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Application of a Method to Estimate Rainfall in Bangladesh Using GMS-5 Data

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ABSTRACT

Japanese Geostationary Meteorological Satellite 5 (GMS-5) data were used to estimate rainfall in Bangladesh over a period of 61 days from June 1, 1996. The 3-hourly digital data over 33 ground-truth stations throughout Bangladesh obtained from GMS-5 were analyzed. Satellite rainfall was estimated by the Convective Stratiform Technique (CST) algorithm. The amount of rainfall calculated by the CST was compared with that calculated from the ground-truth data. That calculated by the CST was 1.1 times larger than that of the ground-truth rainfall. The average daily rainfalls were 15 mm as calculated from satellite and 14.3 mm from the ground-truth data. The correlation between the satellite and the ground-truth rainfall was significant at coastal stations but not at inland ones. Satellite and ground-truth data were used to derive a linear regression equation for estimating the amount of surface rain from satellite data. Data from stations throughout the country that showed good correlations gave a slope term of 0.84 and intercept constant of – 0.1 in the regression equation.

1. INTRODUCTION

Remote sensing data are now widely used for different purposes, and the use of satellite data for rainfall prediction has increased markedly. Many attempts to estimate rainfall from satellite data have been made (Arkin and Meissner, 1987; Adler and Negri, 1988; Arkin, 1989; Carn et al., 1989; Goldenberg et al., 1990; Kikuchi and Uyeda, 1996; Jobard et al., 1996; Islam et al., 1998), but there is still no standard method for making such estimates. The estimation of rainfall for large coverage is essential, especially for a country like Bangladesh, which is affected by flooding almost every year. Floods are one type of natural disaster and can not be entirely avoided, but damage and losses may be decreased if we can predict flooding. For the proper prediction of floodwater in Bangladesh the estimated precipitation for large coverage is required because of the huge expanse of the Ganges-Brahmaputra-Meghna (GBM) basin in the north and northwest of Bangladesh. Rainfall in the GBM basin is the main source of floodwater in Bangladesh. Although very important, few detailed studies of estimated rainfall in Bangladesh have been based on satellite data. There has been an attempt to estimate the rainfall in Bangladesh from satellite data in a joint research project carried out by Japan International Corporation Agency (JICA) and Bangladesh University of Engineering & Technology (BUET). As a result, a Geostationary Meteorological Satellite 5 (GMS-5) receiving station was installed at the Institute of Water and Flood Management (IWFM), BUET in 1996. Using GMS-5 data, Wahid and Islam (1999) calculated the amount of rainfall by the Gross Precipitation Index (GPI) technique. They calibrated the GPI value with the raingauge rainfall recorded for Sylhet district of Bangladesh and suggested further study. Because much of the precipitation in both the mid-latitudes and tropics emanates from meso-scale convective systems (Houze and Betts, 1981), it is necessary to distinguish between the convective and stratiform components of these cloud systems as the physics and dynamics of air motion and precipitation growth in the convective and stratiform regions differ fundamentally (Goldenberg et al., 1990). The GPI method can not differentiate the convective and stratiform regions of clouds, therefore it gives the average instead of the componential actual rainfall.

The amount of the componential rainfall from the convective and stratiform cloud components also must be determined (Liu et al., 1995; Islam et al., 1999). The Convective and Stratiform Technique (CST) was used by Adler and Negri (1988) in the Florida Area Cumulus Experiment (FACE); by Goldenberg et al. (1990) in Winter Monsoon Experiment (WMONEX); as well as by Kikuchi and Uyeda (1996) and Islam et al. (1998) in Tropical Ocean Global Atmosphere (TOGA) – Coupled Ocean Atmosphere Response Experiment (COARE) convections. To apply the CST algorithm to Bangladesh, certain modifications are needed in calculating the slope parameter, determining the stratiform threshold temperature, and assigning convective and stratiform rain rates. The purpose of our study was to apply the CST to Bangladesh in order to calculate its rainfall from GMS-5 data. We also have quantified the amount of surface rain using both ground-truth and CST-calculated rainfall data. Once the real-time rainfall for a large coverage is calculated a prediction model can be developed that estimates the lead-time rainfall. This is very essential for a flood-affected country.

KEY WORDS: Rainfall; Floodwater, Convective; Stratiform; Satellite.

2. DATA USED

TGround-truth and satellite data for a 61 days period starting June 1, 1996 were used. The 3-hourly rainfall data collected from the 33 raingauges of the Bangladesh Meteorological Department were as the ground-truth data used. These manual type raingauges are located in different parts of the country (Fig. 1). Six types of images are sent by the GMS-5. Eight-bit data of the GMS-IR were collected at IWFM, BUET, Bangladesh. These infrared images have 800 pixels in the horizontal direction and 800 lines in the vertical one. A partial image, extending from 88° to 93° E and from 20° to 27° N and covering Bangladesh was constructed from the GMS image. As the satellite is located at 140° E on the equator, the images received by it are deformed because they differ from the actual location. A geometrical correction was used to eliminate this problem (Chowdhury et al., 1997).

3. ANALYSIS METHODS

Raingauge rainfall is compared with that calculated from satellite data. Satellite rainfall was calculated for a 50 km mesh grid box centered on the position of a raingauge. Calculation procedure of rainfall from satellite data is discussed below.

3.1. Convective stratiform technique (CST)

The technique proposed by Adler and Negri (1988) uses satellite IR data to distinguish between convective and stratiform components of a meso-scale convective cloud system. They tested the algorithm called the Convective Stratiform Technique (CST) on data from the Geosynchronious Operational Environmental Satellite (GOES) IR channel obtained over four days during the second Florida Area Cumulus Experiment (FACE). The CST algorithm was modified by Goldenberg et al. (1990) in order to analyze the horizontal precipitation structure of a cloud cluster observed off the northern coast of Borneo during the Winter Monsoon Experiment (WMONEX). They used the IR T_{BB} of the GMS-1 to analyze the entire lifetime of the cluster. These two successful analyses made with the CST encouraged its use in the TOGA-COARE domain. It also should be noted that Kikuchi and Uyeda (1996) analyzed three cases by the modified CST (Goldenberg et al., 1990) during the TOGA-COARE Intensive Observation Period (IOP). They tested the CST algorithm on data from the GMS-4 and compared the results with those of Doppler radar data collected on Manus Island. There was a discrepancy between the rainfall amounts as determined by the CST and radar, but the convective and stratiform rainfall percentages determined by the CST for case 2 of Kikuchi and Uyeda (1996) were good enough to compare with other research results. Islam et al. (1998) applied the CST to the TOGA-COARE domain and analyzed the horizontal precipitation structure (area and rainfall amounts) of cloud clusters based on GMS-4 IR data for the Intensive Flux Array (IFA) region over the western Pacific warm pool. They strongly recommended adapting the CST for a particular region. Islam et al. (1999) modified the CST algorithm for the TOGA-COARE domain and used GMS-4 data to estimate the convective and stratiform rainfall from satellite data. The steps of the CST algorithm are as follows:

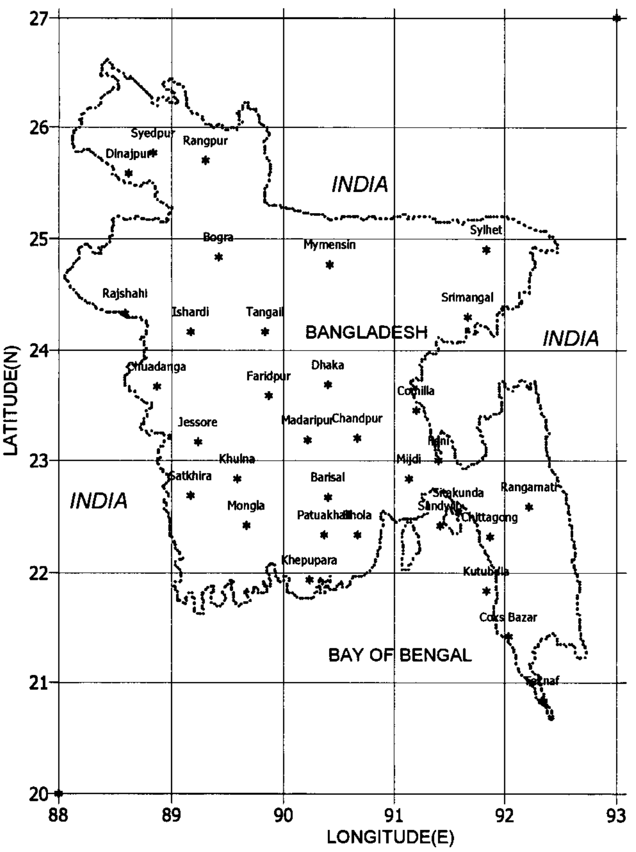

Fig. 1 Raingauge stations in Bangladesh.

a) Identification of convective cores and their locations on GMS-IR imagery

To identify the locations of convective cores in each satellite image, the IR T_{BB} field is examined for relative minima (T_{min}). It may be a single pixel minima or the centroid of a multi-pixel minima in a square 50 km×50 km box. After identifying the pixel location of T_{min}, its strength is measured by calculating the slope parameter (S). In this way, all points colder than their respective environments are regions of enhanced convection. The strength of the slope parameter determines whether the candidate T_{min} pixel is convective. The slope parameter adapted for the TOGA-COARE region (Islam et al., 1999) is

$$S = k\,(T_{i-1,j} + T_{i+1,j} + T_{i,j-1} + Ti_{,j+1} - 4\,_{Ti,j}) \tag{1}$$

Where S is the slope parameter, and i and j refer to the position of the pixel for which S is being calculated. Factor k depends on data resolution. Here k = 0.25 for the four surrounding pixels of GMS-4 (11.1 km x 11.1 km) data resolution.

The calculated pairs of T_{min} and S are compared by use of an empirical discrimination line that separates T_{min} values associated with convective cores. This condition, used to distinguish convective cores from those identified with thin cirrus by Goldenberg et al. (1990), is given by

$$S \geqq \exp\,[\,0.0826\,(\,T_{min} - 207\,)\,] \tag{2}$$

In our analysis, equation (2) was used on the GMS-5 IR data.

According to Adler and Negri (1988), the convective precipitation area (A_c) is directly proportional to cell top height, as indicated by the cloud top temperature. We used the Adler and Negri relationship (1988) given by

$$ln\,(A_c) = a\,T_{ci} + b \tag{3}$$

where *a* and *b* are constant, and index *i* refers to the i-th core. The T_{min} of Adler and Negri (1988) is replaced by the variable T_{ci}. Because the *a* and *b* values calculated by Adler and Negri (1988) for FACE and the those of Goldenberg et al. (1990) for WMONEX are nearly the same, the values of a = -0.0492 and b = 15.27 were used in our analysis.

b) Estimation of stratiform regions

After assignment of areas to selected convective cells, stratiform precipitation areas are identified. The stratiform thresholds temperature, T_s, is given by

$$T_s\,(K) = T_{mod} + X \tag{4}$$

where T_{mod} is the modal cloud-top temperature, and χ is a variable. According to Goldenberg et al. (1990)

$$T_{mod} = \frac{1}{n}\sum_{j=1}^{n} T_{BB,j} \tag{5}$$

where *n* is the number of pixels in the modal grid, and $T_{BB,\,j}$ is the IR temperature of the j-th pixel in that grid. The variable *X* was introduced by Goldenberg et al. (1990), in their case *X*=7 K. The necessity of introducing this variable depends on whether radar reflectivity is compared with the CST analysis results. Adler and Negri (1988) excluded all echoes < 25 dBZ on Miami radar, whereas Goldenberg et al. (1990) included all echoes 1dBZ on the MIT land-based radar. The need for the addition of *X*=7 K was found by Goldenberg et al. (1990) for their case as opposed to using the *X*=0 K of Adler and Negri (1988). Islam et al. (1999) excluded all echoes < 20 dBZ on Keifu Maru radar (weather radar of the Japan Meteorological Agency). In their study *X*=4 K was a good fit for short-term (<1 day) analysis and *X*=7 K a good fit for long-term (10 days) analysis. In this study of Bangladesh, we have no radar data and the *X* value is assigned based on raingauge data as described in subsection 4.2.

c) Assignment of convective and stratiform rain rates

Adler and Negri (1988) used an arbitrary startiform rain rate in their CST analysis. They calculated the convective rain rate using the CST itself and a one-dimensional model (Adler and Mack, 1984). Goldenberg et al. (1990) followed Adler and Negri (1988) in calculating the convective rain rate and assumed the stratiform rain rate from radar data. Islam et al. (1997), however, showed there is a difference between the rain rates determined by radar and by the CST and clearly indicated the need to assign the convective rain rate rather than taking it from the CST algorithm. They used a convective rain rate of 25 mmh^{-1} and a stratiform rain rate of 3.5 mmh^{-1} for the tropical region. In our study both the convective and stratiform rain rates are assigned from the ground-truth rainfall and satellite data analysis, as discussed in subsection 4.3.

4. MODIFICATIONS

Some simple and essential modifications were made to the CST algorithm in order to apply it to Bangladesh and to be able to use GMS-5 data to estimate rainfall for a large coverage.

4.1. Slope parameter

In our study six surrounding pixels rather than four (Adler and Negri, 1988; Islam et al., 1999) were involved in calculating the slope parameter. The variation in pixel number depends on resolution of the satellite data used. Here the slope parameter is given by

$$S = k\,(T_{i-2,j} + T_{i-1,j} + T_{i+2,j} + T_{i+1,j} + T_{i,j-1} + T_{i,j+1} - 6T_{i,j}) \tag{6}$$

and *k*=0.17 for the six surrounding pixels in the GMS-5 (8.5 km×16.5 km) data resolution.

4.2. Best x value fit

As there was no radar data available for assigning the *X* value in our study, we used raingauge data. The *X* value proposed is for raingauges located in a different part of Bangladesh (Fig. 1). To assign the *x* value, the number of stratiform cloud pixels for each value of *X* from 0 to 15 K was calculated. The correlation coefficient for the raingauge rainfall and the number of stratiform cloud pixels for each *X* value then was calculated at each station. Fig. 2 shows the *X* value at stations Feni and Comilla. To set the *X* value for a particular raingauge the following criterion was used: "Choose the *X* value corresponding to the maximum point on the curve nearest *X*=7 K found by the modified CST algorithm (Islam et al., 1999)". Application of the above criterion gives an *X* value

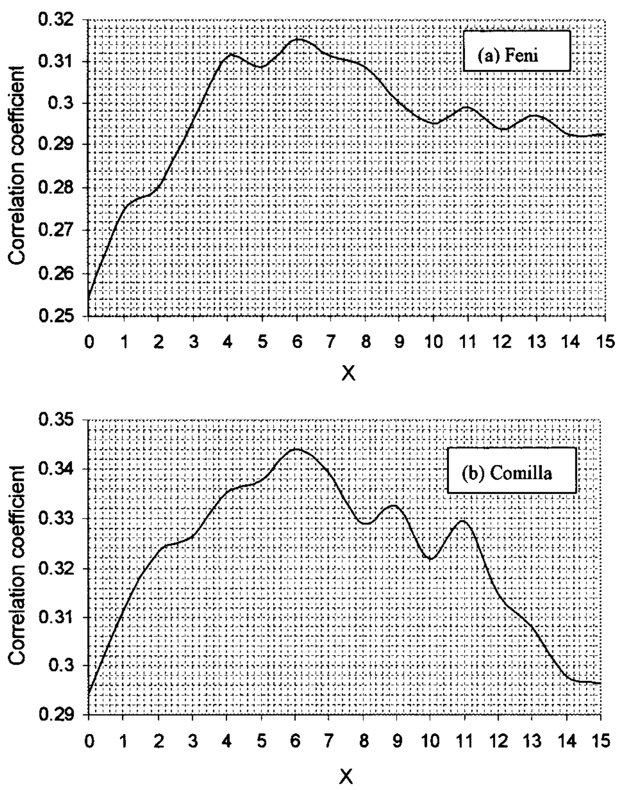

Fig. 2 *x* Values at stations Feni (a) and Comilla (b).

of 6 K for both Feni and Comilla (Fig. 2). The X value ranged from 5 to 7 K for all the raingauge stations (Table 1). The average X value was 6 K for the entire country.

4.3. Assignment of the rain rate

The stratiform rain rate can not be evaluated by the CST algorithm. Adler and Negri (1988) made an arbitrary assignment of 2 mmh^{-1} based on the rate being one-tenth of the mean convective rain rate (20 mmh^{-1}). Goldenberg et al. (1990) also used 2 mmh^{-1} as the average, the lower value being 1 mmh^{-1} and the upper one 3 mmh^{-1}. Islam et al. (1999) used 3.5 mmh^{-1} as the stratiform rain rate for the tropical region, which value is consistent with Rappaport's (1982) 3.3 mmh^{-1} and comparable to Gamache and Houze's (1983) 2.6 mmh^{-1}.

To assign the convective rain rate, 10 to 30 mmh^{-1} was assumed in our study, and for each case the average percent deviation of the CST rainfall was calculated from the raingauge rainfall.

Table 1. x Values at the raingauge stations throughout Bangladesh.

Station	Longitude(E)	Latitude(N)	x
Barisal	90.40	22.67	6
Bhola	90.67	22.33	6
Bogra	89.42	24.83	6
Chandpur	90.67	23.20	5
Chittagong	91.87	22.32	6
Chuadanga	88.87	23.67	6
Comilla	91.20	23.45	6
Cox's Bazar	92.03	21.42	7
Dhaka	90.40	23.68	5
Dinajpur	88.62	25.58	5
Faridpur	89.87	23.58	6
Feni	91.40	23.00	6
Ishardi	89.17	24.17	6
Jessore	89.23	23.17	6
Khepupara	90.23	21.93	6
Khulna	89.58	22.83	7
Kutubdia	91.83	21.83	5
Madaripur	90.22	23.18	6
Maijdi	91.13	22.83	6
Mongla	89.67	22.417	6
Mymensing	90.42	24.77	7
Patuakhali	90.37	22.33	6
Rajshahi	88.58	24.33	6
Rangamati	92.22	22.58	5
Rangpur	89.30	25.70	6
Sandwip	91.42	22.42	5
Satkhira	89.17	22.68	7
Sitakunda	91.58	22.53	5
Srimangal	91.67	24.30	6
Syedpur	88.83	25.77	6
Sylhet	91.83	24.90	6
Tangail	89.83	24.17	6
Teknaf	92.33	20.83	7

A minimum deviation of 4.5% was found for the convective rain rate of 20 mmh-1 (Fig. 3). In our study, the stratiform rain rate was checked from 2 to 5 mmh^{-1} and 3.5 mmh^{-1} assigned to for all raingauges.

5. CALCULATION OF COMPONENTIAL RAINFALL

5.1. Convective rainfall

For the regional grid data the daily average convective rainfall is given by

$$\textit{Convective rainfall}\ (\mathrm{mm}) = C\,(A_c / A)\,T\,R_c \tag{7}$$

where C = number of convective cells within a grid; A_c = convective rain area from equation (3); A = average area covered by each pixel in km^2 (8.5 km $\times$ 16.5 km); T = length of the average period, in hours; and R_c = convective rain rate in mmh^{-1} (20 mmh^{-1}).

5.2. Stratiform rainfall

For a regional grid data the daily average stratiform rainfall is given by

$$\textit{Stratiform rainfall}\ (\mathrm{mm}) = S\,(A_s/A)\,T\,R_s \tag{8}$$

where S = number of stratiform cells within a grid; A_s = stratiform rain area in that grid; A = area covered by the grid; T = length of the average period in hours; and R_s = stratiform rain rate in mmh^{-1} (3.5 mmh^{-1}).

6. RESULTS AND DISCUSSION

The rainfall value obtained in the above analysis was compared with the ground-truth rainfall. Fig. 4 shows the comparison between the daily average rainfall obtained by the CST and that for raingauge data. CST values are shown for both the convective and stratiform components. At all 33 stations the respective convective and stratiform rainfall amounts were 432.31 and 62.63 mm for 61 days starting June 1, 1996. The convective component was 87% and the stratiform one 13%. These percentages differ from those of Islam et al. (1998) whose calculated values were convective 64% and stratiform 36%. For all the stations the CST calculation

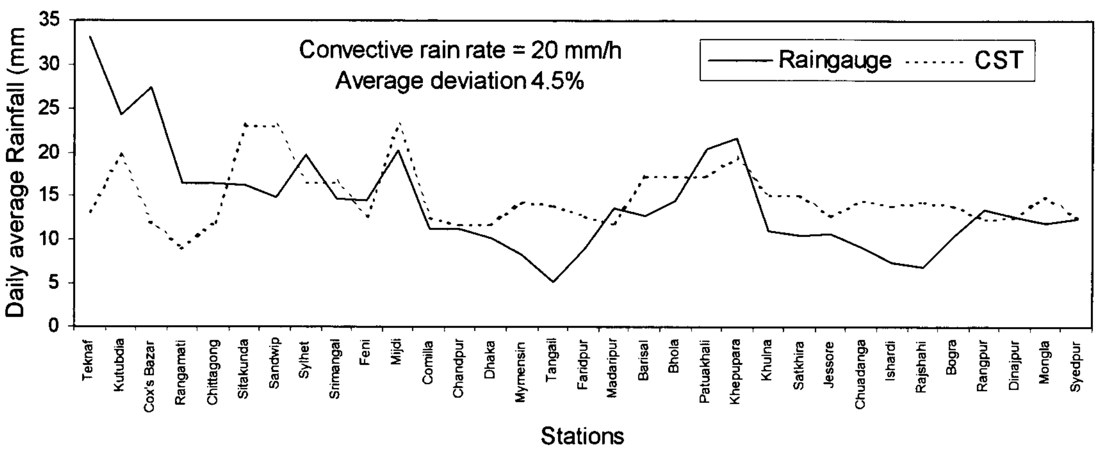

Fig. 3 Determination of rain rates.

was 494.95 mm and the raingauge value 470.57 mm for the 61 days. The average difference in daily rainfall between the CST and raingauge amounts was 0.7 mm; i. e., as expected the CST value was 0.7 mm/day larger than the ground-truth value. Ground-truth values were larger than CST values in all the coastal regions except Sylhet, Feni, and Rangpur. Otherwise, the CST values were larger than the ground-truth ones. On the average, the calculated CST was 1.051 times the ground-truth value, indicative of good agreement between the two values.

Fig.5 shows the correlation between the ground-truth rainfall and that calculated by the CST at the different stations. The correlation coefficients (r) are between 0.068 (Rajshahi) and 0.756 (Khepupara). They are significantly high for the stations Barisal, Bhola, Cox's Bazar, Rangamati, Comilla, Chittagong, Khepupara, Kutubdia, Mongla, Patuakhali, Syedpur and Teknaf, but insignificantly for the rest stations. The average it is 0.32, indicative that even the average correlation is low and that the amount of rainfall calculated by the CST is very close to that found from ground-truth data (Fig. 4). This also shows that the CST is reliable for estimating regional rainfall from GMS-5 data.

Fig.6 shows the relationship between the CST (CST) and ground-truth (RAIN) rainfalls. For all 33 stations the linear regression equation takes the form

$$RAIN = (0.422)\ CST + 8.016 \quad (9)$$

Whereas omitting the very poorly correlated stations, equation (9) becomes

$$RAIN = (0.840)\ CST + 0.104 \quad (10)$$

If the coefficient of CST is given by m and the constant term by c, equation (10) becomes

$$Surface\ rainfall = m\ (Satellite\ rainfall) + c \quad (11)$$

This means that the surface rain value was 0.84 times larger than the satellite rain value plus the constant value of 0.1 used in our study. With equation (11) the surface rain can be estimated from satellite data. Linear regression equations were obtained for individual stations, and the m and c values are shown in Fig. 7. Note that the amount obtained with equation (11) may not be the

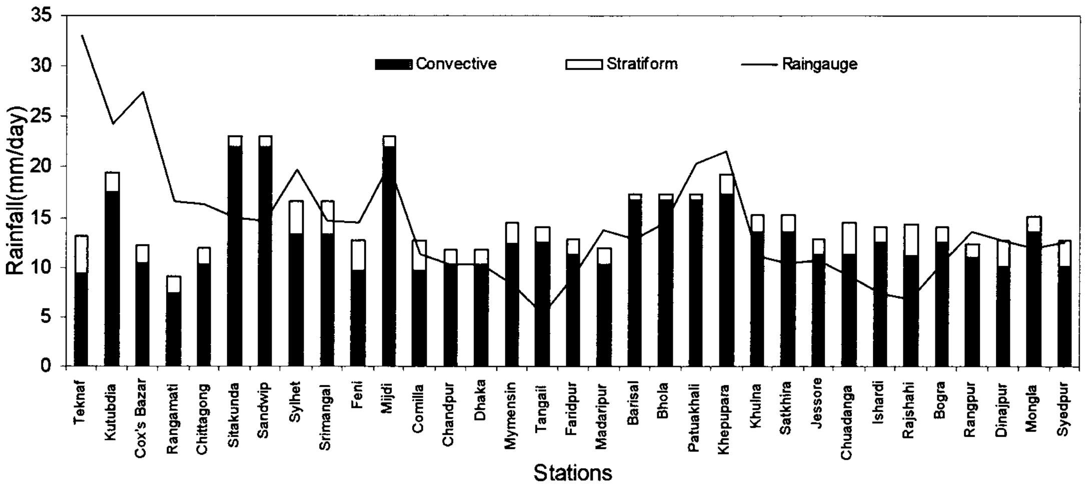

Fig. 4 Rainfall amounts calculated form the CST and raingauge data : convective, stratiform and raingauge rainfalls.

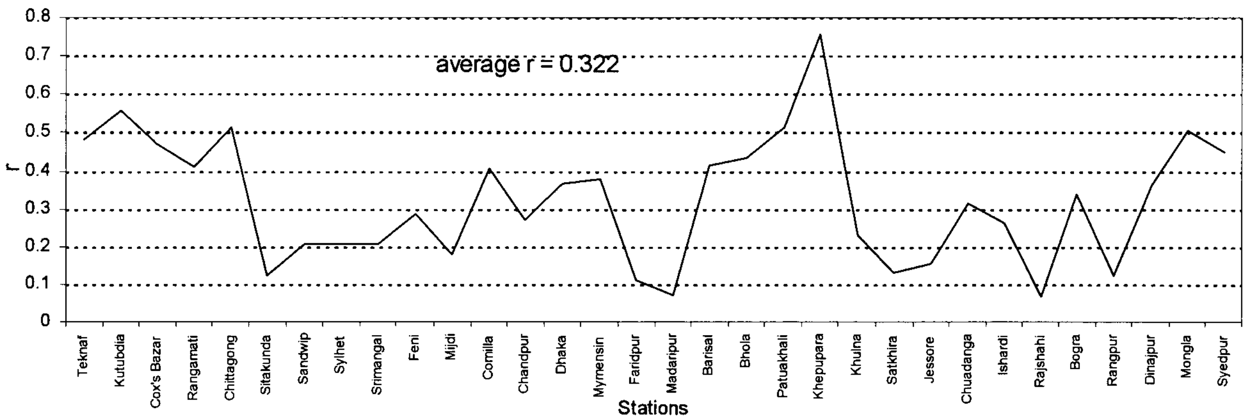

Fig. 5 Correlation between rainfall amounts calculated from the CST and raingauge data for all the stations.

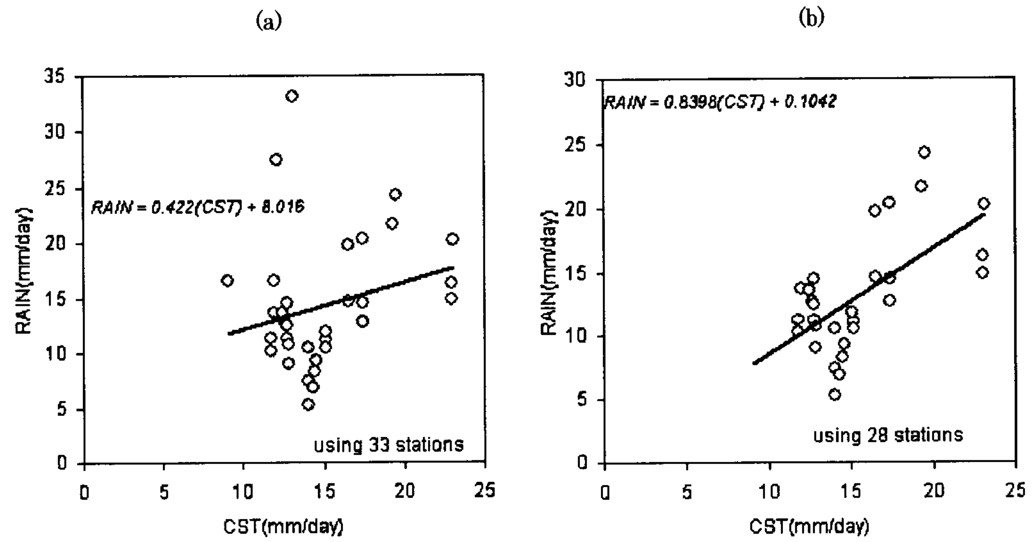

Fig. 6 Relationships between rainfall amounts calculated from the CST and raingauge data : for all stations (a) and omitting poorly correlated stations (b). The solid line is the regression line.

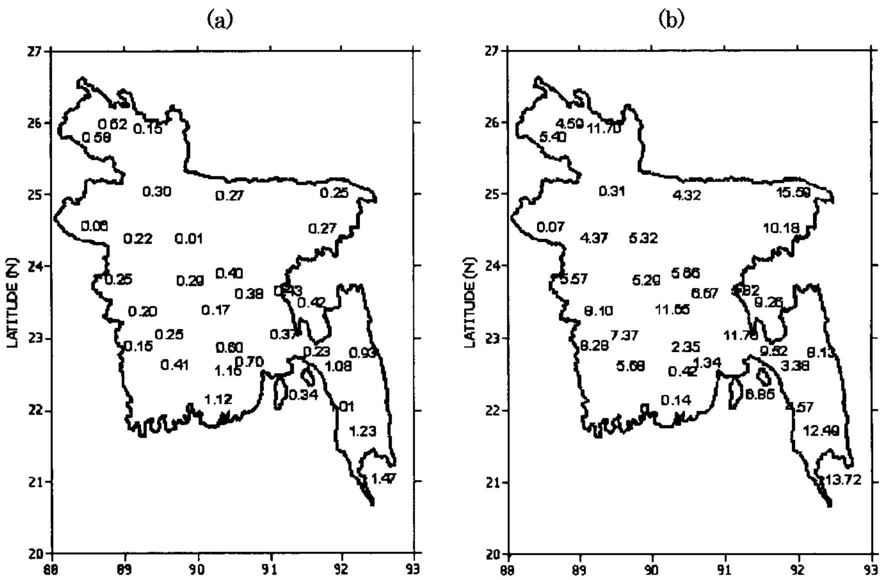

Fig. 7 *m* and *c* values in equation (11) throughout Bangladesh : *m* value (a) and *c* value (b).

actual rainfall amount for all the seasons, but this procedure is applicable to long time data and provides a reliable technique for estimating rainfall from satellite data. It therefore should be useful for estimating floodwater amounts in the large GBM basin, which is essential for flood prediction in Bangladesh.

7. CONCLUSIONS

Analysis of 61 days of 3-hourly GMS-5 data of over 33 raingauge stations in Bangladesh provided the following conclusions:

- The CST method can be used when radar data is not available.
- Rain rates can be assigned from ground-truth data
- Correlation between the satellite and ground-truth rainfall values is significant for coastal but not inland stations.
- The convective component is 87% and the stratiform component 13%.
- Surface rainfall is 1.1 times larger than the ground-truth rainfall.
- Surface rain can be estimated from satellite data.
- The CST algorithm can be successfully used to estimate rainfall in Bangladesh from GMS-5 data.

These encouraging results indicate that calculation of the surface rain for a large coverage from satellite data is possible. Knowing the rainfall over a large coverage is essential for flood forecasting and for determining the surface water budget. To use this procedure in determining surface rain from satellite data further study of long time datasets is required. This is now in progress.

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