A Contribution to the Study of Convection Patterns in the Equatorial Trough Zone Using TIROS-IV Radiation Data

By
K.R. Saha

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A CONTRIBUTION TO THE STUDY OF CONVECTION PATTERNS

IN THE EQUATORIAL TROUGH ZONE USING TIROS-IV

RADIATION DATA.*

BY

K. R. Saha

Institute of Tropical Meteorology,
Poona-5, India

Abstract:

An analysis of TIROS-IV (Channel II (8-12 microns)) radiation data relating to the equatorial trough zone in southeast Asia during April-May, 1962, reveals that in most cases when there are no active synoptic disturbances in the equatorial trough zone, low radiation cells (<0.35 Langleys per minute) appear over lands/islands, few over wide ocean areas, within this zone. Details of the observed low radiation cells in regard to their dimensions, intensity and location are tabulated and it is shown that the land-bound low radiation cells exhibit marked correlation with orographic features and appear during both day and night. When active synoptic disturbances occur, however, low radiation cells may appear over both land and sea depending upon the location and intensity of the disturbance. The evidences furnished in the paper strongly suggest that free and forced convection over land/island areas which constitute no less than 10 per cent of the total area of the equatorial trough zone contributes significantly to the vertical heat transfer in the equatorial trough zone required for the general circulation of the atmosphere.

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1. Introduction

Recent studies in general circulation in the tropics (Riehl, 1950; Riehl and Malkus, 1957; Palmén, Riehl and Malkus, 1958; Palmén, 1964) have emphasized the role of the equatorial trough zone in transporting both sensible and latent heat energy imported by the trades to high troposphere to meet the requirements of radiational loss aloft and provide for poleward heat transfer. Riehl and Malkus (1958) have, however, shown that owing to a minimum in the vertical distribution of total energy (equivalent potential temperature) in the mid-troposphere (between about 750 and 500 mb levels) in this zone, neither a slow meridional mass circulation nor simple convective-diffusion can successfully transport heat from low levels to levels above the heat-energy minimum. A mechanism for transfer of energy against such a gradient by turbulent eddies in the atmosphere was suggested by Priestley and Swinbank (1947) but Riehl and Malkus (1958) considered this mechanism as inadequate in the present case and postulated a mechanism of "selective buoyancy, with undiluted cloud towers in part compensated mass-wise by downdrafts." They hypothesized that a total of 1500 - 5000 hot cloud towers rising to 200 - 100 mb levels and originating in about 30 synoptic disturbances (wave length $\sim$ 1350 km) in a 10° wide equatorial trough belt would be adequate to transport the required amount of heat to balance the radiational loss aloft and provide for the export to higher latitudes.

Analysis of recently available satellite radiation data affords a reliable and potentially powerful means of studying convection patterns in the atmosphere and it was from this point of view that, at the suggestion of Prof. Herbert Riehl, I undertook a study of the infrared radiation data measured by TIROS-IV in its channel II (8 - 12 microns) during its many traverses over the equatorial trough zone of southeast Asia between 27 April and 18 May, 1962. The main purpose of the study was to look for meso-scale evidence of convection and the relation that might exist between this scale and the synoptic scale. For this purpose the detailed structure and distribution of the measured low radiation cells in regard to their dimensions, intensity and locations were investigated. The findings and results of this study are given in the present paper.

Figure 1 gives the mean position of the equatorial trough line over southeast Asia in May, along with those during the seasonal extremes in February and August, as determined from IGY (1957 - 58) synoptic

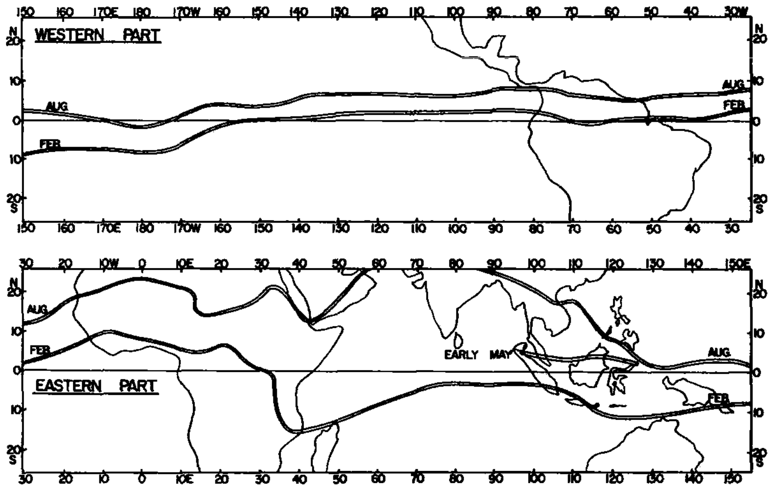

Figure 1 - Mean positions of the equatorial trough line in the western and eastern parts of the Tropical Zone (25° N - 25° S) in the IGY months of Aug/57 and and Feb/58 and over Southeast Asia in early May.

maps of the Tropical zone, prepared by the Deutscher Wetterdienst. Similar positions for January and July were also given by Riehl (1954).

2. Infra-red Radiation Patterns

Fluxes of infra-red radiation from the earth-atmosphere system in southeast Asia, measured in the Window Channel (8-12 microns) by TIROS-IV orbiting the earth at a mean altitude of 780 km during the period April-May, 1962, had been computerized in convenient chart form for analysis. Some of the orbital runs crossed the equator over this region from northwest to southeast whilst others did so from southwest to northeast. Both the series, eighteen of them in all, were available for study. Lateral data coverage on the radiation charts averaged about 750 kms on either side of the orbits. The radiation data between about 85° and 130° E longitudes were considered. For convenience of analysis, areas of low radiation values (<0.35 Ly/min.) were shaded blue and those of high radiation values (>0.40 Ly/min.) red on the radiation contour charts; these limits for low and high radiation values were set rather arbitrarily, but, as will be shown in the next section, they have some relationship with different stages of cloud growth. When so analysed, an infra-red radiation chart exhibits a number of low and high radiation cells in exactly the same manner as low and high pressure areas are found on a synoptic map. Table I gives the dimensions, central radiation values, and geographical locations of the low radiation cells observed by TIROS-IV during some of its orbital passes over southeast Asia during April-May, 1962. The available data were divided under daytime (A) and nighttime (B) orbits, for convenience. Under daytime orbits were included all data which were measured between 07 and 19 LMT (LMT = GMT + 07 hours). Data during the remaining hours (19 - 07 LMT) were considered under nighttime orbits.

Table I. Details of low radiation cells computed from TIROS-IV radiation charts.

A. Daytime orbits (07 - 19 LMT)

B. Nighttime orbits (19 - 07 LMT)

A. Daytime Orbits (07-19 LMT)

Orbit No.	Date and Time of Measurement (LMT)	Total Number of Low Radiation Cells Observed	Details of Low Radiation Cells: Ser. No. of Cell	Approx. Dimension of the 0.35 Ly/min contour (Km X Km)	Central Radiation Value (ly/min)	Location of Center (Lat/long.)
1117	27 April 1962	6	1	300 x 200	.20	2°N/96°E
	$13^h\ 27^m$ -		2	500 x 150	.25	2.5°N/100°E
	$15^h\ 0^m$		3	400 x 200	.20	2.5°N/100°E
			4	300 x 150	.17	1°S/106°E
			5	300 x 100	.22	5.5°/107.5°E
			6	Indeterminable	.15	7°S/99°E
1188	2 May 1962	3	1	600 x 200	.27	1.5°S/99°E
	$12^h\ 10^m$ -		2	150 x 150	.31	5°S/91.5°E
	$13^h\ 42^m$		3	200 x 200	.23	8°S/93.5°E
1202	3 May 1962	6	1	250 x 50	.25	9.5°N/88°E
	$11^h\ 33^m$ -		2	75 x 75	.27	6.5°N/84.5°E
	$13^h\ 5^m$		3	300 x 100	.27	1°N/85.5°E
			4	400 x 200	.23	6.5°N/90°E
			5	350 x 100	.27	6.5°N/93.5°E
			6	250 x 250	.20	6.5°S/98°E
1244	6 May 1962	3	1	350 x 250	.21	9.5°N/97.5°E
	$9^h\ 43^m$ -		2	600 x 400	.16	2°N/96°E
	$11^h\ 17^m$		3	350 x 100	.22	4°N/99°E
1287	9 May 1962	3	1	300 x 200	.22	4.5°S/91°E
	$9^h\ 39^m$ -		2	50 x 50	.25	0.5°S/90°E
	$11^h\ 13^m$		3	50 x 70	.25	0°/88.5°E
1364	14 May 1962	7	1	150 x 50	.29	1°S/99.5°E
	$18^h\ 48^m$ -		2	250 x 150	.15	2.5°N/97°E
	$20^h\ 21^m$		3	70 x 70	.23	2.5°N/101.5°E
			4	300 x 150	.23	4.5°N/99.5°E
			5	50 x 80	.27	6.5°N/88.5°E
			6	300 x 100	.24	11.5°N/102.0°E
			7	250 x 200	.22	14°N/106.5E

A. Daytime Orbits (07-19 LMT) - Continued

Orbit No.	Date and Time of Measurement (LMT)	Total Number of Low Radiation Cells observed	Details of Low Radiation Cells: Ser. No. of Cell	Approx. Dimension of the 0.35 Ly/min contour (Km X Km)	Central Radiation Value(Ly/min)	Location of Center (Lat./long.)
1378	15 May 1962	3	1	400 x 100	.21	8.5°N/104.5°E
	18^h 12^m -		2	100 x 50	.29	8.5°N/108°E
	19^h 45^m		3	100 x 70	.20	11.5°N/106°E
1335	12 May 1962	6	1	200 x 150	.18	5.5°S/96°E
	18^h 13^m -		2	150 x 50	.20	0.5°S/100.5°E
	19^h 47^m		3	250 x 150	.23	2.5°N/109.5°E
			4	50 x 50	.27	0.5°N/112.5°E
			5	200 x 100	.21	0.5°N/116.5°E
			6	300 x 250	.15	4.5°N/114.5°E
1406	17 May 1962	13	1	200 x 200	.21	0°/103°E
	17^h 0^m -		2	250 x 150	.20	5.5°N/103°E
	18^h 29^m		3	120 x 100	.20	8.5°N/107.5°E
			4	80 x 40	.17	9.5°N/108.5°E
			5	100 x 50	.18	10°N/110.5°E
			6	100 x 100	.20	7.5°N/109.5°E
			7	170 x 120	.18	6°N/107°E
			8	100 x 100	.22	1°S/111°E
			9	400 x 150	.19	2°N/112.5°E
			10	430 x 100	.23	1.5°S/114°E
			11	70 x 50	.23	5°N/117.2°E
			12	1000 x 900	.19	Philippines & Adjacent Seas
			13	150 x 100	.24	5°S/101°E
1420	18 May 1962	12	1	100 x 100	.26	2.5°S/102.5°E
	16^h 22^m -		2	150 x 150	.27	1.5°N/103°E
	17^h 55^m		3	700 x 500	.20	Philippines Area
			4	700 x 400	.25	" "
			5	250 x 300	.24	5°N/117.5°E
			6	100 x 100	.29	3°N/114.5°E
			7	200 x 150	.28	1°N/117.5°E
			8	150 x 150	.30	2°N/112.5°E
			9	150 x 200	.27	1°N/122°E

A. Daytime Orbits (07-19 LMT) - Continued

Orbit No.	Date and Time of Measurement (LMT)	Total Number of Low Radiation Cells Observed	Details of Low Radiation Cells: Ser. No. of Cell	Approx. Dimension of the 0.35 Ly/min contour (Km X Km)	Central Radiation Value (Ly/min)	Location of Center (Lat./long.)
			10	150 x 150	.29	$0^{\circ}/108^{\circ}$E
			11	150 x 100	.28	2.5°N/109.2°E
			12	A wide area	.20	Gulf of Siam (center uncertain)

B. Nighttime Orbits (19-07 LMT)

Orbit No.	Date and Time of Measurement (LMT)	Total Number of Low Radiation Cells Observed	Ser. No. of Cell	Approx. Dimension of the 0.35 Ly/min contour (Km X Km)	Central Radiation Value (Ly/min)	Location of Center (Lat./long.)
1123	27 April 1962 $23^{h}\ 54^{m}$ - $01^{h}\ 28^{m}$	7	1	300 x 150	.19	5°S/106°E
			2	400 x 200	.20	4°S/100°E
			3	350 x 100	.17	1°N/100°E
			4	200 x 100	.18	3.5°S/115°E
			5	300 x 200	.22	3°S/112.5°E
			6	400 x 350	.10	1°N/112°E
			7	100 x 100	.28	2°S/121.5°E
1152	30 April 1962 $00^{h}\ 26^{m}$ - $02^{h}\ 00^{m}$	8	1	150 x 70	.28	2.5°S/102°E
			2	200 x 200	.23	1.5°N/95°E
			3	400 x 200	.20	2°N/99°E
			4	200 x 50	.24	1.5°N/104°E
			5	550 x 130	.19	8.5°N/98°E
			6	100 x 80	.24	4.5°N/100°E
			7	300 x 250	.19	12°N/104.5°E
			8	500 x 230	.16	16.5°N/106.5°E
1166	30 April 1962 $23^{h}\ 47^{m}$ - $01^{h}\ 21^{m}$	10	1	220 x 220	.13	3°S/92°E
			2	150 x 120	.16	$0^{\circ}/93.5^{\circ}$E
			3	140 x 130	.17	3°N/91°E
			4	350 x 200	.21	4°N/97°E
			5	250 x 150	.16	6°N/99.5°E
			6	100 x 60	.19	$0^{\circ}/101^{\circ}$E
			7	350 x 100	.19	1.5°N/99.5°E
			8	150 x 150	.26	12.5°N/106°E
			9	200 x 200	.19	13.5°N/100.5°E
			10	420 x 250	.14	16°N/105°E

B. Nighttime Orbits (19-07LMT) - Continued

Orbit No.	Date and Time of Measurement (LMT)	Total Number of Low Radiation Cells Observed	Details of Low Radiation Cells: Ser. No. of Cell	Approx. Dimension of the 0.35 Ly/min contour (Km X Km)	Central Radiation Value (Ly/min)	Location of Center (Lat./long.)
1208	3 May 1962	7	1	550 x 300	.15	5°S/103.5°E
	22^h 20^m -		2	350 x 170	.19	2°S/111°E
	23^h 32^m		3	150 x 120	.23	3°S/108°E
			4	250 x 200	.19	3°N/101°E
			5	200 x 100	.23	0°/104°E
			6	500 x 350	.19	3°N/116°E
			7	100 x 100	.29	5°N/101°E
1222	4 May 1962	5	1	300 x 200	.25	5°S/108°E
	21^h 24^m -		2	350 x 300	.24	1°S/110°E
	22^h 56^m		3	200 x 200	.28	10.5°N/117°E
			4	350 x 150	.19	7.5°N/124°E
			5	250 x 200	.12	10.5°N/127.5°E
1236	5 May 1962	7	1	400 x 300	.12	4°S/102°E
	20^h 45^m -		2	100 x 50	.19	1°N/101°E
	22^h 19^m		3	200 x 100	.09	0°/110°E
			4	50 x 50	.15	0°/111°E
			5	400 x 200	.15	0°/114°E
			6	300 x 20?	.21	6.5°N/125.5°E
			7	100 x 75	.25	6°N/125.5°E
1237	5 May 1962	3	1	150 x 150	.30	7.5°N/98°E
	23^h 28^m -		2	250 x 220	.24	11.5°N/103.5°E
	00^h 05^m		3	300 x 160	.22	15°N/108.5°E
1250	6 May 1962	5	1	150 x 150	.24	3°S/120°E
	20^h 12^m -		2	350 x 200	.26	1°N/122°E
	21^h 44^m		3	150 x 150	.27	3°N/124.5°E
			4	300 x 200	.25	5.5°N/117°E
			5	450 x 250	.12	9°N/125°E

Low radiation cells listed in Table I, except those in orbits No. 1406 and No. 1420 which were associated with definite active synoptic disturbances and which are discussed in Section 7, were composited separately for all orbits, for daytime orbits only, and for night-time orbits only and these composited patterns are presented in Figs. 2-4 respectively. In each of these figures, the shaded area shows the region under low radiation cells. It may be seen from these diagrams that, in general, low radiation cells tend to be associated with land areas. In Table II is presented the frequency of appearance of low radiation cells over different land/island areas of southeast Asia, which lie in the equatorial trough zone. The evidence is very impressive.

Further, analysis of low radiation cells reveals very interesting diurnal variations between day and night of the same day, between one day and the next at about the same hour, and between two successive orbital passes with a measurement time interval of about 2 hours. These are summarized below.

(a) Variation between day and night patterns.

(i) Orbit #1117 (13-15 LMT) oriented NW-SE and orbit #1123 (23-01 LMT) oriented SW-NE had an overlapping area over Sumatra region on 27 April, 1962.

It may be seen from Table I that in the overlapped region a few of the daytime cells disappeared in the night, i. e. , that centered at 7° S, 99° E with central radiation value 0. 15 Ly/min. in orbit #1117 is replaced by a high radiation cell with central value 0. 51 Ly/min. in orbit #1123 and another centered at 1° S, 106° E with central radiation value 0. 17 Ly/min. is replaced by a high radiation area 0. 51 Ly/min.) in the night. On the other hand, a low radiation cell with central value 0. 18 Ly/min. is observed in the night over a region in Sumatra where there was a high radiation area in daytime. One or two daytime low radiation cells, e. g. , that centered at 5. 5° S, 107. 5° E appear to have moved on to new positions by night with little change in their intensity. It is also observed that quite a number of low radiation cells which originate in daytime persist even at midnight. In orbit #1123 a number of low radiation cells with central values in the range 0. 10 to 0. 18 Ly/min. appear over the entire landmass of South Borneo. Similarly, a low radiation cell appears over Celebes at night.

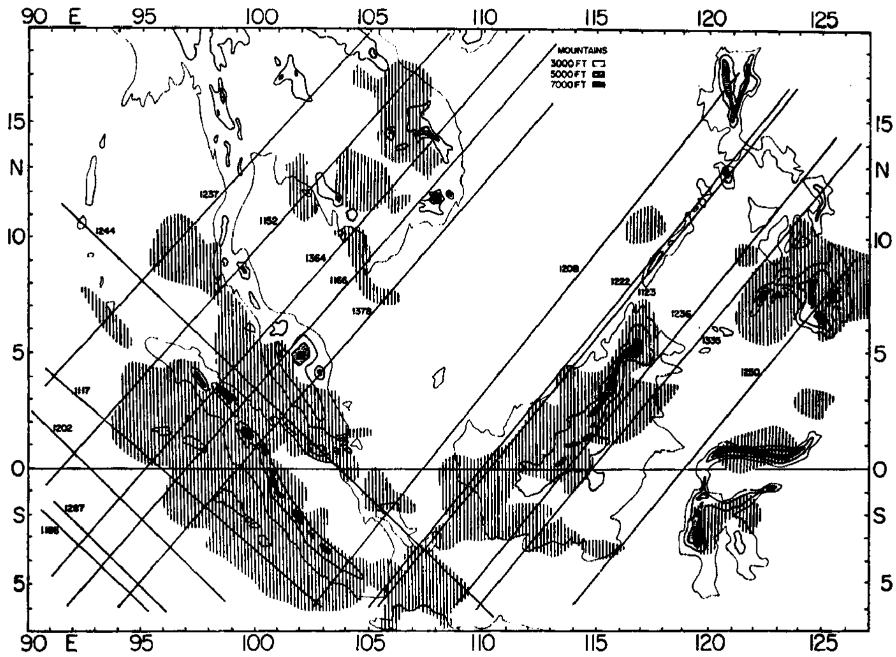

Figure 2 - Main locations of low radiation cells (shaded areas) in the equatorial trough zone over Southeast Asia (composited for all orbits) as observed by TIROS-IV.

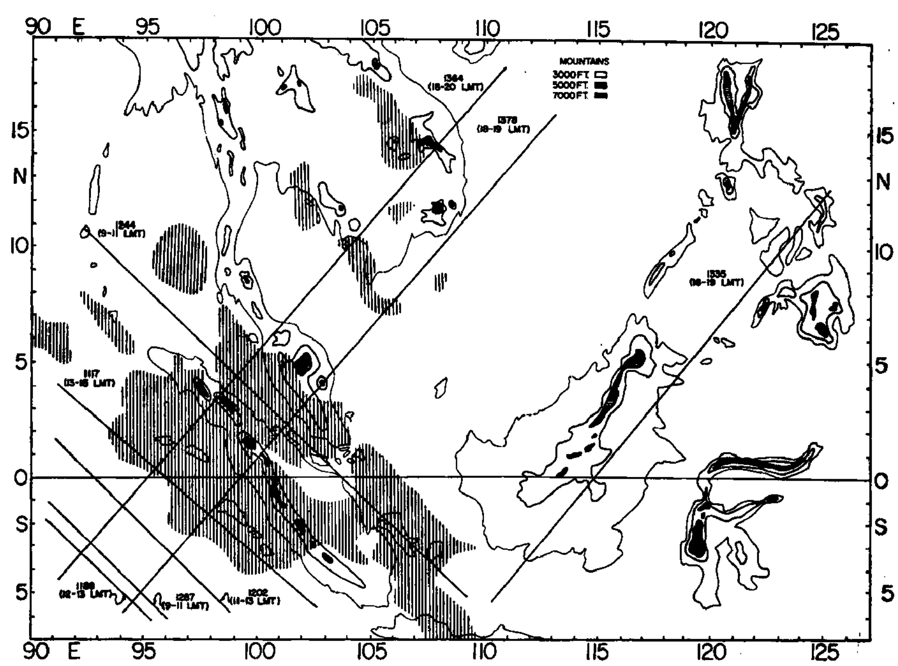

Figure 3 - Locations of low radiation cells (shaded areas) observed by TIROS-IV during daytime (07-19 LMT) (composited for daytime orbits only).

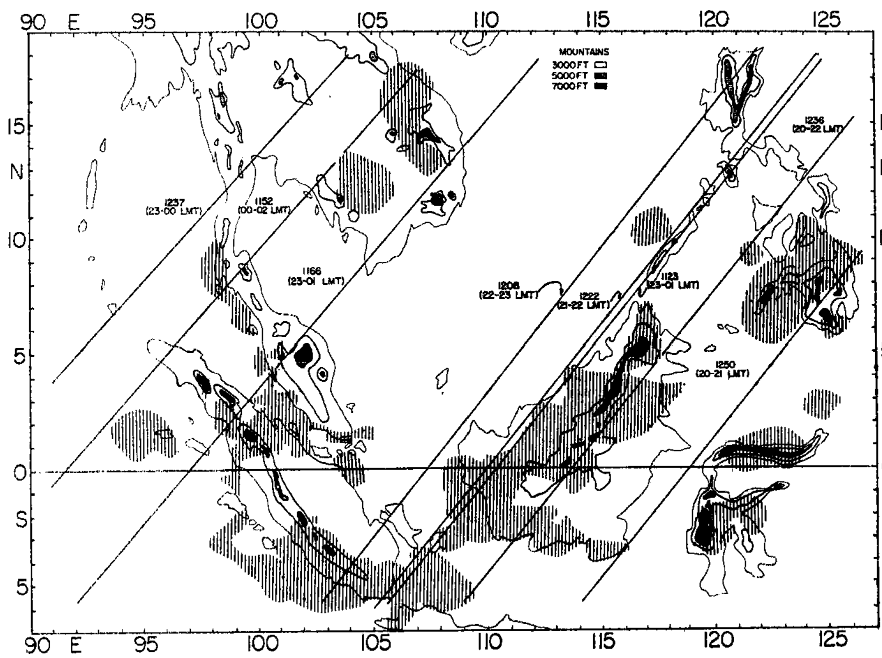

Figure 4 - Locations of low radiation cells (shaded areas) observed by TIROS-IV during night (19-07 LMT) (composited for nighttime orbits only).

Table II

Frequency of measurement of low radiation cells over lands/islands.

	Sumatra	Malaya	Borneo	Java	Celebes	Philippines	Cambodia	South Viet Nam
Number of Satellite Passages	16	8	7	1	4	7	5	5
Number of Times Low Radiation Detected	15	7	7	1	4	6	5	5

(ii) Orbit #1202 (11-13 LMT) oriented NW-SE and orbit #1208 (22-23 LMT) oriented SW-NE overlap over Sumatra-Java region on 3 May, 1962. The radiation patterns over the overlapped area show persistence of daytime low radiation cells into the night. Two low radiation cells with central values (~.34 Ly/min.) centered over South Sumatra and neighboring sea areas appear to have combined and intensified by evening with central radiation value of 0.19 Ly/min. Two well-developed low radiation cells with central value each 0.19 Ly/min. appear at night over South Borneo and Java respectively and another with central value 0.15 Ly/min. over sea about 400 kms southwest of Sunda Strait. A low radiation cell (central value ~0.32 Ly/min.) which was observed in daytime disappeared at night. In the daytime orbit, 4 or 5 scattered low radiation cells with central values in the range 0.22 to 0.27 Ly/min. were observed in the sea areas between Sumatra and Ceylon.

(b) Variation between one day and the next

Orbit #1222 (21-22 LMT) on 4 May, 1962 and orbit #1236 (20-22 LMT) on the next day both oriented SW-NE overlapped over a wide region of Southeast Asia.

Both the orbits show extensive low radiation cells over Sumatra, Borneo and Philippines. A low radiation cell with central radiation value 0.25 Ly/min. which appeared over north Java Sea in orbit #1222, however, disappeared the following day.

(c) Variation between two successive orbits

Orbit #1236 (20-22 LMT) and orbit #1237 (23-24 LMT) passed over Southeast Asia in almost the same orientation on 5 May, 1962. These orbits show conclusively that the low radiation cells over the area are intimately related to land areas and surface orographic features. In orbit #1236, low radiation cells with central radiation values as low as 0.09 to 0.15 Ly/min. appear over Sumatra, Borneo, and the Southern Philippine Island of Mindanao. In orbit #1237, low radiation cells with central values in the range 0.22 to 0.30 Ly/min. are seen to be located over Malaya, South Cambodia, and South Viet Nam.

We may now briefly summarize our findings of the radiation analysis insofar as they relate to the problem under investigation. The charts show that on most of the occasions when there were no active disturbances in the equatorial trough zone, low radiation cells of varying intensity appeared over land and neighboring coastal water areas, and particularly over large oceanic islands. Here also, they appeared to be linked in some way with the local orographic features such as mountain ranges. In fact, some of the lowest radiation cells tended to be located in mountainous regions, extending in some cases to a considerable distance to the leeside over neighboring sea areas. In a few cases, however, low radiation cells were observed over the North Indian Ocean in isolated areas.

3. The Nature and Origin of Low Radiation Cells

The total radiation emitted by a black-body depends on its temperature and the Stefan-Boltzmann law gives this dependence as the fourth power of the absolute temperature of the radiating surface. The earth's surface may be treated, to a very close approximation, as a black-body but the radiating power of its atmospheric envelope departs considerably from black-body conditions. With clear skies the radiating surface is predominantly the earth's surface and the relatively smaller contributions from its atmosphere may be neglected. High fluxes of infrared radiation are, therefore, measured by the satellite radiometer when orbiting over such cloud-free areas. On the other hand, if the skies are overcast with thick, towering clouds such as the cumulus or the cumulonimbus, radiation emitted by the earth's surface is completely absorbed by these clouds and the top of the cloud which is at a much lower temperature becomes the radiating surface. Low radiation cells, thus, can originate in either of the following ways: (i) When the earth's surface is cold such as is found over an extensive snow field, or (ii) when the radiating surface is elevated such as the top of a towering cumulus or a cumulonimbus cloud. TABLE III gives the values of equivalent black-body temperature, and the pressure altitudes of the effective radiating surface in a tropical atmosphere, corresponding to measured fluxes of radiation over this region and Fig. 5 gives a typical analysis of a situation in terms of the equivalent black-body temperatures and the centibaric heights of the effective radiating surface. In a partly-clouded sky with little or suppressed vertical development such as that found under normal trade-wind regime, intermediate values of radiation flux may be measured. Wark, Yamamoto, and Lienesch (1962) have found that the equivalent black-body temperature in the case of a clear sky, as computed from the Stefan-Boltzmann law, is found to be 5-10° C lower than the mean temperature of the earth's surface. This is probably due to a complicated process of absorption suffered by the outgoing radiation in passing through dirt and haze in

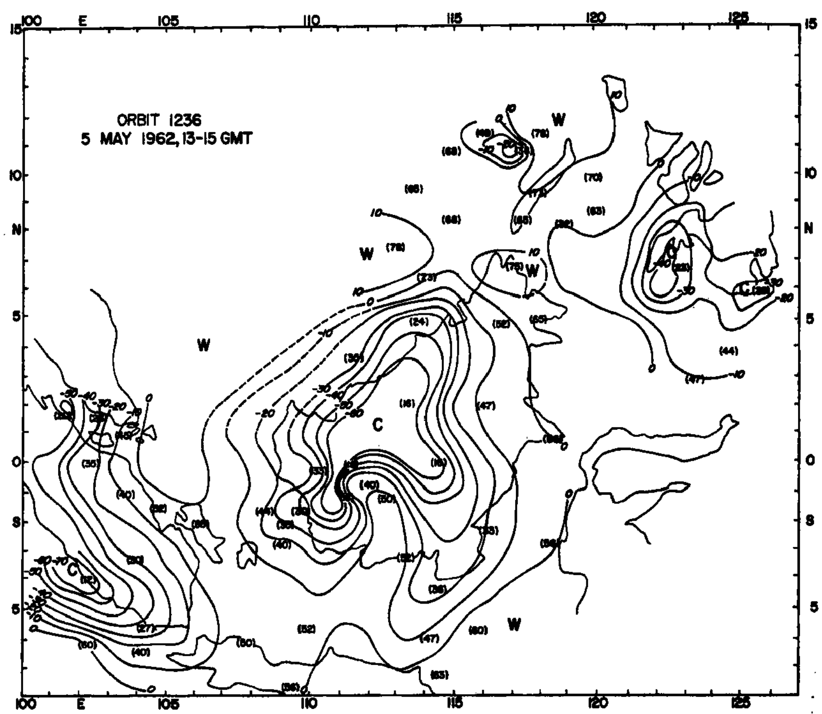

Figure 5 - Analysis of an infrared radiation flux chart in terms of equivalent black-body temperatures (°C) and centibaric heights of the effective radiating surface. C-means cold, W-warm, and the figures within brackets are pressure heights in centibars. Situation May 5, 1962- Orbit #1236 (20-22 LMT)

Table III

Equivalent black-body temperatures (^{o}C) and pressure levels (mb) corresponding to different values of infra-red radiation flux over the Tropics

	.65	.61	.56	.51	.47	.41	.35	.27	.19	.11
Temperature (^{o}C)	25	21	13	8	2	-7	-17	-33	-55	-77
Pressure (mb)	1000	900	800	700	600	500	400	300	200	100

the atmosphere. In comparison, radiation emitted from the cloud-top suffers much less depletion because the interfering dust or haze layers are now substantially below the radiating surface.

Since the temperatures of the earth's surface area are about the highest during April-May throughout southeast Asia and since obviously there are no snow fields in any part of this region during summer, we may take it for granted that the only systems which could produce low radiation values (<0. 35 Ly/min.) in this region were the tops of well-developed clouds such as the towering cumulus or cumulonimbus or the thick altostratus or cirrostratus associated with active large-scale synoptic disturbances. The tops of these clouds rise to 200-100 mb levels on many occasions and the equivalent black-body temperatures corresponding to the observed radiation fluxes from these clouds are, indeed, close to the actual temperatures at these heights.

4. Dynamical Convergence in the Equatorial Trough Zone

An examination of the synoptic situations during the period of study using the surface and upper-air maps published by the regional meteorological services was undertaken with a view to finding out processes that might be at work to produce cloud systems which could provide a reasonable explanation of the low radiation patterns observed by the satellite. Thailand Meteorological Department (1965) has recently published mean monthly streamline charts for the southeast Asia and the adjacent western Pacific region. Fig. 6, reproduced from this work, gives the mean flow patterns over the area during the month of May.

Streamline charts were also prepared from the Colorado State University maps and analyzed for all the individual days for which satellite radiation data were available. It was found that on an average the synoptic maps indicated dynamical convergence in the lower troposphere of the equatorial trough zone over southeast Asia but its intensity varied along the trough line and was, on an average, very slight, indeed. An isotach analysis showed windspeed below 10 knots on most occasions. As already discussed, this feeble dynamical convergence may not be sufficient to produce any large-scale cloud development over the open ocean areas except under additional stimulus. This is, indeed, what is actually observed over most of the sea areas (Malkus and Riehl, 1964). Small clouds, usually the suppressed trade-wind cumulus with tops going up to about 3-4,000 meters are all that meet one's eye over vast stretches of the ocean surface and

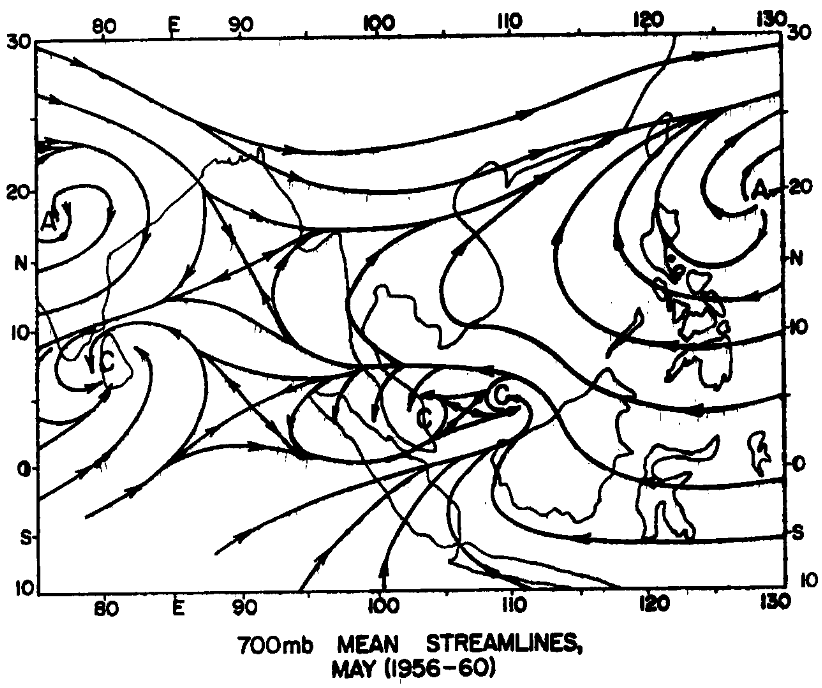

Figure 6 - Normal streamline pattern at 700 mb level during May over Southeast Asia and neighboring areas. C - cyclonic vorticity, A-anticyclonic vorticity.

their presence is clearly testified by high radiation values (~.40/.50 Ly/min.). Except over a few isolat ed areas over the north Indian Ocean on a few occasions and except in association with intense synoptic disturbances as already mentioned, few low radiation cells appeared over the open sea areas far from land masses (see Figs. 2-4). In the absence of adequate synoptic data over the north Indian Ocean, the appearance of low radiation cells on a few occasions over this area could not be investigated. The result of analysis over the southeast Asia region, however, seemed to be conclusive in that it pointed to the need of additional stimulus besides dynamical convergence, for development of towering clouds over land areas, as revealed by TIROS radiation data.

5. Thermal Convection and Orography

Since TIROS-IV radiation data reveal low radiation cells mostly over land areas in the equatorial trough zone, it was considered desirable to look into this association a little more closely. During summer, the land surface in the interior of an island is much hotter than the surrounding water surface. TABLE IV gives the screen maximum temperatures during May, 1962, at a few land stations in southeast Asia, taken from the Summary of Observations published by the Malayan Meteorological Service, whereas the mean sea surface temperature over the south China Sea area during this period, as given by the Marine Climatic Atlas of the World, published by the U. S. Navy (1957) was 28.9° C with very little spatial variation.

The differential heating between the land and the sea gives rise to strong convection currents over the land, which in the presence of moisture leads to development of clouds. The process is aided by the dynamical convergence of the equatorial trough zone, however feeble that may be. It is our experience in the tropical zone that when low-level convergence is superimposed upon intense solar heating of a land surface, rapid development of towering shower clouds occurs if the air is sufficiently moist. As is well known, the atmosphere in the equatorial trough zone, particularly over the oceanic areas, is highly moist and latently unstable up to a large height. Fig. 7 which gives a parcel-method analysis of data of a radiosonde ascent over Singapore on 29 April, 1962 when a low infra-red radiation cell was observed over South Malaya shows the level of free convection at 900 mb level and a very small input energy required to raise surface air to this level. It also shows that once surface air is raised to the

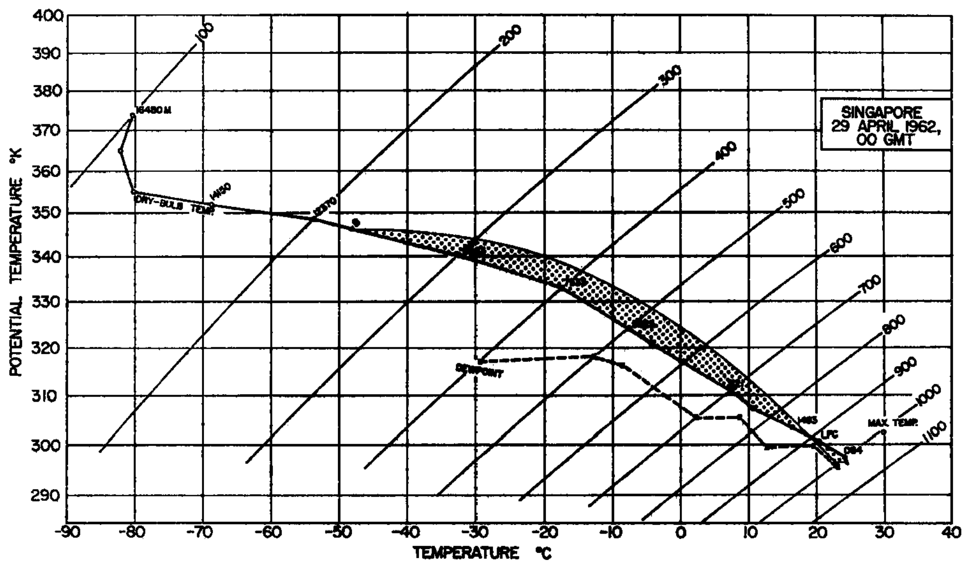

Figure 7 - Upper-air Sounding of Singapore, 29 April, 1962. LFC-level of free convection. B-represents top of cloud.

level of free convection, i. e., up to 900 mb level, it can automatically rise to about 220 mb level which is about the height of the cloud top in this atmosphere. The height of the equivalent blackbody radiating surface as computed from the observed radiation flux of 0.24 Ly/min. was 260 mb (see Table III). The agreement was, therefore, very close.

Considering that the ratio of the land area to the total area of the equatorial trough zone (10^{o}- wide belt) is about one-tenth, one can thus see qualitatively at least the important role played by convection in the total heat balance of this zone.

Another important factor which aids cloud growth over land is forced convection due to orography. If the prevailing wind is moist and from the right direction, rapid ascent occurs against mountain barriers. The land areas of southeast Asia are highly mountainous. Mountain systems as high as 2-3 km with peaks rising to 3.4 km run all along the southern half of Sumatra; equally high mountain ranges run along central and northeastern Borneo. North Malaya, South Philippines, South Cambodia, and South Viet Nam all have orographic features extending to 1.5 to 2.5 km above M. S. L. It is remarkable that most of the low radiation cells observed by TIROS-IV occur repeatedly in the regions of these elevated land features. An analysis made of the position of low radiation cells with reference to mountain ranges with the aid of 500 mb flow patterns showed that out of 55 cells, 37 were centered on the leeside, 4 on the windward side, and 12 right over the mountain ranges. Two cases were indefinite. Judged by the low-level (below 700 mb level) streamlines, however, which often had components opposite to those of the 500 mb level streamlines, one may like to interpret the leeside proportion of such cases among those described as on the leeside of the basis of 500 mb level streamlines is, however, difficult to establish at present in the absence of adequate wind data over some part of the region.

6. Persistence of low radiation cells during night

It is clear from Table I and Figs. 2-4 that low radiation cells appear in both day and night orbits. Since the frequency of satellite observations is small, it is not possible to say how many of the cells observed during the day continue and persist during the night. It is quite likely that many of the shower clouds which originate during the early part of the day dissipate before evening. It is, however, our experience in the tropics* that a large proportion of the convective thunderstorms which arise during the latter part of the day persist and thrive very well even after midnight. Kal-Vaisakhis-the deadly thundersqualls of Bengal-usually start in the Chota Nagpur area of Bihar at about 15 hours I. S. T. and move from a northwesterly direction at an average pace of 10-15 meters per sec., reaching and dissipating over the Delta area sometime about midnight. The mechanism of persistence of these storms after sunset is not clearly understood, but it is believed that they are of the self-regenerating type in which the rain-cooled down-current on striking the ground raises the warm moist air in front of it and the process becomes self-sustaining. The forward movement of the squally wind serves as a trigger to raise the surface air to the level of free convection and the enormous amount of realizable latent energy is set free in this manner to keep the cloud going. Another factor which may be responsible for extensive towering cloud development and maintenance during the night over southeast Asia is the continued radiational cooling of the top surfaces of the clouds, thereby creating a steep temperature lapse rate and consequently, vertical instability inside the clouds. **

7. Radiation patterns observed with synoptic disturbances

When synoptic disturbances occur in the equatorial trough zone, low radiation cells are observed over the sea area as well as over the land. An interesting case occurred on 17 May, 1962, when a typhoon "Hope" lay near the Philippines and a cyclonic circulation developed over the South China Sea in association with the advance of the SW monsoon. Fig. 8 shows the low radiation cells that were observed by TIROS-IV (orbit #1406) on this occasion and the relevant streamline patterns for 850 and 700 mb levels at 00 GMT of the day are presented in Fig. 9 (a) and (b). It may be seen from Fig. 8 that three prominent areas of low radiation appear, one over the Philippines area, one over the South China Sea, and a third over the landmass

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* See "Norwesters of Bengal" - India Met. Dept. Tech. Note No. 10

** This explanation of nighttime persistence of low radiation cells was suggested to me by Dr. Uwe Radok of Australia in the course of a discussion at NCAR, Boulder.

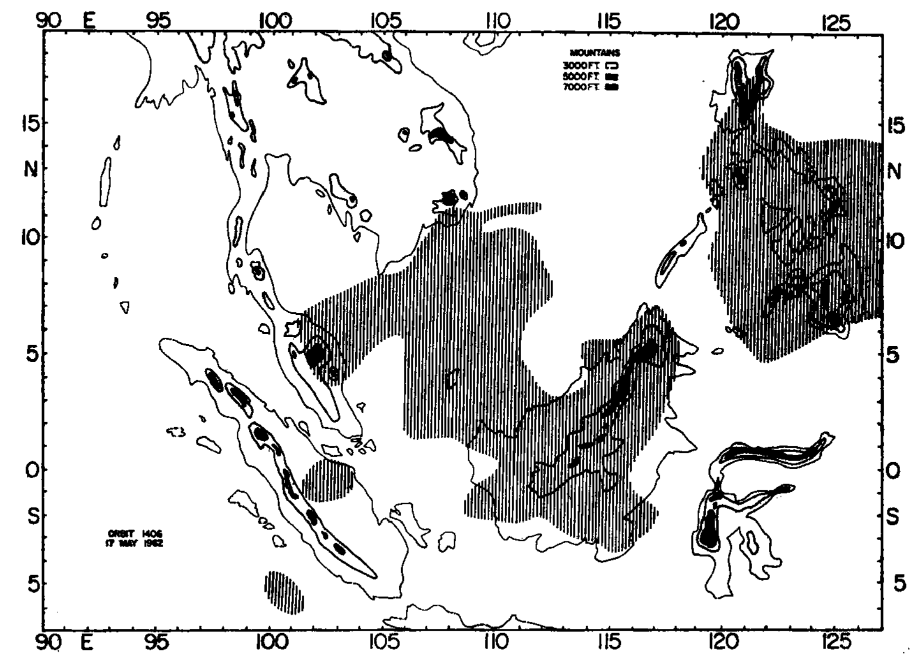
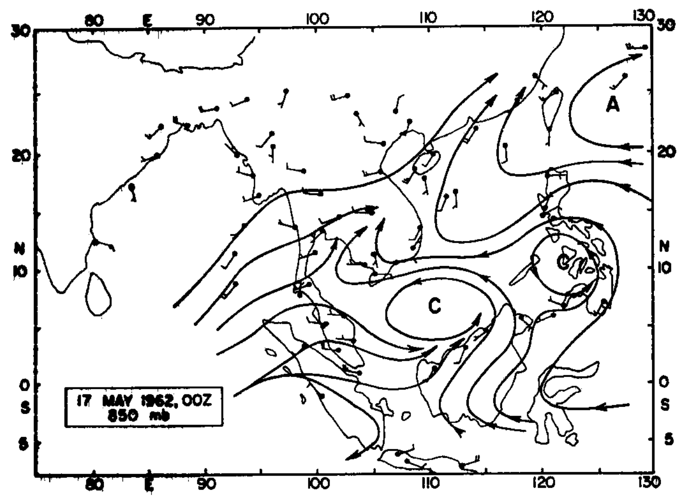


Figure 8 - Locations of low radiation cells during synoptic disturbances, 17 May, 1962.



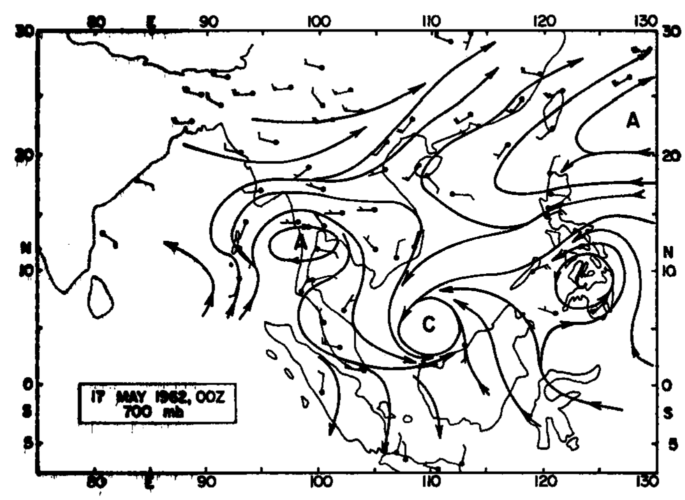


Figure 9 - Cyclonic circulations over South China Sea and the Phillipines on 17 May, 1962. (a) 850 mb level, (b) 700 mb level.

of Borneo. Although the low radiation area over the Philippines appears separately, that over the South China Sea merges with the low radiation area over Borneo. The lowest central values of the three broad low radiation areas are about the same (0.19 Ly/min.). A low radiation cell with central value of 0.21 Ly/min. appeared over Sumatra.

Extensive areas of low radiation appeared over both land and sea areas of the equatorial trough zone on May 18, 1962 in association with the advance of the SW monsoon over southeast Asia.

8. Conclusion

The present study, therefore, reveals the important role of free and forced convection in addition to synoptic disturbances in the heat balance of equatorial trough zone. Radiation data clearly locate over land low radiation cells of intensity comparable with that of synoptic disturbances but while synoptic disturbances of sufficient intensity to produce undilute hot cloud towers may not be quite as numerous as would be required for the heat budget, convection towers of thermal and orographic origin occur over a large part of one-tenth of the total area of the equatorial trough zone almost daily. This is a remarkable finding, since it reveals an effective standing mechanism of daily occurrence for the vertical transfer of heat in the equatorial trough zone. In the absence of adequate upper-air sounding data over the zone, it is not possible at this stage to assess the relative contributions of "hot towers" of land origin and those produced by synoptic disturbances to the total vertical heat transfer required for heat balance. However, in the light of evidence furnished by the TIROS radiation data, we may conclude that given a synoptic situation in the equatorial trough zone we may expect to see cloud towers growing preferentially over large landmasses and islands within this zone particularly in such areas where there are mountain ranges normal to the prevailing wind and relatively little or moderate vertical cloud growth over the wide ocean areas, except, perhaps, when the latter areas are distrubed by an activation of the equatorial trough or by such synoptic disturbances as depressions or tropical storms.

Acknowledgement:

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