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Title: CLOUD COVER AND INCOMING SOLAR RADIATION OVER THE EQUATORIAL PACIFIC

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Canton Island (at 2° 49'S, 171° 41'W) was selected to study equatorial trough weather conditions and their effects on incoming solar radiation. The chosen period of study (July 1957 - June 1958) was highly applicable, since the mean position of the equatorial trough for this year was 4° south of its mean annual position and it frequently affected Canton.

Extensive periods of fair weather at the trough axis and in its immediate vicinity (within 3°), showed that there was no substantiation for the assumption of continuous convergence or routine disturbance type weather in the so-called "intertropical convergence zone." Only one out of five days, on the average, was affected by disturbance-type weather in the immediate vicinity of the trough axis.

The overall average solar radiation transmission percentage, for disturbance situations within 3° of the trough axis, was 34.6; whereas, during fair weather, within 3° of the trough axis, the

overall average transmission percentage was 61.3.

The July 1957 - June 1958 Canton data showed the cirriform contribution to mean total sky cover to be unusually high. Cirriform overcasts with scattered or no low clouds occurred about 40 percent of the time on an annual basis. These thin cirriform overcasts, which were frequently present during fair weather conditions, caused little or no reduction of incoming solar radiation, regardless of solar altitude.

A study of U. S. Air Force weather summaries for Canton and nine additional equatorial Pacific sites, indicated that the unusually high contribution of cirriform cloud to total sky cover was characteristic of a large portion of the west-central and western equatorial Pacific. Since most formulas for computing incoming solar radiation depend on mean total sky cover, a large bias toward thin cirrus, could lead to sizeable underestimations of incoming radiation. Such underestimations would then lead to significant errors in heat budget calculations over this region.

Three sets of cloud cover figures (mean total sky cover, mean low cloud cover, and mean total opaque sky cover) were obtained from the July 1957 - June 1958 Canton data and entered in five commonly used formulas for computing incoming solar radiation. As expected, the usually used mean total sky cover term gave excessively large underestimations of incoming radiation with all formulas, due to the large cirrus contribution. The test results suggested a compromise approach for arriving at a more suitable cloud cover term; and, therefore, 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. With this compromise cloud term, the Kimball, Black and Budyko (Savino Angstrom) formulas gave very satisfactory results. The latter two formulas provided all computations within ten percent of the recorded values. Since they worked well for both the months with very little disturbance activity and months with much disturbance activity, it appeared that they could cope with a wide range of weather activity.

Black's formula, used in conjunction with the proposed compromise cloud term, is particularly suitable, since its computations are 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.

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by

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CLOUD COVER AND INCOMING SOLAR RADIATION OVER THE EQUATORIAL PACIFIC

INTRODUCTION

General Remarks

The principal source of incoming energy for the earth-atmosphere system is the sun. The greatest amount of this energy is received in the tropics, where more heat is absorbed into the system than is emitted back to space. Very little of the relatively short-wave incoming solar radiation is absorbed by the atmosphere; most of it penetrates through to the earth's surface, where it is largely absorbed. Since about 80 percent of the earth in the tropics is covered by water, it is primarily the transfer of heat from ocean to air that establishes the atmospheric heat source (Riehl, 1962). The excess of short wave radiation absorbed over long-wave radiation emitted by the oceans is partly given off to the atmosphere through the transfer of latent and sensible heat, partly transported to higher latitudes by oceanic currents, and partly stored if seasonal rather than mean annual values are considered (Riehl and Malkus, 1958). Riehl (1962) states that recent calculations have suggested that as much as 25 percent of the equatorial heat excess may be exported by the ocean currents.

Most of the latent heat accumulated by the trades is carried into the equatorial trough zone; and, it is principally within the trough zone that this latent heat accumulation is lifted in the convergent zones of disturbances and the latent heat converted to sensible heat as condensation takes place. The vehicles for vertical transport are the huge towering cumulonimbi which result from the original convergent and ensuing convective processes. This lifting and conversion of energy, after balancing atmospheric radiational losses to space, causes a residue of sensible heat and potential energy to be exported poleward aloft (Riehl and Malkus, 1958).

Since the incoming solar radiation is the only appreciable source of energy for atmospheric and oceanic processes and motions, it is essential to know the amount of this incoming solar energy in the lower latitude regions. In this regard, Riehl (1962) makes the following comments:

> . . . The actual heat source of the earth-atmosphere system in the tropics has never been measured. It is computed by an intricate chain of calculations which contains many assumptions especially about cloud cover. . . . (Riehl, 1962, p. 22).

Malkus (1962) and Robinson (1966) also emphasize the need for investigation of the effects that cloud types and characteristics have on incoming solar radiation.

A review of the literature revealed that there had been very little research in regard to the actual incoming solar radiation over the tropical oceans and, of course, even less over the narrower equatorial marine region. A basic cause for this situation is the fact that there are very few tropical marine sites which record incoming solar radiation. As a result, studies that have been performed were primarily based on the use of tropical weather data in formulas for calculating incoming solar radiation from meteorological data; and, such formulas were usually developed for middle latitude conditions. In most cases, mean total sky cover was entered in the formulas, and there was no reference to cloud types or characteristics. Obviously, the cloud distributions by types, amounts, and vertical extent differ considerably between the equatorial marine region and the middle latitudes. Therefore, it is possible that the actual incoming solar radiation over the equatorial region would differ considerably from the values that have been computed by Kimball (1928), Black (1956), Budyko (1956), and others.

An evaluation of incoming radiation in the equatorial region required a detailed investigation of cloud distributions and characteristics there. It was, therefore, necessary first to find a suitable equatorial marine site for which surface weather observations, rawinsonde data, and incoming solar radiation records were available, and then to determine an appropriate period of study. After performing a detailed investigation of the data for the selected site, the findings could then be correlated with long period weather records for this site and additional sites scattered throughout the adjacent equatorial marine region, in an attempt to project the investigation findings in time and space.

Objectives and Purposes of Study

This investigation was undertaken in order to gain further insight into the actual weather conditions in the equatorial marine region, including those of the migratory equatorial trough, and the effects of these weather conditions on the incoming solar radiation. The ultimate objective was to develop a satisfactory method for calculating incoming solar radiation from meteorological data in the equatorial marine region, since the number of stations taking meteorological observations there is many times the number which record solar radiation data.

The findings of this study should provide an essential contribution towards the goal of determining the heat budget of the earth-atmosphere system on a global basis. Although the study was performed over the equatorial Pacific, the findings should be generally applicable to equatorial oceanic areas and also a large part of the tropical marine region as a whole. They should complement the earth-orbiting satellite findings over equatorial oceans, since satellites cannot observe weather and record radiation as it appears within the lowermost portions of the atmosphere and near the air-sea boundary.

Radiant energy received from the sun is a prime necessity to the photosynthetic processes of plant life. Therefore, an accurate estimate of the amount of incoming solar radiation over the equatorial oceans should also be of great value to marine botanists in their investigations of primary production.

Definitions

Disturbance

The term disturbance was used in a broad sense to signify periods of "disturbed weather," since it was desirable to separate such periods of extensive cloud cover and precipitation from periods of fair or relatively fair weather when evaluating incoming solar radiation. Thus the term was not considered as any particular stage in tropical cyclone development and did not follow any other previously defined nomenclatures for specific synoptic features.

The tropical zone weather analyses prepared by the German Weather Service were not constructed in sufficient detail to identify minor disturbances (e.g., waves in the easterlies, small vortices, and shear lines). Those synoptic features which could be identified with observations of extensive cloud cover and rainfall at Canton were small equatorial low pressure centers, the trough itself (at times when it was apparently accompanied by active convergence), the outermost regions of tropical storms centered 400 to 500 miles away in a southwesterly to southerly direction, and occasionally a low pressure center associated with a frontal trough which extended equatorward from an extra-tropical system centered in higher latitudes.

The disturbances considered here had sufficient intensity to cause extensive cloud cover and rainfall to appear in the Canton Island observation records. Consideration of disturbance days as well as non-disturbance days was generally limited in this study to the daylight period at Canton, in order to correlate weather conditions with incoming solar radiation.

Equatorial

Occasionally, such terms as "equatorial Pacific," "equatorial region," "equatorial ocean(s)," "equatorial weather," or "equatorial atmosphere" were used in this report, and yet they did not appear bound rigidly to the geographic equator. The investigation was generally confined to the central and western parts of the equatorial Pacific; however, Christmas Island (1°55'N, 157°20'W) was the easternmost point for which detailed climatological data were studied, Canton Island (2°49'S, 171°41'W) the southernmost limit, Moen Island (7°28'N, 151°51'E) the western limit, and Eniwetok (11°21'N, 162°21'E) the northernmost point. The study was more concerned with the equatorial atmosphere, which is not a stationary geographic feature, but migrates seasonally (and during seasons) with its axial feature, the equatorial trough. Therefore, rather than considering a rigid geographic zone extending 10^{o} either side of the equator, it was deemed appropriate here to consider an area with a slight distortion toward the northern hemisphere, for the purposes of this investigation. This distortion was believed justified by the fact that the mean annual position of the meteorological equator (equatorial trough) is near 5^{o} north latitude (Riehl, 1954).

Equatorial Trough

The equatorial trough is a region of lower pressure found near the equator between the subtropical high pressure areas of the northern and southern hemispheres; its annual mean position being near 5^{o} north latitude. In general, it is situated where the streamlines from both hemispheres converge (Riehl, 1954), and its migration influences the seasonal march of cloudiness and rainfall as well as the formation of tropical cyclones. Riehl (1954) rejects the term "convergence zone," since there is often no convergence in this zone, and instead uses the term, "equatorial trough," to avoid the implication of a causal connotation. He finds that the equatorial trough and heavy rainfall coincide seasonally as well as in the annual mean over the oceans. He indicates that mean trough shifts of as little as $2\text{-}3^{o}$

latitude from one year to the next can produce extreme rainfall differences in the marginal zone.

Equatorial Trough Zone

The equatorial trough zone is a belt about 10° - latitude wide on either side of the trough axis (Malkus, 1962).

Selection of Appropriate Site for Detailed Investigation

It was essential to find a highly representative equatorial marine observation site for the detailed study of relationships between weather conditions and incoming solar radiation. It was also necessary that this site have simultaneous records of atmospheric and solar radiation data.

Lavoie (1963), in his detailed study of surface and upper-air data for Eniwetok, found that the atoll influence on clouds and precipitation over the atoll itself was probably insignificant. Wiens (1962) found that the land area of an atoll was too low to produce orographic rainfall and too small to affect appreciably the time of rainfall. He also referred to a study of the southern Gilberts which involved five reef islands and five atolls with lagoon formations, which were more or less intermixed in location. In this case the two groups showed no significant differences in average annual rainfall that would set reef islands apart from atolls, which would also seem to discredit the notion that lagoons exercise important effects upon rainfall. Since there have been no weather ships stationed in the equatorial region, and oceanographic expeditions rarely stay in one place long enough to provide definitive descriptions, it therefore appeared that a small, isolated atoll with very little surface relief would provide the best available observing platform for the purposes of this study.

Canton Island, a coral atoll located in the central part of the equatorial Pacific (2° 49'S, 171° 41'W), was selected primarily because it was the only suitable marine weather observing site in the vicinity of the equator for which incoming solar radiation records were available. Although its overall attributes were not quite as ideal as those of Eniwetok, its area, configuration, relief, and isolation from continents, made it a reasonably representative marine observation site. Canton is about 21 miles in circumference and is roughly in the shape of a pork chop. Its rim is 150 to 1800 feet wide and encloses a shallow lagoon of about 25 square miles (Degener and Gillaspy, 1955). Its maximum height above sea level is about 20 feet and its total land area about 2850 acres (Hatheway, 1955). The island's coral shelf extends only about 200 yards from the shore line, except at the three more prominent corners where it extends about 400 yards outward. Depths outside the reef line drop off from 100 to more than 300 fathoms within a few hundred yards

(H. O. 80, 1952).

Degener and Gillaspy (1955) in their Appendix A provided an excerpt of a letter from Mr. Myron H. Kerner, Meteorologist In Charge, U. S. Weather Bureau, Canton Island, dated 25 November 1954, in which he discussed the local heating effect of Canton Atoll as follows:

> . . . If the atoll afforded any of the lifting forces, there should be a marked increase in cloudiness as a result, but there appears to be no difference in cloudiness between that over the atoll and that over the ocean. In my 16 months of continuous duty here, I have never observed any deviation in a cloud's course due to the island and there appears to be no reason to believe that the island has any effect on the rain. . . (Degener and Gillaspy, 1955, p. 51).

Therefore, available information indicated that Canton Island was an excellent site for this study.

Selection of Appropriate Period for Detailed Investigation

The period July 1957 through June 1958 was selected for the detailed study for the following reasons:

1) A series of daily tropical weather analyses for the International Geophysical Year (IGY) (July 1957 - December 1958) were being prepared by the German Weather Service, and the first 12 months of analyses were available at the inception of this study. These analyses allowed a rough correlation of Canton Island data with synoptic weather features.

2) It appeared to be particularly suited to a study of weather conditions in the equatorial trough and the effects of these conditions on incoming solar radiation. This opinion was based on an apparent southward shift in the annual mean position of the equatorial trough, which caused it to appear more frequently than usual in the vicinity of, or south of, Canton Island. The data of Table 1, which were extracted from climatological records provided by the National Weather Records Center (NWRC) of the Environmental Science Services Administration (ESSA), clearly show the highly unusual weather that resulted. Nearly three times the normal amount of precipitation was recorded in this year, precipitation occurred on almost twice the mean number of days, thunderstorm days were much more frequent, and on two occasions water spouts were noted close to Canton. There was also an extremely large increase in mean cloud cover and the annual number of cloudy days. The total incoming solar radiation was less than normal over this period. Since these unusual conditions were noted during several months of the year and on several days of these months, they could not be attributed to a few isolated circumstances.

3) Canton surface weather observations and rawinsonde data were complete for the selected period; and, although radiation records were missing from 27 January through 11 March 1958, this was also one of the more complete periods for radiation data.

Table 1. Climatological data for July 1957 - June 1958 and normal/mean values at Canton Island (2° 46'S, 171° 43' W).

Item	Reference	July	August	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May	June	Annual Total	Annual Average
Number of Clear Days	Jul 57-Jun 58 (20)	0	2	3	2	0	1	0	2	0	0	1	1	12	
	Mean	6	8	10	8	6	5	5	6	6	3	6	6	75	
Number of Partly Cloudy Days	Jul 57-Jun 58 (20)	1	5	7	5	0	5	0	3	1	9	7	11	54	
	Mean	13	12	11	11	12	11	11	11	13	16	12	13	146	
Number of Cloudy Days	Jul 57-Jun 58 (20)	30	24	20	24	30	25	31	23	30	21	23	18	299	
	Mean	12	11	9	12	12	15	15	11	12	11	13	11	144	
Mean Sky Cover Sunrise-Sunset	Jul 57-Jun 58 (20)	9.7	8.6	7.9	8.9	10.0	8.9	9.9	9.1	9.4	8.6	8.6	7.9		9.0
	Mean	6.4	5.9	5.4	6.1	6.4	6.8	6.8	6.4	6.4	6.5	6.5	6.2		6.3
Precipitation Total (Inches)	Jul 57-Jun 58 (30)	3.02	3.56	4.34	4.60	14.57	9.85	16.39	9.69	7.73	2.07	3.62	2.78	82.22	
	Normal	2.59	2.50	1.24	1.10	1.61	2.54	2.61	2.13	2.49	3.62	4.35	2.65	29.43	
No. of Days Precipitation -- .01 in. or More	Jul 57-Jun 58 (20)	17	13	7	8	21	16	23	16	15	8	14	14	172	
	Mean	12	10	7	6	6	6	8	6	9	13	11	10	104	
No. of Days with Thunderstorms	Jul 57-June 58 (18)	2	1	1	1	6	5	3	1	1	0	0	0	21	
	Mean	*	*	*	*	*	*	*	*	*	*	1	*	4	
Average Temperature	Jul 57-Jun 58 (30)	83.8	84.2	83.9	85.0	84.0	84.0	83.3	83.8	84.6	85.5	85.0	84.8		84.3
	Normal	83.6	83.5	83.6	83.7	83.6	83.1	83.1	83.0	83.1	83.6	83.9	83.8		83.5
Average Daily Solar Radiation (Langleys)	Jul 57-Jun 58 (12)	535	571	608	626	482	463	415	---	573	544	512	532		533
	Average	543	595	636	649	613	585.	590	630	631	598	560	538		597

* Less than one-half
--- Missing
( ) Length of record, years

Sky cover is expressed in a range of 0 for no clouds or obscuring phenomena to 10 for complete sky cover. The number of clear days is based on average cloudiness 0-3; partly cloudy days 4-7; and cloudy days 8-10 tenths.

Additional Sites

It was necessary to check Canton Island climatological data against that for additional weather observation sites in the equatorial Pacific, to determine whether the findings there were localized or had widespread applicability. The following islands were selected on the basis of location and data availability:

Palmyra	($5^\circ 53'$N, $162^\circ 06'$W)
Fanning	($3^\circ 54'$N, $159^\circ 24'$W)
Christmas	($1^\circ 55'$N, $157^\circ 20'$W)
Baker	($0^\circ 12'$N, $176^\circ 29'$W)
Tarawa	($1^\circ 30'$N, $173^\circ 00'$E)
Majuro	($7^\circ 05'$N, $171^\circ 23'$E)
Kwajalein	($8^\circ 44'$N, $167^\circ 44'$E)
Eniwetok	($11^\circ 21'$N, $162^\circ 21'$E)
Moen (Truk)	($7^\circ 28'$N, $151^\circ 51'$E)

These sites along with Canton Island provide ten evaluation points within 10° latitude of the mean annual position of the equatorial trough in the central and western equatorial Pacific. Fanning, Chirstmas, Canton, Baker, and Tarawa are south of the mean annual position of the trough; Majuro, Kwajalein, Einwetok, and Moen are north of it; and, Palmyra appears to be just about on it.

With the exceptions of Moen and Christmas, these sites are all small, low coral islands with land surfaces extending from sea level to a maximum elevation of about 20 feet. Christmas Island has a land area of about 160 square miles which is relatively large compared to the others; and, although it too is a coral island, has hills that reach to 35 to 40 ft. in height (H. O. 80, 1952). Moen Island is fringed by reefs but rises to several high peaks, the highest of which, Mt. Teroken, attains an elevation of 1214 ft. (H. O. 82, 1964). This elevation would ordinarily limit Moen's usefulness as a marine observation site.

DATA SOURCES, PROCESSING, AND APPLICABILITY

Data Sources

The following Canton Island records for the IGY period, July 1957 - June 1958, were the sources of detailed investigative information:

1) hourly and special surface weather observations as entered on the ESSA WBAN Forms 10A and 10B,

2) twice-daily records of rawinsonde data as recorded on the ESSA Forms WBAN-33,

3) daily records of the total incoming solar radiation[1] as recorded on ESSA Total Sky and Radiation Charts.

These data were generally complete except for missing incoming solar radiation records from 27 January to 11 March 1958.

The IGY tropical zone weather analyses prepared by the German Weather Service and the data contained on these analysis charts were used to study relationships between the observed Canton Island

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[1] Total incoming solar radiation refers here to the direct and diffuse radiation on a horizontal surface as recorded by the Eppley pyranometer. Solar energy received at the earth's surface ranges in wave length from about 0.3 μ to several microns. The Eppley pyranometer is sensitive to all wave lengths between 0.3 μ and 2.5 μ, or more than 99% of the energy which impinges upon the outer surface of the hemispherical glass cover (Hand, 1950).

weather and synoptic features contained in the analyses. They were also used to obtain daily positions of the equatorial trough for the July 1957 - June 1958 period.

Precipitable water tabulations for Canton's twice-daily soundings were procured from the NWRC, ESSA for the selected IGY period. These tabulations included surface to 850 millibar (mb), surface to 700 mb, surface to 500 mb, and surface to 400 mb precipitable water contents. They were used to study moisture distributions and their relation to weather conditions and solar radiation reception.

U. S. Air Force Air Weather Service (USAF AWS) Uniform Summaries of Surface Weather Observations were procured from the NWRC, ESSA, for the following low-latitude Pacific Islands: Canton, Palmyra, Fanning, Christmas, Baker, Tarawa, Majuro, Kwajalein, Eniwetok, and Moen. These summaries contained statistics with regard to various amounts of cloud cover, ceiling heights, precipitation amounts and frequencies, visibilities, and thunderstorms. Periods of record differed (see Tables 8-17), since some of the islands only had active weather stations during World War II, while other islands had stations that continued in operation up to the present. These summaries were used to determine to what extent in time and space the Canton Island findings, from the selected year of data, could be projected over the western and central equatorial Pacific.

The following sources of published ESSA weather data were also used in this study:

Local Climatological Data - This publication comprises three issues: Local Climatological Data (monthly), Local Climatological Data (monthly supplement), and the Local Climatological Data With Comparative Data (annual). These are published individually for ESSA stations. The latter issue, in addition to an annual summary, contains long period normals, means, and extremes.

Pacific Island Summary - This is a monthly summary of weather data for all Pacific island weather stations administered by ESSA.

Climatological Data, National Summary - This publication is issued on a monthly and annual basis. It contains selected climatological data on a national basis, and includes several island stations in the Pacific area and West Indies. Surface weather, rawinsonde, and solar radiation data are included.

Northern Hemisphere Data Tabulations - This is issued on a daily basis and contains synoptic surface and upper air reports. It includes weather data from stations in the tropical Pacific as far south as Canton Island.

Data Processing

A review of the available literature concerning atmospheric effects on incoming solar radiation and a detailed study of one month of Wake Island atmospheric and solar radiation data were performed prior to determining factors to be considered in this investigation. The following items appeared to be quite diagnostic and, therefore, were computed and tabulated for each daylight hour[2] of the July 1957 - June 1958 period for Canton Island:

Solar altitude (a) (Angle in degrees and sine of angle)

Optical air mass[3]

Solar radiation received on a horizontal surface at the top of the atmosphere (in langleys)

Total incoming solar radiation (in langleys), as recorded at the surface by the Eppley pyranometer

Low cloud cover[4] (in tenths of sky covered)

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[2] All time references were converted to the true solar time reference of the solar radiation records.

[3] Optical air mass (or air mass) is a measure of the length of the path through the atmosphere to sea level traversed by light rays from a celestial body, expressed as a multiple of the path length for a light source at the zenith (Huschke, 1959). Here, the values were obtained from Table 10 in Hand (1946), which was computed from Bemporad's formula:

$$m' = \frac{\text{astronomical refraction (in seconds)}}{58.36'' \sin z'}$$

where m' is the air mass and z' (or 90°-a) is the zenith distance of the sun.

[4] Low clouds were determined by type (e.g., stratus, cumulus, swelling cumulus, stratocumulus, cumulonimbus, etc.)

Total sky cover (in tenths of sky covered)

Total opaque sky cover[5] (in tenths)

Precipitable water content[6] surface to 850 mb (in inches)

Precipitable water content surface to 700 mb

Precipitable water content surface to 500 mb

Precipitable water content surface to 400 mb

Weather category.

Solar altitude was computed for the mid-point of each hour of the day for which solar radiation was recorded, by means of the following formula (Sellers, 1965):

$$\sin a = \sin \phi \, \sin d + \cos \phi \, \cos d \cos h \quad (1)$$

where ϕ = the geographic latitude of the site

d = the declination[7] of the sun (the angular distance of the sun north (positive) or south (negative) of the equator)

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[5] 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).

[6] Precipitable water (or precipitable water vapor) is the total atmospheric water vapor contained in a vertical column of unit cross-sectional area extending between any two specified levels, commonly expressed in terms of the height to which that water substance would stand if completely condensed and collected in a vessel of the same unit cross-section (Huschke, 1959).

[7] Values of solar declination for each day and hour of the year were obtained from The American Nautical Almanac, published annually by the U. S. Government Printing Office in Washington, D. C.

h = the hour angle[8] (the angle through which the earth must turn to bring the meridian of the observation point directly under the sun).

The amount of solar radiation incident on a horizontal surface at the top of the atmosphere (I_A) depends on the time of year, the time of day, and the latitude. I_A values were required for the same periods for which radiation values were recorded at the earth's surface. Solar altitude values, as calculated above, were used to compute I_A in langleys per minute by means of the following formula:

$$I_A = \frac{2.00 \, (\sin a)}{r^2} \qquad (2)$$

where 2.00 = the mean solar constant[9] in langleys per minute (Johnson, 1954).

r[10] = the earth's radius vector (the actual distance between the centers of the earth and the sun divided by the mean distance).

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[8] The hour angle is zero at solar noon, when the sun is north or south of the observation site. It increases by 15° for each hour prior to, or following, solar noon (Sellers, 1965).

[9] The solar constant is usually defined as the flux of solar radiation at the outer boundary of the earth's atmosphere that is received on a surface held perpendicular to the sun's direction at the mean distance between the sun and the earth (Sellers, 1965).

[10] Values of the radius vector for each day of the year were obtained from The American Ephemeris and Nautical Almanac, published annually by the U. S. Government Printing Office, Washington, D. C.

The values of I_A were multiplied by 60 in order to obtain the incident radiation in langleys per hour.

The hourly values of total incoming solar radiation, as recorded at the surface, were obtained from the Total Sky and Radiation Charts for Canton Island. All of the solar altitude and radiation data were in relation to true solar time (TST).

Hourly and special surface weather observations, as recorded on the ESSA WBAN Forms 10A and 10B, were used to obtain the hourly low cloud cover, total sky cover, and total opaque sky cover values. It was necessary to correct the cloud cover time references, which were in the 165° longitude local standard time (LST) to TST,[11] so that solar radiation and cloud cover data could be closely correlated. In order to take into account the non-scheduled special

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[11] LST can be converted to TST by making a correction for longitude (a constant correction for any particular location), and a correction in accordance with the equation of time (a correction that varies with the time of the year). The longitude correction, a correction from LST to local mean time (LMT), is made by subtracting from LST (at 165° W longitude) four minutes for each degree of longitude that Canton deviates to the west of the standard time meridian. The equation of time correction, a correction from LMT to TST, is primarily based on two factors:
1: The revolution of the earth in its orbit is not constant due to the elliptical pattern around the sun.
2: The motion of the apparent sun is along the ecliptic which is tilted with respect to the celestial equator along which time is measured. Equation of time corrections in minutes and seconds on a 12-hourly basis were obtained from The American Nautical Almanac. During the year, the total time correction applied to LST ranged from -11 to -41 minutes.

weather observations and the time corrected hourly observations, average cloud and sky cover values were computed for each true solar hour during the daylight hours. The selected cloud cover terms were such that they could be directly estimated by the surface-based observer.

Rawinsonde data, as recorded on the ESSA Forms WBAN-33, were used to study the larger scale atmospheric features in the vertical, such as cloud development, temperature inversions, moisture reductions, wind distribution, and moisture distribution. These data were also used to run an occasional check on the NWRC, ESSA precipitable water tabulations and to compute precipitable water values for cases missing from the NWRC, ESSA tabulations. The following formula from Haltiner and Martin (1957) was used to compute the mass of water per unit area (P) in an atmospheric column:

$$P = \int_{z_1}^{z_2} \rho_v \delta_z = - \int_{p_1}^{p_2} \frac{\rho_v}{g\rho} \delta p \qquad (3)$$

where ρ = the density of air

ρ_v = the density of the water vapor

z_1 = the altitude of lower level

z_2 = altitude of higher level

p_1 = pressure at lower level

p_2 = pressure at higher level

g = acceleration of gravity

Simplifying,

$$P = -\frac{1}{g}\int_{p_1}^{p_2} q\delta p \doteq -\frac{1}{g}\int_{p_1}^{p_2} m\delta p \qquad (4)$$

where q = specific humidity[12]

m = mixing ratio[13]

The following finite difference form of the equation was actually used to obtain precipitable water values from the sounding data:

$$P = \frac{\overline{m}(p_1 - p_2)}{g} \qquad (5)$$

where $\overline{m}$ is the mean mixing ratio, obtained by averaging the mixing ratio values for the base and top of an atmospheric layer. Computations were performed on the layer from the surface to 1000 mb and for each successive layer (50 mb thickness) up to the highest level for which humidity data were available (usually 300 mb). Contributions above 400 mb were found to be quite negligible.

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[12]Specific humidity in a system of moist air is the dimensionless ratio of the mass of water vapor to the total mass of the system (Huschke, 1959).

[13]Mixing ratio in a system of moist air is the dimensionless ratio of the mass of water vapor to the mass of dry air (Huschke, 1959).

In order to arrive at the mixing ratio for a particular level, a Pseudo-Adiabatic Chart was entered with the recorded temperature for the level of concern, and the saturation mixing ratio read off at that point. The saturation value multiplied by the relative humidity for the level provided the actual mixing ratio. The differences between the mixing ratio and specific humidity values were so small, that for practical purposes mixing ratio could be substituted without a significant loss in accuracy. The rawinsonde data were based on Greenwich mean time (GMT). There was about 11 hours and 27 minutes difference in local mean time between Greenwich and Canton due to longitude difference (0000 GMT is the same as 1233 LMT of the previous day at Canton); therefore, the 0000 GMT soundings were generally used to study atmospheric conditions during the daylight period (equation of time corrections were considered inconsequential in this case.)

Four different categories were used to classify the weather conditions for each day (daylight hours only) for the purposes of this study:

1. Predominantly fair weather, trough axis over 3° latitude distant from site.

2. Predominantly disturbance weather, trough axis over 3° latitude distant from site.

3. Predominantly fair weather, trough axis within 3° latitude

of site.

4. Predominantly disturbance weather, trough axis within 3° latitude of site.

Applicability of Summarized Data

The condensed climatological summaries in Tables 8-17, which were obtained from the USAF AWS Uniform Summaries of Surface Weather Observations, were frequently referenced in order to substantiate opinions and findings in this paper. Therefore, it would appear desirable to know what credence might be placed in the figures contained in these summaries, since in some cases the periods of record were quite short.

Short period summaries of tropical rainfall can be quite misleading, due to the large variability in recorded amounts from day to day, month to month, and year to year. Wiens (1962) noted that the highest annual rainfall recorded at Fanning Island was 207.8 in. in 1905; whereas in 1950 the record dropped to an all-time low of 27.8 in. At Malden Island (4° 03'S, 154° 59'W), he reports the highest recorded annual rainfall as 95.6 in. in 1919 and the lowest as 4.0 in. in 1908. Landsberg and Jacobs (1951) refer to studies which indicate that approximately 30 years of rainfall data are required to obtain a stable frequency distribution for tropical islands. Even the 30-year precipitation normals may show significant variations for certain locations. For instance, the normal annual precipitation amount for Canton Island from 1921 to 1950 was 20.01 in., whereas, the normal for the period 1931-1960 was 29.43 in. However, for studies of this nature, monthly and annual deviations from normal in particular years serve definite purposes; in some cases, they direct attention to large changes in the overall synoptic weather pattern (e.g., shifts in the mean position of the equatorial trough); in other cases, they lead to the identification of highly localized, short-period effects (i.e., cases where a day or two of unusually heavy typhoon precipitation make the difference between an abnormally low and an abnormally high monthly record).

In the cases of temperature, humidity, cloudiness and visibility, the estimated numbers of years of data required to provide a stable frequency distribution for tropical islands are five, one, two, and three, respectively (Landsberg and Jacobs, 1951). Since cloudiness is an extremely important factor in this investigation, it is encouraging to note that a comparatively short period of record (two years) may be quite representative of the general situation.

Frequency distributions (in numbers of days per month) for sizeable amounts of precipitation (e.g., Table 2) provide a somewhat quantitative means for determining the frequency of occurrence of weather disturbances which affect the various locations. However, it must be realized that the individual disturbances which caused such rainfall amounts could have affected the station for less than 12 hours or more than 24 hours, and that even a relatively short period of disturbance type weather could occur timewise so as to affect two successive days. Therefore, the exact number of disturbances cannot be inferred from such data. Also, we are only interested here in those disturbances which affect the daylight hours significantly, since they are the ones that reduce the incoming solar radiation.

Table 2. Number of days per month which received rainfall amounts (in inches) within the specified categories.

	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May	June
0.26-0.49	1	1			3	1	4	3	3	2	2	1
0.50-0.99	2		2	2	5	4	2	3	1	2		2
1.00-1.49			2	1		2			2		2	
1.50-1.99				1	2	2	4					
2.00-2.49		1			1			1	1			
2.50-2.99					1		2					
3.00-3.49								1				

ANALYSIS OF DATA

The Equatorial Trough Shift and Attendant Weather

The unusually large increase in cloud cover, precipitation, and thunderstorm activity during several months of the July 1957 - June 1958 period at Canton (see Table 1) indicated the possibility that there had been a southward shift in the mean position of the equatorial trough during this selected IGY period. Over this same period, Majuro Atoll, which is usually on the northern flank of the mean annual trough position, recorded 22.42 inches of rainfall less than normal. In order to obtain a rough quantitative measure of the mean southward shift of the trough over the July 1957 - June 1958 period, daily positions of the trough were taken from the IGY tropical zone analyses along the longitude of Canton, and these were used to arrive at the approximate monthly and annual mean positions of Table 3. Since the long-term mean annual position of the trough is near 5^{o} north latitude along Canton's longitude (from Figure 3.2 of Riehl, 1954), it appears that there was a southward shift of about 4^{o} latitude (see Table 3) in the mean trough position for the selected period. This southward shift in the mean trough position and the associated precipitation increase to the south would cause a significant alteration in the configuration of the arid zone which usually lies a little south of the equator in the central and eastern parts of the equatorial Pacific.

Table 3. Mean monthly and annual latitudinal location of the equatorial trough along the longitude of Canton Island for the period July 1957 - June 1958.

July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.
3.38°N	3.22°N	5.09°N	5.47°N	5.44°N	0.10°S	9.65°S

Feb.	March	April	May	June	Annual Mean
4.52°S	4.00°S	0.35°S	4.26°N	3.94°N	1.03°N

A question arises in regard to the southward shift of the equatorial trough and its relation to increased precipitation, since during January 1958, when the precipitation was extraordinarily high, the mean position of the trough was at 9.65° S, considerably south of Canton. Certainly proximity of the trough itself to Canton could not be the reason for the heavy rainfall in this case. There must be some relation between this mean trough position about 7° south of Canton and the extremely heavy rainfall at Canton. A brief report by Mr. Myron H. Kerner, former Meteorologist in charge, U. S. Weather Bureau, Canton Island, provides the following information in regard to Canton Island precipitation (excerpt of letter in Appendix A, Degener and Gillaspy, 1955, p. 51):

> Our precipitation is caused in three different ways. There are always some cumulus present; these are probably a result of local heating due to distant variation in the sea surface and converging air. Precipitation from these clouds is infrequent, light and spotty. The greatest amount occurs when the inter-tropical convergence zone (the narrow band where the trade winds converge on the doldrum belt giving large scale uplift to the air resulting in thunderstorm activity and copious rain showers) lying to the south of us moves over us for a few hours to a few days. Then Canton may get several inches in a day. The third source of precipitation results from small scale equatorial low pressure systems that move slowly from the Gilberts. The occurrence of precipitation from either of these latter two reasons is very irregular, which accounts for Canton's being a place of great extremes in seasonal precipitation.

Mr. Kerner's third source of precipitation appears to be the primary cause for the heavy precipitation in the January 1958 case. The precipitation source is further discussed in the ESSA (1966) Narrative Climatological Summary for Canton:

> . . . Because of the Island's proximity to the equator, it is well out of the track of tropical storms that originate to the south, but at infrequent intervals small low pressure centers have been known to form to the west or southwest of Canton Island, causing a westerly flow of air and periods of heavy precipitation (ESSA, 1966, p. 1).

The following extract from Berry, Bollay, and Beers (1945) sheds further light on the cause of this situation:

> When the trough lies along the equator or within 3^{o} latitude N or S of it, the winds on both sides are predominantly easterly in direction. When it departs widely from the equator, however, the trough will frequently contain a closed depression with predominantly westerly winds on the equatorward side and easterlies on the poleward side only. As an

> approximate rule, we may say that the equatorial trough must depart more than 5^{o} away from the equator for a closed system to exist within it (Berry, Bollay, and Beers, 1945, p. 776).

Synoptic features noted in the tropical weather analyses of the German Weather Service (for January 1958) appear to be highly compatible with the contents of the above discussion. In one case, a low pressure cell centered about 400 miles southwest of Canton continued to develop in the trough until it reached a tropical storm intensity. It moved southward and reached hurricane intensity prior to leaving the tropics. In all but one of the remaining high precipitation cases, activity was associated with low pressure centers located to the southwest, south and southeast of Canton in the trough. In one case, proximity to the trough itself, during a period of active convergence, appeared to be the cause. Generally at Canton the prevailing January surface wind direction is east (ESSA, 1966); however, in January 1958, 24 of the 31 days had prevailing winds with westerly components, which agrees well with the synoptic findings mentioned above. The preceding discussion shows that the increased precipitation associated with the mean southward displacement of the equatorial trough involves, in some cases, other than a consideration of proximity of the trough to Canton Island.

In November, another month of heavy rainfall, the largest amounts of precipitation which occurred in the first part of the month, were associated with small low pressure cells located just west of Canton in the southern part of the equatorial trough zone. However, heavy rainfall later in the month was not associated with the equatorial trough, but with the low pressure centers in a large frontal trough extending from southeast to northwest equatorward from an extra-tropical system centered in higher southern latitudes.

Atmospheric Conditions in the Equatorial Trough

Scattered cumulus and broken to overcast thin cirrus and cirrostratus were common during periods when no disturbances were in the vicinity of Canton. Swelling cumuli were also frequently present, particularly during the evening and early morning hours. Extensive cumulonimbus and middle cloud developments were noted when disturbances were in the vicinity.

Although the moist layer was often well defined during periods when no disturbance was present, as it was in the case of the trade wind region, the characteristic thermal inversion of the trades was not noted here, due to the absence of the subsidence mechanism prevalent in the trade-wind region. The thickness of the moist layer varied considerably during the selected year. It was generally fairly thin (usually less than 10,000 ft. deep) from July through October 1957 and in June 1958. It was quite thick (often extending up to 20,000 ft. or more) from November 1957 through May 1958). This trend in moist layer thickness and other associated weather aspects might appear to show a seasonal trend; however, the data for other years would not support this idea. The moist layer was very deep in the convergent zones of disturbances and usually fairly shallow during the fair weather periods between disturbances. Deep disturbances were more frequent during the period November 1957 through May 1958, which accounts for the findings on the increased depth of the moist layer during this period.

Precipitable water content of the atmosphere from the surface to 400 mb usually ranged from 4.5 cm to 6.4 cm during disturbance conditions and from 2.8 cm to 4.0 cm when no disturbance was present. However, in the immediate vicinity of the trough axis (within 3°), precipitable water content showed a high degree of variability, ranging from about 3.2 cm to 5.6 cm with no disturbance present. In this region, the cloud structure was also very variable in time and space (Riehl, 1962).

Malkus and Riehl (1964) report that tropical rainfall studies show an enormously skewed distribution, with the major fraction of the monthly precipitation falling on two or three days. This skewed nature is exhibited in the July 1957 - June 1958 precipitation data for Canton. Table 2 shows the number of days per month during which rainfall fell within certain categories from 0.26 in. upward. The heavy rainfall periods were associated with deep moist layers, high precipitable water content, extensive cloud development; and, of course, all of these characteristics were associated with disturbances.

Malkus and Riehl (1964) have indicated that in the equatorial region the so-called "meridional tropical cell" becomes only a misleading average over intermittency; the crucial upward and poleward exports of energy are confined to disturbances, and within these, further confined to the region of organized penetrative cloud towers. The observations at Canton appear to confirm this viewpoint for the following reasons:

1. The presence of fair weather and small cloud cover during some periods when the trough was directly over Canton and others when it was within a few degrees of Canton, emphasizes the fact that significant convergence isn't continuous along the equatorial trough. Considering all cases when Canton was within 3^{o} of the trough axis, only one out of five of these days were affected by disturbance weather.

2. The precipitable water amounts and moist layer depth were in general agreement with 1 above, usually being much less when no disturbance was in the vicinity. This emphasized the distributive effect of disturbances.

3. Within the convergent zones of disturbance areas, the cloud towers would be the only actual penetrative vehicles which could carry energy upward and make it available for poleward export.

Incoming Solar Radiation in the Equatorial Trough

The variations in radiation reception in the trough zone were very large, as was the cloud variability discussed in the previous section. When there was no disturbance present and relatively clear skies prevailed, the total daily incoming solar radiation (direct and diffuse radiation on a horizontal surface) was frequently in the range of 600 to 700 langleys (L). However, in disturbance weather conditions the daily reception was at times less than 100 L. During disturbances, cloud cover was usually extensive horizontally and vertically, and the deep moist layer and cloud towers frequently extended up into the uppermost levels of the troposphere. Table 4 gives average daily transmission percentages[14] for the various tenths of opaque cloud cover recorded during disturbance weather conditions in the equatorial trough zone. Figures in parentheses show the number of cases falling within each category of coverage and emphasize the preponderance of cases with high opaque coverages during disturbance conditions. The lowest average opaque cloud cover for an individual day was 3.6 tenths. Those cases included in the upper

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[14] The individual transmission percentages, used to arrive at these average values, were obtained by dividing the recorded hourly incoming solar radiation (as received at the pyranometer location) by the computed hourly incoming solar radiation on a horizontal surface at the top of the atmosphere, and then multiplying the result by 100.

Table 4. Average transmission percentage for categories of opaque cloud cover during disturbance weather conditions in the equatorial trough zone.[a]

Tenths of opaque cloud cover	< 5.1	5.1-6.0	6.1-7.0	7.1-8.0	8.1-9.0	9.1-10.0
Transmission percent	60.1 (5)[b]	57.5 (6)	51.6 (9)	41.5 (10)	36.3 (8)	21.4 (19)

[a] Equatorial trough zone extends 10° latitude either side of the trough axis.

[b] The figure in parentheses refers to the number of cases in the particular category.

Table 5. Average transmission percentage for categories of opaque cloud cover during other than disturbance conditions for the zone extending 3° either side of the trough axis.

Tenths of opaque cloud cover	< 3.1	3.1-5.0	5.1-7.0	7.1-9.0
Transmission percent	68.6 (5)[a]	65.6 (9)	59.1 (4)	53.8 (9)

[a] The figure in parentheses refers to the number of cases in the particular category.

category (9.1 - 10.0 tenths opaque cloud cover) showed a maximum reception of 358.1 L and a minimum of 89.9 L.

The zone of consideration was narrowed to 3^{o} either side of the trough axis, in order to more specifically evaluate trough effects under other than disturbance conditions. Average transmission percentages for the various opaque cloud cover categories are presented in Table 5. The minimum average opaque cloud cover for an individual day was 2.0 tenths. The average opaque cloud cover exceeded 8.0 tenths in only one case. The overall average transmission percentage was 61.3, which shows that a large amount of radiation penetrated the atmosphere even near the trough axis, when no disturbance was present.

When just those disturbance cases falling within 3^{o} of the trough axis were considered, the overall average transmission percentage was 34.6. Out of a total of 36 cases studied here, only nine were considered disturbance situations. With the period 27 January through 11 March 1958 included (when no radiation data were recorded), there was a total of 58 cases where Canton was within 3^{o} of the trough axis; of these, 11 were considered to be disturbance[15]

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[15] In all cases involving a numerical count of disturbances, only the daylight period was considered. Therefore, if a disturbance was not effectively apparent during the daylight hours (for purposes of correlating weather data with radiation transmission) it was not included in this report. This same policy was followed in regard to fair weather figures.

situations and 47 otherwise. These figures in addition to clarifying the radiation reception conditions in the immediate vicinity of the equatorial trough axis, also tend to substantiate the intermittency aspect of the so-called "meridional tropical cell" (Malkus and Riehl, 1964) discussed in an earlier section of this report.

Peculiarities Noted in Cloud Cover-Solar Radiation Relationships

The July 1957 - June 1958 data for Canton showed exceptionally large departures from normal in cloud cover and precipitation (see Table 1). However, although there was a 43 percent increase in the mean total sky cover and nearly three-times the normal amount of precipitation on an annual basis, the average daily incoming solar radiation was only about 11 percent below normal.[16] This discovery indicated a need to further investigate the types, characteristics, and amounts of clouds present.[17] A survey of the hourly surface weather observations revealed that there was frequently a high-thin cirriform deck composing the major portion of the broken to overcast cloud

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[16] If February data were available, this average reduction might be increased to about 12 percent, which is still very small compared to the magnitude of the meteorological changes.

[17] In an earlier section, it was noticed that during fair weather, cumuliform and cirriform clouds were commonly present. Extensive middle cloud and cumulonimbus coverages were associated with disturbances.

coverages. Also, it appeared that the reduction of incoming solar radiation was hardly noticeable when there was a thin cirriform overcast, and the accompanying low cloud was small in amount.

Although the extensive (vertical and horizontal) cloud coverages of disturbances usually caused a large reduction in incoming solar radiation, they occurred much less frequently than the intervening fair weather conditions. Riehl and Malkus (1958) suggested that about 10 percent of the equatorial trough zone was occupied by synoptic disturbances.

Due to the extensive nature of the fair weather conditions, it became essential to know the percentage of time that thin cirriform overcasts existed in conjunction with scattered or no low clouds, and just how much radiation reduction beyond clear sky conditions was caused by the thin cirriform deck alone. Such information was required in order to establish a more sound basis for determination of incoming solar radiation from available meteorological data in climatic environments similar to that of Canton Island.

The Cirriform Contribution

Percentages of time during which thin overcast cirrus and cirrostratus occurred in conjunction with scattered[18] or no low clouds

[18] The opaque cloud cover essentially represented the low clouds when cirriform clouds were thin. The limits for the scattered low cloud category were 1-5.4 tenths; less than 1 tenth was considered clear.

were computed for the July 1957 - June 1958 Canton Island weather data. Table 6 shows these percentages on a monthly and annual basis for two different low cloud categories. These percentages are quite high, but would be much higher if the specifications were changed so as to include the same low cloud criteria (scattered or none) and all cirriform ceilings (i.e., 6 to 10 tenths coverage of cirrus or cirro-stratus). It must, therefore, be concluded that this cirriform contribution to total sky cover was exceptionally high.[19] However, it must be realized that this situation existed during the extensive fair weather periods when the middle cloud contribution was exceptionally low.

In order to determine the radiation reduction due to the thin cirriform deck alone, it was first necessary to determine the incoming solar radiation during clear sky conditions at Canton. Since there were so few completely clear hours during the selected year, it was found advisable to consider all observations with less than 2.0 tenths total sky cover, after eliminating situations when there were obviously low cloud patches directly between the pyranometer and the sun.[20] To obtain incoming radiation when just the thin cirriform

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[19] Here the comparison was with cloud distributions experienced outside of the tropics.

[20] This was determined by a study of the actual radiation trace for each hour involved. Large short period downward displacements in the radiation trace indicated those situations when a low cloud patch was above the pyranometer.

Table 6. Percentage of time (0600-1800 true solar time) when the indicated opaque cloud coverages occurred with 10.0 tenths total cloud cover at Canton Island during the period July 1957-June 1958.

TOC[a]	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	April	May	June	Annual Average
0-3.0	50.3	28.5	19.4	35.2	24.2	9.4	5.9	13.1	14.0	12.2	13.4	13.6	20.0
0-5.4	74.5	49.5	42.2	59.4	44.4	24.5	21.8	35.4	35.5	31.7	39.2	26.1	40.4

[a] Total opaque cloud cover, which under the stipulated conditions is essentially the amount of low cloud cover.

overcast was present, those hours with 10.0 tenths cirrostratus or cirrus and less than 2.0 tenths total opaque sky cover were used, following the same procedure as stated above to eliminate those cases where a low cloud patch was directly between the pyranometer and the sun. Table 7 contains transmission figures for the various solar altitude ranges.[21] The figures in this table indicate that the thin cirriform overcast caused little or no additional reduction of the incoming solar radiation regardless of the solar altitude. The decrease in transmission percentage with decrease in solar altitude, which did affect both categories similarly, appeared to be due to the increase in air mass penetrated at the lower solar altitudes.

The ESSA (1966), in a short narrative climatological summary for Canton Island, stated that cirriform clouds occurred at or above 30,000 ft. The inflight cloud observations of Malkus and Riehl (1964) also showed the tropical cirriform clouds to be based most frequently between 30,000 and 40,000 ft. The more rarified atmosphere at these high levels would be expected to have low density clouds.

Cirriform clouds were included along with the other clouds in arriving at the average sky cover figures from sunrise to sunset,

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[21] Individual transmission figures, which were used to arrive at the mean values of Table 7, were obtained by dividing the recorded hourly incoming solar radiation by the computed hourly incoming solar radiation on a horizontal surface at the top of the atmosphere, and then multiplying the result by 100.

Table 7. Average transmission percentages for designated solar altitude ranges under stipulated sky cover conditions.

Coverage (in tenths)	Solar altitude ranges						
	0°-14°	15°-29°	30°-44°	45°-59°	60°-74°	75°-90°	Average
< 2.0 TC[a]	46.9 (5)[c]	65.6 (10)	73.2 (10)	76.6 (12)	77.8 (17)	77.6 (5)	69.6 (Pertains essentially to clear sky)
10.0 TC & < 2.0 TOC[b]	45.3 (36)	63.9 (24)	72.3 (24)	76.1 (26)	76.8 (26)	77.4 (6)	68.6 (Pertains essentially to cirriform overcast)

[a] Total sky cover

[b] Total opaque sky cover

[c] Figures in parentheses refer to the number of cases in the particular category.

which appear in standard climatological summaries. Their unusually large contribution to the total sky cover figures for the July 1957 - June 1958 Canton data would certainly have led to large underestimations of the incoming solar radiation, if there was no radiation record available and the types, characteristics, and amounts of cloud contributing to the sky cover were not fully understood.

It was, therefore, necessary to determine whether the findings in regard to cirriform clouds for this limited period of record at Canton were applicable during other years, regardless of proximity to the mean position of the equatorial trough,[22] and whether the condition was localized or widespread over the equatorial Pacific. If such a condition were widespread, the large errors in estimates of incoming solar radiation resulting from the use of mean total sky cover, as it appears in climatological summaries,[23] could result in large errors in earth-atmosphere heat budget computations over this region.

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[22] In an earlier section, the mean annual position of the equatorial trough was reported to be 4^{o} south of its normal position for the period July 1957 - June 1958.

[23] The 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.

Applicability of the July 1957 - June 1958 Canton Island Data

It was necessary to check the data from this selected IGY period of record against data for a long period of record at Canton, in order to determine the general applicability of the cloud cover findings in the previous section. Table 8 provides climatological data obtained from a 209 month USAF AWS Summary for Canton Island. The percentage frequency of ceilings 10,000 ft. and over (see last column of Table 8) was obtained by subtracting the combined percentage frequencies of clear and scattered sky cover conditions from the percentage frequency of ceiling heights 10,000 ft. and over or unlimited. These same figures could be arrived at by subtracting the combined percentage frequencies of ceilings in the 0-5000 ft. and 5500-9500 ft. categories from the combined percentage frequencies of broken and overcast sky covers. These percentage frequencies of ceilings 10,000 ft. and over should primarily pertain to cases with high cirriform ceilings for the following reasons:

1. Fair weather conditions, even during the highly unusual IGY period were found to be far more extensive than disturbance periods at Canton; and, in fair weather, cumuliform and cirriform clouds were the usual types present.

2. Extensive middle cloud covers in this region were associated with disturbance weather conditions, and, when present,

Table 8. Climatological data[a] for Canton Island, Phoenix Islands.

Month	Percentage frequency of occurrence of specified sky covers in tenths: 0	1-5	6-9	10	Mean tenths of sky cover	Percentage frequency of occurrence of specified ceiling heights in feet: 0-5000	5500-9500	10,000 and over or unl	Mean no. of days with measurable precipitation	Mean monthly precipitation	Mean no. of days with precipitation > 0.25 in.	Percentage freq. of occurrence visibility 10 mi. and over	Percentage freq. of occurrence of obs. with pcpn	Percentage freq. of ceilings 10,000 ft. and over
Jan	1.7	40.8	14.1	43.4	6.6	8.1	1.8	90.0	6.3	2.39	1.7	98.7	3.5	47.5
Feb	2.1	40.0	13.8	44.1	6.6	7.8	1.4	90.8	5.5	1.54	1.3	99.2	2.7	48.7
Mar	1.5	38.8	17.3	42.3	6.7	8.2	2.0	89.8	7.7	1.53	1.5	99.4	3.0	49.5
Apr	1.1	39.6	22.0	37.3	6.6	9.9	2.1	88.0	12.0	2.72	2.7	98.9	3.6	47.3
May	1.7	40.2	17.9	40.2	6.6	9.9	2.2	87.9	12.0	3.13	3.8	98.5	3.7	46.0
June	2.1	44.6	17.5	35.8	6.2	9.2	1.9	88.9	11.2	2.84	3.1	99.1	3.5	42.2
July	3.3	41.6	17.4	37.7	6.3	8.0	1.3	90.8	11.8	2.56	2.7	99.4	2.9	45.9
Aug	4.4	45.9	16.9	32.8	5.8	8.0	1.3	90.7	10.5	2.48	2.5	99.2	2.4	40.4
Sept	4.0	49.8	17.0	29.2	5.5	7.7	1.3	91.0	7.3	1.37	1.4	99.6	1.6	37.2
Oct	2.5	42.7	15.1	39.7	6.3	6.0	0.7	93.3	5.4	0.75	0.7	99.7	1.0	48.1
Nov	2.4	40.8	16.1	40.6	6.5	6.5	1.0	92.6	4.3	1.37	1.2	99.1	2.0	49.4
Dec	2.0	34.5	17.0	46.4	6.9	7.4	1.7	90.9	4.8	1.70	1.4	99.0	2.6	54.4
Annual	2.4	41.6	16.8	39.1	6.4	8.1	1.5	90.4	98.9	24.39	23.9	99.1	2.7	46.4

[a] Period of record is in general 209 months during the years 1942-1946 and 1949-1963.

were frequently included in the cases where ceilings were less than 10,000 ft.

3. Since the mean annual precipitation was much less than the total precipitation for the IGY period (see Table 1), and the mean annual number of days with precipitation greater than 0.25 in. (see Table 8) was also much less than the number for the IGY period (see Table 2), the mean annual number of disturbance days must also have been much less than the number that occurred between July 1957 and June 1958. Therefore, it appeared that fair weather conditions were much more prevalent in the mean.

4. Eniwetok Atoll (see Table 16) shows a strong resemblence to Canton (see Table 8) in regard to cloud cover and ceiling distributions, although its mean annual precipitation exceeds that of Canton by about 32 in. The Eniwetok data has the added advantage that its purely high cirriform ceilings have been isolated (see data column 9, Table 16) from the broader category of "Percentage frequency of ceilings 10,000 ft. and over," to which the Canton Island data were limited. At Eniwetok 76 percent of the ceilings 10,000 ft. and over were cirriform on an annual basis. It is expected that this percentage would be higher at Canton, since a smaller number of disturbance situations would be expected from the lower mean annual rainfall and the smaller number of days for which precipitation exceeded 0.25 in., while the mean total sky covers differed very little.

From the data at hand, it would appear that there was a cirriform ceiling about 40 percent of the time at Canton, on a mean annual basis. The IGY data showed a much greater annual mean total sky cover than the long period mean, and also a greater cirriform contribution, since cirriform overcasts for the IGY period were as plentiful as the estimated cirriform ceilings for the long period mean record. However, the findings for the selected year of data appeared to be in general agreement with the extended period of record, and it could be generally inferred that the thin cirriform contribution to total sky cover was unusually high. Situations of this nature must be fully recognized and somehow rectified, in order to avoid large errors in calculations of incoming radiation from meteorological data.[24] When the July 1957 through June 1958 mean total sky cover data for Canton were entered in commonly used formulas for calculations of incoming solar radiation, the resultant values greatly underestimated the actual conditions (see the MTS row for each case in Table 19 and the recorded values in the bottom row).

It was necessary next to check Canton Island climatological data against that for additional observation sites in the equatorial region, in order to determine whether this cloud condition was

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[24] Most formulas used for such computations were developed for cloud distributions and solar altitude ranges as they appeared in middle and higher latitudes.

localized or widespread. Tables 9-17 present data obtained from summaries prepared by the USAF AWS for nine additional low latitude islands. The locations and characteristics of these sites and Canton were discussed in introductory sections. For this study of cirriform cloud contributions, the data from all ten of these sites should be useful.

The data for Palmyra, Fanning, and Christmas Islands (Tables 9-11) indicated that the contribution of cirriform clouds to total cloud cover was very small in their part of the central Pacific. Although the "Percentage frequency of ceilings 10,000 ft. and over," could not be obtained directly from the Fanning data summary, it could be very roughly approximated by subtracting estimated clear and scattered sky cover percentages[25] from the figures for ceilings 10,000 ft. and over or unlimited (see third data column of Table 10). Subtracting the higher level middle cloud ceiling frequency from the annual frequency of ceilings above 10,000 ft. would certainly leave a very small frequency for pure cirriform ceilings. Although the mean annual sky covers for Palmyra and Canton were nearly the same, Palmyra had a much higher percentage of low ceilings and several times more

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[25] These percentages were very roughly estimated from the clear and scattered sky cover figures for Christmas to the south and Palmyra to the north. An annual estimate of 2 percent clear and 45 percent scattered gave a value of about 14 percent for the "Percentage frequency of ceilings 10,000 ft. and over."

Table 9. Climatological data[a] for Palmyra Island, Line Islands.

Month	Percentage frequency of occurrence of specified sky covers in tenths				Mean tenths of sky cover	Percentage frequency of occurrence of specified ceiling heights in feet			Mean no. of days with measurable precipitation	Mean monthly precipitation	Mean no. of days with precipitation > 0.25 in.	Percentage freq. of occurrence visibility 10 mi. and over	Percentage freq. of occurrence of obs. with pcpn	Percentage freq. of ceilings 10,000 ft. and over
	0	1-5	6-9	10		0-5000	5500-9500	10,000 and over or unl						
Jan	---	---	---	---	---	32.3	11.1	56.7	20.5	13.25	10.0	65.4	16.5	---
Feb	---	---	---	---	---	42.8	7.3	50.0	18.7	8.45	9.0	70.7	14.9	---
Mar	0.2	39.4	34.8	25.5	6.5	49.1	11.3	39.5	23.3	12.17	11.0	67.0	17.7	0.0
Apr	0.2	30.6	42.9	26.2	6.9	40.1	7.8	52.2	18.8	7.50	6.0	79.8	10.9	21.4
May	3.8	28.8	33.9	33.6	6.9	42.7	7.3	49.8	23.8	12.21	11.8	71.8	13.9	17.2
June	3.1	35.6	31.5	29.6	6.5	42.9	3.9	53.2	23.7	16.23	15.0	68.3	14.3	14.5
July	0.8	44.9	21.1	33.2	6.5	42.9	4.2	52.7	23.7	14.31	15.3	73.2	15.5	7.0
Aug	---	---	---	---	---	40.2	5.0	55.0	22.0	17.35	14.0	77.0	14.6	---
Sept	0.3	34.5	37.1	28.1	6.7	33.0	9.8	57.3	16.5	13.75	11.0	67.5	9.4	22.5
Oct	6.0	35.9	29.5	28.7	6.1	26.2	9.2	64.6	18.3	9.62	10.3	57.4	8.7	22.7
Nov	---	---	---	---	---	38.2	2.6	59.3	20.5	14.34	8.0	82.6	15.9	---
Dec	---	---	---	---	---	33.6	4.2	62.2	18.5	20.35	13.5	77.2	15.9	---
Annual	3.0	34.1	33.5	29.4	6.6	39.2	7.2	53.5	250.7	152.56	133.3	70.8	13.6	16.4

[a] Period of record is generally 33 months during 1945-1947, 1949, 1951, 1957, and 1962.
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Table 10. Climatological data[a] for Fanning Island, Line Islands.

Month	Percentage frequency of occurrence of specified ceiling heights in feet: 0-5000	5500-9500	10,000 and over or unl	Mean no. of days with measurable precipitation	Mean monthly precipitation	Mean no. of days with precipitation > 0.25 in.	Percentage freq. of occurrence visibility 10 mi. and over	Percentage freq. of occurrence of obs. with pcpn
Jan	42.0	1.5	56.5	18.0	4.39	6.0	97.4	8.7
Feb	35.7	2.6	61.7	17.7	4.89	5.0	96.3	9.0
Mar	37.9	3.0	59.1	17.0	3.27	4.0	94.6	9.0
Apr	45.6	5.2	49.2	22.0	7.34	9.0	93.1	12.7
May	40.8	5.5	53.6	25.5	9.62	9.0	93.7	13.6
June	36.1	6.5	57.4	22.5	9.03	9.0	91.9	13.1
July	33.6	9.7	56.7	22.0	10.63	9.5	94.5	10.5
Aug	26.8	5.2	68.0	12.5	3.35	4.0	98.3	3.9
Sept	18.6	5.5	75.9	10.0	0.67	0.0	99.4	1.8
Oct	19.5	8.9	71.6	11.0	2.47	2.5	98.7	3.2
Nov	26.8	5.0	68.2	8.0	1.51	2.0	99.4	2.8
Dec	39.3	4.8	55.8	13.5	6.50	4.5	97.6	8.9
Annual	34.1	5.2	60.7	199.7	63.67	65.2	96.1	8.3

[a] Period of record is in general 23 months during the years 1943-1945.

Table 11. Climatological data[a] for Christmas Island, Line Islands.

Month	Percentage frequency of occurrence of specified sky covers in tenths: 0	1-5	6-9	10	Mean tenths of sky cover	Percentage frequency of occurrence of specified ceiling heights in feet: 0-5000	5500-9500	10,000 and over or unl	Mean no. of days with measurable precipitation	Mean monthly precipitation	Mean no. of days with precipitation > 0.25 in.	Percentage freq. of occurrence visibility 10 mi. and over	Percentage freq. of occurrence of obs. with pcpn	Percentage freq. of ceilings 10,000 ft. and over
Jan	0.8	65.0	24.5	9.8	4.8	26.7	2.2	71.1	6.3	0.93	1.2	99.0	2.5	5.3
Feb	0.1	57.0	29.5	13.5	5.4	26.8	2.5	70.7	8.9	1.53	1.4	97.7	4.7	13.6
Mar	0.2	57.2	30.2	12.4	5.3	26.5	3.5	69.9	12.3	2.50	2.8	94.1	5.7	12.5
Apr	0.9	43.7	33.0	22.4	6.1	32.7	4.9	62.4	19.9	8.12	8.0	87.3	10.3	17.8
May	0.5	60.2	28.1	11.2	5.0	20.1	3.2	76.7	11.6	3.50	3.9	95.8	5.3	16.0
June	1.4	61.3	28.8	8.5	4.9	16.4	3.3	80.4	9.3	2.85	2.4	97.9	3.8	17.7
July	2.4	61.5	28.3	7.8	4.8	18.2	2.2	79.5	5.0	2.00	2.3	98.0	2.7	15.6
Aug	2.8	69.0	22.6	5.7	4.5	13.9	1.6	84.4	4.6	0.56	0.4	99.5	1.5	12.6
Sept	1.5	78.4	16.6	3.4	3.7	10.5	2.8	86.7	2.3	0.10	0.0	99.6	0.8	6.8
Oct	1.3	76.6	18.4	3.8	3.9	12.0	1.5	86.5	2.4	0.14	0.0	99.9	0.7	8.6
Nov	0.5	73.6	22.1	3.7	4.2	14.4	2.6	82.9	1.6	0.06	0.0	99.8	1.3	8.8
Dec	0.4	74.4	20.9	4.3	4.2	18.2	1.7	80.0	4.1	0.63	0.0	99.3	1.2	5.2
Annual	1.0	64.1	25.5	9.3	4.8	19.6	2.7	77.6	90.7	24.46	24.0	97.3	3.4	12.5

[a] Period of record is in general 77 months during the years 1941-1948 and 1962.

precipitation than Canton. Obviously, such large differences in cloud distributions by type and amount should be reflected in the cloud entry of formulas for computation of incoming solar radiation.

At Baker Island, there was no ceiling 64.4 percent of the time on an annual basis, and ceilings below 10,000 ft. only occurred 13.4 percent of the time. The very low "Percentage frequency of occurrence of observations with precipitation" would indicate a very small amount of disturbance activity and, therefore, a very low percentage of extensive middle cloud. As a result, the 22.1 percent figure for ceilings 10,000 ft. and over (shown as high ceilings in Table 12) implied that the cirriform contribution to mean total sky cover must have been quite large in comparison to that of other cloud types at this location.[26]

The percentage frequency of ceilings 10,000 ft. and over (shown as high ceilings in Table 13) at Tarawa was quite high. On an annual basis, about 59 percent of all ceilings fell in this category. The low "Percentage frequency of occurrence of observations with precipitation" inferred a rather small percentage of middle cloud ceilings[27] (based on the assumption that extensive middle clouds were

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[26]The indefinite nature of this statement was based on the facts that October data were missing and the period of record was very short (13 months). Rainfall figures for such a short period could be highly misleading.

[27]Here, as at Baker Island, figures based on precipitation data were not reliable, due to the short period of record.

Table 12. Climatological data[a] for Baker Island.

Month	Percentage frequency of occurrence of specified sky conditions[b]					Percentage frequency of occurrence of specified ceiling heights in feet			Percentage freq. of occurrence of obs. with pcpn	Percentage freq. of occurrence visibility 10 mi. & over
	Clear	Scattered	Hi Brkn or Hi Ovc with sctd or no low clouds	Low broken	Low overcast	0-5250	5251-9750	9751 and over or unl		
Jan	12.0	34.1	35.0	12.7	6.2	16.1	2.8	81.1	4.4	98.6
Feb	16.5	47.5	24.1	10.0	1.9	10.3	0.8	88.9	1.4	100.0
Mar	29.4	36.3	7.3	16.5	10.5	27.0	0.0	73.0	4.0	99.6
Apr	39.7	27.2	20.1	7.2	5.7	12.9	0.0	87.1	3.9	100.0
May	35.2	40.0	9.3	10.2	5.2	15.5	0.0	84.5	4.6	99.6
Jun	15.7	56.2	16.0	7.6	4.4	11.8	0.3	87.9	4.6	99.0
July	24.2	51.3	15.6	6.3	2.6	7.1	1.8	91.1	2.6	99.5
Aug	13.7	68.6	7.4	8.1	2.3	7.8	2.6	89.6	0.8	99.7
Sept	17.6	63.1	12.4	4.9	2.1	4.3	2.6	93.1	0.7	99.7
Oct	---	---	---	---	---	---	---	---	---	---
Nov	1.2	39.6	48.1	9.6	1.4	10.2	1.0	88.9	0.7	100.0
Dec	11.2	27.8	47.5	11.8	1.6	10.6	2.7	86.7	1.7	99.8
Annual	19.7	44.7	22.1	9.5	4.0	12.1	1.3	86.5	2.7	99.6

[a] Period of record is about 13 months during the years 1943-1945.

[b] The "High broken or high overcast with scattered or no low clouds" category is the same as the "Percentage frequency of ceilings 10,000 ft. and over" in the other tables.

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Table 13. Climatological data[a] for Tarawa Island, Gilbert Islands.

Month	Percentage frequency of occurrence of specified sky conditions[b]: Clear	Scattered	Hi Brkn or Hi Ovc with sctd or no low clouds	Low broken	Low overcast	Percentage frequency of occurrence of specified ceiling heights in feet: 0-5250	5251-9750	9751 and over or unl	Percentage freq. of occurrence of obs. with pcpn	Percentage freq. of occurrence visibility 10 mi. & over
Jan	1.6	27.0	37.2	22.7	11.4	31.4	2.7	65.9	8.7	97.3
Feb	0.3	31.6	30.6	24.3	13.2	31.2	6.2	62.5	4.5	99.0
Mar	0.1	47.3	16.4	27.0	9.1	31.0	5.1	63.8	3.1	99.7
Apr	0.0	30.0	46.5	16.1	7.4	20.6	2.9	76.5	3.9	98.6
May	0.1	36.3	23.5	30.6	9.4	35.6	4.7	59.7	10.2	94.9
June	0.0	42.1	33.0	18.7	6.2	22.1	2.8	75.1	8.3	96.3
July	0.5	36.7	41.8	17.5	3.6	19.4	1.6	79.0	5.2	97.1
Aug	0.6	44.1	40.4	12.9	1.9	12.6	2.3	85.1	4.2	98.2
Sept	1.2	52.7	34.8	10.5	0.9	10.3	1.0	88.7	1.6	99.2
Oct	2.8	47.9	37.3	9.8	2.2	10.4	1.6	88.0	3.5	98.6
Nov	0.7	32.4	40.3	16.6	10.0	20.3	6.3	73.3	7.3	96.8
Dec	0.2	27.1	49.7	17.9	5.2	21.0	2.1	76.9	6.2	97.7
Annual	0.7	37.9	36.0	18.7	6.7	22.2	3.3	74.5	5.6	97.8

[a] Period of record is about 20 months during the years 1944-1946.

[b] The "High broken or high overcast with scattered or no low clouds" category is the same as the "Percentage frequency of ceilings 10,000 ft. and over" in the other tables.

associated with disturbance conditions which could be further associated with precipitation frequency). Therefore, it was indicated that Tarawa experienced a high cirriform contribution to its total sky cover.

The climatological records for Majuro, Kwajalein, and Eniwetok were of sufficient length to provide reasonably representative figures for comparison purposes. Since these islands were all north of the mean annual position of the equatorial trough, had similar relief, were in reasonable proximity to one another, and were primarily affected by similar synoptic features, they were considered here in a group.[28] All show a high "Percentage frequency of ceilings 10,000 ft. and over" (see the last column in Tables 14 and 15 and data columns 8 and 9 of Table 16). As mentioned earlier in this section, the Eniwetok summary provided cirriform ceiling data directly (see data column 9, Table 16). On an annual basis, 58 percent of the ceilings were found at cirriform levels over Eniwetok. This would certainly provide an unusually high cirriform contribution

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[28] All three are atoll islands without significant vertical relief and are located within a span of 600 nautical miles. Majuro is closest to the mean annual position of the equatorial trough with Kwajalein and Eniwetok progressively further north of the trough, respectively. Their weather is primarily affected by proximity to the trough and its associated disturbances. Cloud cover and precipitation increase progressively from Eniwetok to Kwajalein to Majuro. During the late fall, winter and early spring, Eniwetok experiences much weather typical of the trade-wind region.

Table 14. Climatological data[a] for Majuro Atoll, Marshall Islands.

Month	Percentage frequency of occurrence of specified sky covers in tenths: 0	1-5	6-9	10	Mean tenths of sky cover	Percentage frequency of occurrence of specified ceiling heights in feet: 0-5000	5500-9500	10,000 and over or unl	Mean no. of days with measurable precipitation	Mean monthly precipitation	Mean no. of days with precipitation >0.25 in.	Percentage freq. of occurrence visibility 10 mi. and over	Percentage freq. of occurrence of obs. with pcpn	Percentage freq. of ceilings 10,000 ft. and over
Jan	0.4	17.0	15.7	66.9	8.4	17.1	2.1	80.8	18.0	11.53	9.1	96.1	9.8	63.4
Feb	0.9	23.4	20.4	55.2	7.8	15.8	4.4	79.7	17.1	8.26	7.2	96.7	8.2	55.4
Mar	0.9	23.1	18.5	57.5	7.9	16.4	5.3	78.3	17.8	10.97	9.7	92.7	9.2	54.3
Apr	0.9	18.8	21.1	59.3	8.2	17.3	4.4	78.2	20.8	11.63	9.7	90.0	13.0	58.5
May	0.3	22.1	20.9	56.5	8.0	15.2	3.4	81.3	23.3	11.73	11.3	91.5	11.9	58.9
June	0.5	19.1	18.6	62.0	8.3	13.9	1.9	84.2	23.9	13.36	13.0	96.3	11.0	64.6
July	0.5	17.9	17.1	64.4	8.4	13.0	1.0	86.0	24.2	11.55	10.6	96.7	11.0	67.6
Aug	0.2	17.5	17.8	64.5	8.4	11.4	1.5	87.1	22.6	11.54	11.4	97.4	10.7	69.4
Sept	0.4	15.1	15.4	69.0	8.6	12.9	2.8	84.5	23.0	12.86	11.8	96.5	11.0	69.0
Oct	0.3	14.8	18.8	66.1	8.6	13.2	4.0	82.8	24.8	15.42	13.4	94.8	11.7	67.7
Nov	0.4	12.9	15.9	70.9	8.8	15.0	3.9	81.2	23.8	16.83	13.6	94.7	14.7	67.9
Dec	0.6	13.1	14.6	71.7	8.7	13.4	1.4	85.1	21.0	9.80	10.1	96.9	10.2	71.4
Annual	0.5	18.0	18.0	63.4	8.3	14.7	3.1	82.2	259.4	144.74	130.4	94.8	11.0	63.7

[a] Period of record is generally for 112 months of 1946, 1948, 1951, 1952, 1954, and 1955-1963.

Table 15. Climatological data[a] for Kwajalein Atoll, Marshall Islands.

Month	Percentage frequency of occurrence of specified sky covers in tenths: 0	1-5	6-9	10	Mean tenths of sky cover	Percentage frequency of occurrence of specified ceiling heights in feet: 0-5000	5500-9500	10,000 and over or unl	Mean no. of days with measurable precipitation	Mean monthly precipitation	Mean no. of days with precipitation >0.25 in.	Percentage freq. of occurrence visibility 10 mi. and over	Percentage freq. of occurrence of obs. with pcpn	Percentage freq. of ceilings 10,000 ft. and over
Jan	0.7	33.7	32.5	33.1	6.9	19.3	3.4	77.2	14.7	3.77	3.8	95.4	5.2	42.8
Feb	0.8	34.8	29.5	34.8	6.9	17.6	2.9	79.4	12.7	2.51	2.6	96.5	4.2	43.8
Mar	0.7	30.5	30.9	37.9	7.2	19.8	5.2	75.1	15.9	6.11	5.3	94.0	6.3	43.9
Apr	0.2	23.2	35.4	41.2	7.7	19.0	5.0	75.9	16.2	5.34	5.7	93.0	6.8	52.5
May	0.3	24.0	35.4	40.4	7.6	22.5	5.8	71.6	19.9	8.92	8.8	90.7	9.3	47.3
June	0.2	28.0	35.4	36.4	7.4	20.3	5.1	74.6	21.1	8.83	9.1	92.1	7.6	46.4
July	0.0	26.4	36.3	37.2	7.5	18.5	4.2	77.4	23.5	9.17	10.0	92.4	8.9	51.0
Aug	0.2	25.7	37.1	37.0	7.5	16.7	4.8	78.5	23.0	9.96	10.5	91.5	9.3	52.6
Sept	0.2	25.1	34.7	39.9	7.6	17.2	5.3	77.5	21.4	10.65	10.4	91.3	10.2	52.2
Oct	0.1	23.7	35.9	40.3	7.7	18.1	4.6	77.3	22.9	10.86	11.5	90.9	11.0	53.5
Nov	0.1	23.0	34.3	42.7	7.8	21.5	5.8	72.7	23.2	12.44	11.5	88.8	12.3	49.6
Dec	0.5	28.4	32.6	38.5	7.4	18.9	4.2	76.8	18.7	8.86	7.3	91.4	8.6	47.9
Annual	0.3	27.1	34.2	38.3	7.4	19.2	4.7	76.2	233.7	97.63	96.9	92.3	8.3	48.8

[a] Period of record is generally for 233 months between 1944 and 1963.

Table 16. Climatological data[a] for Eniwetok Atoll, Marshall Islands.

Month	Percentage frequency of occurrence of specified sky covers in tenths: 0	1-5	6-9	10	Mean tenths of sky cover	Percentage frequency of occurrence of specified ceiling heights in feet: 0-5400	5500-9400	9500-< 19,000	≥19,000[b]	Mean no. of days with measurable precipitation	Mean monthly precipitation	Mean no. of days with precipitation > 0.25 in.	Percentage freq. of occurrence of obs. with pcpn	Percentage freq. of occurrence visibility 10 mi. and over
Jan	2.8	51.7	24.6	20.9	5.5	12.2	3.2	5.5	24.6	11.1	1.03	0.7	3.7	95.0
Feb	2.8	48.8	23.5	24.9	5.8	11.2	3.0	4.2	30.0	9.1	0.81	0.5	2.8	94.4
Mar	1.6	41.6	27.1	29.7	6.3	11.2	3.8	7.7	34.1	11.5	1.80	1.7	3.8	93.7
Apr	0.4	41.9	25.3	32.3	6.5	8.5	2.8	8.3	38.1	12.7	2.19	2.2	3.3	94.5
May	0.3	29.6	26.3	43.8	7.4	12.0	4.4	14.0	39.7	16.8	5.63	4.9	6.3	91.7
June	0.8	36.8	24.6	38.0	6.9	9.9	4.1	9.6	38.8	17.1	3.76	4.7	4.6	93.4
July	0.3	29.5	27.2	43.0	7.4	9.3	4.3	13.3	43.3	21.4	6.87	7.2	6.6	93.0
Aug	0.3	27.2	28.0	44.5	7.6	9.2	4.8	13.8	44.7	21.4	6.79	8.0	7.0	92.7
Sept	0.2	29.0	25.0	45.9	7.5	8.0	4.4	17.4	41.0	20.2	6.99	8.3	7.3	93.3
Oct	0.2	26.7	26.5	46.4	7.6	11.0	6.7	17.2	38.2	21.7	9.76	9.8	9.1	90.7
Nov	1.0	39.3	24.4	35.4	6.7	10.6	3.8	15.2	30.1	20.7	7.01	7.1	7.5	92.0
Dec	2.0	50.0	22.9	25.1	5.8	10.9	3.3	8.0	25.8	15.2	3.48	3.3	4.7	93.9
Annual	1.0	37.3	25.4	36.1	6.7	10.3	4.1	11.3	36.0	199.1	56.13	58.4	5.6	93.2

[a] Period of record is in general 182 months during the years 1949-1965.
[b] Does not include unlimited conditions.

Table 17. Climatological data[a] for Moen Island (Truk), Caroline Islands

Month	Percentage frequency of occurrence of specified sky covers in tenths: 0	1-5	6-9	10	Mean tenths of sky cover	Percentage frequency of occurrence of specified ceiling heights in feet: 0-5000	5500-9500	10,000 and over or unl	Mean no. of days with measurable precipitation	Mean monthly precipitation	Mean no. of days with precipitation > 0.25 in.	Percentage freq. of occurrence visibility 10 mi. and over	Percentage freq. of occurrence of obs. with pcpn	Percentage freq. of ceilings 10,000 ft. and over
Jan	0.2	11.2	17.2	71.4	8.9	18.1	1.2	80.7	18.9	8.98	6.8	93.1	10.4	69.3
Feb	0.1	8.1	17.9	73.9	9.0	17.2	1.5	81.3	16.1	6.82	7.2	95.9	8.1	73.1
Mar	0.1	8.8	19.5	71.5	9.0	18.5	1.9	79.6	17.9	7.69	7.0	96.9	8.1	70.7
Apr	0.2	8.9	19.0	71.9	9.0	22.2	1.7	76.1	20.9	13.31	11.2	95.7	12.4	67.0
May	0.0	10.1	18.4	71.6	8.9	19.5	1.8	78.7	25.1	15.79	13.1	95.1	15.9	68.6
June	0.2	11.1	19.9	68.8	8.8	18.4	1.7	79.9	24.9	12.77	13.8	96.9	12.8	68.6
July	0.1	13.9	20.1	66.0	8.6	16.6	1.7	81.6	24.6	14.72	12.7	96.1	13.6	67.6
Aug	0.1	11.1	20.5	68.4	8.8	18.4	1.3	80.2	25.1	13.90	13.9	95.3	14.5	69.0
Sept	0.0	11.5	19.7	68.8	8.8	18.0	1.2	80.9	24.0	13.54	12.4	93.9	14.3	69.4
Oct	0.4	14.5	19.9	65.2	8.5	17.0	0.8	82.2	23.3	13.35	12.7	94.2	12.8	67.3
Nov	0.2	12.5	18.7	68.5	8.7	20.0	0.9	79.1	24.1	13.24	12.5	93.8	14.3	66.4
Dec	0.2	10.8	17.6	71.3	8.9	19.5	1.2	79.3	22.1	13.92	11.0	95.0	13.0	68.3
Annual	0.2	11.1	19.1	69.7	8.8	18.7	1.4	79.9	266.9	148.11	134.5	95.1	12.5	68.6

[a] Period of record is generally 186 months during the years 1946-1963.

to the mean total sky cover. The cirriform contributions at Majuro and Kwajalein should also be quite high, due to their regional similarities to Eniwetok, which were mentioned previously. Although Majuro's precipitation was very heavy, and it could be expected to have quite a large amount of middle cloud, its increased percentage of ceilings 10,000 ft. and over, would imply that it also had a very large amount of cirriform ceilings.

Cloud distribution and precipitation data for Moen (Table 17) are very similar to that for Majuro. Both are located just a little to the north of the mean annual position of the trough. It is quite likely that the same conditions which applied to Majuro also apply to Moen, and that here too the cirriform clouds provide a very large contribution to total sky cover values.

This study of additional stations indicates that the unusually high cirriform contribution to total sky cover is not limited to the Canton Island vicinity but extends over a large portion of the equatorial Pacific, with the definite exception of the region represented by Palmyra, Fanning and Christmas Islands. Therefore, it appears that computations based on mean total sky cover could result in sizeable underestimations of incoming solar radiation over a large part of the western and west-central equatorial Pacific, and thereby contribute significantly to errors in earth-atmosphere heat budget studies.

ATTACK ON THE PROBLEMATIC CLOUD COVER TERM

Consideration of Possible Cloud Cover Terms

Findings of the preceding section indicated that the cirriform contribution to mean total sky cover was unusually high over a large part of the western and west-central Pacific; and, also, it was shown that the thin fair weather cirriform clouds alone caused little or no reduction to the incoming solar radiation recorded at the surface. Therefore, it became essential to determine a cloud term that would be more appropriate than mean total sky cover as a cloud cover entry in formulas for computing incoming solar radiation. A term used in this capacity had to 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,[29] but it could not take into account the extensive (in the vertical and horizontal) clouds at higher levels during disturbances.

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[29] Low cloud amount should be an excellent term, since it can be estimated directly (without obscuration by intervening clouds). It has always been carefully estimated and kept under constant surveilance by observing personnel of all weather services, due to its critical importance to airfield operations. Special weather observations pertaining to clouds are usually based on changes in low cloud cover amounts or heights.

Haurwitz (1945), in his rather detailed middle latitude continental study (at Blue Hill Observatory), found that the incoming solar radiation with cloudy skies depended not only on the percentage of sky covered by clouds, but also on the cloud density which was a measure of transparency. When referring to five different categories of cloud density, he noted that considerable inhomogeneity entered the density evaluations due to the different subjective determinations introduced by the various observers working on the observation shifts. However, he showed that the effect of cloud density was very important, especially with larger values of cloudiness.

The total opaque sky cover, which refers to that portion of the sky cover dense enough to hide the outline of the sun or moon, was considered as a possible substitute for the mean total sky cover in existing formulas. This term would represent cloud density to some degree, and might eliminate the critical weakness of the mean total sky cover term with regard to the large fair weather cirriform contribution. In addition to accounting for 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 was the highly subjective nature of its measurement. However, with contrasts in cloud types and weather conditions, as they occurred in the equatorial region, it might be possible for different observers to come up with similar evaluations.

Test of Cloud Cover Terms

It was considered desirable to try all of the previously discussed cloud cover terms (mean total sky cover, mean low cloud cover, and mean total opaque sky cover) in some of the more commonly used formulas for computing incoming solar radiation, in order to determine a suitable method for handling cloud distributions similar to those of Canton.[30] The individual computations[31] could be evaluated through comparisons with the recorded data for Canton. It was expected that findings in regard to the Canton data would be generally applicable to a large part of the western and west-central equatorial Pacific. The following formulas were used, since they each had a slightly different approach and have been quite widely recognized:

$$Q = Q_o(1.0 - 0.71C) \quad \text{(Kimball, 1928)} \qquad (6)$$

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[30] Only the Canton data for July 1957 - June 1958 was processed so as to provide all three terms for the comparison study. However, it was possible to use the long period record of Table 1 for an additional test of the mean total sky cover term.

[31] Long period computations (i. e., monthly values) were considered here. Cloud terms were mean daily amounts calculated on a monthly basis. This long period limitation prevented disturbance situations from dominating the period of consideration. In the case of short period computations, such as five days or less, disturbance weather could occasionally dominate an entire period.

$Q = Q_A(0.803 - 0.340\,C - 0.458C^2)$ (Black, 1956) (7)

$Q = Q_o[1 - (1-k)C]$ Savino-Angstrom formula (Budyko, 1956) with $k = 0.345$ for Canton's latitude, this formula becomes $Q = Q_o\,(1-0.655\,C)$ (8)

$Q = Q_o\,(1-0.0006\,C_t^3)$ (Laevastu, 1960) (9)

$Q = Q_o\,(1.000 - 0.0895\,C_o + 0.00252a')$ (Tabata, 1964) (10)

where Q = total incoming solar radiation near the ocean surface (in langleys)

Q_o = total incoming solar radiation near the ocean surface with a clear sky (in langleys)

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

C = proportion of sky covered by clouds

C_t = cloud cover in tenths of sky

C_o = cloud amount in oktas

a' = the mid-month solar altitude in degrees

By using the data of Tables 18 and 1 in the formulas shown above, the figures contained in Tables 19 and 20 were obtained.

The mean total sky cover term for the period July 1957 - June 1958 gave excessively low incoming solar radiation values in all months with all formulas (see Table 19). Using the 20-year mean sky cover figures of Table 1, all formulas again gave lower than recorded values for the computations in every instance (see Table 20).

Table 18. Radiation and cloud cover[a] entries used in formulas for computing incoming solar radiation.

Item	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
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
MCS	2.6	2.7	2.3	2.4	4.8	4.5	5.9	---	2.9	3.0	3.3	3.0

[a]MTS, MLC, MTOS, and MCS pertain only to sky and cloud cover values for July 1957-June 1958.

SRTA - Solar radiation received on a horizontal surface at the top of the atmosphere.

SRCS - Total incoming solar radiation received at the surface with clear skies.

SAN - Solar altitude at noon in degrees.

MTS - Mean total sky cover in tenths.

MLC - Mean low cloud cover in tenths.

MTOS - Mean total opaque sky cover in tenths.

MCS - A mean cloud cover value based on the mean low cloud cover for days of fair weather and me an total opaque sky cover for days when disturbance weather is evident.

Table 19. Calculated and recorded incoming solar radiation (in langleys) with computations based on specified formulas and indicated cloud terms for July 1957-June 1958.

Formula used	Cloud term[a]	July	Aug	Sept	Oct	Nov	Dec	Jan	Mar	Apr	May	June
Kimball	MTS	190	254	302	258	201	253	208	233	262	245	264
1928	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	MTS	35	147	224	126	5	123	16	72	152	142	196
(1956)	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	MTS	223	284	331	292	239	285	244	271	294	275	291
(1956)	MLC	508	540	582	600	543	563	544	599	571	526	495
	MTOS	480	493	529	540	421	424	339	470	462	431	444
Laevastu	MTS	277	402	509	404	277	395	290	354	416	389	424
(1960)	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	MTS	288	370	444	402	326	369	328	385	390	350	359
(1964)	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 rad. (recorded)		535	571	608	626	482	463	415	573	544	512	532

[a] MTS - mean total sky cover; MLC - mean low cloud cover; MTOS - mean total opaque sky cover (in tenths).

Table 20. Calculated and recorded incoming solar radiation (in langleys) with computations based on specified formulas and 20 year mean sky covers of Table 1.

Formula Used	Jan	Feb	Mar	Apr	May	June	July	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
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
Avg. daily solar rad.[a]	590	630	631	598	560	538	543	595	636	649	613	585

[a] Based on a 12 year record.

However, in this latter case, Laevastu's formula gave values that were reasonably close although consistently low. The 20-year mean figures provided very little range in cloud cover for evaluation purposes. In general, it appeared that the use of the mean total sky cover term was highly unsatisfactory and would usually result in greatly underestimated amounts of incoming solar radiation for locations with cloud distributions like that of Canton.

The mean low cloud term gave excessively high values in all months with Laevastu's and Tabata's formulas (see Table 19). Kimball's, Black's, and Budyko's formulas gave excessively high values for the month's of heaviest rainfall (November, December, and January), when the disturbance activity was greatest.

The mean total opaque cloud cover term gave radiation amounts which were too low in all months with the formulas of Kimball, Black and Budyko. Laevastu's formula gave values that were consistently too high. The computed values from Tabata's formula were reasonably close to the recorded amounts, but were in general on the high side.

Discussion of Test Results

It was shown in the previous section that the mean total sky cover was quite unsatisfactory as a radiation reduction term in cases where the cirriform cloud contribution was unusually high. The mean low cloud term appeared to work fairly well in the Kimball, Black, and Budyko formulas during months when very little disturbance activity was noted between sunrise and sunset, but it gave much higher than recorded values during months with a large amount of disturbance activity. The mean total opaque sky cover term only worked reasonably well in Tabata's formula. However, it appeared quite significant that this opaque cloud cover term gave much lower than recorded values in the Kimball, Black, and Budyko formulas, since this contrasted well with the much higher values obtained when the low cloud cover term was used for months with a large amount of disturbance activity. Perhaps a compromise solution, using the low cloud term for fair weather and the opaque cloud term for disturbance weather would provide the desired results.

A reconsideration of earlier findings in this investigation and the computations of the preceding section, revealed that the suggested compromise solution was quite logical. The study of Canton data, and a scan of data from additional tropical marine locations indicated that the low cloud coverage could quite adequately represent the radiation reduction during fair weather conditions in most cases at most locations. Also, the opaque cloud cover term appeared to be the only simple term which could represent the cloud cover under disturbance 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 for this computation. The opaque cloud cover values would of course reflect the limitations of highly subjective estimations. However, during disturbance periods the opaque features should be quite clearly defined.

SOLUTION OF THE PROBLEM

Proposed Solution and Its Evaluation

It was proposed that the compromise solution for the cloud cover term, as discussed in the previous section, be used in place of the mean total sky cover term. 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 figures of row designated MCS in Table 18). These monthly mean cloud term figures were entered in the same five formulas previously used. The calculated mean daily incoming solar radiation values, on a monthly basis, are contained in Table 21 along with their departures from the mean daily recorded values.

The formulas of Laevastu and Tabata gave figures which were consistently too high with this approach (see Table 21). However, Kimball's, Black's, and Budyko's formulas gave very satisfactory results. For seven out of 11 months Black's formula provided computations closest to the recorded values, in one month Black's and Budyko's formulas were equally successful, in two months Budyko's formula gave more accurate values, and in one month Kimball's formula showed superior results. Considering the departures of

Table 21. Calculated mean daily incoming solar radiation values (in langleys), using specified formulas with proposed approach, and departures from mean recorded values for July 57-June 58.

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

[a] Mean recorded value.

computed from recorded values on an annual basis, Black's and Budyko's formulas, with the proposed cloud term approach, appear to be equally effective and superior to the other formulas and approaches from the data at hand.[32] Both of these formulas provided computations within ten percent 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 approach worked well in three of the commonly used formulas for computing incoming solar radiation during both the months with very little disturbance activity (July-October 1957)[33] and the months with a large amount of disturbance activity (November 1957 - January 1958). This indicated that the proposed approach could be used to cover a wide range of weather activity in the equatorial marine region.

Recommended Approach

It would appear that a formula should be specifically tailored to meet the peculiarities of the climatic region in which it is to be used.

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[32] This includes a consideration of the departure of computed from recorded values for Tabata's formula, using the mean total opaque cloud cover approach.

[33] This discussion refers to the disturbance activity and fair weather periods which predominated during daylight hours.

However, a larger amount of data for Canton and additional locations would be required prior to embarking on such a task. Therefore, it is recommended at this time that the proposed cloud cover entry be used with either Black's or Budyko's formula for computing incoming solar radiation from meteorological data in the equatorial marine region. It appears also that this approach might be suitable throughout the more extensive tropical marine area, except for those regions which are under the influence of extra-tropical weather conditions (poleward portions of the tropics during the late fall, winter, and early spring seasons).

Black's formula is particularly appropriate, since its computations are based on the incoming solar radiation received on a horizontal surface at the top of the atmosphere above the computation location, rather than on 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 available astronomical and meteorological data for any equatorial marine location would be sufficient to compute the incoming radiation with this formula. The following formula (Sellers, 1965), discussed in an earlier section of this report, can be used to obtain the incoming solar radiation on a horizontal surface at the top of the atmosphere in langleys per minute.

$$I_A = 2.00\ (\sin\phi\ \sin d + \cos\phi\ \cos d\ \cos h)/_{r}2 \qquad (2)$$

I_A values obtained for the midpoint of each daylight hour can be multiplied by 60 to obtain hourly values of incoming solar radiation. Then, 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.

SUMMARY AND CONCLUSIONS

Objectives of this investigation were to obtain further insight into the atmospheric conditions in the equatorial marine region, and in particular, to determine the little known effects of existing cloud types and distributions on the incoming solar radiation there. The ultimate goal was to develop a satisfactory approach for computing incoming solar radiation from meteorological data in the equatorial marine region, since the number of stations taking meteorological observations there is several times the number which record solar radiation data. The following is a summary of findings and conclusions developed during the course of this investigation.

1. A small, isolated atoll with very little surface relief can be an excellent marine atmospheric observation platform.

2. The highly unusual cloud cover, rainfall, and other weather aspects, which occurred at Canton Island during the July 1957 - June 1958 period, appear to correlate well with a 4° southward shift in the annual mean position of the equatorial trough.

3. The frequent appearance of the equatorial trough in the vicinity of Canton during the July 1957 - June 1958 period provided an excellent opportunity to study equatorial trough weather conditions and their effects on incoming radiation. A study of the extraordinarily high January 1958 precipitation at Canton, showed that although

this precipitation increase was associated with the southward displacement of the trough, it was not in this case due to proximity of the trough to Canton, since the mean position of the trough at this time was 9.65° S. In this case, high precipitation was associated with the low pressure cells which developed along the trough while it was south of Canton. Such developments can occur once the trough is over 5° south of the equator so that a closed system can exist within it (Berry, Bollay, and Beers, 1945).

4. The common types of cloud encountered during fair weather conditions were cumulus, swelling cumulus, thin cirrus and cirrostratus. Extensive cumulonimbus and middle cloud development were noted during disturbance periods.

5. The great variability in moist layer depth, cloud development, and precipitable water content in the vicinity of the trough (within 3°) during fair weather periods, unlike the more persistent atmospheric structure of the trade wind region under similar weather conditions, appeared to be due to the absence of the subsidence inversion control mechanism in the trough.

6. Disturbances were ordinarily accompanied by extensive cloud development, deep moist layers, high precipitable water contents and sizable amounts of precipitation.

7. Rainfall distribution for the period July 1957 - June 1958 was greatly skewed, a common characteristic of tropical rainfall

(Malkus and Riehl, 1964). The major portion of monthly precipitation usually fell on a few days.

8. The extensive periods with relatively fair weather conditions at the trough axis and in its immediate vicinity (within 3^{o}), emphasize the fact that there is no substantiation for continuous convergence or routine disturbance-type weather conditions in the so-called "intertropical convergence zone." This one-year study indicated that only one out of five days was affected by disturbance-type weather when the trough axis was within 3^{o} of the site.

9. In a study of those cases within 3^{o} of the trough axis, the overall average percent of solar radiation transmitted during disturbance periods was 34.6; whereas, for fair weather conditions it was 61.3 percent.

10. A detailed analysis of the Canton weather data for July 1957 - June 1958 showed that the cirriform contribution to mean total sky cover was unusually high. Cirriform overcasts with scattered or no low clouds occurred approximately 40 percent of the time during daylight hours on an annual basis.

11. The analysis also showed that the thin cirriform overcasts, which were frequently present during fair weather conditions, caused little or no reduction of the incoming solar radiation, regardless of solar altitude.

12. A 209 month USAF AWS summary of weather data for

Canton Island gave general confirmation to the July 1957 - June 1958 finding in regard to the unusually high contribution of cirriform cloud to total sky cover.

13. A study of USAF AWS summaries of weather data for nine additional equatorial Pacific observation sites, revealed the following information:

a) Palmyra, Fanning, and Christmas Islands showed a much different cloud distribution than Canton and indicated very small cirriform contributions to total sky cover. Palmyra, which is about on the trough axis, had nearly the same mean sky cover as Canton but had a much higher percentage of low ceilings and several times as much rainfall in the mean.

b) Baker, Tarawa, Majuro, Kwajalein, Eniwetok, and Moen Islands did indicate an unusually high contribution of cirriform cloud to total sky cover. Therefore, it appeared that a large portion of the west-central and western Pacific would show this unusually high cirriform contribution.

14. A test of three different cloud cover terms (mean total sky cover, mean low cloud cover, and mean total opaque sky cover), as obtained from the July 1957 - June 1958 data, in five different commonly used formulas (those of Kimball (1928), Black (1956), Budyko (1956), Laevastu (1960), and Tabata (1964)) for computation of incoming solar radiation from meteorological data, revealed the

following:

a) The ordinarily used mean total sky cover term was highly unsatisfactory for use in formulas for computing incoming solar radiation when there was an unusually high cirriform contribution, since it then caused large underestimations of the incoming radiation. Such underestimations could lead to sizeable errors in heat budget computations for the earth-atmosphere system over a large portion of the equatorial Pacific.

b) The mean low cloud cover term worked quite well in the Kimball, Black and Budyko (Savino-Angstrom) formulas during months when little or no disturbance activity occurred during the daylight hours, but it gave much higher than recorded values for months with large amounts of disturbance weather.

c) The mean total opaque sky cover term only gave reasonable results in Tabata's formula. However, it gave much lower than recorded values in the Kimball, Black, and Budyko formulas; and, they contrasted well with the much higher than recorded values that were obtained when the low cloud cover term was used in these formulas for months with a large amount of disturbance activity.

15. A compromise approach was proposed, on the basis of previous findings, in order to arrive at a more suitable cloud cover term. 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.

16. A test of the proposed cloud term, as obtained from the July 1957 - June 1958 Canton data, in the same five formulas, revealed the following:

a) The formulas of Laevastu and Tabata gave figures which were consistently too high.

b) Kimball's, Black's, and Budyko's formulas gave very satisfactory results. The formulas of Black and Budyko provided computations within ten percent of the recorded values for all months of the July 1957 - June 1958 period.

c) This approach worked equally well in these three formulas (see b above) for both the months with very little disturbance activity and the months with a large amount of disturbance activity, which indicated that it could cope with a wide range of weather activity.

17. Although it would be desirable to tailor a new formula to meet the specific peculiarities of the equatorial marine region, the data processed for this study was not sufficient to accomplish such an objective. Therefore, it is recommended for the present that the proposed cloud term be used with either Black's or Budyko's formula for obtaining incoming solar radiation in the equatorial marine region. This approach may also be suitable throughout the tropical marine area as a whole, except for those portions which are under

the influence of extra-tropical weather conditions.

18. Black's formula is particularly suitable to this approach, since its computations are based on the incoming solar radiation on a horizontal surface at the top of the atmosphere for the particular location, rather than on the radiation received at the earth's surface under clear sky conditions. Therefore, available astronomical and meteorological data for any equatorial marine location would be sufficient to compute incoming radiation by this method.

19. Since the equatorial trough in the mean migrates through 20^{o} latitude between seasons (Riehl, 1954), it is expected that many of the findings in this study would apply throughout the tropics.

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APPENDIX

APPENDIX

List of Symbols

a	solar altitude in degrees
a'	mid-month solar altitude in degrees
C	proportion of sky covered by clouds
C_o	mean cloud amount in oktas
C_t	mean cloud cover in tenths
d	declination of the sun in degrees
g	acceleration of gravity
h	local hour angle
I_A	amount of incoming solar radiation on a horizontal surface at the top of the atmosphere in langleys per minute
k	coefficient used in Budyko's (Savino-Angstrom) formula. It is actually an empirically determined constant that varies with latitude. It attempts to include the effects of different altitudes and thicknesses of the climatologically prevalent cloud forms (Malkus, 1962).
L	langley, a gram calorie per square centimeter
m	mixing ratio
$\overline{m}$	mean mixing ratio between two pressure levels
p	atmospheric pressure

P	mass of water per unit area
q	specific humidity
Q	average daily total incoming solar radiation at the surface in langleys.
Q_A	average daily incoming solar radiation at the top of the atmosphere in langleys
Q_o	average daily incoming solar radiation at the surface with clear sky
r	earth's radius vector, actual distance between the centers of the earth and sun divided by the mean distance
z	altitude above sea level
μ	micron, a unit of length equal to 1.0×10^{-4} cm
ρ	density of air
ρ_v	density of water vapor
ϕ	geographic latitude of observation site