

Application of GMS-5 data in estimation of rainfall distribution

MD. NAZRUL ISLAM*, A. K. M. SAIFUL ISLAM**

and

HIROSHI UYEDA***

**Bangladesh University of Engineering & Technology, Dhaka-1000, Bangladesh*

***IFCDR, Bangladesh University of Engineering & Technology, Dhaka-1000, Bangladesh*

****HyARC, Nagoya University, Nagoya 464-8601, Japan*

(Received 16 November 2001, Modified 5 September 2002)

सार — इस शोध-पत्र में बंगलादेश में और उसके आसपास हुई धरातलीय और चक्रवातीय वर्षा का आकलन करने के लिए जी.एम.एस.—डब्ल्यू.ई.एफ.ऐ.ऐक्स. बिंबों को द्विआधारी आँकड़ों में बदलने की प्रक्रिया का अध्ययन किया गया है। जी.एम.एस. वृष्टि सूचकांक (जी.पी.आई.) और संवहन स्तरितरूपी तकनीक (सी.एस.टी.) का उपयोग करते हुए जून-जुलाई 1996 के महीनों के जी.एम.एस.—5 आँकड़ों के साथ उपग्रह से प्राप्त वर्षा के आँकड़ों का परिकलन किया गया है। जी.पी.आई. और सी.एस.टी. से आकलित किए गए वर्षा के आँकड़ों का वर्षामापी से लिए गए आँकड़ों के साथ अंशशोधन किया गया है। जून-जुलाई 1996 की औसत आकलित प्रतिदिन की वर्षा वर्षामापी, सी.एस.टी. और जी.पी.आई. से क्रमशः 14 मि.मी., 14.5 मि.मी. और 27.5 मि.मी. प्राप्त की गई थी। उपग्रह से प्राप्त आँकड़ों से धरातलीय वर्षा का आकलन करने के लिए जी.पी.आई. और सी.एस.टी. दोनों के समाश्रयण समीकरण प्राप्त किए गए। धरातलीय वर्षा का आकलन करने के लिए जी.पी.आई. की अपेक्षा सी.एस.टी. पद्धति कहीं अधिक बेहतर पाई गई। सी.एस.टी. का उपयोग करते हुए 27-30 अक्टूबर 1999 में बंगाल की खाड़ी में आए चक्रवात की घटना से चक्रवातीय वर्षा के आँकड़ें प्राप्त किए गए।

ABSTRACT. The process of converting GMS-WEFAX imagery into binary data to calculate surface and cyclonic rain in and around Bangladesh was presented in this study. Satellite rainfall was calculated from GMS-5 data for the months of June-July 1996 using GMS Precipitation Index (GPI) and Convective Stratiform Technique (CST). The rainfall calculated by GPI and CST was calibrated with that of calculated by rain gauge. On an average for June-July 1996, daily rainfall calculated by rain gauge, CST and GPI was 14 mm, 14.5 mm and 27.5 mm respectively. The regression equation was obtained for both GPI and CST analyses to calculate surface rain from satellite data. The CST method was found better than the GPI method in calculating surface rain. Then cyclonic rain was obtained using CST method on the event of a Cyclone occurred 27-30 October 1999 over the Bay of Bengal.

Key words – Surface rain, Cyclone, Cyclonic rain, Geostationary Meteorological Satellite (GMS)

1. Introduction

Rainfall data is considered an important parameter for studying water resources related problems like flooding, which is common phenomenon in many countries. Heavy rainfall in the catchment of the Ganges-Brahmaputra-Meghna basin contributes a considerable amount to the flood flow passing through Bangladesh. A rainfall estimation method applicable in a large coverage is therefore an important component of a flood-forecasting model for Bangladesh. Rainfall data is also important for cultivation and other purposes of a country. Cyclonic rainfall estimation is important for studying flooding damages.

There are two fundamental methods for rainfall measurement. One method is to catch the rain as it falls and measure the amount it accumulates by a raingauge. Despite problems with the shape of the container, the wind and the evaporation between measurements, rain gauge provides the best available estimates of precipitation (Arkin and Meisner, 1987). But, a raingauge network is impossible over ocean and inaccessible areas. The other fundamental method for rainfall measurement is using remote sensors such as radar and satellite. Despite problems such as variation in the reflectivity, variable droplet size and beam attenuation, good estimates of average rainfall can be obtained using suitable calibrated digital radar (Hudlow and Patterson, 1979). However,

radar ranges are rather small (100-500 km approximately) and its deployment is impracticable over the ocean and expensive to have a large radar network on land. So a solution to overcome the difficulties of land-based equipment is to make use of satellite based remote sensing devices in conjunction with radars and raingauges. Satellites provide data continuously and they can monitor very large areas. Therefore, in many regions meteorological satellite data are the only realistic means to monitor the spatial and temporal distribution of rainfall.

In recent years, the use of satellite data for rainfall estimation has increased enormously. All meteorological satellites are currently used routinely for estimation of over-land precipitation (Petty and Krajewski, 1996). Though very important, there are few detailed available works in Bangladesh to estimate rainfall using satellite data. An effort to estimate rainfall from satellite data was taken up by the joint research project between Japan and Bangladesh University of Engineering & Technology (BUET). As a result, Geostationary Meteorological Satellite (GMS-5) receiving station was installed at the Institute of Flood Control and Drainage Research (IFCDR) at BUET in 1996. That project concluded with an average correlation between raingauge rainfall and satellite infrared brightness temperature data for four greater regions of the country (Rahman *et al.*, 1997). After that, Wahid and Islam (1998) used GOES Precipitation Index (GPI) method for estimating rainfall from satellite cloud top temperature and used a smaller grid ($1^\circ \times 1^\circ$) system for the country rather than large four regional divisions. They calculated GPI for the whole country but calibrated it with a dense raingauge rainfall network over Sylhet district of Bangladesh. However, much of the precipitation in both mid-latitudes and the tropics fall from meso-scale convective systems (Houze and Betts, 1981). So, it is necessary to distinguish between the convective and stratiform components of these cloud systems; since the physics and dynamics of the air motions and precipitation growth in the convective and stratiform regions are fundamentally different (Goldenberg *et al.*, 1990). But, the GPI method cannot distinguish between convective and stratiform regions of the cloud and so it gives an average rainfall. A rainfall measuring technique developed by Adler and Negri (1988) separates convective and stratiform regions of the cloud, which is known as Convective Stratiform Technique (CST). The CST was successfully adapted for rainfall estimation during Winter Monsoon Experiment (WMONEX) by Goldenberg *et al.* (1990) and during Tropical Ocean Global Atmosphere-Coupled Ocean Atmosphere Response Experiment (TOGA-CORE) by Islam *et al.* (1998). The goal of this study is to apply GMS-5 data in estimating rainfall in Bangladesh.

A cyclone case is also studied to calculate cyclonic rain during the lifetime of the cyclone.

1.1. *The Geostationary Meteorological Satellite (GMS-5)*

The Japanese GMS-5 sub-satellite position is over the equator at 140°E and about 35850 km from the earth's surface. Different types of images (A, B, C, D, K, J and I) are being sent by the GMS. Bangladesh is covered by 'A' and 'K' images, which are sent at every 3 and 12 hours respectively. Image 'A' is near-infrared and image 'K' is mid-infrared (water volume) image. Each image consists of 800 pixels in the horizontal direction and 800 lines in the vertical direction while we get $8.5 \times 16.5 \text{ km}^2$ mesh resolution. In this study near-infrared 'A' images, which represent earth surface and cloud top temperature, are used to calculate surface and cyclonic rain.

1.2. *Problems of directly using GMS-5 data for rainfall analysis*

There are some problems in direct use of GMS-5 images for some regions like Bangladesh (90°E), which is far from satellite location sub satellite point (Equator, 140°E). These problems are:

- (i) The GMS-WEFAX images are received as 6-bit integer. But, the personal computer (PC) and all the software system recognise integer consists of 8-bit. Therefore, image data need to be converted from 6-bit to 8-bit integer.
- (ii) The positions of the coast and other lines are not on the same pixel for each imagery. This is due to the drift of the satellite, which is commonly known as attitude of the satellite. Therefore, the satellite status parameter due to drift must be calculated for the proper identification of the pixel.
- (iii) The intensity of the pixels on the latitude, longitude and coastal lines of an image is changed from its original intensity by the Japan Meteorological Satellite Center to show these lines clearly. Those extra borderlines also needed to be eliminated.
- (iv) The satellite (GMS-5) is located on the equator over 140°E , so that the images received by the satellite are not much deformed near the above location. But, the images are much more deformed far away from that location for a region like Bangladesh, which is located at 90°E . The deformation of the imagery is caused by the earth curvature and some image corrections are needed to improve the deformed imagery.

In this study attempts have been made to overcome above problems for calculating surface and cyclonic rain in and around Bangladesh using GMS-5 data.

2. Outline of the technique used in data processing by newly developed software

GMS-WEFAX signals are received by various available commercial systems namely, Hakuyo and Kenwood. However, these commercial software packages cannot overcome the regional problems described before. Therefore, a set of programs is developed to improve this situation.

2.1. Conversion from WEFAX data to normal data format

The data format of Hakuyo system for each image consists of 800 lines where each line consists of 800 pixels and each pixel consists of the combination of six successive bits of binary. So, a conversion was needed from 6-bit integer to 8-bit normal integer that was performed in this study.

2.2. Coordinate transformation

The positions of latitude and longitudinal lines vary from image to image. To calculate the rotation of the satellite and the operational small-scale displacement from its original position, the procedure of Chowdhury *et al.* (1997) is adopted in this study.

2.3. Elimination of artificial borderlines

The artificially adapted lines by the Japan Meteorological Satellite Center in GMS-WEFAX signals are eliminated using the follows steps:

Step 1 : Using earth satellite relation and probable satellite disturbances, the position of pixel on images are detected.

Step 2 : The difference between the intensity of that detected pixel and the surrounding pixel is found. The difference of intensities is multiplied to find G value.

$$G = (\text{Intensity of detected pixel} - \text{Intensity of surrounding pixel}) \times (\text{Intensity of detected pixel} - \text{Intensity of next point})$$

The G value is the highest for that detected pixel located on the artificial lines.

Step 3 : Intensity of the detected pixel through interpolation in the surrounding pixels is assigned, which eliminates artificial lines.

2.4. Orthogonal image formation from deformed image

It is already mentioned that due to the earth curvature a deformation occurs which need to be corrected. The orthogonal image was constructed from deformed imagery using the procedure described by Chowdhury *et al.* (1997). Coastal lines of Bangladesh and other lines applied where needed for proper visualization of the cloud structure.

3. Material and methods used

Daily rainfall data from 33 raingauge stations of Bangladesh Meteorological Department (BMD) and three hourly GMS-5 near-infrared data during June-July, 1996 were used in this study. The GMS-5 data of one cyclone event occurred 27-30 October 1999 over the Bay of Bengal was also used.

The main steps of data processing involved in this analysis are mentioned in previous section. A set of computer programs was developed to process raw image collected by GMS-5. The GOES Precipitation Index (GPI) method is used to calculate satellite rainfall from GMS-5 data. In this work the GPI adjusted for Bangladesh region (Wahid and Islam, 1998) using GMS-5 data is used. The different steps of the GPI algorithm are (i) identification of cloudy and non-cloudy pixels using 235K as a threshold, (ii) calculation of the coverage of cloudy area and (iii) estimation of rainfall. Details of the GPI method are described by Arkin and Meisner (1987) and Wahid and Islam (1998). The rainfall (here GPI) from satellite data is calculated by

$$\text{GPI} = (\text{Fractional cloud coverage}) \times (\text{constant rain rate}) \times (\text{average length of time})$$

Another method named Convective Stratiform Technique (CST) is also used to estimate precipitation from GMS-5 data. Details of CST algorithm are described by Alder and Negri (1988), Goldenberg *et al.* (1990) and Islam *et al.* (1998). In CST algorithm the cloud boundary, which is the threshold temperature for stratiform cloud, is given by

$$T_s = T_{\text{mode}} + x$$

where T_s is the stratiform threshold temperature, T_{mode} is the modal temperature and x is the parameter to be decided from radar data. In this analysis radar data is absent and we tried to use raingauge data instead of radar data that is explained in the next section. The convective temperature must be lower than stratiform temperature. So, T_s measures the cloud boundary under which both

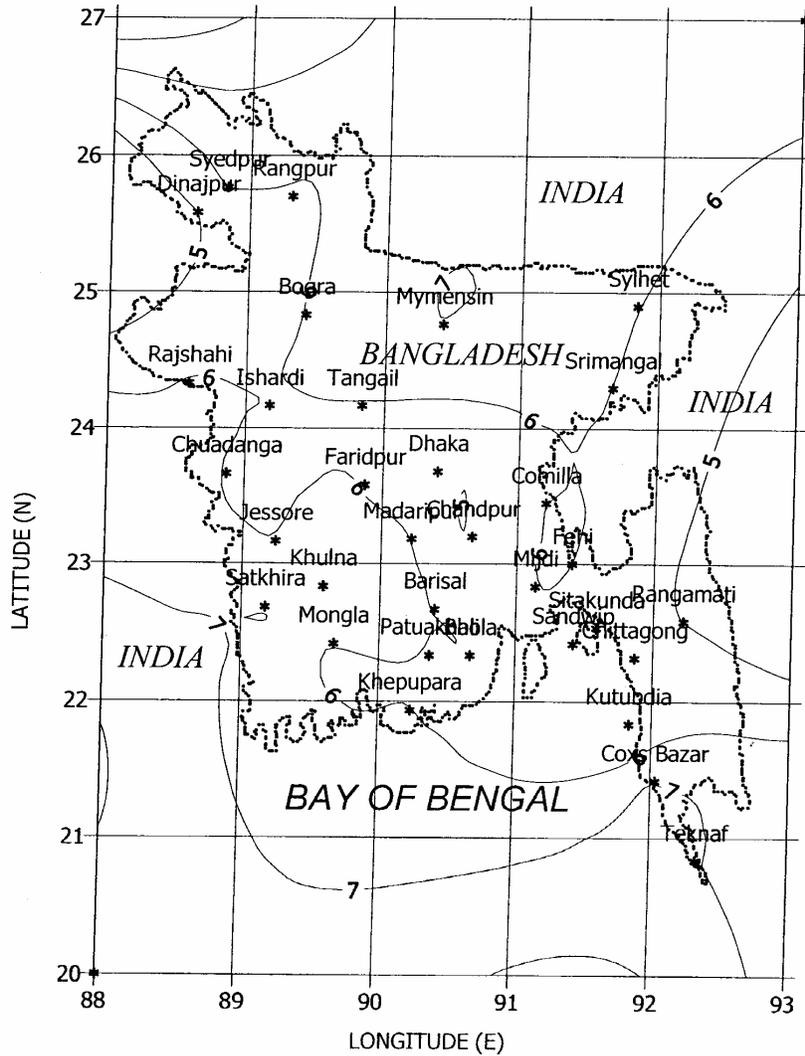


Fig. 1. The distribution of x value over Bangladesh. The location of raingauges over the country is also shown

convective and stratiform components exist. Counting the number of convective and stratiform pixels identified by CST and knowing the area of each pixel the cloud coverage of each type was calculated. Then cloud coverage was converted into rainfall using the respective convective and stratiform rain rate.

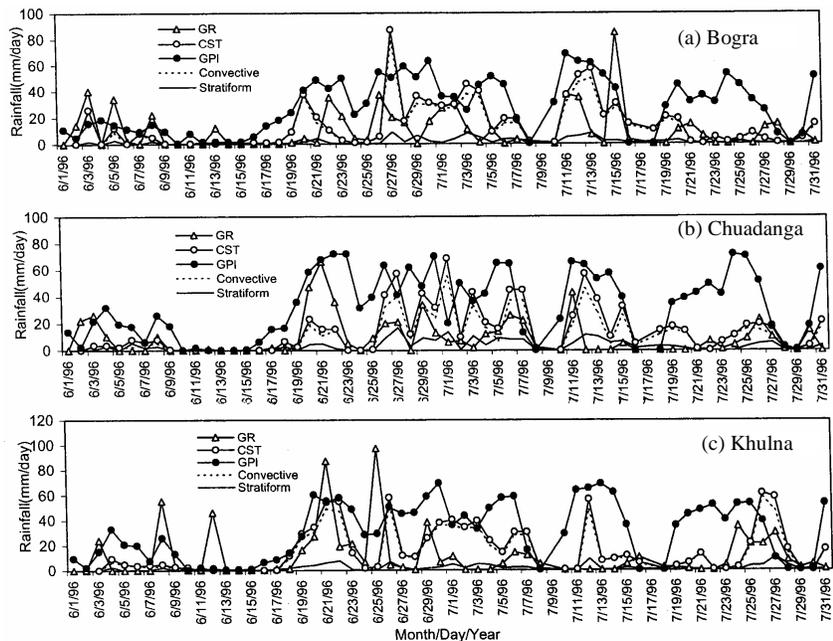
In this study rain rate for both GPI and CST algorithms was assigned from rain gauge rainfall (not explained). Finally, the results obtained from GPI and CST were calibrated with the rain gauge rainfall obtained at different regions of Bangladesh.

To analyze the cyclone event GMS-5 images were retrieved to monitor the cyclone. This case specific region

was divided into $1^\circ \times 1^\circ$ grid boxes, each box containing pixels of $8.5 \times 16.5 \text{ km}^2$. The number of convective and stratiform cloudy pixels determined by CST represents the cloudy pixels. Then cyclonic rain was calculated using cloud area, rain rate and average time during the lifetime of the analyzed cyclone. The area-integrated cyclonic rain is calculated by

Area – Integrated Rain =

$$\sum_{\text{initial grid}}^{\text{final grid}} \left\{ \frac{(\text{Cloudy pixels}) (\text{pixel area})}{(\text{total pixels}) (\text{pixel area})} (\text{rain rate}) (\text{length of time}) \right\}$$



Figs. 2(a-c). The time sequences of rainfall calculated by raingauge (GR), GPI and CST methods at three stations named (a) Bogra (b) Chuadanga and (c) Khulna

For convective component cloudy pixels is to be the number of convective raining pixels and for stratiform component cloudy pixels is to be the number of stratiform raining pixels. The rain rate is to be the cloudy pixel related rain rate.

4. Results and discussion

4.1. Estimation of surface rain

The location of raingauges over Bangladesh is shown in Fig. 1. Satellite data were analyzed for each grid cell where there was atleast one raingauge present. If the number of raingauge was more than one in a grid cell then the average was taken.

The distribution of x (in K) value over the country is shown by contour in Fig. 1. The x value was used in the CST algorithm to adjust CST for this region. Adler and Negri (1988) used radar data to fit for x value. Goldenberg *et al.*(1990) and Islam *et al.* (1998) used the same procedure. In this analysis radar data is absent for study. So available raingauge data was used. It is seen that x value is between 5K-7K and on an average it was 6K for this region. This value is very close to 4K-7K reported in other studies (Goldenberg *et al.*, 1990; Islam *et al.*, 1998).

The time sequences of rainfall calculated by raingauge (GR), GPI and CST methods at three stations named Bogra, Chuadanga and Khulna is shown in

Figs. 2(a-c). It is mentioned here that GPI and CST is the representative of rainfall calculated from satellite data using respective algorithms. It is seen that patterns of the results of all three analyses were very similar at all stations except very few exceptions. On 27 June 1996 CST overestimated GR at Bogra and on 15 July 1996 GR overestimated CST at the same station. At other two stations these types of little differences were observed. Generally GPI value was larger than CST and GR values. Convective and stratiform components calculated by CST are also shown for these three stations. The convective component is consistently larger than the stratiform component. The CST was just the addition of convective and stratiform components. On an average daily GR, CST and GPI at station Bogra was 10.27 mm, 14 mm and 28 mm; at station Chuadanga was 9.06 mm, 14.55 mm and 33.11 mm; at station Khulna was 10.97 mm, 15.18 mm, 30.50 mm respectively. Quantitatively, GPI values were about three times of GR values and CST values were close to GR values. This represents that CST analysis shows better result than GPI analysis in calculating surface rain from satellite data.

Fig. 3 shows the comparison of daily rainfall averaged from June-July 1996 calculated by raingauge (GR), GPI and CST methods at 12 stations indicated on the figure. It is seen that CST values were closer to GR values than GPI values except at Cox’s Bazar where CST value was closer to GPI value. On an average over 12 stations daily GR, CST and GPI were 14 mm, 14.5 mm

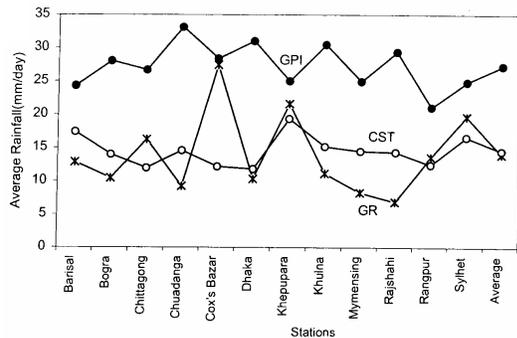


Fig. 3. The comparison of daily rainfall averaged from June-July 1996 calculated by raingauge (GR), GPI and CST methods at 12 stations indicated on the figure

and 27.5 mm respectively. These indicate that CST is more reliable method in calculating surface rain from satellite data.

The regression analyses of rainfall calculated by GPI and CST methods at 12 stations (mentioned in Fig. 3) over the country have been made to get surface rain from satellite data. According to GPI analysis surface rain is given by

$$\text{Surface rain (mm)} = -0.532 \text{ GPI(mm)} + 28.245$$

where the surface rain was -0.532 time the GPI value plus a constant value of 28.245. The intercept term 28.245 was significantly different from zero. The slope term 0.532 was negative that indicated that regression trend was decreasing with increasing GPI value. It is easy to show that for $\text{GPI} \geq 53$, surface rain cannot be calculated that means we cannot calibrate GPI higher than 52 mm using this method. On the other hand the relationship between CST and surface rain is given by

$$\text{Surface rain (mm)} = 0.336 \text{ CST(mm)} + 9.085$$

where the surface rain was 0.336 times the CST value and a constant value of 9.085. Here also the intercept term was significantly different from zero but much lower than for GPI. The slope term 0.336 was positive that indicated that surface rain was increasing with increasing CST value.

4.2. Estimation of cyclonic rain

Successful agreement between the results of CST and ground-truth (RG) data encouraged us to use CST in calculating cyclonic rain from satellite data. To calculate cyclonic rain the devastating cyclone named "Super Cyclone" occurred during 27-30 October 1999 over Bay of Bengal was considered to study.

(i) History of the cyclone event

A well marked low pressure area formed over Thai Ocean on 26 October and developed into a depression *in situ* and lay centered near $14.5^\circ \text{N}/92.5^\circ \text{E}$ at 1200 UTC of 26 October. It intensified into a strong depression and further intensified into a cyclone with its centre near at $15.8^\circ \text{N}/91.7^\circ \text{E}$ and located at about 900 km S from Chittagong Port and 1020 km SE from Khulna City at about 1500 UTC of 27 October. The system moved NW direction for sometime and remained practically stationary centered near $16.5^\circ \text{N}/90.5^\circ \text{E}$ for the rest of 27 October. The wind speed was 65 km/hr within 54 km of its centre. At 2100 UTC on 27 October the cyclone was located at about 730 km SSW from Chittagong Port and 730 km S from Khulna City. On 28 October its coverage was about 300 km in diameter with an affecting area of about 1000 km in diameter. It was located at about 610 km SW from Chittagong Port and 500 km SSW from Khulna City. From this cyclone 1-5 ft tidal waves affected low lands of coastal districts Bagerhat, Khulna, Pirozpur and Sathkira of Bangladesh. The system then intensified into a severe cyclonic storm with a core of hurricane winds at 0600 UTC of 28 October. On 29 October it hit the eastern coast of India, Orissa and produced huge damages.

(ii) GMS cloud features

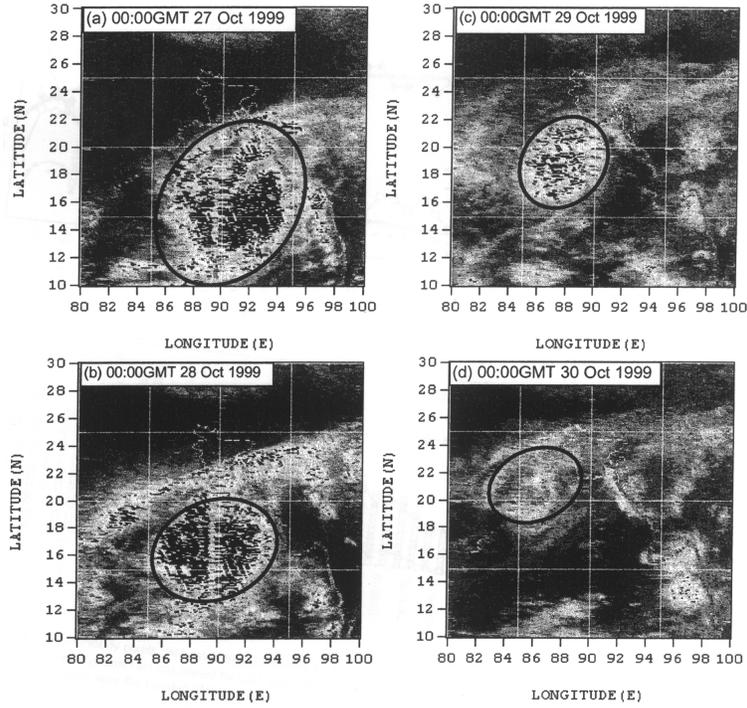
The cyclone system was observed by three hourly GMS-5 cloud imageries. The cloud feature at some particular periods is shown in Fig. 4: (a) GMS-5 Image at 0000 UTC on October 27, (b) GMS-5 Image at 0000 UTC on October 28, (c) GMS-5 Image at 0000 UTC on October 29 and (d) GMS-5 Image at 0000 UTC on October 30. From the 24 hours interval cloud features for the four days it is seen that the system developed over the Bay of Bengal and moved NW with time and hit the eastern coast of India.

(iii) Damages

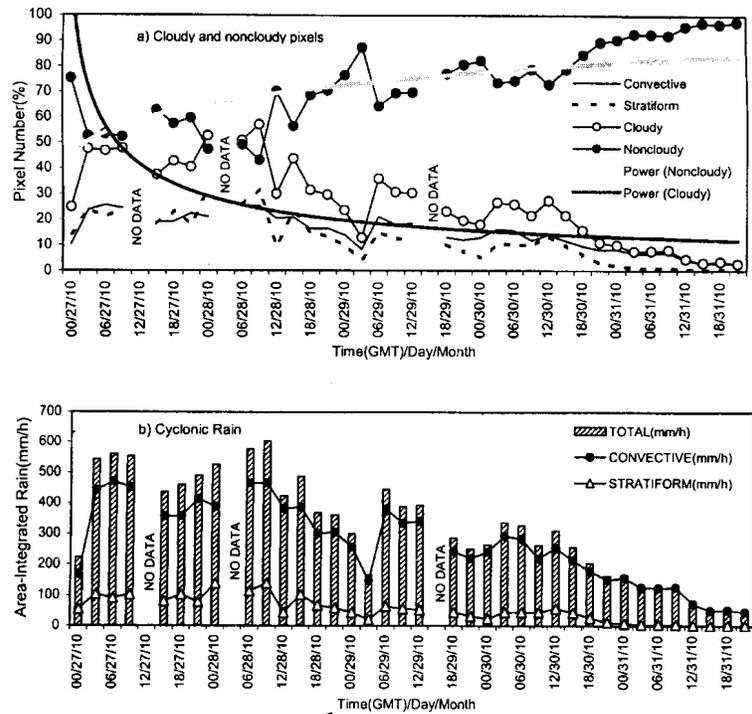
According to press reports, there were 942 deaths (Government) at Orissa, West Bengal and Bihar. The other sources reported the number of death might be 3000–10000. About 1.5 million homes were damaged or partially damaged and affected 10 million people due to the gale wind and heavy rains in these regions. Severe damages to roads, electric poles, telecommunication and water supply were also reported from these areas.

(iv) CST analysis

Fig. 5(a) shows the cloudy and non-cloudy pixels during the cyclone event identified by CST analysis. Cloudy pixels were divided into convective and stratiform



Figs. 4(a-d). The cloud features at some particular period during the cyclone occurred 27-30 October, 1999 over the Bay of Bengal. The circle represents the coverage of the cyclone



Figs. 5(a&b). (a) Cloudy and non-cloudy pixels calculated by CST during the cyclone event and (b) Area-integrated cyclonic rain calculated by CST analysis. Counting and rainfall is also shown after the landfall of the cyclone

portions. The number of convective pixels was larger than the number of stratiform pixels for all over the cyclone period. This feature is different from general feature of non-cyclonic cloud cluster. In general, for a cloud cluster feature, the number of convective pixels is larger than the number of stratiform pixels at early stage and *vice-versa* in the dissipating stage (Goldenberg *et al.*, 1990). Hence the large number of convective part indicated that during cyclone period a number of convections were born within the system while the system was composed of a number of cloud clusters. The trend line represents that the numbers of cloudy pixels decreased with the lifetime of cyclone and for non-cloudy pixels it was *vice-versa*.

Fig. 5(b) shows the area-integrated cyclonic rain calculated by CST analysis. The legend represents the convective and stratiform components of rainfall at different time during the lifetime of the cyclone. It is seen that large amount of area-integrated cyclonic rain comes from convective component. Here the percentages were convective = 83.82% and stratiform = 16.18%. These differ from the percentages reported by Islam *et al.* (1998). They reported convective = 64% and stratiform = 36% for TOGA-COARE cloud features in 1992 over Oceanic Warm Pool. Goldenberg *et al.* (1990) reported convective = 51% and stratiform = 49% for a large cloud cluster observed over the South China Sea during WMONEX. However, 25-50% of the total rain reaching the ground from stratiform cloud is reported in other studies (Houze and Hobbs, 1982; Leary, 1984). In this study stratiform percentage for cyclonic rain was little bit lower than the reported non-cyclonic case studies. This was because a cyclonic cloud structure was composed of a number of cloud clusters. New convection was born with time under each cloud cluster and the convective rain rate was larger than stratiform rain rate. So the convective component contributed more rainfall than the stratiform component. Using this procedure we can estimate the amount of rainwater that comes from a cyclone. To apply this method in calculating cyclonic rain we need to check more cyclone cases to verify the percentages contributed by convective and stratiform components.

5. Conclusions

The process of using GMS-5 data in calculating surface and cyclonic rain in and around Bangladesh was studied. Comparing the results of two methods and calibrating with ground-truth data it was found that surface rain can be calculated from satellite data using CST method with a good accuracy. The result of CST was found good agreement with that of ground-truth data. The amount of rainfall calculated by CST was 1.034 times that obtained by ground-truth data. The amount of rainfall from a cyclone during its lifetime was also calculated.

Using the procedure presented in this paper it is possible to calculate surface and cyclonic rain from GMS-5 data at a region far from satellite radii location, which are very important for agriculture, flood forecasting and other daily activities of a country.

Acknowledgements

The authors would like to express their thank to "Japan-Bangladesh Joint Study Project" supported by Japan International Cooperation Agency (JICA) under which GMS-5 data is collected, and Bangladesh Meteorological Department for providing raingauge data. The authors also wish to thank Dr. Rezaur Rahman, IFCDR, BUET for his encouragement during this study.

References

- Adler, R. F. and Negri, A. J., 1988, "A satellite infrared technique to estimate tropical convective and stratiform rainfall", *J. Appl. Meteor.*, **27**, 30-51.
- Arkin, P. A. and Meisner, B.N., 1987, "The relationship between large-scale convective rainfall and cold cloud over the western hemisphere during 1982 - 1984", *Mon. Wea. Rev.*, **115**, 51-74.
- Chowdhury, A. K., Nishimura, H. and Shi-gai, H., 1997, "Development of software for the boarder application of WEFAX data", *J. Japan Soc. Civil & Water Resour.*, **10**, 248-258.
- Goldenberg, S. B., Houze, Jr. R. A. and Churchill, D. D., 1990, "Convective and stratiform components of a winter monsoon cloud cluster determined from geo-synchronous infrared satellite data" *J. Meteor. Soc. Japan*, **68**, 37-63.
- Hudlow, M. D. and Patterson, V. L., 1979, "GATE Radar Rainfall Atlas", NOAA Special Report, Environmental Data and Information Service, Washington, DC, p155.
- Houze, R. A. Jr. and Betts, A. K., 1981, "Convection in GATE", *Rev. Geophys. Space Phys.*, **19**, 4, 541-576.
- Houze, R. A. Jr. and P. V. Hobbs, 1982, "Organization and structure of precipitating cloud systems", *Advances in Geophysics*, **41**, 3405-3411.
- Islam, M. N., Uyeda, H., Kikuchi, O. and Kikuchi, K., 1998, "Convective and Stratiform Components of Tropical Cloud Clusters in Determining Radar Adjusted Satellite Rainfall during the TOGA-COARE IOP", *J. Fac. Sci. Hokkaido Univ. Japan, Ser. VII (Geophysics)*, **11**, 1, 265-300.
- Leary, C. A., 1984, "Precipitation structure of the cloud clusters in a tropical easterly wave", *Bull. Amer. Meteor. Soc.*, **63**, 619-627.
- Petty, G. W. and Krajewski, W. F., 1996, "Satellite Estimation of Precipitation over land", *Hydrological Sciences Journal*, **41**, p435.
- Rahman, R., Islam, M. N., Alam, S. and Chowdhury, A.M., 1997, "Application of remote sensing technology to rainfall forecasting", Final report, Japan Bangladesh Joint study Project, IFCDR, BUET, Dhaka, 1-37.
- Wahid, C.M. and Islam M. N., 1998, "Patterns of rainfall in the northern part of Bangladesh", *Bang. J. Sci. Res.*, **17**, 1, 115-120.