AN OPERATIONAL SYSTEM FOR MAPPING GLOBAL SOLAR RADIATION FROM GMS SATELLITE DATA

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ABSTRACT

A system for mapping the mesoscale insolation over large geographical areas in Southeast Asia from GMS-3 satellite data has been developed and made operational for implementation on an IBM 3083 computer at the Asian Institute of Technology (AIT). An energy balance model of the earth-atmosphere system is used in conjunction with the satellite data to estimate daily insolation at the surface. Tests of the model showed good agreement between the actual and model-derived daily insolation, with root mean square errors less than 14% of the means.

The model was implemented operationally, using satellite data display facilities and software, to compute insolation fields within the region 10°N-20°N and 98°E-105°E for the winter and the summer months of 1986 and 1987. The insolation mapping was of high quality, with relatively small spatial scale resolution at a grid point spacing of ½ degree in latitude and longitude.

INTRODUCTION

At present, there is a need to develop more complete solar information in most developing countries, particularly in the tropics, to improve analysis in solar energy applications. For example, solar information is often needed in order to help countries establish national building codes for efficient use of energy. In agricultural applications, comprehensive and accurate solar energy information is frequently required in order to predict the response of agricultural and food production systems to changes in the weather, particularly in periods of drought. Unfortunately, detailed solar information has not yet been obtained in most developing countries due to lack of pyranometric measuring sites.

An alternative solution to this problem is to derive the distribution of insolation on the surface through the analysis of images from meteorological satellites. The meteorological satellites provide extensive and frequent observations, at both the visible and the infra-red (IR) wavelengths. The earth images taken

in the visible spectrum by these satellites show the brightness of the reflected solar radiation at each point of the earth-atmosphere system, while the infra-red images show the earth-atmosphere system temperatures.

The possibility of determining insolation at the ground from satellite data was first studied by Fritz et al.¹. Methods for determining the global radiation at the surface by satellites can be separated into two main approaches: statistical and theoretical methods. Statistical methods are based on the statistical relationships between satellite data and solar radiation data measured by pyranometers on the ground. The work of Tarpley² is an example. Theoretical methods rely on mathematical calculations of the physical radiative transfer processes in the atmosphere to formulate a relationship between satellite and ground measurements. One of the best known works of this type is by Gautier et al.³ Gautier⁴ used the theoretical method mentioned to map available solar energy at a mesoscale over southeastern Canada and northern United States during April–December in 1978.

In this paper we present an operational system based on a statistical bispectral method developed at AIT in 1987⁵ for determining daily insolation in Southeast Asia.

THE STUDY AREA

The study area is bounded by latitudes 10°N and 20°N and longitudes 98°E and 105°E over the central land mass of Southeast Asia as shown in Figure 1. The study area covers most of Thailand, the southern part of Burma, the lower part of Laos, the western parts of Kampuchea and small parts of Vietnam. It extends approximately 1,120 km from north to south, and 760 km from east to west with the four main ground pyranometer sites at Bangkok (13°44'N, 100°34'E), Chiang Mai (18°47'N, 98°59'E), Ubon Ratchathani (15°15'N, 104°52'E) and Khon Kaen (16°26'N, 102°50'E) within the boundary.

METHODOLOGY

The method has been described in detail by Sorapipatana et al.⁵ and here is only summarized. The basic idea is that clouds are the main attenuators of the incoming solar radiation. The representation of cloud effects is in terms of fractional cloud amount over a given area and cloud optical thickness, which can be obtained from the infra-red and visible brightness satellite data, respectively. The fractional cloud amount and the cloud optical thickness are then combined into a single cloud parameter which statistically determines the global radiation for the given area.

Fig. 1 Location of the study area in Southeast Asia.

1. The Model

Under cloudless conditions, the visible albedo of the earth-atmosphere system as measured by the satellite is minimum A_p , while the insolation at the surface G_s has its maximum value $G_s(\text{max})$. As the sky becomes contaminated with clouds, the visible albedo with a cloud contaminated sky, A , increases and G_s is reduced to $G_s(\text{cloud})$. Since G_s is dependent on the downward extra-terrestrial solar radiation G_o , the quantities $G_s(\text{cloud})$ and $G_s(\text{max})$ are normalised to make dimensionless variables defined by the equations

$$T_p = G_s(\text{max})/G_o \quad (1)$$

and

$$T = G_s(\text{cloud})/G_o, \quad (2)$$

where T_p and T are the atmospheric transmissivities with cloudless and cloud contaminated skies, respectively.

If a fraction N of the sky over an area is contaminated with clouds, the atmospheric transmissivity over that area is assumed to be a combination of the clear and cloud contaminated sky transmissivities thus:

$$\begin{aligned} G_s/G_o &= NT + (1-N)T_p \\ &= N(T-T_p) + T_p. \end{aligned} \quad (3)$$

The relationship between the atmospheric transmissivity and the albedo of the earth-atmosphere system is calculated from the energy balance equation

$$G_o = G_R + G_A + G_G, \quad (4)$$

where G_R , G_A and G_G are the components of the downward incident energy (a) reflected upward to space, (b) absorbed in the atmosphere and (c) absorbed by the ground, respectively.

Let A_s be the surface albedo; then

$$G_G = (1-A_s) G_s. \quad (5)$$

Substituting (5) into (4), solving for G_s and normalizing G_s by G_o yields

$$G_s/G_o = (1 - G_R/G_o - G_A/G_o)/(1 - A_s). \quad (6)$$

Thus

$$T = (1 - A - G_A/G_o)/(1 - A_s) \quad (7)$$

for a cloud contaminated sky. Similarly,

$$T_s = (1 - A_p - G_A/G_o)/(1 - A_s) \quad (8)$$

for a cloudless sky. Substituting (7) and (8) into (3) and normalizing the albedo terms of (7) and (8) with respect to the clear sky albedo A_p , to compensate for ground albedo variations from area to area, yields

$$G_s/G_o = C_1 N(A/A_p - 1) + C_2, \quad (9)$$

$$\text{where} \quad C_1 = -A_p/(1 - A_s) \quad (10)$$

$$\text{and} \quad C_2 = (1 - A_p - GA/G_o)/(1 - A_s). \quad (11)$$

It was found that the atmospheric transmissivity is a simple linear function of $N(A/A_p - 1)$ provided that the variations of ground albedo A_s and relative atmospheric absorption GA/G_o are not large. We call the quantity $N(A/A_p - 1)$ the *cloud effectiveness*.

2. Determination of the Cloud Effectiveness from Satellite Data

After suitable analysis, the visible data can give information on cloud optical depth and the infra-red data can be interpreted as cloud top temperature. Furthermore, a frequency histogram of infra-red temperatures can give information on cloud amounts, provided that surface temperatures are not too variable.

2.1 Determination of the Infra-red Radiance I_p and Short Wave Albedo A_p of Cloud-free Pixels

Each element of a geostationary image (pixel) represents the satellite sensor spectral response to the energy received at the satellite. This energy corresponds to the emitted radiance or reflected solar energy from the small portion of the earth-atmosphere system viewed by the limited aperture radiometer in the infra-red and visible channels, respectively. The emitted or reflected intensity from the earth-atmosphere system is very different from cloud-covered and cloud-free areas. Thus, it is possible to distinguish pixels covered by clouds from those having no cloud contamination.

A set of stored pixel brightness measurements over a target area for a number of days at the same time of the day is examined to determine the minimum pixel brightnesses at infra-red and visible wavelengths, and hence to determine I_p and A_p .

2.2 Determination of the Cloud Contaminated Fraction N

The method used for determining the cloud contaminated fraction of the sky N over a target area follows the basic concept of Smith⁶ and Smith et al.⁷ A frequency distribution of infra-red radiances can give information on

cloud amounts. The infra-red radiance distribution of pixel brightnesses over the cloud-free target area can be assumed to be Gaussian with a mean I_p equal to the ground temperature radiance and a dispersion produced by noise, with a standard deviation σ equal to the known standard random error of measurement. When some pixels in the target are contaminated by clouds, the observed peak radiance, I , tends to be biased towards lower temperatures, and the dispersion is greater due to the increased variation of the radiances produced by the broken clouds. When the entire target area is covered with a thick uniform overcast, the dispersion is small and close to the standard random error of noise again but with the observed peak radiance having a lower temperature than with the cloud-free sky. By observing the standard deviation and the mean of the infra-red radiance distribution over the target area, one can determine the fraction of the clouds N as

$$N = (I - I_p)/(I_c - I_p), \quad (12)$$

$$\text{where } I_c = I - \sigma. \quad (13)$$

2.3 Determination of Cloud Albedo A

The cloud albedo over the target area can be determined by averaging the visible albedo of all cloud contaminated pixels over that area.

VERIFICATION OF THE MODEL

Data from the GMS-3 satellite were used for this study. The images of the whole disc observed between 2:31 and 3:00 GMT, and between 5:31 and 6:00 GMT, which correspond to 9:31-10:00 and 12:31-13:00 local time, respectively, were used. The times at which the satellite scans Southeast Asia are about 9:45 and 12:45 local time. For convenience of identification the times of the images will be called 3 and 6 GMT.

1. Model Testing

Data taken for 22 days from 26 May to 2 October 1986 were used to test and to verify the model. The test results have already been given in detail by Sorapipatana et al.⁵ and here are only summarized.

The locations of target points on each satellite image were found by a process called navigation, which projects target locations onto the corresponding pixels on the image. The satellite data taken from a 15×15 pixel array centered at each pyranometer site on the ground were then used to calculate the cloud effectiveness for the 3 GMT and 6 GMT images. (A 15×15 pixel array covers an area approximately 43km square.) The derived cloud effectivenesses at both times were then averaged to make single daily values which were then regressed against the values of daily atmospheric transmissivity measured by the pyranometers on the ground.

The pyranometer measurements at Bangkok and Chiang Mai were regressed against the satellite-derived cloud effectivenesses to determine the regression coefficients of equation (9). The derived regression coefficients were then used to predict and verify the daily insolation at the same sites and at two other sites, Ubon Ratchathani and Khon Kaen, which are several hundred kilometers from Bangkok and Chiang Mai.

The results from 13 observations in the first test (26 May–19 July 1986) and from 32 observations in the second test (21 August–2 October 1986) showed good agreement between the actual and model-derived daily insolation values with standard errors less than 14% of the means in both the tests, and with correlation coefficients 0.943 and 0.828, respectively, as shown in Figure 2.

Fig. 2 Relationship between estimated and measured daily global solar radiation. Diagonal line shows perfect agreement between pyranometer measurements and satellite estimates.

THE METHOD OF INSOLATION MAPPING

Mapping insolation over large geographical areas in Southeast Asia for long periods of time using the bi-spectral model described earlier entails an enormous amount of data processing and requires the use of relatively complex software.

Although the software was designed to handle large satellite data sets, not all data points (pixels) in the images were utilized in the calculation of daily insolations. Instead only those 15×15 pixel arrays centered on the $\frac{1}{2}$ degree grid points covering the study area were used. The aggregate of all satellite data points was very large; to include every data point in the calculation would consume excessive Central Processing Unit (CPU) time.

The procedure for producing an insolation map can be described in four discrete steps: satellite data archiving, navigation, regression and processing.

1. Satellite Data Archiving

Image data measured by the satellite are first transmitted to the satellite center in Japan where they are pre-processed and retransmitted via the satellite to users in a standard format. The images received are recorded by users on a Computer Compatible Tape (CCT) in the form of machine (ASCII) codes which allow the data to be handled in a computer peripheral system.

A satellite image of the full disk in one channel consists of $6,144 \times 6,144$ bytes. A standard reel of CCT has a capability of recording 43.2 Mbytes. Thus, one GMS full disk image in one channel containing about 37.7 Mbytes can be recorded on one reel of CCT.

Satellite images can be displayed on a Cathode-Ray Tube (CRT) terminal of an image processor in conjunction with specially designed software in a connecting computer. In this experiment, the image processor "RAMTEX", which is related to "DIMAPS", an IBM 3083 software system, was used on the Man-Computer Interaction on the image processor for data retrieval.

To apply satellite images to these display facilities, specially formatted tapes suitable only for displaying are needed. However, this format is not applicable for retrieving data for numerical manipulations. Another format is needed if numerical calculation is desired.

A visual display of the full disk is made before archiving. The area of interest is then selected and its data subset transcribed for archiving. The display is made to visually check the quality of satellite images and the general weather conditions. Poor quality images with low signal/noise values (snow images) are discarded.

2 . Navigation

Since the model uses GMS images to estimate daily insolation over a target point and to derive the average monthly insolation there, all images must be aligned geographically to the best possible accuracy. The exact correspondence between points in the image and geographical locations is determined by a navigation system. The system has already been developed at AIT and is given in full detail by Sorapipatana⁸. The system is based on the co-ordinates of grids which have been preprocessed and annotated into the images by the Japanese Meteorological Satellite Center (JMSC). The grid points are generally annotated for each 10 degrees of latitude and longitude. From a knowledge of the co-ordinates of these 10 degree grid points in terms of the number of lines and columns of the image elements the image element (pixel) corresponding to any target location at a given latitude and longitude can be found.

3. Regression of Satellite Data

The visible and infra-red data are expressed in digital counts representing the visible albedo and equivalent temperature of the earth-atmosphere system. Since the archived digital data are suitable only for displaying, the digital data recorded in the machine codes must be reformatted and converted to calculable numerical values. The data are then used to calculate the cloud parameters according to the bi-spectral model.

The locations of the pyranometric stations are first navigated, and the digital values of the 15×15 pixels centered at each of the pyranometric stations are retrieved and analysed to obtain the cloud parameters. The cloud parameters are then calibrated by regression with a set of training pyranometer data (at Bangkok, Chiang Mai, Ubon Ratchathani and Khon Kaen) using a set of subroutines.

4. Processing of Data

The first step is to extract the digital values from the visible and infra-red images at each of the ½ degree grid points over the study area (10°N–20°N and 98°E–105°E). The second step is to produce the daily insolation map. Both steps are performed by four sets of software programs as follows:

At each of the target points, the satellite images have already been navigated and reformatted. An array of 15×15 pixel brightness values centered at each point is extracted. The extracted data in the machine code are then converted to calculable numerical values. For efficiency, both steps are performed with a single software program.

The second program is to determine the minimum brightness among those mean brightness values with low standard deviations in the visible and infra-red data at each target point taken over a period of one month. The

minimum brightness is chosen as a cloud-free reference brightness according to the method mentioned earlier.

The third program is used to estimate the daily insolation at the $\frac{1}{2}$ degree grid points, except at the sea surface. The cloud effectiveness for each array of 15×15 pixels is calculated at each grid point. The daily insolation at each grid point is then predicted with the help of the bi-spectral model. The estimated daily insulations at each grid point are printed out in a table.

For ease of analysis in a climatology study, the fourth program was designed to display a map of insulations on an image processor. The estimated daily insulations at each target point are classified into 12 gray levels for display as a graphic map. Latitude and longitude labels and reference scales for the insolation gray levels are also given. The insolation map displayed on an image processor is photographed either by an electronic camera built in as a part of the image processor, or by an ordinary camera directly from the CRT terminal.

Finally, when producing averages for periods extending from weeks to seasons, running means and running standard deviations are calculated from individual daily insolation values for each of the 15×15 pixel arrays.

A summary of the main programs concerned is given as a flowchart in in Appendix I.

MAPPING INSOLATION OVER SOUTHEAST ASIA BY THE SATELLITE

To demonstrate the capability of satellites in mapping insolation, we describe in this section an application of the method to map the average daily insolation at each $\frac{1}{2}$ degree grid point, corresponding to a 54km spacing along 15°N , over the whole study area except at the sea surface. Insolation estimates were not made for the sea surface because of the difference between the nature of the surface albedo of the sea and the land; pyranometer measurements at sea would be needed to obtain the regression coefficients of equation (9) for the sea surface. Since such a pyranometer network does not exist, the regression coefficients for the sea could not be found.

The daily satellite data were sampled from 5 November 1986 to 31 January 1987 on 30 days, and from 19 May 1987 to 14 August 1987 on 31 days. Each monthly period contained 9 to 11 days of sampled satellite data. These sampled satellite data sets were used to calculate the values of daily insulations, and were then averaged for each month and for the entire 3-month winter and summer monsoon seasons. The results of the winter and summer monsoon insolation mapping are presented in full detail by Sorapipatana et al.⁹; only summaries are given here.

1. The Regression of Satellite Data with Ground Truth Data for Mapping Insolation

The regression parameters C_1 and C_2 were estimated for each month according to the model. The standard error of the regression model was found to be 5.65% of the means in the clear months to 11.58% in the cloudy months. The accuracy in the clear months is much better than in the cloudy months due to the fact that diurnal cloud cover variation in the clear months is less.

2. The Representation of Insolation Maps

The estimates of the daily insolation on the sampled days at each $\frac{1}{2}$ degree grid point were calculated as numerical values of the daily insolation in $\text{MJ m}^{-2}\text{d}^{-1}$. The calculated numerical values for the seasonal insolation maps for the winter and the summer monsoon in 1986–87 are tabulated in the Appendix.

In addition, the insolation maps are also presented as photographic prints of a checkered array of gray scale brightnesses. Mean insolation values are classified into 12 categories, ranging from ≤ 2 to $\leq 24 \text{ MJ m}^{-2}\text{d}^{-1}$. The insolation at each target is assigned to one of these categories, and the appropriate gray scale brightness is assigned to each insolation category. The lowest and highest insolation values are assigned to the darkest and the brightest levels, respectively. At the sea surface, where insulations are not determined, the brightness is assigned to be black.

Figure 3 represents a map of the grid points, coastal outlines, national boundaries, mountain contours at 450 m and Lake Tonle Sap in Kampuchea, with the checkered form superimposed. Figures 4 and 5 are the seasonal insolation maps. Horizontal and vertical scales denote longitudes and latitudes of the $\frac{1}{2}$ degree grid, respectively; a column of gray scale brightnesses is given on the right hand side of each picture for reference. Numbers on the reference scales show upper limits of values corresponding to each of the gray scale levels. For example, in Figure 4 the mean daily insolation at the grid point 17°N and 104°E is greater than $14 \text{ MJ m}^{-2}\text{d}^{-1}$ but less than or equal to $16 \text{ MJ m}^{-2}\text{d}^{-1}$ (the estimated value is actually $15.88 \text{ MJ m}^{-2}\text{d}^{-1}$).

Fig. 3 Map showing grid points for insolation estimates superimposed on geographical terrain.

Fig. 4 Map of seasonal means of daily insolation ($\text{MJ m}^{-2}\text{d}^{-1}$), winter 1986.

Fig. 5 Map of seasonal means of daily insolation ($\text{MJ m}^{-2}\text{d}^{-1}$), summer 1987.

DISCUSSION

1. The Satellite Technique's Capability in Detecting Mesoscale Insolation Variability

Insolation variability is predominantly the result of cloudiness variability; it can be large even at a relatively small spatial scale. The results of the present study clearly show that the satellite technique has the ability to detect such variations accurately even at this small spatial scale.

Figure 6 depicts a large scale topographic map with grid locations (19°N , 105°E) and (18°N , 105°E) where the local minimum insolations were found, respectively, during the winter and summer monsoons (Figures 4 and 5). The two points are separated by a mountain ridge 50km wide, and are located on opposite sides in lower ground 24 and 32 km away from the ridge. Since the observed minima occurred on the cloudy windward side of the ridge in each season, the implication is that the satellite technique can resolve spatial variations of insolation to at least within $\frac{1}{2}$ degree grid point separations. This result is particularly important for solar energy studies since the variability of insolation can now be quantified on a relatively small spatial scale in a manner not possible with any existing conventional method.

In Figures 4 and 5 it is interesting to note the effects of the Lake Tonle Sap, and the marsh areas near the lake, on the surface insolation. Here the influence of the lake and the marsh areas produced cloudiness when cold dry air masses of the winter monsoon moved over the relatively warm water of the lake and the marshes.

2. The Expected Accuracy of the Results

The results obtained here are as yet difficult to evaluate since (i) there is no mesoscale pyranometer network available in the survey region and (ii) the errors in the estimated monthly or seasonal means in the present study include errors introduced by the random sampling of days selected to calculate the monthly average. However, if daily insolation values are continuously monitored and the monthly mean is estimated from all the days of a certain month, then the random sampling errors are eliminated. Thus, the accuracy of the mapping results is expected to be the same as that of the model test and of the regression model.

In the second test⁵ the 32 observations for the bi-spectral model had mean bias error only 3% of the mean value in the estimates. (The bias error is the difference between the mean of the estimates and the mean of the actual observations.) This implies that a monthly mean of daily insolations estimated from individual daily insolation values continuously monitored by the satellite over a period of one month would give errors in the predictions not more than 3% of the mean values. This level of accuracy is commensurate with the accuracy

Fig. 6 Topographical map showing grid points 19°N, 105°E and 18°N, 105°E where the lowest insulations were often found during the winter and summer monsoon seasons.

obtainable with good pyranometric instrumentation. However, the absolute accuracy of our results must, of course, rest upon the absolute accuracy of the pyranometric measurements on the ground.

The ability to produce insolation maps daily by using a near real-time operational system with r.m.s. errors ranging from 6% of the mean in a clear month to 12% of the mean in a cloudy month is very useful in a variety of important applications. It is also possible to publish climatological summaries giving the statistical characteristics of the archived data in space and time in forms adapted to the needs of various users.

3. Prospects for Implementing the Operation System on a Small Computer System

The validation of the bi-spectral model was performed operationally to compute daily insolation on the IBM 3083 mainframe. It would obviously be desirable to have this method implemented at relatively low cost in the near future using small personal computers as dedicated processors.

At present, a daily insolation map can be produced from two scenes of data (two pairs of satellite images) by the system. Approximately one minute of CPU processing time is required for each daily insolation map on the IBM 3083 computer. This time is given as a rough estimate of computer requirements. It does not include the time spent pre-processing the images on an image processor.

It is difficult to speculate on how much CPU time would be needed if the same satellite data were to be processed on a small personal computer, since the time will vary among machines depending on their hardware configurations. However, it would take not more than one hour of CPU time for a 16-bit micro-computer with a CPU memory of 625 kbytes. Since it requires about 1.05 Mbytes to store a sub-scene image (covering only Southeast Asia) for one channel on a disk, it will take 4.20 Mbytes to store four images of two sub-scenes per day. Thus, a 5 Mbyte hard disk utilized as a secondary memory unit should be adequate for data processing.

It takes another half hour to handle and display a satellite image on an image processor in order to obtain a high degree of accuracy in the navigation. Thus, two hours are required for data pre-processing for two sub-scenes of the satellite images. Consequently, it takes a total of about three hours for the entire operation, including data handling and access, if processing is on a small personal computer system.

It is interesting to note that, except for data access and display, the development of the bi-spectral model and the navigation program in the first period of the study were performed on a small IBM-XT personal computer. Consequently, an operational system for producing daily insolation maps in

near real time by a small personal computer is expected to emerge in the near future.

The main problem is, however, data archiving. A large number of CCT tapes are required if all images received are stored and kept for reference. A solution to this problem is to produce insolation maps in near real time and to reuse the CCT tapes to record new incoming satellite images. Minimum cloud free brightnesses for each target are updated on a daily basis by comparing a new measured brightness with the stored cloud free brightness reference.

The last unsolved problem is the cost of an image processor for the *Man-Computer Interaction* system for data retrieval. The cost of the equipment and its related image processing software is still considerable in the light of the limited financial capabilities of most developing countries. Recently, a small image processing unit PERICOLOR of French design having a 1 Mbyte CPU has been developed for commercial marketing at a moderate cost (\$280,000). Because of the continuous reduction in price of special purpose image processors, it can be expected that small personal computers will be used as dedicated processors in the near future.

4 . Potential for Applications

The satellite technique will make possible the study of mesoscale variations of solar radiation over distances of 50-100 km, and of the relationships between solar radiation and synoptic-scale weather patterns of the order of 1,000 km across and persisting for several days. This will open up the possibility of issuing solar radiation forecasts¹⁰ which could become important in modern agricultural and power-generating operations.

In agriculture, solar radiation is used in models of crop growth and evapotranspiration, and for determining irrigation needs. In marine biology, a knowledge of insolation over the sea will contribute to our understanding of the growth of plankton and fish.

In architecture, solar radiation information helps engineers to make good designs for thermal insulation and shading to reduce solar heat gain and improve the efficiency of air conditioning systems in the buildings, particularly in the tropics where reliable solar radiation data are often unavailable. This will help countries to establish national building codes for the efficient use of energy in relation to the influence of solar radiation on their environment.

SUMMARY AND CONCLUSION

An attempt has been made to develop a new method suitable for developing countries in Southeast Asia for estimating daily insolation. The effort was designed to overcome the problem of data unavailability due to lack of pyranometric measuring sites. The method involves the use of the visible and infra-red data from GMS-3 to obtain cloud effectiveness to estimate the incoming solar radiation. The model was tested with a set of four pyranometers on the ground. The results showed good agreement between the actual and satellite derived daily global radiation with r.m.s. errors less than 14% of the means.

Moreover, in a second longer period of study, the accuracy was found to be better than in the first period of study, with the r.m.s. errors of daily global radiation ranging from 6% of the mean in a clear month to 12% of the mean in a cloudy month. This accuracy is adequate for most agricultural and solar energy applications.

The technique has been used to map insolation over large geographical areas of the region. This is possible because the operational system has been developed for implementation on an IBM 3083 computer. The system includes: (i) satellite data display and editing facilities, (ii) expertise in the navigation of satellite imagery and regression of satellite data, (iii) a library of software developed for the IBM 3083 to process satellite imagery. Although at present the insolation mapping has not yet been performed by a small personal computer system, this can be expected to happen in the near future.

Finally, the capability of daily insolation mapping from satellite measurements has been demonstrated. The method has been implemented operationally and has been used to compute insolation fields over the region for the winter and the summer months of the years 1986-87. The insolation mapping results obtained were of high quality, with relatively small spatial scale resolution. At the moment, the accuracy of the mapping results obtained is still difficult to evaluate due to the absence of mesoscale pyranometer networks in this region. Nevertheless, the results are expected to be credible based on the previous model tests and on the quality of the regression between satellite derived parameters and the pyranometric data.

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REFERENCES

1. Fritz, S., Rao, P.K. and Weinstein, M. Satellite Measurements of Reflected Solar Energy and the Energy Received at the Ground. *J. Atmos. Sci.*, 1964, **21**, 141-151.
2. Tarpley, J.E. Estimating Incident Solar Radiation at the Surface from Geostationary Satellite Data. *J. Appl. Meteor.*, 1979, **18**, 1172-1181.
3. Gautier, C., Diak, G. and Masse, S. A Simple Physical Model to Estimate Incident Solar Radiation at the Surface from GOES Satellite Data. *J. Appl. Meteor.*, 1980, **19**, 1005-1012.
4. Gautier, C. Mesoscale Insolation Variability Derived from Satellite Data. *J. Appl. Meteor.*, 1982, **21**, 51-58.
5. Sorapipatana, CH., Exell, R.H.B. and Borel, D. A Bispectral Method for Determining Global Solar Radiation from Meteorological Satellite Data. *Solar Wind Technol.*, 1988, **5**, 321-327.
6. Smith, W.L. An Iterative Method for Reducing Tropospheric Temperature and Moisture Profiles from Satellite Radiation Measurements. *Mon. Weath. Rev.*, 1967, **95**, 363-369.
7. Smith, W.L., Rao, P.K., Kolfler R. and Curtis, W.R. The Determination of Sea-surface Temperature from Satellite High Resolution Infra-red Window Radiation Measurements. *Mon. Weath. Rev.*, 1970, **98**, 604-611.
8. Sorapipatana, CH. Mapping Solar Radiation over Southeast Asia by Meteorological Satellite Images. Doctoral Dissertation, Asian Institute of Technology, Bangkok, 1988.
9. Sorapipatana, CH. and Exell, R.H.B. Mesoscale Mapping of Average Daily Insolation Derived from Satellite Data over Southeast Asia. Submitted for publication to *Solar Wind Technol.*
10. Exell, R.H.B. Mapping Solar Radiation by Meteorological Satellite, *Renewable Energy Rev. J.*, 1984, **6**, 27-39.

APPENDIX I

Flowchart of Computer Programs

APPENDIX II

Winter's Seasonal Means of Daily Insolation ($\text{MJ m}^{-2}\text{d}^{-1}$) 1986

Long.	98.0E	98.5E	99.0E	99.5E	100.0E	100.5E	101.0E	101.5E	102.0E	102.5E	103.0E	103.5E	104.0E	104.5E	105.0E
Lat.															
20.0N	14.55	13.89	13.15	13.60	14.34	13.73	12.56	12.21	11.65	12.00	13.06	12.14	10.22	8.28	7.57
19.5N	13.92	13.41	12.53	12.19	14.28	13.55	12.73	12.01	12.57	12.59	11.81	10.35	8.37	6.76	6.10
19.0N	13.72	12.95	13.90	12.81	13.93	13.88	14.90	12.80	13.05	13.44	12.77	12.94	11.18	7.03	5.21
18.5N	14.20	13.61	15.27	14.99	15.13	14.91	15.27	13.56	14.38	14.74	13.36	14.53	15.28	12.85	8.50
18.0N	14.15	14.37	14.67	15.47	16.05	15.28	15.46	14.93	14.35	15.39	15.86	15.70	15.92	15.55	14.45
17.5N	15.88	14.62	14.62	15.73	16.58	16.53	15.08	15.83	15.99	16.25	16.38	16.11	16.46	16.36	15.50
17.0N	16.76	16.02	15.69	16.77	17.01	17.03	16.55	16.22	15.81	16.37	16.54	16.52	15.88	16.10	16.55
16.5N	16.91	16.60	15.88	16.81	17.16	17.41	16.71	16.00	15.92	16.91	16.86	17.11	17.27	16.14	15.76
16.0N	17.80	16.98	15.39	16.43	17.33	17.63	17.93	17.33	17.06	17.07	17.20	17.26	17.11	17.25	16.13
15.5N	17.75	16.98	15.44	15.58	17.08	17.25	17.63	17.34	17.43	17.20	17.31	17.35	17.22	17.06	16.92
15.0N	17.72	16.99	15.83	15.53	17.22	17.79	17.50	17.30	17.91	17.27	16.75	16.65	16.56	17.07	16.97
14.5N	17.79	16.86	16.38	16.37	17.59	17.59	17.68	15.75	15.73	16.84	16.86	16.87	15.77	15.76	15.87
14.0N	16.61	17.95	15.69	17.32	17.44	17.29	17.98	18.44	18.08	16.79	17.15	16.31	15.09	15.35	15.93
13.5N	16.03	17.18	15.87	16.94	16.89	17.60	18.44	18.06	17.10	17.18	17.59	16.61	16.21	15.38	15.79
13.0N	99.00	99.00	17.07	15.56	15.76	99.00	17.21	17.84	17.33	15.52	16.05	15.68	14.38	15.43	16.15
12.5N	99.00	99.00	18.46	16.35	99.00	99.00	99.00	99.00	99.00	16.38	14.36	13.27	15.54	15.31	15.80
12.0N	99.00	99.00	16.47	16.96	99.00	99.00	99.00	99.00	99.00	99.00	16.13	13.35	13.94	14.91	16.10
11.5N	99.00	99.00	15.19	16.82	99.00	99.00	99.00	99.00	99.00	99.00	15.57	15.21	14.22	15.48	15.70
11.0N	99.00	99.00	15.60	16.20	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	15.88	15.18	16.33
10.5N	99.00	15.35	14.66	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	16.53	16.05
10.0N	99.00	99.00	13.79	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00

Remarks: 99 indicates the calculation was omitted for the grid points at the sea surface.

APPENDIX III

Summer's Seasonal Means of Daily Insolation ($\text{MJ m}^{-2}\text{d}^{-1}$) 1987

Long.	98.0E	98.5E	99.0E	99.5E	100.0E	100.5E	101.0E	101.5E	102.0E	102.5E	103.0E	103.5E	104.0E	104.5E	105.0E
Lat.															
20.0N	17.05	15.69	14.28	14.59	16.20	15.51	13.15	12.82	13.85	15.93	16.20	15.00	15.05	15.96	16.44
19.5N	14.08	13.40	13.68	14.25	16.23	15.20	14.57	13.38	14.31	16.06	15.95	15.18	16.24	16.27	16.74
19.0N	14.14	14.03	14.62	13.72	15.35	15.98	15.72	15.64	15.17	14.77	13.53	14.54	13.91	15.12	16.30
18.5N	12.18	13.34	16.55	15.32	15.88	16.88	16.24	15.83	15.22	15.77	14.18	14.06	11.73	12.76	12.67
18.0N	13.77	15.19	16.25	16.38	17.18	17.23	16.38	15.76	15.60	15.27	15.98	14.73	14.59	12.44	10.86
17.5N	11.87	13.83	16.37	16.94	18.25	17.99	15.93	16.88	15.84	15.98	16.21	16.47	15.97	15.44	12.57
17.0N	13.35	14.45	16.31	18.13	18.59	17.86	17.13	15.94	16.16	17.11	16.74	15.46	15.49	15.88	15.55
16.5N	13.90	15.34	16.57	17.93	18.93	18.88	17.58	16.26	16.63	17.63	17.42	17.30	17.96	17.80	17.02
16.0N	15.00	15.49	16.12	17.96	18.78	18.93	18.86	17.61	17.69	18.20	17.72	17.72	17.19	17.40	17.37
15.5N	14.37	14.96	15.65	17.27	18.55	18.62	18.70	18.68	17.97	18.36	17.36	17.35	17.14	17.43	18.08
15.0N	13.88	14.31	13.79	17.36	17.91	18.18	17.95	17.89	18.49	17.74	16.97	18.15	18.02	17.49	18.01
14.5N	13.43	13.81	15.13	17.20	18.30	18.82	18.57	17.67	16.67	16.39	16.74	18.40	18.30	17.56	16.50
14.0N	13.99	14.10	15.74	17.12	17.73	17.35	16.84	16.59	17.22	16.94	17.27	17.57	17.64	16.83	16.51
13.5N	11.91	14.55	13.38	15.98	16.48	16.50	17.48	17.84	17.73	16.56	16.91	17.43	17.85	16.99	17.52
13.0N	99.00	99.00	13.16	14.85	15.86	99.00	16.56	15.34	15.16	15.53	17.30	17.62	17.87	18.16	17.43
12.5N	99.00	99.00	15.29	14.05	99.00	99.00	99.00	99.00	99.00	14.25	15.38	17.20	18.50	17.51	15.97
12.0N	99.00	99.00	14.97	14.79	99.00	99.00	99.00	99.00	99.00	99.00	12.49	13.19	15.50	17.16	17.96
11.5N	99.00	99.00	15.79	15.85	99.00	99.00	99.00	99.00	99.00	99.00	12.58	11.58	13.72	16.82	17.39
11.0N	99.00	99.00	16.70	17.48	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	13.17	16.37	16.93
10.5N	99.00	16.68	16.66	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	15.29	15.37
10.0N	99.00	99.00	16.87	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00

Remarks: 99 indicates the calculation was omitted for the grid points at the sea surface.