Journal of Natural Disaster Science, Volume 27, Number 1, 2005, pp17-23

Characteristics of Precipitation Systems Analyzed from Radar Data over Bangladesh

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(Received for 19 Jan., 2004 and in revised from 21 Sep., 2005)

ABSTRACT

At present, a low-dense rain-gauge network over Bangladesh is the only tool by which to measure rainfall, so there is no way of understanding the properties of the precipitation systems occurring there. To obtain precise rainfall distributions and to clarify the characteristics of precipitation systems, radar data from the Bangladesh Meteorological Department (BMD) were used in the first investigation in Bangladesh. The BMD radar collects rain status data in six ranges. The precipitation rate was retrieved from the rain status obtained from BMD radar data. Correlation between three-days-running averaged rainfall estimated by radar and rain-gauges ranged from 0.63-0.89 over the months of 2000. The radar data was systematically underestimated by about one-fourth the rain-gauge value. Small size (~80 km^2) echoes contribute greatly to the total precipitation, but there were few large size echoes. The distribution of precipitation over Bangladesh obtained from radar data shows heavy precipitation in the northeast and southeast of the country, which is consistent with the rain-gauge rainfall data.

Using the radar data characteristics of 185 analyzed convective systems, the development location, lifetime, shape, size, propagation speed, and direction were identified. The BMD radar data coverage (600km × 600km) is divided into 3-regions: Northern, Central, and Southern, each being 600km east to west and 200km north to south. In general, precipitation systems develop in the Northern region and tend to move eastward. Precipitation system development in the Central and Southern regions is significant during the peak-monsoon months (June-August). Analysis of the radar data shows that the average time of maximum precipitation in the Northern region is 00-06 LST, in the Central region 06 LST and 15-18 LST, and in the Southern region 06-09 LST. The average lifetime of these systems is ~5.7 hours. Movement speed is ~5 ms^{-1}.

1. INTRODUCTION

Precise estimation of precipitation is essential because of such important consequences as flooding and drought, which are particularly common natural disasters in Bangladesh. Thunderstorms in Bangladesh cause death and huge damage due to flash floods every year. Matsumoto (1998) discussed the flood situation in Bangladesh and pointed out that heavy rainfall there together with other phenomena is one of the causes of floods. Precipitation is an invaluable source of renewable fresh water, the importance of which is vital to a region such as Bangladesh, which has an excessive amount of Arsenic in its ground water. Knowledge of the precise distribution and quantification of precipitation therefore may prove helpful for disaster prevention and water management. Agriculture-dependant and flood-affected Bangladesh also needs to obtain accurate information on the distribution and exact amount of precipitation on a monthly basis. However, there have been few detailed studies on the distribution of precipitation that have not been based on radar data for the entire country. A few investigations have used rain gauge data, Karmaker and Khatun (1995), Islam and Shafee (1998), and Wahid and Islam (1999), Wahid and Islam (2000). The information obtained from rain-gauges is not always sufficient for the quantification of the exact amount of precipitation, in particular, precipitation from small clouds that cannot be collected by the low density network of rain-gauges. A dense rain-gauge network is required to produce accurate estimates of precipitation, but this is impossible in remote areas and is very expensive for extensive coverage. Moreover, characteristics of precipitation such as growth location, lifetime, shape, size, propagation speed and the direction of precipitation systems are not obtainable from rain-gauge data, but they are very important for determining the mechanism of a monsoon system as well as model parameterization. Efforts to estimate surface rain over Bangladesh using every three-hours satellite data were made by Islam and Wahid (1999), but due to the low spatial and temporal resolutions of the data there were very poor correlations (average 0.3) between the rainfalls calculated from twelve rain-gauges and satellite data.

Radar is more advantageous than rain-gauges for determining various characteristics of precipitation over the country, which is still unknown by researchers and is essential for understanding the monsoon mechanism. Obtaining the actual precipitation distribution over Bangladesh and making BMD radar useful is a challeng-

KEY WORDS: Radar, Precipitation, Lifetime, Propagation speed and direction, Cloud development

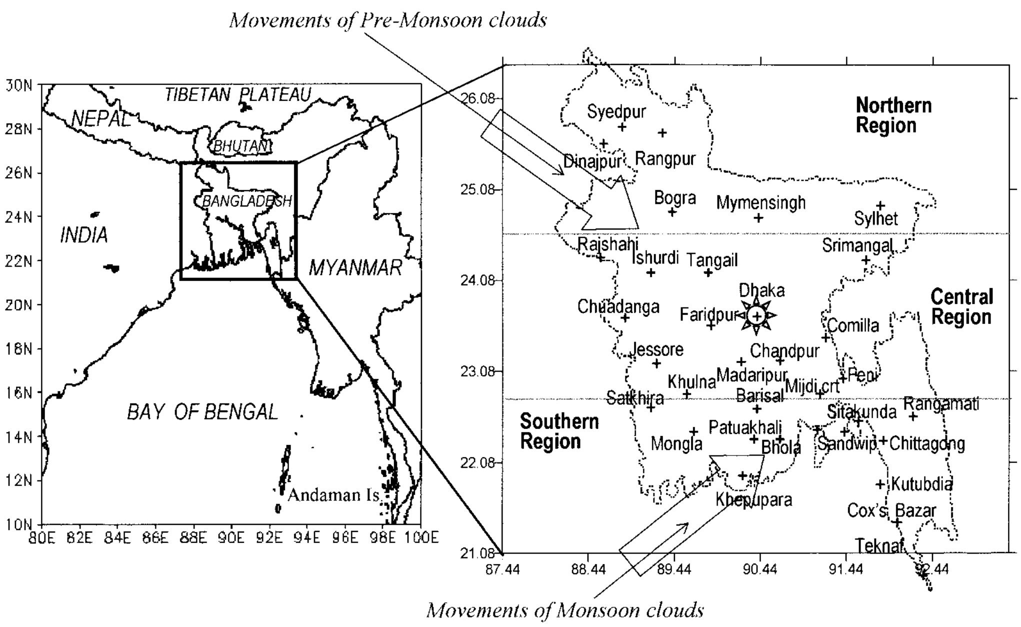

Fig. 1 Regional map showing BMD radar coverage (solid bold line, left panel). Rain-gauge locations (plus mark, right panel) throughout Bangladesh with the station names. The star at the center of Bangladesh shows the location of the BMD radar. The northern, central, and southern regions in the right panel are used for **Fig. 3**. The arrows are used for **Fig. 6**.

ing task. At present, there is no reliable way to retrieve precipitation from the Bangladesh Meteorological Department (BMD) radar data. There are two problems in using BMD radar data. One is that the data provide only a six-range rain status, the other is that a precise Z (Reflectivity) - R (Rain rate) relationship is needed for this region. In this work, attempts have been made to obtain the precipitation rate from the rain status of BMD radar data. Of course, rain-gauge data are also invaluable in calibrating the results obtained from radar data.

In addition, detailed examinations of precipitation systems by means of high spatial and temporal resolution data is essential to clarify the characteristics of the various types of mesoscale cloud systems that develop. Fortunately, high spatial and temporal resolution data for Year 2000 from radar over Bangladesh is available to analyze.

2. DATA USED AND ANALYSIS METHODS

Radar PPI (Plain Position Indicator) scans and rain-gauge rainfall data from the Bangladesh Meteorological Department (BMD) were used. The BMD collects 3-hour rain-gauge rainfall at 33 ground stations (plus marks) throughout the country (right panel, **Fig. 1**). It has installed an S-band weather radar (wavelength ~10cm, beam width 1.7°, elevation angle 0° at the center of the country (star in the right panel), which gives data coverage for a 600km × 600km rectangular area (**Fig. 1**). The BMD radar is designed to cover a radius of 400km, at present the effective radius being about 250km. The radar collects 2-3 minute-interval PPI scan data (reflectivity in dBZ) continuously for 1-hour with a 2-hour interval in operation. Radar data (pixel size 2.5km × 2.5km) are available for the analysis of the period April 16 to August 30, 2000.

The BMD radar collects reflectivity (dBZ) data and automatically converts it to the precipitation rate (mm/h) and stores data in six statuses; 1 (1-4mm/h), 2 (5-16mm/h), 3 (17-32mm/h), 4 (33-64mm/h), 5 (65-128mm/h), and 6 (>128mm/h). A procedure for retrieving the precipitation rate from the precipitation status is proposed. Radar data are sampled in a 10km grid box; each grid containing 16 pixels with a pixel resolution of 2.5km. The precipitation rate is retrieved from the precipitation status using the following equations.

The hourly precipitation rate *HPR* is defined as

$$HPR = (1/N)\sum_{I=1}^{I=N} R_I \quad \cdots\cdots\cdots\cdots(1)$$

where R_I is the instantaneous precipitation rate per unit area in a 10km grid box, and N is the total number of scans per hour with

$$R_I = (1/A)\sum_{r=1}^{r=6} S_r A_{R,r} \quad \cdots\cdots\cdots\cdots(2)$$

where A is the grid area (100km^2 in this analysis), S_r the status precipitation rate averaged from the possible values in a status, and A_R the rainy area corresponding to each status in the 10km grid box. For $r = 1, 2, 3, 4, 5$, and 6 the respective possible status values are 1-4, 5-16, 17-32, 33-64, 65-128, and 129mm/h. The respective S_r values obtained are 2.5, 10.5, 24.5, 48.5, 96.5, and 129 for $r = 1, 2, 3, 4, 5$, and 6.

As stated, BMD radar usually stores data continuously for one hour with a two hour interval in operation. Sometimes the radar is operated for several hours without a break. There are about 20 PPI data scans available during each hour of operation. Radar data are sampled in each PPI scan, and all the available PPI scans per hour are used to obtain the hourly value. Hourly values are used to obtain the daily and monthly values for different parameters. In the radar analysis, the Echo Embedded Area (EEA) is the pixel coverage for the rain rate ≥ 1mm/h. The Frequency of Occurrence (FO) is the number of echoes or echo-systems determined from all the PPI scans used. The echo length, lifetime, propagation speed, and direction of the echo systems are obtain subjectively from 2-3 minutes interval PPI scan data. The pattern-matching technique (Islam et al., 1997) is used to detect echoes during their lifetime. In this analysis, we have tried to use available continuous PPI scans, but when radar data are missing for a continuous two hours, Japanese Geo-stationary Meteorological Satellite (GMS-5) data were used as supporting information to detect the system in the next available PPI scan. Note that 30-minute interval GMS-5 data were available during the analysis period.

3. RESULTS AND DISCUSSION

3.1 Disasters in Bangladesh in 2000

In 2000, Bangladesh suffered from severe flooding and river erosion for the third consecutive year. Heavy monsoon rains began six weeks early that year with no sign of letting up. In 2000, monsoon-related disasters left some 4 million people homeless (Report 6). The nine worst-affected western districts were Satkhira, Jessore, Jenaidah, Chuadanga, Meherpur, Kustia, Magura, and Rajshahi. By August 11, 2000, approximately 1.26 million people in 41 sub-districts had been affected by flooding (ADRC Disaster Report, 2000/09). The usually dry southwest part of Bangladesh was affected in the last week of September 2000. Flooding killed more than 100 people, damaged 625,000 acres (250,000 hectares) of rice and other crops, and washed away nearly 675 miles (1,080km) of roads.

3.2 Precipitation in Bangladesh in 2000

Data coverage by the BMD radar is shown on the regional map (solid bold line, left panel, **Fig. 1**) together with the rain-gauge network over Bangladesh (right panel, **Fig. 1**). Plus marks represent the location of rain-gauge stations. The entire coverage (87.44°-93.33°E, 21.08°-26.45°N, right panel, **Fig. 1**) represents the rectangular coverage of the BMD radar data, whereas the radar center is positioned at the center of the country (star mark).

Time sequences for EEA, determined by the BMD radar that covers the whole of Bangladesh and surrounding areas are presented in **Fig. 2** together with the amount of rainfall averaged for 33 rain-gauge stations located throughout the country. With few exceptions, the EEA and rainfall provide very similar patterns for all the days. Some days, the EEAs were not as large as the high amount of rainfall; e.g., on May 23 and 24 the amounts of rainfall were high but the EEA was not very large. This situation continued for many days in July. The reasons for the differences include the fact that the low-density rain-gauge network (25-140km) throughout the country is insufficient for catching the rainfall from tiny clouds. Sometimes when the precipitation rate is very high, a small echo area provides a large amount of rainfall. Other reasons

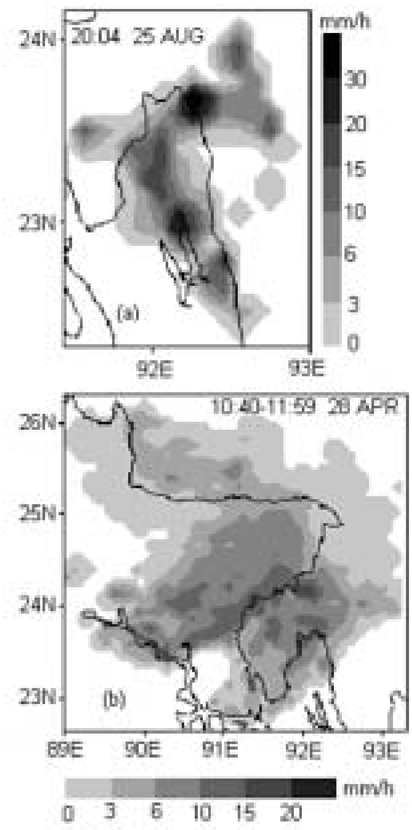

Fig. 3 (a) An instantaneous precipitation (mm/h) system at 20:04 LST on 25August. (b) An event from 10:40-11:59 LST on 28 April detected by the BMD radar in 2000.

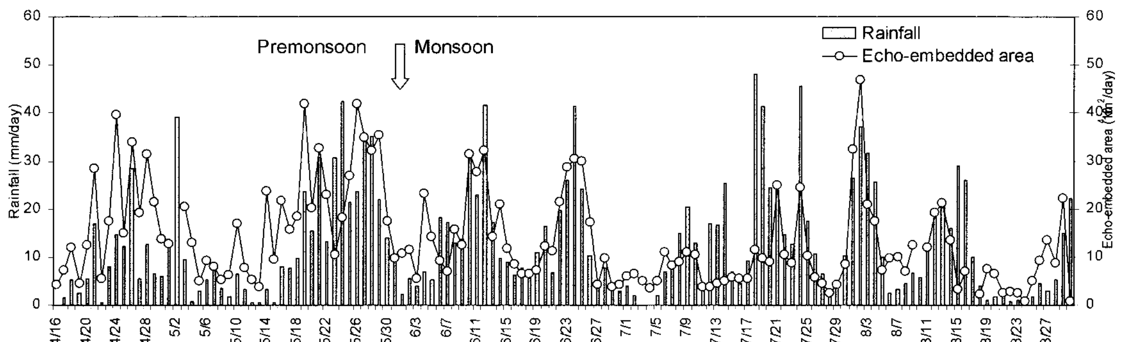

Fig. 2 Time sequences of daily rain-gauge rainfall (mm) showing echo-embedded area (EEA) detected by the BMD radar from 16 April to 30 August 2000.

Table 1. Characteristics of precipitation systems in Bangladesh as observed by BMD radar

Month	Growth region	Type	Shape	Maximum length (km)	Speed (m/s)	Movement direction	Traversed path (km)	Lifetime (hours)
April	Northern	Solitary	Oval	60	5.555	ESE	60	3.0
(Total 33	Northern	Merge	Line	200	4.542	SE	130	7.95
cases)	Northern	Merge	Arc	150	4.655	ESE	120	7.16
	Northern	Merge	Arc	140	6.924	E	170	6.82
	Northern	Solitary	Line	120	8.888	E	80	2.5
	Central	Merge	Arc	500	2.096	SE	200	26.5
May	Northern	Solitary	Oval	35	1.851	E	20	3.0
(Total 45	Northern	Merge	Line	210	0.529	W	20	10.5
cases)	Northern	Merge	Line	310	3.535	ESE	350	27.5
	Southern	Merge	Arc	300	1.811	NE	105	16.1
	Central	Solitary	Oval	90	2.834	ESE	100	9.8
	Central	Merge	Arc	220	4.448	SE	245	15.3
June	Southern	Solitary	Line	105	11.11	E	140	3.5
(Total 46	Central	Merge	Oval	210	1.937	NE	100	14.34
cases)	Northern	Merge	Arc	330	4.722	SE	340	20.0
	Northern	Solitary	Oval	55	4.938	E	80	4.5
	Central	Solitary	Oval	75	0.0	ML	0.0	3.5
	Southern	Merge	Line	140	9.444	NE	170	5.0
July	Southern	Solitary	Line	100	8.249	NNE	245	8.25
(Total 29	Northern	Solitary	Oval	90	1.207	ESE	50	11.5
cases)	Southern	Merge	Arc	160	5.910	NNE	150	7.05
	Central	Merge	Line	90	3.968	ESE	50	3.5
	Central	Solitary	Line	75	0.0	ML	0.0	3.0
	Southern	Merge	Line	140	1.307	SW	40	8.5
August	Central	Solitary	Line	215	4.629	E	75	4.5
(Total 32	Southern	Merge	Oval	95	2.5	SW	90	10.0
cases)	Northern	Merge	Line	580	6.547	ESE	330	14
	Southern	Solitary	Line	100	0.0	ML	0.0	2.0
	Southern	Merge	Arc	130	1.893	SW	75	11.0
	Central	Merge	Oval	140	5.228	NNW	160	8.5

N=Northward, S=Southward, E=Eastward, W=Westward, NE=Northeastward, SE=Southeastward, SW=Southwestward, NW=Northwestward, ESE=East-southeastward, NNW=North-northwestward, NNE=North-northeastward, ML=Motionless.

are given in Section 3.4.

3.3 Characteristics of precipitation in Bangladesh

For the five months (April-August) analyzed, 20846 PPI scans were available for analysis. On inspection of all the PPI scans, 185 cases were selected to determine such characteristics of the cloud clusters as location of growth, movement, shape, size, and lifetime; all of which are discussed here.

To understand the properties of the precipitation areas that developed over Bangladesh, an example of an instantaneous precipitation system at 20:04 LST on August 25(upper panel) and an event from 10:40 to 11:59 LST on April 28(lower panel), detected by the BMD radar are shown in **Fig. 3**. Rain-gauge data cannot recognize the fact that strong precipitation cores are surrounded by light precipitation regions. The strength of precipitation in **Fig. 3** is reduced because the PPI scans were processed in a 10km × 10km grid box. This analysis however, facilitates our understanding of the shapes, sizes, dimensions, patterns, movements, and lifetimes of precipitation systems.

In Bangladesh, pre-monsoon cloud systems usually develop in the northern part of the country, whereas monsoon cloud systems develop throughout the country and are associated with southwestern monsoon flow. Radar data coverage (600km × 600km) is divided into three regions: Northern (northern boundary to 200km south), Central (radar center to 100km north and 100km south) and Southern (southern boundary to 200km north), each measuring 600km east to west and 200km north to south as shown in the right panel of **Fig. 1**. Characteristics of the 185 analyzed precipitation systems were examined in the three predefined regions, some of which are given in **Table 1** as examples. Details of type and shape are described in Islam et al. (2004). The types are solitary and merged the shapes Oval, Line, and Arc. The preferred locations for the development of precipitation systems are presented in **Fig.**

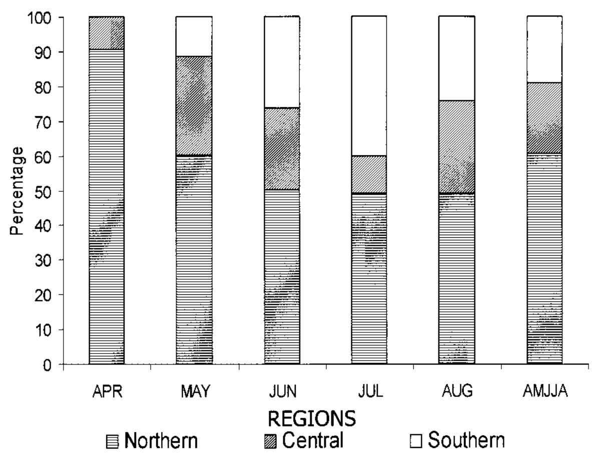

Fig. 4 Regional development precipitation systems analyzed for 185 cases in 2000.

4. In the Northern region, development is 90% in April, gradually decreasing to 50% in June, continuing to decrease until August. Precipitation systems tend to develop in the Southern region during the peak-monsoon months (JJA). In the Central region they tend to develop before and after the peak-monsoon month, July. On average, the preferred locations of the development of precipitation systems are Northern 60%, Central 21%, and Southern 19%.

Fig. 5 shows the size distribution and frequency of occurrence (FO) during the analysis period. Small size echoes contribute markedly below the cluster size of ~80km^2. Alternatively, convective activity becomes less organized for producing large clusters. Large clusters, however, contribute to the total precipitation due to their huge coverage.

Fig. 6 shows the propagation speed and direction of the 185 cases analyzed. Propagation speed varies from 0.4 to 19.8ms^{-1}, but on average is ~5ms^{-1}. The propagation direction, with few exceptions is almost east-northeast or east-southeast. The lifetime averaged of all 185 cases is ~5.7 hours (not shown) for the five month period from April to August (AMJJA).

3.4. Spatial distribution and times of maximum precipitation in Bangladesh

Fig. 7 presents the spatial distribution of the averaged daily rainfall (mm) as estimated from BMD radar data (left panel) and that estimated by the rain-gauge system (right panel) during the entire analysis period. The radar-estimated precipitation is calculated for a 100km^2 grid box with 2.5km pixel resolution at each rain-gauge site. Precipitation in the northeast and southeast parts of Bangladesh is significantly high. In the southeast corner, precipitation is low due to the long distance from the radar center, and one station is beyond radar coverage. There are a number of stations located outside the effective radar radius of 250km (circle, **Fig. 7**). Precipitation varies greatly with location in the country, and this distribution pattern coincides with rain-gauge results,

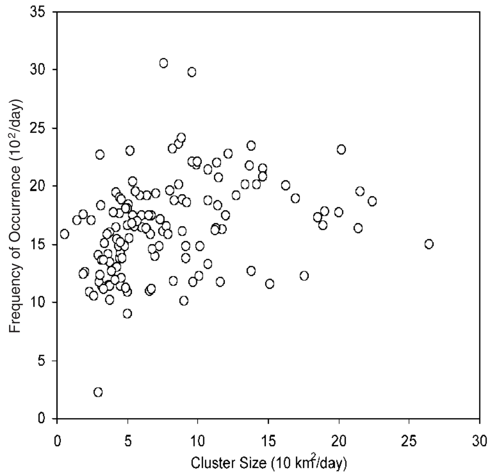

Fig. 5 Frequency of occurrence and cluster size determined by the BMD radar for 185 cases in 2000.

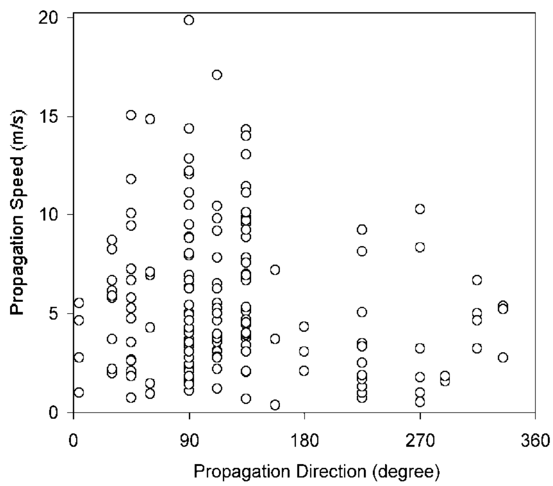

Fig. 6 Propagation speed and direction of the 185 cases analyzed in 2000.

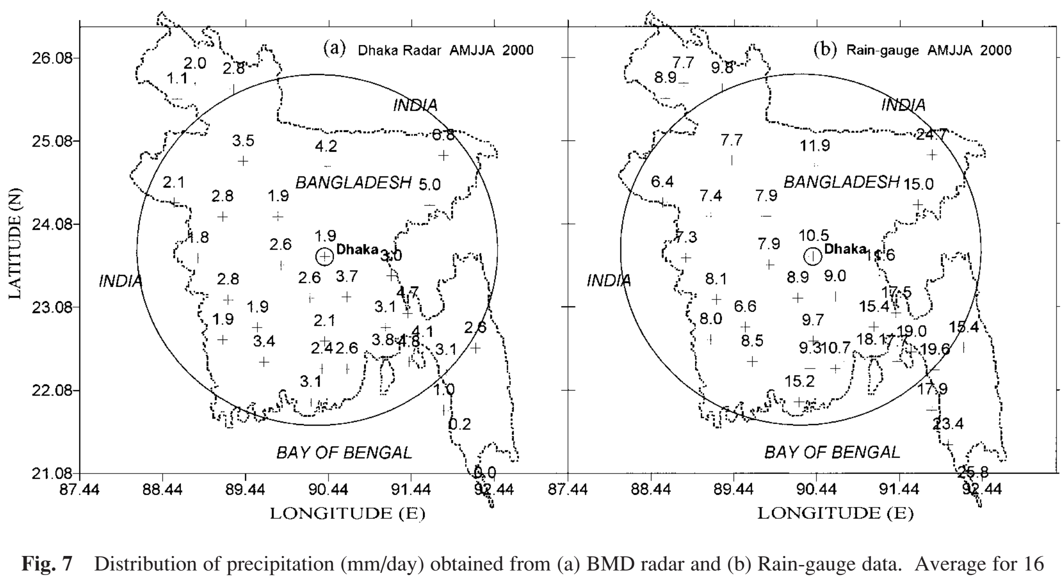

Fig. 7 Distribution of precipitation (mm/day) obtained from (a) BMD radar and (b) Rain-gauge data. Average for 16 April to 30 August 2000. Large circle represents the effective radius of BMD radar.

however, the rain-gauge provides a large amount of rainfall compared to radar. The discrepancy between the rainfall estimations based on the BMD radar and rain-gauge systems is due to the following: (i) radar rainfall is estimated from the areal average of 100km^2 grid boxes, whereas rain-gauges indicate point values; (ii) there is inconsistency in the temporal and spatial averaging of the radar and rain-gauge data; (iii) rain status is calculated based on a single Z-R relationship, details of spatial variation in the precipitation in Bangladesh are discussed in Islam et al. (2005). The northern border of Bangladesh, close to the Shillong Hills of India, is the region with the highest rainfall, the second highest rainfall occurring along the eastern border.

Fig. 8 gives the areal averaged precipitation rates determined by BMD radar in the three predefined regions. The rate has the maximum value at 00-06 LST in the Northern, at 06 and 15-18 LST in the Central, and at 06 LST in the Southern regions. These times are consistent with the results reported by Ohsawa et al. (2001) in an analysis of rainfall in Bangladesh but differ from the general characteristics reported for inland rainfall (e. g., Gray and Jacobson, 1977; Riehl, 1978; Meisner and Arkin, 1987; Al-bright et al., 1985; Short and Wallace, 1980; Mapes et al., 2003; Warner et al., 2003). In reality, the precipitation rates in the Northern and Southern regions tend to be much higher because these regions are beyond the BMD radar effective radius (250km). At any rate, the time of maximum rate is very important for determining exact diurnal variations in the tropical convective activity that developed in those regions. Details of diurnal cloud activity variation in Bangladesh are discussed in Islam et al. (2004). The nature of the diurnal precipitation cycle in Bangladesh is a morning peak at 0600 LST and a minimum at noon.

Rain-gauge rainfall versus radar rainfall scatter plot (left panel, **Fig. 9**) shows the relationships between them for the entire BMD radar coverage in different months (April-August) of 2000. The right panel in **Fig. 9** shows the relationships between rainfall calculated from the rain-gauge and radar data averaged from April-August 2000 inside the effective BMD radar coverage (<250km). Clearly, the radar data underestimates rainfall by about one-fourth that of the rain-gauge value. The correlation coefficients for the different months (0.63-0.89) are tabulated in **Table 2**. For all five months (April-August) the correlation coefficient is 0.64. The coefficient increases in magnitude (0.70) inside the effective radius of the BMD radar. If a new best-fit Z-R relationship is obtained for BMD radar that considers the same temporal and spatial aver-

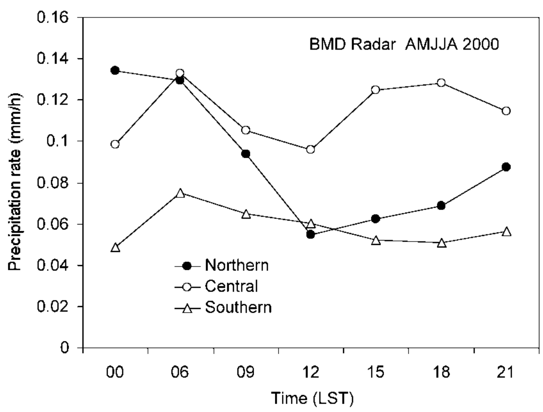

Fig. 8 Precipitation rates (mm/h) determined by the BMD radar at three regions in Bangladesh. Averages for 16 April to 30 August 2000 (AMJJA 2000).

Table 2. Relationship between rainfall obtained by radar and rain-gauge

Months	Regression Equation	Correlation Coefficient
April	Y=0.1952X+2.1434	0.678
May	Y=0.176X+1.4876	0.787
June	Y=0.212X-0.2329	0.892
July	Y=0.0779X+0.309	0.634
August	Y=0.1791X-0.0794	0.809
April-August (Radar data coverage)	Y=2.7751X+5.5005	0.644
April-August (Radar effective radius)	Y=0.178x+1.1376	0.70

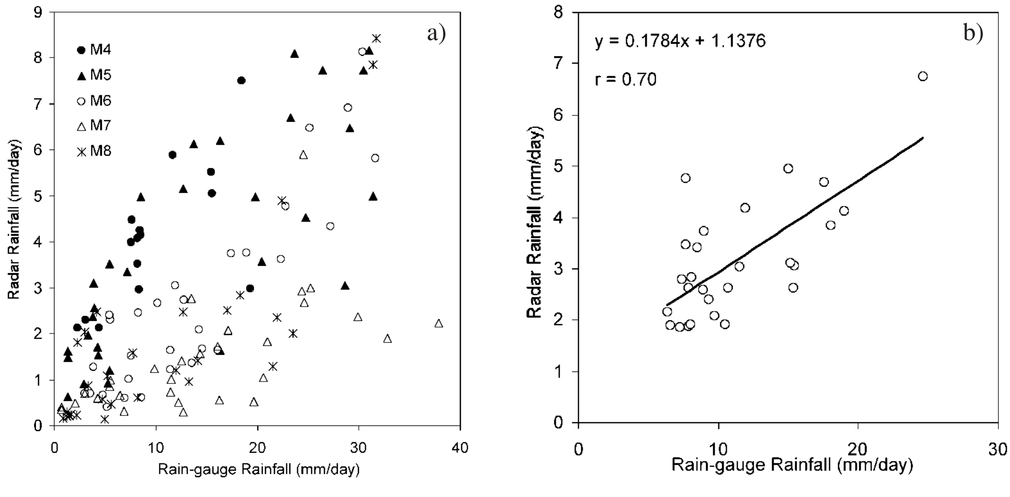

Fig. 9 Relationships between rainfall calculated by radar and rain-gauge data. a) in different months of 2000 and b) averaged for all months (March-August) in 2000 inside radar effective radius. Symbols in a) represent for different months (M4 = April, M5 = May, M6 = June, M7 = July, and M8 = August).

aging then the correlation further increases. The discrepancy in the rainfall values estimated by radar and rain-gauge, as shown in **Fig. 9**, will be reduced. Research in this topic on going.

4. CONCLUSIONS

The rain rate could be retrieved successfully from the BMD radar rain status and the correlation coefficients obtained between the rainfall as calculated by radar and rain-gauge data ranging from 0.63-0.89 for the different months, but there was substantial systematic underestimation. Analysis of 185 cases over five months (AMJJA) of 2000, revealed the characteristics of precipitation systems-development locations, sizes, shapes, dimensions, lifetimes, propagation speeds, and directions for the first time in Bangladesh. Most of the precipitation systems were found to develop in the Northern region then move east-northeast or east-southeast. The average lifetime of these systems is ~5.7 hours and the speed of movement ~5 m/s. Midnight to morning (00-06 LST) is the optimum period for maximum precipitation in the Northern region of Bangladesh whereas it is 06 LST in the Southern region. The optimum times in the Central region are 06 LST and 15-18 LST. The above information on precipitation systems in Bangladesh is important for model parameterization, which should prove useful for forecasting that can be used for water management and for the prevention of natural disasters. An up-grade of the BMD radar system has been proposed, and in the near future it will be possible to obtain quantitative amounts of rainfall from BMD radar data.

ACKNOWLEDGEMENTS

We thank the BMD for providing the radar and rain-gauge data collected under the JICA "Japan Bangladesh Joint Study Project-Phase II", grant no 11691151. One of the authors Nazrul Islam was fully supported during this work by Islamic Development Bank (IDB), Saudi Arabia, under an IDB merit scholarship program. Dr. Jun Matsumoto, the University of Tokyo is thanked for his assistance in the copying of the radar data. We are also grateful to Takeshi Maesaka of Nagoya University for his invaluable help in the data processing. Disaster information on Bangladesh can be obtained at http://www.ifrc.org.

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