Surface Solar Irradiance in the Central Pacific during Tropic Heat: Comparisons between In Situ Measurements and Satellite Estimates

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(Manuscript received 19 May 1987, in final form 11 February 1988)

ABSTRACT

We present the first results concerning solar radiation at the ocean surface during the Tropic Heat experiment. Using calibrated GOES visible brightness measurements, a simple radiative transfer model calculates hourly and daily surface solar irradiance values. To validate the satellite-estimated solar irradiance, surface solar irradiance measurements are taken from three sources: the Tropic Heat buoy 3, the R/V *Wecoma*, and the small tropical Pacific island of Hiva Oa. The comparison with the limited set of ocean measurements demonstrates that the method's accuracy is about 12 W m^{-2} on a daily basis (for the range of observed values: 240 to 310 W m^{-2}), which meets the requirements of the TOGA program. These results, however, are not yet statistically significant. In comparing model estimates to island data, both satellite observations and measurements indicate that the island's topography influences the oceanic environment by causing local, daily orographic cloud formation over the island's highest mountain. In partly clear conditions these clouds have a twofold effect: 1) to reduce solar irradiance under the mountain by shadowing; and 2) to increase surface solar irradiance near the mountain (instrument location) by cloud side reflection. Because of these effects, near-noon surface measurements are often larger than the model estimates (up to 80 W m^{-2}). Comparisons between the model results and oceanic measurements (buoy and the R/V *Wecoma*) suggest that the satellite-based estimates represent the oceanic conditions better than the island measurements.

1. Introduction

Although solar irradiance is an important component of the net surface heat flux, it is seldom measured over tropical oceans. This has resulted primarily from the difficulty in making radiation measurements at sea. Until the development of remote sensing techniques, large-scale solar irradiance fields at the sea surface had been obtained entirely from bulk parameterizations, requiring visual cloud cover observations from ships of opportunity. This approach to determining solar irradiance, however, is limited by the number of ship observations and to the conventional shipping lanes.

Recently, it has been shown possible to derive daily averaged solar irradiance at the surface with an accuracy of about 10% when using geostationary satellite visible brightness measurements (e.g., Hay and Hanson 1978; Tarpley 1979; Gautier et al. 1980). So far, only two such satellite methods have been validated over tropical regions (Hanson and Hay 1978; Gautier 1981), and in both cases this was done using limited surface radiation data measured from research ships during the GARP Atlantic Tropical Experiment (GATE). If satellite-derived solar irradiance fields are to be widely accepted and used for long-term monitoring, they need to be validated over long time periods and for all tropical regions. Because the research-quality measurements required for these validations are only available from research ships on an irregular basis, the question arises whether additional research-quality measurements could be taken from other reliable and steady sources, such as small tropical islands.

In situ measurements made from small tropical islands could provide comprehensive datasets and statistically significant accuracy assessments of satellite methods, ensuring that satellite-based computations of solar irradiance are without long-term biases. The issues of accuracy and bias are of crucial importance to ongoing and future climate monitoring and research programs because long-term climate variations are usually very small. For instance, in order to achieve its stated scientific objectives, the Tropical Ocean Global Atmosphere (TOGA) program requires an accuracy of 10 W m^{-2} and no bias for monthly solar irradiance estimates in tropical regions.

In an effort to better understand these problems of validation and accuracy, we have used data collected during the Tropic Heat experiment. Tropic Heat, initiated in October of 1983, had the broad goal of describing and modeling the processes that contribute to the evolution of warm and cold surface waters in the central Pacific (110° to 140°W) on seasonal and interannual scales (Niiler 1984; Eriksen 1985). One im-

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portant element of this experiment has been the study of surface heat flux variability over different time scales to understand how it affects upper ocean heat content and sea surface temperature. The solar irradiance, one of the surface heat flux's largest components, was computed using geostationary satellite measurements and following the method developed by Gautier et al. (1980) and refined by Gautier and Frouin (1984). Monthly solar irradiance fields were also calculated for a 2-year period but will be presented in a subsequent paper. Here we present a first assessment of satellite-derived solar irradiance at the ocean surface during Tropic Heat. This assessment focuses on small-scale comparisons (10–100 km) between both hourly and daily surface measurements and satellite-derived estimates in the central tropical Pacific at about 140°W.

Section 2 of this paper describes the surface solar radiation flux measurements used for the validation of the satellite predictions. These were made from two oceanic platforms, a research vessel and a buoy, and an island, Hiva Oa. In section 3 we present the data, procedure, and model used to compute solar surface irradiance using geostationary satellite data and discuss its expected accuracy. Section 4 is devoted to a detailed presentation of hourly and daily comparisons between the different surface measurements and the satellite estimations. In section 5 we discuss the comparison results and assess the accuracy of the satellite-based method. The island measurements are used to illustrate problems encountered when making comparisons with measurements made on a volcanic island whose irradiance field is influenced by the presence of orographic clouds. In section 6, a summary, conclusions, and recommendations for future validation are given.

2. Surface measurements

During Tropic Heat, in situ measurements were taken to provide the research-quality surface irradiance data needed to validate satellite-estimated solar irradiances. Three data sources were used for this validation: one set of pyranometer measurements made from the *Wecoma* research vessel, one small set of measurements made from a buoy, and a larger set of measurements made on the island of Hiva Oa, Marquesas.

Solar irradiance was measured[1] on board the R/V *Wecoma* during a 16-day period (with 4 days between 3°N and 3°S and 140°W, and 12 days at 0°, 140°W) in November 1984 with an Eppley Laboratory Model 8-48 pyranometer. This instrument was calibrated by the manufacturer prior to the cruise and was accurate to within 1%. The output of the pyranometer was sampled every 2 min and averaged over half-hourly intervals. The exposed glass hemisphere was cleaned daily. The instrument was not gimballed on the ship, so errors due to occasional shading and the ship motion (pitch and roll) are expected to have contaminated the data. Errors due to pyranometer tilt have been shown by Katsaros and DeVault (1986) to be highest for clear sky conditions and to reach a maximum of 10% for daily averaged solar irradiance values in tropical regions. The noise due to radio transmission was edited out of the data.

Solar irradiance was measured from the Tropic Heat buoy 3 (0.5°S, 140°W) for a 2-day period with a similar Eppley Laboratory Model 8-48 pyranometer. The pyranometer output was sampled 64 times per 7½-min recording interval. The pyranometer, mounted on top of the ARGOS antenna of the buoy, was not shaded at any time, and the antenna output did not affect the pyranometer data. Accuracy of the pyranometer was given to be 3%. Accumulation of sea spray is usually a problem with moored buoys, but because of the shortness of the time series (2 days) it is not expected to be important here.

Solar irradiance was measured at the meteorological station on the island of Hiva Oa (9°S, 139°W, Marquesas Islands). This island was chosen because it was the only island within the Tropic Heat experimental region. Although solar irradiance measurements were routinely made at the island's meteorological station (Atuona), the pyranometer had been irregularly calibrated prior to the experiment. This prompted us to make our own measurements. We installed an automated measuring system consisting of an Eppley Laboratory Model 8-48 pyranometer, a calibrated electronic amplifier, and a Handar instrument for digitizing, encoding, formating, and transmitting the data. The calibration of the pyranometer was estimated by the manufacturer to be about 5% and the errors related to the measurement amplification, digitization, and transmission to be about 8%. The dome of the pyranometer was cleaned daily. Daily averaged solar irradiance values, obtained by integrating 15-min averages, are presented together with theoretically computed clear sky values in Fig. 1. Note that for several days, the surface measurements indicated larger values than the model-computed clear sky values. This discrepancy will be explained later.

3. Satellite estimates

a. Data

To compute solar irradiance, full resolution (1 km at satellite subpoint) GOES-6 Visible and Infrared Spin Scan Radiometer (VISSR) data are sampled every four pixels to obtain a spatial resolution of about 4 km. For comparing the satellite estimates with surface measurements, small subimages centered on the surface measurement location are extracted from the larger GOES images. The size of image subsets is dictated by the averaging time of the surface instrument and the displacement speed of clouds in the region. The normal range of wind speeds in this region (mostly trade winds)

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[1] Measurements by C. Paulson.

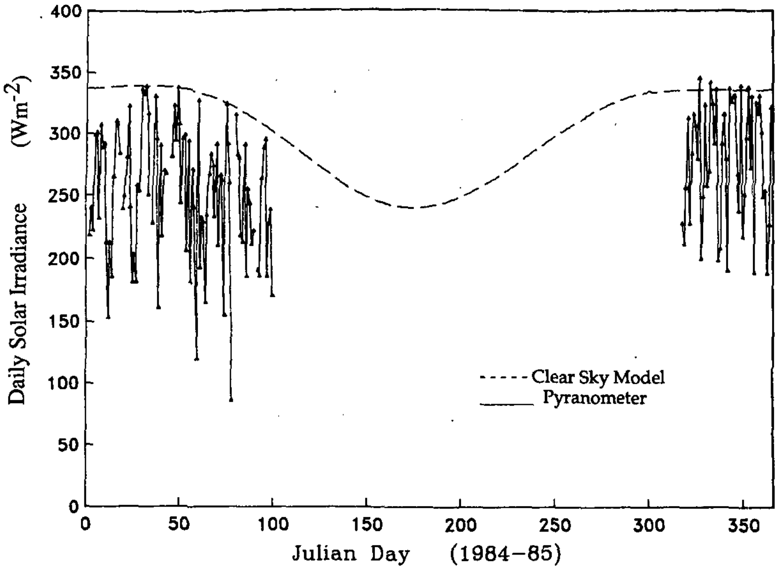

FIG. 1. Daily solar irradiance time series of clear sky model values and island measured values (Hiva Oa, 9°S, 139°W). Time series is from 16 November 1984 (right side of plot) to 15 April 1985 (left side of plot). Daily solar irradiance is calculated by integrating 15-min pyranometer averages.

is 4 to 10 m s^{-1}. Accordingly, surface measurements averaged over 1 h are compared with satellite estimates made for each 4 km pixel but averaged over 5 × 5 pixels (about 20 × 20 km) to 20 × 20 pixels (about 80 × 80 km).

These subimages must then be co-registered (i.e., aligned) for two reasons. First, it is necessary to coregister because we use images at hourly intervals to compute hourly averaged solar irradiance, and we combine these results to obtain daily averaged values. Second, since our method is based on a threshold approach for determining cloud presence, and since the threshold is computed from a surface albedo image (see below), all the images must also be co-registered with the albedo image.

The image alignment accuracy depends on the accuracy of the GOES satellite navigation location system. In general, this accuracy is good to within one image element, but it can vary largely at times of satellite maneuvers. A large image misalignment can induce significant errors in solar irradiance computations, especially in regions where regional cloud variability is high. This is of particular importance in our comparisons with surface measurements because Hiva Oa is a volcanic island with a local quasi-permanent orographic cloud cover over its highest mountain.

On clear or partly clear days we visually realign all the images by using landmarks, such as the island's coast, on our display system (Gautier et al. 1985). On cloudy days it is impossible to locate the island exactly on the image subset, and therefore we work with the operational navigation. The effects of any navigational inaccuracies, however, are lessened by horizontal cloud homogeneity, which causes uniform surface solar irradiance.

Since the VISSR onboard GOES-6 is not calibrated after launch by the agency operating the satellite (NOAA), we must perform its in-flight calibration. Calibrations were performed on a regular basis during the period September 1983 to March 1985 by viewing a target on the earth's surface (White Sands Monument area, New Mexico) and by computing the apparent reflectance measured at the satellite with a radiative transfer model (Frouin and Gautier 1985). Quantifying calibration uncertainty effects on solar irradiance computations has been presented in Gautier and Frouin (1984). Here, it is expected that the calibration uncertainty is on the order of 10%, which typically introduces errors of 2 to 10% in surface solar irradiance calculations under cloudy skies.

b. Model

The model used to compute surface solar irradiance is a modified version of Gautier et al. (1980) in which we have included the effects of ozone (Diak and Gautier 1983) and aerosols (Gautier and Frouin 1984). In the calculations the solar constant is taken as 1372 W m^{-2} (Neckel and Labs 1984). It is important to note that surface solar irradiance and cloud threshold computations require the surface albedo (Gautier et al. 1980). Assuming that the island albedo is equal to the surrounding ocean albedo leads to errors of more than 5% in the solar irradiance because the island is regarded as a cloud in the model. We therefore calculated the average island surface albedo over a several month period using the procedure presented in Gautier (1986) and, since the vegetation does not vary much over the year, used this albedo for the entire study period.

c. Accuracy

The method's accuracy is a function of uncertainties in the radiative transfer modeling, the data calibration, and the retrieval algorithm. The sum of these uncertainties has been quantified in other papers (e.g., Gautier et al. 1980) and found to be on the order of 10% for daily time scales and 50 km space scales.

Another source of uncertainty in this study stems from sun specular reflection effects, also known as sun glint. With the GOES-6 located at 150°W during the experiment, the sun glint occurs at high zenith angles (i.e., late in the day) during clear or partly clear conditions. Sun glint can cover several thousand square kilometers at times, making cloud region identification difficult since it is based on a brightness threshold technique. The overall surface brightness can become large and the brightness patterns so complex (e.g., reverse contrast) that the small and low clouds are missed by the automatic threshold technique. To overcome this problem, pattern recognition techniques based on spatial brightness structure and cloud time continuity could be developed to recognize clouds better, but such techniques would be relatively expensive to use in operational computations. We found, however, that by partitioning the dataset into subsets which were affected and unaffected by sun glint, the sun glint only marginally altered the satellite estimates.

When computing daily values a quadrature error is also introduced. As mentioned above, daily values are computed by integrating hourly estimates using the trapezoidal method. Since local noon, time of maximum solar irradiance, is not centered on the hour throughout the year, an integration error is induced, the importance of which depends on the day of the year. To assess the magnitude of this error our clear sky model computed daily integrated values from both 12-min and hourly estimates. A difference of up to 4 W m^{-2} was found between the two daily values for the latitude of our surface measurements. Such an error could be partly reduced by using available satellite data at half-hourly intervals, but this would make computational procedures twice as large.

4. Comparison results

Hourly and daily comparisons were performed between the three sets of surface measurements and the satellite estimates. First, daily solar irradiance comparisons are presented in Fig. 2 between satellite estimates and research-quality ship measurements taken aboard R/V *Wecoma* during one of the Tropic Heat intensive observing periods. (Since the meteorological conditions were mostly clear, the hourly comparisons are not presented.) The correlation between the two daily time series is 0.6, the rms difference 12 W m^{-2}, and the bias 6 W m^{-2}. The low rms difference and yet poor correlation are explained by the cloud field effects and how the satellite technique accounts for ship position. On the one hand, the rms difference is low because only a few small clouds were present during the comparison period, and thus large average irradiance values were detected by both the ship and satellite (the period average was ~290 W m^{-2}). On the other hand,

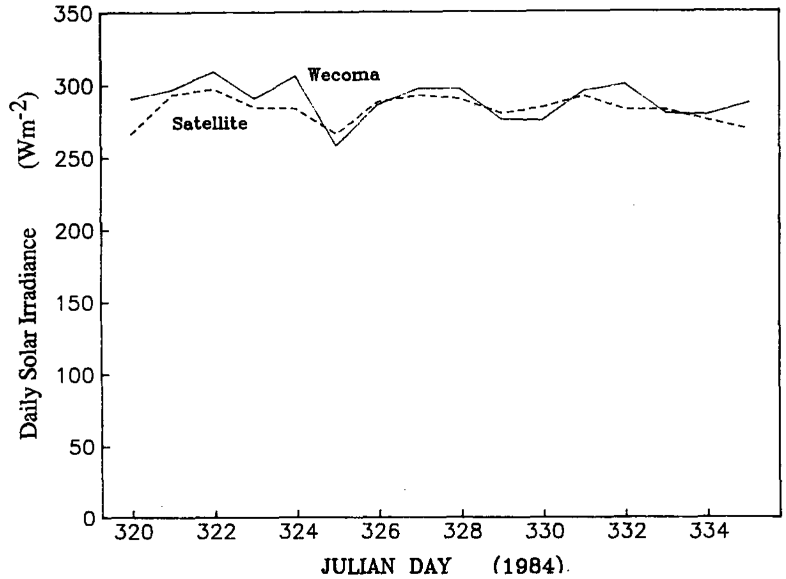

FIG. 2. Daily solar irradiance comparisons between 16 days of research-quality ship measurements and satellite estimates.

the correlation is low for two reasons: 1) the solar irradiance variability between the two datasets is small (50 W m^{-2} or about 20% of the mean signal); and 2) the satellite technique uses a mean daily ship location, in spite of the ship's movement, and thus a cloud field not exactly corresponding to that of the ship's measurements.

Second, hourly comparisons with two days of buoy data are presented in Fig. 3. The satellite estimates correspond well to the hourly averaged measurements. The daily buoy values and the satellite estimates are within 10 W m^{-2}. The weather conditions for these two days of comparison were also very clear (over 300 W m^{-2}), which might explain the quality of the satellite estimates.

Third, hourly and daily comparisons were made with the island measurements. The advantage of this dataset is that cloud conditions encountered at 9°S are more representative of the convective activity in the tropics than the two previous sets of measurements near the equator where little convective activity is observed. (The lowest daily averaged value of the comparison is 255 W m^{-2}.) Furthermore, the island dataset is a longer

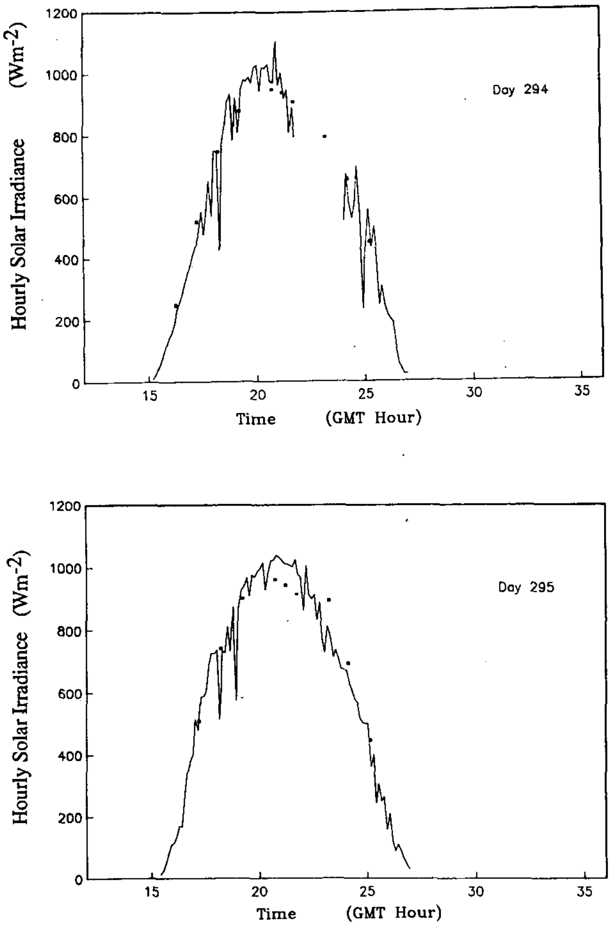

FIG. 3. Hourly solar irradiance comparisons between buoy measurements and satellite estimates for 2 separate days (294 and 295). The solid line corresponds to the buoy measurements and the squares correspond to satellite estimates.

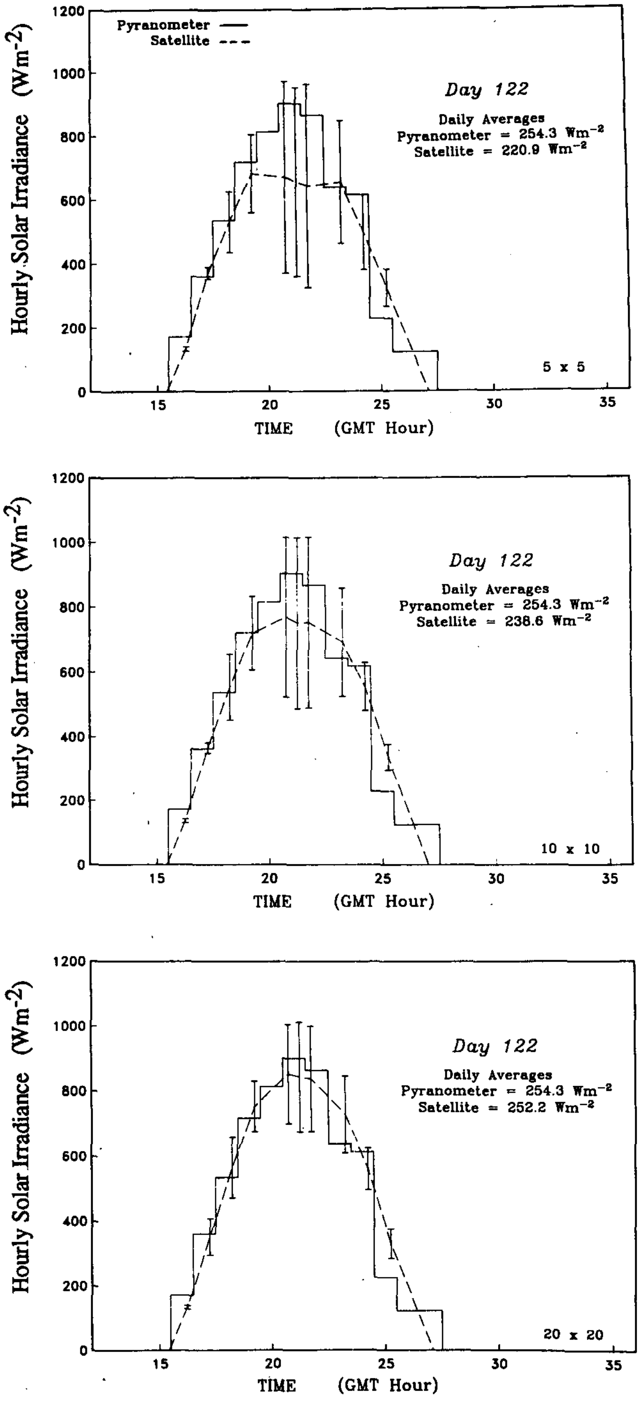

FIG. 4. Hourly solar irradiance comparisons between island pyranometer measurements (solid line) and satellite estimates (dashed line) for three satellite averaging scales, starting with the 5 × 5 pixel scale on top. Included are the respective daily averages and standard deviations (represented by vertical bars) for each satellite averaging scale.

dataset and thus spans a larger range of conditions. There are, however, difficulties in using solar irradiance datasets obtained on volcanic islands because these islands are often subjected to higher convective activity than the surrounding ocean and, thus, are not entirely representative of oceanic regions. Island datasets, nonetheless, can still provide a reasonable validation if 1) the satellite data provide the necessary information about cloud conditions in the island vicinity; and 2) the computation method reproduces the cloud effects on the surface solar irradiance. We shall see here that the method used to compute surface solar irradiance is not appropriate to reproduce the effects of an orographic cloud.

To help in the interpretation of the island results, comparisons for three different spatial averaging scales (5 × 5, 10 × 10, and 20 × 20) are presented in Fig. 4 for day 122. The differences between the satellite averages over the three scales illustrate the effects of the orographic clouds over the island's highest mountain. These clouds have two effects: they reduce surface solar irradiance beneath them by reflecting radiation back into space, as all clouds do, but they also increase local surface solar irradiance by reflecting radiation off their sides, owing to their vertical extension and limited horizontal size. As a result, these clouds are responsible for the decreasing averaged values and increasing spatial variability of the satellite estimates with decreasing spatial averaging scale. In addition to these effects, there is a tendency to overestimate with the satellite method in the afternoon, which might result from the orographic clouds shadowing the surface instrument.

The hourly comparisons between the island-measured values and the satellite estimates in Fig. 5 and the associated statistics (Tables 1 and 2) indicate that in relatively clear conditions the model values (i.e., the largest values) are generally lower than the measured ones. Although values as high as 1042 W m^{-2} are computed for local noon in clear conditions, the surface measured values are often much larger (as high as 1161 W m^{-2}).

Selected days of the island dataset are also represented in Fig. 6, comparing surface measurements with the three different satellite resolution measurements. These days have been chosen because they illustrate several typical conditions. Days 348, 357, 364, and 16 are characterized by large surface solar irradiance variability, as indicated by the changing pyranometer measurements. This variability is well reproduced by the satellite estimates. Days 350 and 9, however, appear clear from the pyranometer's measurements, and in both cases the satellite computations underestimate the surface measurements, particularly day 9. Days 348 and 16 exemplify increased surface solar irradiance

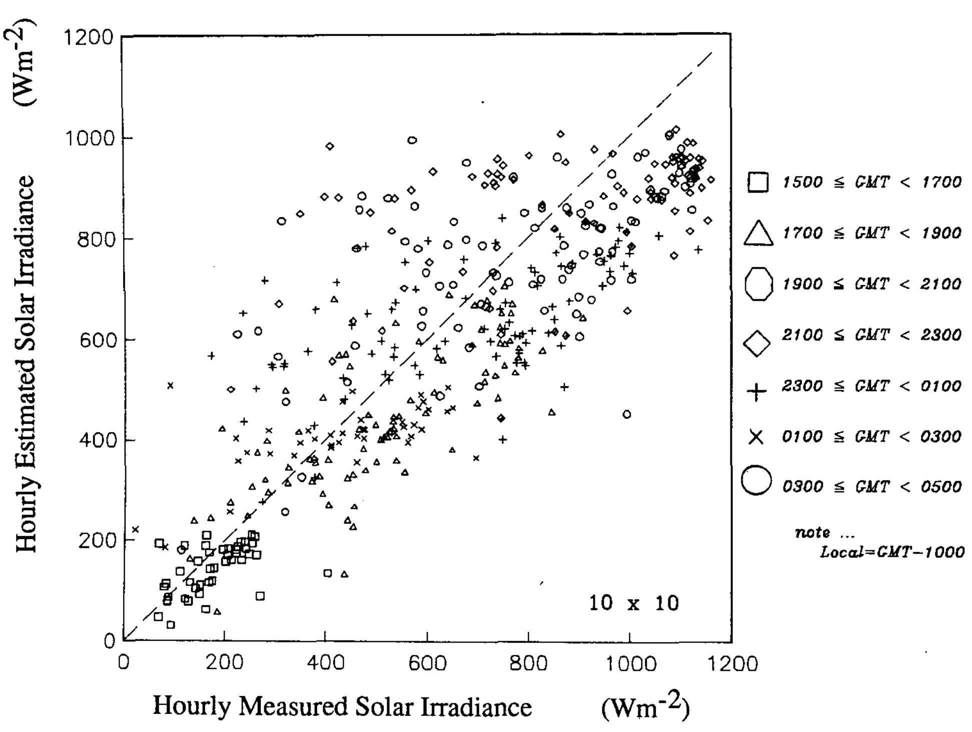

FIG. 5. Hourly solar irradiance comparisons between island measurements and satellite estimates. The scatter plot corresponds to only the 10 × 10 averaging scale and includes 76 days of measurements, whose statistics are given in Tables 1 and 2. To illustrate the hourly measurements, symbols representing different hours are given on the right-hand legend.

TABLE 1. General statistics of measured and calculated solar irradiance at Hiva Oa (9°S, 140°W) during the period 16 November 1984–15 April 1985.

	Mean (W m^{-2})	SD (W m^{-2})	Min (W m^{-2})	Max (W m^{-2})
Pyranometer	633.3	300.6	21.5	1161.2
Satellite (20 × 20)	622.0	260.4	44.4	1042.0
Satellite (10 × 10)	596.7	254.7	31.2	1012.6
Satellite (5 × 5)	578.4	250.3	32.6	998.6

(peaks around local noon) resulting from temporary cloud clearing and the cloud-side reflection discussed previously.

A close look at Fig. 5 reveals that the satellite estimates do not scan the entire variability of the pyranometer measurements (satellite values range from 44 to 1042 W m^{-2}; pyranometer values range from 22 to 1161 W m^{-2}). This can be interpreted in two ways: either the satellite method cannot always properly assess the presence of clouds, which could result from the spatial sampling of the original data, or, there are some physical processes taking place which are incorrectly parameterized in the method. The second possibility seems more likely because this reduced variability in satellite estimates is observed often in this dataset.

Most of the results presented above hold for daily comparisons. These comparisons are presented in Fig. 7, with associated statistics in Tables 3 and 4. The agreement between calculated and measured values appears good on an averaging scale of 10 × 10 pixels and for measured values below 300 W m^{-2}, but include relatively large (up to 80 W m^{-2}) underestimations on some days for measured values above 300 W m^{-2}. These days correspond to clear to partly clear conditions during which orographic cloud effects are the largest. This could be expected following the analysis of the hourly comparisons. Yet, considering the previous discussion, the statistics of the daily comparisons should be interpreted with some care. Specifically, they may not represent the surface irradiance accuracy over the ocean because of the particular geographic configuration of the island and its effect on the local cloudiness.

TABLE 2. Comparison statistics.

Scale	Correlation	Standard error (W m^{-2})	Relative error (W m^{-2})	Bias (W m^{-2})
(20 × 20)	0.81	151.2	175.7	11.3
(10 × 10)	0.81	147.3	177.9	36.6
(5 × 5)	0.80	149.8	188.4	55.0

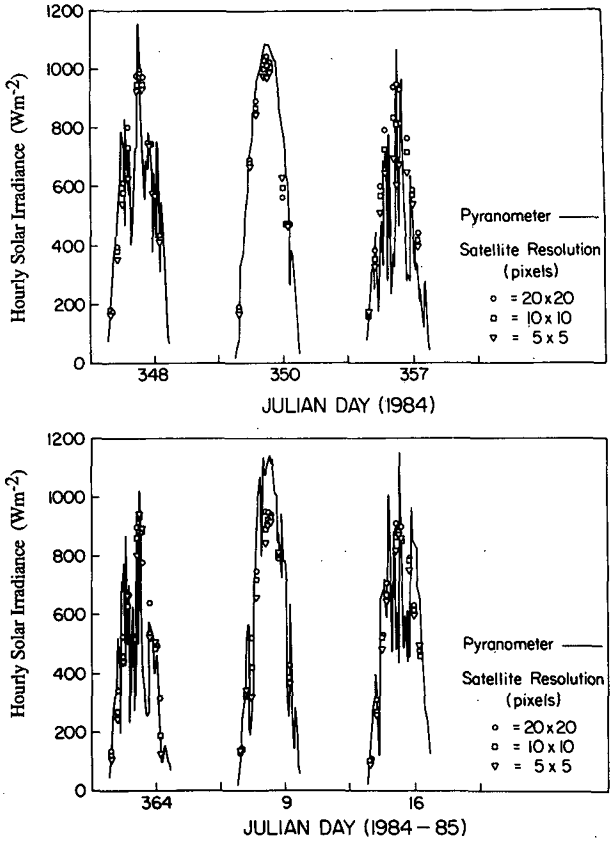

FIG. 6. For 6 selected days, hourly solar irradiance comparisons between island measurements and satellite estimates from the three averaging scales.

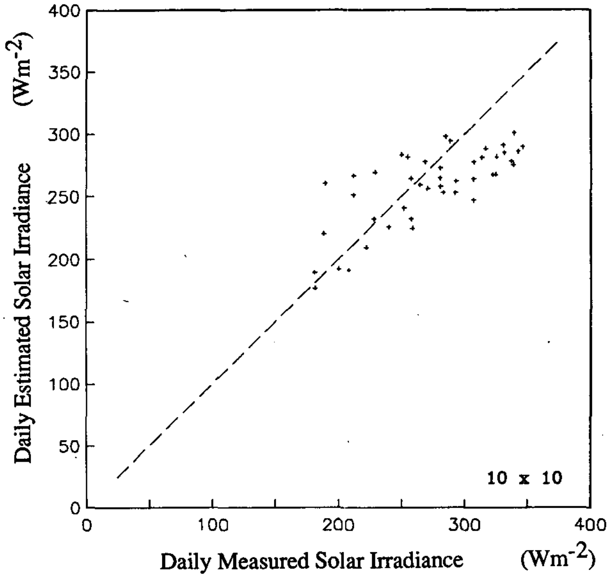

FIG. 7. Daily average solar irradiance scatter plot comparison between island measurements and satellite estimates (10 × 10 averaging scale). The corresponding statistics are in Tables 3 and 4.

TABLE 3. General statistics of measured and calculated daily solar irradiance at Hiva Oa (9°S, 140°W) during the period 16 November 1984 to 15 April 1985.

	Mean ($W m^{-2}$)	SD ($W m^{-2}$)	Min ($W m^{-2}$)	Max ($W m^{-2}$)
Pyranometer	273	49	181	346
Satellite (20 × 20)	267	29	197	303
Satellite (10 × 10)	258	31	177	301
Satellite (5 × 5)	251	32	163	299

5. Discussion

The comparison statistics presented above for the oceanic conditions (*Wecoma* and buoy data) are very similar to those obtained during GATE under similar tropical conditions in the Atlantic [i.e., a standard error of 17 $W m^{-2}$ (Gautier 1981)]. The island comparisons are much poorer and this warrants some clarification.

In the case of Hiva Oa, the in situ observations indicate that there is a semipermanent orographic cloud cover over the island's highest mountain. The influence of such orographic clouds on the surface measurements can be seen in Fig. 6 (for day 348), where both satellite estimates and surface measurements indicate high variability and a reduction in cloudiness around local noon resulting in higher irradiance values. But the model is unable to completely reproduce the observed short increase in surface irradiance values. This increase at the surface is maximum at small solar zenith angles and is most likely the result of two components adding to the surface measured irradiance: the direct solar radiation and the added radiation reflected by orographic cloud sides. Such an increase in clear surface irradiance from cloud side reflection has been observed previously (by the author and others during a field experiment in the Indian Ocean and also by Dr. Bölle, personal communication). A similar geometric cloud configuration occurs with plane parallel clouds at grazing angles. In this case, reflectances larger than 0.8 have been theoretically calculated (Welch et al. 1980). It is also interesting to note that for many years the French meteorological services measured similar high surface irradiance values at Hiva Oa which were never indicated in daily reports. At that time these measured high values were considered to be incorrect pyranometer readings because they could not be explained by a simple direct-irradiance model alone.

TABLE 4. Comparison statistics.

Scale	Correlation	Standard error ($W m^{-2}$)	Relative error ($W m^{-2}$)	Bias ($W m^{-2}$)
(20 × 20)	0.72	20	35	5
(10 × 10)	0.74	20	36	15
(5 × 5)	0.72	22	40	22

In addition to this physical cloud effect, it is possible that the model, itself, slightly underestimates solar irradiance at small solar zenith angles in clear tropical conditions. The suggestion for that is given by the buoy measurements and earlier comparisons with GATE data, which indicate that the model underestimates surface solar irradiance at small solar zenith angles. With the hourly buoy measurements, for instance, underestimation is evidenced for a few hours at small solar zenith angles. And for some days during GATE, similar underestimations were found for the near-noon hourly comparisons with high quality ship measurements. But during GATE no particular attention was paid to them because the dataset was small and they were not reflected in the daily comparison statistics. Thus, in an attempt to clarify the origin of this underestimation with the buoy data, we ran the model with the same observational conditions at the buoys while reducing the total atmospheric water content by 1 cm, a reduction which would correspond to a significant drying of the atmosphere. The resulting increase in the satellite estimates, however, was still not sufficient to explain the computed underestimation. The possibility that the solar constant used is too small was discarded because its value was taken from the latest satellite measurements.

On the other hand, a definitive conclusion about the model's underestimating deficiency is still difficult to reach because the comparisons with the *Wecoma* research vessel do not indicate similar underestimations. On the contrary, the clearest hourly ship measurements reported during its observation period are about 1018 $W m^{-2}$, very close to the maximum values obtained with our method in the same region. Although this value for small solar zenith angles is relatively low (1018 $W m^{-2}$), it could be explained by the continuous presence of small trade wind cumuli and/or high, thin cirrus clouds, which reduce the solar irradiance and are typical of tropical regions. From visual observation, it is well known that oceanic conditions are characterized by trade wind cumuli moving at about 6 to 8 $m s^{-1}$, the speed of the trade winds. The other possible explanation is that since the R/V *Wecoma* was cruising during the first 4 days, the pyranometer, which was not gimballed, could be responsible for underestimations in instantaneous solar irradiance.

Assuming (for now) that the *Wecoma* and buoy measurements are sufficient to assess the accuracy of our satellite method for tropical oceanic conditions, we obtain a 12 $W m^{-2}$ rms difference and 6 $W m^{-2}$ bias for daily time scales and about 20 km space scales.

6. Summary and conclusions

Measurements of the surface solar irradiance made from the R/V *Wecoma,* a moored Tropic Heat buoy, and the island of Hiva Oa (9°S, 139°W) from November 1984 to April 1985 were compared with concurrent satellite estimates obtained using GOES-West digital data in the visible.

Comparisons with buoy and ship measurements indicate that the satellite estimates are accurate to within 12 W m^{-2} (or less than 5% of the mean value) on a daily basis and for the range of values scanned by this set of validation measurements. Although this accuracy would meet the TOGA requirements (World Climate Research Programme 1984), it is not statistically significant because of the limited dataset size. Hourly comparisons and former work in the tropical Atlantic suggest that the model slightly underestimates the surface measurements by a few percent at small solar zenith angles under clear conditions. Still, this deficiency in the model remains inconclusive since other comparisons with high-quality ship measurements demonstrate good agreement at small solar zenith angles.

The surface measurements were found to be strongly influenced by quasi-permanent orographic clouds over the island's highest mountain. This influence was indicated by the reduced mean satellite estimated values and the increased spatial variability for the smallest spatial averaging scale. These clouds have a twofold effect: 1) to reduce local solar irradiance over the mountain itself by shadowing; and 2) to increase surface solar irradiance near the mountain (the instrument location) as a result of cloud side reflection.

It is doubtful, however, that the high near-noon values measured at Hiva Oa represent typical oceanic conditions; rather, they are associated with the abovementioned stationary orographic clouds and their cloud side reflection. While the presence of small clouds may enhance local surface solar irradiance through reflection, conservation of energy dictates that it must be compensated for on some other scale. Thus on a larger scale than the surface comparisons (10–20 km), the satellite estimates represent the solar irradiance field at the ocean surface better than do the island surface measurements.

Our results have demonstrated that, while the dataset obtained from Hiva Oa is comprehensive enough to be statistically significant, it was not sufficient to assess satellite estimation accuracy completely because of the island's particular cloud effects. Nonetheless, owing to the difficulty in collecting data at sea, we suggest that long-term quality surface measurements be made from small atolls which have only marginal effects upon mean oceanic cloud conditions. This technique, however, should be complemented by short-term, high-quality research vessel measurements to ensure that the atoll datasets accurately represent oceanic conditions.

Acknowledgments. This work has been supported by the National Science Foundation under Grant NSF OCE82-14791. I deeply appreciate the logistic and friendly support I received from the Meteorological Services in Tahiti and Atuona. Without this support the surface measurements would not have been possible. I particularly want to thank Mr. Neau, head of the Meteorological Services in Tahiti, and Mr. H. Kwong, head of the Atuona station during the system's installation. In addition, I would like to thank Dr. C. Paulson for providing the R/V *Wecoma* data and Dr. R. Payne for supplying the buoy data.

I also appreciate Dr. Robert Frouin's assistance in reviewing the manuscript and making insightful comments; and Mr. Robert Wylie and Ms. Beth Di Julio for their programming and processing support. Also thanks to Brian Bloomfield for his editing the manuscript and to Robert Markworth for typesetting it.

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