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RADIATION MEASUREMENTS OVER THE EQUATORIAL CENTRAL PACIFIC

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ABSTRACT

During the Line Islands Experiment in spring 1967, surface shortwave and net radiation was continuously recorded at Palmyra, and Suomi-Kuhn infrared radiationsondes were released daily at the islands of Palmyra, (5°53′ N., 162°05′ W.) and Christmas (1°59′ N., 157°22′ W.) as part of an extensive surface and upper air observation program. Data are evaluated in terms of the diurnal march of the surface radiation balance and the radiation budget characteristics of the troposphere-ocean system. These direct measurements indicate a substantially larger surface net radiation than is expected from available climatic mean charts based on empirical formulas. Implications for the tropical heat budget are pointed out.

1. INTRODUCTION

It is generally recognized that the radiation balance of the Tropics plays a key role in the global heat budget. Net radiation at the surface enters into considerations of the sensible and latent heat exchange at the sea-air interface and the poleward heat transport within the ocean. However, measurements of the shortwave and longwave radiation fluxes at the surface are extremely scarce, particularly in lower latitudes. Instead, radiation is usually computed from available information on cloudiness, applying empirical formulas, the validity of which has been questioned in recent years (e.g., Ashburn 1963, 1966).

The importance of direct measurements over the tropical oceans will therefore be appreciated. Just such measurements of the surface radiation budget, along with an extensive program of surface and upper air observations were performed during the Line Islands Experiment (LIE) in spring 1967. Results are summarized in the present paper.

2. INSTRUMENTATION AND OBSERVATION PROGRAM

A surface radiation instrument site was in operation on Palmyra Island (5°53′ N., 162°05′ W.) during most of the daytime and some nighttime hours for the period Mar. 24 to Apr. 19, 1967. The total downward shortwave irradiance, SW↓, was measured with a 50-junction thermopile Eppley pyranometer.[1] The net irradiance, $-R_0$, was measured with a Suomi-Islitzer ventilated net radiometer (Suomi et al. 1954).

Both radiation instruments were located on a pier piling approximately 15 m from shore in Palmyra Lagoon. The Eppley pyranometer was mounted on the top of the piling and was approximately 3 m above the water surface. The ventilated radiometer was mounted at the end of a 3-m catwalk approximately 2½ m above the lagoon surface. Geometrical obscuration of the upper hemisphere into which the sensors looked was less than 0.2 steradian (sr) out of the total 2 sr and was always lower than 0.17 radians (rad) above the horizontal plane defined by the sensors' surface.

Data from the two sensors, in addition to a zero point, were recorded on a 10-millivolt (mV) scale sequentially for intervals of 20 sec each. The normal mode of operation was to sample the radiometers for a period of 5 min each half hour. However, there were periods during the experiment where both more and less frequent sampling rates were maintained. Shortwave and net radiation measurements were not made at exactly the same time, but lag each other by 20 to 40 sec.

Separation of data into upward and downward shortwave (SW↑ and SW↓) and infrared longwave (LW↑ and LW↓) components was accomplished from the relation

$$-R_0=\mathrm{SW}\downarrow-\mathrm{SW}\uparrow+\mathrm{LW}\downarrow-\mathrm{LW}\uparrow. \tag{1}$$

Before solving equation (1) for LW↓, we must make several assumptions involving the SW↑ and LW↓ terms. For determining SW↑ over a plane water surface, the SW↓ term must be partitioned into direct and diffuse components. The ratios as a function of solar height given in the "Smithsonian Meteorological Tables" (List 1968, table 155) were used to divide SW↓ into SW↓(DIR) and SW↓(DIF). Values of the surface reflectivity, ρ, of salt water as a function of angle of incidence were also adopted from List's (1968) table 155. If we assume the SW↓(DIF) is isotropic, an integrated water reflectivity, ρ(DIF), over all angles is approximately 17 percent. The ρ(DIR) is directly given in List's (1968) table 155. Thus we find

$$\mathrm{SW}\uparrow=\mathrm{SW}\downarrow(\mathrm{DIR})\times\rho(\mathrm{DIR})+\mathrm{SW}\downarrow(\mathrm{DIF})\times\rho(\mathrm{DIF}). \tag{2}$$

With a mean surface temperature of the lagoon of 28.0°C and assuming an emissivity of the water surface of 1.0, Stefan-Boltzmann's law yields LW↑=0.6696 ly min^{-1}.

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[1] Mention of commercial products does not constitute an endorsement.

With the above assumptions, only LW↓ in equation (2) remains unknown. Rearranging equation (1) and substituting from equation (2), we have

$$LW\downarrow = -R_0 - \rho(\mathrm{DIR}) \times SW\downarrow(\mathrm{DIR}) - \rho(\mathrm{DIF}) \times SW\downarrow(\mathrm{DIF}) + SW\downarrow + LW\uparrow. \quad (3)$$

Equation (3) was applied to the average value of each set of data points grouped around the hour and half hour. By taking a mean value, the data were smoothed, and the inconsistencies arising from the fact that the two instruments were not sampled simultaneously were minimized.

When the surface data were first analyzed, LW↓ deduced from the net radiometer appeared consistently smaller than LW↓ measured at the surface by the radiationsonde at the same time. Further investigation showed that a numerical radiation divergence calculation (Kuhn 1962) for LW↓ agreed well with the radiationsonde for a clear atmosphere, while the surface station tended to give systematically lower values of LW↓ than theory predicts for a clear atmosphere. The theoretical computation for a clear gaseous atmosphere should represent a minimum value, since the presence of any aerosol emitters in the atmosphere would increase LW↓. Based upon the above evidence, LW↓ has been adjusted by adding +43 ly day^{-1} to each value, and a corresponding adjustment was also applied to the net irradiance, $-R_0$. The 43 ly day^{-1} increment was derived from four simultaneous readings of the ventilated net radiometer and radiationsondes. All four comparisons yielded an increment within 5 ly day^{-1} of the 43 ly day^{-1} value.

The pyranometer data were not always available for the entire day, and one-half to one-hour periods after sunrise and before sunset were commonly missing. For quoting daily values, these data-void periods were filled in by interpolating between zero, denoting before sunrise and after sunset, and the first recorded data points. The shape of this interpolated curve was modeled from a cosine curve depicting incident shortwave radiation at the top of the atmosphere as a function of time.

Suomi-Kuhn balloon-borne radiationsonde (Suomi 1958) ascents were made nightly from Christmas Island and Palmyra rawinsonde stations from March 21 to April 20. These ascents were made at approximately 2000 LST and yielded values of LW↑ and LW↓ as a function of height. Preflight baseline or calibration checks of the instruments were performed in the manner outlined by Cox et al. (1968) to insure maximum confidence in the measurements.

3. SURFACE BUDGET AT PALMYRA

DIURNAL MARCH

The diurnal march of the various radiative fluxes at the surface, as obtained by averaging over the entire period (Mar. 24, 25, 30, and Apr. 3 through 18, 1967) is represented in figure 1. Three-hour observations of low, middle, and high clouds and hourly observations of total opaque cloudiness are also reproduced in figure 1.

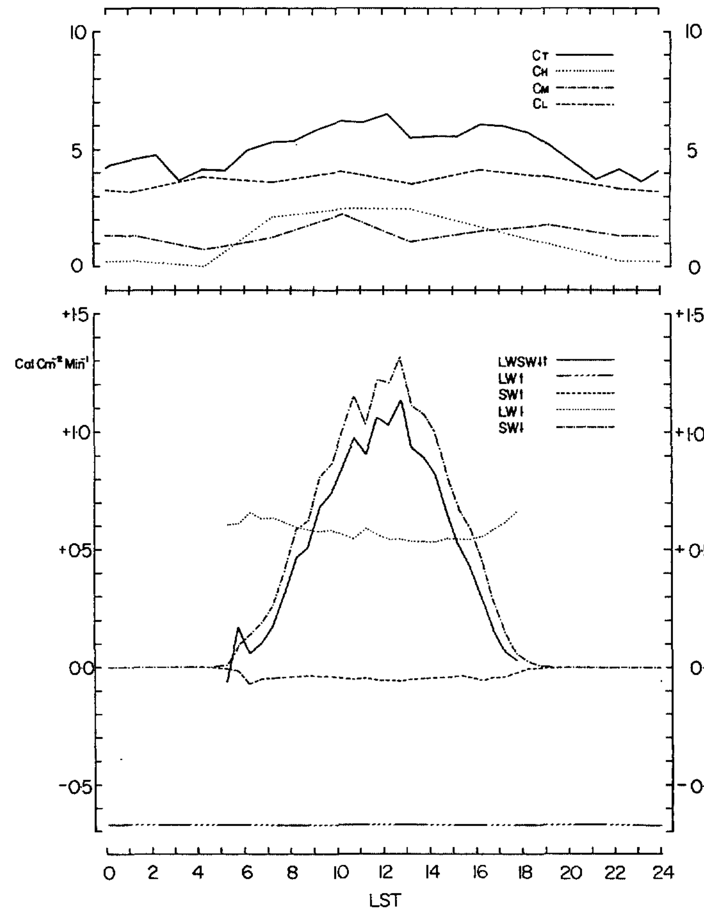

FIGURE 1.—Diurnal march of the surface radiation budget at Palmyra, all days (Mar. 24, 25, 30 and Apr. 3 through 18, 1967). Downward-directed shortwave radiation, SW↓, upward-directed shortwave radiation, SW↑, downward-directed longwave radiation, LW↓, upward-directed longwave radiation, LW↑, net radiation, SWLW↓↑; in cal cm^{-2} min^{-1}. C_L low clouds, C_M middle clouds, C_H high clouds; C_T total opaque cloudiness, in tenths.

For comparison, the surface radiation budget during the days with an average daily opaque cloudiness $C_T \leq 0.4$ (April 3, 4, 10 through 14, and 18) and during the days with an average daily opaque cloudiness $C_T > 0.7$ (March 30 and April 8 and 9) is plotted in figures 2 and 3.

Net radiation $-R_0$ shows a pronounced difference between clear and cloudy days, its diurnal march being largely dominated by that of SW↓. The SW↑ for the entire period reaches weak maxima after sunrise and before sunset, as a consequence of the decrease of the effective albedo with solar height. The diurnal march is least pronounced on cloudy days, as can be expected from the smaller contribution of direct solar radiation.

The LW↑ entered in figures 1 through 3 corresponds to a constant water surface temperature of Palmyra Lagoon of 28.0°C. As explained in section 2, LW↓ was obtained

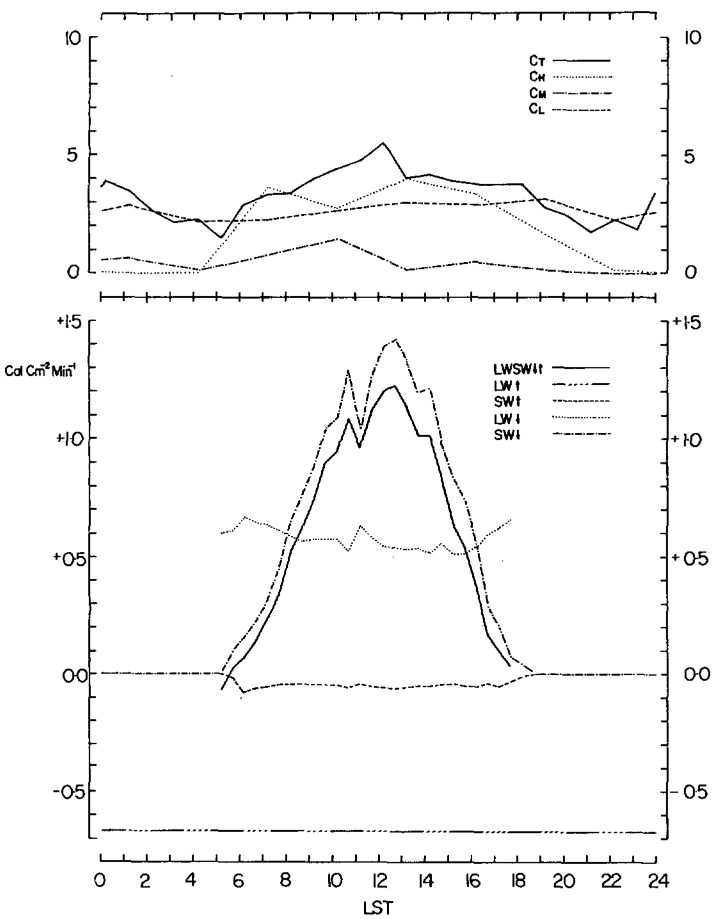

FIGURE 2.—Diurnal march of the surface radiation budget at Palmyra during clear days, $C_T \leq 0.4$ (April 3, 4, 10 through 14, and 18). Symbols used as in figure 1.

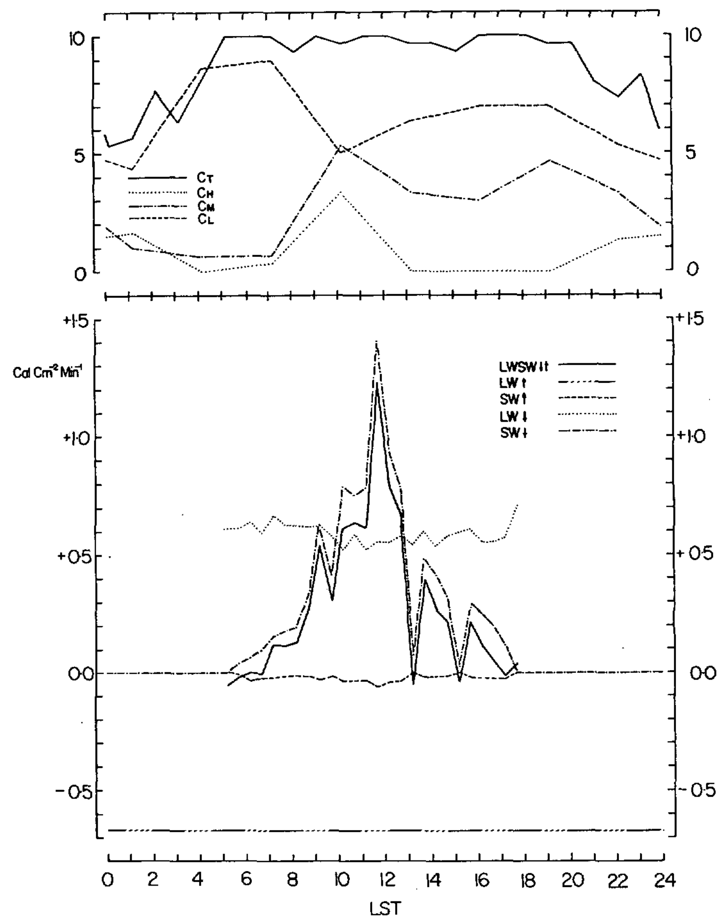

FIGURE 3.—Diurnal march of the surface radiation budget at Palmyra during cloudy days, $C_T > 0.7$ (March 30 and April 8 and 9). Symbols used as in figure 1.

as a residual from equation (1). Figures 1 through 3 indicate a pronounced diurnal march, with lowest values of LW↓ during the midday hours. The net-radiometer used is not a precision instrument, and the possibility that the measurement error might have a diurnal march cannot be completely ruled out. However, in qualitative terms, the diurnal march of LW↓, displayed by figures 1 through 3, seems consistent with the cloudiness conditions. Low and middle clouds show a tendency to a decrease during the midday hours. This could indeed account for a decrease in LW↓. The marked effect of cloudiness on LW↑ is further illustrated by a comparison of figures 2 and 3, which indicate on clear days substantially smaller LW↓ than on cloudy days.

MEAN RADIATIVE FLUXES

Values of radiation as averaged over the entire period are listed in table 1. Components of the radiation budget of the atmosphere, to be discussed in section 4, are also included in table 1. For consistency, measurements by radiationsondes only were used for longwave radiation. The $LW\uparrow_{sfc}$ computed from Stefan-Boltzmann's law corresponds to a temperature of 27.5°C for Palmyra and 25.8°C for Christmas. From the available airborne radiometric measurements during the LIE, these sea-surface temperatures are considered representative for the open ocean in the two areas. It will be noticed that the assumed effective radiation temperature at Palmyra differs from that used in section 2. Assessment of the radiative flux components for the surface measuring site at Palmyra Lagoon required the local surface temperature of the lagoon, whereas we are here concerned with a radiation budget representative of a larger area.

TABLE 1.—*Longwave* (LW) *and shortwave* (SW) *radiation budget of ocean surface and atmosphere during the LIE, upward- and downward-directed radiation at 100 mb,* rad $\uparrow_{100}$, *and* rad $\downarrow_{100}$; *infrared radiative flux divergence and solar radiation absorbed in the layer 1000 to 100 mb, respectively,* $[\text{rad}]_{1000}^{100}$; *upward- and downward-directed radiation at the surface,* rad $\uparrow_{sfc}$, rad $\downarrow_{sfc}$; *units, cal cm*$^{-2}$ *min*$^{-1}$

	Palmyra		Christmas	
	LW	SW	LW	SW
rad $\uparrow_{100}$	0.3126	0.1928	0.3653	0.1354
rad $\downarrow_{100}$	.0490	.6090	.0361	.6080
$[\text{rad}]_{1000}^{100}$	.2327	.0996	.2859	.0887
rad $\uparrow_{sfc}$	.6647	.0324	.6501	.0261
rad $\downarrow_{sfc}$	.6338	.3490	.6068	.4100

LW⇅ at the surface should be compared to the general magnitude of values measured by Charnell (1967) near the Hawaiian Islands (0.04 to 0.12 ly min^{-1}) and values obtained from Budyko's (1963) charts (0.064 ly min^{-1}). Wyrtki (1965, 1966) computed the net longwave radiation at the surface, $I=\text{LW}⇅$, from the following empirical formula presented by Budyko:

$$I=\epsilon\sigma T_W^4\,(a_1-a_2\sqrt{e})\,(1-a_3\times C_T^2)+4\epsilon\sigma T_W^3\,(T_W-T_a) \quad (4)$$

where σ is the Stefan-Boltzmann constant, ϵ emissivity, T_W and T_a water surface temperature and air temperature, respectively, in degrees Kelvin, C_T the fraction of total cloudiness, and e water vapor pressure in millibars. The values of the coefficients adopted by Wyrtki are $a_1=0.39$, $a_2=0.05$, and $a_3=0.5$. After using temperature, humidity, and cloudiness values for Palmyra during the LIE, equation (4) yields a value for the net longwave radiation at the surface of about 0.074 cal $\text{cm}^{-2}\,\text{min}^{-1}$. Table 1 shows for Palmyra a value of 0.0309 from the evening radiationsondes only. Accounting for the daily march of LW↓ as obtained from the surface installation yields a value of 0.0875 cal $\text{cm}^{-2}\,\text{min}^{-1}$ for the average of all days and values of 0.0902 and 0.0778 for clear and cloudy days, respectively (figs. 1 to 3).

The ratio of the daily sums of reflected to incoming shortwave radiation corresponds to an effective albedo of the sea surface of 6.5 percent, which agrees with earlier estimates and values commonly used (Anderson 1952, Houghton 1954, Hutchinson 1957, Bernhardt and Philipps 1958, and Colón 1963). Downward-directed shortwave radiation measured at Palmyra is considerably larger than expected from available climatic mean maps (Black 1956, Bernhardt and Philipps 1958, and Budyko 1963), based on empirical relationships, but seems compatible with the findings of Quinn and Burt (1967). Wyrtki (1965, 1966) computed the downward shortwave radiation at the surface, $I=\text{SW}\downarrow$, from the following empirical formula

$$I=I_0\,(1-a_1C_T-a_2\times C_T^2) \quad (5)$$

where the downward-directed shortwave radiation for clear-sky conditions, I_0, is taken from Budyko's (1958) table, and C_T is total cloudiness. Wyrtki used $a_1=a_2=0.38$. After using the observed cloudiness ($C_T=0.49$) at Palmyra during the LIE, equation (5) yields a value of $I=504$ cal $\text{cm}^{-2}\,\text{day}^{-1}$, which is practically identical to the observed value.

The net (shortwave plus longwave) radiation, $-R_0$, turns out to be larger than available climatic mean estimates (Budyko 1963 and Wyrtki 1965, 1966). In this connection, it should be recalled that cloudiness during the LIE seems to have been less than the average value for this season of the year. Some implications of this result will be discussed further below.

STATISTICAL RELATIONSHIPS

In view of the paucity of direct measurements, empirical formulas have been widely used in the computation of shortwave and longwave radiation fluxes at the surface. Direct measurements during the LIE invited an attempt to test these statistical relationships.

A least-squares fit was performed on the following expressions for longwave radiation:

$$I=a_1\sigma T_a^4, \quad (6)$$

$$I=a_1\sigma T_a^4(1+a_2C_T), \quad (7)$$

$$I=a_1\sigma T_a^4(1+a_2C_L+a_3C_M+a_4C_H), \quad (8)$$

$$I=\sigma T_a^4(a_1+a_2 10^{-a_3e}), \quad (9)$$

$$I=\sigma T_a^4(a_1+a_2 10^{-a_3e})(1+a_4C_T), \quad (10)$$

$$I=\sigma T_a^4(a_1+a_2 10^{-a_3e})(1+a_4C_L+a_5C_M+a_6C_H), \quad (11)$$

$$I=\sigma T_a^4(a_1+a_2\sqrt{e}), \quad (12)$$

$$I=\sigma T_a^4(a_1+a_2\sqrt{e})(1+a_3C_T), \quad (13)$$

$$I=\sigma T_a^4(a_1+a_2\sqrt{e})(1+a_3C_L+a_4C_M+a_5C_L), \quad (14)$$

$$I=(a_1+a_2C_T), \quad (15)$$

and

$$I=(a_1+a_2C_L+a_3C_M+a_4C_H) \quad (16)$$

where C_L, C_M, and C_H denote fractions of low, middle, and high cloudiness, respectively, and the other symbols are used as previously. Expressions (6) through (16) were fitted for $I=\text{LW}\downarrow$ and $I=\text{LW}⇅$. For $I=\text{LW}⇅$, equation (4) and the following two equations were applied additionally:

$$I=\epsilon\sigma T_W^4(a_1+a_2\sqrt{e})(1-a_3C_T^2) \quad (17)$$

and

$$I=\epsilon\sigma T_W^4(a_1+a_2\sqrt{e}), \quad (18)$$

assuming an emissivity of 1.0.

Equation (9) for $I=\text{LW}⇅$ was proposed by Ångström (1916), and equation (12) is due to Brunt (1932). Bolz and Falckenberg (1949) and Bolz and Fritz (1950) applied equation (9) for $I=\text{LW}\downarrow$. Attempts at accounting for the effect of cloudiness through expressions in the form of equations (7), (10), (11), (13), and (14) have been reviewed by Budyko (1958).

Regarding $I=\text{SW}\downarrow$, a least-squares fit was applied on equation (5) and the following expressions

$$I=I_0(a_1+a_2C_T+a_3C_T^2) \quad (19)$$

and

$$I=I_0(1-a_1C_T). \quad (20)$$

A clear-sky value $I_0=0.482$ ly min^{-1} for Palmyra in March–April was adopted from Budyko's (1958) table.

TABLE 2.—*Least-squares fit to daily means of downward-directed shortwave radiation,* SW↓, *(cal cm^{-2} min^{-1}); a_i=coefficients in equations (5), (19), and (20) with 95-percent confidence limits in parentheses;* VR=*variance of residuals after regression;* df=*degrees of freedom.*

Eq. no.	a_1	a_2	a_3	a_4	a_5	a_6	VR	df
5	0.240 (±.318)	0.518 (±.456)					0.003448	18
19	.809 (±.406)	−.453 (±1.511)	1.069 (±1.258)				.003470	17
20	.584 (±.111)						.004204	19

Least-squares fitting for LW⇅ and LW⇅ was performed on the daily totals (20 data points) and separately on the individual half-hourly mean radiation fluxes (66 data points). The number of half-hourly data points available is limited by the 3-hr cloud observations. Computations for SW↓ were performed on the daily data only. Results are summarized in tables 2 through 6.

Table 2 for SW↓ shows equations (5) and (19), where the square of total cloudiness is used, to be superior to the more simple equation (20), which requires the same basic information. This would support suggestions by Budyko (1956) and Wyrtki (1965, 1966).

Table 3 for the daily values of LW↓ illustrates that, for the uniform moisture conditions in the environment of Palmyra, vapor pressure offers little information. Brunt's equation (12) and the extended versions (13) and (14) are clearly to be preferred to Ångström's exponential expression (9) and the corresponding equations (10) and (11). This seems to be partly due to the small variation in vapor pressure. It is noticed that equations (9) through (11) are not better than the simple equation (6). The most critical information is cloudiness. Thus equation (7) yields a drastic improvement upon (6). In fact, the best fit is provided by the simple equations (15) and (16), using cloudiness only.

Table 4 presents computations for the daily values of LW⇅. Vapor pressure seems to have little information value. Ångström's expression (9) and equations (10) and (11) are even less satisfactory than Brunt's equation (12) and its versions (13) and (14). Contrary to LW↓ (table 3), air temperature rather than cloudiness is the critical information. Thus equations (7) and (8) yield no improvement upon (6). Similarly, (10) and (11) and (13) and (14) give a poorer fit than (9) and (12), respectively. The least-squares fit is poorest for equation (4), with somewhat better results for the simpler versions (17) and (18). Equations (15) and (16) based on cloudiness only are comparatively less successful than for LW↓, and by far the best fit for LW is⇅ provided by the simple expression (6), using air temperature only.

The relative merit of the various formulas in the least-squares fit for half-hourly values of LW↓ and LW⇅ differs somewhat from the daily values as a consequence of the greatly increased number of degrees of freedom.

Results for the half-hourly values of LW↓ are summarized in table 5. The variance of residuals obtained for equations (6), (9), and (12) suggests that vapor pressure is of subordinate importance. Brunt's equation (12) and equations (13) and (14) are preferable to Ångström's equation (9) and the corresponding expressions (10) and (11). With a relatively large number of degrees of freedom available, the added cloud information in equations (10), (11), (13), and (14) provides an improvement upon equa-

TABLE 3.—*Least-squares fit to daily means of downward-directed longwave radiation,* LW↓, *(cal cm^{-2} min^{-1}); a_i=coefficients in equations (6) through (16) with 95-percent confidence limits in parentheses;* VR=*variance of residuals after regression;* df=*degrees of freedom.*

Eq. no.	a_1	a_2	a_3	a_4	a_5	a_6	VR	df
6	0.879 (±.134)						0.000400	19
7	.881 (±.331)	−0.029 (±.079)					.000321	18
8	.869 (±.048)	.026 (±.145)	0.071 (±.140)	−0.066 (±.127)			.000360	16
9	.298 (±77.080)	.364 (±70.860)	−.009 (±1.140)				.000398	17
10	.138 (±437)	.600 (±431)	−.004 (±2.244)	−.045 (±.105)			.000403	16
11	.176 (±4032)	.644 (±4026)	−.001 (±8.988)	−.015 (±.233)	−0.076 (±.180)	−0.060 (±.120)	.000411	14
12	.328 (±.726)	.117 (±.153)					.000374	18
13	.577 (±.899)	.060 (±.196)	−.044 (±.100)				.000378	17
14	.750 (±1.320)	.026 (±.285)	−.014 (±.202)	−.076 (±.163)	.059 (±.152)		.000384	15
15	.577 (±.021)	.017 (±.040)					.000321	18
16	.590 (±.030)	.011 (±.077)	.035 (±.082)	−.042 (±.070)			.000319	16

TABLE 4.—*Least-squares fit to daily means of net longwave radiation,* $LW\uparrow\downarrow$, *(cal* cm^{-2} min^{-1}*);* a_i*=coefficients in equations (6) through (16), (4), (17), and (18) with 95-percent confidence limits in parentheses;* VR*=variance of residuals after regression;* df*=degrees of freedom.*

Eq. no.	a_1	a_2	a_3	a_4	a_5	a_6	VR	df
6	0.126 (±.013)						0.000309	19
7	.137 (±.032)	−0.157 (±.406)					.000317	18
8	.117 (±.045)	.190 (±1.051)	−0.439 (±1.092)	0.545 (±1.055)			.000316	16
9	.126 (±.013)	97.570 (±3.717×10^8)	4.181 (±3.717×10^8)				.000345	17
10	.137 (±.034)	103.3 (±3.779×10^8)	4.773 (±3.779×10^8)	−.157 (±.432)			.000357	16
11	.117 (±.059)	8.831 (±3.802×10^8)	.782 (±3.082×10^8)	.190 (±1.124)	−0.439 (±1.167)	5.545 (±1.128)	.000361	14
12	.405 (±.665)	−.059 (±.141)					.000314	18
13	.352 (±.851)	−.047 (±.185)	.083 (±.581)				.000331	17
14	.153 (±1.061)	−.008 (±.230)	.221 (±1.468)	−.454 (±1.251)	.529 (±1.183)		.000337	15
15	.093 (±.021)	−.017 (±.40)					.000321	18
16	.080 (±.030)	.011 (±.077)	−.035 (±0.81)	.042 (±.071)			.000319	16
4	.450 (±.910)	−.068 (±.195)	.327 (±.465)				.000372	17
17	.330 (±.831)	−.042 (±.178)	.131 (±.462)				.000331	17
18	.436 (±.665)	.066 (±.140)					.000318	18

TABLE 5.—*Least-squares fit to half-hourly means of downward-directed longwave radiation,* $LW\downarrow$, *(cal* $cm^{-2}min^{-1}$*);* a_i*=coefficients in equations (6) through (16) with 95-percent confidence limits in parentheses;* VR*=variance of residuals after regression;* df*=degrees of freedom.*

Eq. no.	a_1	a_2	a_3	a_4	a_5	a_6	VR	df
6	0.853 (±.020)						0.003002	65
7	.824 (±.046)	0.063 (±.095)					.002962	64
8	.834 (±.064)	.063 (±.112)	0.051 (±.124)	−0.033 (±.093)			.002967	62
9	.417 (±7.242)	.614 (±6.778)	.007 (±.113)				.003059	63
10	.470 (±4.632)	.658 (±3.221)	.012 (±.167)	.079 (±.102)			.002979	62
11	.323 (±5.735)	1.245 (±2.163)	.017 (±.185)	.085 (±.111)	0.054 (±.122)	−0.082 (±.100)	.002832	60
12	1.167 (±.021)	−.066 (±.150)					.003012	64
13	1.271 (±.688)	−.063 (±.147)	.079 (±.100)				.002931	63
14	1.740 (±.817)	−.190 (±.171)	.084 (±.111)	.054 (±.120)	−.082 (±.097)		.002784	61
15	.562 (±.028)	.019 (±.047)					.002548	64
16	.567 (±.033)	.017 (±.056)	.025 (±.064)	−.019 (±.049)			.002553	62

TABLE 6.—*Least squares fit to half-hourly means of net longwave radiation,* LW⇅, (*cal cm*$^{-2}$ *min*$^{-1}$); a_i=*coefficients in equations* (*6*) *through* (*16*), (*4*), (*17*), *and* (*18*) *with 95-percent confidence limits in parentheses;* VR=*variance of residuals after regression;* df=*degrees of freedom.*

Eq. no.	a_1	a_2	a_3	a_4	a_5	a_6	VR	df
6	0.146 (±.018)						0.002471	65
7	.160 (±.042)	−0.159 (±.397)					.002488	64
8	.153 (±.049)	−.140 (±.510)	−0.246 (±.576)	0.178 (±.514)			.002494	62
9	−.023 (±5.199)	.058 (±3.642)	−.021 (±.629)				.002500	63
10	−.041 (±5.058)	.064 (±3.436)	−.023 (±.546)	−.218 (±.404)			.002499	62
11	−.044 (±1.255)	.019 (±.415)	−.044 (±.282)	−.265 (±.485)	−0.202 (±.564)	0.550 (±.705)	.002359	60
12	−.191 (±.643)	.071 (±.136)					.002467	64
13	−.296 (±.743)	.098 (±.159)	−.219 (±.377)				.002465	63
14	−.708 (±1.603)	.181 (±.153)	−.270 (±.475)	−.212 (±.549)	.531 (±.686)		.002334	61
15	.108 (±.030)	−.019 (±.295)					.002548	64
16	.103 (±.033)	−.017 (±.405)	−.025 (±.410)	.019 (±.658)			.002553	62
4	−.334 (±.138)	.106 (±.171)	.363 (±.341)				.003001	63
17	−.277 (±.711)	.092 (±.151)	.203 (±.352)				.002527	63
18	−.191 (±.654)	.071 (±.138)					.002532	64

tions (9) and (12), respectively. As in the case of the daily values of LW↓ (table 3), the simple equations (15) and (16) using cloud information only yield the most satisfactory fit.

Table 6 presents the results for the half-hourly values of LW⇅. As seen from a comparison of equations (6), (9), and (12), vapor pressure offers comparatively little information. Brunt's equation (12) and versions (13) and (14) are again found superior to Ångström's expression (9) and the corresponding equations (10) and (11). Equations (4), (17), and (18) again yield the poorest fit, along with (15) and (16) based on cloud information only. Contrary to the daily values with few degrees of freedom, the added cloud information in equations (10), (11), (13), and (14) yields some improvement upon (9) and (12) and make (14) clearly preferable to the simple expression (6), which in table 4 was found to be the best predictor for the daily values of LW⇅.

Conceivably, coefficients may vary depending on whether half-hourly, daily, or monthly means are used in the various formulas. Application to other areas may not always be feasible, since, for example, moisture variations may play a more prominent role. Tables 2 through 6 are meant to provide general background information on the dependence of radiative fluxes on temperature, humidity, and cloudiness conditions at Palmyra.

4. RADIATION BUDGET OF THE TROPOSPHERE

Longwave radiation has been measured directly by radiationsondes during the LIE. Profiles of infrared radiative cooling over Palmyra and Christmas are plotted in figure 4. Longwave fluxes in the vicinity of the tropopause are included in table 1. In contrast to computed profiles available in the literature (Yamamoto and Onishi 1953, London 1957, and Rodgers and Walshaw 1966), measurements bear out a more pronounced infrared cooling in the lower layers and much smaller values in the upper troposphere. This is in qualitative agreement with Riehl's (1962) findings for the Caribbean. Cox (1969) has shown results of computing infrared cooling for a clear tropical atmosphere and compared these with actual observations. Even for the clear case, the measurements show more radiative cooling near the surface and less cooling in the upper troposphere than the computations. Clouds may act to enhance this discrepancy even more. Cox attributes the disagreement to the presence of aerosols, even in a "clear" atmosphere, and to the change in the area viewed by the instrument as it passes from a cool island to a warm water underlying surface.

Absorption of solar radiation was computed from conventional radiosondes and surface observations of cloudiness during the LIE, following the procedure of Mügge

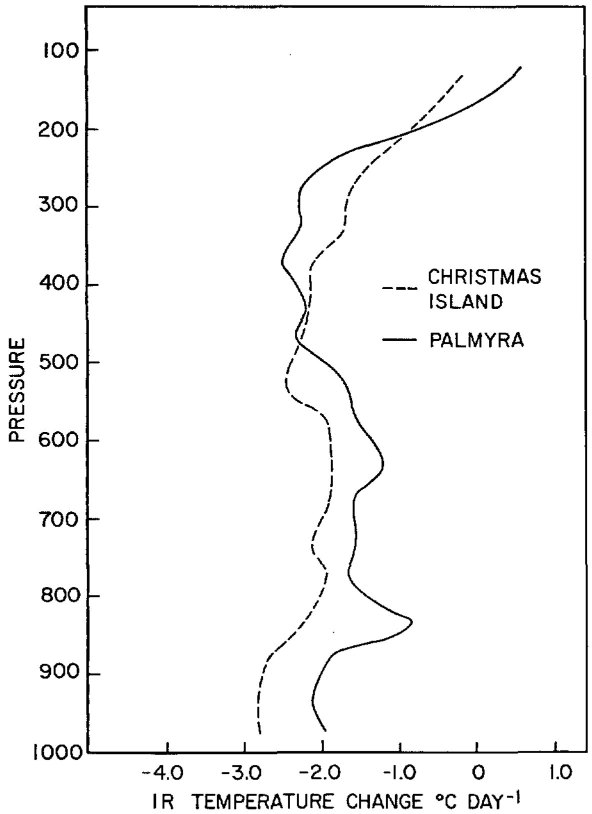

FIGURE 4.—Vertical profiles of infrared radiative cooling over Palmyra and Christmas Islands.

and Möller (1932) for clear sky and using the values of reflectivity, absorptivity, and transmissivity presented by Korb et al. (1956) for different cloud types. Computations were performed for 100-mb-thick layers between 1000 and 300 mb separately for clear sky, an overcast of low clouds (900–800 mb), and an overcast of middle clouds (650–600 mb). Results were then weighted for every 100-mb-thick layer, according to the 3-hr surface observations of cloudiness at Palmyra, Fanning, and Christmas, assuming no overlap of areas with low clouds and middle clouds, respectively. For the layer 300 to 100 mb, Yamamoto's (1962) values for April and the latitude belt 0°–10° N. were adopted. Results of these calculations are included in table 1.

From the surface radiation measurements, the radiation soundings, and the computed absorption of solar radiation in the troposphere, the net shortwave, $SW\downarrow_{100\text{ mb}}$, and the net shortwave plus longwave radiation in the vicinity of the tropopause, R_{0a}, over Palmyra is obtained (table 1). Longwave radiation fluxes at 100 mb listed in table 1 were adjusted slightly, so as to match exactly the longwave fluxes at the surface and the infrared radiative flux divergence in the layer 1000 to 100 mb. The amount of adjustment is within the accuracy of measurements (Kuhn and Johnson 1966).

An attempt was made to arrive also at an estimate of R_0 and R_{0a} over Christmas Island during the LIE. At Christmas only, longwave radiation has been measured by radiationsondes. However, some inference on the shortwave budget is possible, using the Palmyra measurements.

Solar radiation at the top of the atmosphere according to latitude and season can be taken from the "Smithsonian Meteorological Tables" (List 1968). Subtracting Rodgers' (1967) value for the solar radiation absorbed in the layer 7 to 100 mb yields an estimate of the downward-directed shortwave radiation at the tropopause, $SW\downarrow_{100\text{ mb}}$, over Palmyra and Christmas, respectively. Values thus obtained are listed in table 1. For Palmyra, the net shortwave radiation at the tropopause, $SW\downarrow\!\uparrow_{100\text{ mb}}$, has been determined additionally, as described above. From this, an estimate of the planetary (shortwave) albedo at Palmyra during Mar. 24–Apr. 19, 1967, is readily obtained. The estimated value of 32 percent is larger than values read from Raschke's (1968) albedo maps for various fortnightly periods in May–June 1966. This may seem compatible with the characteristic seasonal variation of cloudiness in the Line Islands region. However, unpublished precipitation records (courtesy of the British Meteorological Office, London) for Christmas and Fanning Islands indicate larger rainfall in May–July 1966 than in March–April 1967. It must also be recalled that Raschke's maps are based on noontime observations. The consistency of planetary albedo estimates for the LIE with Raschke's (1968) maps can thus not be clearly assessed. Surface albedo at Palmyra was found to be about 6.5 percent for clear sky. Total cloudiness is available from surface observations during the LIE (C_T=0.49 for Palmyra). From this information and weighting albedo according to the proportion of clear and cloudy areas, a representative average cloud albedo over Palmyra can be derived (55 percent).

Now assume that the Palmyra estimates of surface and cloud albedo are approximately valid for Christmas, and use the surface observations of total cloudiness over Christmas during Mar. 24–Apr. 19, 1969 (C_T=0.32). Then a value of the planetary albedo representative of the Christmas region can be derived (22 percent). From the planetary albedo and the downward-directed shortwave radiation at the tropopause, as assessed further above, an estimate of the net shortwave radiation at the tropopause is obtained. Subtracting the solar radiation absorbed between 100 and 1000 mb then yields the net shortwave radiation at the surface. A surface albedo of 6.5 percent then leads to the estimates of downward and reflected shortwave radiation at the surface, as listed in table 1. It is noted that the downward-directed shortwave radiation thus obtained agrees closely with the value computed from equation (5), using the observed total cloudiness at Christmas.

Combining these computed shortwave radiation values with the directly measured longwave radiation finally leads to an estimate of R_0 and R_{0_a} for Christmas (table 1).

5. CONCLUDING REMARKS

Measurements of the surface radiation budget at Palmyra during the LIE were limited to a period of only about 3 weeks. However, the program is considered particularly valuable, in view of the chronic scarcity of direct measurements in lower latitudes. Results indicate a larger surface net radiation than seems to be generally accepted for climatic mean conditions. It is noticed, however, that cloudiness during the LIE was below average.

Absorption of solar radiation and infrared radiative loss, arrived at in the present study for the tropospheric column as a whole, do not essentially differ from the general magnitude of estimates obtained in earlier studies (e.g., London 1957). Taken in conjunction with the surface radiation measurements, this would agree with an upward adjustment of the net radiative flux at the tropopause compared to estimates of the presatellite era, as has been suggested by House (1965) and Vonder Haar and Hanson (1969).

The ratio of surface net radiation to the net radiative gain of the earth-troposphere column has a bearing on the relative importance of ocean and atmosphere in the heat export to higher latitudes. Increased net radiation at the sea surface implies a larger lateral export of heat by ocean currents, unless there is reason for an upward adjustment of the present estimates of sensible and latent heat transfer at the sea-air interface. In this connection, more direct measurements of the surface net radiation over the tropical oceans appear desirable.

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