*Mausam*. (1995). 46. 1. 47-56

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# Variability and probabilistic estimates of rainfall extremes in Bangladesh during the southwest monsoon season

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**सार** — इस अध्ययन में, दक्षिण-पश्चिम मानसून ऋतु के दौरान बंगलादेश में औसत मासिक वर्षा के क्षेत्रीय एवं सामयिक वितरण तथा उसकी परिवर्तिता और अधिकतम वर्षा की संभाव्यता के आकलनों के क्षेत्रीय वितरण का वर्णन किया गया है। अधिकतम वर्षा की संभाव्यता का अभिकलन दो समयावधियों के लिए किया गया है : (क) 4 वर्षों में से एक वर्ष के लिए और (ख) 10 वर्षों में से एक वर्ष के लिए, जिसमें अधिकतम वर्षा की अपेक्षाकृत कम घटनाएं शामिल की गई हैं। बंगलादेश के अधिकतर स्थानों में औसत मासिक वर्षा जून से जुलाई तक बढ़ती है और तत्पश्चात् सितंबर तक कम होती रहती है। बहुत से स्थानों में जुलाई तक वर्षा में वृद्धि के साथ ही वर्षा की परिवर्तिता कम होती जाती है और तत्पश्चात् सितंबर तक बढ़ती रहती है। अध्ययन से पता चला कि औसत और अधिकतम वर्षा की संभाव्यता देश के दक्षिण-पूर्वी और उत्तर-पूर्वी भागों में सर्वाधिक होती है जहां कि वर्षा में परिवर्तन कम होता है तथा वर्षा निश्चित रूप में होती है। बंगलादेश के मध्य भाग में करीब 23 और 24 उ. अक्षांशों के मध्य एक ऐसा क्षेत्र है जहां कम वर्षा होती है। उत्तर-पूर्वी बंगलादेश में वर्षा की प्रवणता अधिकतम है और कम वर्षा की अपेक्षा अधिक वर्षा होने की संभावना ज्यादा होती है।

**ABSTRACT.** The present study describes the temporal and spatial distributions of mean monthly rainfall and its variability together with the spatial distributions of the probabilistic estimates of rainfall extremes over Bangladesh during the southwest monsoon season. The probabilistic rainfall extremes have been computed for two time scales : (*a*) in 1 year out of 4 years, and (*b*) in 1 year out of 10 years — representing relatively less extreme events and extreme events respectively. The mean monthly rainfall increases from June to July at most places over Bangladesh and then decreases up to September. The variability of rainfall decreases with increasing rainfall up to July at many places and then increases up to September. The study also reveals that the mean rainfall and the probabilistic rainfall extremes are maximum over the southeastern and northeastern parts of the country where the variability of rainfall is low and the rainfall is reliable. There exists a belt of low rainfall over the central part of Bangladesh roughly between 23°N and 24°N. The rainfall gradients are maximum over northeastern Bangladesh. and the gradients of the probabilistic high rainfall are more than those of the probabilistic low rainfall in this area.

**Key words** — Rainfall. Probabilistic. Variability. Maximum. Minimum. Distribution pattern. Temporal. Extreme.

## 1. Introduction

Rainfall is the main linking component in the hydrologic cycle. There is a tremendous increasing need for fresh water use in all types of man's economic activities. For this reason. the rainfall analysis and its distribution are very important. The quantitative analysis of rainfall, its spatial and temporal variations have wide applications in agriculture and hydrology (Anderson 1970. Carr 1972. Das 1968. Kutiel 1982. Kromm 1985 and Vines 1986).

Rainfall amounts generally vary from place to place and from one month to another. For the purpose of agricultural. industrial and hydrological planning and water management. it is very important to know the average amount and the variability of rainfall which can be expressed in terms of its probabilistic occurrence. The spatial variation of the probabilistic occurrence of low and high rainfall extremes is very significant due to the fact that such extreme amounts affect both agriculture and hydrology of a given region. The technique of probabilistic analysis was effectively used by Glover and Robinson (1974) for mapping the reliability of annual rainfall in East Africa, by Ahmed (1978. 1989), and Sanderson and Ahmed (1979) for the probabilistic estimation of water balance components and probabilistic estimates of rainfall extremes in Bangladesh during the pre-monsoon season.

The southwest monsoon enters Bangladesh through the southeastern region, *i.e.*, Cox's Bazar. then moves northwards up to Shillong plateau across Sylhet region and finally moves westward (Ahmed and Karmakar 1993). The mean arrival dates of the summer monsoon in the extreme southeastern coastal part and in the extreme



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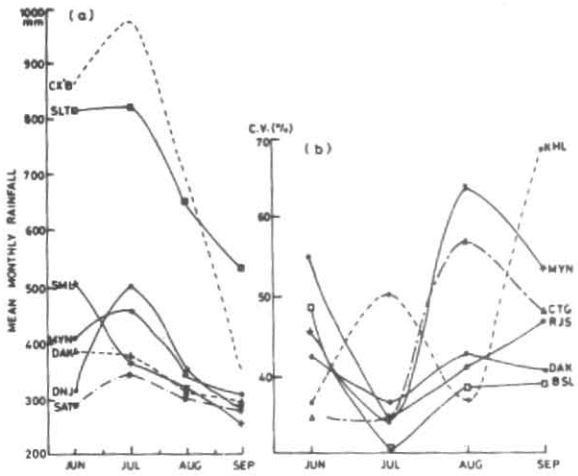



Figs. 1 (a & b). Temporal variation of : (a) mean monthly, and (b) coefficient of variation of monthly rainfall during the southwest monsoon season for some selected stations of Bangladesh

northwestern part of Bangladesh are 2 June and 15 June respectively. Mean withdrawal dates of the summer monsoon from the extreme northwestern part and extreme southeastern part of the country are 30 September and 17 October respectively. During the southwest monsoon, Bangladesh receives about 75-80% of the total annual rainfall. The life-style and the socio-economic condition of the people of Bangladesh are governed mainly by this rainfall. Since the economy of the country mainly depends on agriculture which, in turn, relies on rainfall, the study of rainfall pattern is very important for its agricultural planning. When rains fail or are too abundant, crops may be seriously damaged. Excessive rains persisting for a few days may even prevent crops from maturing. On the other hand, if the rainfall is below normal but properly distributed, it may help the farmers to grow crops successfully. The present paper is aimed at gaining insight into the analysis of variability and probabilistic occurrences of less extreme and extreme rainfall amounts in Bangladesh on a monthly basis during the southwest monsoon season.

## 2. General synoptic condition during the southwest monsoon season

The heat low over northern India and neighbourhood is a quasi-stationary feature of the southwest monsoon months. This is the seasonal low. From the seasonal low, a trough extends southeastwards to Gangetic West Bengal, sometimes upto the northeast Bay. The trough line, known as 'monsoon axis', runs at the surface from Ganganagar to Calcutta (Rao 1976) with west to southwest winds to the south and easterlies to the north of the trough line. This trough line is also seen in the upper air flow patterns up to about 6 km, the trough line sloping southwards with height. Rainfall is concentrated near the trough line and over the entire southern part of Bangladesh and India. When the axis of the monsoon trough moves towards the Himalayas and lies there, the rain on the plains decreases and a 'break' in the monsoon occurs, while the rain on the hills increases and heavy rain occurs at the foot of the Himalayas, *i.e.*, over the northern parts of India and Bangladesh. Sometimes the axis of the monsoon trough passes across northern Bangladesh and exists there for a longer period when northern Bangladesh receives copious rainfall. The orographic barriers of Myanmar, Chittagong Hill-tracts, Sylhet the Himalayas and the Tibetan plateau play an important role in channelling the monsoon current and thus contribute to the formation of monsoon trough (Huq 1978).

During the southwest monsoon, low pressure waves frequently travel from the east to the west over upper Myanmar, the north Bay of Bengal and Bangladesh. These low pressure waves, locally kown as 'easterly waves', have been traced to have their origins in the China Sea and sometimes in the Pacific. Often a disturbance is found in the form of a cyclonic vortex superimposed upon the prevailing monsoon winds. On occasions, such a vortex may develop into a tropical depression or storm mostly associated with the passage of an easterly low pressure wave (Huq 1978). As the monsoon depression deepens in the Bay and moves westwards, moderate to heavy rain occurs over southern part of Bangladesh. The main synoptic factors responsible for intense rain storms over Bangladesh are the monsoon depressions and 'break' in the monsoon. The position and intensity of the upper tropospheric anticyclone over the Tibetan plateau and adjoining area and easterly jets over India appear to control, to a considerable extent, the activity of the monsoon over this region (Flohn 1960).

## 3. Data

(*i*) *Source* : Bangladesh Meteorological Department.

(*ii*) *Stations* : 20 [as shown in Fig. 3 (a)].

TABLE 1

**Mean monthly rainfall (mm) during the southwest monsoon over Bangladesh for the period 1961-1990**

| Station | June | | July | | August | | September | |
|---|---|---|---|---|---|---|---|---|
| | $n$ | $\bar{x}$ | $n$ | $\bar{x}$ | $n$ | $\bar{x}$ | $n$ | $\bar{x}$ |
| Sylhet | 27 | 816.89 | 29 | 821.79 | 29 | 650.00 | 28 | 533.96 |
| Srimangal | 24 | 505.67 | 23 | 368.70 | 25 | 324.96 | 24 | 255.13 |
| Comilla | 26 | 403.35 | 26 | 430.15 | 26 | 351.19 | 27 | 259.70 |
| Rangamati | 28 | 521.25 | 29 | 602.03 | 28 | 431.18 | 29 | 277.34 |
| Chittagong | 28 | 599.57 | 28 | 798.46 | 27 | 515.85 | 28 | 253.64 |
| Cox's Bazar | 29 | 867.10 | 29 | 976.69 | 30 | 700.10 | 29 | 354.07 |
| Sandwip | 23 | 620.83 | 23 | 852.13 | 24 | 695.33 | 23 | 407.35 |
| Maijdee Court | 21 | 526.00 | 21 | 675.86 | 22 | 697.32 | 22 | 413.00 |
| Faridpur | 28 | 356.50 | 25 | 341.84 | 28 | 292.50 | 30 | 256.40 |
| Dhaka | 29 | 385.72 | 28 | 377.07 | 29 | 312.03 | 27 | 296.33 |
| Mymensingh | 24 | 412.83 | 24 | 458.95 | 25 | 348.40 | 26 | 311.81 |
| Khulna | 22 | 369.09 | 22 | 336.68 | 23 | 339.09 | 20 | 251.25 |
| Barisal | 29 | 403.07 | 27 | 389.63 | 29 | 366.76 | 29 | 298.52 |
| Satkhira | 26 | 289.07 | 26 | 348.96 | 26 | 302.50 | 26 | 284.65 |
| Jessore | 28 | 303.64 | 29 | 303.76 | 29 | 295.59 | 27 | 231.74 |
| Ishurdi | 26 | 297.42 | 27 | 360.70 | 26 | 266.69 | 26 | 247.85 |
| Bogra | 28 | 328.54 | 28 | 421.00 | 28 | 277.18 | 29 | 255.00 |
| Rajshahi | 23 | 271.91 | 25 | 351.96 | 25 | 280.76 | 25 | 247.04 |
| Dinajpur | 20 | 313.65 | 19 | 501.53 | 22 | 354.45 | 21 | 283.33 |
| Rangpur | 27 | 411.37 | 27 | 495.11 | 24 | 359.13 | 27 | 320.30 |

$\bar{x}$ — Mean rainfall (mm). $n$ — No. of years.

(*iii*) *Period of observations* :

(*a*) June through September.

(*b*) 1961 through 1990 (*i.e.*, for 30 years).

(*iv*) *Variable* : Monthly rainfall (mm).

It may be noted that for some stations, observations are not available for a few years and some stations have been established much after 1961. These data are considered as missing and have not been used in the statistical analysis.

## 4. Methodology

The mean monthly rainfall amounts and their standard deviations have been computed for June through September during the period 1961 through 1990. The measure of variability of a distribution about the mean is the Coefficient of Variation (*CV*) which can be expressed (in %) as :

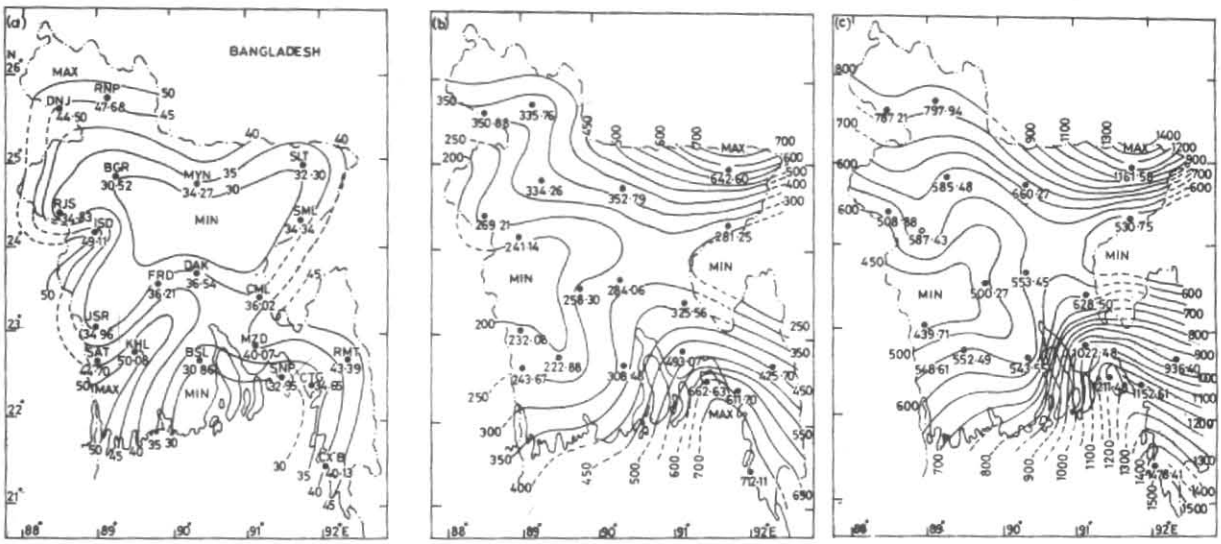
$$CV = \frac{100 \times \sigma}{\bar{x}} \qquad (1)$$

where, $\sigma$ is the standard deviation of monthly rainfall and $\bar{x}$ is the mean monthly rainfall.

The probability of an amount of rainfall in some expected percentage can be obtained by the concept of $z$ score (Alder and Roessler 1964), which can be written as :

$$x' = \bar{x} \pm z\,\sigma \qquad (2)$$

where, $x'$ is the probabilistic estimate of the variable. For two time scales, the formulae for the computation of probabilities are given below :




Figs. 2 (a-c). (a) Coefficient of variation (%) of rainfall in July. (b & c) probabilistic low and high rainfall (mm) in 1-year out of 4 and 10 years in July respectively over Bangladesh

(*i*) In 1 year out of 4 years : $x' = \bar{x} \pm 0.675\,\sigma$

(*ii*) In 1 year out of 10 years : $x' = \bar{x} \pm 1.28\,\sigma$

75% of the occurrence will be below $(\bar{x} + 0.675\,\sigma)$ and 75% of the occurrence will be above $(\bar{x} - 0.675\,\sigma)$. These are the cases of less extreme events and are relatively frequent events that will occur in 1 year out of 4 years. Similarly, 90% of the occurrence will be below $(\bar{x} + 1.28\,\sigma)$ and 90% of the occurrence will be above $(\bar{x} - 1.28\,\sigma)$. These are the cases of extreme events which will occur in 1-year out of 10 years.

For the study of the probability, it is necessary that the data have a normal distribution. To test the normality of monthly rainfall from June to September of 30 years from 1961 to 1990, Cornu test (Geary 1936) has been used for four sample stations, namely, Dhaka, Chittagong, Khulna and Rajshahi. It has been found that the monthly rainfall data of these stations are normally distributed within 95% level of significance.

## 5. Results and discussion

### 5.1. *Temporal and spatial variation of mean monthly rainfall*

5.1.1. *Temporal variation* — The mean monthly rainfall of each station has been computed for each month of the southwest monsoon period. The mean values are given in Table 1. The temporal variation of the mean monthly rainfall over 20 stations have been studied by graphical method. Some of the results are given in Fig. 1 (a). Over 15 stations, the mean monthly rainfall has been found to increase from June to July and then to decrease up to September except over Maijdee Court, where the mean rainfall is maximum in August. The mean monthly rainfall over stations, *viz.*, Srimangal, Khulna, Barisal, Dhaka and Faridpur are found to have maximum value in June with the decreasing trend in the subsequent months.

5.1.2. *Spatial variation* — The distributions of mean monthly rainfall over Bangladesh during June through September have been studied. It has been found that the mean rainfall in June, as shown in Fig. 3 (b), is maximum in the southeastern and northeastern regions having the value of more than 800 mm with maximum values 867.10 and 816.89 mm at Cox's Bazar and Sylhet respectively, and the mean rainfall is minimum (about 250 mm) in the western part of the country with the minimum values of 271.91 and 297.42 mm at Rajshahi and Ishurdi respectively. This type of rainfall distribution can be attributed to the advancing nature of the southwest monsoon over Bangladesh. The Fig. 3 (b) also shows that there exists a belt of low mean rainfall between latitudes 23°N and 24°N. The distribution pattern in July [as shown in Fig. 3 (c)] differs slightly from that in June which may be due to the spreading of the monsoon with its on-going activity over the whole of Bangladesh. The maximum rainfall regions are the southeastern and northeastern parts of the country having the maximum values of 976.69 and 821.79 mm at Cox's Bazar and Sylhet

TABLE 2

**Coefficient of variation (%) of rainfall during the southwest monsoon over Bangladesh**

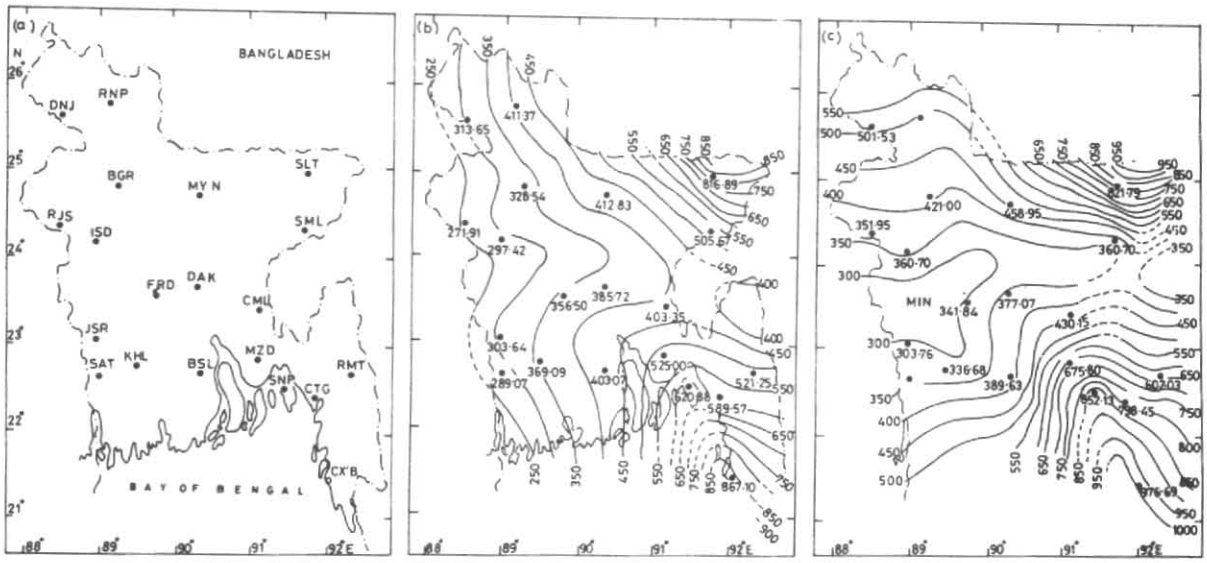
| Station | Coefficient of Variation (%) | | | |
|---|---|---|---|---|
| | June | July | August | September |
| Sylhet | 28.07 | 32.30 | 34.31 | 45.57 |
| Srimangal | 42.82 | 34.34 | 30.06 | 50.21 |
| Comilla | 44.63 | 36.02 | 46.27 | 52.94 |
| Rangamati | 38.49 | 43.39 | 37.97 | 38.05 |
| Chittagong | 34.81 | 34.65 | 56.52 | 47.78 |
| Cox's Bazar | 34.51 | 40.13 | 43.46 | 53.95 |
| Sandweep | 40.54 | 32.94 | 36.43 | 47.30 |
| Maijdee Court | 35.79 | 40.07 | 35.70 | 37.23 |
| Faridpur | 33.06 | 36.21 | 49.43 | 53.40 |
| Dhaka | 42.57 | 36.54 | 42.51 | 40.29 |
| Mymensingh | 45.50 | 34.27 | 63.34 | 52.92 |
| Khulna | 36.62 | 50.08 | 36.67 | 67.85 |
| Barisal | 48.58 | 30.86 | 38.71 | 38.99 |
| Satkhira | 57.19 | 44.70 | 32.57 | 57.57 |
| Jessore | 52.88 | 34.96 | 47.74 | 52.21 |
| Ishurdi | 70.36 | 49.11 | 55.41 | 53.27 |
| Bogra | 56.21 | 30.52 | 48.51 | 48.36 |
| Rajshahi | 54.88 | 34.83 | 40.99 | 46.83 |
| Dinajpur | 65.67 | 44.50 | 55.23 | 41.31 |
| Rangpur | 46.44 | 47.68 | 42.99 | 47.19 |

respectively, and the region of minimum rainfall is the central western region having the minimum value of about 300 mm with 303.76, 341.84 and 351.96 mm at Jessore, Faridpur and Rajshahi respectively. In the month of August, the mean monthly rainfall has almost similar distribution pattern as in July, the maximum values being over the same are as in June and July with 700.10 and 650.00 mm at Cox's Bazar and Sylhet respectively, and the minimum value being 250 mm over the central western part of the country. The minimum values are 266.69, 280.76, 292.50 and 295.50 mm at Ishurdi, Rajshahi, Faridpur and Jessore respectively. In September, the mean rainfall has almost similar distribution pattern in respect of maximum and minimum rainfall regions. In this month, the mean rainfall has further decreased, the primary zone with maximum rainfall is located over the Sylhet region with 533.96 mm at Sylhet and the secondary maximum rainfall being located over the southern part of Bangladesh with 413.00 mm at Maijdee Court. The mean rainfall is minimum (about 200 mm) over the central western region in September. The minimum values of rainfall are 231.74, 247.04 and 247.85 mm at Jessore, Rajshahi and Ishurdi respectively. The study of the spatial distribution of mean monthly rainfall during June-September substantiates that there exists a belt of low rainfall over the central Bangladesh roughly between latitudes 23°N and 24°N, and this may be due to the existence of the monsoon axis over the southern and northern parts of the country for a longer period. The areas of maximum mean rainfall are also the same for all the months. This may be due to the fact that orography plays an important role in rainfall distribution over these regions and that these areas are the eastern end of the monsoon trough where more influx of moisture from the Bay of Bengal and its subsequent convergence take place.

### 5.2. *Variability of monthly rainfall*

5.2.1. *Temporal variation* — The coefficient of variation of monthly rainfall has been computed for the months of June through September and is given in Table 2. The temporal variation of the CV for each station has been studied by graphical method, some of which are given in Fig. 1 (b). It is seen that the curves show no definite pattern of variation. However, at 10 stations, CV of monthly rainfall has been found to decrease from June attaining the minimum value in July and then has an increasing trend in the subsequent month. Four stations such as Cox's Bazar, Faridpur, Khulna and Sylhet have minimum CV in June, and 5 stations, namely, Srimangal, Rangamati, Maijdee Court, Satkhira and Rangpur, have minimum CV in August whereas only Dinajpur has the minimum CV in September. The coefficient of variation of rainfall is maximum in June or in September in most of the places of Bangladesh as can be seen from Table 2.

5.2.2. *Spatial variation* — The spatial distributions of the variability, coefficient of variation, of monthly rainfall during June through September have been studied separately for each month. The patterns of distribution are more or less the same for all months. The variability of rainfall in June ranges between 28 and 71%. The minimum variability of 30-35% is found over southern Bangladesh and along a belt from Khulna-Faridpur region to Sylhet region with the minimum values of 34.51, 34.81 and 28.07% at Cox's Bazar, Chittagong and Sylhet respectively. The variability of rainfall in June increases in the western part and Chittagong hill tracts having 65-70% in the western Bangladesh and




Figs. 3 (a-c). (a) Station location map of Bangladesh, (b & c) distribution of mean monthly rainfall (mm) over Bangladesh in June and July respectively

40-50% in the Chittagong hill tracts. The maximum values of 70.36 and 65.67% are found at Ishurdi and Dinajpur respectively. The maximum variability over the western part of Bangladesh may be due to the nature of the advancing southwest monsoon. In July, the variability, in general, ranges between 30 and 50% [Fig. 2 (a)], having the maximum variability over the western and northwestern parts of the country with 50.08 and 49.11% at Khulna and Ishurdi respectively, and the minimum variability is observed over the southern part of Bangladesh and over the area between Mymensingh and Dhaka. The minimum values are 30.86, 32.95, 30.52 and 32.30% at Barisal, Sandwip, Bogra and Sylhet respectively. In August, the rainfall variability ranges between 30 and 64%. The minimum variability lies over Dhaka-Srimangal-Sylhet region and south of Satkhira-Barisal-Sandwip region with 30.06, 32.57 and 35.70% at Srimangal, Satkhira and Maijdee Court respectively. The maximum variability exceeding 55% lies over Mymensingh, Dinajpur, Ishurdi-Jessore and Chittagong hill tracts with 63.34, 55.23, 55.41 and 56.52% at Mymensingh, Dinajpur, Ishurdi and Chittagong respectively. In this month, a clear belt of minimum variability in the range of 30-40% has been found over Rangpur-Rajshahi-Bogra-Dhaka-Srimangal-Sylhet region. This may be due to the presence of the monsoon axis over this region for a longer period in the month of August. In September, the variability of rainfall ranges between 37 and 68%, the maximum variability being over the southwestern part of Bangladesh with 67.85% at Khulna and 57.67% at Satkhira. The minimum variability lies over the area south of Barisal and Maijdee Court where the variabilities are 38.99 and 37.23% respectively. The variability ranges between 47 and 54% over the Chittagong-Cox's Bazar region. A belt of variability of about 40% has been found over the Rangpur-Dinajpur-Rajshahi-Bogra-Dhaka-western Sylhet region having 41.31% at Dinajpur and 40.29% at Dhaka.

### 5.3. *Probabilistic monthly rainfall*

Probabilistic high and low rainfall amounts for each month of the southwest monsoon season have been computed for two time scales, *viz.*, in 1 year out of 4 and 10 years. Stationwise results are given in Table 3. The spatial distributions of these rainfall amounts over Bangladesh have been studied and discussed in the following sub-sections. The distribution patterns of probabilistic monthly rainfall are almost similar in all the months of the southwest monsoon period. Figs. 2 (b & c), for example, show the distribution patterns of the probabilistic monthly rainfall in July.

5.3.1. *Probabilistic monthly rainfall in June* — From the distribution of probabilistic high rainfall over the country, it is seen that in 1 year out of 4 years, the maximum rainfall areas are the southeastern and northeastern parts of the country having 1069.10 mm at Cox's Bazar and 971.69 mm at Sylhet. The western part of Bangladesh receives less rainfall ranging from 372.64 mm at Rajshahi to 412.01 mm at Jessore (Table 3). There exists a belt of minimum rainfall over the central Bangladesh

between about 23° and 24°N. The maximum probabilistic high values of rainfall over the northeastern region may be due to the orographic effects and passing of the monsoon axis through this region most of the time, and that over the southeastern region may be due to: (*a*) the orographic effects, (*b*) the movement of the monsoon axis from the south to the north when this area gets the first impact of the monsoon rain spells, and (*c*) the formation of the monsoon low/depression over north Bay and their subsequent movements towards west/northwest when steep pressure gradients exist over this region. The distribution pattern of the probabilistic high rainfall amounts in 1 year out of 10 years is the same as that in 1 year out of 4 years, but the rainfall amounts are higher ranging from 462.92 mm at Rajshahi in the west to 1050.15 mm at Cox's Bazar in the southeast and 1110.43 mm at Sylhet in the northeast. The belt of minimum rainfall also exists over the same area.

The probabilistic low rainfall in 1 year out of 4 years ranges from 156.16 to 665.10 mm, having the maximum and minimum values over the same areas as mentioned earlier. The minimum values of 156.16, 171.18 and 195.27 mm are found at Ishurdi, Rajshahi and Jessore respectively, while the maximum values of 665.10 and 662.09 mm are found at Cox's Bazar and Sylhet respectively. In 1 year out of 10 years, the probabilistic low rainfall ranges from 29.55 to 523.35 mm with almost similar pattern of distribution. In the west, 29.55 is at Ishurdi, and 484.05 and 523.35 mm are found at Cox's Bazar and Sylhet in the southeastern and northeastern parts of the country. In all of the above distributions of probabilistic rainfall, it has been found that the rainfall gradients are maximum in the northeastern part of Bangladesh and that the probabilistic high rainfall gradients are much more than the probabilistic low rainfall gradients.

5.3.2. *Probabilistic monthly rainfall in July* — In July, the distributions of probabilistic high rainfall amounts lie in the range of 375.45 to 1241.27 mm in 1 year out of 4 years and 439.71 to 1478.41 mm in 1 year out of 10 years (Table 3). In 1 year out of 4 years, the maximum rainfall of 1241.27 and 1000.98 mm are found at Cox's Bazar and Sylhet respectively, while the minimum rainfall values of 375.45, 425.38, 434.71 and 480.26 mm lie at Jessore, Faridpur, Rajshahi and Ishurdi respectively. The maximum rainfall over the Cox's Bazar region may be due to the higher variability at Cox's Bazar ($\sigma$ = 391.97, CV = 40.13%) than that at Sylhet ($\sigma$ = 265.46, CV = 32.30%) and higher mean rainfall at Cox's Bazar ($\bar{R}$ = 976.69) than that at Sylhet ($\bar{R}$ = 821.79). The rainfall gradients are also maximum over the Sylhet region. It may also be noted that the probabilistic high rainfall amounts in July are greater than that in June at most of the stations. In 1 year out of 10 years, maximum rainfall at Cox's Bazar and Sylhet are 1478.41 and 1161.58 mm respectively.

The distribution of the probabilistic low rainfall amounts for July in 1 year out of 4 and 10 years shows the same distribution patterns and rainfall gradients as mentioned earlier. In 1 year out of 4 years, the range of the probabilistic low rainfall over the country is 222.88-712.11 mm and it is 120.87-492.78 mm in 1 year out of 10 years as can be seen from Table 3.

The belt of minimum rainfall exists between about 23°N and 24°N in all the above spatial distributions.

5.3.3. *Probabilistic monthly rainfall in August* — The distributions of the probabilistic high and low rainfall over Bangladesh in 1 year out of 4 and 10 years for the month of August are similar to the patterns of distribution as in the earlier months of the monsoon season. The probabilistic high and low rainfall values have been found to decrease in August (Table 3) over the country, and this decrease in rainfall is due to the fluctuations in monsoon intensity in August. The ranges of the probabilistic high rainfall in August are 358.45-905.50 and 428.08-1089.59 mm in 1 year out of 4 and 10 years respectively. The ranges of the probabilistic low rainfall over the country are 166.95-529.29 and 77.56-378.69 mm in 1 year out of 4 and 10 years respectively. The distribution patterns have also shown that the gradient of high probabilistic rainfall over the Sylhet region are more than those of the probabilistic low rainfall. The belt of minimum rainfall also exists between 23°N and 24°N.

5.3.4. *Probabilistic monthly rainfall in September* — The distribution of the probabilistic high and low rainfall amounts over Bangladesh in 1 year out of 4 and 10 years have been studied for the month of September. The distribution patterns, the areas of maximum and minimum rainfall remain the same as in the earlier months, but the gradients, in general, over the Sylhet region have become less as compared to the months of June through August. This may be due to the decrease in the intensity of the southwest monsoon which starts retreating at the end of September from the north or northwestern parts of the country. The ranges of the probabilistic high rainfall are 313.40-689.20 and

TABLE 3

**Probabilistic monthly rainfall (mm) during the southwest monsoon over Bangladesh**

| Station | Probabilistic monthly rainfall | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | | | July | | | | August | | | | September | | | |
| | In 1 year out of 4 years | | In 1 year out of 10 years | | In 1 year out of 4 years | | In 1 year out of 10 years | | In 1 year out of 4 years | | In 1 year out of 10 years | | In 1 year out of 4 years | | In 1 year out of 10 years | |
| | L | H | L | H | L | H | L | H | L | H | L | H | L | H | L | H |
| Sylhet | 662.09 | 971.69 | 523.35 | 1110.43 | 642.60 | 1000.98 | 482.00 | 1161.58 | 499.48 | 800.52 | 364.57 | 935.43 | 369.73 | 689.20 | 222.54 | 845.38 |
| Srimangal | 359.51 | 651.83 | 228.50 | 782.84 | 283.25 | 454.16 | 206.65 | 530.75 | 259.03 | 390.89 | 199.22 | 449.99 | 168.66 | 341.60 | 91.16 | 419.09 |
| Comilla | 281.84 | 524.86 | 172.92 | 663.78 | 325.55 | 534.75 | 231.80 | 628.50 | 241.50 | 460.88 | 143.19 | 559.79 | 166.89 | 352.51 | 83.10 | 435.70 |
| Rangamati | 385.84 | 656.66 | 264.47 | 778.03 | 425.70 | 778.36 | 267.66 | 936.40 | 320.66 | 541.70 | 221.59 | 640.77 | 206.11 | 348.57 | 142.26 | 412.42 |
| Chittagong | 458.69 | 740.45 | 332.42 | 866.72 | 611.70 | 985.22 | 444.31 | 1152.61 | 319.05 | 712.65 | 142.66 | 889.05 | 171.83 | 335.45 | 98.50 | 408.78 |
| Cox's Bazar | 665.10 | 1069.10 | 484.05 | 1250.75 | 712.11 | 1241.27 | 474.96 | 1478.41 | 494.79 | 905.50 | 310.61 | 1089.59 | 213.06 | 457.08 | 103.70 | 566.44 |
| Sandwip | 450.93 | 790.73 | 298.65 | 943.00 | 662.63 | 1041.63 | 492.78 | 1211.48 | 524.37 | 866.29 | 371.13 | 1019.53 | 277.30 | 537.39 | 160.74 | 653.95 |
| Maijdee Court | 398.17 | 651.83 | 284.50 | 705.50 | 494.07 | 858.65 | 329.24 | 1022.48 | 529.29 | 865.34 | 378.69 | 1015.95 | 309.30 | 516.80 | 216.16 | 609.84 |
| Faridpur | 276.94 | 436.06 | 205.63 | 507.37 | 258.30 | 425.38 | 183.41 | 500.27 | 194.91 | 390.09 | 107.44 | 477.56 | 163.97 | 348.83 | 81.13 | 431.67 |
| Dhaka | 274.89 | 496.56 | 175.54 | 595.90 | 284.06 | 470.09 | 200.69 | 553.45 | 222.50 | 401.56 | 142.26 | 481.80 | 215.73 | 376.93 | 143.50 | 449.16 |
| Mymensingh | 286.03 | 539.63 | 172.38 | 653.28 | 352.79 | 565.11 | 257.63 | 660.27 | 199.43 | 497.37 | 65.92 | 630.88 | 200.42 | 423.20 | 100.58 | 523.04 |
| Khulna | 277.86 | 460.32 | 196.05 | 542.09 | 222.88 | 450.49 | 120.87 | 552.49 | 255.17 | 423.01 | 179.95 | 498.23 | 136.18 | 366.32 | 33.05 | 469.45 |
| Barisal | 270.90 | 535.24 | 152.43 | 653.71 | 308.46 | 470.80 | 235.71 | 543.55 | 270.94 | 462.58 | 185.05 | 548.47 | 219.75 | 377.09 | 149.55 | 477.51 |
| Satkhira | 177.49 | 400.65 | 77.47 | 500.67 | 243.67 | 454.25 | 149.31 | 548.61 | 235.99 | 369.00 | 176.39 | 428.61 | 174.04 | 395.26 | 74.91 | 494.39 |
| Jessore | 195.27 | 412.01 | 98.14 | 509.14 | 232.08 | 375.45 | 167.82 | 439.71 | 200.35 | 390.83 | 114.98 | 476.20 | 150.07 | 313.40 | 76.87 | 386.39 |
| Ishurdi | 156.16 | 438.67 | 29.55 | 565.29 | 241.14 | 480.26 | 133.97 | 587.43 | 166.95 | 366.43 | 77.56 | 455.82 | 158.74 | 336.96 | 78.86 | 416.84 |
| Bogra | 203.89 | 453.19 | 92.16 | 565.92 | 334.26 | 507.74 | 256.52 | 585.48 | 186.41 | 367.95 | 105.06 | 449.30 | 171.76 | 338.24 | 97.15 | 412.85 |
| Rajshahi | 171.18 | 372.64 | 80.90 | 462.92 | 269.21 | 434.71 | 195.04 | 508.88 | 203.07 | 358.45 | 133.44 | 428.08 | 168.96 | 325.12 | 98.97 | 395.11 |
| Dinajpur | 174.62 | 452.70 | 50.00 | 577.29 | 350.88 | 652.18 | 215.85 | 787.21 | 223.64 | 485.26 | 106.40 | 602.50 | 204.33 | 362.33 | 133.53 | 133.13 |
| | 282.41 | 540.33 | 166.83 | 655.91 | 335.76 | 654.46 | 192.94 | 797.28 | 254.89 | 464.36 | 161.47 | 556.79 | 218.27 | 422.33 | 126.83 | 513.77 |

L — Low value of probabilistic monthly rainfall. H — High value of probabilistic monthly rainfall.

386.61-845.38 mm in 1 year out of 4 and 10 years respectively (Table 3). In this month, the ranges of the probabilistic low rainfall are 136.18-369.73 and 33.05-222.54 mm in 1 year out of 4 and 10 years respectively.

## 6. Conclusions

On the basis of the present study, the following conclusions can be drawn :

(*i*) The mean monthly rainfall over Bangladesh increases from June to July at most places and then decreases up to September. The mean monthly rainfall over Srimangal, Khulna, Barisal, Dhaka and Faridpur has been found to have maximum value in June with decreasing trend in the subsequent months. The mean monthly rainfall is maximum in the southeastern and northeastern parts of Bangladesh during the southwest monsoon season. There exists a low amount of mean rainfall in the central part of the country roughly between 23°N and 24°N having the lowest value in the west.

(*ii*) The variability of rainfall decreases with increasing rainfall up to July at many places over the country and then increases upto September. High variability exists over west central, northwestern and southwestern parts of Bangladesh during the monsoon season. The variability of rainfall over the rest of part of the country is lower and the rainfall is more reliable.

(*iii*) The distribution patterns of the probabilistic high and low rainfall extremes over Bangladesh in 1 year out of 4 and 10 years respectively are similar to those of mean monthly rainfall throughout the monsoon season.

(*iv*) In June, the maximum probabilistic high rainfall values over the northeastern and southeastern parts of Bangladesh are 971.69 and 1069.10 mm in 1 year out of 4 years respectively, and 1110.43 and 1250.75 mm in 1 year out of 10 years respectively. The minimum probabilistic high rainfall values over the western part are 372.64 and 462.92 mm in 1 year out of 4 and 10 years respectively. In this month, the ranges of the probabilistic low rainfall over Bangladesh are 156.16-665.10 and 29.55-523.35 mm in 1 year out of 4 and 10 years respectively.

(*v*) In July, the ranges of the probabilistic high rainfall over Bangladesh are 375.45-1241.27 and 439.71-1478.41 mm in 1 year out of 4 and 10 years respectively, and the ranges of the probabilistic low rainfall are 222.88-712.11 and 120.87-492.78 mm in 1 year out of 4 and 10 years respectively.

(*vi*) In August, the probabilistic high rainfall over Bangladesh ranges from 358.45-905.50 and from 428.08-1089.59 mm in 1 year out of 4 and 10 years respectively. The ranges of the probabilistic low rainfall are 166.95-529.29 and 77.56-378.69 mm in 1 year out of 4 and 10 years respectively.

(*vii*) In September, the ranges of the probabilistic high rainfall over Bangladesn are 313.40-689.20 and 386.61-845.38 mm in 1 year out of 4 and 10 years respectively, and the ranges of the probabilistic low rainfall are 136.18-369.73 and 33.05-222.54 mm in 1 year out of 4 and 10 years respectively.

(*viii*) The gradients of the probabilistic high and low rainfall are maximum over the northeastern part of Bangladesh. The gradients of the probabilistic high rainfall are comparatively greater than those of the probabilistic low rainfall.

(*ix*) A belt of minimum values of the probabilistic high and low rainfall exists over the central part of the country roughly between latitudes 23°N and 24°N.

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### References

Ahmed, R., 1978. The variability of some water balance parameters of the pre-monsoon season in Bangladesh, Ontario : Department of Geography, University of Windsor, M.A. Thesis.

Ahmed, R., 1989, "Probabilistic estimates of rainfall extremes in Bangladesh during the pre-monsoon season". *Indian Geogr. J.* **64**, pp. 39-53.

Ahmed, R. and Karmakar, S., 1993, "Arrival and withdrawal dates of the summer monsoon in Bangladesh", *Intern. J. Climatol., R. Met. Soc.* **13**, pp. 727-740.

Alder, H. L. and Roessler, E. B., 1964, Introduction to Probability and Statistics, W. H. Freeman and Company, London.

Anderson, J. R., 1970, "Rainfall correlations in the Pastoral zone of Eastern Australia", *Austr. Met. Mag.* **18**, pp. 94-101.

Carr, M. K. V., 1972, "The climatic requirements of the tea plant — A Review", *Experi. Agric.* **8**, pp. 1-14.

Das, N., 1968, Agroclimatic factors in rice production, 21st International Geographical Congress, **1**, pp. 192-197.

Flohn, H., 1960, Recent investigations on the mechanism of the summer monsoon of the southern and eastern Asia, Monsoons of the World, pp. 75-88.

Geary, R. C., 1936, "Moments of the ratio of the mean deviation to the standard deviation for normal samples", *Biometrika*, **28**, pp. 295-307.

Glover, J. and Robinson, P., 1974, "Provisional map of the reliability of annual rainfall in East Africa", *Quart. J. R. Met. Soc.* **80**, pp. 602-611.

Huq, M. S., 1978, "The southwest monsoon over the subcontinent of India, Pakistan and Bangladesh — A survey", *Indian J. Met. Hydrol. Geophys.* **29**, 1 & 2, pp. 109-117.

Kromm, D. E., 1985, "Regional water management — An assessment of Institutions in England and Wales", *Profes. Geogr.*, **37**, pp. 181-191.

Kutiel, M., 1982, "Spatial coherence of monthly rainfall in Israel Ar fur Meteorologie", *Geophysik und Bioklimatologie*, **Series B, 31**, pp. 353-367.

Rao, Y. P., 1976, Southwest Monsoon, Met. Monograph, Synop. Met. No. 1/1976, pp. 90.

Sanderson, M. E. and Ahmed, R., 1979, "Pre-monsoon rainfall and its variability in Bangladesh — A trend surface analysis," *Hydrol. Sci. Bull. (UK)*, **24**, pp. 277-287.

Vines, R. G., 1986, "Rainfall patterns in India", *J. Clim.*, **6**, pp. 135-148.