Bull. Disas. Prev. Res. Inst., Kyoto Univ., Vol. 42, Part 1, No. 364, March, 1992

Comparison of Rainfall on the Japanese Islands and Their Adjacent Ocean

By Pingping XIE

(Munuscript received on Jan. 14, 1992; revised on Feb. 17, 1992)

Abstract

Rainfall features of the Baiu season estimated from GMS IR images are investigated for the Japanese islands and their adjacent ocean for June 1989. The total monthly rainfall for the period is distributed in a band-like shape extending from west to east, showing its maximum on 35°N in the latitudinal section and a sudden decrease to the west of 130°E in the longitudinal section. The latitudinal distributions of rainfall relative to the Baiu front show almost the same shape with the maximum at 1.25° north of the front at the surface over both land and ocean, but the peak amount is larger over the island than that over the ocean. The temporal changes of rainfall are dominated by a period of synoptic scale for all regions over both land and ocean, and secondly, by a peak corresponding to daily variation observed only over the continent. The rainfall region moves eastward along the Baiu front with almost same phase speed of about 7.5° longitudes per 12 hours over almost all regions.

1. Introduction

Investigation of the spatial distribution and temporal change of rainfall of the Baiu front (Mei-yu in China) is an important subject in understanding the water and energy budget in East Asia. The Baiu front extends widely from the central portion of China to the east of Japan, moving slowly from south to north during the period from late spring to summer.

Yoshino1) investigated the climatic rainfall characteristics of the Baiu front by using rain gage data of 1954 and showed a band-like distribution of rainfall over continental China and the Japanese islands (**Fig. 1**). The distribution over the East China sea was unknown, but he tried to link the isohyets subjectively between the east coast of China and the Kyushu island. During the last two decades, a series of works by Ninomiya, Akiyama and their collaborators (e.g. Ninomiya and Akiyama2)3), Akiyama4)5), Ninomiya and Muraki6), Ninomiya and Mizuno7), Akiyama8)9)10)) has contributed much to the understanding of the features of Baiu rainfall by using mainly radar and gage observations. Their studies have revealed many important aspects of the nature of the clouds and rainfall of the Baiu front. The main conclusions are that 1) frontal depressions with meso-α scale develop along the Baiu front; 2) intense Baiu rainfall is produced by successive development of these depressions; and 3) in many cases, a precipitation system is composed of several meso-β precipitation systems. However, their studies have also been limited to the clouds and rainfall over land (mainly over the

Japanese islands) because of the lack of data over the ocean. That is, rainfall features of the Baiu front have not yet been investigated either over the East China sea or over the Pacific ocean and the Japan sea because of the lack of observational data. In order to investigate the rainfall features of the Baiu front as a whole system, rainfall data of adequate accuracy is necessary for the oceanic regions.

The practical use of satellite observation has made it possible to infer rainfall over both land and ocean especially for that in tropical areas where convective clouds dominate (e.g. Arkin[11], Arkin and Meisner[12], Shin et al.[13], Janowiak and Arkin[14]. Estimation of rainfall in midlatitudes, however, has been a much more difficult task because of the existence of non-rain cirrus and rain stratiform clouds (Wylie[15], Xie and Mitsuta[16]). Recently, the present author has developed a method to estimate rainfall in midlatitudes from the IR observation data of the Geostationary Meteorological Satellite of Japan (GMS) (Xie[17][18]). The method has shown a resonable success in estimating rainfall of the Baiu front in June 1989 (Xie[19]).

The present paper will give a description and analysis of the features of rainfall of the Baiu front as the first step toward the understanding of the Baiu front as a system, by using the results of the previous research on the estimation of rainfall in 1.25° meshes (Xie[19]). Among the many aspects of rainfall, the present work will focus on 1) spatial distribution of the rainfall of Baiu front on a climatic scale; 2) temporal change features of rainfall at various regions over land and ocean; 3) phase speed of rainfall region along the Baiu front.

2. Data

The data set of the First Algorithm Intercomparison Program of the Global

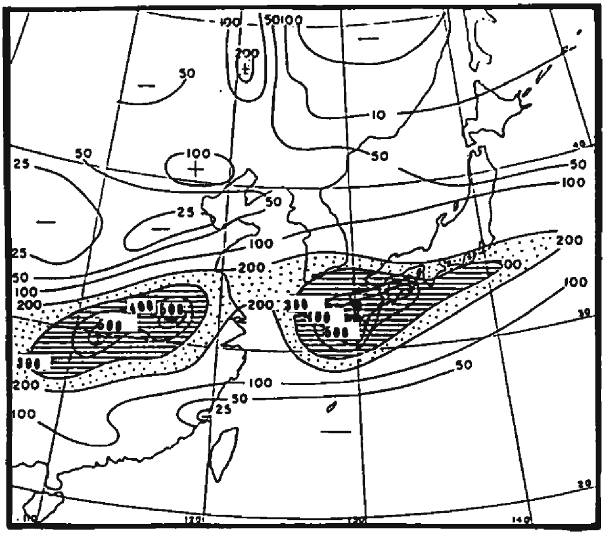

Fig. 1. The Baiu rainfall distribution for the period from June 24 to July 31, 1954. (After Yoshino[1])

Precipitation Climatology Project (GPCP-AIP/1) is used in the present study to investigate the rainfall features of the Baiu front. The data area extends from 120°E–147.5°E; 22.5°N–46.25°N and the period covers from 1 to 30 June, 1989 (see **Fig. 1** in Xie[19]).

The hourly rainfall has been estimated for 22 × 19 meshes with size of 1.25° × 1.25° in latitude and longitude for the entire period from the hourly observation of GMS IR

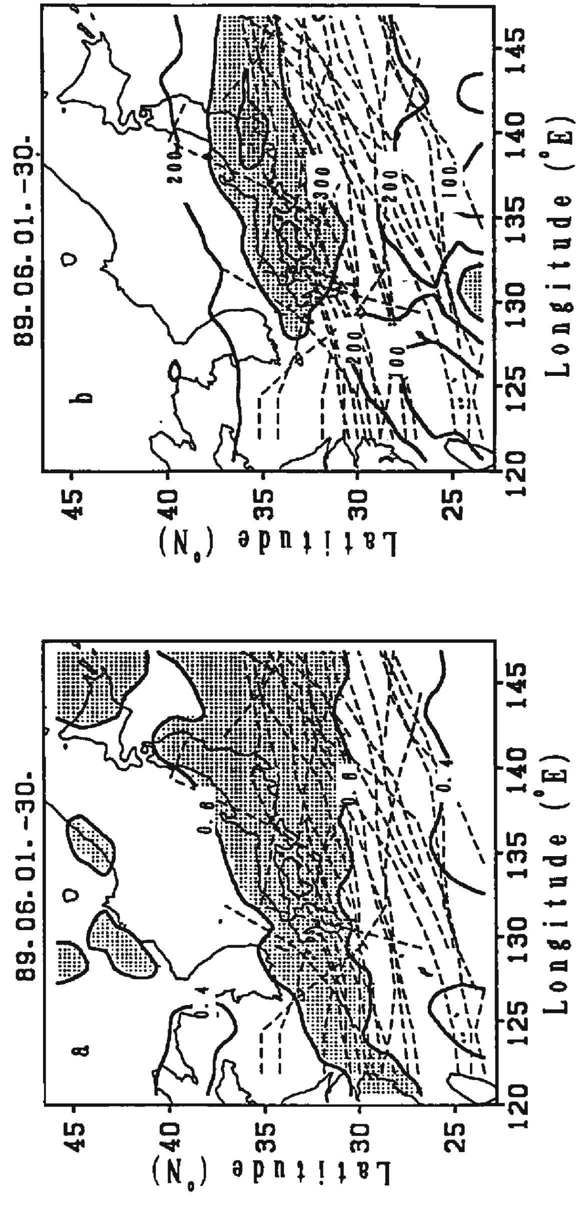

Fig. 2. Spatial distributions of a) monthly averaged cloud amount and b) monthly accumulated rainfall of June 1989 over the investigation area.

images, by using the modified rainfall estimation method described in Xie[19]. This estimation has been shown to satisfy the useful level of accuracy requirement for climatic application presented by Browning[20], when compared with the results of the concurrent radar-AMeDAS composite rainfall over the main islands of Japan (Xie[19]). Besides the satellite data mentioned above, daily surface weather charts at 0900JST for the period are also employed to determine the positions of Baiu front. These position data are then used to derive latitudinal distribution of rainfall relative to the Baiu front.

During the period, a large band of clouds and rainfall moved slowly south and north. Several depressions developed and moved eastwardly along the front in intervals of about 7 days. As shown in the daily rainfall distributions of the period in the Appendix of Xie[19], these depressions resulted in rainfall over both land and ocean over the investigation area.

3. Spatial Distribution of Rainfall

Fig. 2 shows the distribution of the estimated monthly rainfall over the area,

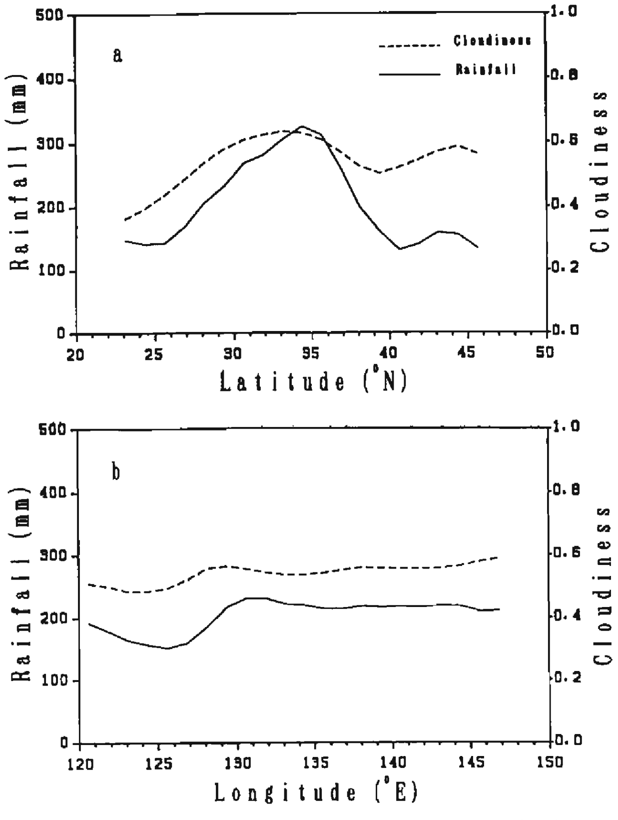

Fig. 3. a) latitudinal and b) longitudinal profiles of rainfall (solid line) and cloud amount (dash line) over the investigationa area.

together with the estimated average cloud amount. Positions of the Baiu front obtained from the surface weather charts at 0900JST of each day for the whole period are also ploted on these figures.

While the cloud amount forms a band extending from (120°E, 30°N) to (147.5°E, 35°N) almost continuously, the monthly rainfall distribution has a distinct break over the East China sea (120°E–130°E). The band of the monthly rainfall more than 300 mm centers on about 35°N and extends from 130°E to the east side of the area with width of about 5°N. Maximum rainfall of more than 500 mm is observed in the Kanto area. This result is in good agreement with the estimation in the rainfall distribution over the East China sea by Yoshino[1] as shown in **Fig. 1**.

Figs. 3a and **b** show the averaged latitudinal and longitudinal profiles of rainfall (solid line) and cloud amount (dashed line) over the area for the whole period. The latitude profile (**Fig. 2a**) of both rainfall and cloud amount shows a single peak shape extending from about 25 to 40°N. The rainfall peak of 325 mm appears at 35°N, and the peak of cloud amount of 0.63 is at 33.75°N, a little south to the rainfall peak in latitudinal profile.

In the longitudinal profile shown in **Fig. 3b**, both rainfall and cloud amount show nearly constant values (rainfall 210–230 mm, cloud amount 0.55–0.58) over areas to the east of 130°E (Kyushu), while those over the East China sea are obviously smaller than the values over land, with their minimum at about middle of the East China Sea. The decreases in rainfall and cloud amount are 14% and 34% when compared with those at

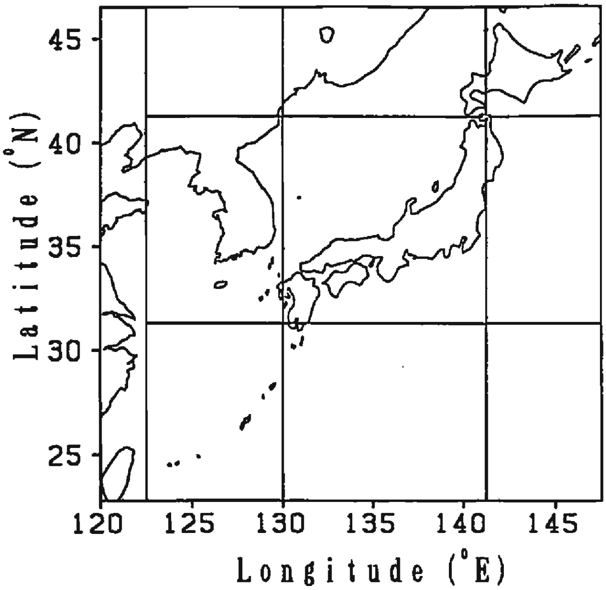

Fig. 4. 9 sub-regions in the area for investigating the rainfall features in various areas over both land and ocean. The latitudinal bound lines are at 41.25°N and 31.25°N. The longitudinal bound lines are at 122.5°E, 130.0°E and 141.25°E, respectively.

Kyushu.

In order to investigate the rainfall features relative to the frontal structures over land and ocean, the whole area east to 122.5°E (excluding portions over the east coast of China) is divided into 3 × 3 sub-regions as shown in **Fig. 4** and the latitudinal profiles of rainfall and cloud amount relative to the position of surface front are calculated by averaging the daily rainfall at various positions for the entire period of 30 days. **Fig. 5** shows the results for the 6 sub-regions with latitudes south of 41.25°N. No relative profile is obtained for the 3 sub-regions with latitudes north of 41.25°N because the Baiu front did not move into any of them during the period.

The resultant relative profiles of rainfall and cloud amount have almost the same shape for all of the 6 sub-gerions. The maximum of the rainfall is not just at the position of surface front, but about 1 mesh (1.25° latitudes) north of it. The values of rainfall and cloud amount, however, are different for the sub-regions over ocean and over land. **Table 1** shows the rainfall (bottom) and cloud amount (upper) values at the peaks. The peak rainfall varies from 11 mm over the East China sea to 21 mm over the main islands of Japan, while the peak cloud amount varies from 0.71 to 0.85 for the same subregions. Both the rainfall and cloud amount are greater while the Baiu front lies over the Japanese islands and less while over the surrounding ocean. The difference of rainfall peaks over the Japanese islands and their adjacent ocean is about 50%, while

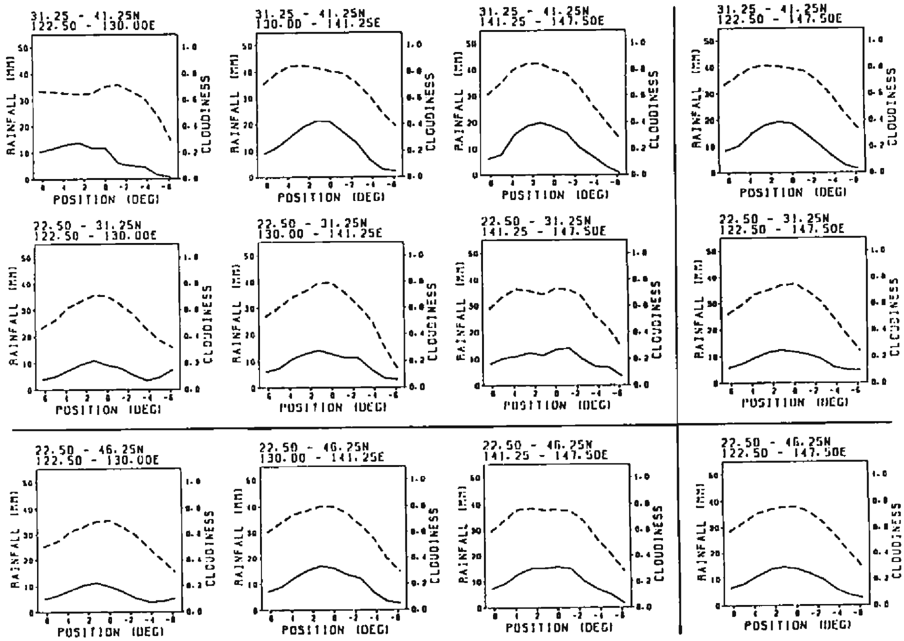

Fig. 5. Latitudinal distributions of daily rainfall (solid line) and daily-averaged cloud amount (dash line) relative to the position of surface front in the subregions. The results for the most northerly 3 subregions are not shown in the figure because no front moved into the range during the period. The surface front positions are read from the surface weather chart at 0900JST.

Table 1. Peak values of cloud amount and rainfall at Baiu front

Area	122.5–130.0 E	130.0–141.25 E	141.25–147.5 E	122.5–147.5 E
31.25–41.25 N	0.72 94%	0.85 111%	0.85 111%	0.81 107%
	13.9 95%	21.3 146%	19.8 137%	19.3 132%
22.50–31.25 N	0.71 93%	0.79 104%	0.73 96%	0.75 98%
	11.0 75%	14.0 96%	14.0 96%	12.3 84%
22.50–41.25 N	0.71 93%	0.80 105%	0.77 101%	0.76 100%
	11.1 76%	16.8 115%	14.9 102%	14.6 100%

Upper: cloud amount Bottom: rainfall in mm

The percentages in the table show the ratios of the cloud amount (rainfall) for the subregion to the mean for all subregions.

compared with that over the islands. These facts show that the frontal rainfall peak is at the position where the slanting frontal surface gains higher altitude to north of the surface front and also that the rainfall pattern is the same over the islands and ocean but the peak amount of rainfall is larger over the islands than over the ocean by about 50%.

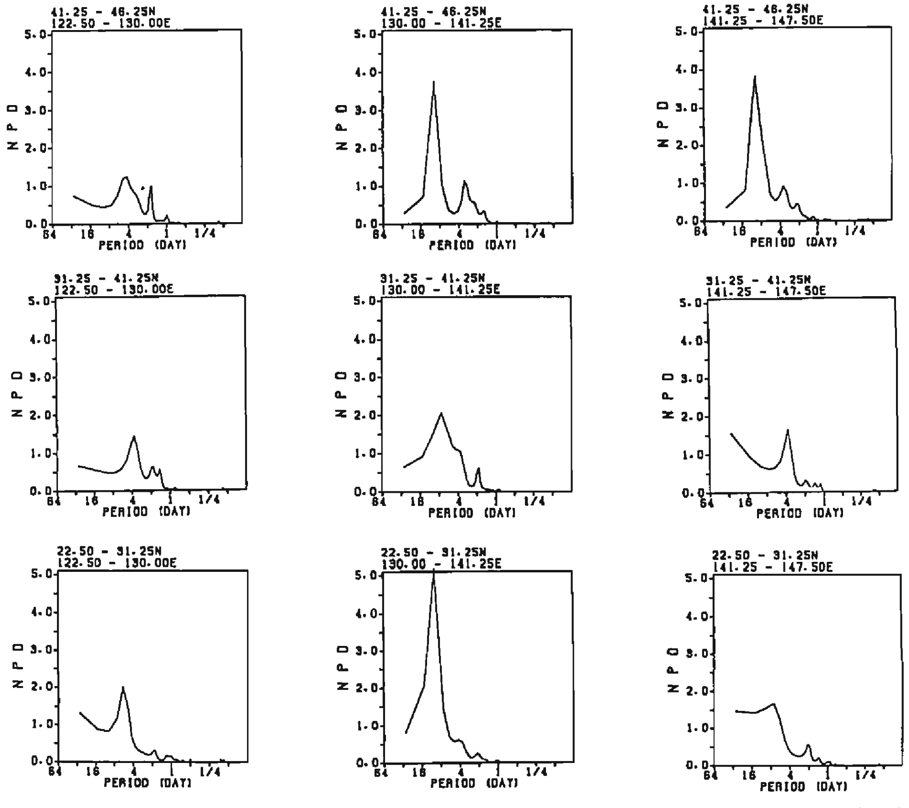

Fig. 6. Normalized spectral density (NSD) distributions of the time series of rainfall for the 9 subregions.

4. Temporal Change of Rainfall

Temporal changes of rainfall are also investigated for the various subregions as shown in **Fig. 4**. **Fig. 6** shows the power spectral density distributions of the area-averaged 3 hour rainfall for the subregions calculated by the Maximum Entropy Method (MEM)[21]. The data number of each time series is 240.

The spectra for the 9 subregions have well defined peaks at periods corresponding to the variations of synoptic scale (4–8 days) and their half periods. Another small peak is also seen at period of 1 day in the spectra of the subregion extending from 122.5°E–130.0°E; 41.25°N–46.25°N (Northeastern provinces of China). These facts suggest that the temporal changes of the area-averaged rainfall are dominated by the variations of synoptic scales for all of the 9 subregions, while that for the subregion over continental China has an addtional peak related to the daily variation. Peaks are also observed in periods of about 2–4 days. We can not, however, confirm if the peaks are resulted really from the time change or suspictions in spectral analysis, after investigating the time series of rainfall. The features of time change of rainfall revealed here are similar to the result for the spectra of high cloud amounts of the Baiu front investigated by Akiyama[10], which show obvious peaks in synoptic scale (about 5.86 days) over whole portions of the front and in daily scale only over the continent.

Fig. 7 shows the spectrum of the time series of the area averaged rainfall for the entire region to the east of 122.5°E. The spectra is also characterized by the peak at

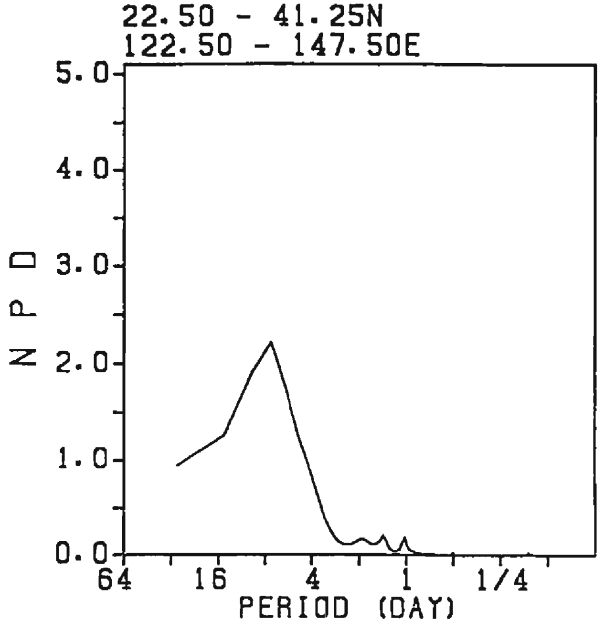

Fig. 7. Normalized spectral density (NSD) distribution of the time series of rainfall averaged over all of the 9 subregions.

periods of about 7 days (synoptic).

5. Movement of the rainfall along the Baiu front

Fig. 8 shows the results of space-time correlations of rainfall when the Baiu front lies over various sub-regions shown in **Fig. 4**. Five lines in each figure represent the correlations with lag times of −12, −6, 0, 6 and 12 hours, respectively. Almost all of the correlation lines have single mode shapes, with their maximums at distances proportional to the time lag, suggesting the eastward movement of the rainfall region along the Baiu front with constant speed. The peak values of the correlations for time lags of ±12 hours, however, are very low, which suggests that the rainfall pattern usally does not keeps its shape for longer period while moving eastward along the Baiu front. This fact agrees with the conclusions of Ninomiya and Akiyama[2)3)], in which they revealed that the rainfall of the Baiu front is directly caused from several meso scale cloud clusters, by using radar and gage observations.

Table 2 shows the phase speeds of the movement of the rainfall region for the 6 sub-regions which are determined from the correlations with time lag of ±6 hours. The phase speeds are 7.5°E per 12 hours over most of the subregions except the sub-regions

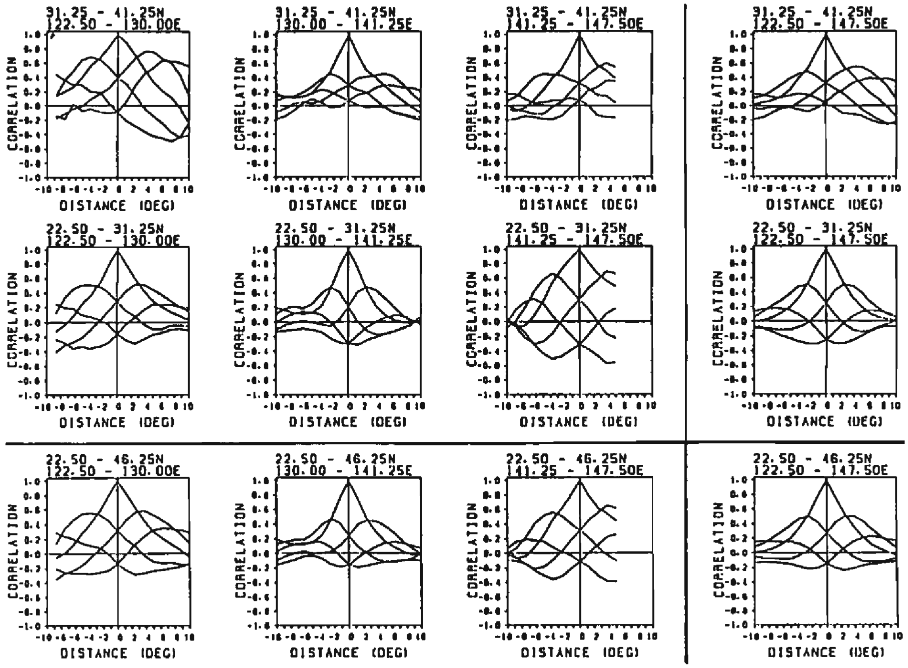

Fig. 8. Space-time lagged correlations of the rainfall for all of the subregions except the most northerly three. The 5 lines in each figure show the correlations with time lags of −12, −6, 0, 6 and 12 hours, respectively. The value in the abscissa represents the longitudinal distance to the east of the reference point.

Table 2. Phase speeds of the movement of rainfall region over various subregions

Area	122.5–130.0 E	130.0–141.25 E	141.25–147.5 E	122.5–147.5 E
31.25–41.25 N	7.5	7.5	7.5	7.5
22.50–31.25 N	7.5	5.0	7.5	6.25
22.50–41.25 N	7.5	5.0	7.5	6.25

unit: °E/12 hr

over ocean to the south of Japanese islands, over which the speed is slower (5.0°E per 12 hours). The phase speed averaged over all of the sub-regions is 6.25°E per 12 hours or about 55 km/hr. This speed is almost the same as the wind speed at 500 mb.

6. Conclusions

Rainfall features are investigated by using the satellite IR rainfall estimation data of June 1989 over an area of 27.5° longitudes × 23.75° latitudes surrounding Japan, with special attention on the spatial distribution, temporal change and the movement of the Baiu front.

The rainfall of the investigation period is mainly that of Baiu front, which moves slowly south and north. The accumulated monthly rainfall for the period has a band-like distribution, extending from (120°E, 30°N) to (145°E, 35°N) with a width of about 5° latitudes. The latitudinal profile of the rainfall averaged from 120°E to 147.5°E shows that the rainfall of the Baiu front is in an one-mode shape with its peak at 35°N. The longitudinal profile of rainfall shows that the rainfall of the Baiu front has almost the same values over longitudes east to Kyushu, but rainfall over the East China sea decreases to about 2/3 of that over Kyushu.

The latitudinal distribution of rainfall relative to the surface front also has an common one-mode shape, with its maximum at meshes 1.25° north to the surface front. Although the shapes for the distributions are almost the same for all regions over both land and ocean, the peak amount over land (main islands of Japan) is about 1.5 times larger than that over ocean (the East China sea).

The temporal change of the rainfall is characterized by a dominant period of the synoptic scale (about 7 days).

The phase speeds of the eastward movement of rainfall along the Baiu front show almost the same value of about 7.5° latitudes per 12 hours (about 55 km/hr) for all subregions except over the ocean to the south of Japanese islands where the speed is a little slower.

As summarized above, the estimation of rainfall obtained from the IR imagery data of GMS has revealed some important aspects of the rainfall of the Baiu front, although it still has some deficiencies in accurancy and resolution. Further efforts toward improvement and extension of such a satellite-based rainfall estimation method are needed to supply more reliable data on global scale.

Acknowledgements

The author would like to thank Prof. Y. Mitsuta of the Disaster Prevention Research Institute (DPRI) of Kyoto University for his continous guidance and encouragement during the study. The author is also grateful to Dr. P. A. Arkin and Dr. J. E. Janowiak of MMC/NOAA, for supplying the satellite and ground data of AIP/1. Discussions with Prof. M. Yamada and other members in the Severe Storm Division of DPRI were very helpful. The computations were performed by FACOM M-730 computer at the Information Processing Center of DPRI.

References

1) Yoshino, M. M.: Four stages of rainy season in early summer over east Asia, Part 2. J. Met. Soc. Japan., Vol. 44, 1966, pp. 209–217.
2) Ninomiya, K. and T. Akiyama: Medium-scale echo clusters in the Baiu front as revealed by multi-radar composite echo maps, (Part 1). J. Met. Soc. Japan, Vol. 50, 1972, pp. 558–569.
3) Ninomiya, K. and T. Akiyama: Medium-scale echo clusters in the Baiu front as revealed by multi-radar composite echo maps, (part 2). J. Met. Soc. Japan, Vol. 51, 1973, pp. 108–118.
4) Akiyama, T.: The large-scale aspects of the characteristic features of the Baiu front. Pap. Met. Geophy., Vol. 24, 1973, pp. 157–188.
5) Akiyama, T.: Mesoscale pulsation of convective rain in medium-scale disturbance developed in Baiu front. J. Met. Soc. Japan, Vol. 56, 1978, pp. 267–283.
6) Ninomiya, K. and H. Muraki: Large-scale circulations over East Asia during Baiu period of 1979. J. Met. Soc. Japan, Vol. 64, 1986, pp. 409–429.
7) Ninomiya, K. and H. Mizuno: Variations of Baiu precipitation over Japan in 1951–1980 and large-scale characteristics of wet and dry Baiu. J. Met. Soc. Japan, Vol. 67, 1989, pp. 639–658.
8) Akiyama, T.: Large, synoptic and meso scale variations of the Baiu front, during July 1982. Part 1: Cloud features. J. Met. Soc. Japan, Vol. 67, 1989, pp. 57–81.
9) Akiyama, T.: Large, synoptic and meso scale variations of the Baiu front, during July 1982. Part 2: Frontal structure and disturbances. J. Met. Soc. Japan, Vol. 68, 1990, pp. 557–574.
10) Akiyama, T.: Large, synoptic and meso scale variations of the Baiu front, during July 1982. Part 3: Space-time scale and structure of frontal disturbances. J. Met. Soc. Japan, Vol. 68, 1990, pp. 705–727.
11) Arkin, P. A.: The relationship between fractional coverage of high cloud and rainfall accumulations during GATE over the B-scale array. Mon. Wea. Rev., Vol. 107, 1979, pp. 1382–1387.
12) Arkin, P. A. and B. N. Meisner: The relationship between large-scale convective rainfall and cloud cover over the western hemisphere during 1982–84. Mon. Wea. Rev., Vol. 115, 1987, pp. 51–74.
13) Shin, K-S., G. R. North, Y-S. Ahn and P. A. Arkin: Time scales and temporal variability of tropical oceanic rainfall. Mon. Wea. Rev., Vol. 118, 1990, pp. 1507–1516.
14) Janowiak, J. E. and P. A. Arkin: Rainfall variations in the tropics during 1986–1989. J. Geophys. Res., Vol. 96, 1991, pp. 3359–3373.
15) Wylie, D. P.: An application of a geostationary satellite rain estimation technique to an extratropical area. J. Appl. Meteor., Vol. 18, 1979, pp. 1640–1648.
16) Xie, P. and Y. Mitsuta: Rainfall estimation from GMS infrared and visible imagery data. Annuals. Disas. Prev. Res. Inst., Kyoto Univ., Vol. 31B-1, 1988, pp. 201–217. (in Japanese)
17) Xie, P.: Nephanalysis of the GMS imagery data. Bull. Disas. Prev. Res. Inst., Kyoto Univ., Vol. 40, 1990, pp. 57–77.
18) Xie, P.: Rainfall estimation in the midlatitudes from GMS infrared imagery data. Bull. Disas. Prev. Res. Inst., Kyoto Univ., Vol. 41, 1991, pp. 109–120.
19) Xie, P.: Estimation of rainfall on the Japanese islands and their adjacent ocean from satellite (GMS) infrared imgery. Bull. Disas. Prev. Res. Inst., Kyoto Univ., Vol. 42, 1992, pp. 1–18.

20) Browning, K. A.: Rain, rainclouds and climate. Q. J. R. Meteorol. Soc., Vol. 116, 1990, pp. 1025–1051.
21) Hino, M.: Spectral Analysis. Asakura, 1977, pp. 300. (in Japanese)