A Comparison of Satellite and Empirical Formula Techniques for Estimating Insolation over the Oceans

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ABSTRACT

Surface insolation data collected during the Mixed Layer Dynamics Experiment are used to intercompare the satellite technique of Gautier et al. (1980) and five commonly referenced empirical formulas for estimating daily insolation over the oceans. The results demonstrate the superiority of the satellite technique, which exhibits a 0.97 correlation coefficient, a 12.0 W m^{-2} standard error of estimate, and a −4.9 W m^{-2} bias error, and which is also able to account for water vapor, ozone, and dust amount variations in the atmosphere and monitor quasi-instantaneously vast extents of ocean. Among the empirical formulas, Mosby's (1936) yields the best predictions with a 0.84 correlation coefficient, a 19.1 W m^{-2} standard error of estimate, and a 3.4 W m^{-2} bias. Kimball's (1928) and Reed's (1977) formulas, however, perform nearly as well. The largest biases are obtained with Berliand's (1960) and Laevastu's (1960) formulas, which overestimate insolation by 15.2 and 24.5 W m^{-2}, respectively. It is suggested that empirical formulas, even though established from visual cloud cover observations, would provide useful insolation estimates if employed with satellite-derived cloud cover.

1. Introduction

Solar radiation reaching the ocean surface is important in both physical and biological oceanography. From a physical perspective, it affects water density distribution and, hence, oceanic motion; from a biological one, it perpetuates the process from which all marine life originates, namely photosynthesis.

Because of the difficulty in making radiation measurements at sea, oceanographers have long investigated alternatives for estimating insolation over the oceans. Facing the complexity of modeling radiative transfer in a cloudy atmosphere, they have generally favored an empirical approach. Various formulas have been proposed (e.g., Kimball 1928; Mosby 1936; Laevastu 1960; Berliand 1960; Lumb 1964; Reed 1977), which involve cloud cover, a parameter regularly observed from ships. The cloud cover dataset is large, but vast geographical gaps still exist, especially in the southern oceans. Although empirical formulas were established at particular locations and usually assume no variations in the transparence of the cloudless atmosphere, investigators such as Budyko (1963), Wyrtki (1965), Bunker (1976), Hastenrath and Lamb (1978), Weare et al. (1981), Esbensen and Kushnir (1981) have nonetheless relied on these formulas and summaries of marine weather reports to compute climatological averages of surface insolation over the world's oceans.

Since clouds are the major variable altering surface insolation and since they can be easily observed from space, several studies (e.g., Raschke and Preuss 1979; Tarpley 1979; Gautier et al. 1980; Dedieu et al. 1987) have attempted to infer surface insolation from satellite radiances. The chief advantage of the satellite measurements is their spatial and temporal coverage, which offers the possibility of a global surface insolation picture over the oceans.

Until now, however, satellite and empirical formula techniques have only been verified separately, by comparing insolation estimates to in situ pyranometer measurements. No attempt has been made, using the same comparison dataset, to directly compare the performance of empirical formulas with that of the satellite techniques. In this article, we compare five commonly referenced empirical formulas with the satellite technique of Gautier et al. (1980). For this comparison, we use pyranometer data collected aboard two research vessels during the Mixed Layer Dynamics Experiment (MILDEX), which was conducted from 26 October through 13 November, 1983 approximately 300 km off the central California coastline (Lind and Katsaros 1987).

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2. Empirical formulas

From a primarily theoretical basis, Kimball (1928) derived the following formula:

$$I = I_0(1 - 0.71C), \qquad (1)$$

where I is the average daily insolation at the surface when C is the fraction of the sky covered by clouds and I_0 is the average daily insolation at the surface in the absence of clouds. Using monthly means of air temperature and relative humidity at 140 coastal stations scattered around the world, Kimball computed I_0 as a function of latitude and season. His I_0 values, which also account for average aerosol turbidity, were widely used in early oceanic heat budget studies, such as those by Jacobs (1951) and Masuzawa (1952).

Mosby (1936) gave the following formula to compute clear sky insolation:

$$I_0 = k\bar{h}, \qquad (2)$$

where $\bar{h}$ is the mean solar altitude and k a factor slightly increasing with latitude, equal to 0.023, 0.024, and 0.027 at the equator, 40°, and 70° of latitude, respectively. For calculating insolation by varying cloudiness, Mosby used Kimball's cloud factor.

Few radiation data were available over oceanic areas when Kimball and Mosby derived their insolation formulas. From pyranometer recordings over a large area in the Atlantic, which included low and middle latitude regions, Laevastu (1960) showed that insolation can be conveniently represented by

$$I = 0.014h_0t_d(1 - 0.6C^3), \qquad (3)$$

where h_0 is noon solar altitude for angles up to 75° and t_d is the duration of sunlight. Above 75°, h_0 is taken as a constant and the formula reads

$$I = 1.06t_d(1 - 0.6C^3). \qquad (4)$$

The same year, Berliand (1960), using numerous new observational data, established that accurate insolation results could be obtained using the following formula:

$$I = I_0[1 - (a + bC)C], \qquad (5)$$

where a and b are dimensionless. Values of a, which depend on latitude, and b, which are comparatively more stable, can be found in Budyko (1974). In the formula, the term $a + bC$ accounts for correlations between the amount of clouds and their form.

Except for Berliand's formula, which crudely attempts to account for cloud type, all the above formulas assume a constant cloud transmittance with respect to incoming solar radiation. Several studies (e.g., Haurwitz 1948; Welch et al. 1980), however, have reported large differences in cloud transmittance, which typically varies from 0.2 for stratus to 0.7 for cirrus. Because he was aware of this dependence on cloud type, Lumb (1964) distinguished between eight cloud categories for which eight separate empirical formulas were developed. Lind and Katsaros (1986) attempted to classify Lumb's cloud categories with the shortened cloud reports used on research vessels. Lumb's formulas, however, cannot be used if C is the only cloud parameter available.

In a more recent study, Reed (1975, 1977) suggested that insolation under clear skies could be computed reliably with a formula derived by Seckel and Beaudry (1973) from Smithsonian meteorological tables:

$$I_0 = A_0 + A_1 \cos\phi + B, \sin\phi + A_2 \cos 2\phi + B_2 \sin 2\phi, \qquad (6)$$

where A_1, A_1, B_1, A_2 and B_2 are coefficients that depend on latitude and take different functional forms in the latitude ranges of 20°S–20°N and 20°–60°N. Reed presumed that the formula would be suitable everywhere, although it has not been tested far south of the equator. In (6), $\phi = (J - 21)360/365$ where J is Julian day. For estimating cloud effects on isolation, Reed (1976, 1977) proposed the following relation:

$$\frac{I}{I_0} = 1 - 0.62C + 0.0019h_0. \qquad (7)$$

In this expression the dependence upon solar altitude is introduced because, when the sun is low, the optical path through clouds is increased and broken clouds are more likely to intercept the solar beam. Note, however, that Reed's cloud factor is not equal to 1 when C is equal to 0, which does not make sense physically.

Other formulas, derived from physical considerations, have been proposed to compute daily totals of surface insolation, in particular, those by Atwater and Brown (1974) and Davies et al. (1975). These formulas, which have potential for global applications, have not been widely used in oceanographic studies because they require information on cloud type and altitude not routinely available from ships. Therefore, like Lumb's formula, they will not be considered in the present study.

3. Satellite technique

We have selected the satellite technique described in Gautier et al. (1980) and later refined by Diak and Gautier (1983) and Gautier and Frouin (1984). This technique has been extensively verified (e.g., Gautier 1981, 1984; Gautier and Katsaros 1984) and widely used, in particular to study the relationship between insolation and the evolution of the Indian monsoon (Gautier 1986). Furthermore, a recent review of operational techniques that use satellite data to compute insolation (Raphael and Hay 1984) has demonstrated the better performance of Gautier et al. technique, especially in cloudy conditions.

In Gautier et al., the approach is to physically model the most important processes that occur within the atmosphere and clouds. Under clear sky conditions, instantaneous insolation is given by

$$I_0 = S_0 \cos\theta \exp(-C_1/\cos\theta)(1 - a_{oz}) \times (1 - a'_{oz})(1 - a_w)/(1 - C_2 A_s), \quad (8)$$

where S_0 is solar constant, a_{oz} and a'_{oz} are absorption coefficients for ozone (visible and ultraviolet, respectively), a_w is absorption coefficient for water vapor, θ is solar zenith angle, and A_s is surface albedo. In (8), C_1 and C_2 are coefficients that depend on atmospheric turbidity. These coefficients were obtained by comparing (8) with the radiative transfer model of Tanré et al. (1979) and performing a regression analysis. For a 23 km visibility atmosphere containing maritime aerosols, they take typical values of 0.093 and 0.135 (when S_0 is expressed with W m^{-2}), respectively. Water vapor and ozone amounts are specified from climatology and A_s is fixed at 0.06. Under cloudy conditions, the clear sky formulation is modified to account for reflection and absorption by clouds, which are assumed to occur in a single layer. Insolation is expressed as

$$I_c = I_0(1 - A_c - a_c), \quad (9)$$

where A_c is cloud reflectance and a_c is cloud absorption. In (9), multiple reflections between the cloud layer and the surface are neglected and a_c is taken as 20% of A_c. Cloud albedo is obtained from calibrated geostationary satellite measurements in the visible by solving a quadratic equation in A_c (for details, see Diak and Gautier 1983). Under partly cloudy skies, the fluxes computed for clear and cloudy regions, I_0 and I_c, respectively, are combined according to

$$I = CI_c + (1 - C)I_0. \quad (10)$$

In this case a threshold technique, also described in Gautier et al., is employed to partition the study areas into clear and cloudy components.

Thus, the model explicitly accounts for atmospheric transmission variations due to water vapor, ozone, aerosols and clouds. The cloud parameter governing insolation in overcast conditions, namely A_c, is obtained directly. This is not the case with empirical formulas that, as we have seen, use cloud type or solar altitude. Even though A_c depends on cloud type and radiation geometry, it is certainly more desirable to estimate A_c directly.

4. Data

The data used for the comparisons are 23 days of insolation measurements taken aboard R/P FLIP (FLoating Instrument Platform) and *R/V Acania* during MILDEX. The R/P FLIP served as the central coordinate for the experiment, and *R/V Acania* traveled a few kilometers away in box-like patterns around R/P FLIP. R/P FLIP drifted freely during the experiment, generally toward the north, with positions ranging from 33.4°N and 126.4°W at the beginning of the experiment to 34.1°N and 126.3°W at the end. From 26 October through 9 November, *R/V Acania* was always within 2 km of R/P FLIP.

Gimbal-mounted precision pyranometers were installed on both platforms. These instruments measure hemispheric solar irradiance in the 0.28–2.8 μm range and have a nominal accuracy of 2% (<10 W m^{-2}). The instrument on R/P FLIP (Eppley PSP) was attached to one of the booms, approximately 18 m from the hull and 3.5 m above mean sea level. The instrument on *R/V Acania* (Kipp and Zonen) was installed on the rear upper deck at 8 m above mean sea level. These instrument locations were carefully selected to minimize the influence of ship structures on the measurements. Moreover, cleaning of the pyranometer domes was performed daily (except during periods of bad weather). Exposure errors were therefore minimal, so that an estimated error in individual measurements is 10 W m^{-2}. Averaging over time reduces this error substantially. Also relevant to our analysis, fractional cloud cover was visually observed and logged hourly.

After the experiment, the raw radiation data (voltage outputs) were filtered for radio-frequency noise and converted into geophysical units (Lind et al. 1984; Lind and Katsaros 1987). Average daily totals of insolation were then constructed. From the hourly cloud cover observations, nonweighted daily averages of cloud cover (over sunlight hours only) were also computed.

Note that side-by-side comparisons were made between the Eppley PSP and Kipp and Zonen pyranometers on two occasions: March 1984 in Mount Vernon, Washington, and May 1985 in Seattle (rooftop at the University of Washington). In both cases, differences between hourly averaged sensor outputs (including amplifying systems) were less than 2% over 23 days of comparison. Mean irradiances compared to better than 1% over the period. Although this does not include a comparison with an absolute standard, we must trust Eppley Laboratories for the original sensitivity of the PSP. An additional comparison was made between the PSP used during MILDEX and another PSP acquired in 1985. The agreement between the two PSPs is similar (if not better) than that found between the MILDEX PSP and Kipp and Zonen. These considerations substantiate the 10 W m^{-2} error indicated above and make comparisons with measurements from the two MILDEX instruments valuable.

Table 1 summarizes the insolation and cloud cover data. Cloud cover varied from 0.09 to 0.88 and insolation from 33.7 W m^{-2} to 177.9 W m^{-2}. During certain days when R/P FLIP and *R/V Acania* were close (7 and 9 November), large discrepancies in the two vessels' cloud cover observations exist, which illustrates the subjectivity of estimating cloud cover visually.

For the days listed in Table 1, GOES-6 VISSR images in the visible (0.5–0.75 μm) were acquired at hourly intervals from 1545 UTC to 2145 UTC. Each

TABLE 1. Daily values of insolation observed aboard R/P FLIP and *R/V Acania* during MILDEX. The two ships traveled near the same site, which was given as 33.8°N and 126.3°W. Visual cloud cover estimates are also given.

Date	Ship	Insolation (W m^{-2})	Cloud cover
26 Oct 1983	*R/V Acania*	171.2	0.25
27 Oct 1983	*R/V Acania*	156.0	0.51
28 Oct 1983	*R/V Acania*	141.0	0.45
29 Oct 1983	*R/V Acania*	175.6	0.28
30 Oct 1983	*R/V Acania*	137.4	0.37
31 Oct 1983	*R/V Acania*	92.2	0.62
01 Nov 1983	*R/V Acania*	149.8	0.47
02 Nov 1983	*R/V Acania*	177.9	0.16
03 Nov 1983	*R/V Acania*	133.0	0.77
04 Nov 1983	*R/V Acania*	126.2	0.61
05 Nov 1983	*R/V Acania*	165.5	0.15
05 Nov 1983	R/P FLIP	172.6	0.09
06 Nov 1983	*R/V Acania*	144.2	0.34
06 Nov 1983	R/P FLIP	152.0	0.34
07 Nov 1983	*R/V Acania*	124.8	0.38
07 Nov 1983	R/P FLIP	121.4	0.63
08 Nov 1983	*R/V Acania*	120.9	0.76
08 Nov 1983	R/P FLIP	125.7	0.52
09 Nov 1983	R/P FLIP	83.7	0.85
10 Nov 1983	R/P FLIP	37.5	0.88
11 Nov 1983	R/P FLIP	131.2	0.20
12 Nov 1983	R/P FLIP	156.8	0.17
13 Nov 1983	R/P FLIP	138.4	0.50

image contained noncalibrated brightness counts coded on a 6-bit scale. At the latitude and longitude of MILDEX, the spatial resolution of the data is 1.2 km. The noncalibrated brightness counts were converted into geophysical units by applying Frouin and Gautier's (1987) procedure. To compare with surface measurements, 25 × 25 km subareas centered on the ship locations were selected. The size for the subareas is typical of the distance atmospheric disturbances travel between the hourly observations. The Gautier et al. technique was applied to these data, and insolation estimates at hourly intervals were integrated over time to yield average daily totals. In the computations, a horizontal visibility of 23 km was assumed to represent average aerosol loading during the experiment.

5. Results and discussion

Plots of computed versus measured insolation are presented in Fig. 1 for the five empirical formulas and the satellite technique. All the empirical formulas overestimate insolation, whereas the satellite technique underestimates insolation. The satellite predictions, however, agree best with the measurements. This is substantiated by the comparison statistics, which show a 0.97 correlation coefficient, a 12.0 W m^{-2} standard error of estimate, and a −4.9 W m^{-2} bias. Among the empirical formulas, Mosby's gives the best results. The correlation coefficient is 0.84, the standard error of estimate 19.1 W m^{-2}, and the bias 3.4 W m^{-2}. Kimball's formula performs similarly to Mosby's, with only slightly degraded correlation coefficient (0.81) and standard error of estimate (20.2 W m^{-2}). Reed's formula yields the best correlation coefficient (0.85) and standard error of estimate (17.9 W m^{-2}) of all the empirical formulas, but exhibits a 6.2 W m^{-2} bias. Laevastu's and Berliand's formulas display the largest biases, 24.5 and 15.2 W m^{-2} respectively. Note that short-term biases compared to measurements of less than 5 W m^{-2} cannot be considered as significant, since a difference of this magnitude may be due to pyranometer error as well. Thus the empirical formulas, except Laevastu's and Berliand's, give reasonably good insolation estimates compared to the satellite technique, although the satellite technique remains definitely better.

The results obtained with the empirical formulas must be compared to those of previous studies. Reed (1977) discussed the performance of the various empirical formulas examined here under clear sky conditions. He concluded that Kimball's and Mosby's formulas give insolation values appreciably greater (20%–50%) than the Smithsonian's. At 25°N in autumn, Laevastu's and Berliand's predictions were found to be too low by less than 5% and about 10%, respectively. Kimball's cloud factor, however, is smaller than Reed's by 0.1 and 0.2 depending on the noon solar altitude, which reduces the clear sky discrepancies. This, in fact, explains why in Fig. 1 the biases obtained with Kimball's and Mosby's formulas on the one hand and with Reed's on the other are similar. Analyzing radiation measurements collected in February 1975 near 35°N and 155°W (northeast Pacific), Simpson and Paulson (1979) found that Kimball's formula underestimates insolation by 18%, whereas Reed's overestimates insolation by 6% (about the same amount as found in this study). In other words, Kimball's predictions were lower than Reed's by 24%. This can be explained by the prevailing overcast conditions and the low noon solar altitudes during the experiment, which resulted in Kimball's cloud factors being 40%–60% smaller than Reed's. For the same reason (i.e., because Laevastu's cloud factor is greater than Reed's and, especially, Berliand's) Laevastu's predictions are found to be higher than Reed's and Berliand's.

The empirical formulas' predictions, however, are based on visual cloud cover estimates that are inherently subject to large errors (see, for example, Holle and McKay 1975) and are generally sparse over oceanic areas. It is therefore useful to consider, as an alternative, the utilization of cloud cover derived from satellites. Unfortunately, the factors describing the reduction of insolation by clouds were established from visual cloud cover data not directly comparable with satellite estimates. It has been noted (e.g., Malberg 1973) that satellite sensors yield cloud cover estimates that are systematically smaller than those obtained by observers. Reed (1976, 1977) suggested that cloud cover derived

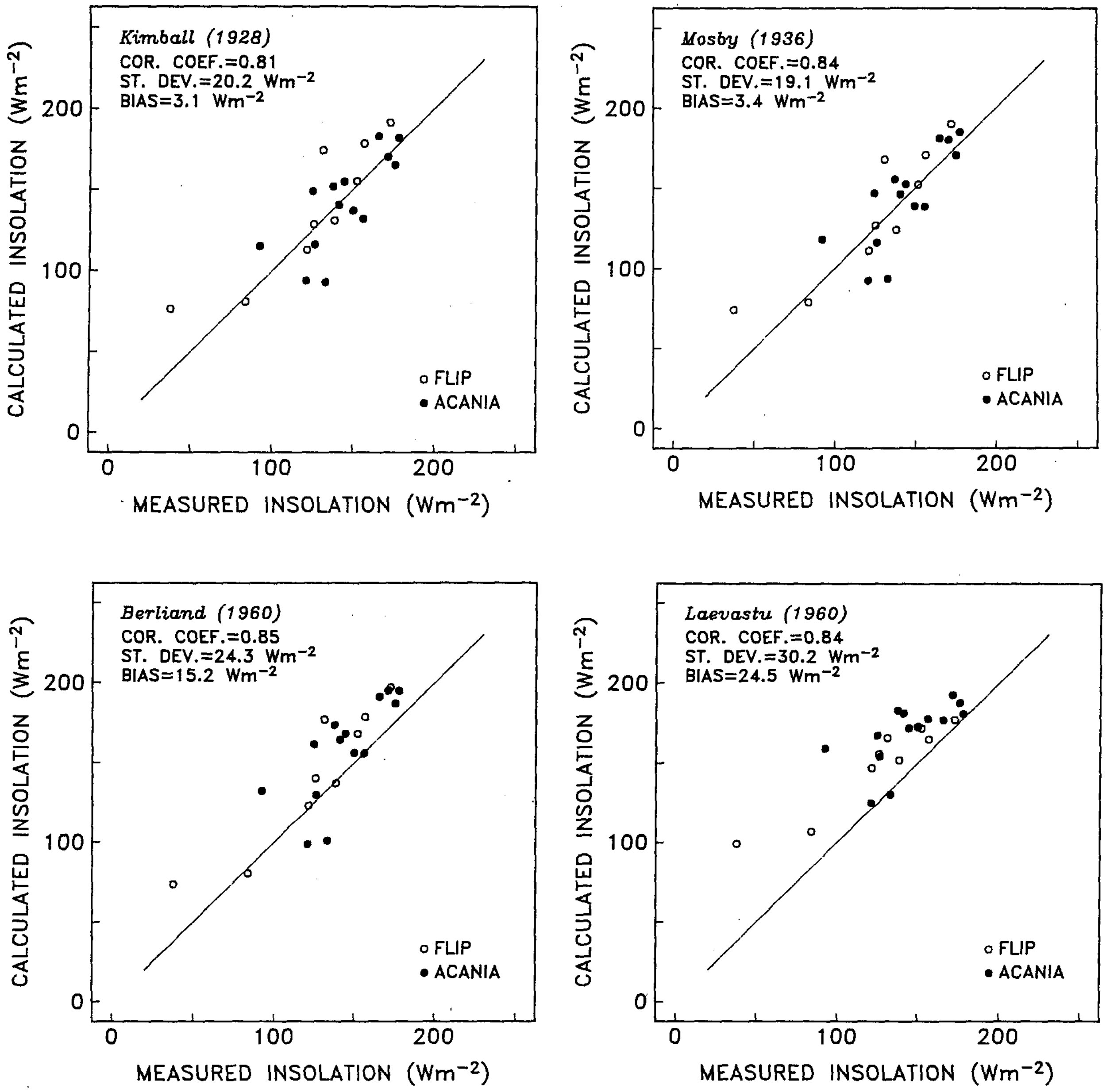

FIG. 1. Plots of daily insolation computed with the formulas of Kimball (1928), Mosby (1936), Berliand (1960), Laevastu (1960), Reed (1977), and with the satellite technique of Gautier et al. (1980) versus observations from R/P FLIP and *R/V Acania* during MILDEX. Included in the figure are the comparison statistics.

from satellite nephanalyses should be increased by 0.2 to agree with surface estimates. There is no convincing evidence, however, that the recent satellite techniques of cloud detection (e.g., Reynolds and Vonder Haar 1977; Gautier et al. 1980; Coakley and Bretherton 1982; Debois et al. 1982; Simmer et al. 1982; Chahine 1982; Phulpin et al. 1983; Arking and Childs 1985), some of them allowing for partially filled fields of view, are negatively biased.

Figure 2 presents the comparison of satellite-derived and visual cloud cover estimates during MILDEX. The satellite estimates were computed from the 25 × 25 km GOES-6 images described in section 3. The estimates of cloud cover obtained at hourly intervals were then averaged to produce daily means. The scatter plot in Fig. 2 indicates that the two types of estimates are in fair agreement. A correlation coefficient of 0.9 and a standard error of estimate of 0.18 are computed. This is not quite expected considering the subjective nature of visually estimating cloud cover from ships. The satellite predictions, however, are generally higher than those obtained visually, especially when cloud cover is

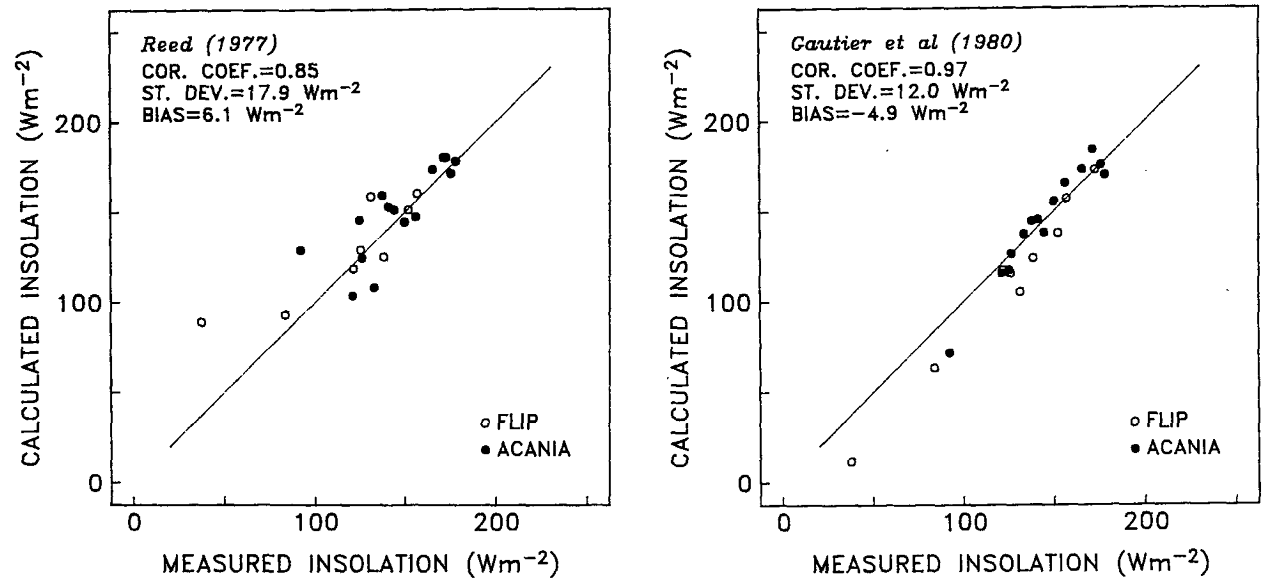

FIG. 1. (*Continued*)

greater than 0.4. The bias is 0.11 and cannot be attributed to relatively large viewing zenith angles during MILDEX (about 48°) because no overestimation is observed at lesser cloud amounts. The fact that the satellite values tend to be higher than the visual amounts is apparently in contradiction with Reed's (1976, 1977) earlier findings. Reed, however, derived his satellite estimates from visual nephanalysis of satellite photographs and this procedure differs from the threshold technique employed here. Moreover, his comparisons were made with 5–12 day averages deduced from photographs taken once per day (either 0900 or noon local time).

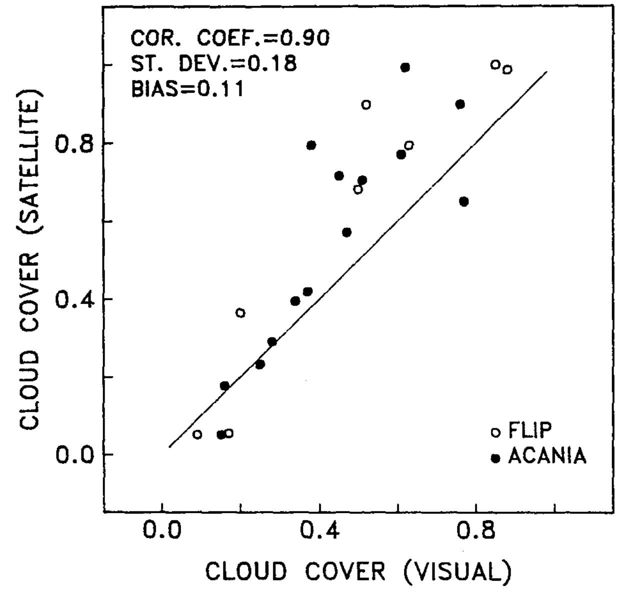

FIG. 2. Daily cloud cover estimates from GOES-6 VISSR images and from visual observations aboard R/P FLIP and *R/V Acania* during MILDEX.

Using the cloud cover derived from GOES-6 data, the predictions of the various empirical formulas were recomputed. Table 2 gives the new comparison statistics as well as those obtained previously. With the exception of Laevastu's formula, all the empirical formulas are now negatively biased. This is a direct consequence of the higher (0.11 on the average) satellite cloud cover. The biases are generally higher in magnitude, which is reflected to a lesser extent in the standard errors of estimate. These range, almost as before, from 19 to 30 W m^{-2}. Laevastu's formula, which gives the worst predictions when employed with visual cloud cover, now exhibits the best comparison statistics.

In view of these results, we conclude that cloud factors established from visual cloud cover observations would provide useful insolation estimates if employed uncorrected with satellite-derived cloud cover data. This does not imply, however, that visually observed and satellite-derived cloud cover should be used together (such an approach has not been evaluated in the present study). The procedure is warranted by the strong dependence of satellite-derived cloud cover upon the size of the areas considered and the large differences between cloud factors, which can reach 75% in overcast conditions (Reed 1977). The verifications by Reed (1978, 1982) also suggest that cloud factors have only a 10%–15% accuracy on monthly time scales, and are therefore expected to be much more uncertain on daily time scales. The main argument in favor of using sat-

TABLE 2. Comparison statistics of observed and calculated daily insolation during MILDEX. Cloud cover is either (a) visually observed or (b) derived from satelite data. Correlation coefficient, standard deviation, and mean difference (calculated minus observed) are denoted by r, σ and δ, respectively.

	(a)			(b)		
References	r	σ (W m^{-2})	δ (W m^{-2})	r	σ (W m^{-2})	δ (W m^{-2})
Kimball (1928)	0.81	20.2	3.1	0.81	30.2	−13.2
Mosby (1936)	0.84	19.1	3.4	0.82	29.3	−12.9
Laevastu (1960)	0.84	30.2	24.5	0.89	18.8	6.7
Berliand (1960)	0.85	24.3	15.2	0.85	29.2	−5.7
Reed (1977)	0.85	17.9	6.1	0.84	20.4	−6.2
Gautier et al. (1980)	—	—	—	0.97	12.0	−4.9

ellite data, however, is that many oceanic areas are not well sampled for visual cloud cover, and the satellite is the most appropriate tool to provide global coverage. Furthermore, cloud climatologies based on data from meteorological satellites (e.g., Sadler et al. 1976; Shideler and Sadler 1979; Saunders 1985) are now routinely produced. In fact, the International Cloud Climatology Project (Schiffer and Rossow 1983) will provide in the coming years a global climatology of cloud cover. Note finally that the technique of Gautier et al. is relatively simple to apply, the most computer-intensive task being the cloud cover computation. We therefore recommend that it be incorporated in the ISCCP analyses.

6. Conclusions

Comparisons of the satellite technique of Gautier et al. with five commonly referenced empirical formulas to estimate daily insolation over the oceans demonstrate the superiority of the satellite technique, which exhibits a 0.97 correlation coefficient, a 12.0 W m^{-2} standard error of estimate, and a −4.9 W m^{-2} bias error. Of the empirical formulas examined, Mosby's yields the most accurate predictions with a 0.84 correlation coefficient, a 19.1 W m^{-2} standard error of estimate, and a 3.4 W m^{-2} bias. Kimball's and Reed's formulas, however, perform nearly as well. In fact, Reed's formula displays the best correlation coefficient and standard error of estimate (0.85 and 17.9 W m^{-2}, respectively), but is definitely more biased than Kimball's and Mosby's. The other formulas, namely Laevastu's and Berliand's, largely overestimate insolation, which makes them only marginally suitable for climate studies.

Cloud cover derived from GOES-6 images is found to be higher than that observed visually, by 0.11 on the average. This appears to contradict earlier findings, which indicate that satellite estimates are generally less than visual amounts, but the discrepancy is linked to the different cloud detection techniques applied.

When used with satellite-derived cloud cover, all the empirical formulas except Laevastu's display larger negative biases. The standard errors of estimate, however, describe almost the same range (19–30 W m^{-2}). The results suggest that empirical formulas, if employed with satellite-derived cloud cover, would provide useful insolation estimates in oceanic areas where visual cloud observations are sparse.

It should be emphasized, finally, that the above analysis is based upon a limited time period and a single geographic location. Consequently, the conclusions cannot be readily generalized.

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