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Rainfall Estimation in the Midlatitudes from GMS Infrared Imagery Data

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Abstract

A new method is proposed for estimation of rainfall in mid-latitudinal areas from GMS infrared imagery data. This method was developed by using the satellite and gage data in 5 areas of about $10^4\,km^2$ in Japan, taking account of the different features of rainfall from various types of clouds. In this method, clouds are classified into six types, S(Clear Sky), F(Fine), A(Cumulus), B(Cumulonimbus), C(Middle Clouds) and D(High Clouds), by using the discriminate analysis technique from IR imagery data. The cloud types S, F and D are assumed to be no-rain cases and in the cases of A, B and C, rainfall is assumed to be proportional to the cold cloud fractional coverage (FC). A proportional constant for each cloud type is determined from the regression equation between FC and 3-hr rainfall, where the threshold T_{BB} used to define FC is determined to give the highest correlation for each cloud type. This method gives a good rainfall estimation for 24 hr cumulative rainfall with the correlation coefficient of 0.651 and relative root mean square error (RRE) of 0.968. To apply this method to the Hokkaido area, the results should be adjusted by an empirically determined factor, because weather conditions are different in this area.

1. Introduction

Investigation of the spatial distribution and time change of global rainfall is a fundamental requirement in understanding global weather systems. However, the present rainfall observation network consisting of radars and gages does not cover the oceanic area and upcountry (Browning[1]). The recent development of the meteorological satellite has enabled us to observe rainfall from space, and many methods have been proposed to estimate rainfall from infrared (IR) and visible (VIS) imagery data of meteorological satellites (*e. g.* Martin and Scherer,[2] Barrett and Martin,[3] Tsuchiya[4] and Arkin and Ardanuy[5]). Besides these methods, passive microwave radiometer and active radar observation of rainfall from satellite are also under development (Simpson *et al.*[6]). However, observation from the geosychronous satellite is the best in terms of spatial and time resolution of the global distribution of rainfall, although it has the limitation of being an indirect method.

Among the rainfall estimation techniques using geosynchronous satellite data which have been developed so far, the "life cycle" methods and the "cloud coverage" methods are typical and are considered to be relatively successful. The life cycle method, as developed by the group of Griffith and Woodley (Griffith *et al.*[7], Woodley *et al.*[8], Augustine *et al.*[9], and Griffith[10]) estimates rainfall volume for individual clouds under the assumptions that: a) rainfall falls from cold clouds; b) rainfall is proportional to cloud area and c) the constant of proportionality is related to the life cycle stage of the clouds. Rainfall was then calculated from the cloud area colder than a threshold (253K in Griffith and Woodley's method) and life cycle stage parameters derived from the time series of the cloud images. In this method clouds must be tracked throughout their lifetimes on satellite images, and thus relatively complex procedures and long CPU time are required. However, testing the method of Griffith and Woodley with the same data, Negri *et al.*[11] found that the estimated rainfall is highly correlated with the cloud area but not so well with the parameters related to the life cycle stage, and they concluded that comparatively good estimation can be made using only appropriately defined cloud areas.

The cloud coverage method, as developed by the group of Arkin *et al.* (Arkin[12], Richards and Arkin[13], Arkin and Meisner[14], Meisner and Arkin[15] and Arkin *et al.*[16]) estimated rainfall for climatic scales ($\geq 10^4$ km^2 in space and ≥ 5 days in time) from cloud coverage colder than a threshold (235k in Arkin's method) under the assumption that the cloud life cycle effect is diminished by averaging the states in both space and time. Rainfall was then estimated from cold cloud coverage by using an empirically established linear relation between them, where the threshold temperature was determined by empirical methods.

Most of the methods described above have been developed for estimating rainfall in tropical areas, where rainfall is associated mainly with convective clouds. In mid-latitudinal areas near Japan, however, it becomes more difficult to estimate rainfall from satellite data, because precipitation from stratiform clouds and nonprecipitating cirrus clouds often appear. Wylie[17], Griffith *et al.*[18] and Arkin and Meisner[14] tried to apply the methods developed for tropical areas to estimate mid-latitudinal rainfall, and obtained reasonable success in estimating convective rainfall. However, to estimate total rainfall in mid-latitudes, it is necessary to consider various types of clouds.

Xie and Mitsuta[19] tried to distinguish cirrus that does not cause rain from other clouds by joint use of GMS (Geostationary Meteorological satellite of Japan) IR and VIS imagery data and to estimate hourly rainfall for the noncirrus cases by using a linear regressional equation between rainfall and cold/bright cloud coverage. Relatively good correlation ($r=0.76$) was obtained between the estimated rainfall and gage-observed rainfall. However, this method can not be applied at night, which prevents long range cumulative rainfall estimation in this method. Recently, Xie[20] developed a method for classifying six cloud types from GMS IR imagery data by using a discriminate analysis technique, which can be used for rainfall estimation.

In the present paper, a method applicable for both day- and night-time has been developed to estimate rainfall in mid-latitudinal areas of about 10^4 km^2 by using cold cloud fractional coverage and the cloud type classified by the method of Xie[20], and some examples of its application are shown.

2. Satellite and Gage Data

The same satellite data sets as those used in Xie[20] and gage rainfall data for the same periods are employed to develop the rainfall estimation method. These data sets are for the six testing areas of about 10^4 km^2, Hokkaido, Kanto, Kinki, Setonaikai, Sanin and Kyushu, located in plain areas in Japan (see **Fig.1** of Xie[20]). Rather large testing areas have been chosen, because Richards and Arkin[13] and Negri and Adler[21][22] have shown that good rainfall estimations in the tropics can be made from satellite **IR** data only for areas with spatial scales larger than 1.0° latitude.

The data sets consist of **GMS IR** digital data and gage–observed rainfall data for 18 days: September 3–11, 1980; July 23 and August 1–3, 1982; July 22–23 and August 7–9, 1983. The precipitation at those times was mainly due to typhoons, fronts and extratropical cyclones, respectively, and the area averaged hourly rainfall for the six areas are 0.4, 1.3, 2.7, 1.4, 1.7 and 2.0mm, respectively. Only 105 **GMS IR** images are available for these days since **GMS** observation was performed only at intervals of 3 hours in those days.

For tropical areas, Arkin[12] made use of the fractional coverage (**FC**) of cloud pixels colder than a threshold temperature from **IR** imagery for rainfall estimation. Later, Adler and Mack[23], Adler and Negri[24] and Goldenberg *et al.*[25] made use of several parameters such as minimum value and standard deviation of T_{BB} (Blackbody Temperature) for the tropical half hourly rain estimation for an area of 10^4 km^2, and obtained a

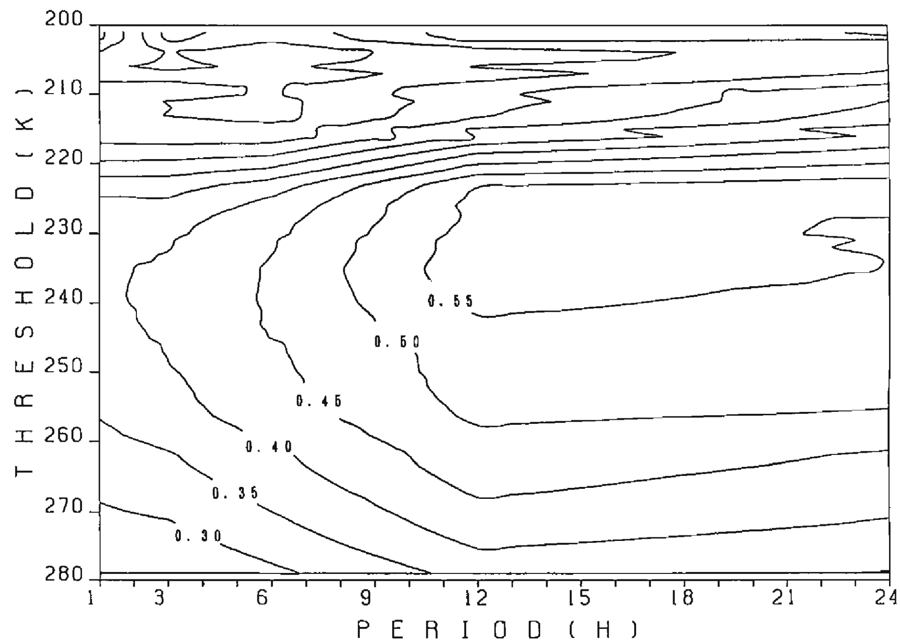

Fig. 1. The correlation coefficients between gage observed rainfall and **IR** cold cloud fractional coverage (**FC**) on various temperatures over time scale from 1 to 24 hr.

Table 1. Cloud type definition

SIGN	CLOUD TYPE	DEFINITION
S	Clear Sky	$CA^{*} < 0.3$
F	Fine	$0.3 \leqq CA < 0.7$
A	Cumulus	$CA \geqq 0.7$; Significant Cumulus
B	Cumulonimbus	$CA \geqq 0.7$; Significant Cumulonimbus
C	Middle Clouds	$CA \geqq 0.7$; Significant Middle Clouds
D	High Clouds	$CA \geqq 0.7$; Significant High Clouds

* : Total cloud amount estimated from **GMS** infrared data by **TTM** (Two Threshold Method) as described in Xie[20].

root mean square difference of 0.39 mm from the gage–adjusted radar observation, which was only a little improvement compared to that obtained by Arkin's method (0.48) by using the same data. Also, for mid–latitudinal areas, Xie and Mitsuta[19] showed that the **FC** is useful for estimation of daytime rainfall by joint use of **IR** and **VIS** data. In the present paper, **FC** obtained only from T_{BB} histogram of **IR** data, together with the cloud type classification method developed by Xie[20], are used to estimate rainfall in the mid–latitudes.

For this reason, at first, the **IR** imagery data of the six testing areas were extracted from the original full disc **GMS VISSR** observation data, and then the T_{BB} histograms were constructed with an interval of 1K, from 200K–280K, referring the T_{BB} calibration tables. The total number of pixels for each area varies with an average of about 550.

Cloud type information is also used to discriminate the rain case and no–rain case and to estimate the rainfall caused by convective and stratiform clouds. Six types of clouds (see **Table 1** for definitions) are classified in two steps from **GMS IR** imagery data, as described in Xie [19] in detail, namely :

1) Estimate total cloud amount **CA** from **GMS** T_{BB} histograms by **TTM**(Two Threshold Method) which takes account of the ground–related spectral peak and of the partially cloud covered pixels. Define the cases with **CA** smaller than 0.3 and between 0.3 and 0.7 as Type **S**(Clear Sky) and **F**(Fine), respectively.

2) Classify clouds into four types (**A**: cumulus, **B**: cumulonimbus, **C**: middle clouds and **D**: high clouds) from the selected 4 **IR** parameters for the cloudy cases with **CA** equal to or larger than 0.7 by using the discriminate analysis technique as described by Okuno *et al.*[26] The six cloud types have been chosen to reflect the rainfall–cloud relationship in mid–latitudinal areas.

Hourly rainfall observed by **AMeDAS** (Automated Meteorological Data Acquisition System) is used as the ground truth of the rainfall. The gage distribution density of the system is about 27 km^2/gage. Although spatial variation of rainfall can be very large, the simple arithmetical average of the hourly rainfall observed by all gages located in each area is taken as the ground truth of the hourly rainfall of the area, because the gage numbers in the six testing areas (vary from 18 to 44, with an average of 25 over about 10^4 km^2) are sufficiently large and their distribution is relatively uniform. The sum of the hourly rainfalls of HH, HH+1 and HH+2 o'clocks is used as the gage observation corresponding to the 3 hourly **GMS IR** observation of **HH** o'clock which scans the area near Japan on about 20 min ahead of **HH**.

The satellite and gage data described above are then used to investigate the relationship between rainfall and cold cloud fractional coverage (**FC**) for various types of clouds and to establish the rainfall estimation method for mid-latitudes.

3. Rainfall Estimation Method

The selection of testing areas with similar meteorological conditions is very important for developing a good empirical estimation method. A preliminary study showed that the ratios do not vary much for the testing areas except for the Hokkaido area where rainfall is much less than in the other 5 areas. For this reason, at first, the rainfall estimation method was developed by using the data of the 5 similar areas, and then the method was adjusted to estimate the rainfall for the Hokkaido area.

The correlation coefficient and relative root mean square error were used to evaluate the correspondence between gage-observed and **IR**-estimated rainfall. The correlation coefficient and the relative root mean square error (Hereafter referred to as **RRE**; see caption in **Table 3** for definition.) were used to evaluate the similarity in temporal variability and the difference in value between the **IR** estimates and gage observations, respectively.

The possibility of applying a simple linear estimation method without regard to cloud type, such as that of Arkin, to mid-latitudinal areas, was first checked by calculating the correlations between the area-averaged rainfalls and cold cloud fractional coverages (**FC**) disregarding cloud type, for 1, 3, 6, 12 and 24 hr averages. **Fig. 1** shows the contours of the resulting correlation coefficients between rainfall and **FC** for various time scales and temperature thresholds. The correlation increased with the time scales less than 12 hr, with its maximum at the temperature threshold of 230-240k. The correlation is 0.418 for the time scale of 3 hr and 0.561 for 12 hr at the threshold of 240k. The highest correlation appears at almost the same temperatures as those in tropical areas (235K in Arkin[12], Richards and Arkin[13]). However, the poor correlation coefficients obtained indicate that it is difficult to use a simple linear relationship between rainfall and **FC** without regard to cloud type in estimatig rainfall in the mid-latitudes.

This poor correlation is considered to be caused mainly by inclusion of non-precipitating cold cirrus clouds and from disregard of different precipitating mechanisms between convective and stratiform clouds. Cloud type classified by the method of Xie[20] was thus introduced to improve the accuracy of **IR** rainfall estimation. **Fig. 2a-f** shows the scattering between 3 hr rainfall and FC at a threshold of 240k for cloud type **S**, **F**, **A**, **B**, **C** and **D**, respectively. Among the total of 72, 71 and 74 cases of cloud types of **S**, **F** and **D**, 65, 65 and 60 cases respectively show no-rain (<1.0mm). Although no significant linear distributions could be found for the cases of cloud type **A**, **B** and **C**, their scattering concentrated mainly in the right-bottom of the figtures and made it appear that cases with larger **FC** have more rainfall on the average, suggesting a rough linear relationship between the rainfall and FC.

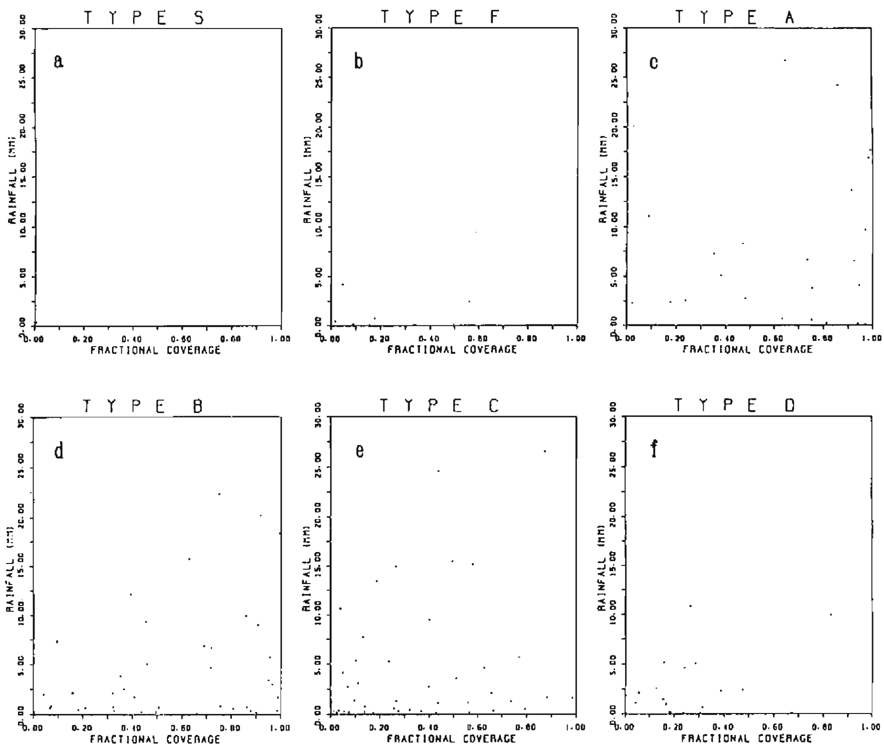

Fig. 2. The scattering of 3 hourly rainfall and IR fractional coverage (**FC**) at temperature threshold 240 k for the cases with cloud type a) **S**(clear sky), b) **F**(fine), c) **A** (cumulus), d) **B**(cumulonimbus), e) **C**(middle clouds) and f) **D**(high clouds), respectively.

Based upon these results, it was decided to discriminate cloud type by **IR** parameters and to estimate rainfall for the mid-latitudes as follows:

1) Discriminate the cases with cloud type of **S**(Clear Sky), **F**(Fine) and **D**(High Clouds) as no-rain cases, and other cloud types (**A**, **B** and **C**) as rain cases.

2) Estimate 3 hr rainfall for the cases with cloud type **A**(Cumulus), **B**(Cumulonimbus) and **C**(Middle Clouds) by using the linear regressional equations between 3 hr rainfall and **FC** defined by the optimal threshold for each type of raining clouds. The correlation coefficients between rainfall and **FC** at various temperature thresholds are calculated and those with the highest correlation coefficients are selected as the optimal thresholds, for the 3 types of raining clouds, respectively.

Table 2 shows the optimal thresholds and regressional equations for the 3 raining types for all 5 testing areas. Computation of respective relation for each area is difficult because of a lack of data. The optimal thresholds are 245K, 235K and 255K for type **A**, **B** and **C**, respectively. While type **B**(Cumulonimbus) has the coldest threshold and the largest proportional constant (8.460), type **C**(Middle Clouds) has the warmest and the smallest values (3.713). These differences in the thresholds and constants are characteristic if one considers the respective cloud features.

Table 2. Optimal thresholds and regression equations

TYPE	THRESHOLD	REGRESSION EQUATION
A	245 K	$E_3 = 7.582 \cdot FC$
B	235 K	$E_3 = 8.460 \cdot FC$
C	255 K	$E_3 = 3.713 \cdot FC$

E_3 : 3 hr rainfall estimation

Table 3. The comparison between the **IR** estimation and gage observation*)

PERIOD	KANTO	KINKI	SETONAI	SANIN	KYUSHU	5 AREAS
3 HR	0.495	0.588	0.471	0.324	0.410	0.428
	2.349	1.783	2.223	2.506	2.615	2.291
6 HR	0.537	0.651	0.526	0.391	0.592	0.516
	2.103	1.545	1.916	2.144	2.070	1.951
12HR	0.688	0.781	0.650	0.662	0.826	0.677
	1.550	1.305	1.295	1.252	1.216	1.364
24 HR	0.524	0.821	0.693	0.791	0.822	0.651
	1.487	0.848	0.938	0.765	0.853	0.968

*) The statictics on the top and bottom are correlation coefficients and **RRE** (Relative Root Mean Square Error) between the **IR** estimated and gage observed rainfall, respectively. **RRE** is defined as follows:

$$RRE = \frac{[\Sigma(R_i - E_i)^2/N]^{1/2}}{\Sigma R_i/N}$$

where R_i, E_i are the gage observation and **IR** estimation respectively, **N** is the data number.

In order to evaluate the present method for estimating rainfall for various time scales, **IR** estimations and gage observations were accumulated and compared at 6, 12 and 24 hr. **Table 3** shows the results of correlations and **RRE**(Relative **RMS** Error) between the **IR** estimations and gage–observed rainfalls. No obvious differences can be seen among the results for the 5 testing areas. Correspondence is higher for longer time scales until 12 hr (4 images). The correlation and RRE for 24 hr estimation are 0.651 and 0.968 respectively for all the 5 testing areas. These values show improvement over the estimation which disregarded cloud type for all time scales, *e. g.* r increased from 0.561 to 0.651 for 24 hr.

Fig. 3 shows the time series of the estimations and rainfalls plotted in intervals of a) 3 hr, b) 6 hr, c) 12 hr and d) 24 hr for the Sanin area. Although the estimation fails to reflect some significant rainfall peaks caused by heavy rain, the agreement is relatively good in both variation pattern and absolute value in a time series accumulated for a long time *e. g.* for 24 hr series. **Fig. 4** shows the scattering of the **IR** estimation and rainfall for 24 hr accumulations for all of the 5 testing areas. Most of the points are distributed near the diagonal line except for one case of heavy rain in the upperleft corner, which indicates that the present method can estimate 24 hr rainfall with relatively good

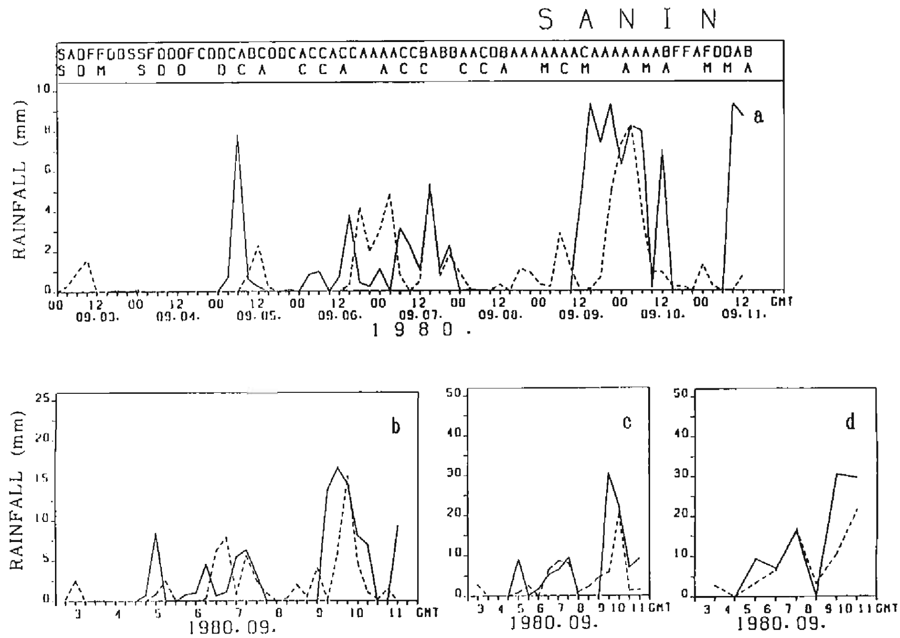

Fig. 3. Time series of the gage-observed rainfall (dashed line) and **IR** estimation (thin line), with intervals of a) 3 hr, b) 6 hr, c) 12 hr and d) 24 hr, for the Sanin area for the period from 3 to 11 Sept. 1980. The cloud types derived from surface observation and **IR** data as described in Xie[20] are also listed in the lower and upper lines above a). **S**, **F**, **A**, **B**, **C** and **D** denote Clear Sky, Fine, Type **A**, **B**, **C** and **D**, respectively. M includes Mixed **A**, **B**, **C** and **D**.

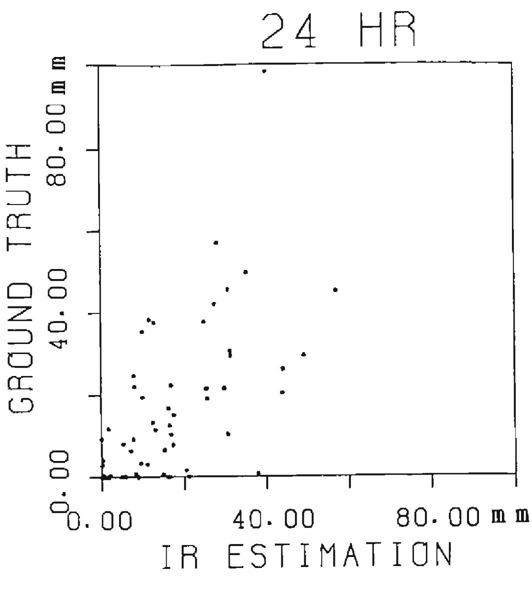

Fig. 4. Scatter plot of the gage-observed rainfall and **IR estimation for 24 hr for all the 5 areas.**

accuracy except for rain storms.

The possibility of improving the estimate by applying higher and fractional exponential equations, as well as by including other parameters such as cloud top temperature and time change of **FC** into the rainfall-cloud relationship were also investigated, but no significantly improved results were obtained when compared to those obtained by using linear relations as described above.

4. Adjustment for the Hokkaido Area

When an empirically-based estimation method developed for one area is applied to other areas with different weather conditions, adjustment is necessary to take into account many factors such as the environmental field or instabilities. Although attempts (Wylie[17], Alder and Mack[23]) have been made to account for these factors by using a cumulus model, it seems difficult to apply the model to an estimation area where sonde observation is rarely available. For this purpose, a simple method was tried to adjust the present method for estimating rainfall for the Hokkaido area by using the ratio of gage observation data. This adjustment method is expected to be applicable for the rainfall estimation in those marine and remote areas where at least sparse gage observation is available so that the adjustment factor for the surrounding areas can be calculated.

Fig. 5 and **Table 4** show the time series and the statistics for the comparison between the gage observed rainfall and the **IR** estimation derived by the same method for the Hokkaido area as was done in the other 5 areas. The **IR** estimation was much too high (**RRE** = 5.065 for 24 hr), inspite of the relatively high correlation to the gage rainfall (r=0.780 for 24 hr). These facts suggested that the estimation could be improved by multiplying by an adjustment factor $\mathbf{F}(\mathbf{F}<1)$.

In order to correct the overestimation, the adjustment factor **F** was then taken to be the ratio of the total rainfall of Hokkaido to those of the other 5 areas in the testing period, namely :

$$\mathbf{F}=\frac{\mathbf{R}_{HK}}{\mathbf{R}_5}$$

where, $\mathbf{R}_{HK}$ is the total rainfall in depth for the Hokkaido area, and $\mathbf{R}_5$ is the average of the total rainfall in depth for the other 5 areas used to develop the present method in the same period. The calculated value is 0.19, which indicates that only about 1/5 rainfall falls from the same cloud coverage in Hokkaido compared to the other 5 areas.

The adjustment of the rainfall estimation for Hokkaido is then made by multiplying the estimation made by the same method as for the other 5 areas by **F**(0.19). **Fig. 5** and **Table 4** show the resulting time series and the statistics of the comparison with the concurrent gage rainfall. The significant decrease of **RRE**(from 5.065 to 0.937 for 24 hr) shows the improvement achieved by the present adjustment.

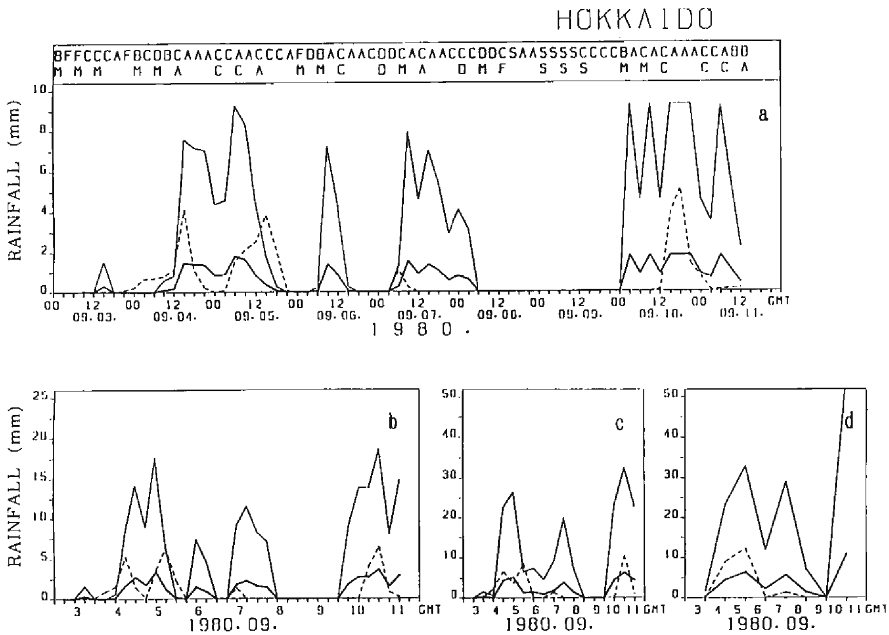

Fig. 5. As in Fig. 3, except for the gage observed rainfall (dashed line), unadjusted (thin line) and adjusted (thick line) IR estimation for the Hokkaido area.

Table 4 The comparison between the IR estimation and gage observation for Hokkaido area

PERIOD	UNADJUSTED	ADJUSTED
3 HR	0.456	
	8.478	2.294
6 HR	0.521	
	7.407	1.860
12 HR	0.565	
	7.213	1.591
24 HR	0.780	
	5.065	0.937

5. Conclusions

A new method has been developed to estimate the rainfall for midlatitudinal areas of about 10^4 km^2, by using the **IR** histograms and **IR** derived cloud types of the 5 areas in Japan with similar meteorological conditions with the concurrent gage rainfall data observed by **AMeDAS** as ground truth.

In order to take account of the difference of precipitating mechanisms of different types of clouds in mid-latitudinal areas, the cloud type is discriminated from **IR** parameters into S(Clear Sky), F(Fine), A(Cumulus), B(Cumulonimbus), C(Middle Clouds) and D(High Clouds). Then the cases with cloud type of **S**, **F** and **D** are assumed to be no-rain cases, and estimation of the rainfall for the rest of cases is made by using the linear regressional equations between 3 hr rainfall and **FC** defined by the optimal temperature thresholds for each cloud type. The present rainfall estimation method is found to give a fairly good estimation. The 24 hr estimation shows correlation of 0.651 and **RRE** of 0.968 with the concurrent gage observation. The method is also applied to estimate the rainfall for the Hokkaido area where the weather conditions are different from the other 5 areas. While direct application resulted in a significant overestimation, the estimation was improved greatly by multiplying an adjustment factor **F** defined as the ratio of Hokkaido's rainfall to the total rainfall of the 5 other areas.

Although the present method was developed by using limited data (18 days), the relatively high correlation and small bias between the IR estimation and the gage observation suggest that it has promise for the estimation of rainfall for climatic studies. In order to validate the present method, tests are now underway by using independent data sets for various seasons and regions. Following that, the present rainfall estimation method, together with the cloud amount estimation and cloud type classification methods described in Xie[20], will be used to derive and study the spatial and temporal distribution of cloud amount, cloud type and rainfall over the oceanic areas near Japan.

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