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Rainfall statistics evaluation of ECMWF model and TRMM data over Bangladesh for flood related studies

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ABSTRACT: Quantitative precipitation estimates from the European Centre for Medium-Range Weather Forecasts (ECMWF) modelling system and the Tropical Rainfall Measuring Mission (TRMM) may be used for areas where rainfall data are not available or where the number of rainfall stations is inadequate. In this study, ECMWF 40 years re-analysis (ERA40) and TRMM satellite estimated daily rainfall data have been analysed at three station locations, Dinajpur, Rangpur, and Sylhet, in the Bangladesh territories of Ganges, Brahmaputra and Meghna basins, respectively. Statistical verifications (visual verification, yes/no dichotomous verification and continuous variables verification methods) have been applied to these data. Bangladesh Meteorological Department (BMD) rainfall data are used as the reference data.

The continuous variables verification methods show the better accuracy of the TRMM data. The probability of occurrence of TRMM rainfall is close to the BMD-observed data. It implies that the TRMM data can be used for modelling of design flood in areas where observed rainfall data are not available. However, in the case of the TRMM rainfall data, the chances of missing a flood event are higher compared to the ECMWF data. Yes/no dichotomous verification methods show that ECMWF rainfall data are safe to use for flood-forecasting-related planning purposes because rain events are estimated better in ECMWF. The probability of occurrence of ECMWF rainfall shows that these data can also be used to estimate the design flood flow. Both ECMWF and TRMM rainfall data may be used where locally observed rainfall data are not available. Copyright © 2011 Royal Meteorological Society

KEY WORDS ECMWF; TRMM; yes/no dichotomous; visual verification; continuous variables; design flood; flood forecasting; GBM basins

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1. Introduction

Rainfall estimates are required for developing flood forecasting and early warning systems. The estimated rainfall products from satellite data and numerical weather prediction modelling systems are particularly useful for trans-boundary basins such as the Ganges, Brahmaputra and Meghna (GBM) basins, where observed data exchange does not happen in real time (MoWR, 2008).

The rainfall stations in Bangladesh are sparsely located, rendering the estimation of floods difficult. The rainfall is highly variable in space and time. For example, at Sylhet in the northeastern part of Bangladesh, the annual average rainfall is 4180 mm, at Sunamganj near the foot of the abrupt Meghalaya Plateau it is 5330 mm and rainfall of 6400 mm is recorded at Lalakhal. Moreover, Cherapunji (India) records an average of 10 820 mm annually and is only 16 km away from the Bangladesh northern border (ODA and JICA, 1993; Asiatic Society of Bangladesh, 2006).

The Bangladesh Meteorological Department (BMD) maintains 34 hydrometeorological observatories in the country where observation, recording and archiving of rainfall data are done. Among these 34 stations, only two stations, Sylhet and Srimangal, observe rainfall in the northeastern zone which lies in the Meghna basin. Similarly few stations can be found in the northwestern part of Bangladesh in the Ganges and Brahmaputra basins, which are prone to chronic floods.

In this study, ECMWF and TRMM daily rainfall data for three locations in the Ganges, Brahmaputra and Meghna (GBM) basins (Dinajpur in the Ganges basin, Rangpur in the Brahmaputra basin, and Sylhet in the Meghna basin (Figure 1)) have been analysed by visual verification, yes/no-dichotomous verification and continuous variables verification methods. BMD rainfall data are used as the reference data.

Chowdhury and Ward (2004) described the hydrometeorological variability of the GBM basins by correlating the stream flows of these rivers in Bangladesh with the rainfall in the upper catchments and found that the stream flows in Bangladesh could be estimated for 1–3 months in advance (especially for the Ganges and Brahmaputra rivers). They emphasized the need for developing a spatially distributed knowledge base for seasonal stream flow forecast in the GBM basins in Bangladesh.

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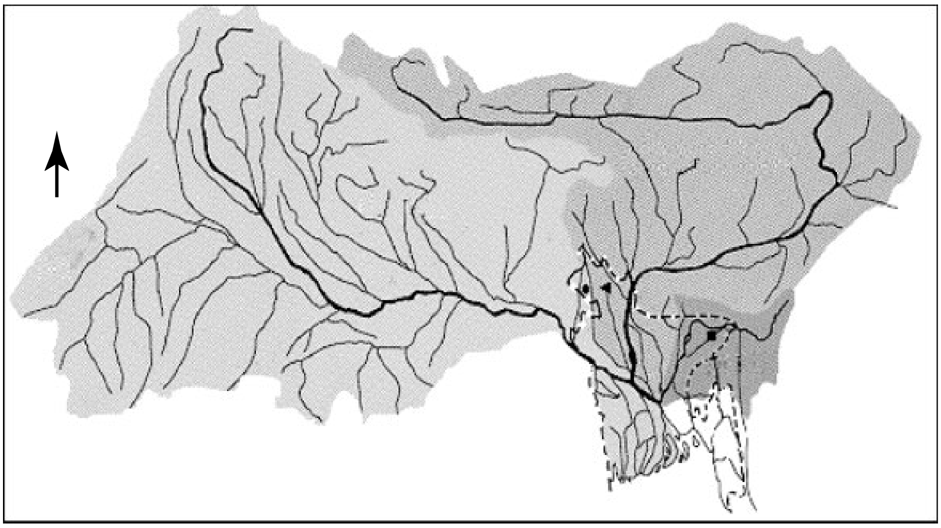

Figure 1. The map shows the GBM Basins and location of three rainfall stations. Light, medium, and deep shades show Ganges, Brahmaputra, and Meghna Basins, respectively. Dark lines show the river system in the respective basins. Dotted line shows international boundary of Bangladesh. Circular, triangle, and square points are rainfall stations at Dinajpur, Rangpur, and Sylhet, respectively, within the respective basin. Arrow sign shows north direction. The figure is not to scale.

Mirza *et al*. (1998) analysed trends and persistence in time series of annual precipitation for each of the 16 meteorological subdivisions covering the GBM basins. They found that precipitation in the Ganges basin is by-and-large stable whereas the rainfall of the Brahmaputra and Meghna basins in Assam (India) shows that precipitation in these two areas is not a random phenomenon from year to year and that the chance of occurrence of high (or low) precipitation in consecutive years is higher than would otherwise be the case.

The Meghna River is smaller and originates in the southern slopes of the mountain range in the north of Manipur, India. These three river basins cover about 1.75×10^6 km^2 across five countries: China, Nepal, India, Bhutan and Bangladesh.

Satellite data are a valuable source for deriving information on clouds and rainfall (Todd *et al*., 1995). The objective of the present study is to determine the rainfall statistics of TRMM and ECMWF rainfall data for evaluation of its potentiality in flood studies such as design flood estimation, calibration and validation of hydrological models, and flood forecasting.

2. Data used for the study

2.1. Rainfall data

2.1.1. ECMWF rainfall data

ECMWF is one of the leading global modelling centres, producing high quality analyses and forecasts at various time scales. In the last few decades, ECMWF has maintained high standards for its products (Woods, 2006). ECMWF's analysis and re-analysis products are very popular worldwide for various applications including flood and hydrological process studies. Improvements in representation of the moist physics processes in the ECMWF model have shown better diurnal cycle of convective rainfall in tropics (Bechtold *et al*., 2004; Tompkins *et al*., 2004; Thepaut *et al*., 2005).

The ERA40 rainfall data used in this study come from the ECMWF state-of-the-art forecasting system used at a lower resolution than the medium range forecast model resolution (Uppala *et al*., 2005; Simmons *et al*., 2010). In this ERA40 reanalysis, the high resolution global model uses the 6 h forecast as the first guess in the analysis. During 6-hourly data assimilation cycle (four times a day) fresh atmospheric observations are added to this first guess to produce the final analysis. These 6 h model rainfall forecasts (first guess in analysis) are very realistic and close to observations. From ERA40 6-hourly precipitation values, daily values (past 24 h) are computed which are then used as a proxy for observed accumulation for each grid of the region of study. As the TRMM satellite life period is over, conclusions from the use of such proxy data from operational weather modelling systems will provide useful guidelines for flood management and planning studies.

The ECMWF ERA40 rainfall data have been obtained from the Climate Forecasting Applications Network (CFAN) project, which is being used for flood forecasting by the Bangladesh Water Development Board (BWDB) in Bangladesh. The details of the CFAN data used for flood forecasting in Bangladesh are described by Webster and Hoyos (2004) as well as in http://cfab.eas.gatech.edu/cfab/cfab.html. The ECMWF rainfall data for 2 years, 2004 and 2006, cover the tropics between 20°N, 70°E, and 35°N, 100°E, with horizontal resolution of 0.5° × 0.5° (latitude/longitude).

2.1.2. TRMM rainfall data

Over the last three decades, researchers have been using satellite information to estimate rainfall. The satellite and gauge data were combined by Huffman *et al*. (1997) to create a post-real-time monthly satellite–gauge (SG) combination, which is a Tropical Rainfall Measuring Mission (TRMM) research-grade product (3B43). Mitra *et al*. (2009) tested an algorithm to merge TRMM Multi-satellite Precipitation Analysis (TMPA) satellite estimates with the Indian Meteorological Department's rain gauge values were tested for the Indian region. They found that the merged data are more informative than the TMPA values alone. Huffman *et al*. (1997) and Adler *et al*. (2003) described the computation of monthly TMPA rainfall at a relatively coarse scale, 2.5° × 2.5° latitude–longitude grid, by combination of satellite and gauge information within reasonable error characteristics under the Global Precipitation Climatology Project (GPCP).

The TRMM rainfall data have been downloaded from the NASA TRMM website. The tropical rainfall measuring mission of the National Aeronautics and Space Administration (NASA) produces merged 3-hourly rainfall rates incorporating spaceborne radar, microwave data and infrared imagery. The data are then processed at the United States Geological Survey's Earth Resources Observation and Science centre to convert them to daily accumulations and for converting to GIS-ready images.

The NASA-TRMM product (version 3B42) covers the tropics between 50°N and 50 °S, with grid cells of spatial resolution 0.25° by 0.25°. The NASA TRMM daily rainfall products are available from 1998 to the present. The processed rainfall data are made available within 12 h after the remote sensing data collection. While other satellite-derived rainfall products are available, the NASA TRMM 3B42 products are used in this application because of their superior performance in regions with limited *in situ* gauges (Dinku *et al*., 2007). The TRMM 3B42 satellite estimate is a merged product comprising calibrated IR rainfall and microwave-rainfall. These satellite estimates are again calibrated by precipitation radar of TRMM and gauges over land. The final product of TRMM 3B42 is a gridded data available 3-hourly for extended tropical regions of the globe. Even though TRMM is a polar-orbiting satellite, the merging of IR and microwave-rain from many other satellites compensate for the deficiency to produce rainfall data of very high quality (Huffman *et al*., 2007).

2.1.3. Ground observation data

The observed rainfall data were available from two sources BMD and BWDB. The daily rainfall data of Rangpur, Dinajpur and Sylhet stations were collected for the years 2004 and 2006 from either source and used in this study. These 2 years are selected on the basis of full data from all sources: model, satellite and gauge data were available.

Floods are generally associated with either relatively severe weather systems passing over Bangladesh or persistence of very active monsoon conditions. In early June of 2004, heavy monsoon rains occurred in the Meghna basin, which reached the highest ever recorded flood level in early July. The Ganges and Brahmaputra rivers also swelled their banks in early July due to heavy rains in the north of the country. Eventually, 38% of the land area and 36 million people (about 25% of the population) were affected, sustaining heavy property damage and loss of life. During the 2006 monsoon season as many as 16 low pressure systems formed over the Indian region (12 over the Bay of Bengal, 1 over the Arabian Sea and 3 over land). Of these systems, eight intensified (seven over the Bay of Bengal and one over land) into monsoon depressions and one into a severe cyclonic storm (over the Arabian Sea). During the study period of these 2 years, there were enough transient weather systems associated with the changing synoptic atmospheric conditions to represent typical monsoon associated flood events. Therefore, as a showcase, results from these 2 years will indicate the reliability and usability of rainfall estimates from satellites and NWP.

2.2. Scoring methods

In this study, ECMWF and TRMM rainfall data for the years 2004 and 2006 are compared and analysed with the ground observation daily rainfall data at Dinajpur, Rangpur and Sylhet climate stations in the Ganges, Brahmaputra, and Meghna (GBM) basins (Figure 1). The selection of stations and data collection years was on the basis of availability of data from BWDB, BMD, the CFAN website and TRMM rainfall data portal.

Murphy (1993) described three types of 'goodness' in verification of consistency, quality and value. Murphy (1993) also described nine attributes that contribute to the quality of estimation: bias, association, accuracy, skill, reliability, resolution, sharpness, discrimination and uncertainty. Stanski *et al*. (1989) classified the verification methods into visual, dichotomous and continuous variable verification categories. These categories are used for the validation of quantitative rainfall estimates in the present study.

Visual verification methods are based on looking at the computed and observed value side-by-side using instantaneous human judgment to differentiate the estimation errors. A common way to present data for verification is how the values of the estimation differ from the values of the observations. The verification of continuous estimations often includes some exploratory plots such

Table I. Contingency table for yes/no dichotomous method.

		Observed		
		Yes	No	Total
Estimate/ forecast	Yes	Hits	False alarms	Estimate/ forecast yes
	No	Misses	Correct negatives	Estimate/ forecast no
Total		Observed yes	Observed no	Total

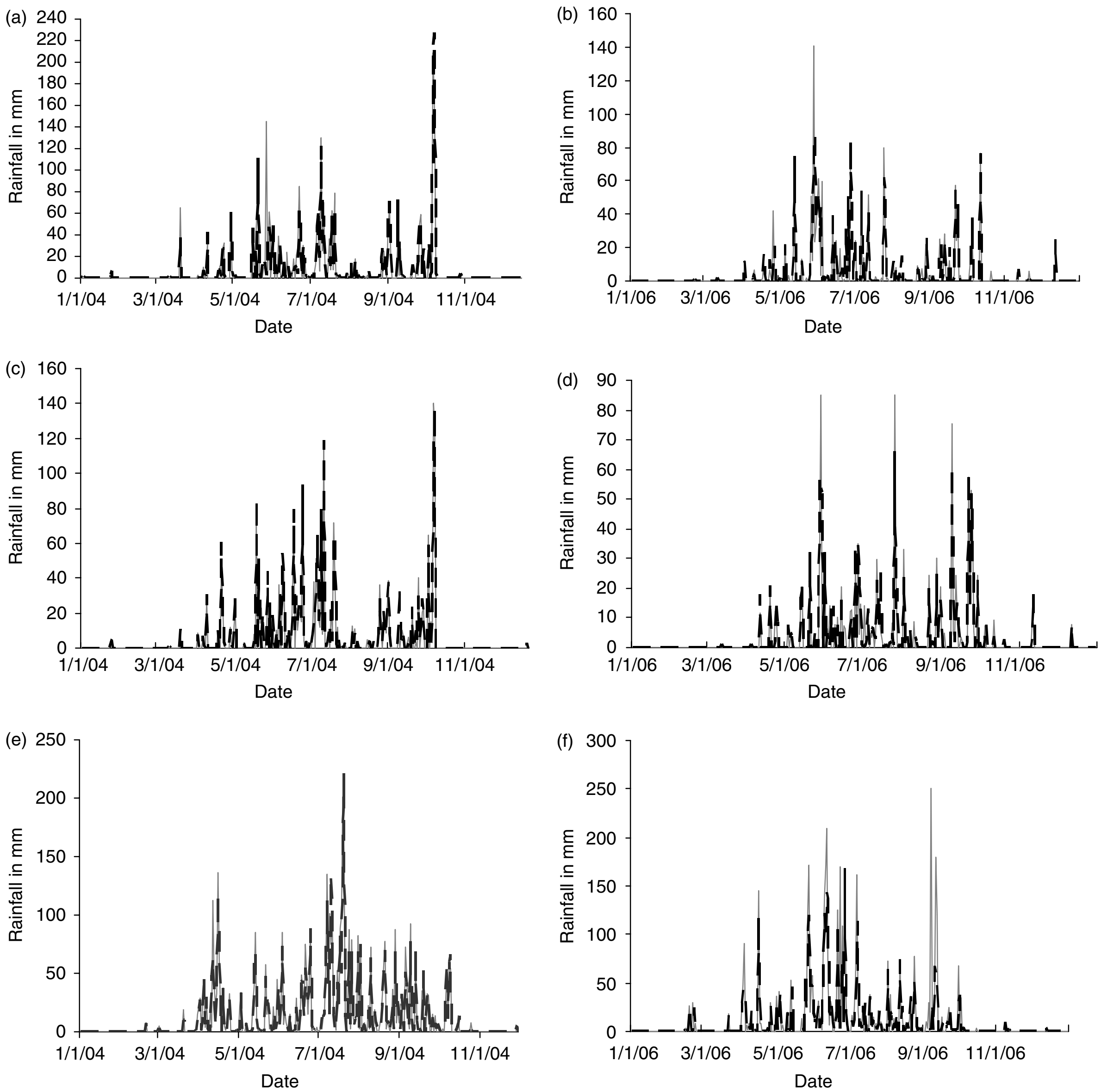

Figure 2. Time series of daily rainfall data observed by BWDB and BMD. Shaded and dashed lines show Bangladesh Water Development Board (BWDB) and Bangladesh Meteorological Department (BMD) time series, respectively. Daily time series of the years 2004 and 2006 at Rangpur, 2004 and 2006 at Dinajpur, and 2004 and 2006 at Sylhet, are shown in (a) and (b), (c) and (d), and, (e) and (f), respectively.

as time series graphs (Nurmi, 2003), histogram (Hirsch *et al*., 1993) and Cumulative Distribution Function (CDF) curves (Hirsch *et al*., 1993).

The yes/no-dichotomous verification methodology is fundamentally based on the statistical framework for the verification developed by Murphy and Winkler (1987) which was later modified for aviation forecasts by Brown *et al*. (1997). The dichotomous method describes, 'yes, an event will happen', or 'no, the event will not happen'. Precipitation estimation has a yes/no response. In this case, the threshold may be specified to separate 'yes' and 'no', for example rainfall greater than 5 mm. A contingency table is given by Brown *et al*. (1997) for the frequency of 'yes' and 'no' estimates and occurrences are presented in Table I. The four combinations of estimations (yes or no) and observations (yes or no), called the joint distribution, are:

- Hit – event estimation to occur, and did occur
- Miss – event estimation not to occur, but did occur
- False Alarm – event estimation to occur, but did not occur, and,
- Correct Negative – event estimation not to occur, and did not occur

A perfect estimation system would produce only hits and correct negatives, and no misses or false alarms. Different categorical statistics are computed from the contingency table to verify the estimation performance. Categorical statistics that can be computed from the yes/no contingency table are described by WMO/TD-No. 1485 (2008).

Finally, verification of continuous variables measures how the values of the estimations differ from the values of the observations. Verification of continuous estimations

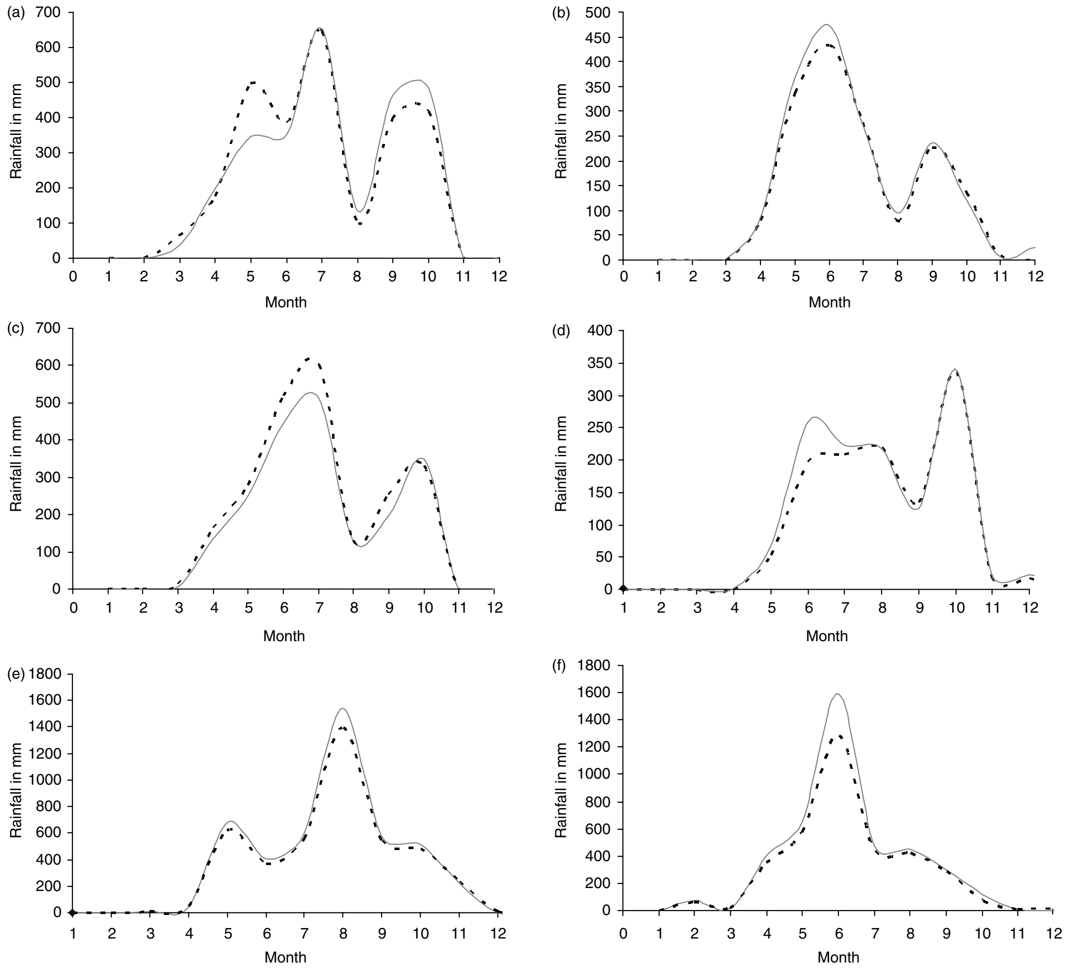

Figure 3. Time series of monthly rainfall data observed by BWDB and BMD. The dotted and shaded lines show Bangladesh Water Development Board (BWDB) and Bangladesh Meteorological Department (BMD) time series of monthly rainfall, respectively. Monthly rainfall of the years 2004 and 2006 at Rangpur, 2004 and 2006 at Dinajpur, and 2004 and 2006 at Sylhet, are shown in (a) and (b), (c) and (d), and, (e) and (f), respectively.

often includes various summary scores, as described by Lettenmaier and Wood (1993) and WMO/TD-No. 1485 (2008).

3. Data analysis, results and discussion

The different verification methods have been applied for the sensitive analysis of the 2004 and 2006 estimated data at Rangpur, Dinajpur and Sylhet. The analysis and results are discussed below.

3.1. Analysis of observed rainfall data

The reliability of the BMD rainfall data have also been verified with the third party RF data of BWDB. In this regard, verification methods for visual and continuous variables have been applied to both the daily and monthly data. The rainfall (RF) data collected by BMD have been considered as the reference observed data in this study.

Figure 2 shows the daily rainfall time series comparison. The shapes of BWDB and BMD RF data graphs matching in maximum cases but, during extreme events, in some cases the graph shows higher values for the BWDB observed data. Time series of monthly rainfall data are plotted in Figure 3. Figure 3 illustrates that the Rangpur station shows more values in May 2004 for the BWDB data. Figures 2 and 3 show that most of the differences between the BWDB and BMD data are found in May, June and July. The differences in the data occurred systematically and are found to be smaller in 2006 than in 2004. This indicates that there are different observational techniques either at the BWDB or BMD stations. BWDB observes the rainfall data manually, whereas BMD measures by automatic rain gauge. Data at Dinajpur in 2004 and 2006, Sylhet 2004 and 2006, and Rangpur in 2006, contain consistent bias: the monthly totals of BMD rainfalls are greater than those of BWDB. Inconsistency of data at Rangpur in 2004 (BMD<BWDB) also implies some typical reasons, such as change of observer or instruments.

For verification by continuous variables, additive bias i.e. mean error (ME), multiplicative bias (Bias), coefficient of correlation (r) and skill score (SS) are calculated. For calculation of skill score, BMD data have been taken as the reference data. Table II gives the comparison of

Table II. Statistical comparison of Bangladesh Meteorological Department (BMD) and Bangladesh Water Development Board (BWDB) observed rainfall data.

Station	Year	Data type	Continuous variable statistics			
			ME	Bias	*r*	SS
Rangpur	2004	Daily	0.01	1.00	0.88	0.75
		Monthly	−0.02	1.00	0.97	0.97
	2006	Daily	0.00	1.00	0.86	0.73
		Monthly	0.29	0.94	0.99	0.99
Dinajpur	2004	Daily	−0.72	1.13	0.99	0.98
		Monthly	0.73	0.89	0.99	0.98
	2006	Daily	−0.27	1.08	0.89	0.79
		Monthly	0.27	0.92	0.99	0.98
Sylhet	2004	Daily	0.92	0.93	0.92	0.84
		Monthly	0.94	1.08	0.99	0.99
	2006	Daily	1.35	0.88	0.82	0.67
		Monthly	1.56	1.28	0.97	0.88
Reliability assessment			ME is minimum error for Rangpur and Dinajpur but Sylhet shows some non-reliability.	Minimum bias for Rangpur and Dinajpur but Sylhet shows small non-reliability	Very good correlation	Very good for Rangpur and Dinajpur but Sylhet shows some non-reliability in 2006

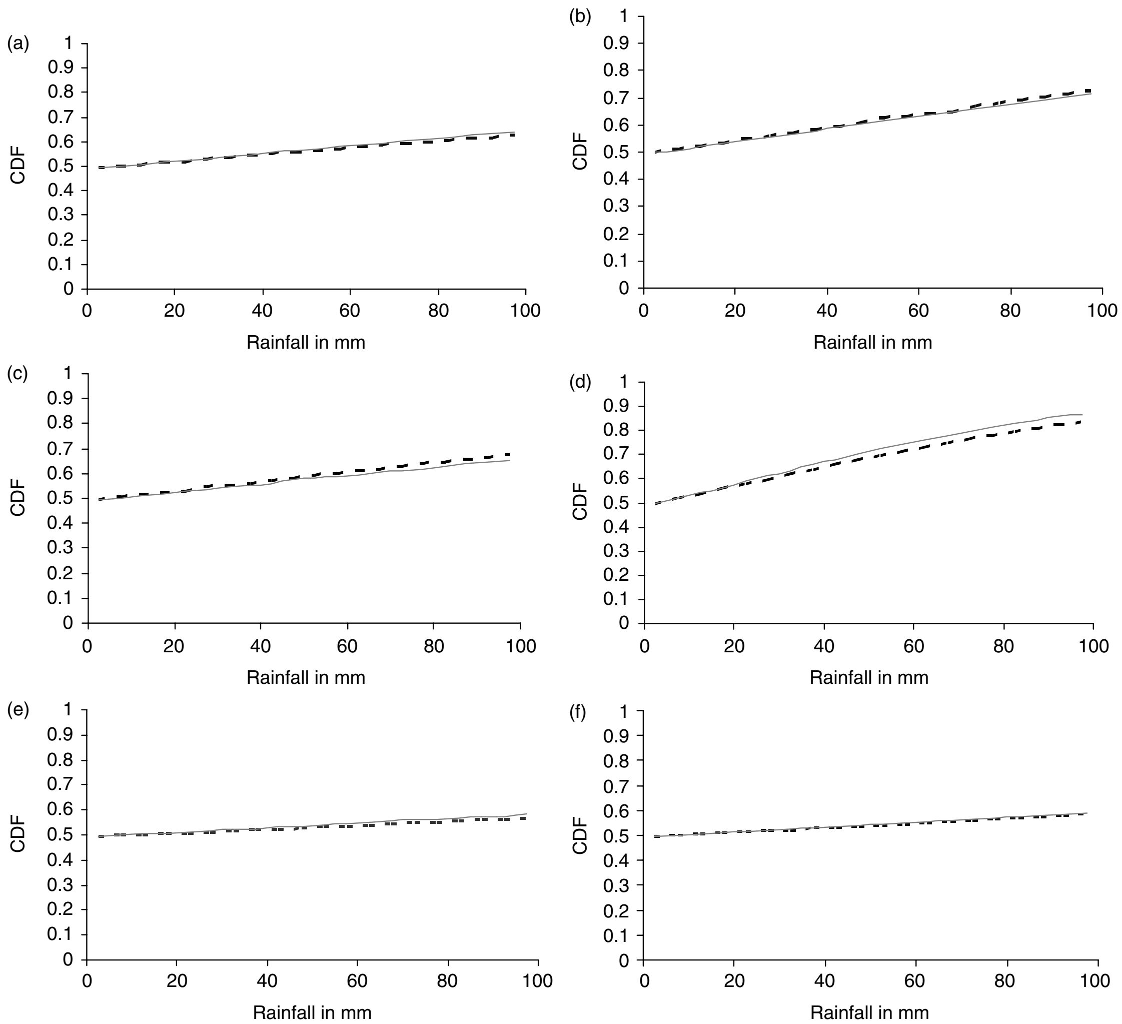

Figure 4. Comparison of CDF of observed rainfall of BWDB and BMD. Dashed and shaded lines show Cumulative Distribution Function (CDF) of Bangladesh Water Development Board (BWDB) and Bangladesh Meteorological Department (BMD), respectively. CDF of the years 2004 and 2006 at Rangpur, 2004 and 2006 at Dinajpur, and 2004 and 2006 at Sylhet, are shown in (a) and (b), (c) and (d), and, (e) and (f), respectively.

the biases. The comparison shows reasonably good agreement between BMD and BWDB rainfall data. The ME, Bias, r, and SS of daily rainfall at Rangpur (Brahmaputra basin) and Dinajpur (Ganges Basin) show better agreement between BMD and BWDB data, but other stations have some disagreement. The Sylhet station (Meghna Basin) shows the largest disagreement between two set of data which might have been caused from geographical location of stations and measurement techniques. CDF of rainfall in each year for three stations in both the years are plotted and shown in Figure 4. Comparison of the probabilities again shows good agreement between the BMD and BWDB data.

Having seen a good agreement between BMD and BWDB observed rainfall data and considering the fact that BMD is the main agency for collecting meteorological data in Bangladesh, the BMD rainfall data have been used as the reference data for further analysis of the ECMWF and TRRM data.

3.2. ECMWF and TRMM rainfall data preparation

The daily time series of ECMWF and NASA-TRMM 3B42 rainfall data have been extracted from their spatial distribution grid boxes for the stations at Rangpur, Dinajpur and Sylhet during the years 2004 and 2006.

The time series of ECMWF data for four corners of the grid boxes under the domain of each of the locations have been extracted using a visual basic programme. The time series of the three locations at 25.73 °N, 89.23 °E, and 25.65 °N, 88.68 °E, have then been derived by the arithmetical mean method (Chow *et al*., 1988), inverse distance-weighing (IDW) method (Smith, 1993) and area-averaged method (Chow *et al*., 1988). The derived time series have been compared with the observed data of

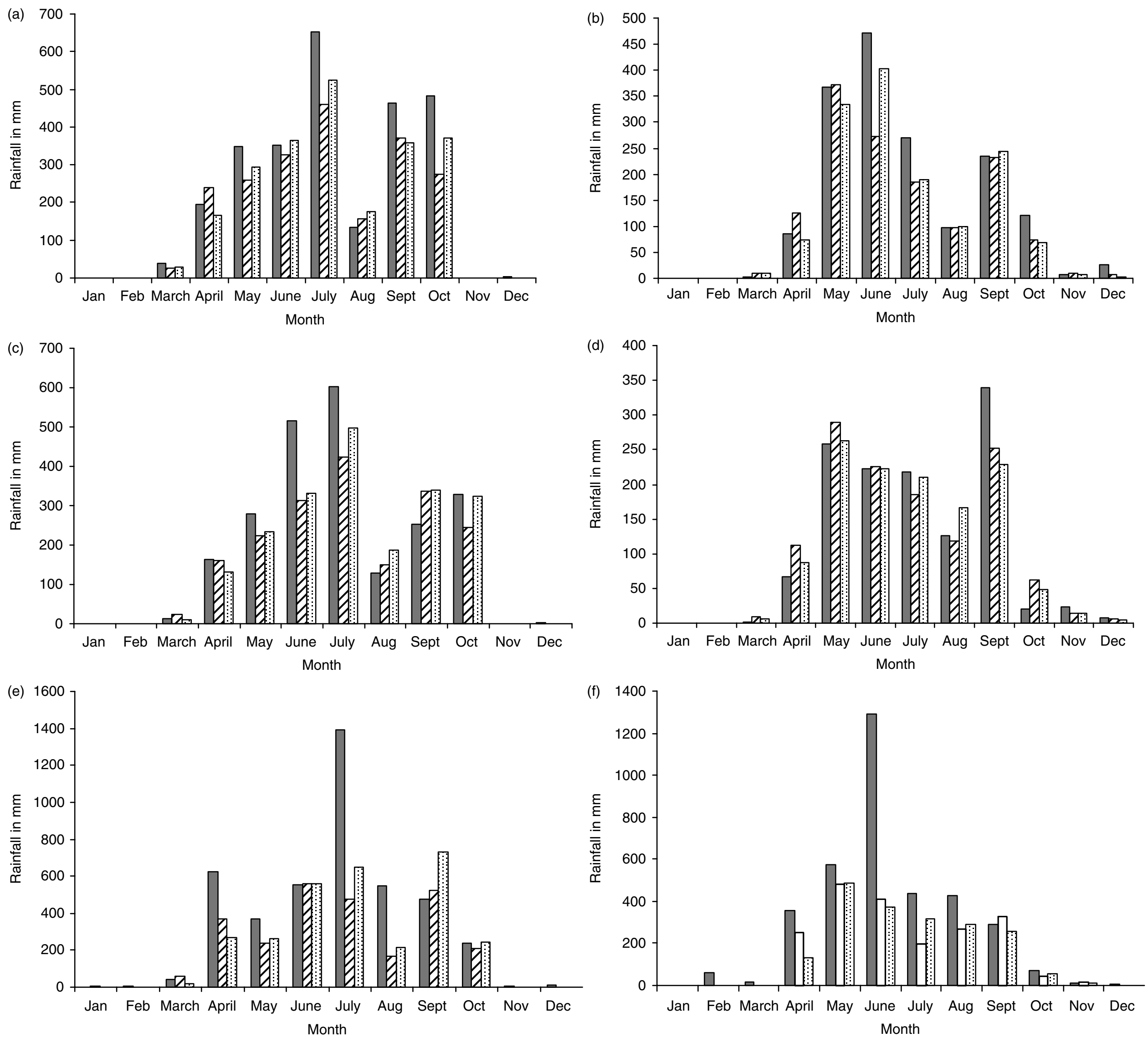

Figure 5. Bar chart of BMD observed, ECMWF, and TRMM monthly rainfall data. Bangladesh Meteorological Department (BMD), ECMWF, and TRMM monthly rainfall have been shown in bar chart as shaded, hatched, and dotted, respectively. Bar charts of monthly rainfall of the year 2004 and 2006 at Rangpur, 2004 and 2006 at Dinajpur, and 2004 and 2006 at Sylhet, are shown in (a) and (b), (c) and (d), and, (e) and (f), respectively.

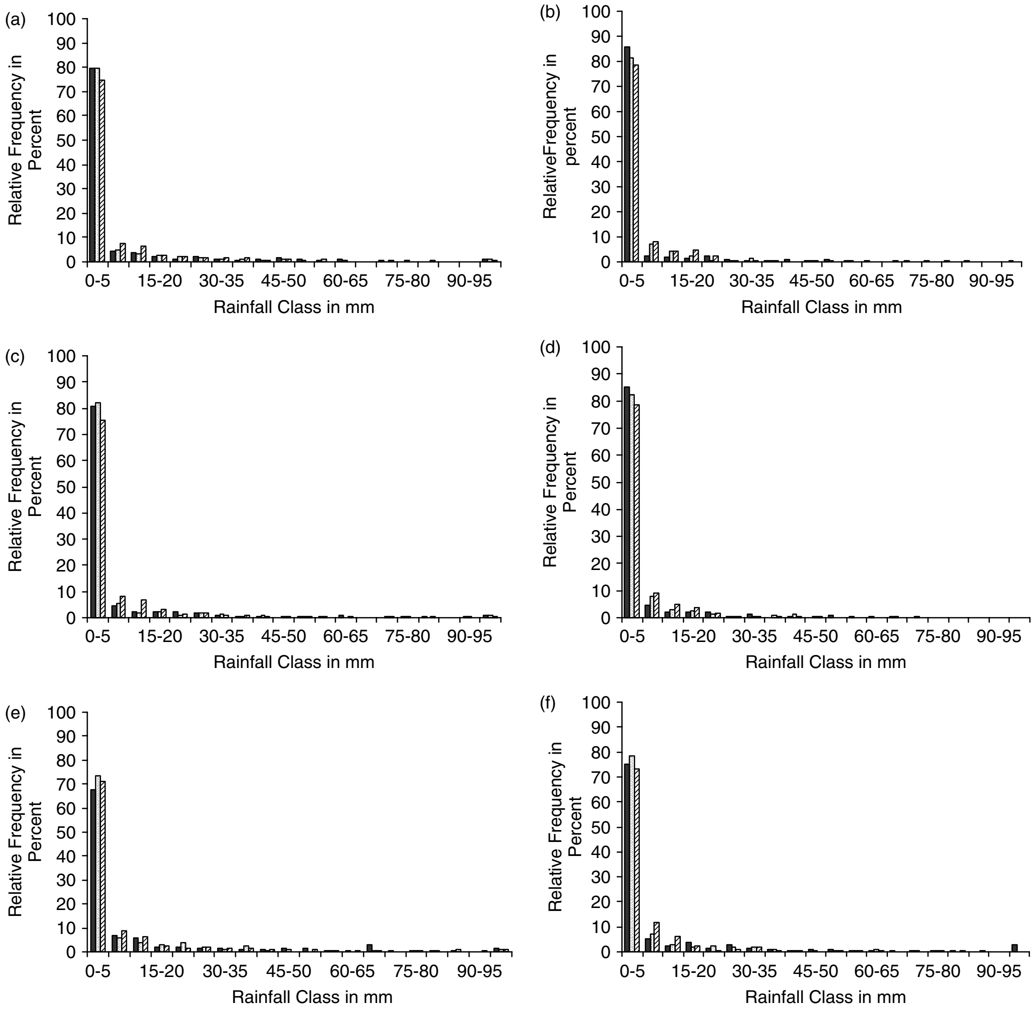

Figure 6. Histogram of relative frequency of rainfall distribution of Bangladesh Meteorological Deportment (BMD) observed, TRMM and ECMWF daily rainfall data. Relative frequency of BMD, TRMM, and ECMWF rainfall has been shown in shaded, dotted and hatched histograms, respectively. Histograms of relative frequency of rainfall distribution of the year 2004 and 2006 at Rangpur, 2004 and 2006 at Dinajpur, and 2004 and 2006 at Sylhet are shown in (a) and (b), (c) and (d), and, (e) and (f), respectively.

Table III. Comparison of the extracted time series of ECMWF RF data by different methods with the BMD observation.

Station	Year	Arithmetical mean	Area averaged	Inverse distance weighing
Rangpur	2004	0.55	0.55	0.56
	2006	0.59	0.58	0.59
Dinajpur	2004	0.51	0.52	0.52
	2006	0.49	0.48	0.5
Sylhet	2004	0.41	0.42	0.44
	2006	0.43	0.44	0.45
Selection of method		After comparing all methods, it is decided that the inverse distance squared method is acceptable.		

BMD. The correlation coefficient between derived time series of the ECMWF RF data and BMD observed rainfall at the three locations are given in Table III. It has been found that the IDW gives the better result.

Smith (1993) described the Inverse Distance-Squared Method, it is commonly used for this purpose and the Rainfall Estimation for the $\underline{j}^{\text{th}}$ grid box is:

$$\overline{P_j} = a \sum_{i=1}^{n} d_{ij}^{-2} P_i \tag{1}$$

where d_{ij} is the distance from gauge i to centre of grid box j and a is the inverse of the sum of the Inverse Distance-Squared values for all gauges:

$$a = \left(\sum_{i=1}^{n} d_{ij}^{-2} \right)^{-1} \tag{2}$$

Hence, the data set derived using the IDW interpolation method have been used for further analysis in this study.

The TRMM Rainfall data have been derived for the three stations from the spatial distributed grid directly from the their website and used in this study without any pre-processing.

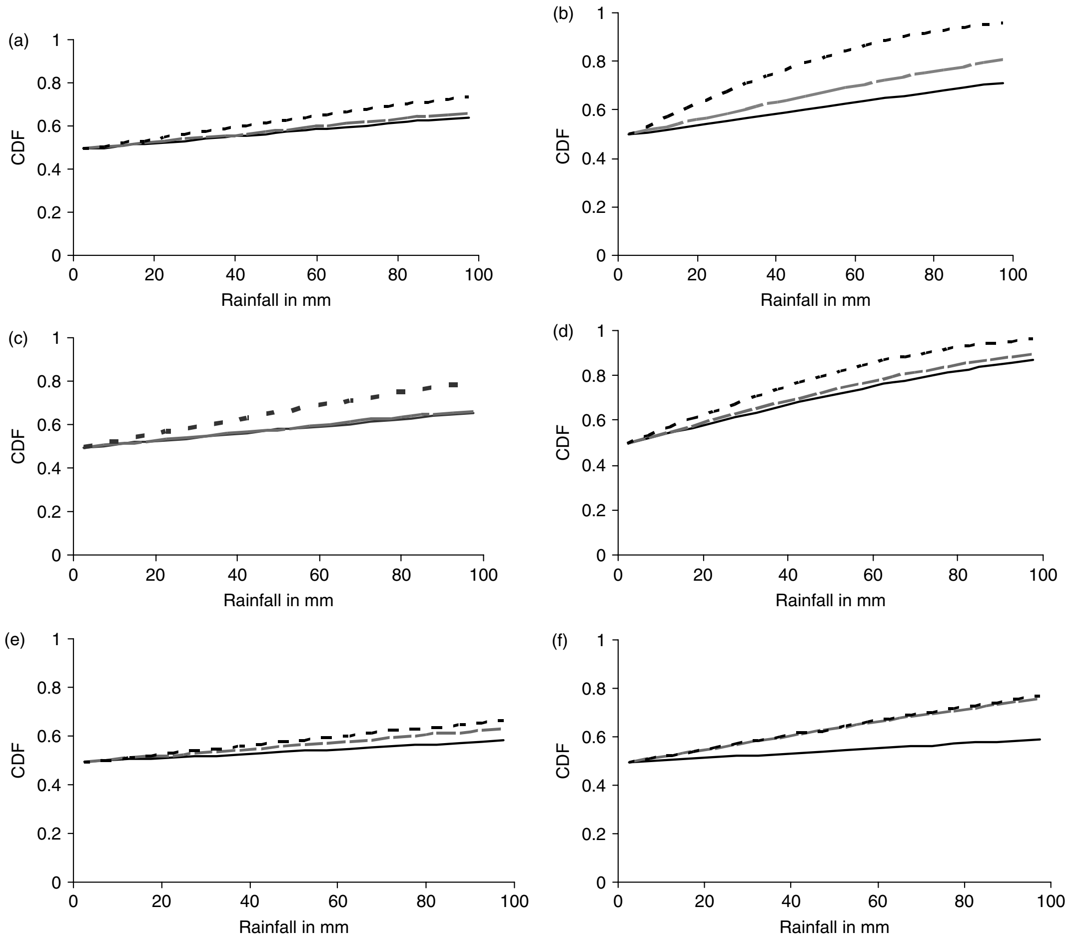

Figure 7. Comparison of Cumulative Distribution Function (CDF) among Bangladesh Meteorological Department (BMD) observed, ECMWF, and TRMMM daily rainfall data. The dark, dashed and shaded lines show CDF of BMD, ECMWF and TRMM, respectively. CDF of the years 2004 and 2006 at Rangpur, 2004 and 2006 at Dinajpur, and 2004 and 2006 at Sylhet, are shown in (a) and (b), (c) and (d), and, (e) and (f), respectively.

3.3. Evaluation of ECMWF and TRMM rainfall (RF) data

The methods of visual verification, yes/no dichotomous statistics and continuous variables verification have been used in this study and the results are discussed in this section. In the visual verification methods, bar charts of monthly values of time series, histograms of relative frequency of rainfall and plotting cumulative distribution function (CDF) have been used to compare the ECMWF and TRMM data with BMD data.

Figure 5 shows the bar chart of monthly ECMWF, TRMM and BMD observed RF data. It shows that the monthly values of ECMWF and TRMM RF data are close to the monthly values of BMD observed RF data with a few random differences in the case of extreme events of higher or lower rainfalls, such as in June 2004 (there is 100 mm difference between the ECMWF and TRMM rainfall data at Dinajpur). At Sylhet in the Meghna basin, during monsoon both the ECMWF and TRMM rainfall data show significantly lower values than the observed value. Comparison between ECWMF and TRMM shows that in most cases, however, the monthly rainfall totals are in agreement with each other.

The comparison of the relative frequency histograms of ECMWF, TRMM and BMD daily rainfall data are shown in Figure 6. The figure shows that the different data classes have good agreement among ECMWF, TRMM and BMD RF data.

Figure 7 shows the inter-comparison of CDF of ECMWF, TRMM, and BMD RF data. From Figure 7 it is observed that CDF of higher values of ECMWF rainfall data are passing above the CDF of higher values of BMD observed rainfall data for all the stations. The CDF of TRMM rainfall data are passing close to the CDF of BMD rainfall data except at Sylhet in 2006. It implies that the probability of occurrence of higher values of ECMWF rainfall data is more than the probability of occurrence of BMD RF data, whereas for TRRM RF data it is close to that of BMD RF data. Therefore, flood warning using ECMWF RF data will not have any chance of missing floods.

Table IV shows the results of yes/no-dichotomous verification method. In the yes/no-dichotomous verification method, the accuracy of TRMM RF data shows values between 0.73 and 0.76 and the ECMWF RF data gives values between 0.71 and 0.79 (a perfect value is 1.00). Thus, both methods result in a minimum of

Table IV. Evaluation of ECMWF and TRMM daily rainfall data with BMD observed rainfall data using yes/no dichotomous verification method.

Station	Year	Estimation type	Dichotomous verification statistics						
			Accuracy	BIAS	POD	FAR	POFD	TS	OR
Rangpur	2004	TRMM	0.76	0.78	0.51	0.34	0.12	0.40	7.50
		ECMWF	0.76	1.29	0.76	0.41	0.24	0.49	9.70
	2006	TRMM	0.76	1.13	0.57	0.50	0.18	0.37	6.00
		ECMWF	0.71	1.64	0.72	0.56	0.30	0.37	6.00
Dinajpur	2004	TRMM	0.74	0.77	0.46	0.40	0.14	0.36	5.39
		ECMWF	0.76	1.24	0.74	0.40	0.23	0.49	9.58
	2006	TRMM	0.76	0.96	0.55	0.43	0.15	0.39	6.59
		ECMWF	0.71	1.45	0.69	0.53	0.29	0.39	5.48
Sylhet	2004	TRMM	0.75	0.77	0.61	0.21	0.13	0.52	10.08
		ECMWF	0.79	1.00	0.76	0.23	0.19	0.61	13.37
	2006	TRMM	0.73	0.83	0.56	0.33	0.16	0.44	6.62
		ECMWF	0.78	1.22	0.82	0.33	0.24	0.58	14.09
Evaluation of the statistical parameters			TRMM estimation is more or less same as ECMWF	ECMWF estimation (rain frequency) is over estimated	Rain events are estimated better in ECMWF	TRMM estimation gives less false detection	'No rain' events were estimated better in TRMM	'Rain' events were more correctly estimated in ECMWF	'Rain' events are correct multiple times than the 'rain' events are incorrect in both cases

21% inaccuracy. This inaccuracy may inflate some of the scores. The bias parameter shows that ECMWF estimates without any bias at Sylhet in 2004, but overestimates 64% at Rangpur in 2006, whereas the TRMM underestimates the rainfall data in the range of 4–22%.

TRMM estimates 'rain' events with a probability of detection (POD) from 0.46 to 0.61, whereas ECMWF produces 'rain' events comparatively better and with a higher POD (0.69–0.82). False alarm ratio (FAR) analysis of TRMM rainfall data indicates a false alarm rate from 0.21 to 0.50. ECMWF RF data gives slightly higher false alarm rate (from 0.23 to 0.56) than the TRMM RF data. Probability of false detection (POFD) analysis shows that TRMM estimates 'no rain' events between 0.12 and 0.18 which is slightly better than the ECMWF RF data (0.19–0.30). ECMWF gives better response to detect 'rain' events with a threat score (TS) between 0.37 and 0.61. The likelihood of 'yes estimation being correct' (hit) rather than 'yes estimation being wrong' (false alarm) is better for the ECMWF than the TRMM data because the odds ratio (OR) (Stephenson, 2000) of the ECMWF RF data is better than that of the TRMM RF data.

From the yes/no dichotomous verification method it is found that both TRMM and ECMWF rainfall data sets may be used in hydrological design. However, ECMWF rainfall data would be safe to use for flood forecasting purposes because rain events are estimated better in ECMWF but may generate a false flood warning due to overestimation of rain events. In the case of TRMM rainfall data the chances of missing a flood event are higher.

Table V shows the results of the continuous variables verification methods. Methods for estimation of continuous variables verification describe the Additive Bias (i.e mean error), Multiplicative Bias, Correlation Coefficient and Skill Error of both the ECMWF and TRMM RF data series. These parameters show better accuracy for TRMM rainfall data than that of ECMWF data, but coefficient of correlation and skill scores show that both sets of data have less agreement with the observed data in all stations during both the years.

4. Conclusions

Floods are one of the major causes of loss of life and property every year across Bangladesh, which adversely affects the economy of the country. Accurate rainfall estimations are essential for reliable flood estimation for mitigation of loss. Due to the complex geography and hydrology of the Ganges, Brahmaputra and Meghna

Table V. Evaluation of ECMWF and TRMM daily rainfall time series by continuous variables verification methods.

Station	Year	Data type	Continuous variables statistics			
			ME	Bias	r	SS
Rangpur	2004	TRMM	1.08	0.85	0.36	−0.08
		ECMWF	1.52	0.80	0.16	−0.20
	2006	TRMM	0.68	0.85	0.34	−0.16
		ECMWF	0.80	0.83	0.39	0.12
Dinajpur	2004	TRMM	0.65	0.89	0.32	−0.34
		ECMWF	1.09	0.83	0.23	−0.16
	2006	TRMM	0.09	0.97	0.43	−0.09
		ECMWF	0.03	0.99	0.40	0.08
Sylhet	2004	TRMM	3.59	0.69	0.25	−0.25
		ECMWF	4.52	0.61	0.23	−0.13
	2006	TRMM	4.41	0.55	0.30	−0.03
		ECMWF	4.18	0.57	0.28	−0.03
Evaluation of the statistical parameters			TRMM estimation contains less mean error	Average bias magnitude is better in TRMM estimation	TRMM estimation shows better correlation coefficient but both estimated data show less agreement with observed values	ECMWF shows better results but both estimated data show less agreement with observed values

(GBM) basins, the available stations for land-based measurement of rainfall data are not sufficient for analysing and modelling flood estimation.

This study was undertaken to analyse the rainfall statistics of the ECMWF 40 years re-analysis (ERA40) and TRMM satellite based estimated daily rainfall data of the years 2004 and 2006 for Dinajpur, Rangpur and Sylhet climate stations in the GBM basins in Bangladesh for evaluation of its potentiality in flood studies like estimation and forecasting of flood. Different verification methods were applied to analyse the data. The observed rainfall data were selected to be the reference dataset to assess the value of ECMWF and TRMM rainfall data.

The results indicate that both the ECMWF and TRMM data products may be used in flood studies. The ECMWF also provides rainfall data in advance and hence these can be used in flood forecasting studies. Both ECMWF as well as TRMM rainfall data may be used in flood estimation studies where observed rainfall data are not available. The above conclusions are not generalized, but are from the data of three rainfall stations in the GBM basin for 2004 and 2006 only. In spite of that, the results are important for flood management studies. However, such studies should be developed with a greater number of stations and longer data sets, to develop the relationships between observed rainfall and estimated rainfall by ECMWF or TRMM. The supremacy of either of the methods of rainfall estimation over the other can not currently be established.

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