ELSEVIER

Agricultural and Forest Meteorology 82 (1996) 219–226

AGRICULTURAL AND FOREST METEOROLOGY

A note on first estimates of surface insolation from GOES-8 visible satellite data

George R. Diak [a,*], William L. Bland [b], John Mecikalski [a]

[a] *Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin— Madison, Madison, WI, USA*

[b] *Department of Soil Science, University of Wisconsin— Madison, Madison, WI, USA*

Received 5 September 1995; accepted 5 December 1995

Abstract

Visible imagery from geostationary satellites have a long history of providing accurate estimates of surface insolation over large spatial domains and at high horizontal resolution. In 1995, the United States launched its second generation of these geostationary (GOES) satellites, GOES-8 and GOES-9, with somewhat different visible sensor characteristics than their predecessors (GOES 1–7). In this work, we discuss first results of the estimation of daily insolation from these new data and compare the results to a pyranometer network maintained in Wisconsin by the University of Wisconsin—Madison. These results appear to be good and will be applied to estimating potential evapotranspiration for areas in Wisconsin where such knowledge of surface insolation is of primary importance for the scheduling of irrigation.

1. Introduction

The estimation of fluxes of incident shortwave radiation at the earth's surface is of importance for a number of applications including climate monitoring, regional solar energy availability assessment for heating and electrical power generation purposes and for the evaluation of the cloud and radiation parameterizations used in weather and climate models. Agriculture may also benefit from such techniques, and the satellite-derived solar energy results to be discussed in this work are being applied as part of a

* Corresponding author at: CIMSS, Space Center and Engineering Center, 1225 West Dayton Street, Madison, WI 53706, USA.

PII S0168-1923(96)02331-3

program to evaluate potential evapotranspiration and assist in irrigation scheduling for those regions of the state of Wisconsin where irrigation is required due to the character of the crops and/or soils.

Historically, the evaluation of shortwave radiation at the earth's surface has been a success story. For more than fifteen years investigators too numerous to detail have reported accuracy on daily insolation on the order of 10% or less when compared to ground-based pyranometers and better results for longer time integrations, such as values of monthly mean insolation. A short list of these investigators include Ellis and Vonder Haar (1978), Tarpley (1979), Gautier et al. (1980), Diak and Gautier (1983), Pinker and Ewing (1985), Pinker and Laszlo (1992) and Frouin and Chertock (1992). Two excellent reviews of progress in the estimation of shortwave fluxes from satellites have been given by Schmetz (1989) and most recently by Pinker et al. (1995).

The success of satellite visible data in estimating surface insolation primarily stems from their ability to detect cloud presence and the high horizontal resolution of such satellite data. As shown by Tarpley (1979), the temporal resolution of the data may be important as well. Satellite estimates of insolation are fundamentally different from estimates made by surface-based pyranometers, which may give a continuous time history of solar energy over the day, but only at one point. In contrast, the satellite data are essentially instantaneous and are taken at fixed time intervals and thus represent 'snapshots' of the solar energy at the surface at a particular time. These snapshots must be numerically integrated to give daily insolation values. Again, as shown by Tarpley (1979), in general, the more samples during the day, the better, which is the reason why geostationary satellites, with their relatively high temporal resolution (potentially several images per hour), perform well for insolation estimation. A second difference between pyranometer measurements and satellite estimates of solar energy is that the satellite estimates represent an areal average, which may vary with the pixel size of the particular satellite sensor and the number of pixels used for evaluating a particular location. Depending on the application, this areal averaging may be an advantage or a disadvantage compared to the point measurement made by an individual pyranometer, but it does make comparisons between satellite and pyranometer data inherently somewhat incongruous. There is, however, little other choice but to employ pyranometers for evaluation of the accuracy of the satellite methods. A definite advantage of satellite data over pyranometer data, however, is spatial coverage. The satellite insolation results to be presented here are spatial averages made at about 20 km resolution (although finer resolution is possible). For the same coverage, several hundred pyranometers would be required for a state the size of Wisconsin. This satellite areal coverage and resolution, however, is of most importance in regions or situations where there are high spatial gradients of clouds and insolation and may or may not be significant for a particular region or day.

For the Western Hemisphere, many of the satellite insolation studies in previous years have been accomplished using geostationary satellite data from the first generation of GOES satellites (GOES 1–7). Beginning in 1995, data from the following generation of these satellites, GOES-8 and GOES-9, are available. The visible data from the newer instruments offer advantages in resolution and calibration over previous GOES systems, which will be described later in this paper. In this study we present our first insolation results using these new data in a comparison with a pyranometer network maintained by the University of Wisconsin.

2. The simple physical model

The radiative transfer models and associated equation sets for the evaluation of solar energy from GOES satellite data have been presented in detail in Gautier et al. (1980), with updates and improvements in Diak and Gautier (1983). Thus, for reasons of brevity, only first principles will be described in this work. The methodology has recently been used by Bland and Clayton (1994), Lipton (1993) and McNider et al. (1994) for calculation of solar insolation using first-generation GOES satellite data. The physical parameterization is very simple, but has proven accurate under a variety of circumstances and computationally very efficient, an important consideration considering the large data volumes required for accurate estimates of insolation from geostationary satellites.

The simple physical model is based on conservation of radiant energy in the Earth-atmosphere column. To detect the presence of cloud, a surface albedo field of the target area (within the GOES bandpass) is retained as a reference. This surface albedo estimate is made by using the GOES image closest to solar noon at each surface location within the area to calculate a surface albedo for each day (whether the location is cloudy or clear). The model for the calculation of the surface albedo accounts for the effects of ozone absorption and Rayleigh scattering in the clear atmospheric path and within the GOES bandpass. Water vapor absorption, while potentially very important for the entire solar spectrum, is weak within the GOES visible bandpass and is neglected. A running two weeks of these daily albedos are stored. At the end of each day, the minimum surface albedo from these prior two weeks is selected at each geographic location under the presumption that it represents cloud-free conditions.

To detect the presence of cloud, this surface albedo is used with the atmospherics and sun geometry particular to a given data point to estimate the digital brightness which the satellite would record if the point were clear. If the actual brightness of the data is at or below this 'threshold', the point is designated clear and a clear model of atmospherics is employed to calculate the surface insolation. This model of the clear atmosphere includes the effects of ozone absorption, Rayleigh scattering and also water vapor absorption, using simple bulk relationships for the entire solar spectrum. Precipitable water in the column, required for the water vapor absorption parameterization, is estimated using a synoptic data analysis/forecast system (see Diak et al., 1992) run daily at the Cooperative Institute for Meteorological Satellite Studies (CIMSS).

GOES visible brightness measurements contain no explicit information on cloud type or height. When clouds are detected via the measured brightness exceeding the estimated clear threshold, a cloud parameterization is invoked which is tuned for the middle and low cloud types which most influence the solar radiation at the surface. The parameterization generates a quadratic equation (see Diak and Gautier, 1983) in which the independent variable is the cloud albedo within the GOES visible bandpass. The cloudy radiation model used to estimate this cloud albedo, similar to the clear model, accounts for ozone absorption and Rayleigh scattering within that bandpass. Rayleigh scattering processes are assigned above a cloud top (which we fix at approximately 700 mbar) and adjusted in magnitude by lowering the Rayleigh scattering optical depth to represent the fraction of atmospheric mass above the cloud top. Ozone absorption processes are also assigned to be above cloud top height.

After solving for the cloud albedo within the GOES bandpass, the cloudy solar radiation at the surface is calculated, taking into account the cloud albedo and again Rayleigh scattering, ozone absorption and water vapor absorption above and below the cloud using bulk parameterizations applicable to the entire solar spectrum. It is also assumed that the cloud albedo calculated within the GOES bandpass can be applied to the entire solar spectrum. For the water vapor absorption calculation, the bulk of the atmospheric water vapor (typically 70%) is assigned below cloud base level. A cloud absorption term is also calculated as a linear function of the cloud albedo, with a maximum absorption of 7% of the incident flux at cloud top and this term is also applied in the calculation of the surface insolation.

3. Data and calibration

For the insolation estimates for Wisconsin and the Midwest region to be described, the GOES-8 satellite offers the best angle of view. While visible data from this satellite is available at higher time resolution, we have used the imagery from the satellite at hourly intervals, which has proven adequate in prior studies. The visible imagery has a nadir resolution of about one km. To reduce data volume, however, we employ data which has been prior averaged to two km nadir resolution. Such minimal averaging has been shown to have little influence on the insolation estimates in previous work (Gautier et al., 1984). The second-generation GOES satellites also offer improved digitization in the visible data (10 bits versus 8 bits for GOES 1–7), however, given other limiting factors of the methods and models, accuracy gains in estimates of insolation from this improvement are dubious.

Quantitative calibration of the visible sensor (the relationship of digital counts to energy and reflectance or albedo) for the first generation of GOES satellites was a ongoing problem, since the sensor was really never intended to perform quantitative functions, but rather depict the position and movement of cloud and weather systems. While pre-flight calibration of the sensor existed, it was frequently changed at the ground station to maintain the visual quality of the imagery. Calibration for the purpose of estimating insolation from physical models had to be performed vicariously and often. This was usually accomplished knowing the functional response curve (of digital counts to energy) of the detectors and fitting this curve between dark and bright targets of known reflectance, such as a region of black space and the bright gypsum sand target of White Sands, NM (see, for example, Frouin and Gautier, 1987).

This situation is somewhat improved for GOES-8 and GOES-9. Visible data is normalized (to reduce striping) in real-time by the Sensor Processing System (SPS) at the Wallops Island ground station. The data transmission from the ground station includes visible bias, first order gain and second order gain calibration coefficients to compute visible radiances. An albedo conversion factor is supplied to allow computation of albedos (reflectances) from these visible radiances. In this work, we have employed these coefficients and albedo conversion factor in place of the calibration techniques described for visible data from the previous GOES satellites.

4. Logistics of satellite data processing

The Man-computer Interactive Data Processing System (McIDAS) at the University of Wisconsin Space Science and Engineering Center (SSEC) is used for data gathering and processing. GOES satellite data is ingested by the mainframe McIDAS facility at SSEC. Each hour, the relevant GOES data is sent via the Internet to a UNIX-McIDAS facility running on an IBM RISC-6000 workstation. The GOES data times extend from approximately two hours after local sunrise at a location to two hours before sunset.

All subsequent processes are run on the UNIX-McIDAS workstation. After the last data time, first the surface albedo is updated in the manner which has been described above. Subsequently, each hourly GOES image is processed into a field of insolation values on a regular grid with an equal latitude-longitude spacing of 0.2 degrees. For this grid spacing, an 8 by 8 pixel box of GOES data (pixels averaged to 2 km nadir resolution, as described in the prior section) is appropriate at the latitudes to be investigated here. Subsequently, these hourly fields of insolation are numerically integrated to obtain daily insolation values, including an extrapolation to zero insolation at sunrise and sunset times (times before and after the first and last image, respectively). Image times closer to sunrise and sunset are available, but are not used because of difficulties with cloud detection, radiative transfer calculations and resulting hourly insolation estimates for such low sun angles (dim images).

The entire process of estimating daily insolation is automated and runs with a minimal amount of manual intervention. Processing time is only several minutes on a model 3BT RISC-6000 IBM workstation.

5. Results and conclusions

The primary results of this study are a comparison between daily totals of insolation estimated from the satellite methods described above and a network of pyranometers maintained in Wisconsin. Ground-based pyranometer measurements of insolation were made at 15 stations of the University of Wisconsin's Agricultural Observation Network (Bland and Murdock, 1994). Pyranometers are LI-COR, Inc. (Lincoln, NE) model LI-200 silicon cell devices, fitted with pick-off resistors by Campbell Scientific, Inc. (Logan, UT). Pyranometers are returned to the manufacturer every two years for recalibration, per their recommendation, and calibration shifts are always insignificant. Instrument readings are recorded every minute and averaged over hourly and 24-hourly periods by Campbell Scientific, Inc. Model CR10 data acquisitions systems. Data were reviewed daily during this experiment by comparison to neighboring stations. Fig. 1 shows the locations of these pyranometers in Wisconsin.

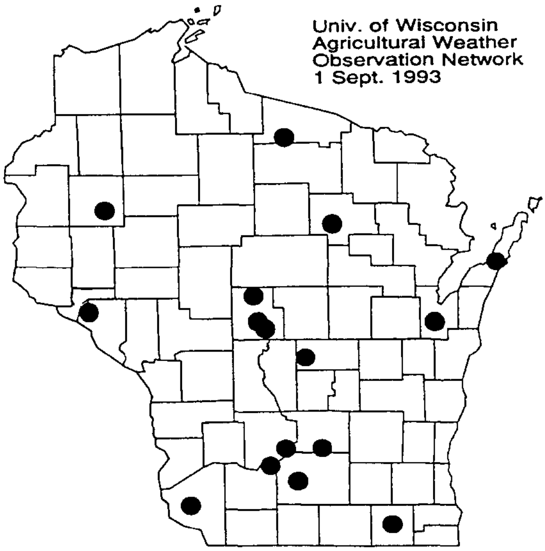

Fig. 1. Locations of pyranometer sites in Wisconsin.

Fig. 2 shows a comparison of daily insolation estimates from GOES-8 satellite data and counterpart insolation values measured by these 15 pyranometers for a total of 144 matches between Julian days 220 and 229 in Summer 1995. The standard error of

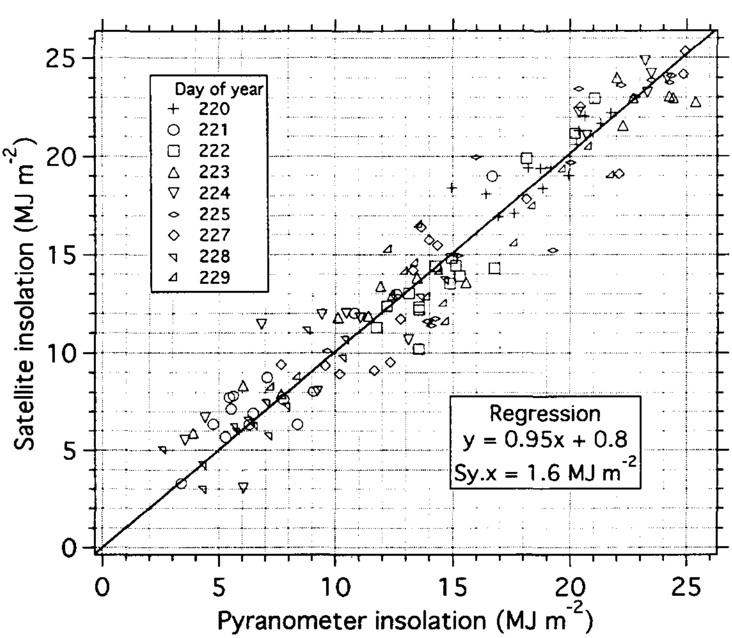

Fig. 2. Comparison of daily insolation results from pyranometers to satellite estimates (both $MJ\,m^{-2}$).

Fig. 3. Contour map of daily insolation values (MJ m^{-2}) on an GOES-8 image on the same day.

estimate is 1.6 MJ m^{-2} between the pyranometer measurements and satellite insolation estimates over a large range of insolation values. The correlation coefficient between the two is 0.963, giving an explained variance of 0.927 and the regression equation shown on this figure. Considering the accuracy of pyranometers (about 5%) and the disparity between the nature of measurements of satellite and pyranometers, as explained in the introduction, we consider this to be very acceptable results, especially for the first trials with a new satellite instrument. Fig. 3 shows an example of daily insolation results for the area of study, which includes Wisconsin and portions of some neighboring Midwestern states, on a day where the insolation field is particularly structured. The isolines of daily insolation values from satellite (MJ m^{-2}) are displayed on a GOES-8 image for the day at approximately solar noon for Wisconsin (1815 UTC).

Thus, in conclusion, with minimal effort, a system for the estimation of surface insolation from GOES satellite data has been modified to work with data from the second generation of these satellites. The results will be applied to the estimation of potential evapotranspiration in Wisconsin for irrigated croplands.

Acknowledgements

This research was supported by NASA Grant NAG5-2877 for the use of space science data over the Internet.

References

Bland, W.L. and Clayton, M.K., 1994. Spatial structure of solar radiation in Wisconsin. Agric. For. Meteorol., 69: 75–84.

Bland, W.L. and Murdock, L.M., 1994. Hourly weather data collected by the University of Wisconsin Agricultural Weather Network in 1993. New Horizons in Soil Science, 3-94, Department of Soil Science, University of Wisconsin—Madison, Madison, WI.

Diak, G.R. and Gautier, C., 1983. Improvements to a simple physical model for estimating insolation from GOES data. J. Clim. Appl. Meteorol., 22: 505–508.

Diak, G.R., Kim, D., Whipple, M.S. and Wu, X., 1992. Preparing for the AMSU. Bull. Am. Meteorol. Soc., 73: 1971–1984.

Ellis, J., and Vonder Haar, T., 1978. Application of meteorological satellite visible channel radiances for determining solar radiation reaching the ground. Proceedings 3rd Conference on Atmospheric Radiation, Davis, CA. Am. Meteorol. Soc., 21: 141–151.

Frouin, R. and Chertock, B., 1992. A technique for global monitoring of net solar irradiance at the ocean surface. Part I: Model. J. Appl. Meteorol., 31: 1056–1066.

Frouin, R.D. and Gautier, C., 1987. Calibration of NOAA-7, AVHRR, GOES-5 and GOES-6 VISSR/VAS solar channels. Remote Sens. Environ., 22: 73–101.

Gautier, C., Diak, G.R. and Masse, S., 1980. A simple physical model to estimate incident solar radiation at the surface from GOES satellite data. J. Appl. Meteorol., 19: 1007–1012.

Gautier, C., Diak, G. and Masse, S., 1984. An investigation of the effects of spatially averaging satellite brightness measurements on the calculation of insolation. J. Clim. Appl. Meteorol., 22: 1380–1386.

Lipton, A.E., 1993. Cloud shading retrieval and assimilation in a satellite-model coupled mesoscale analysis system. Monthly Weather Rev., 121: 3062–3081.

McNider, R.T., Song, A.J., Casey, D.M., Wetzel, P.J., Crosson, W.L. and Rabin, R.M., 1994. Toward a dynamic-thermodynamic assimilation of satellite surface temperature in numerical atmospheric models. Monthly Weather Rev., 122: 2784–2799.

Pinker, R.T. and Ewing, J.A., 1985. Modeling surface solar radiation: model formulation an validation. J. Clim. Appl. Meteorol., 31: 389–401.

Pinker, R.T. and Laszlo, I., 1992. Modeling surface solar irradiance for satellite applications on global scale. J. Appl. Meteorol., 31: 194–211.

Pinker, R.T., Frouin, R. and Li, Z., 1995. A review of satellite methods to derive surface shortwave irradiance. Remote Sens. Environ., 51: 105–124.

Schmetz, J., 1989. Towards a surface radiation climatology. Retrieval of downward irradiance from satellites. Atmos. Res., 23: 287–321.

Tarpley, J.D., 1979. Estimating incident solar radiation at the surface from geostationary satellite data. J. Appl. Meteorol., 18: 1172–1181.