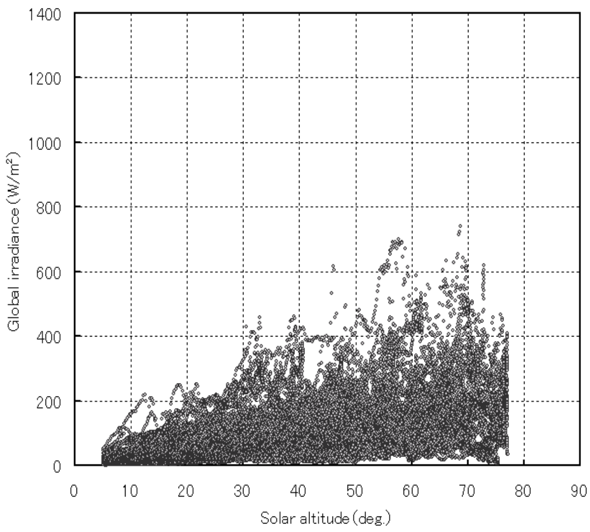

Figure 4. Measured data for the Overcast sky conditions

Figures 2 to 4 plot the measured global irradiance values against solar altitude for the three sky conditions, and Table 1 shows the error of the calculated values in comparison to this measured data.

In the table, the Pearson relative equation (R) and mean bias error (MBE) were calculated as follows.

$$R = \frac{\sum_i ((y_i - y_{ave})(x_i - x_{ave}))}{\sum_i ((y_i - y_{ave})^2 (x_i - x_{ave})^2)} \qquad (4)$$

y_i : Measured value
y_{ave} : Average measured value
x_i : Estimated value
x_{ave} : Average estimated value

$$MBE = MBE_0 / M_{ave}$$

$$MBE_0 = \sum_i \frac{C_i - M_i}{N} \qquad (5)$$

M_{ave} : *Average of all measured data*
C_i : *Estimated value*
M_i : *Measured value*
N : *Number of data*

EFFECT OF GEOGRAPHICAL ALTITUDE

The data measurement at the fixed point of geographical altitude 59 m is plentiful and reliable. The measured data shown in Figure 5 represents the approximate value for each geographical altitude. There is a distinct variation in global irradiance with altitude, and this trend was used to created a prediction formula in reference to the data obtained at 59 m, as follows.

$$Eeg_{CL} = (650(\sin\frac{4}{3}h - 30) + 325) \times (0.00008hg + 1) \quad [\mathrm{W/m^2}] \qquad (6)$$

hg : Geographical altitude[m]

The higher the geographical altitude and solar altitude, the greater the global irradiance. Figure 5 shows the values calculated according to the prediction formula together with the measured data at several geographical altitudes. Table 2 shows the error between the calculated value and the measured data of global irradiance at four locations.

Table 2. Error of calculated values

	Manali	La-Paz Titikaka Lake	Kunzum Pass	Chakrutaya
R	0.9988	0.9970	0.9982	0.9996
MBE	0.0033	0.0110	-0.0100	-0.0409
RMSE	0.0123	0.0283	0.0443	0.0419

In the table 2, the root mean square error (RMSE) is calculated by the following equations.

$$\mathrm{RMSE} = \mathrm{RMSE}_0/\mathrm{M}_{ave}$$

$$RMSE_0 = \sqrt{\sum_i \frac{(C_i - M_i)^2}{N}} \qquad (7)$$

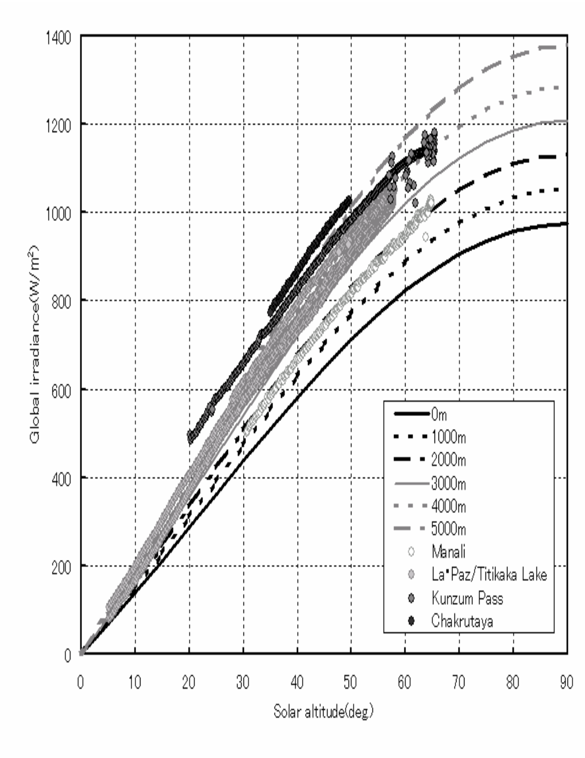

Figure 5. Predicted and measured global irradiance

ESTIMATION OF CUMULATIVE GLOBAL IRRADIANCE OVER A YEAR

The frequency of each sky condition throughout the year can be estimated from the yearly average sunshine duration for the target location using a formula proposed previously by the present authors (Nakamura et al., 1986, 1987)(Oki et al., 2002). The average sunshine duration can be easily obtained from meteorological records at almost places around the world. P_{CL}, P_{IN} and P_{OV} indicate the proportions of the Clear, the Intermediate (partly cloudy) and the Overcast sky conditions over a year, and are calculated by the following equations.

$$P_{CL} = \frac{5.689}{1.054 - \sigma/100} - 5.397 \quad (\%) \qquad (8)$$

$$P_{IN} = 100 - \frac{5.689}{1.054 - \sigma/100} - \frac{78.629}{0.551 + \sigma/100} + 56.091 \quad (\%) \qquad (9)$$

$$\mathrm{POV} = \frac{78.629}{0.551 + \sigma/100} - 50.694 \quad (\%) \qquad (10)$$

σ : Yearly average sunshine duration

The cumulative global irradiance throughout a year can then be calculated using the proportions of sky conditions above and the global irradiance equations assuming 100% of each sky condition. That is, using the following equations for each sky condition;

$$Eeg_{CLy} = \sum_{h=0}^{90} (Eeg_{CL}(h) \times ht(h)) \times (60 \times 10^{-6}) \quad (MJ/m^2) \quad (11)$$

$$Eeg_{INy} = \sum_{h=0}^{90} (Eeg_{IN}(h) \times ht(h)) \times (60 \times 10^{-6}) \quad (MJ/m^2) \quad (12)$$

$$Eeg_{OVy} = \sum_{h=0}^{90} (Eeg_{OV}(h) \times ht(h)) \times (60 \times 10^{-6}) \quad (MJ/m^2) \quad (13)$$

ht : Numbers of occurrence of each solar altitude

and multiplying by the relevant proportion of each sky condition as calculated above, gives the following formula.

$$\mathrm{Eeg}_{y} = (Eeg_{CLy} \times P_{CL}) + (Eeg_{INy} \times P_{IN}) + (Eeg_{OVy} \times P_{OV}) \quad (MJ/m^2) \quad (14)$$

The estimated irradiance and measured data are compared in Figure 6, and the relative error is shown.

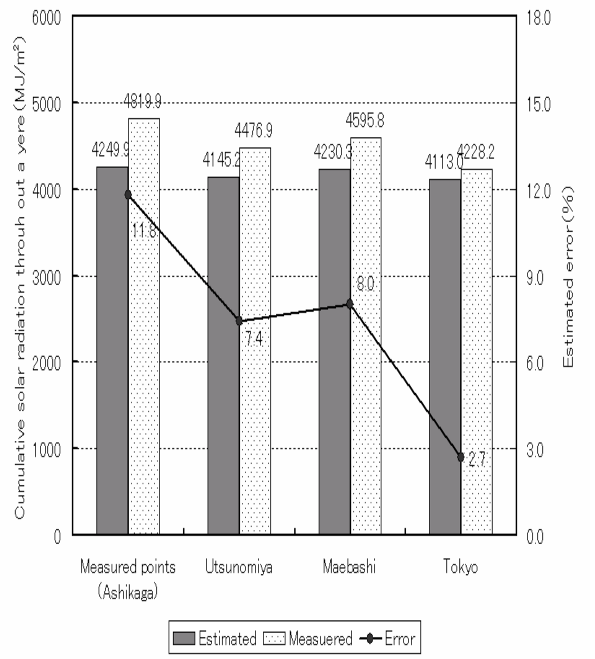

Figure 6. Estimated and measured cumulative global irradiance over a year

MEASUREMENT METHODS

Global irradiance, global illuminance and ultraviolet radiation have been measured by the authors at several locations in Japan and the rest of the world using fixed and mobile measurement systems (Shiina et al., 2001, 2002). Only the data for global irradiance is addressed in this study.

(1) Fixed measurements
Consecutive automatic measurements were taken by the Solar Radiation Automatic Measurement System installed in the "Square of Wind and Light" (latitude 36.34°N, longitude 139.40°E, altitude 49 m) on the campus of the Ashikaga Institute of Technology. The sensors of the fixed measurement system were installed on a 10 m-high measurement platform located at an altitude of 49 m.

These measurements were taken in concert with the IDMP, and measurements of global irradiance, global illuminance, UV-A, UV-B and other properties have been taken regularly since 1995.

In July 2001, the system progressed to an Internet-based weather observation system called the Net Meteorological Observatory (www.net-eko.com, powered by EKO Instruments, Japan) to allow continuation of the automatic measurements.

(2) Mobile Measurements
Mobile measurements were taken using a compact and lightweight portable solar radiation measurement system capable of automatically recording data.

MEASUREMENT LOCATIONS

Measurements were taken at various locations around the world between 1997 and 2001, including six locations in South America (Ecuador, Bolivia, and Brazil), ten locations in China, several locations in India and Europe, one site each in Nepal and Iceland, and at three mountains in Japan, with geographical altitudes ranging from 40 to 5,200 m. The present study examines selected data from Ashikaga, Mt. Akagi, Mt. Norikura, and India and Bolivia under the Clear sky conditions.

Mt. Akagi in Gunma Prefecture, Japan, has several peaks, the highest of which is 1,828 m, and also has a crater lake. The measurement points are located at geographical altitudes of 500, 950, and 1,400 m on the highest peak, the highest of which has an unobstructed view of the sky on the southern slope of the mountain. Measurements were taken simultaneously at these points in May 2001.

Mt. Norikura in Nagano Prefecture, Japan, has several smaller peaks with craters connected to the main peak (3,026 m). The Mt. Norikura Tatami-daira parking area, at an altitude of 2,702 m, is the highest point accessible by car in Japan. The measurement points are located at geographical altitudes of 1,580, 2,702, 2,570, and 3,026 m, the highest of which has an unobstructed view of the sky from the eastern slope of the mountain. Measurements were taken simultaneously at these points over a three-day period in July 2001.

The mobile measurement points at high geographical altitude in India and in Bolivia are shown in Table 3. Manali town in India is located at a mountain slope and Kunzan Pass in India is located on a mountain highway, and both points have an unobstructed view of the sky.
La-Paz is a high altitude city, Titikaka Lake is a high altitude lake and Chakrutaya is the highest ski field in the world in Bolivia. These all points have an unobstructed view of the sky.

Table 3. Mobile measurement locations in India and Bolivia

Country	Measured point	Geographical altitude (m)
India	Manali	1962
Bolivia	La·Paz	3850
	Titikaka Lake	
India	Kunzum Pass	4551
Bolivia	Chakrutaya	5200

DATA RECORDING

The major elements related to solar radiation are the latitude, longitude, and measurement date and time, which are related to solar altitude and climate, which in turn is related to sky conditions, daylight hours, the amount of cloud, and cloud conditions.

However, it is difficult to record details of the sky condition at each site, and even if recorded will change over time, thus making it impossible to record any conditions except those at the instant at which the measurement was taken. This makes it virtually impossible to accurately record mobile measurements that are taken while moving from one location to another. Thus, when taking mobile measurements, weather conditions including the amount of cloud and cloud conditions were only recorded by sight and camera.

The sky condition for the fixed measurements were recorded on the basis of records from the Kumagaya meteorological observatory located approximately 23 km south of the measurement station at the Ashikaga Institute of Technology.

CONCLUSIONS

The measured data shows that the higher the solar altitude, the greater the global irradiance under the Clear and the Intermediate (partly cloudy) sky conditions. Under the Overcast sky conditions, the radiance values are significantly lower an exhibit little correlation with solar altitude. Estimation formulae for the three sky conditions are proposed based on long-term data measured at a fixed station in Japan. In the future, these formulae should be modified taking into account the latitude, climate etc. of various locations to give a more precise estimation model that can be applied to more locations around the world.

A simple estimation method for cumulative global irradiance over a year at any location in the world was proposed using the yearly sunshine duration.

A formula for global irradiance as function of solar altitude and geographical altitude was proposed for the Clear sky condition.

$$Egl_{CL}=[650(\sin 4/3h-30)+325]x(8x10^{-5}hg+1) \quad (W/m^2) \quad (15)$$

h:Solar altitude(deg.)
hg:Geographical altitude(m)

Formulations for the Overcast and the Intermediate (partly cloudy) sky conditions are currently under investigation and will be presented in the future.

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