A Study of Several Approaches to Computing Surface Insolation over Tropical Oceans

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(Manuscript received 30 September 1968, in revised form 10 December 1968)

ABSTRACT

The goals of this study were to investigate the potential of various meteorological factors for representing the more variable insolation reductions in the tropical atmosphere, and to develop curves and formulas for those relationships which appeared to be effective. Emphasis was placed on developing approaches that depend on simple meteorological entries.

The following were studied in relation to the average daily atmospheric transmission ratio (insolation recorded at the earth's surface divided by the computed insolation on a horizontal surface at the top of the atmosphere) on a monthly basis using four years of Canton Island data and considering only hours between sunrise and sunset: average total opaque sky cover, average total sky cover, average daily duration (in minutes) of precipitation, average daily amount (in inches) of precipitation and fraction of days with precipitation. Also, the average daily amount of precipitation and fraction of days with precipitation were studied on an annual basis in the above manner considering all hours of the day and seven years of Canton Island data.

For monthly insolation estimates, the method using average total opaque sky cover during daylight hours should give the best results (perhaps within 8% of measured values). The method using average daily duration of precipitation during daylight hours should also give good results (perhaps within 12% of measured values). For annual insolation estimates, the approach using average daily amounts of precipitation appears to show considerable promise.

The more suitable monthly approaches should be applicable at least to that part of the equatorial Pacific which experiences weather affecting the dry zone area in its more extensive state. They may also be useful over the greater part of the equatorial Pacific and that part of the tropics extending into the summer hemisphere of the western Pacific. The methods using annual averages could only be useful in the equatorial region. In the future it would be desirable to consider sites which record much larger monthly and annual amounts of precipitation.

1. Introduction

Recent studies (Quinn and Burt, 1968b) have shown the inadequacy of using mean total cloud cover as a radiation reduction factor in formulas for computing insolation (incoming solar radiation) at the earth's surface[1] over the equatorial Pacific. However, the recommended method for improving these computations requires meteorological information which is usually not available to field workers. Marine life and environmental scientists have a need for surface insolation data in relation to tropical Pacific Islands, their intertidal zones and shallow water zones, as well as the euphotic zone in general of the tropical Pacific.

The objective of this investigation was to study various types of meteorological data (from Canton Island observations) with regard to the feasibility of using them to estimate insolation at the earth's surface. In those cases where relationships between meteorological elements and insolation appeared to be meaningful, a further objective was to develop curves and/or formulae which could be entered with meteorological data to obtain insolation amounts. Emphasis was placed on the development of a variety of simplified approaches, so that any available and applicable meteorological data could be used to obtain insolation estimates.

2. Background

Mean total cloud cover was found to be inadequate in the western equatorial Pacific, due to the frequently large thin cirriform contribution to total sky cover (Quinn and Burt, 1968a). From previous study, it appeared that the mean total opaque sky cover[2] had some advantages as a radiation reduction factor. However, precipitation data might also prove useful in view of the following considerations:

1) In the equatorial region, weather disturbances (as defined in Quinn and Burt, 1967), with their extensive cloud development cause large reductions in daily insolation values. Since they are also responsible for significant precipitation, it appeared that insolation might possibly be related to precipitation data.

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[1] Insolation at the earth's surface denotes the total direct and diffuse solar radiation on a horizontal surface as recorded by the Eppley pyranometer (range ~0.3–2.5 μ).

[2] Opaque sky cover is the amount (in tenths) of sky cover that completely hides all that might be above it—opposed to transparent sky cover (Huschke, 1959). It is recorded in a column of the WBAN Form 10B, but it is not included in teletype weather transmissions or climatological summary data.

2) Since rainfall data can be obtained with a minimum of effort and are essential to many other environmental studies, there are many more sites that record rainfall than record complete surface weather observations. If rainfall information could be put to use as an insolation indicator, long periods of record for such data at a large number of island sites would be immediately available for use.

3) The more completely instrumented weather observation sites usually have precipitation gages located close to radiation sensors. Therefore, precipitation data are representative of weather conditions directly above the radiation sensor. However, cloud cover observations generally represent the entire visual hemisphere, which usually takes into account several hundred square miles; thus, they frequently do not accurately reflect cloud conditions directly above the observation point.

4) Rough plots showing total annual rainfall in relation to annual insolation values, based on several years of Canton Island data, indicated that a meaningful relationship existed between these quantities. Similar results were obtained considering days with precipitation vs insolation. It appeared that further refinements, such as considering precipitation data for daylight hours only of days with insolation data, would improve correlations. Since time during which precipitation occurs, regardless of precipitation intensity, would indicate periods when thick clouds were above the pyranometer, this term should also be an effective radiation reduction indicator.

A limitation to the precipitation approach would be the inability to account for extensive disturbance cloud covers which occur without accompanying precipitation. However, a study of the Canton Island WBAN Forms 10A and 10B, in conjunction with applicable insolation data, indicated that the extensive cloud covers of disturbances were generally associated with significant rainfall and large reductions in insolation. Precipitation approaches could only be suggested for a tropical region where fog and associated low stratus or frontal weather conditions do not occur.

3. Canton Island

Insolation data suitable for climatological studies are very scarce over low latitude oceanic areas. The only reasonably suitable site (by virtue of size, lack of relief and isolation from large land masses) in the vicinity of the equator, which recorded both weather and insolation data over a somewhat extensive period, was Canton Island. Physical attributes of Canton Island, as well as certain reasons for selecting it as an equatorial marine site, were discussed in Quinn and Burt (1967). However, the question still arises as to whether findings derived from Canton's data can be considered applicable to other parts of the equatorial or tropical Pacific.

Canton is located near the axis of the equatorial dry tongue which extends westward across the Pacific. This dry zone is discussed and illustrated in Seelye (1950) and Palmer and Pyle (1966). Sometimes this tongue is unusually dry and extensive, extending westward beyond Nauru (0°32′S, 166°55′E); at other times meteorological conditions are such that a large amount of rainfall is received in this equatorial zone. Table 1 shows the results of an extensive dry situation (January–December 1950) and a wet situation (June 57–May 58) as they affect rainfall at several sites in the central and western equatorial Pacific. Although the dry period in this case started near the middle of 1949 at many of the affected sites (e.g., Canton had 5.27 inches of rain from June 49–May 50), the calendar year 1950 was used since it was part of the same dry period and data were much more complete for this 12-month span. The wet conditions over the zone were generally noted from near the middle of 1957 to about mid-1958, with involved stations in most cases receiving much heavier than average rainfall over a period of 10–15 months. Some of the more extensive dry situations of the present century occurred within the following periods: 1906–1910, 1916–1918, 1924–1925, 1926–1927, 1933–1934, 1937–1939, 1949–1951, 1954–1956, 1961–1963. Some of the more extensive wet situations (in excess of five months duration at most stations involved) occurred in: 1904–1905, 1911–1912, 1914–1915, 1918–1919, 1930–

TABLE 1. Precipitation (in inches) for dry, average and wet years at several sites in the central and western equatorial Pacific.

Station	Location	Precipitation January–December 1950	Average[a] annual precipitation	Precipitation June 57–May 58
Fanning	3°51′N, 159°22′W	27.80	79.56 (40)	171.10
Christmas	1°59′N, 157°28′W	—	30.51 (16)	91.22
Penrhyn	9°01′S, 158°03′W	38.27[b]	79.24 (23)	121.33
Canton	2°46′S, 171°43′W	15.09	29.43[c]	82.82
Hull	4°31′S, 172°11′W	—	42.29 (11)	115.27
Gardner	4°40′S, 174°32′W	—	51.92 (13)	131.86
Sydney	4°29′S, 171°16′W	—	41.03 (9)	98.42
Little Makin	3°18′N, 173°08′E	50.29	98.31 (23)	168.03
Butaritari	3°00′N, 173°30′E	56.85	115.97 (15)	—
Marakei	2°00′N, 173°18′E	19.76	72.58 (24)	142.02
Abaiang	1°46′N, 173°08′E	12.43	77.92 (23)	110.17
Tarawa	1°24′N, 172°56′E	15.64	71.10 (28)	152.44
Maiana	0°55′N, 173°04′E	9.99	65.27 (22)	161.49
Abemama	0°21′N, 173°51′E	7.69	56.15 (25)	137.91
Kuria	0°16′N, 173°23′E	8.20	51.84 (17)	133.19
Aranuka	0°02′N, 173°24′E	5.87	51.18 (10)	—
Nonouti	0°40′S, 174°20′E	6.46	53.05 (22)	135.26
N. Tabiteuea	1°30′S, 175°20′E	7.47	44.77 (21)	130.16
Beru	1°21′S, 175°58′E	9.77	51.85 (22)	127.81
Nikunau	1°24′S, 176°28′E	6.39	45.43 (21)	134.63
Onatoa	1°51′S, 175°30′E	6.26	48.76 (26)	103.94
Tamana	2°29′S, 175°58′E	11.86	50.95 (20)	93.15
Arorae	2°40′S, 176°53′E	11.43	59.05 (23)	122.33
Nanomea	5°39′S, 176°06′E	78.25	110.16 (18)	146.50
Ocean	0°52′S, 169°35′E	9.73	69.64 (51)	154.03

[a] Number of years on which average is based is shown in parentheses. Data for Line Islands, Phoenix Islands (except for Canton), Nanomea and Ocean are from the British Meteorological Service; most of data for Gilbert Islands prior to 1953 from Sachet (1957); most of data for 1953 and later from British Meteorological Service.

[b] Penrhyn data for April 50–June 50 missing.

[c] Figure for Canton Island is the ESSA-Weather Bureau normal.

1931, 1940–1941, 1957–1958, 1965–1966. (In years such as 1918 the dry period ended during the early part of the year and the wet period started later in the year.) The beginning or ending of these situations may vary by a few months or more for stations widely separated in the zone. The areal extent of the region affected varies somewhat from situation to situation; in the most extensive cases, the involved zone may extend north to Washington Island (4°44′N, 160°25′W), usually extends westward beyond Nauru, and on the southern side may extend into the Ellice, Tokelau, southern Line and Marquesas Islands. The unusually dry conditions may extend over periods up to 3–4 years and the wet conditions up to about 2 years. However, over very long periods there may be a short relapse from the general condition (in either case) for a period of 1–3 months, usually during the normal seasonal period of heavy rainfall or drought conditions, as the case may be for that part of the zone so affected. There were additional shorter dry and wet periods (e.g., about five months duration) which similarly affected extensive portions of this equatorial zone.

Based on the climatological similarities in the recurring phenomena mentioned above and Canton's intimate relation from a weather standpoint with the other parts of this affected region, it appears that relationships developed from Canton Island data might be applicable over much of this region. The very few synoptic analyses which Palmer and Pyle (1966) possess for wet years show that the unusually heavy rains (over the dry zone) accompany cyclonic low-pressure systems similar to those found every year in the far western Pacific. A limited study of cloud distributions (Quinn and Burt, 1968b) indicated similarities of the Canton Island cloud distribution to those of other western equatorial Pacific sites and also to the Wake Island cloud distribution during the Northern Hemisphere summer. Hence, it appears that findings based on Canton Island data might also be applicable to much of the western equatorial Pacific region and possibly the rest of the western tropical Pacific in the summer hemisphere.

4. The data

Canton Island Local Climatological Data and the Climatological Data National Summary were considered for all years in which reasonably complete insolation data were recorded (January 1954–December 1959 and January–December 1966).[3] For the more detailed monthly relationships of this study, Canton WBAN 10A and 10B data for the years 1957–1959 and 1966 were used, since there were several months during these years which experienced sufficient weather activity to provide a reasonable range for studying relationships between weather (cloud cover and rainfall) and insolation. As indicated in the previous section, 1954–1956 was a dry period. (Canton's annual rainfall was 7.79 inches for 1954, 17.32 inches for 1955 and 16.34 inches for 1956). A rough study of monthly precipitation data for the daylight hours in these years (obtained from the hourly precipitation record on Local Climatological Data forms) showed all monthly precipitation amounts to average less than 0.1 inch per day, with most $\leqslant 0.01$ inch per day. Cloud data showed a similar trend. The computed average daily transmission percentages would cause these data to fall in the midst of the area saturated with data points from the large number of dry months included in the selected four year period. Since monthly data for these years could not provide a significant contribution to graphic relationships and economy (cost of procuring duplicate WBAN's) was a consideration, the monthly data for these years were not included. However, the annual data for these three dry years were used, since they provided the three points on the left side of Figs. 6 and 7.

The additional data used in earlier work (Quinn and Burt, 1967) were also used in this study. A discussion of observed, recorded and computed data are contained in this earlier paper.

5. Data processing

Data for the period January 1957–December 1959 and January–December 1966 were processed as follows, in order to have them in a suitable form for studying relationships on a monthly basis.[4]

1) Daily transmission ratios were obtained by dividing recorded daily insolation at the earth's surface by computed daily insolation on a horizontal surface at the top of the atmosphere. These values were summed up over each individual month and then divided by the number of days in the month for which insolation data were recorded to obtain average daily transmission figures on a monthly basis.

2) Average daily total opaque sky cover figures (in tenths of sky covered) from sunrise to sunset were computed from hourly surface weather observation data (WBAN Forms 10B). These values were averaged on a monthly basis for days with insolation records.

3) The number of minutes between sunrise and sunset during which precipitation occurred was recorded for each day with insolation data and then summed up for the month. This sum was divided by the number of days in the month for which insolation was recorded to provide the average number of minutes per day (during daylight hours) with precipitation on a monthly basis.

4) The total amount of precipitation (in inches), which fell between sunrise and sunset, was recorded for each day with insolation data. The precipitation sum

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[3] The Canton Island Weather Station ceased operating September 1967.

[4] Data were used for all months having insolation records available for greater than 50% of the days. Days with insolation data available for Canton are indicated in the applicable issues of Climatological Data National Summary.

for each month was divided by the number of days in the month for which insolation was recorded to obtain the average amount of precipitation per day (during daylight hours) on a monthly basis.

5) The number of days with precipitation occurring between sunrise and sunset was also summarized on a monthly basis for days with recorded insolation. In this case, days recording a trace of precipitation were included as days with precipitation. The total was divided by the applicable number of days to obtain the fraction on a monthly basis.

6) For purposes of comparison, the average daily total sky cover (in tenths of sky covered) from sunrise to sunset was computed on a monthly basis considering only those days with insolation records.

Data for the period January 1954–December 1959 and January–December 1966 were processed as follows to study relationships on an annual basis:

1) Average daily transmission ratios were obtained on an annual basis by dividing the annual sum of daily values by the number of days in the year for which figures were obtained.

2) Average daily amounts of precipitation on an annual basis were obtained by dividing the total amount of precipitation received on days when radiation was recorded by the annual number of days involved. In this case, all hours of the applicable days were included for precipitation figures.

3) The total number of days (with recorded insolation) which recorded measurable precipitation ($\geqslant 0.01$ inch) on an annual basis was divided by the applicable number of days to get the fraction of days on an annual basis. Here too, the entire day for applicable days was considered.

The reason for considering annual data in the indicated forms was that such data were more likely to be obtainable from climatological summaries.

6. The atmospheric transmission ratio

It was essential to determine the suitability of using the atmospheric transmission ratio (or per cent) as the ordinate quantity in graphic relationships and formulas. The total insolation on a horizontal surface at the top of the atmosphere (Q_A, as discussed in Quinn and Burt, 1968b), which was obtained by using the fundamental equation in Klein (1948), takes into account the essential terms (i.e., latitude of site, declination of sun, hour angle data, distance between the earth and sun, solar constant[5]) and can be considered a reliable element of the transmission ratio. However, the insolation Q received at the surface of the earth is always affected by the solar air mass[6] penetrated. The mean daily solar air mass penetrated at a particular site would vary during the year in accordance with solar declination; however, it was expected that this variation would be minimized at the equator. The basic question is: "Does the mean daily solar air mass, when considered on a monthly basis, vary sufficiently during the year near the equator to cause significantly large changes in the atmospheric transmission ratio so as to necessitate corrections?"

In order to evaluate the solar air mass effect on insolation at the earth's surface and, therefore, on the atmospheric transmission ratio in the equatorial region, the following formula of Kennedy (1949) was employed:

$$I = I_0 a^m,$$

where I is the total solar and sky radiation received on a horizontal surface of the earth, I_0 is the total insolation received on a horizontal surface at the exterior of the atmosphere, a, atmospheric transmission coefficient, and m, solar air mass. (Here Q was substituted for I and Q_A for I_0, and the terms used in the equation were average daily values on a monthly basis.) This approach was selected for the evaluations, because computations of clear sky insolation Q_0, using Kennedy's (1949) clear sky atmospheric transmission coefficient ($a = 0.91$), and his average daily solar air mass values, as determined by date and solar declination (Kennedy, 1940, 1949), along with the total insolation on a horizontal surface at the top of the atmosphere, varied less than 2% from the usually recorded clear sky values for Canton during all months of the year.

At Canton (2°46′S latitude) the minimum average daily solar air mass on a monthly basis[7] was 2.73 (March) and the maximum 2.96 (June). Using these extreme monthly solar air mass values for Canton in the formula $Q_0/Q_A = a^m$, with $a = 0.91$ for the clear sky situation, we get atmospheric transmission ratios of 0.773 and 0.756, giving a maximum difference of 0.017 in the ratios for the Canton Island location. In studying the ratios obtained from recorded surface insolation values during clear sky conditions, no clear-cut difference could be noted between the values for March and June at Canton. Evaluation of the clear sky situation appeared to be the only feasible approach for investigating the solar air mass factor at this time. Based on this limited evaluation, it appears that the atmospheric transmission ratio Q/Q_A can be considered a reasonably dependable variable for our relationships in the immediate vicinity of the equator. On extending this evaluation out to the outer limits of the equatorial region (10N and 10S), the maximum average daily solar air mass on a monthly basis for the entire equatorial region was found to be about 3.10. Using this value and the extreme minimum monthly figure (2.73) in Kennedy's formula, we get atmospheric transmission

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[5] The mean solar constant, 2.00 langleys per minute, as proposed by Johnson (1954), was used in the computations of this study.

[6] Solar air mass is defined as the ratio of the length of the actual path of the solar beam to that through the zenith.

[7] The lowest average daily solar air mass value for any complete month at any location in the equatorial region was 2.73.

ratios of 0.746 and 0.773, respectively. Therefore, there is a maximum difference of 0.027 in the clear sky atmospheric transmission ratio, due to solar air mass effects, in the zone extending 10° either side of the equator. The uncorrected transmission ratio still appears to be a fairly reliable variable for relationships in this zone when considered with respect to the gross nature of the methods used in this study.

Use of the uncorrected transmission ratio could also be extended to the trade-wind zone of the summer hemisphere if the weather and insolation relationships were applicable. At the outer tropical limits of 23°27′ latitude during the late spring, summer and early fall (December–March or June–September, depending on the hemisphere) the maximum daily solar air mass on a monthly basis is about 2.90, resulting in a maximum transmission ratio difference of 0.012 (considering 0.773–0.761).

7. Discussion

The data in processed form were plotted with atmospheric transmission per cent along the ordinates and meteorological factors along the abscissas (Figs. 1–7). Curves and their equations were determined from these data by using the method of least squares (Brooks and Carruthers, 1953). Linear and exponential relations along with a measure of the deviation of observations from the line of regression[8] are provided for each relationship that shows some potential.

1) The plot of total opaque sky cover vs per cent transmission (Fig. 1) shows very little scatter when compared to the other monthly plots. The equations obtained and the measures of deviation (in parentheses) are

$$y=88.40-5.52x \quad (1.97),$$

$$y=95.88e^{-0.0934x} \quad (2.17).$$

The linear relation (Fig. 1) gives a closer fit. By entering average daily total opaque sky cover (computed for daylight hours on a monthly basis) as the x variable, the y value, a transmission per cent, is obtained. Over the range considered here, the largest deviation in per cent transmission between the curve and any actual data point (in the y direction) was less than 5%. On multiplying the applicable insolation received on a horizontal surface at the top of the atmosphere by the transmission ratio, the surface insolation is obtained. The maximum deviation between computed and observed surface insolation values over the studied range was less than 10% of the observed figure. Although there may be significant day-to-day differences in the degree of opacity considered, such differences appear to be sufficiently tempered by considering monthly averages. The opaque cloud cover formula can only be used effectively down to a two-tenths coverage. At and below this figure insolation reception is generally that for a clear sky. An average monthly coverage of less than two-tenths total opaque cloud would be highly unlikely, since the scattered cumulus, which are frequently present over tropical oceans during fair weather, are mostly opaque. This type of cloud observation can be obtained by a surface based observer and provides a much more effective term than total sky cover in the equatorial (and perhaps tropical) region, since it can account for the contrast between thin fair weather cirrus coverages which have very little effect on surface insolation, and thick disturbance weather cloud coverages which significantly reduce surface insolation. It appears that this approach might generally provide monthly surface insolation estimates within 8% of pyranometer measurements.

2) The plot involving average daily duration (in minutes) of precipitation during daylight hours on a monthly basis (Fig. 2), appears to display a fairly reasonable pattern, although it would be desirable to have much more data in the high duration range. The equations and measures of deviation are

$$y=69.63-0.194x \quad (3.05),$$

$$y=69.92e^{-0.0033x} \quad (2.77).$$

The exponential equation (Fig. 2) gives a closer fit. Over the range evaluated here, the largest departure in per cent transmission between the curve and any data point was less than 7% and the maximum deviation between computed and observed insolation was about 13%. No matter how light the rain is in the tropics, it is usually indicative of a thick cloud cover; therefore, this approach assumes that any time precipitation occurs during daylight hours, it involves clouds that significantly reduce insolation. The relatively low maximum (near 70%) for the average monthly per cent transmission during months with little or no precipitation results from the fact that periods of considerably thick cloud cover occasionally occur without precipita-

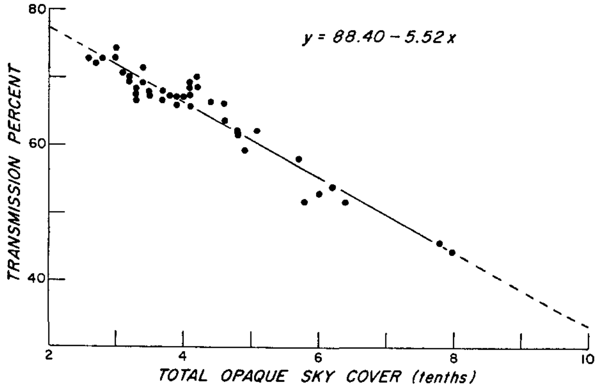

Fig. 1. Average daily per cent transmission as a function of average total opaque sky cover during daylight hours (monthly basis).

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[8] These figures, which appear in parentheses following the equations listed in this section, represent the positive square root of an unbiased estimate of the variance which remains after that part of the variance which is accounted for by regression is removed (Li, 1964, p. 299).

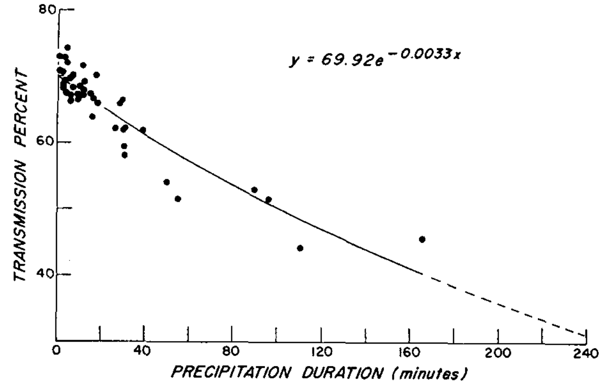

FIG. 2. Average daily per cent transmission as a function of average daily precipitation duration during daylight hours (monthly basis).

tion. In particular, there are those situations where disturbance precipitation ceases just prior to sunrise or starts just after sunset, yet associated disturbance clouds may still reduce insolation considerably during the morning hours (i.e., 0600–0900 true solar time, TST) or late afternoon hours (i.e., 1500–1800 TST), respectively. This maximum monthly figure near 70% does not appear to present any problem, since daily values of clear sky transmission in the equatorial region are likely to run between 74 and 77%, and it would be unusual for clear sky conditions to persist throughout a month at a site in the equatorial Pacific. A weakness to this approach lies in the bookkeeping aspect. In some cases observers kept meticulous minute-by-minute records of rainfall occurrence and its intensity; whereas in others, relatively long continuous periods of rainfall were recorded in association with "trace" amounts. It appears that this approach (exponential relation) might ordinarily provide monthly insolation estimates within 12% of measured values.

3) The plot of the average amount of precipitation (in inches) per day during daylight hours (on a monthly basis) in relation to associated per cent transmission (Fig. 3) shows a higher degree of scatter than Fig. 2 and the need for much more data in the high precipitation range. The equations and measures of deviation are

$$y = 69.04 - 64.66x \quad (3.48),$$

$$y = 69.24e^{-1.12x} \quad (3.30).$$

The exponential relation (Fig. 3) gives the closer fit. For the range evaluated here, the largest departure in per cent transmission between the curve and any data point was just below 10% and the maximum departure between computed and observed surface insolation was about 18.5%. The principal weakness to this approach is that a small amount of precipitation falling over a long period of time (light intensity) may cause a much larger reduction in a day's surface insolation than a large amount falling over a short period of time (heavy intensity).

4) The plot involving the fraction of days per month with precipitation (trace reports included) during daylight hours shows wide scattering (Fig. 4). In this case, the equations and measures of deviation are

$$y = 75.50 - 32.39x \quad (4.58),$$

$$y = 77.04e^{-0.545x} \quad (4.71),$$

the linear relation (Fig. 4) giving a closer fit. Over the evaluation range, the largest departure in per cent transmission between the curve and any data point was 11.4% and the maximum departure between computed and observed surface insolation about 23%. The principal weakness to this approach is the fact that precipitation occurring over a very short part of the daylight period counts just as much as continuous precipitation from sunrise to sunset. Although this method can take into account the number of days experiencing significant insolation depletion at some time during the daylight hours, it cannot in any way represent the quantitative aspect of insolation reduction. This monthly approach can result in large computational errors and is not considered suitable for estimating surface insolation.

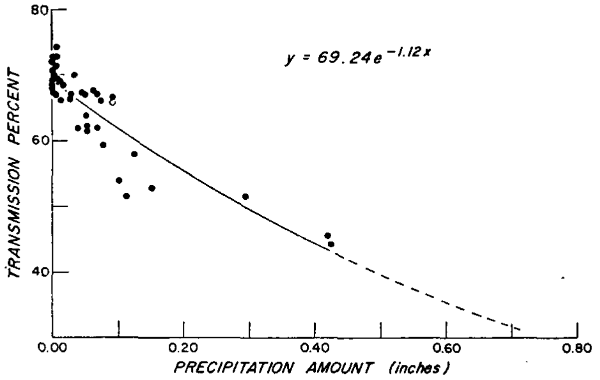

FIG. 3. Average daily per cent transmission as a function of average daily precipitation amount during daylight hours (monthly basis).

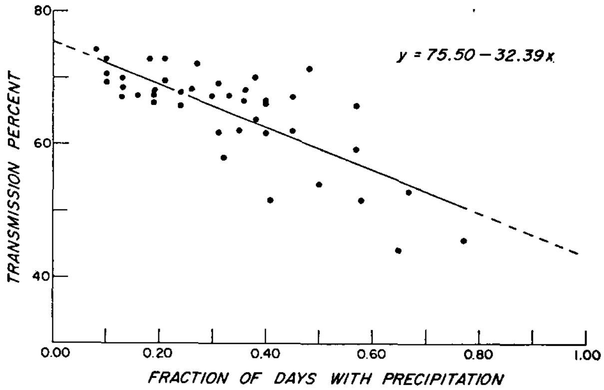

FIG. 4. Average daily per cent transmission as a function of the fraction of days per month with precipitation (includes traces) during daylight hours (monthly basis).

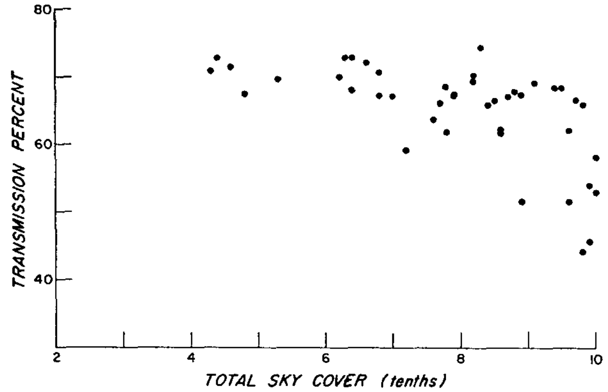

Fig. 5. Average daily per cent transmission as a function of average total sky cover during daylight hours (monthly basis).

5) The plot involving total sky cover (sunrise to sunset) on a monthly basis shows a very unusual scatter pattern (Fig. 5) with some semblance of order in the lower sky cover range, which is most likely due to the fair weather cumulus input. The scattered cumulus are frequently present over tropical oceans during the predominant fair weather periods. The wide spread in transmission values over the high sky cover range (i.e., 7/10–10/10) is caused by the large transmission difference between thin cirrus coverages and coverages caused by disturbance weather conditions. Due to the unusual nature of this plot, no attempt was made to obtain least squares fits for these data. It is expected that this term would be unsatisfactory for use over most of the tropical marine region.

6) Average daily amounts of precipitation on an annual basis (considering all hours of the day) are plotted with relation to associated per cent transmission in Fig. 6. Although data were very limited, this annual relationship shows considerable promise from the appearance of the plot. The least-squares fits for these data (omitting the circled point) provides the relations

$$y = 72.47 - 59.14x \quad (0.95),$$

$$y = 72.60e^{-0.877x} \quad (0.94),$$

where the exponential relation (Fig. 6) gives a slightly better fit. It is interesting to see that the circled point, which represents a 12-month period (July 1957–June 1958) with precipitation near 80 inches, falls very close to the curve. Although the weakness in the monthly approach [see 3) above] is included here, and is perhaps amplified by considering all hours of the day, it appears that the tempering caused by using the much longer annual period offsets this inherent weakness to the extent of making the method useful. This approach is suitable for use, since most climatological summaries include applicable precipitation data.

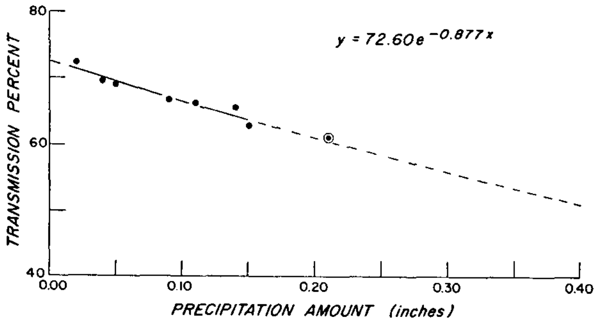

Fig. 6. Average daily per cent transmission as a function of average daily precipitation amount (annual basis).

7) A plot involving the fraction of days per year with precipitation (including all hours of the day, but just days with precipitation $\geqslant 0.01$ inch) is shown in Fig. 7. The least-squares method applied to these data (omitting the circled point) provides

$$y = 76.55 - 35.18x \quad (1.38),$$

$$y = 77.07e^{-0.519x} \quad (1.36),$$

with the exponential equation (Fig. 7) giving a slightly better fit. The circled point represents a wet period (July 1957–June 1958) at Canton and falls quite close to the curve. This method has the inherent limitations of the monthly approach [see 4) above] except that all hours of the day are considered and days recording only a trace are ignored. Although the tempering that results from use of the long annual period causes an improvement, this method is not recommended for general use. Many climatological summaries include applicable precipitation data for this approach.

8. Conclusion and recommendations

The study indicates that additional simple approaches could be used to compute surface insolation over much of the tropical Pacific which would be more suitable than those that rely on a mean total cloud cover input. Average total opaque sky cover during daylight hours appears to be the best, of the simple independent variables studied here, for providing monthly surface insolation estimates. By using the equation $y = 88.40 - 5.52x$, it is expected that monthly estimates within about 8% of measured values can generally be obtained at sites over much of the equatorial Pacific

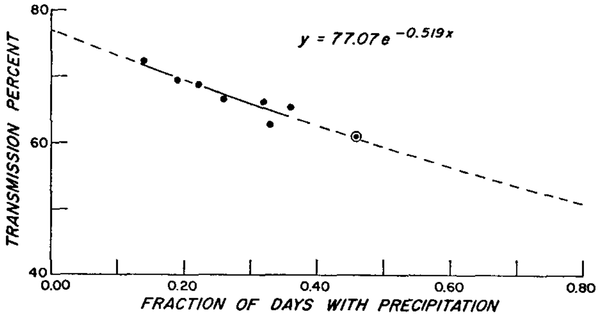

Fig. 7. Average daily per cent transmission as a function of the fraction of days per year with measurable precipitation ≥ 0.01 inch (annual basis).

and possibly that part of the tropics extending into the summer hemisphere of the western Pacific (Section 3). This formula can be used down to two-tenths opaque cover where conditions essentially reach a clear sky state. Average daily rainfall duration (in minutes during daylight hours) appeared to be the next most suitable independent variable for determinations of average daily insolation on a monthly basis. When inserted in the formula $y=69.92e^{-0.0033x}$, it is expected that the resulting per cent transmission will generally provide surface insolation estimates within 12% of measured values. For annual surface insolation amounts, the equation $y=72.60e^{-0.877x}$, using the average daily amount (in inches) of precipitation (on an annual basis) as an independent variable, appears to provide figures reasonably close to observed values. The use of annual value, however, is limited to the equatorial Pacific.

Certain references will facilitate applications of these formulas. Standard nautical or air almanacs will provide sunrise and sunset data for any location. An article by Kubota (1967) provides an appendix with the daily, 5-day monthly, and yearly mean solar radiation (ly day^{-1}) incident on the outer atmosphere at each 5° latitude from pole to pole. Kubota uses the 1.98 ly min^{-1} solar constant value, however, rather than the 2.00 value used here.

Since results are based on relatively small samples, there is a need to evaluate these approaches by using data from additional low latitude sites, particularly those recording larger monthly and annual amounts of precipitation.

Acknowledgments. This research was supported by the National Science Foundation, under Grants GA-1571 and GP-5165, and the Office of Naval Research under Contract Nonr 1286(10). Appreciation is expressed to Mr. Parke Starke, ESSA-Weather Bureau, for stimulating discussions on this subject and Miss Barbara J. Baldridge for assistance in data processing and computer programming. Appreciation is also expressed to Le Chef du Service Meteorologique, Polynesie Francaise (Papeete, Tahiti), the Director-General of the Meteorological Office (Bracknell, England) and the National Weather Records Center, ESSA, for providing meteorological data in support of this study.

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