NOTES AND CORRESPONDENCE

**Estimation of Monthly Rainfall from Satellite-Observed
Cloud Amount in the Tropical Western Pacific****By Taketo Maruyama, Tsuyoshi Nitta and Yoshie Tsuneoka***Meteorological Research Institute, Tsukuba Gakuen, Ibaraki 305, Japan**(Manuscript received 1 July 1985, in revised form 14 December 1985)***1. Introduction**

It has been known that heat sources in the tropics play an important role in general circulations of the global atmosphere. In recent years works by Bjerknes (1969) in which atmospheric teleconnections from the equatorial Pacific were emphasized have been revived in connection with long-term variations of global weathers.

Since heat sources in the tropics are mostly due to condensation heating, spatial and temporal variations of rainfall in the tropics are quite important for the studies of long-term variations of the atmospheric circulation. However, reliable estimation of spatial distributions of precipitation in the tropical oceans is quite difficult due to sparseness of surface rainfall stations which are mostly located on islands. Moreover, rainfall amounts observed on large island stations with high mountains are sometimes affected by island topography and do not always represent mean precipitation rate over large areas around stations.

Diagnostic methods to estimate rainfall by the use of meteorological satellites have been derived and tested by a number of investigators. Barrett (1970) made a pilot study estimating monthly rainfall distributions from ESSA nephanalyses, but those nephanalysis data were determined subjectively. Kilonsky and Ramage (1976) proposed a simple and inexpensive method which relates monthly frequencies of highly reflective cloud measured by ESSA visible mosaics with monthly

rainfall totals. However, the comparative study by Garcia (1981) suggested that some discrepancy between rainfall estimates by this method and observed rainfall may arise in the regions where diurnal variations of precipitation are large, since this method is based on daytime data only.

Rao *et al.* (1976) published the "Satellite-Derived Global Oceanic Rainfall Atlas" based on the Electrically Scanning Microwave Radiometer (ESMR) data. Although the Atlas describes global rainfall patterns beautifully, the absolute values are underestimated by a factor of two or so. Griffith *et al.* (1978) proposed an outstanding method of rain estimation from geosynchronous visible and infrared satellite imagery by including the information on stages of cloud development and their method was successfully tested by the GATE observations. However, this method based on one hourly digital infrared data needs tremendous amounts of computer time to get global-scale rainfall estimates for long periods and may not be practical for the climatological studies.

In this note we propose an empirical formula estimating monthly rainfall amounts using high-cloud amount derived by the geostationary meteorological satellite (GMS). This method is very simple based on cloud amount data routinely processed by the Meteorological Satellite Center in Japan and may be practically useful for the purposes of climatological studies. Since the cloud amount determined 6 hourly from the GMS infrared

(IR) observations is used to obtain monthly mean cloud amount, effects due to diurnal variations of clouds are taken into account in this method.

2. Data

Monthly rainfall data at surface stations on small islands in the tropical western Pacific between 20°N and 20°S are used in this study. Stations on large islands such as Borneo and New Guinea are not used to eliminate effects by large-island topography. Their locations are shown in Fig. 1 (one station, Cocos, is located in the Indian Ocean). We use high-cloud amounts routinely observed by GMS at the Meteorological Satellite Center in Japan for the comparison with surface rainfall. The original high-cloud amount is

Fig. 1 Locations of stations within 20° latitudes used in this study.

determined 6 hourly from the number ratio of cloud pixels with equivalent black-body temperature lower than climatic 400 mb temperature within a 1-degree latitude-longitude area using the GMS IR data. The results by the GATE observations (ex. Houze and Betts, 1981) showed that most of the precipitation in the tropical oceanic areas fell from large echoes ($>10^3$ km in area) whose tops usually reach the upper troposphere. The high-cloud amount derived by GMS may represent the degree of convective activities due to deep clouds which account for most of the tropical precipitation. The monthly mean high-cloud amount in the $1^{\circ}\times 1^{\circ}$ square where each island station is included is used for comparison. The analyzed period is for 71 months from February 1978 to December 1983 during which the cloud amount data are uniform in quality with no change of the IR sensors and data processings.

3. Comparison between monthly rainfall at island stations and satellite-observed cloud amount

In Fig. 2, we show time series of monthly rainfall amount (units: mm) and cloud amount (units: 1/1000) for Tarawa (1°N , 173°E). We can see in the figure that cloud amounts and monthly rainfall show similar variations roughly proportional to each other. Cloud amounts in 1/1000 units generally correspond to monthly rainfall amounts in mm.

Similar proportional relationship between the cloud amount and the monthly rainfall

Fig. 2 Time series of monthly rainfall amount (in mm, thick lines) and high-cloud amount (in unit of 1/1000, thin lines) for Tarawa.

is also found for most of the other stations distributed widely in the western Pacific and the eastern Indian Ocean as shown in Fig. 1. However, observed rainfall amounts are systematically larger than those expected from cloud amounts for Ponape (7°N , 158°E) and smaller for Honiara (9°S , 160°E) (not shown). Ponape has a mountain with about 700 m height, and Honiara is located in Guadalcanal Island having several high mountains with heights around 2000 m. The enhancement or the suppression of rainfall may occur for these stations due to local topography.

When the monthly rainfall is larger than about 400 mm, the corresponding cloud amount has an upper-limited value of about 400/1000. This upper limit of the cloud amount may be caused by the fact that the 400-mb level is fixed as the threshold level for the high-cloud amount and that no information of cloud top heights above 400 mb is not used to determine high-cloud amounts. Deeper cloud systems may produce larger amounts of rainfall than shallower cloud systems, even when both reach upper levels above 400 mb. Detailed histograms of cloud top heights by GMS IR data may be needed to overcome this problem. However, cases for the rainfall larger than 400 mm are quite rare and general relationships between the rainfall and cloud amounts may be obtained from these data sets.

4. Cloud amount-rainfall relationship

Scatter diagrams for the rainfall and the cloud amount are examined in order to obtain more detailed relationship between these parameters. Fig. 3 presents the diagrams for Tarawa. A linear proportional line starting the zero point is fitted by the least mean square method. We find in the figure that the cloud amount and the monthly rainfall are roughly proportional to each other. The proportional ratios for all stations are listed with the location of observation site, island area, and mountain height nearby in Table 1. Though the observation stations are distributed widely in the western Pacific and the Indian Ocean as shown in Fig. 1, the proportional ratios for most stations fall into narrow ranges from 1.0 to 1.3. The largest

Fig. 3 Scatter diagrams between rainfall (R , mm) and cloud amount (C , 1/1000) for Tarawa. A linear proportional line is fitted by least mean square method and the proportional ratio is noted.

ratio is 1.56 for Ponape and the smallest is 0.53 for Honiara. Secondary extreme ratio values are estimated at Nausori and Nandi. The ratio at Nausori is large and that at Nandi is small. These two stations belong to the same island, Viti Leve Island, Fiji. Nausori is located at the east side, Nandi at the west side, and mountains with height about 1300 m lie between them. Topographic rainfall enhancement and suppression effects seem to occur at Nausori and Nandi. Topographic rainfall enhancement effect is also expected to some extent for the estimates at Koror, Guam, Yap and Truk where small hills lower than 400 m are located nearby. Other islands—Kwajalein, Funafuti, Cocos, Tarawa, Wake and Majuro—are small and flat, and have no significant peaks to be described. The estimates at these stations fall in a narrower range from 1.04 (Majuro) and 1.15 (Kwajalein). Orographic effects is considered to be negligible for these stations.

Fig. 4 shows a scatter diagram in which the data for Kwajalein, Funafuti, Cocos, Tarawa, Wake and Majuro are plotted together. A straight line is fitted by the least square method. We get the formula between

Table 1 Proportional ratios of monthly rainfall (in mm) to high-cloud amount (in unit of 1/1000) with station locations, island areas, and mountains nearby (peak height, direction and distance from the station). Island areas smaller than $0.1 \times 10^3 \text{ km}^2$ and no peak descriptions are blanked. (After *Nomenclatur of Stations*, WMO, and *The Times Atlas of the World*, Times Books, London, 1977)

Station	Ratio	Latitude	Longitude	Height	Island Area	Mountain nearby
Ponape	1.56	7N	158E	37m	$0.3 \times 10^3 \text{ km}^2$	791m S 12km
Nausori	1.39	18S	178E	6	10	1204 W 50
Koror	1.33	7N	134E	29	0.3	224 N 10
Guam	1.32	14N	145E	110	0.6	309 SW12
Yap	1.17	9N	138E	16		187 N 5
Kwajalein	1.15	9N	168E	2		
Truk	1.13	7N	152E	2		670 S 5
Funafuti	1.11	9S	179E	1		
Cocos	1.09	12S	96E	3		
Tarawa	1.07	1N	173E	2		
Wake	1.05	19N	167E	3		
Majuro	1.04	7N	171E	3		
Nandi	0.97	18S	177E	19	10	1324 E 70
Honiara	0.53	9S	160E	58	6	2331 S 30

Fig. 4 Scatter diagrams between rainfall (R , mm) and cloud amount (C , 1/1000). The data for Kwajalein, Funafuti, Cocos, Tarawa, Wake and Majuro are plotted together. A linear line is fitted by the least mean square. Mean rainfall and its standard deviation for each 50/1000 cloud amount are marked.

monthly rainfall R (mm) and the monthly mean high-cloud amount C (in unit of 1/1000) as follows :

$$R=1.13C-10, \tag{1}$$

with the correlation coefficient 0.78. Though computation does not assume its starting from the zero point here, deviation from the zero point is found to be negligibly small, only -10 (mm). To examine this relationship more closely, we devide the plotted data into each 50/1000 cloud amount, and calculate the mean value and standard deviation for each range of the cloud amount (Table 2). The computed values are also plotted in Fig. 4. Using these results, we obtain an expected monthly rainfall amount by

$$R=(1.1 \pm 0.3)C \tag{2}$$

for the cloud amount larger than 250/1000.

5. Relationship between rainfall and cloud amount averaged in the ITCZ

In the previous sections we examined the relationship between monthly rainfall and monthly mean cloud amount for each obser-

Table 2 Mean monthly rainfall ($\bar{R}$, mm) and its standard deviation (R_σ) for each 50/1000 cloud amount (C in unit of 1/1000). Proportional ratios ($\bar{R}/\bar{C}$) and relative deviations ($R_\sigma/\bar{R}$) are also calculated.

C	$\bar{C}$	$\bar{R}$	R_σ	$\bar{R}/\bar{C}$	$R_\sigma/\bar{R}$
0—50	21.6	46.2	41.1	2.1	0.9
51—100	77.9	87.0	55.4	1.1	0.6
101—150	126.7	143.4	69.5	1.1	0.5
151—200	174.6	208.0	110.6	1.2	0.5
201—250	229.1	256.9	109.4	1.1	0.4
251—300	275.5	291.8	99.4	1.1	0.3
301—350	327.2	344.3	114.9	1.1	0.3
351—400	374.8	400.5	127.0	1.1	0.3

vation station. However, our main concern is to derive large-area averaged precipitation from the cloud amount. The relationship for individual stations may be biased by local effects as discussed previously. In this section we examine the relationship between the two parameters averaged over the Northern Hemisphere ITCZ.

Five stations—Koror, Yap, Truk, Kwajalein and Majuro—which are located in the tropical western Pacific from 135°E to 175°E and from 7°N to 10°N are used to calculate averages of rainfall and cloud amount. Ponape is also located in this zone, but we do not include its data in consideration of its extremely large proportional ratio. These averaged values may represent mean monthly rainfall and cloud amount in the northern ITCZ, respectively. Their time series and scatter diagram

are shown in Figs. 5 and 6. We find that the relationship between the two parameters becomes much closer to each other than that for individual stations shown in the previous sections. A straight line fitted by the least square method is also shown in Fig. 6. The correlation coefficient is 0.86 and an expected value of monthly rainfall averaged in the ITCZ is

$$R = 1.21C - 4. \quad (3)$$

This relation is nearly the same as (1) and (2) obtained from individual station data, but the former results show smaller deviations from the line than the latters.

6. Concluding remarks

Analyzing monthly rainfall data at 14 tropical stations in the western Pacific and

Fig. 5 Time series of monthly rainfall amount (in mm, thick line) and high-cloud amount (in 1/1000, thin line) of averaged values for five stations in the northern ITCZ (Koror, Yap, Truk, Kwajalein, Majuro).

Fig. 6 Scatter diagram between rainfall (R , mm) and cloud amount (C , 1/1000) of averaged values for five stations in the northern ITCZ.

the Indian Ocean and satellite-derived high-cloud amount averaged in the $1^\circ \times 1^\circ$ square region nearby stations for about 6 years, empirical relationships between the two parameters are obtained. Both parameters for each station vary almost proportionally and the proportional ratios of monthly rainfall in mm (R) to cloud amount in 1/1000 (C) for most stations fall into values from 1.0 to 1.3. The empirical relation, $R = 1.13C - 10$, is obtained from the scatter diagram including the data for the stations on small flat islands.

Similar comparison is made between the two parameters averaged in the northern ITCZ to eliminate local effects. The rainfall—cloud amount diagram exhibits smaller deviations from the proportional line than obtained from individual station data. The obtained proportional rate is 1.21 which is slightly larger than that obtained from all individual station data. This larger value may be due to the effects of the upper limit of the satellite derived cloud amount around 400/1000, because the activity of deep clouds in the ITCZ region is stronger than in the other tropical regions. However, orographic rainfall enhancement effect is also to be considered to some extent.

Fig. 7 demonstrates distributions of rainfall rate in January averaged for 5 years (1979–1983) and in July averaged for 6 years (1978–1983) derived from high cloud amounts. Fig. 7 indicates that during northern winter heavy precipitation area is situated in the Southern Hemisphere equatorial region to the south of Borneo with the maximum precipitation rate of about 15 mm day^{-1} . On the other hand, during northern summer the northern ITCZ extends from the eastern Pacific and the maximum precipitation with values of about 15 mm day^{-1} occurs to the south of Philippines. These approximate values of precipitation rate over the ITCZ estimated by the cloud amount is generally larger than those estimated from surface observations by Möller (1951), although both spatial patterns are quite similar. Dorman and Bourke (1979) estimated oceanic rainfall for the Pacific Ocean by using 23 years ship observations. The distributions and the amplitudes of the precipitation estimated in this

Fig. 7 Distributions of rainfall rate derived from mean high-cloud amount for (a) January (1979–1983) and (b) July (1978–1983).

study are generally consistent with their results.

The advantage of this method is the simplicity by using the routinely processed cloud amount data and no troublesome data processings based on original IR data are needed. Although the method is very simple, the quantitative monthly mean precipitation can be estimated by this method. It might be possible to analyze long-term variations of heat sources in the western tropical Pacific quantitatively based on these data. This method, however, has a deficiency in estimating high rainfall values above about 400 mm month⁻¹ (~13 mm day⁻¹) probably due to using one threshold level at 400 mb. Detailed histograms of cloud top heights by GMS IR data might be needed to obtain more reliable estimates in higher ranges of precipitation.

Similar analysis was performed by using total cloud amount which includes all cloud pixels with equivalent black-body temperature lower than that at the sea surface, but a proportional relationship between total cloud amount and monthly rainfall as observed for high-cloud amount was not obtained. As pointed in Section 1, most of precipitation in the tropics is due to deep clouds penetrating into the upper troposphere and contributions due to shallow clouds are quite small.

Relationships between the high-cloud amount and the monthly precipitation were also analyzed for stations in the subtropics higher than 20° latitude (not shown). The results indicated that there exists a linear relationship between two parameters during summer seasons but no clear relationship during winter seasons. Probably types of clouds producing precipitation may be different for different seasons in the subtropical regions.

No cloud amount data are available over the continent and large islands as shown in Fig. 7, but we have surface observation

stations over lands. It will be interesting to construct the whole distributions of precipitation in the tropical western Pacific by combining surface rainfall observations over lands and satellite-derived rainfall over oceans. This will be examined by future papers.

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衛星観測の雲量から推算した熱帯域西太平洋の月平均雨量

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