

A METHOD FOR THE DETERMINATION OF THE GLOBAL SOLAR RADIATION FROM METEOROLOGICAL SATELLITE DATA

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Abstract—A statistical method is presented for the determination of the global solar radiation at ground level. It makes use of data from the meteorological satellites, which provide extensive coverage as well as adequate ground resolution. In the first step, a reference map of ground albedo is deduced from the time-sequence of satellite images. Then, by comparing the satellite data with the computed albedo map, a cloud coverage index is determined for each ground point of $5 \text{ km} \times 5 \text{ km}$. This index is linearly correlated to the atmospheric transmission factor. The regression parameters are estimated using a training set provided by ground pyranometers. Tests for two different time periods show a good agreement between the actual and model-derived hourly global radiation.

1. INTRODUCTION

Though the global radiation measurements network in developed countries is still in progress, the average distance between stations in Europe is about 100 km and is thus too large for the current applications of solar meteorology. In many other parts of the world the networks are even sparser, especially over the oceans.

On the other hand, meteorological satellites provide extensive and frequent observations of the earth-atmosphere system, both in the visible and infrared wavelengths. The ground resolution depends upon the satellite sensor and the latitude of measurements, and varies from 1 to 5 km; the period of observations ranges from 30 minutes to 12 hours.

Adequate processing of these data provides a wealth of information useful in the production of solar energy indices, particularly for those areas where no traditional means of observation are available. Besides their usefulness in solar energy engineering, such global radiation atlases provide new scientific information. For example, they can be used in climatology studies which require accurate data on the ocean heat flux balance, in which the sun radiation plays a major role.

Both the Solar Energy R&D of the Commission of the European Communities (Project F) and the Agence Française pour la Maîtrise de l'Énergie (AFME) are involved in the determination of global radiation using satellite data. This paper presents the work carried out by the authors under these auspices.

Methods for estimating the global radiation at ground level using satellite data can be divided in two categories: a statistical approach based on re-

lations between satellite and ground data and a physical approach using radiative transfer models to formulate a relationship between satellite and ground measurements.

While more likely to be precise when applied to small areas, statistical methods are usually less general and require comparison with ground data. The work of Tarpley[1] is perhaps the best known of these methods. On the other hand, physical methods use simple models, because satellites only measure a few parameters among the many that govern radiative transfer. The best known methods are certainly those of Raschke, Preuss[2] and Gautier *et al.*[3].

The approach now developed here is of a statistical kind. A training set of ground data is required to determine the parameters of the regression model, which in turn will predict the global radiation. The basic idea of this method is that the amount of the cloud cover over a given area statistically determines the global radiation for that area. Thus, the processing is divided in two steps. A cloud cover index is first derived for each location (i, j), called a pixel, of the original satellite image and subsequently used in a second step for a statistical estimation of the global radiation.

In preparation to the determination of the cloud cover index, a reference map of the planetary albedo for clear sky is constructed and updated daily. The cloud cover index map is then derived from the comparison of the current satellite image and the reference albedo map. Following this determination, the atmospheric transmission factors are computed using pyranometric data and a statistical regression between these factors and the cloud cover index at the same locations is then performed. Finally, the global radiation map is computed on a refined grid using an interpolation technique between ground stations.

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2. SATELLITE DATA

The basic remote sensing data are taken from the geostationary satellite Meteosat observations, both in the visible and the thermal infrared spectral ranges. Each satellite image is preprocessed using geometric correction with landmark correlation, noise filtering, and normalization of digital counts by the direct spectral irradiance which would be measured on an horizontal plane located at each pixel under a clear sky.

Because the digital counts can be directly related to the upward radiance, this normalization is equivalent to the computation of a bidirectional reflectance factor. Furthermore, since most continental surfaces may be considered as lambertian for the observation angles under concern (except for water and snow) within a small error, the transformation is equivalent to the computation of an image of the albedo of the system clear sky-ground (planetary albedo for clear sky) with variable cloudiness. For convenience the planetary albedo for clear sky will be called reference albedo in the following. In fact, the exact relationship between the upward radiance and digital count is unknown, because the satellite Meteosat has no calibration. However, the term albedo will be used for convenience.

3. CONSTRUCTION OF THE REFERENCE ALBEDO MAP

Generally, the cloud albedo is greater than the ground albedo, except over snow and some desert soils. Usually, one makes use of this fact in the construction of the reference albedo map by assuming that, given a satellite image time-series, the clouds are nonstationary and that the minimum value observed at each pixel will provide a reference albedo map.

In this method, the construction of the albedo map is based on the fact that, if the cloud albedo is greater than the reference albedo, then in a time series of satellite images, the appearance of a cloud in the field of view of the sensor will result in increased measured radiance. Cloud detection can thus be performed by the difference between the cloud induced response and the corresponding signature of the ground under a clear sky.

After the clear sky model of Bourges[4], the global radiation at ground G_c at instant t is:

$$G_c(t) = I_0(\sin \nu)^{(1+a)}, \quad (1)$$

where I_0 is the extraterrestrial solar irradiance for the day under concern, normal to beam multiplied by 0.7; and ν is the elevation of the sun.

The parameter a characterizes the total atmospheric transmittance and ranges between 0.14–0.17 depending upon the geographical location[4].

In this work, a value of 0.15 has been chosen and therefore the irradiance measured by the satellite sensor in absence of clouds and coming from

the system clear sky-ground of albedo $\rho(t)$ may be expressed by the following:

$$E(t) = \rho(t)I_0(\sin \nu)^{1.15}. \quad (2)$$

The various terms of this formula are considered as random variables, in order to take into account the approximate character of the clear sky model and the instrumental noise. The reference albedo is evaluated at each pixel in a recursive fashion by minimizing the variance of the difference between the measured radiances and the radiances resulting from the clear sky model, the cloudy cases being eliminated at each step.

Under some assumptions, this way of estimating the ground albedo can be justified mathematically[5]. It is assumed that the reference albedo is a stationary random variable ρ_g of mean $\bar{\rho}_g$ and variance σ_g^2 , and that the cloud albedo is a stationary random variable ρ_c of mean $\bar{\rho}_c$ and variance σ_c^2 . If the apparent albedo is a stationary random variable X equal to ρ_g (reference albedo) with a probability P_g and equal to ρ_c (cloud albedo) with a probability P_c , it can be shown that the iterative minimization of the variance of the difference between the observed and clear sky model radiances is equivalent to an iterative computation of the mean \bar{X} of the variable X , with elimination of the cloudy pixels at each step.

$$\bar{X} = P_g \rho_g + P_c \rho_c. \quad (3)$$

This convergence property is met if the difference between the means $\bar{\rho}_g$ and $\bar{\rho}_c$ is much larger than the standard deviation σ_g and larger than σ_c :

$$\begin{aligned} \bar{\rho}_c - \bar{\rho}_g &\geq \sigma_g \\ \bar{\rho}_c - \bar{\rho}_g &> \sigma_c. \end{aligned} \quad (4)$$

In the case of cloud discrimination, those conditions are typically fulfilled, and the iterative average \bar{X} converges to the mean ground albedo value $\bar{\rho}_g$. Two important exceptions are snow and some desert surfaces.

The method is illustrated in Fig. 1, which shows the reference albedo map of Europe obtained from ten Meteosat images of May 1979. Of course, if a cloud layer remained stationary in the time-series, the model hypotheses are not fulfilled, and the apparent albedo is the albedo of the cloud, as it is the case over Ireland in Fig. 1. A second example of satellite derived reference albedo map is given in Fig. 2, which relates to the western central part of Africa for the last days of January 1984.

4. EVALUATION OF THE CLOUD COVER INDEX

The cloud cover index $n'(i, j)$ at point (i, j) for given time t is defined as a function of the characteristic reference albedo $\rho(i, j)$, the apparent al-

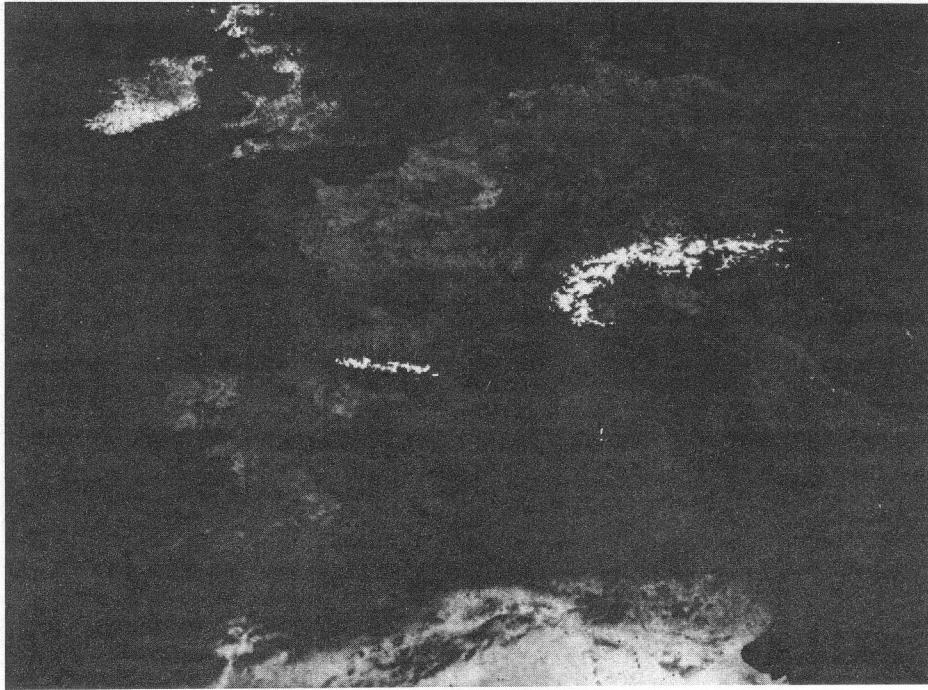


Fig. 1. Map of the reference albedo of Europe obtained from Meteosat data for May 1979. The albedo value increases from black to white. Because the sky was always cloudy over Ireland, the local albedo is very high, and does not represent the ground albedo.

bedo at the same point as measured by the satellite $\rho'(i, j)$, and the average albedo of the cloud tops ρ_c . It is computed for each pixel using the following formula:

$$n'(i, j) = (\rho'(i, j) - \rho(i, j)) / (\rho_c - \rho(i, j)). \quad (5)$$

The reference albedo of the Europe area is determined in the previous step for each $5 \times 5 \text{ km}^2$ pixel of the Meteosat image by iterative detection and elimination of cloudy areas. The computation of cloud albedo, ρ_c , is performed using the inverse of the previous algorithm retaining only the cloudy areas. The histogram of this "only cloud" image provides an estimation of ρ_c using mode computation.

This cloud cover index ranges from 0 to 1 and can be interpreted as the percentage of the cloud cover per pixel. It also provides an indicator of the transmission of an atmospheric column above the pixel, with low values corresponding to a high transmission factor.

The cloud cover index determination relies on a reliable reference albedo map, which is affected by seasonal variations. In order to take these variations into account, the reference albedo map is updated during the processing by weight averaging a new cloud-free pixel with previously determined cloud-free pixels.

However this method does not perform properly when the reference albedo is of the same order of magnitude as the albedo of the clouds. Over Eu-

rope, this is specifically the case over snowy areas. In this case, Cano[5] proposes that an alternate cloud index is defined using the radiance $R^+(i, j)$ measured by the satellite in the thermal infrared spectral band:

$$n''(i, j) = (R^+(i, j) - R_s) / (R_c - R_s), \quad (6)$$

where R_c is the radiance of the clouds, and R_s the radiance of cloud-free snow areas, both determined using image histogram in the thermal infrared. However no further study of this alternate approach was performed. In this case the cloud index may become negative in case of temperature inversion in the lower atmosphere. Also there must be an objective procedure to decide which of the two approaches should be adopted. None of these problems is presently addressed and the method here described does not use this alternative.

5. STATISTICAL RELATIONSHIP BETWEEN CLOUD COVER INDEX AND GROUND MEASURED TRANSMISSION FACTOR

The method uses linear regression between the satellite determined cloud cover index and the ground measured transmission coefficient. This simple and efficient approach is based on previous work from Bourges[4], and correlations coefficients determined by Pastre[6] between sunshine duration and cloud cover index.

The total atmospheric transmission factor $K(i, j)$

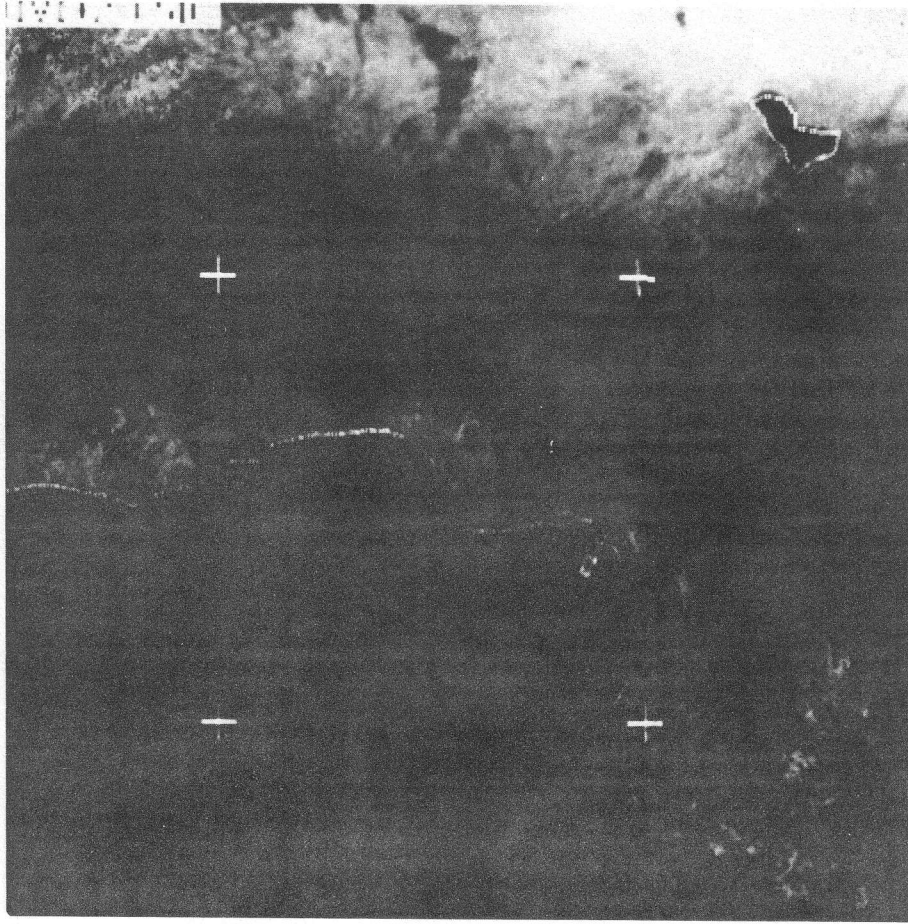


Fig. 2. Map of the reference albedo of western Central Africa, obtained from Meteosat data received in WEFAX format for the last days of January 1984. The albedo increases from black to white.

is defined as the ratio of global radiation at ground on a horizontal surface $G(i, j)$ to the horizontal irradiance outside the atmosphere $G_0(i, j)$:

$$K(i, j) = G(i, j)/G_0(i, j). \quad (7)$$

This quantity ranges typically from 0.2 to 0.8. If one interprets the cloud cover index $n'(i, j)$ as the percentage of pixel covered by clouds, the global ground irradiance at time t is expressed as a linear combination

$$G'(i, j) = n'(i, j)G_b(i, j) + (1 - n'(i, j))G_c(i, j), \quad (8)$$

where G_b and G_c are the global ground irradiance for overcast and clear skies, respectively.

For each of these extreme conditions, one can define a transmission factor, respectively K_b and K_c , which is supposed to be constant for a given hour. This realistic hypothesis leads to the following linear relation:

$$\begin{aligned} K'(i, j) &= n'(i, j)K_b(i, j) + (1 - n'(i, j))K_c(i, j) \\ &= n'(i, j)(K_b(i, j) - K_c(i, j)) + K_c(i, j) \\ &= a(i, j)n'(i, j) + b(i, j). \end{aligned} \quad (9)$$

In order to test the linear relationship between the cloud cover index and the total transmission factor, measurements of hourly global irradiation during May 1979, provided for 27 French stations by the French Meteorological Office, were reduced to transmission factors and compared to the closest $5 \times 5 \text{ km}^2$ pixel in the image with a location root mean square (r.m.s.) error less than half a pixel. The correlation coefficient is almost everywhere greater than 0.80, thus indicating that the hypothesis of a linear relationship can be relied upon (Fig. 3).

6. DETERMINATION OF HOURLY GLOBAL RADIATION AT GROUND

The previous step provides for each pixel and hour time interval t , the coefficients $a(i, j)$ and $b(i, j)$, defining a linear regression between the transmission factor $K'(i, j)$ and the cloud cover index $n'(i, j)$ determined from satellite. Once these coefficients are known at the ground stations, a method of interpolation (krigeage) between the stations is applied in order to define the complete field of coefficients a and b for the studied area and for each hour interval.

