Weather and Solar Radiation Reception in the Equatorial Trough

WILLIAM H. QUINN AND WAYNE V. BURT

Oregon State University, Corvallis

(Manuscript received 28 June 1967, in revised form 29 August 1967)

ABSTRACT

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

Cloud distribution, moist layer thickness, precipitable water content and weather conditions in the equatorial trough zone (out to 10° on either side of the trough axis) are discussed. Incoming solar radiation is considered in relation to opaque sky cover since the total sky cover often included an excessively large thin cirriform contribution which did not significantly reduce incoming solar radiation.

In the vicinity (within 3°) of the trough axis only one out of five days was affected by disturbance type weather (extensive cloud cover and precipitation). In these disturbance cases, for an overall average, 34.6% of the solar radiation on a horizontal surface at the top of the atmosphere penetrated through to the earth's surface. For fair weather cases 61.3% penetrated through to the earth's surface.

1. Introduction

The tropics are the principal heat source of the atmosphere; and, since the troposphere as a whole is a cold source at all latitudes, the excess of short-wave radiation absorbed over long-wave radiation emitted is absorbed entirely by the earth. The radiation excess received by the tropical oceans, which cover approximately 80% of the earth's surface (in the tropics), is partly given off to the atmosphere through the transfer of latent and sensible heat, partly transported to higher latitudes by ocean currents, and partly stored if seasonal rather than mean annual values are considered (Riehl and Malkus, 1958). It is principally within the equatorial trough zone[1] that the latent heat accumulated in the trades is lifted and converted to sensible heat in the convective clouds of weather disturbances. Here, radiational losses of energy are balanced and the residue is transported poleward aloft in the form of sensible heat (Riehl and Malkus, 1958).

A search of the literature did not reveal any studies of recorded incoming solar radiation in relation to weather conditions in the equatorial trough zone. The objectives of this study were to provide further insight into the weather conditions that occur in the equatorial trough and to determine the effects of these weather conditions on incoming solar radiation.

2. Investigation site

Canton Island was the only suitable equatorial marine site that observed and recorded the required meteorological and incoming solar radiation data. It appeared to be a reasonably representative marine site by virtue of its small land area, lack of relief, and complete isolation from continental influence.

Canton is a coral atoll about 21 mi in circumference and roughly in the shape of a pork chop. The atoll's rim, 150 to 1800 ft wide, encloses a shallow lagoon of about 25 mi² (Degener and Gillaspy, 1955). It has a maximum height above sea level of 20 ft and its total land area is about 2850 acres (Hatheway, 1955).

The reports of Lavoie (1963) and Wiens (1962) indicate that the atoll influence on clouds and precipitation over an atoll itself are negligible. Degener and Gillaspy (1955, p. 51) provide an excerpt of a letter from Myron H. Kerner, Meteorologist-in-Charge, U. S. Weather Bureau, Canton Island, in which he discusses the local heating effect of Canton Island 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 ...."

3. Investigation period

July 1957 through June 1958 was selected for this investigation for the following reasons:

1) A daily series of tropical weather analyses had been prepared by the German Weather Service for the International Geophysical Year (IGY) (July 1957–

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

TABLE 1. Climatological data for July 1957–June 1958 and normal/mean[1] values at Canton Island (2°46′S, 171°43′W).

Item	Time period	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	Annual total	Annual average
No. of clear days[2]	Jul 57–Jun 58	0	2	3	2	0	1	0	2	0	0	1	1	12	
	Mean (20)	6	8	10	8	6	5	5	6	6	3	6	6	75	
No. of partly cloudy days[2]	Jul 57–Jun 58	1	5	7	5	0	5	0	3	1	9	7	11	54	
	Mean (20)	13	12	11	11	12	11	11	11	13	16	12	13	146	
No. of cloudy days[2]	Jul 57–Jun 58	30	24	20	24	30	25	31	23	30	21	23	18	299	
	Mean (20)	12	11	9	12	12	15	15	11	12	11	13	11	144	
Mean sky cover sunrise–sunset[2]	Jul 57–Jun 58	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 (20)	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	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 (30)	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 of 0.01 in. or more	Jul 57–Jun 58	17	13	7	8	21	16	23	16	15	8	14	14	172	
	Mean (20)	12	10	7	6	6	6	8	6	9	13	11	10	104	
No. of days with thunderstorms	Jul 57–Jun 58	2	1	1	1	6	5	3	1	1	0	0	0	21	
	Mean (18)	*	*	*	*	*	*	*	*	*	*	1	*	4	
Average temperature	Jul 57–Jun 58	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 (30)	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 (ly)	Jul 57–Jun 58	535	571	608	626	482	463	415	—	573	544	512	532		533
	Average (12)	543	595	636	649	613	585	590	630	631	598	560	538		597

* Less than one-half.
[1] Based on length of record, in years, given in parentheses.
[2] 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 tenths; partly cloudy days 4–7 tenths; and cloudy days 8–10 tenths.

December 1958), which allowed a rough correlation of Canton Island data with synoptic weather features.

2) 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 years for radiation data.

3) It appeared to be particularly suited to the objectives of this study, since there was 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 and 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, and the number of days with rainfall in excess of 0.25 inch was three times the average number (see Table 2). The mean cloud cover for this year was 43% above average, and there was over twice the mean number of cloudy days. There was over five times the mean number of thunderstorm days and the total incoming solar radiation was below average.

4. Disturbances

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, shear lines). Synoptic features which could be identified with observations of extensive cloud cover and precipitation at Canton were small

TABLE 2. Number of days per month which received rainfall amounts (in inches) within the specified categories and average number of days with rainfall in excess of 0.25 inch.

	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	Annual
0.26–0.49	1	1			3	1	4	3	3	2	2	1	21
0.50–0.99	2		2	2	5	4	2	3	1	2		2	25
1.00–1.49			2	1		2			2		2		9
1.50–1.99				1	2	2	4						9
2.00–2.49		1			1			1	1				4
2.50–2.99					1		2						3
3.00–3.49								1					1
Average no. of days precip. >0.25 inch*	2.7	2.5	1.4	0.7	1.2	1.4	1.7	1.3	1.5	2.7	3.8	3.1	24.0

* Based on a 209-month record.

equatorial low pressure centers, the trough itself (when accompanied by sufficient convergence), the outermost portions of tropical storms centered about 400–500 n mi away in the southwesterly quadrant, and occasionally low pressure centers associated with frontal troughs which extended equatorward from extratropical systems centered in higher latitudes.

Since it was desirable to separate periods of extensive cloud cover and precipitation from those with fair or relatively fair weather, in order to evaluate incoming solar radiation at such times, the term disturbance was used in a broad sense to signify periods of "disturbed weather." Consideration of disturbance days as well as fair weather days was limited to the daylight period at Canton, in order to correlate weather conditions with incoming solar radiation.

5. Solar radiation data

The zenith angle Z of the sun for any particular time and place on the earth can be obtained from the equation (Sellers, 1965)

$$\cos Z = \sin\phi \sin d + \cos\phi \cos d \cosh,$$

where ϕ is the geographic latitude of the site, d, the declination of the sun, and h, the hour angle between noon and sunrise or sunset. The incoming solar radiation is directly proportional to the sine of the angle of solar altitude, or to the cosine of the sun's zenith angle. Its intensity on a horizontal surface at the top of the atmosphere I_A (ly min^{-1}) can be computed by the equation (Sellers, 1965)

$$I_A = 2.0(\cos Z)/r^2,$$

where r is the earth's radius vector (the actual distance between the centers of the earth and the sun divided by the mean distance), and a value of 2.0 has been used as the mean solar constant (Johnson, 1954). Hourly incoming solar radiation at the top of the atmosphere, individual daily values, and mean daily values for each month of the July 1957–June 1958 period were computed for the purposes of this study.

Hourly and daily values of the total incoming solar radiation,[2] as recorded at the surface, were obtained from the July 1957–June 1958 Total Sky and Radiation Charts for Canton Island.

The individual radiation transmission percentages, used to obtain the average transmission percentages referred to in Tables 4 and 5, were obtained by dividing the recorded daily incoming solar radiation at the surface by the computed daily incoming solar radiation on a horizontal surface at the top of the atmosphere and multiplying the result by 100. Transmission percentages were shown in relation to opaque sky cover rather than total sky cover for the following reasons:

1) The cirriform cloud contribution to total sky cover was found to be exceedingly high. In fact, 40% of the time, during the period July 1957–June 1958, there was a thin cirriform overcast and scattered or no low clouds.

2) Thin cirrus overcasts alone did not appear to appreciably reduce the incoming solar radiation beyond that of a clear sky condition.

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.
3.38N	3.22N	5.09N	5.47N	5.44N	0.10S	9.65S
Feb.	**Mar.**	**Apr.**	**May**	**June**	**Annual mean**	
4.52S	4.00S	0.35S	4.26N	3.94N	1.03N	

6. The equatorial trough and its weather

The equatorial trough is a region of lower pressure near the equator and between the subtropical high

[2] Total incoming solar radiation refers here to the direct and diffuse radiation on a horizontal surface, as recorded by the Eppley pyranometer. The Eppley pyranometer is sensitive to all wavelengths between 0.3 and 2.5 μ, or more than 99% of the energy which impinges upon the outer surface of the hemispherical glass cover (Hand, 1950).

TABLE 4. Average transmission percentage for categories of opaque cloud cover during disturbance weather conditions in the equatorial trough zone.[1]

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 per cent	60.1 (5)[2]	57.5 (6)	51.6 (9)	41.5 (10)	36.3 (8)	21.4 (19)

[1] Equatorial trough zone extends 10° latitude either side of the trough axis.
[2] The figure in parentheses refers to the number of cases in the particular category.

pressure areas of the Northern and Southern Hemispheres. In general, it is situated where the streamlines from both hemispheres converge and its migration influences the seasonal march of cloudiness and rainfall as well as the formation of tropical cyclones (Riehl, 1954). Riehl finds that the equatorial trough and heavy rainfall coincide seasonally as well as in the annual mean over the oceans, and indicates that mean trough shifts of as little as 2–3° latitude from one year to the next can produce extreme rainfall differences in the marginal zone. Such a shift was indicated as a mean southward displacement along the longitude of Canton Island for the period July 1957–June 1958. The large departures from the mean in cloud cover and precipitation for several months of this period can be seen in Tables 1 and 2. For this same year, Majuro Atoll (7°05′N, 171°23′E), 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 trough's mean southward shift for this year, daily positions were recorded along the longitude of Canton from the IGY tropical zone analyses. 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 5N latitude along Cantons' longitude [from Fig. 3.2 of Riehl (1954)], it appears that there was a mean southward shift of about 4° latitude for the selected year.

A question arises here in regard to the southward shift of the equatorial trough and its relation to increased precipitation at Canton Island, since during the month of January 1958, when precipitation was extraordinarily high, the mean position of the trough was at 9.65S, considerably south of Canton. Certainly, proximity of the trough to Canton could not be the reason for heavy rainfall in this case. A check of the tropical zone analyses indicated that nearly all cases of sizeable rainfall (>0.25 inch) could be associated with low pressure centers located from ESE through S to WSW of Canton in the equatorial trough. This relationship was clearly shown by Canton's unusual surface wind distribution. Ordinarily, Canton's prevailing surface wind direction for January is east; however, in this year 24 of the 31 days had prevailing winds with westerly components. The association of heavy rainfall with low pressure centers of this nature is discussed in the extracted letter of Mr. Kerner, the Narrative Climatological Summary for Canton (ESSA, 1966), and Palmer and Pyle (1966). Berry *et al.* (1945) clarify the situation with their approximate rule that the equatorial trough must depart more than 5° away from the equator for a closed system to exist within it.

During fair weather in the trough zone Canton commonly reported scattered cumulus and broken to overcast thin cirrus or cirrostratus. However, swelling cumulus were often present, particularly during the late evening and early morning hours. Extensive cumulonimbi and middle cloudiness were usually noted when disturbances were present.

Although the moist layer[3] was often well defined when no disturbance was present, as it usually is in the trade-wind region, the characteristic thermal inversion of the trades was not noted here, due to the absence of the subsidence mechanism which is ordinarily prevalent in the trade-wind region. The thickness of the moist layer varied considerably. It was generally thin (less than 10,000 ft deep) from July through October 1957 and quite thick (often 20,000 ft or more deep) from November 1957 through May 1958. This trend in moist layer thickness might appear to show a seasonal pattern; however, the data for other years would not support this idea. This layer was deep in the convergent zones of disturbances and usually quite shallow during the fair weather periods between disturbances.

Precipitable water content of the atmosphere from the surface to 400 mb usually ranged from 4.5 to 6.4 cm during disturbance conditions and from 2.8 cm to 4.0 cm during fair weather. In the immediate vicinity of the trough axis (within 3°) the precipitable water content showed a high degree of variability, ranging from about 3.2 to 5.6 cm in fair weather. This same variability was noted in the low cloud development.

Malkus and Riehl (1964) noted that tropical rainfall shows an enormously skewed distribution. Such a distribution is particularly noticeable in these IGY data for Canton Island. Table 2 shows the number of days per month during which precipitation fell within certain categories from 0.26 inch upward. Heavy rainfall was associated with deep moist layers and high precipitable water contents.

[3] The moist layer, for the purposes of this paper, refers to that part of the troposphere with relative humidities of 70% or higher.

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 per cent	68.6 (5)[1]	65.6 (9)	59.1 (4)	53.8 (9)

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

7. Incoming solar radiation in the equatorial trough

Variations in radiation reception in the trough zone were large. When there was no disturbance in the vicinity and scattered or no low clouds with thin cirriform coverages prevailed, the total daily incoming solar radiation at the surface frequently exceeded 600 ly and usually exceeded 500 ly. On disturbance days,[4] the incoming radiation was usually less than 450 ly and in some cases less than 100 ly.

Table 4 gives average daily radiation transmission percentages for various amounts of opaque cloud cover 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 average daily opaque cloud coverages during disturbance conditions. Those cases included in the upper category (9.1–10.0 tenths average daily opaque cloud cover) showed a maximum reception of 358.1 ly and a minimum of 89.9 ly.

The zone of consideration was narrowed to 3° either side of the trough axis, in order to evaluate trough effects under other than disturbance conditions. Average transmission percentages for the various opaque cloud cover categories are presented in Table 5. For an overall average, the incoming solar radiation transmission under these conditions was 61.3% of the radiation impinging on a horizontal surface at the top of the atmosphere. This shows that a large amount of radiation penetrated through to the surface, even in the vicinity of the trough axis when no disturbance was present.

If just the disturbance cases occurring within 3° of the trough axis were considered, the overall average transmission of incoming solar radiation under these conditions was 34.6%. Out of the 36 cases occurring within 3° of the trough axis which were studied here, only 9 were considered to be disturbance conditions. With the period 27 January–11 March 1958 included (when no radiation data were recorded), there was a total of 58 cases with Canton within 3° of the trough axis; of these, 11 were considered disturbance situations and 47 otherwise. Therefore, even when Canton was within 3° of the trough axis, only one out of five days was affected by disturbance weather.[5]

Although there was a 43% increase in mean total sky cover and nearly three times the normal amount of precipitation on an annual basis for July 1957–June 1958, the average daily incoming solar radiation was only about 11%[6] below the 12-yr average (see Table 1 data). The apparent disparity between the increased total sky cover and the associated radiation reduction can be explained by the cloud distribution. Much of the sky cover consisted of thin fair weather cirrus which did not noticeably reduce incoming solar radiation.[7]

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

REFERENCES

Berry, F. A., E. Bollay and N. R. Beers, 1945: *Handbook of Meteorology*. New York, McGraw-Hill, 1068 pp.

Degener, O., and E. Gillaspy, 1955: Canton Island, South Pacific. Atoll Research Bulletin No. 41, 1–51.

Deutscher Wetterdienst, July 1957–June 1958: World weather maps, Part II: Tropical zone. Hamburg, Seewetteramt.

Environmental Science Services Administration, July 1957–June 1958: Local climatological data: Canton Island, South Pacific; Surface weather observations (WBAN Forms 10A and 10B) for Canton Island, South Pacific. Asheville, N. C.; Summary of constant pressure data (WBAN-33) for Canton Island, South Pacific. Asheville, N. C.; Total sky and radiation charts for Canton Island, South Pacific. Asheville, N. C.

——, 1966: Local climatological data, annual summary with comparative data: Canton Island, South Pacific. Washington, D. C.

Hand, I. F., 1950: Insolation on clear days. *Heating and Ventilating*, 47, 92–94.

Hatheway, W. H., 1955: The natural vegetation of Canton Island, an equatorial Pacific atoll. Atoll Research Bulletin No. 43, 1–9.

Johnson, F. S., 1954: The solar constant. *J. Meteor.*, 11, 431–439.

Lavoie, Ronald L., 1963: Some aspects of the meteorology of the tropical Pacific viewed from an atoll. Atoll Research Bulletin No. 96, 1–80.

[4] Disturbance days with higher recorded radiation values were usually those when disturbances were effectively present only part of the daylight hours. The thick precipitation clouds greatly reduced incoming radiation, but the break-up clouds were not as effective.

[5] In all cases involving a numerical count of disturbances, only the daylight period was considered. For uniformity, this same policy was followed in regard to fair weather figures.

[6] If February data were available, this average reduction might be increased to 12%, which is still quite small compared to the magnitude of the meteorological changes.

[7] As mentioned in an earlier part of the paper, thin cirrus overcasts with scattered or no low clouds occurred 40% of the time.

Malkus, J. S., 1962: Large-scale interactions. *The Sea*, Vol. 1, New York, Interscience Publishers, Wiley, 88–294.

——, and H. Riehl, 1964: *Cloud Structure and Distributions over the Tropical Pacific Ocean*. Berkeley, University of California Press, 229 pp.

Palmer, C. E., and R. L. Pyle, 1966: The climatological setting of the Galapagos. *The Galapagos*. Berkeley, University of California, 93–99.

Riehl, H., 1954: *Tropical Meteorology*. New York, McGraw-Hill, 392 pp.

——, and J. S. Malkus, 1958: On the heat balance in the equatorial trough zone. *Geophysica*, **6**, 503–537.

Sellers, W. D., 1965: *Physical Climatology*. University of Chicago Press, 272 pp.

Wiens, H. J., 1962: *Atoll Environment and Ecology*. New Haven, Yale University Press, 532 pp.