Computation of Incoming Solar Radiation over the Equatorial Pacific

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(Manuscript received 29 November 1967)

ABSTRACT

This paper discusses findings in regard to cloud distributions over the equatorial Pacific and the development of a method, compatible with actual cloud distributions, for using certain existing formulas to compute incoming solar radiation from meteorological data.

U. S. Air Force Uniform Summaries of Surface Weather Observations for 10 central and western equatorial Pacific sites indicate that the very large cirriform cloud contribution to total sky cover, noted in the July 1957–June 1958 Canton Island weather data, is a general characteristic of the cloud distribution over a large part of the western equatorial Pacific. Since most formulas for computing incoming solar radiation depend on a mean total cloud cover entry, a large bias toward thin cirriform cloud could lead to sizeable underestimations of incoming solar radiation and cause significant errors in heat budget calculations for this region.

In order to determine a suitable cloud cover term, monthly mean total sky cover, low cloud cover and total opaque sky cover values were obtained from the July 1957–June 1958 Canton Island weather data and tested in six commonly used formulas for computing incoming solar radiation. On comparing computations with recorded values, the mean total sky cover entry gave large underestimations of incoming solar radiation with all formulas. Test results suggested the use of a monthly mean sky cover term obtained by using mean low cloud cover values for the daylight hours of fair weather days and mean total opaque sky cover for the daylight hours of days dominated by disturbance weather. The Kimball, Black, Budyko and Berliand formulas gave very satisfactory results when using the suggested term. Computations from the latter three formulas were within 10% of recorded values for all months. The use of this approach with Black's formula is particularly appropriate, since the computations are then based on the incoming solar radiation on a horizontal surface at the top of the atmosphere, rather than on the radiation received at the earth's surface under clear sky conditions.

1. Introduction

An earlier paper (Quinn and Burt, 1967), which was primarily based on a study of Canton Island weather and solar radiation data for July 1957–June 1958, revealed that thin fair weather cirriform cloud frequently contributed an unusually large amount to the total sky cover; also, the thin cirriform overcasts, alone, did not appear to reduce incoming solar radiation significantly beyond that received with a clear sky. Since very few sites in the tropical Pacific have recorded incoming solar radiation, the various mean monthly and/or annual presentations of Kimball (1928), Black (1956), Budyko (1963), and Wyrtki (1965) have relied heavily on computed values over this region. The computations usually depended on formulas having a mean total cloud cover[1] input. These formulas were generally developed for higher latitude locations, where cloud distributions (by type and amount), weather and solar altitude ranges, differ considerably from those of the equatorial region. Therefore, if the cloud distribution noted at Canton was widespread, it could cause a sizeable underestimation of incoming solar radiation, and significant errors in the heat budget figures for the region involved.

Therefore, it was desirable to determine whether the unusually large cirriform contribution to total sky cover during July 1957–June 1958 was generally applicable to Canton; and, if it was, to determine to what extent this cloud distribution applied to other parts of the equatorial Pacific. If the condition was widespread, the objective would then be to develop a suitable approach for computing incoming solar radiation from meteorological data which displayed this unusual cloud distribution.

2. Discussion of the involved sites and data

Basic data used in this study were the July 1957–June 1958 hourly and special surface weather observations, rawinsonde data and total incoming solar radiation records for Canton Island. Canton was the only reasonably representative equatorial marine weather observing site (by virtue of its small land area, lack of relief, and isolation from continental influence) that recorded total incoming solar radiation. The particular year of data was selected because it provided a wide range of weather and an unusually large amount of disturbance type weather at Canton. A description of

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[1] These figures come from climatological cloud cover data which were derived from the much more numerous surface weather observations taken over this region.

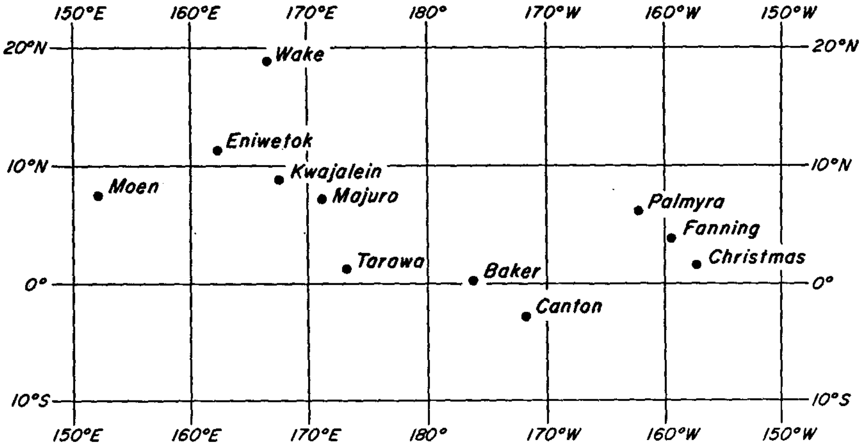

FIG. 1. Locator chart for referenced Pacific islands.

Canton Island and a discussion of the observed and recorded data, data processing and certain findings are contained in the earlier paper (Quinn and Burt, 1967).

U. S. Air Force Air Weather Service (USAF AWS) Uniform Summaries of Surface Weather Observations for the following islands (see Fig. 1) were used to determine whether the Canton Island findings (e.g., the unusually high cirriform contribution to total sky cover) from the July 1957–June 1958 data could be extended in time and space over the central and western equatorial Pacific: Palmyra (5°53′N, 162°06′W), Fanning (3°54′N, 159°24′W), Christmas (1°55′N, 157°20′W), Canton (2°46′S, 171°43′W), Baker (0°12′N, 176°29′W), Tarawa (1°30′N, 173°00′E), Majuro (7°05′N, 171°23′E), Kwajalein (8°44′N, 167°44′E), Eniwetok (11°21′N, 162°21′E), Moen (7°28′N, 151°51′E) and Wake (19°17′N, 166°39′E). Tables 1 and 2 contain climatological data extracted and derived from these summaries. With the exceptions of Moen and Christmas, these sites are all small, low coral islands with land surfaces extending from sea level to a maximun elevation of about 20 ft. Christmas has a land area of nearly 160 mi^2 which is very large compared to the others (U. S. Naval Oceanographic Office, 1952). Moen island is fringed by reefs and rises to several high peaks, the highest of which, Mt. Teroken, attains an elevation of 1214 ft (U. S. Naval Oceanographic Office, 1964). However, since high cloud distribution is an important consideration here, the data from Christmas and Moen are useful.

3. Attenuation of solar radiation

Solar radiation passing through the earth's atmosphere is modified by the following processes (Drummond *et al.*, 1958):

1) Scattering by molecules of air and particles much smaller than the wavelength of light (Rayleigh scattering);
2) Selective absorption by atmospheric gases, particularly oxygen, ozone, carbon dioxide and water vapor;
3) Scattering and absorption by cloud masses; and
4) Scattering and diffuse reflection from particles (dust, soot, salt and other solid and liquid particles) of size comparable with or larger than the wavelength of light.

In the absence of volcanic eruptions, the attenuation factors which are most likely to have a variable effect on the radiation recorded by the Eppley pyranometer (0.3–2.5 μ) at an isolated equatorial marine location are water vapor, salt particles and cloud masses. ESSA (1966) indicates there is quite a bit of salt haze in the air in the vicinity of Canton, but that surface visibilities are almost always $\geq$15mi, except during showers. Entries in the "Remarks" and "Weather and obstructions to vision" columns of the Canton hourly and special surface weather observations (WBAN Forms 10A and 10B) for July 1957–June 1958 did not indicate haze as a significant factor in visibility limitation.

Daily precipitable water vapor values for July 1957–June 1958 ranged from a minimum of about 2.8 cm to a maximum of 6.4 cm. This extreme difference in water vapor content could cause a recorded radiation variation of 3–4% due to water vapor absorptivity (McDonald, 1960). Monthly average values of precipitable water vapor ranged from about 3.9 cm for the driest month (September 1957) to 5.4 cm for the wettest month (January 1958). Such a difference might cause a monthly variation (in recorded radiation) of about 1–2% due to water vapor absorptivity (McDonald, 1960).

In an attempt to evaluate water vapor effects, plots of recorded incoming solar radiation vs solar altitude (on an hourly basis) were made within various short precipitable water ranges for clear sky conditions. The available samples were very small, due to the limited num-

TABLE 1. Climatological data (on an annual basis) for equatorial Pacific sites. (Data were extracted and derived from USAF AWS Uniform Summaries of Surface Weather Observations.)

Island*	Mean tenths of sky cover	Percentage frequency of occurrence of scattered or no clouds	Percentage frequency of occurrence of specified ceiling heights (ft)				Percentage of ceilings ≥10,000 ft	Percentage frequency of occurrence of ceilings ≥20,000 ft	Percentage of ceilings ≥20,000 ft	Mean annual precipitation (inches)	Mean number of days with precipitation >0.25 inch	Percentage frequency of occurrence of observations with precipitation
			0–5000	5500–9500	≥10,000 or unlimited	≥10,000						
Palmyra (33)	6.6	37.1	39.2	7.2	53.5	16.4	26.1	—	—	152.56	133.3	13.6
Fanning (23)	—	—	34.1	5.2	60.7	—	—	—	—	63.67	65.2	8.3
Christmas (77)	4.8	65.1	19.6	2.7	77.6	12.5	35.9	—	—	24.46	24.0	3.4
Canton (209)	6.4	44.0	8.1	1.5	90.4	46.4	82.9	—	—	24.39	23.9	2.7
Baker (13)	—	64.4	12.1	1.3	86.5	22.1	62.2	—	—	—	—	2.7
Tarawa (20)	—	38.6	22.2	3.3	74.5	36.0	58.5	—	—	—	—	5.6
Majuro (112)	8.3	18.5	14.7	3.1	82.2	63.7	78.2	—	—	144 74	130.4	11.0
Kwajalein (233)	7.4	27.4	19.2	4.7	76.2	48.8	67.2	—	—	97.63	96.9	8.3
Eniwetok (182)	6.7	38.3	10.3	4.1	85.6	47.3	76.7	36.0	58.3	56.13	58.4	5.6
Moen (186)	8.8	11.3	18.7	1.4	79.9	68.6	77.3	—	—	148.11	134.5	12.5

* Period of record in months ( ).

ber of clear hours during this year of unusually high rainfall and cloud cover (July 1957–June 1958); therefore, findings in this regard are inconclusive. However, there did not appear to be any clear-cut transmission difference when comparing a relatively dry atmosphere (2.8–3.2 cm precipitable water) to a relatively moist one (4.9–5.2 cm precipitable water). It must be considered that the dry atmosphere is likely to contain a much larger number of salt particles than the moist atmosphere, since rainfall, which is more likely to be associated with moist conditions, tends to clear salt particles from the atmosphere (Thomson, 1927). Therefore, there may often be a compensatory relationship between precipitable water vapor amounts and salt particle content in the atmosphere with respect to the attenuation of incoming solar radiation. Certainly, this aspect requires much more investigation. However, we are now left with cloud cover as the significant variable factor in solar radiation attentuation.

4. Implications from summarized data

The Canton Island cloud distribution is very similar to that of Eniwetok according to the long period records (see Table 1). Due to the generally smaller amount of disturbed weather activity at Canton as compared to Eniwetok (see precipitation data of Table 1), the associated frequency of extensive middle cloudiness should be less and the fair weather cirriform cloud proportionately more extensive than at Eniwetok. Therefore, although Canton's cloud cover figures from the USAF AWS Summaries are considerably lower than those recorded for the unusual July 1957–June 1958 period at Canton (Quinn and Burt, 1967), the cloud distribution with regard to relative amounts of different types of cloud appears to be quite analogous.

Palmyra, Fanning and Christmas appear to have very much different cloud distributions than the rest of the listed equatorial sites which are located further to the west. Their low cloud contributions to total sky cover are relatively large, whereas their cloud contributions at 10,000 ft and above are very small when compared to like cloud categories for the other sites (see data columns 3 and 7 of Table 1). Although the mean sky covers for Canton (6.4 tenths) and Palmyra (6.6 tenths) differ very little, Palmyra has a much higher percentage of low ceilings, a much lower percentage of ceilings 10,000 ft and above, and several times more precipitation than Canton. Certainly, such large differences in cloud distribution and weather could not be properly represented by a simple total sky cover entry in formulas for computation of incoming solar radiation.

It appears that the high percentages of ceilings 10,000 ft and over at the seven western equatorial Pacific stations can be attributed mostly to large cirriform contributions, based on the following information:

1) Extensive middle clouds in this region are usually associated with disturbance weather conditions which

TABLE 2. Summer and winter season data for Wake Island. (Data were extracted and derived from USAF AWS Uniform Summaries of Surface Weather Observations.)

Period*	Mean tenths of sky cover	Percentage frequency of occurrence of scattered or no clouds	Percentage frequency of occurrence of specified ceiling heights (ft) 0–5000	5500–9500	≥10,000 or unlimited	≥10,000	Percentage of ceilings ≥10,000 ft	Percentage frequency of occurrence of ceilings ≥20,000 ft	Percentage of ceilings ≥20,000 ft	Mean monthly precipitation (inches)	Mean number of days with precipitation >0.25 inch	Percentage frequency of occurrence of observations with precipitation
July	6.2	44.9	10.6	3.2	86.2	41.3	75.0	31.0	56.3	4.46	4.4	6.6
August	6.1	46.0	10.7	2.8	86.5	40.5	75.0	28.6	53.0	6.41	6.2	7.4
September	5.7	50.9	9.7	2.4	87.9	37.0	75.4	27.9	56.8	4.83	5.0	5.5
Average (July–Sept.)	6.0	47.3	10.3	2.8	86.9	39.6	75.1	29.2	55.4	5.23	5.2	6.5
January	4.5	64.7	24.5	4.2	71.3	6.6	18.7	4.9	13.9	1.03	1.0	3.8
February	4.1	68.5	24.7	3.2	72.1	3.6	11.4	2.7	8.6	1.03	0.9	3.4
March	4.3	67.5	21.9	3.8	74.3	6.8	20.9	4.5	13.8	1.56	1.5	4.1
Average (Jan.–Mar.)	4.3	66.9	23.7	3.7	72.6	5.7	17.0	4.0	12.1	1.21	1.1	3.8

* Period of record is approximately 210 months.

occur much less frequently than fair weather. This was noted in a detailed study of Canton Island weather data for July 1957–June 1958 (Quinn and Burt, 1967). It was also indicated by the flight weather data over the tropical Pacific in Malkus and Riehl (1964). Riehl and Malkus (1958) have suggested that about 10% of the equatorial trough zone is occupied by disturbances.

2) The extensive middle clouds associated with disturbances are frequently included in the category where ceilings were less than 10,000 ft, which further diminishes the possible higher level (above 10,000 ft) middle cloud contribution to total sky cover.

3) Precipitation figures such as those included in the last column of Table 1 give a rough idea of the percentage of time that disturbances occur. Of course, these figures are minimal and generally indicate only the percentage of time that the more active parts of disturbances affected the location. Some small disturbances only reflect cumulus congestus and cumulonimbus developments in the hourly cloud observations. (Here it has been assumed that the precipitation which is not associated with disturbances is infrequent, light and spotty.)

4) Eniwetok, which shows a cloud distribution similar to the other sites in the western equatorial Pacific, provides a direct figure on the precentage of ceilings 20,000 ft and over (data column 9, Table 1). This figure tends to confirm the large high cloud contribution to total sky cover.

5) The intervening fair weather periods are far more extensive than disturbance periods and, during fair weather, cumuliform and cirriform clouds are the usual types present (Quinn and Burt, 1967).

6) Since equatorial type weather conditions might be expected to extend further to the north during the Northern Hemisphere summer, Wake Island[2] weather data were studied to see if the characteristic weather conditions, attributed to the western equatorial Pacific, were reflected in Wake's summer weather record. It can be seen, from a comparison[3] of summer data in Table 2 with annual weather data for the last seven stations in Table 1, that the summer cloud distribution and weather at Wake are quite similar to the general cloud distribution and weather for sites in the western equatorial region. This summer cloud distribution and weather at Wake very closely resembles the general situation at Eniwetok. Mean monthly soundings for summer months of the July 1957–June 1958 period at Wake were very similar to those of Canton Island for the same months. Table 2 shows an extremely large contrast between summer and winter cloud distributions and weather at Wake. A large contrast is also shown between the Wake Island soundings for summer and winter seasons. The seasonal differences between high cloud ceiling percentages at Wake (data columns 8 and 9, Table 2) are particularly striking. The relatively large high cloud contribution to total sky cover during the summer months is typical of the general situation postulated for western equatorial Pacific locations.

5. Cloud cover terms

The findings presented in the previous section indicate that computations based on mean total sky cover could result in sizeable underestimations of incoming solar radiation over a large part of the western equatorial Pacific (due to the large cirriform component). The necessity of finding a more suitable cloud term to enter into formulas for computation of incoming solar radiation was now apparent. The ideal cloud term must somehow be able to take into account the type and thickness of clouds present, as well as their coverage.

It would appear that low cloud cover could represent the fair weather situations very well; however, it could not take into account the extensive clouds at higher levels during disturbance periods.

Total opaque sky cover,[4] which refers to that portion of the sky cover dense enough to hide the outline of the sun or moon, might also be a suitable cloud term. It would represent cloud density to some degree, and might eliminate the weakness of the mean total sky cover term with regard to the large fair weather cirriform contribution. In addition to representing the low cloud contribution, it could also account for dense patches of upper level cloud during transition periods, and, during disturbance conditions, it could account for clouds at all levels. The principal weakness of this term is the highly subjective nature of its measurement. However, with contrasts in cloud types and weather conditions as they occur in the equatorial region, it might be possible for different observers to come up with similar evaluations.

6. Test of cloud cover terms

The previously discussed cloud cover terms (mean total sky cover, mean low cloud cover and mean total opaque sky cover) were tested in some of the more commonly used formulas for computing incoming solar radiation, in order to determine a more suitable method for handling cloud distributions similar to those of Canton. Only the Canton data for July 1957–June 1958 were processed so as to provide all three terms for this comparison study. However, it was possible to use the long period record (see MTSG in Table 3) for an additional test of the mean total sky cover term. It was expected that findings in regard to the Canton data would be applicable, in general, to cloud distributions as they

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[2] Wake Island is quite ideal as a marine weather observing site by virtue of its size, isolation, lack of relief and favorable weather station location (on the east side of the island) in relation to the prevailing easterly winds. Also, Wake has a long period of high quality weather data available.

[3] Note that the figures in data columns 10 and 11 of Table 2 are monthly values, which are not directly comparable to figures in like columns of Table 1.

[4] Total opaque sky cover, which is recorded in a column of the WBAN Form 10B, is not included in teletype weather transmissions or climatological summary data.

TABLE 3. Radiation and cloud cover entries used in formulas for computing incoming solar radiation.

Item	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.
SRTA	805	855	903	923	912	900	913	932	927	885	827	792
SRCS	612	650	686	701	693	684	694	709	705	673	629	602
SAN	65.86	73.78	84.60	83.80	74.24	69.74	72.15	80.13	86.85	77.30	68.29	64.15
MTS	9.7	8.6	7.9	8.9	10.0	8.9	9.9	...	9.4	8.6	8.6	7.9
MLC	2.6	2.6	2.3	2.2	3.3	2.7	3.3	...	2.3	2.3	2.5	2.7
MTOS	3.3	3.7	3.5	3.5	6.0	5.8	7.8	...	5.1	4.8	4.8	4.0
MTSG	6.4	5.9	5.4	6.1	6.4	6.8	6.8	6.4	6.4	6.5	6.5	6.2
MCS	2.6	2.7	2.3	2.4	4.8	4.5	5.9	...	2.9	3.0	3.3	3.0

SRTA Solar radiation (ly) received on a horizontal surface at the top of the atmosphere.
SRCS Total incoming solar radiation (ly) received at the surface with clear skies.
SAN Solar altitude at noon in degrees.
MTS Mean total sky cover in tenths (July 1957–June 1958).
MLC Mean low cloud cover in tenths (July 1957–June 1958).
MTOS Mean total opaque sky cover in tenths (July 1957–June 1958).
MTSG Mean total sky cover in tenths (20-yr period).
MCS A mean cloud cover value based on the mean low cloud cover for days of fair weather and mean total opaque sky cover for days when disturbance weather is evident (July 1957–June 1958).

occur over a large part of the western equatorial Pacific. The following formulas were used since they are quite widely recognized and each had a somewhat different makeup:

$Q=Q_0(1.0-0.71C)$ [Kimball, 1928]

$Q=Q_A(0.803-0.340C-0.458C^2)$ [Black, 1956]

$Q=Q_0[1-(1-k)C]$ [Savino-Ångström formula (Budyko, 1956)]. With $k=0.345$ for Canton's latitude, this formula becomes $Q=Q_0(1-0.655C)$.

$Q=Q_0(1-aC-bC^2)$ [Berliand, 1960]. With $a=0.39$ for Canton's latitude and $b=0.38$, this formula becomes $Q=Q_0(1-0.39C-0.38C^2)$.

$Q=Q_0(1-0.0006C_t^3)$ [Laevastu, 1960]

$Q=Q_0(1-0.0895C_0+0.00252a')$ [Tabata, 1964]

where:

Q = total incoming solar radiation (ly) near the ocean surface,

Q_0 = total incoming solar radiation (ly) near the ocean surface with a clear sky,

Q_A = total incoming solar radiation (ly) on a horizontal surface at the top of the atmosphere,

C = proportion of sky covered by clouds,

C_t = cloud cover in tenths of sky $(1-10)$,

C_0 = cloud amount in oktas $(1-8)$,

a' = mid-month solar altitude in degrees.

By using the applicable data of Table 3 in the formulas shown above, the figures contained in Tables 4 and 5

TABLE 4. Calculated and recorded incoming solar radiation (ly) with computation based on specified formulas and indicated cloud terms for July 1957–June 1958.

Formula used	Cloud term*	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Mar.	Apr.	May	Jun.
Kimball (1928)	MTS	190	254	302	258	201	253	208	233	262	245	264
	MLC	502	533	576	589	534	554	534	592	565	516	488
	MTOS	471	481	514	526	395	404	312	451	444	415	433
Black (1956)	MTS	35	147	224	126	5	123	16	72	152	142	196
	MLC	551	585	633	652	585	610	585	650	620	570	537
	MTOS	516	525	567	580	396	407	237	474	473	442	470
Budyko (1956)	MTS	223	284	331	292	239	285	244	271	294	275	291
	MLC	508	540	582	600	543	563	544	599	571	526	495
	MTOS	480	493	529	540	421	424	339	470	462	431	444
Berliand (1960)	MTS	159	247	309	245	159	239	167	211	256	239	271
	MLC	532	566	611	624	575	588	576	627	599	554	518
	MTOS	508	527	556	568	437	438	326	494	485	453	470
Laevastu (1960)	MTS	277	402	509	404	277	395	290	354	416	389	424
	MLC	606	643	681	697	678	676	679	700	668	623	595
	MTOS	599	630	668	683	603	604	496	649	628	587	579
Tabata (1964)	MTS	288	370	444	402	326	369	328	385	390	350	359
	MLC	600	650	719	738	660	672	657	743	693	625	583
	MTOS	569	599	660	673	525	521	433	602	573	521	527
Average daily solar radiation (recorded)		535	571	608	626	482	463	415	573	544	512	532

* MTS, mean total sky cover; MLC, mean low cloud cover; MTOS, mean total opaque sky cover.

TABLE 5. Calculated and recorded incoming solar radiation (ly) with computations based on specified formulas and 20-yr mean sky covers of Table 3.

Formula used	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Kimball (1928)	359	387	385	362	339	337	334	378	423	397	378	354
Black (1956)	329	371	369	344	322	329	320	379	439	392	363	324
Budyko (1956)	385	412	409	387	361	358	355	399	443	421	402	379
Berliand (1960)	382	418	416	397	371	367	361	416	466	435	409	376
Laevastu (1960)	563	598	594	562	525	516	516	570	621	606	584	555
Tabata (1964)	482	527	536	491	445	432	433	496	567	543	505	471
Average daily solar radiation*	590	630	631	598	560	538	543	595	636	649	613	585

* Based on a 12-yr record.

were obtained. The mean total sky cover term for the months of July 1957–June 1958 gave excessively low incoming solar radiation values with all formulas (see Table 4). Using the 20-yr mean monthly sky cover figures, all formulas again gave lower than recorded values for computations in each instance (see Table 5). In this latter case, however, Laevastu's formula gave values that were reasonably close. The 20-yr mean monthly figures do not provide sufficient range in conditions for proper evaluation of formula capabilities.

The mean low cloud term gave excessively high values in all months with the formulas of Laevastu and Tabata (see Table 4). Kimball's, Black's Budyko's and Berliand's formulas gave excessively high values for the months of heaviest rainfall (November, December and January) when the disturbed weather was most frequent.

The mean total opaque sky cover term gave radiation values which were generally too low with the formulas of Kimball, Black, Budyko and Berliand. The use of this term in Laevastu's formula gave values that were ordinarily too high. Computed values from Tabata's formula, although reasonably close to the recorded amounts, were generally on the high side.

7. Discussion of test results

The mean total sky cover term appeared to be quite unsatisfactory as a radiation reduction term in cases where cirriform cloud was an unusually large contributor to sky cover. The mean low cloud term appeared to work fairly well in Kimball, Black, Budyko and Berliand formulas during months when very little disturbance weather was noted between sunrise and sunset. The mean total opaque sky cover term only worked reasonably well in Tabata's formula. However, in the Kimball, Black, Budyko and Berliand formulas it gave lower than recorded values which contrasted well with the higher than recorded values obtained when the low cloud cover term was used for months with a large amount of disturbed weather. Perhaps a compromise approach, using the low cloud term for fair weather days and the total opaque sky cover term for days with disturbed weather, would provide the desired results. This approach seemed logical, since low cloud cover appeared to represent quite adequately the radiation reduction during fair weather periods of the July 1957–June 1958 Canton Island weather data, when using the first four formulas. Also, the opaque cloud cover appeared to be the only simple term which could represent the effective cloud cover during disturbance weather conditions. The more accurate observations of low cloud cover, and the ordinarily large contribution of fair weather conditions to long period evaluations (i.e., monthly) should provide considerable stability to this computation. Although opaque cloud cover values would reflect the limitations of highly subjective estimations, the opaque features during disturbance periods should be quite clearly defined.

8. Proposed solution and its evaluation

Based on test results, it was proposed that the compromise cloud term, suggested in the preceding section, be tried in each of the six formulas previously used. Monthly mean cloud term values were obtained by using mean low cloud cover amounts for the daylight hours of fair weather days and mean total opaque sky cover values for the daylight hours of days dominated by disturbance weather (see MCS row of Table 3). The calculated mean daily incoming solar radiation values (on a monthly basis) along with their departures from the mean daily recorded values, are contained in Table 6.

The formulas of Laevastu and Tabata gave figures which were consistently too high with this approach. However, the formulas of Kimball, Black, Budyko and Berliand gave very satisfactory results; and, the last three of these formulas provided computations within 10% of the recorded values for all months of the July 1957–June 1958 period. Although the test sample was small, it was very encouraging to see that this compromise cloud term worked well in four of the commonly used formulas for computing incoming solar radiation during both the months with very little disturbance weather (July–October 1957) and the months with a large amount of disturbance weather (November 1957–January 1958). This indicated that the proposed approach could be used to cover a wide range of weather activity in the equatorial Pacific. It is recommended,

Table 6. Calculated mean daily incoming solar radiation values (ly), using specified formulas with proposed approach, and departures (ly) from mean recorded values (MRV) for July 57–June 58.

Formula used	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Mar.	Apr.	May	Jun.
Kimball (1928)	502	525	574	582	457	465	403	560	530	482	474
MRV departure	−33	−46	−34	−44	−25	+2	−12	−13	−14	−30	−58
Black (1956)	551	580	633	641	487	501	404	617	584	530	523
MRV departure	+16	+9	+25	+15	+5	+38	−11	+44	+40	+18	−9
Budyko (1956)	508	535	582	591	475	482	426	571	540	493	483
MRV departure	−27	−36	−26	−35	−7	+19	+11	−2	−4	−19	−49
Berliand (1960)	532	559	611	624	499	506	444	606	572	522	512
MRV departure	−3	−12	+3	−2	+17	+43	+29	+33	+28	+10	−20
Laevastu (1960)	606	642	681	695	647	646	609	694	662	615	592
MRV departure	+71	+71	+73	+69	+165	+183	+194	+121	+118	+103	+60
Tabata (1964)	600	645	719	728	584	584	527	713	660	589	570
MRV departure	+65	+74	+111	+102	+102	+121	+112	+140	+116	+77	+38

therefore, that the proposed cloud cover entry be used with the formulas of Black, Budyko or Berliand for computing incoming solar radiation from meteorological data in the equatorial marine region.

Although the results of this test show Berliand's formula to give values closest to the recorded amounts, Black's formula has an advantage, since computations are based on the incoming solar radiation received on a horizontal surface at the top of the atmosphere, rather than the radiation received at the earth's surface under clear sky conditions. Therefore, no prior measurements of incoming solar radiation at the surface would be required, and the geographical, astronomical and meteorological data for any equatorial marine location would be sufficient to compute the incoming solar radiation with this formula. The following formula (Klein, 1948) can be used to obtain the incoming solar radiation (ly min^{-1}) on a horizontal surface at the top of the atmosphere:

$$I_A = 2.00\ (\sin\phi \sin d + \cos\phi \cos d \cos h)/r^2,$$

where:

I_A = the amount of solar radiation incident on a horizontal surface at the top of the atmosphere,
2.00 = the mean solar constant (Johnson, 1954),
ϕ = the geographic latitude of the site,
d = the declination of the sun (the angular distance of the sun north (positive) or south (negative) of the equator),
h = the hour angle (the angle through which the earth must turn to bring the meridian of the observation point directly under the sun),
r = the earth's radius vector (the actual distance between the centers of the earth and the sun divided by the mean distance).

I_A values obtained for the midpoint of each daylight hour can be multiplied by 60 to obtain approximate hourly values of incoming solar radiation. The daily sums of hourly values can be added together for the month and divided by the number of days in the month to get the Q_A entry for Black's formula.

9. Summary

1. The cloud distribution over a large part of the western equatorial Pacific appears to be characterized by a very large cirriform contribution to the mean total sky cover.

2. Most of the formulas used for computation of incoming solar radiation from meteorological data depend primarily on a mean total cloud cover input for radiation reduction. A large bias toward thin fair weather cirrus, such as is experienced over much of the western equatorial Pacific, causes large underestimations of incoming solar radiation over this region.

3. It is highly essential to have an appropriate method for computing incoming solar radiation from meteorological data over the equatorial oceans, since there are several sites that record meteorological data but very few that record incoming solar radiation.

4. Three different cloud terms (mean total sky cover, mean low cloud cover and mean total opaque sky cover) were evaluated in six of the commonly used formulas for computing incoming solar radiation, in order to determine a more suitable computational approach. Mean low cloud cover appeared to represent fair weather days most effectively and mean total opaque sky cover seemed more suitable for days when disturbance weather predominated.

5. A mean monthly cloud cover term, obtained by using mean low cloud cover for fair weather days and mean total opaque sky cover for days when disturbance weather prevailed, gave computations in close agreement with recorded radiation values when using the formulas of Kimball (1928), Black (1956), Budyko (1956) and Berliand (1960). The latter three formulas provided computations within 10% of recorded values for all months of the Canton Island July 1957–June 1958

test data. This approach worked well for fair weather months as well as those with a large amount of disturbance weather.

6. Black's formula shows a certain advantage since its computations are based on the incoming solar radiation received on a horizontal surface at the top of the atmosphere, rather than that received at the earth's surface under clear sky conditions; therefore, computations only require weather, geographical and astronomical data.

Acknowledgments. This work was supported by the National Science Foundation, Grant No. GP-5165, and by the Office of Naval Research, Contract No. Nonr 1286(10), Project No. NR 083-102, and is the result of thesis research toward the Ph.D. degree at Oregon State University. Appreciation is expressed to Mrs. Sally A. Kulm and Mrs. Susan J. Borden for their assistance in computing the hourly solar radiation received on a horizontal surface at the top of the atmosphere. Appreciation is also expressed to Mr. Robert M. Black, Weather Bureau, ESSA, and to the National Weather Records Center, ESSA, for their support to this investigation.

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