

**STUDY OF DIURNAL VARIATION OF RAINFALL IN  
BANGLADESH USING GSMaP DATA**

**M. Sc. Thesis**

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DHAKA-1000, BANGLADESH  
June, 2017**

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BANGLADESH USING GSMaP DATA**

A dissertation submitted to the Department of Physics,  
Bangladesh University of Engineering and Technology (BUET), Dhaka  
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**MASTER OF SCIENCE IN PHYSICS**

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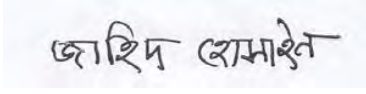
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## CANDIDATE'S DECLARATION

It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

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*Dedicated to,  
My Parents and Teachers*

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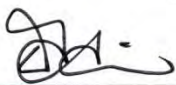
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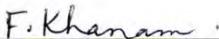
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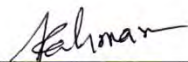
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**2:286** *On no soul doth Allah Place a burden greater than it can bear. It gets every good that it earns, and it suffers every ill that it earns. (Ayah al Baqarah)*

**2:216** *But perhaps you hate a thing and it is good for you; and perhaps you love a thing and it is bad for you. And Allah Knows, while you know not. (Ayah al Baqarah)*

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## Abstract

To study the diurnal variation of rainfall and possibility to use of Global Satellite Mapping of Precipitation (GSMaP) data in Bangladesh, GSMaP hourly data of spatial resolution of 0.1 degree by 0.1 degree and three hourly rain gauge data of 35 stations of Bangladesh Meteorological Department (BMD) are used. Daily, monthly, seasonal and yearly diurnal variation of rainfall and their spatial distribution are studied during the period 2001-2015. It is found that GSMaP data is well correlated with rain gauge data. The correlation coefficients between GSMaP and BMD rain gauge for 3-hourly, daily, monthly and yearly rainfall are found 0.71, 0.74, 0.82 and 0.66, respectively. From this study, it is found that monthly diurnal variation of BMD rain gauge rainfall showed two peaks of maximum rainfall; one at 0600 Local Standard Time (LST) and other at 1500 LST whereas GSMaP found these peaks at 0300 LST and 1500 LST. During pre-monsoon season both datasets found well matched maximum rainfall peak at 1500 LST (primary peak) and 21 LST (secondary peak). GSMaP found primary peak at 0300 LST and secondary peak at 1500 LST whereas rain gauge found these peaks at 0600 LST and 1500 LST during monsoon season. During the post-monsoon season the well matched primary and secondary peaks of rainfall of both data sets are found at 1500 LST and 0600 LST, respectively. In winter, both datasets showed only one peak of maximum rainfall at 0300 LST. Rain gauge measured yearly maximum rainfall over Bangladesh at 0600 LST with a secondary maximum peak at 1500 LST whereas GSMaP observed primary peak at 1500 LST with a secondary peak at 0300 LST. The spatial distribution of occurrence time of maximum rainfall showed that the western, north-eastern part of the country experiences maximum rainfall at 0300-0900 LST and central and southern part at 1800-2100 LST during pre-monsoon season. During monsoon season maximum rainfall is observed in the western and north-western region at 0300-0900 LST, whereas rest part of the country showed at 1200-1500 LST. In post-monsoon season, maximum rainfall occur in the western, north-western part of the country at 0900-1200 LST whereas central and southern part observed at 1200-1500 LST. Station wise analysis of diurnal variation of rainfall confirmed that most of the stations showed continental type diurnal variation during pre-monsoon and post-monsoon season whereas during monsoon and winter seasons dominated maritime type diurnal properties. Yearly average of station wise diurnal variation of rainfall confidently confirmed that Bangladesh is dominating the maritime type diurnal properties.



# CHAPTER ONE

## INTRODUCTION

### 1.1 Preface

Bangladesh is the home of the world's largest river delta which is situated in South Asia and is bordered by India from three sides, a small boundary with Myanmar from the southeast corner and the Bay of Bengal from the south. Its climate is tropical monsoon-type with a dry winter and a hot and rainy summer. Bangladesh is considered as a heaviest rainfall area in the world [1] which may responsible to become an agro-based economic country. Precipitation, especially rainfall has a dramatic effect on agriculture system; the rainfall pattern is momentous to healthy living plants and greens. National economy and economic development of Bangladesh is vehemently linked with rain-fed-agriculture system. So, to understand the physical mechanism and variability of precipitation, especially rainfall is very important to us. Rain and other form of precipitation are major input and component to the water resource system such as water cycle and hydrology. The weather of a certain region is highly dominated by different diurnal processes and the diurnal variation of rainfall is their direct result.

Diurnal variation of rainfall in a certain region means the amount of rainfall which occurs in every 24 hours as a full rotation of earth with respect to its axis. It is a significant aspect and catalyst of a certain regional climate because rainfalls occur regularly during a particular time of the day which is connected with the regional and local atmospheric circulation and/or dynamics [2]. It is often related to physical processes governed by geographical features or atmospheric dynamics controlling rainfall over that area. The pattern of diurnal variation may change with the season as a changing circulation pattern may lead to changes in the dominating physical process giving rainfall in that region [3]. The nature of diurnal variation of rainfall depends on the nature of the underlying surface, location, season and precipitation type. Over land and near coastlines the thermal properties of the land surface and the land-sea-breeze

circulation induced by the contrast between the land and ocean surfaces can explain much of the diurnal cycle of clouds and rainfall. Over the open or flat ocean the thermal properties of the ocean surface and atmospheric boundary layer undergo a diurnal variation that is relatively weak compared with that of land surface. Whereas, the seasonal distribution of rainfall is an important attribute of the climate of a region, its diurnal variation is not less important climatic feature. It affects communication, controls the weather conditions and many other outdoor activities. The diurnal cycle of rainfall influences the rainfall effectiveness in agriculture, because a large part of the rainwater during the warmer part of the day is lost through the process of evaporation.

Two main types of diurnal variation of rainfall can be recognized [4]: (a) continental or inland type, and (b) maritime or coastal type. The main dominant feature of the diurnal cycle is a rainfall maximum in late-evening/Early-morning (LE-EM) hours in oceanic area, while over land the dominant maximum occurs in the mid- to late-afternoon (MLA) [5]. There are many local factors, such as the coastline, the topography of coastal areas, the presence of rivers, lakes and irrigated fields, etc. which influence the diurnal variation of rainfall. The continental type has its maximum of rainfall during the late morning or afternoon. In this type, topography is the main cause of local differences in diurnal variation. The maximum amount of rainfall falling in the afternoon is mainly due to the convective dynamism which over land areas is strongest in the early afternoon.

There is a tendency to produce a rainfall maximum about the warmer part of day. Since convection is more robust during summer than during winter. In the tropics, because of the intensity of solar radiation and the greatest convective dynamism, there occur the most pronounced afternoon maxima of rainfall. Convectonal showers over some areas are produced much earlier than over others. Drainage conditions, moisture of soil, color of the surface or types of vegetation may also cause variations in the diurnal rainfall regime [6]. In certain areas, a change in the direction of prevailing winds may cause a change in the diurnal regime of rainfall. This is the main reason why coastal area in the monsoon lands experience large seasonal variations in the diurnal rainfall regime. On

other hand, the maritime or coastal type shows a maximum of rainfall during the night or in the early hours of morning. This type of variation is caused by nocturnal jet convection. This is because of a steepened lapse rate. During night, the upper troposphere cools off by radiation losses, mainly from cloud tops, while the surface layers of atmosphere lying in close contact with the water surface remain warm. Analogously, the vertical temperature gradient is greater at night. Again, during day the lower layers of atmosphere are warmed up by directly absorbing the solar radiation, while the water surface is heated slowly. Therefore, atmospheric stability is created at low levels which are opposed to rainfall. As a result of this fact, convective dynamism over the ocean is greater at night than during the day [7]. Besides these, many local factors strongly modify the diurnal rainfall distribution, e.g. inhibiting gravity wave. Notably, the mechanism of gravity wave dynamics influencing diurnal cloud and rainfall variability has attracted much attention of late [5].

The knowledge of diurnal variation of rainfall is essential in understanding in the physics of the tropical atmosphere, earth radiation budget, and regional radiation balance and also infers the transportation of energy in the atmosphere of land and ocean [5, 7-9]. In essence, diurnal variability over the Earth is heterogeneous but regionally coherent and due to multiple mechanisms competing for dominance.

There have been a few investigations on the diurnal variability of rainfall over Bangladesh. The diurnal variation of rainfall is different at the different part of the Bangladesh. Islam et al., [10] found that the average time of maximum precipitation is at 0000-0600 LST in the Northern region, at 1500-1800 LST in the Central region, and at 0600-0900 LST in the Southern region of Bangladesh from the analysis of the radar data. Wahid et al., [11] found the morning and afternoon/evening peak in the northeast part (Sylhet) of Bangladesh using rain gauge rainfall data. Azam et al., [12] analyzed the TRMM PR (Tropical Rainfall Measuring Mission Precipitation Radar) data and showed that dual maxima of rainfall; one at 0300 LST other at 1500 LST. Bhuiyan et al., [13] also showed dual maxima, which occur during noon to afternoon (1200-1500 LST) and

late night to early morning (0300-0600 LST) over Bangladesh using TRMM 3B42 data. Terao et al., [14] investigated diurnal variations of rainfall and upper wind over Bangladesh during summer monsoon season using rain gauge, 4 time's daily rawinsonde and pilot balloon observations data. The rainfall peak appears in the early morning (0300 to 0600 LST) over the north-eastern part, where the total monsoon rainfall is heavy. The southeasterly is accelerated in the evening, in the lower troposphere and the wind direction exhibits the clockwise change during the night.

In the present study, we utilize fifteen years (2001-2015) of high spatiotemporal resolution (0.1 degree hourly) rainfall data from Global Satellite Mapping of Precipitation (GSMaP) and three hourly Bangladesh Meteorological Department (BMD) rain gauges, in order to describe the mean characteristics of diurnal pluviometric variation as well as its spatial distribution. Furthermore, we have identified the main dynamical mechanism regulator of the diurnal pluviometric variability in the study area.

Bangladesh Meteorological Department (BMD) has less dense rain gauge network (only 35 rain gauge stations) and not uniformly distributed. Rain gauge data are usually limited by their spatial coverage. Again in remote area such as hilly region or over the ocean it is very much difficult to observe the weather (or precipitation) by rain gauge. Remote sensing techniques use microwave and space borne sensors that provide an excellent complement to continuous monitoring of precipitation event both spatially and temporally. So, it is a suitable chance to use Satellite-born GSMaP data to characterize the dynamical mechanism related to the diurnal variability of rainfall over Bangladesh. Hence, to make the following purpose of the present research work, we use the GSMaP data for analyzing diurnal variation of rainfall in and around of Bangladesh.

## 1.2 Objectives of the Research

The specific objectives of the present research work are:

- ❖ To check the validation of GSMaP product with BMD rain gauge observation data.
- ❖ To find the correlation coefficient and root mean square error (RMSE) between GSMaP data and rain gauge data of BMD.
- ❖ To study monthly, seasonal, yearly and yearly average diurnal variation of rainfall in Bangladesh using GSMaP and BMD rain gauge data.
- ❖ To investigate the spatial distribution of maximum occurrence time of rainfall over Bangladesh during study period.
- ❖ To find out regional diurnal variability of rainfall.

The results of this research work will be helpful to understand the characteristics of diurnal variation of rainfall in Bangladesh. It will be also conducive to understand the hydrological system accurately and validity of GSMaP data in Bangladesh as well as give valuable information of the features and mechanisms of diurnal rainfall variation and mechanism of rainfall.

## **CHAPTER TWO**

### **LITERATURE REVIEW AND OVERVIEW OF THE STUDY**

#### **2.1 Review**

Past studies concern to diurnal variation of rainfall and its different criteria using rain gauge, radar and satellite data are narrated in this chapter.

Islam et al., [15] analyzed the diurnal variations of cloud activity in Bangladesh and north of the Bay of Bengal in 2000 using Japanese Geostationary Meteorological Satellite (GMS-5) of high resolution (10 km mesh) hourly data. They observed the cloud embedded area shows afternoon (~1700 LST) and morning (~0003 LST) peaks over land typically composed of relatively small deep (< 214 K) and shallow (< 243 K) convective cloud systems by using Japanese Geostationary Meteorological Satellite (GMS-5). In contrast, only afternoon (1400-1600 LST) peak is observed over ocean typically composed of small shallow and large deep convective cloud system. They also used radar data from Bangladesh Meteorological Department (BMD) for consecutive 135 days from 16 April 2000 over Bangladesh to obtain the diurnal variations and characteristics of precipitation in relation to cloud activity. They found the nature of the diurnal cycle of precipitation in Bangladesh that is a morning peak at 0600 LST with minimum at noon. The frequency of the echoes exhibits two peaks, one in the afternoon (~1500 LST) and other in the morning (~0600 LST) hours. The smaller echoes dominant in the afternoon while large echoes develop in the early morning.

Singh et al., [16] studied the diurnal variation in total lightning flashes is analyzed using TRMM/LIS data during 1998-2007. The precipitation over central India during wet periods is characterized by a large amount of rainfall with a high frequency of rain and a secondary morning peak. The precipitation in dry periods is characterized by a strong diurnal variation with convective rainfall and enhanced electrical activity over central India. Characteristics of wet and dry periods over central India are generally supported over the southern Himalayan foothills. During wet periods; the rain rate shows a weak

diurnal variation with a broad peak in the afternoon around 15 LST. During dry periods, the rain rate shows a strong diurnal variation with a narrow peak at around 15 LST. During wet periods, broad peaks of frequency of rainfall centered at night (18–21 LST) and morning (03–06 LST) appear. During dry periods, a peak is observed in the afternoon around 15 LST. During wet periods, two broad peaks are observed in the afternoon (12–18 LST) and around early morning (03–06 LST), but for dry periods, a sharper peak is observed in the afternoon (12–18 LST).

Chen et al., [17] analyzed the surface diurnal variations during November 1992-February 1993 over the tropical Pacific warm pool. They used hourly infrared (IR) images from the Japanese Geosynchronous Meteorological Satellite (GMS) with about 10 km resolution (re-sampled from the original 5 km pixel size with highest resolution of 4km at the sub satellite point (0° and 140° E) as the primary data set to examine the diurnal variation of cold cloud tops over the Indo-Pacific warm-pool region (80°E-160°W and 20°N-20°S). During the convectively active phases of intra-seasonal oscillation (ISO), the cold cloud coverage is dominated by spatially large, long-lived cloud systems. They tend to form in the afternoon (1400-1900 LST) and reach a maximum areal extent of very cold cloud tops (< 208 K) before dawn (0000-0600 LST). As part of their life-cycle, the subsequent decay of these large systems extends into the next day; the satellite-observed maximum cloud coverage is dominated by successively warmer cloud tops, from 208-235 K in the early afternoon (-1400 LST) to 235-260 K in the early evening (-1800 LST). Meanwhile the frequency of small cloud systems exhibits two peaks-one in the afternoon and the other in the pre-dawn hours. The latter is evidently triggered by outflows from the large convective systems.

Kataoka et al., [18] pointed out the nighttime acceleration of lower troposphere monsoon south-westerly. They also showed that the mountain wind does not play major role in the development of the convective systems at night over the northeastern part of Bangladesh. To clarify the mechanism responsible for the midnight-early morning peak, they

propose that observation should be made at high temporal and spatial resolution especially over the area surrounding the Meghalaya Plateau.

Deshpande et al., [19] investigated that diurnal cycle of rainfall over India using hourly data of self-recording rain gauge during the period of 1969 to 2005. They examined to determine the role of intra-seasonal variations of Indian summer monsoon in modulating the diurnal cycle of rainfall over four homogenous regions. Harmonic analysis of the diurnal cycle of rainfall shows predominance of principal harmonic during the break phase of monsoon. During an active phase first two harmonics contribute substantially to the total variance in central parts of the country. They also observed that peak rainfall occurs in the morning hours during both the active and break phases along the West Coast with small diurnal variation in rainfall. Two peaks in the diurnal cycle are observed during active phases over central India. This region shows delay in the occurrence of afternoon peak and rise in rainfall intensity during the break phase of recent years, while, increase in rainfall intensity at all hours during break phases is observed along the West Coast of India in recent years. Further analysis of meteorological parameters indicates that lower-level convergence during late afternoon hours, reduction in geo-potential height and increase in specific humidity (850 hPa) in central parts of India during morning and evening hours are in phase with the two maxima observed in the diurnal cycle of rainfall in this region.

Shrestha et al., [20] investigated that diurnal cycle of precipitation revealed an afternoon maximum during the pre-monsoon season (March–May) and midnight–early morning maximum during the summer monsoon season (June–August) over the southern slopes of the Himalayas utilizing 13-year (1998–2010) high resolution ( $0.05^\circ \times 0.05^\circ$ ) Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) data. The summer monsoon exhibited a robust spatial variation of diurnal cycle of precipitation, during afternoon–evening time, primary rainfall peak appeared along the Lesser Himalayas ( $\sim 2,000$ – $2,200$  m above Mean Sea Level-MSL), while early-morning rain in contrast showed maximum concentration along the southern margin of the Himalayas ( $\sim 500$ – $700$



m above MSL). An afternoon-evening rainfall peak was attributed to higher rain frequency, whereas early-morning rainfall peak was attributed to fewer but rather intense rainfall. They suggested that, confluence between down slope and moist southeasterly monsoon flow triggers convection near the foothills of the Himalayas during early morning period. They suggested the morning precipitation moves southward in the mature monsoon season.

Ray et al., [21] studied diurnal variation of rainfall of different intensities using self-recording rain gauge data of about 150 stations spread across India is presented here. Analysis of annual average number of rainfall hours revealed that the highest number (>900) is realized over northeast India, followed by west coast (700–800). Lowest incidence (<100) was found over west Rajasthan. Distribution was nearly similar for hours with rainfall >10, >20 and >30 mm. A zone of less number of hours with different intensities extended from west Rajasthan to west Uttar Pradesh; and another one to south Tamil Nadu through Gujarat, west Madhya Pradesh and the rain shadow zones of Maharashtra, Karnataka and Andhra Pradesh. The percentage of contribution to total annual rainfall by intense rainfall of >20 mm and >30 mm, however, was found to be higher in the low rainfall zones and northwest India. Diurnal variation of rainfall showed prominent maxima in the early morning over northeast India; and in the afternoon/evening over northwest India and interior Peninsula. Coastal areas on east and west coast, however, did not exhibit any significant diurnal variations, but a tendency of higher frequency in the early morning was noticed.

Bharti et al., [22] analyzed diurnal variations of precipitation during Indian summer monsoon over northwestern Himalayan state using TRMM 3B42V7 from 1998 – 2013. They deal with the spatial and diurnal variations of seasonal rainfall, seasonal extremes and the examination of their trends. A pronounced maxima occurs during late night to early morning hours (0230 – 0530 LT) for elevations up to 2 km whereas secondary maxima peaks during afternoon (1430 – 1730 LT) at regions having altitude 2 – 4 km. The minimum mean 3-hourly rainfall, intensity – frequency of heavy and very heavy

rainfall events is registered at 2030 LT. Precipitation occurs most frequently with high intensity over the western regions of the state. Further, trend analysis did not show any significant trend in mean 3-hourly rainfall and intensity-frequency of very heavy rainfall events. Only significant increasing trend (at 5% significance level) was found in intensity of heavy rainfall events for morning hours. The dominant intensity frequency peak for heavy rainfall events is at 0530 LT whereas for very heavy rainfall events, it is at 0230 LT.

Sahany et al., [23] studied the Tropical Rainfall Measuring Mission 3-hourly, 0.25 by 0.25 degree 3B42 rainfall product for nine years (1999–2007) over the Indian region. Using harmonic analysis, they extracted the signal corresponding to diurnal and sub diurnal variability. Subsequently, the 3-hourly time period or the octet of rainfall peak for this filtered signal, referred to as the „peak octet,“ is estimated, with care taken to eliminate spurious peaks arising out of Gibbs oscillations. They suggested that over the Bay of Bengal, there are three distinct modes of the peak octet of diurnal rainfall corresponding to 1130, 1430, and 1730 Indian standard time (IST), from the north central to south bay. Over the Arabian Sea, there is a spatially coherent pattern in the mode of the peak octet (1430 IST), in a region where it rains for more than 30% of the time. In the equatorial Indian Ocean, while most of the western part shows a late night/early morning peak, the eastern part does not show a spatially coherent pattern in the mode of the peak octet owing to the occurrence of a dual maximum (early morning and early/late afternoon). The Himalayan foothills were found to have a mode of peak octet corresponding to 0230 IST, whereas over the Burmese mountains and the Western Ghats (west coast of India) the rainfall peaks during late afternoon/early evening (1430–1730 IST). This implies that the phase of the diurnal cycle over inland orography (e.g., Himalayas) is significantly different from coastal orography (e.g., Western Ghats). They also found that over the Gangetic plains, the peak octet is around 1430 IST, a few hours earlier compared to the typical early evening maxima over land.

Limsakul et al., [24] studied on the basis of Empirical Orthogonal Function (EOF) and harmonic analysis, spatial patterns of diurnal cycles of precipitation during a rainy season over Thailand and its vicinity were examined using 3-hourly, 0.25° TRMM data for the time period 2000-2009. They revealed that the leading two EOFs and harmonics could explain most of diurnal precipitation variations. The first EOF and harmonic represent the diurnal cycle with an afternoon-evening peak and amplitude of 30-88% of the climatologically mean. This dominant feature reflects land-sea difference in the atmospheric response to solar radiation forcing, representing potential instability forced by the surface heat flux, insolation and long-wave radiative cooling during the day and night. Whereas, the second EOF and harmonic denote the semidiurnal cycle, with nocturnal and early morning maxima and amplitude of 10-33% of the climatological mean. The secondary sub-daily cycle represents a complementary local variation, and is associated with mesoscale dynamics of convective systems and its interactions with local thermally induced circulations.

Yu et al., [25] studied diurnal variations of summer precipitation over contiguous China using hourly rain-gauge data from 588 stations during 1991–2004. It is found that summer precipitation over contiguous China has large diurnal variations with considerable regional features. Over southern inland China and northeastern China summer precipitation peaks in the late afternoon, while over most of the Tibetan Plateau and its east periphery it peaks around midnight. The diurnal phase changes eastward along the Yangtze River Valley, with a midnight maximum in the upper valley, an early morning peak in the middle valley, and a late afternoon maximum in the lower valley. Summer precipitation over the region between the Yangtze and Yellow Rivers has two diurnal peaks: one in the early morning and another in the late afternoon.

Mori et al., [26] investigated that the diurnal cycle of rainfall and its regional variation over Sumatera Island, Indonesian Maritime Continent using Tropical Rainfall Measuring Mission (TRMM) satellite precipitation radar (PR) and intensive radiosonde sounding data. The TRMM PR sensor can detect raindrops directly, regardless of ground and

cloud conditions, and can distinguish between convective and stratiform types of rainfall. They showed rainfall variation over this area was found to have the following characteristics: 1) convective rainfall with a broad peak between 1500 and 2000 LT predominates over the land region of Sumatera Island, whereas rainfall in the early morning, composed almost equally of stratiform and convective types, is predominant over the surrounding sea region. 2) A rainfall peak in the daytime and one in the nighttime migrate with time starting from the southwestern coastline of the island into the inland and offshore regions, respectively. The distance of each rainfall peak migration from the coastline is up to 400 km, and the average speed of migration is approximately 10 meter per second. 3) Using intensive radiosonde sounding data, they also found that remarkable diurnal variations of wind, humidity, and stability appear in the lower troposphere corresponding to the migrating rainfall peaks over both the inland and the coastal sea regions.

Begum et al., [25] studied the impact of climate change on rainfall over Bangladesh for last 6 decades. They found decreasing trend for annual land monsoon rainfall during 1981-2010) and increasing trend for the same rainfall during the period of 1951-2011. Seasonal rainfall analysis for last 30 years (1981-2010) showed the maximum rainfall variation in monsoon season. They also found the decreasing trend of rainfall for all seasons except post-monsoon during this period. That means, rainfall is decreasing in recent years due to climate change. Again, the divisional rain trend analysis showed decreasing trend for all divisions except Dhaka and Rajshahi during 2000-2011. But, at the same time, the extremely decreasing trend is found for mostly rainy division Sylhet which is found about 0.4377mm/yr. That means the rainfall events have increased over Dhaka and decreased over Sylhet division significantly during last decades due to climate change.

Takahashi et al., [28] observed diurnal rainfall pattern using 10 year (1998–2007) Tropical Rainfall Measuring Mission Precipitation Radar (TRMM-PR) observations. Results revealed that the diurnal variations in rainfall over the Indochina region had

three distinct peaks. An early afternoon maximum of rainfall occurred along the mountain ranges and on coastal land. Evening rainfall was observed near the foot of mountain ranges, in a valley, and in a basin-shaped plain; this rainfall weakened before the middle of the night. Heavy rainfall in the early morning was found around the coasts over the eastern Gulf of Thailand and the Bay of Bengal, as well as over the eastern Khorat Plateau. We found that nearly half of the total rainfall occurred in the early morning over these regions, which indicated that early morning rainfall significantly contributes to the climatologically rainfall pattern. They also noted the regions with early morning heavy rain did not correspond to windward faces of mountains but to the windward plain or to an offshore area apart from the mountain ranges in the windward direction.

## **2.2 Overview of the study**

Precipitation does not occur all the time, yet it is common to consider only total amount. Just as important is the frequency and intensity of the precipitation. The diurnal cycle of precipitation frequency and intensity has large effects on surface hydrology (runoff, evaporation). For example; rainfall during the afternoon is likely to be evaporated more quickly than night. Diurnal variations of precipitation can modulate the surface temperature range and closely related to the diurnal cycles of atmospheric moist convection and cloudiness, which greatly affects the solar and long-wave radiation at the surface.

Diurnal variability of rainfall over short time scales, such as diurnal variations, is significant aspect of regional climate since precipitation occurring regularly during a specific time of the day is a result of complex interaction of regional and local dynamics and atmospheric circulation. The change in diurnal cycle of rainfall signifies a gradual change in climate patterns on the region. Urbanization can lead to adjustments in local precipitation pattern and mechanisms leading to changes in the diurnal cycle of rainfall [29]. Diurnal variation in middle and low latitudes as follows:

- a) Middle latitudes

The simplest and predominant diurnal variation of precipitation originates in cumulus convection due to daytime boundary layer heating, peaking in afternoon over inland areas during warm seasons, especially over mountains, and nocturnally over basins or plains to the lee of mountains. Early morning enhancement exists over inland and coastal areas all year around. An early morning maximum is also observed over the ocean.

b) Low latitudes

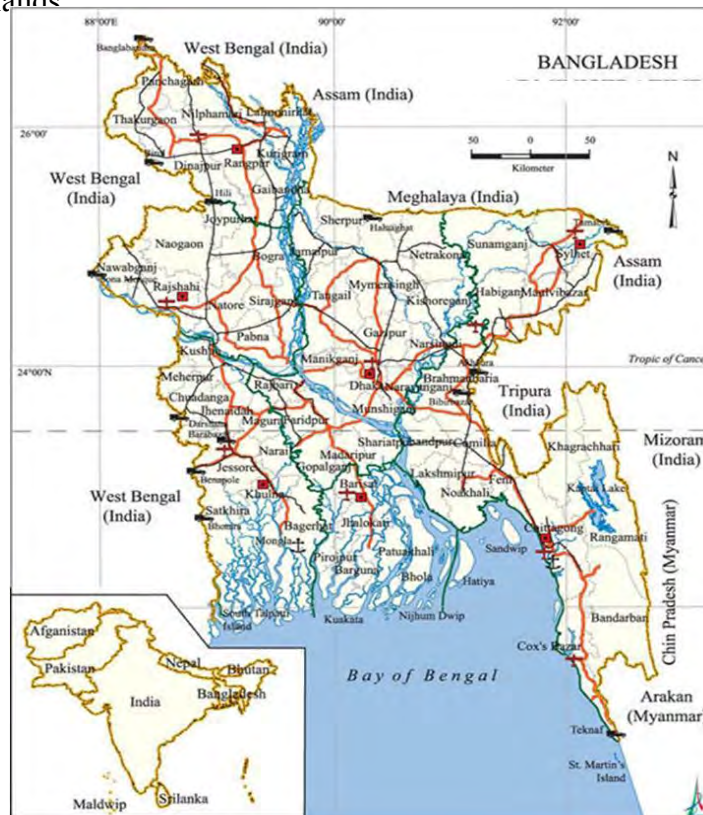
Inland areas exhibit deep cumulus convection in the afternoon with no increase in the morning. Coastal regions show maximum precipitation in early morning, depending on the direction of the prevailing wind. An afternoon maximum over larger islands, superimposed on a diurnal cycle peaking in the morning over all sized islands, is reported in the western North Pacific Ocean.

Diurnal variations of precipitation play a significant role in modulating the mountain climate systems. Diurnal cycle of mountain winds and solar insolation plays a major role in the set-up of necessary atmospheric conditions for precipitation in mountains. So irradiative heating produces thermally driven mountain winds which are debated as majorly responsible for triggering convective systems over southern slopes of the Himalayas [30]. Many researchers have reported usually late night/early morning rainfall peaks over the Himalayan foothills while some suggested afternoon peaks [30-33]. Local circulations due to surface heating, triggering of gravity waves, mountain-valley breeze circulations and propagation of mesoscale convective systems are some of the processes that have been related with diurnal variations of precipitation over land [3, 35-40].

### **2.3 Geography of Bangladesh**

Bangladesh is a riverine and low-lying flat country located between  $20.67^{\circ}$  to  $26.63^{\circ}$  north latitude and  $88.05^{\circ}$  to  $92.72^{\circ}$  east longitudes, with an area of 147,570 sq km. It has a population density more than 1000 per sq km. It has a border on the west, north, and east with India, on the southeast with Myanmar, and the Bay of Bengal is to the south. The geographical position of Bangladesh is shown in Figure 2.3 [41]. Geologically,

Bangladesh is a part of the Bengal Basin, one of the largest geosynclines in the world. The Basin is surrounded on the north by the steep Tertiary Himalayas; on the northeast and east by the late Tertiary Shillong Plateau, the Tripura hills of lesser elevation, and the Naga-Lusai folded belt; and in the west by the moderately high, ancient Chotanagpur plateau. The southern fringe of the basin is not distinct, but geophysical evidence indicates it is open towards the Bay of Bengal for a considerable distance. The country consists of low and flat land formed mainly by the sediments carried by the Ganges and the Brahmaputra River systems except for the hilly regions in the north-eastern and south-eastern parts. From physiographic point of view, about 80 percent of the land is floodplains with very low mean elevation above the sea level with the rest made up of hills and elevated lands.



**Figure 2.3:** Geographical location of Bangladesh

Topography of the country is characterized by very low differences in the elevation between adjoining ridge tops and depression centers, which range from less than 1 meter

on tidal floodplains, 1 to 3 meters on the main river and estuarine floodplains, and up to 5 to 6 meters in the Sylhet Basin in the north-east. Only in the extreme north-west land elevations exceed 30 meters above the mean sea level. There are two uplifted land blocks, known as the Madhupur and the Barind tracts, which generally have higher elevation: within 1 and 5 meters above the adjoining floodplains. In some places, however, they reach up to 25 meters higher than the adjoining floodplains. Hills are located along the northern and eastern borders of the country. These tertiary hills have higher elevation, some reaching over 1000 meters above mean sea level [42].

Bangladesh is situated within two different environments, one is the Bay of Bengal to the South and other is the Himalayas to the north. Due to the geographical position of Bangladesh, it experiences highest amount of country average monsoon and annual rainfall among SAARC countries .Bangladesh is one of the most flood-prone countries in the world due to its geographic position [43-44].

#### **2.4 Seasons of Bangladesh**

The country prevail a humid, warm, tropical climate. Its climate is strongly influenced by monsoon. The south-west monsoon originates over the Indian Ocean and carries warm, moist, and unstable air. The monsoon has its onset during the first week of June and withdraws in the first week of October; however, the onset and withdrawal dates vary from year to year. The main rainy period begins with the onset of the moisture-laden south-west trades which are drawn to the Indian sub-continent by the intense heat and consequent low pressure over Punjab (in Pakistan and India) and the Upper Ganges Valley and the filling up of the equatorial lows by air masses from these hot areas. Besides monsoon, the easterly trade winds are also active, providing warm and relatively drier circulation. In Bangladesh there are four prominent seasons, namely, Pre-monsoon (March to May), Monsoon (June to September), Post-monsoon (October to November) and winter (December to February). The general climatic characteristics of these seasons are as follows:



- **Pre-monsoon:** pre-monsoon is rather hot with an average maximum of 36.7 °C, predominantly in the west for up to 10 days, very high rate of evaporation, and erratic but occasional heavy rainfall from March to May. In some places the temperature occasionally rises up to 40°C or more and average maximum temperature of 36.7°C. The peak of the maximum temperatures are observed in April, the beginning of pre-monsoon season. In pre-monsoon season the mean temperature gradient is oriented in southwest to northeast direction with the warmer zone in the southwest and the cooler zone in the northeast.
- **Monsoon:** monsoon is hot and humid, brings heavy rainfall throughout the country. About 70% of the mean annual rainfall is occurred during the monsoon season. The temperature difference of land and ocean is the main factor of the Asian monsoon causes seasonal scale sea breeze circulation. The mean monsoon temperatures are higher in the western districts compared to that for the eastern districts. Warm conditions generally prevail throughout the season, although cooler days are also observed during and following heavy downpours.
- **Post-monsoon:** post-monsoon is a short-living season characterized by withdrawal of rainfall and gradual lowering of night-time minimum temperature. Post-monsoon is the transitional season from monsoon to winter. Moderate and heavy rainfalls are occurred in this season.
- **Winter:** winter is relatively cooler and drier, with the average temperature ranging from a minimum of 7.2 to 12.8 °C to a maximum of 23.9 to 31.1°C. The minimum occasionally falls below 5 °C in the north though frost is extremely rare. There is a south to north thermal gradient in winter mean temperature; generally the southern districts are 5 °C warmer than the northern districts. Generally light rainfall occurred in winter season.

The mean annual rainfall is about 2300mm, but there exists a wide spatial and temporal distribution. Annual rainfall ranges from 1200mm in the extreme west to over 5000mm

in the east and north-east [45]. Generally, the eastern parts of the country enjoy higher rainfall than the western parts.

## **2.5 Global Satellite Mapping of Precipitation**

Earth Observation Research Center (EORC) of Japan Aerospace Exploration Agency (JAXA) processed and released GSMaP\_MWR Version 4.8.4 during 1998-2006 and MVK during 2003-2006 via JST/CREST GSMaP Project Website of Osaka Prefecture University at March 2007. In 21 July 2009, GSMaP Project Website was moved to JAXA/EORC Web site .GSMaP\_MVK Version 5.112 for 2007 was processed and uploaded at 7 December 2010. The Files of Satellite Information Flag and Observation Time Flag were newly added. In 6 March 2012, GSMaP\_MVK Version 5.222 during March 2000 to November 2010 was processed and uploaded. All files except text format file and Time Information Flag are available .Time Information Flag files were uploaded at 30 March 2012.Updated satellite operation period in USERS\_GUIDE\_MVK\_v5.222.pdf uploaded at 12 April 2012. GSMaP\_MVK Version 5.222.1 was uploaded at 17 August 2012. Correct input database (rain/no-rain detection) for AMSR-E retrievals from 2006 to 2010, and remove several anomalous data (NOAA-N16 over the land from 2008 to 2010, NOAA-15/-16/-17 over the ocean during 1-5 January,2004, DMSP-F17 from 21Z 30 June to 19Z 1 July, 2008, and DMSP-F17 at 12Z 18 March,2008.). Daily products in text format of the GSMaP\_MVK Version 5.222.1 were uploaded at 18 October, 2012. Hourly products in text format of the GSMaP\_MVK Version 5.222.1 were uploaded at 10 July, 2013. The detailed GSMaP\_MVK data are available at the website link <ftp://rainmap:Niskur+1404@hokusai.eorc.jaxa.jp> (Last access: March 2017). GSMaP products composed with following satellite (figs 2.5.1):

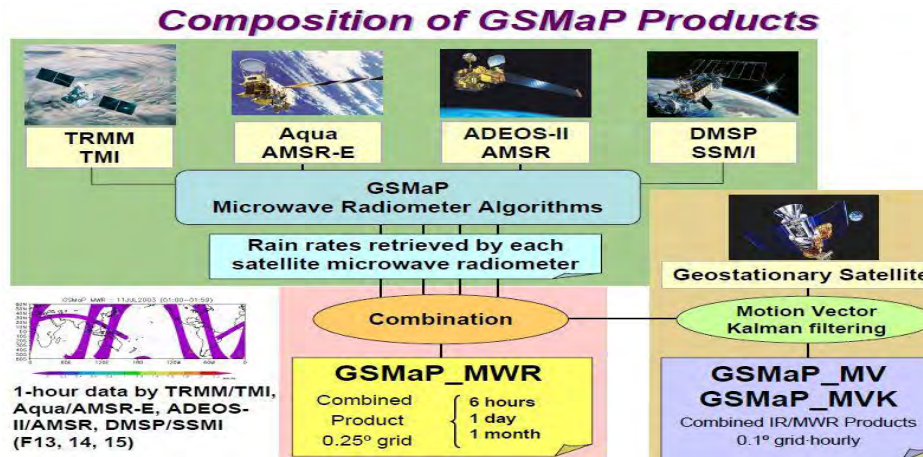


Figure.2.5.1: Composition of GSMaP project.

### Status of satellite-borne microwave radiometer data processed by GSMaP algorithm

**Table1: Status of each satellite data**

Satellite (Sensor)	Processed period	Features
TRMM (TMI)	Jan 1998-Dec 2005	Ver.4.7.2
Aqua (AMSR-E)	Jan 2003-Dec 2005	Ver.4.7.2
ADEOS-II (AMSR)	Apr 2003-Oct 2003	the same as above
DMSP F13, F14, F15 (SSM/I)	Jan 2003-Dec 2005	the same as above

**Table2: Status of each products**

Spatial resolution	Time resolution	Archives	Data source
0.1 degrees	hourly	July 2005	Combined microwave radiometers (TMI, AMSR-E, AMSR, SSM/I × 3) (Latitude ± 60°)
0.25 degrees	Various*	Jan 2003-Dec 2005	Combined TMI and AMSR-E (AMSR added from April 2003-October 2003) (Latitude ± 60°)
0.25 degrees	Various*	Jan 1998-Dec 2005	TMI (Latitude ± 40°)

*Various\* (6-hourly, 1 day, 1 month)*

Figure 2.5.2: Status of used satellites in GSMaP algorithm.

**TRMM Microwave Imager (TMI):** The TMI is a passive microwave sensor designed to provide quantitative rainfall information over a wide swath under the TRMM satellite. By carefully measuring the minute amounts of microwave energy emitted by the Earth and its atmosphere, TMI is able to quantify the water vapor, the cloud water, and the rainfall intensity in the atmosphere. It is a relatively small instrument that consumes little power. It combined with the wide swath and the good, quantitative information regarding rainfall make TMI the "workhorse" of the rain measuring package on TRMM. The TMI measures the intensity of radiation at five separate frequencies: 10.7, 19.4, 21.3, 37, 85.5 GHz. These frequencies are similar to those of the SSM/I, except that TMI

has the additional 10.7 GHz channel to provide a more-linear response for the high rainfall rates common in tropical rainfall. TMI has a 547 mile (878 km) wide swath on the surface. The higher resolution of TMI on TRMM, as well as the additional 10.7 GHz frequency, makes TMI a better instrument than its predecessors.

**Aqua/AMSR-E:** The National Aeronautics and Space Administration (NASA) National Snow and Ice Data Center Distributed Active Archive Center (NSIDC DAAC) archives and distributes daily, weekly, and monthly Level-1A, Level-2A, Level-2B, and Level-3 data products from the Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) sensor on NASA's Aqua satellite. The AMSR-E instrument launched on 02 May 2002 and ceased operations 04 December 2011. Temporal coverage for the data products is from 18 June 2002 through 04 October 2011. The AMSR-E instrument provides measurements of the following terrestrial, oceanic, and atmospheric parameters for the investigation of global water and energy cycles, including precipitation rate sea, surface temperature, sea ice concentration, snow water equivalent, soil moisture, surface wetness, wind speed, atmospheric cloud water and water vapor.

**ADEOS-2/AMSR:** The Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E) is a twelve-channel, six-frequency, passive-microwave radiometer system. It measures horizontally and vertically polarized brightness temperatures at 6.9 GHz, 10.7 GHz, 18.7 GHz, 23.8 GHz, 36.5 GHz, and 89.0 GHz. Spatial resolution of the individual measurements varies from 5.4 km at 89 GHz to 56 km at 6.9 GHz. AMSR-E overpass times are near 1:30 a.m. (ascending) and 1:30 p.m. (descending) local time at the equator. AMSR-E is developed and provided by the Japan Aerospace Exploration Agency (JAXA, Contractor: Mitsubishi Electric Corporation) with close cooperation of U.S. and Japanese scientists. AMSR-E was modified for Aqua from the design used for AMSR, which is on board the Japanese ADEOS-2 satellite. The AMSR-E instrument measures geophysical variables related to the earth's water cycle, including: precipitation rate, cloud water, water vapor, sea surface winds, sea surface temperature, sea ice concentration, snow water equivalent, and soil moisture.

**DMSP series SSM/I:** The National Snow and Ice Data Center (NSIDC) produces daily gridded brightness temperatures from orbital swath data generated by the Special Sensor Microwave/Imager (SSM/I) aboard the Defense Meteorological Satellite Program (DMSP) F8, F11, and F13 platforms and the Special Sensor Microwave Imager/Sounder (SSMIS) aboard DMSP-F17. The SSM/I and SSMIS channels used to calculate brightness temperatures include 19.3 GHz vertical and horizontal, 22.2 GHz vertical, 37.0 GHz vertical and horizontal, 85.5 GHz vertical and horizontal (on SSM/I), and 91.7 GHz vertical and horizontal (on SSMIS). Thus, a total of nine channels result from vertical and horizontal polarization for each of five frequencies, with the exception of 22.2 GHz, which is vertical only. Data at 85.5 GHz and 91.7 GHz are gridded at a resolution of 12.5 km, with all other frequencies at a resolution of 25 km.

**Geostationary Satellite:** A geostationary satellite is an earth-orbiting satellite, placed at an altitude of approximately 35,800 kilometers (22,300 miles) directly over the equator that revolves in the same direction the earth rotates (west to east). At this altitude, one orbit takes 24 hours, the same length of time as the earth requires rotating once on its axis. The term geostationary comes from the fact that such a satellite appears nearly stationary in the sky as seen by a ground-based observer.

**Table 2.1 Standard product (Latency: 3 days)**

Product name	Variables	Horizontal resolution	Temporal resolution	Latency	Correction
L3 GSMaP Hourly	Hourly preci rate (GSMaP_MVK)	0.1×0.1 deg.	1 hour	3 days	None
	Gauge-adjusted Hourly Precip Rate (GSMaP_Gauge)	lat/lon			Adjusted by daily rain gauges (NOAA CPC Gauge-Based, Chen et al.2008)

**Table 2.2. Near-real-time product (Latency: 4 hours)**

Product name	Variables	Horizontal resolution	Temporal resolution	Latency	Correction
L3RG SMaP Hourly	Hourly precip Rate (GSMaP_NRT)	0.1×0.1 deg.lat/lon	1 hour	4 hours	None
	Gauge-adjusted Hourly Precip Rate (GSMaP_Gauge_NRT)				Correction by empirical coefficients

From the above GSMaP products GSMaP\_Gauge\_MVK products are used in this research work.

# CHAPTER THREE

## DATA AND METHODS

### 3.1 Data Sources and Duration

In this research two types of data are analyzed, they are

- Global Satellite Mapping of Precipitation (GSMaP) hourly rainfall data and
- Bangladesh Meteorological Department (BMD) three- hourly rain gauge data

Study period: 2001 to 2015

The above data duration has chosen because GSMaP data are available from 2001.

### 3.2 Data Description

#### 3.2.1 GSMaP Product

The Global Satellite Mapping of Precipitation (GSMaP) project is sponsored by Core Research for Evolutional Science and Technology (CREST) of the Japan Science and Technology Agency (JST) during 2002-2007. Since 2007, GSMaP project activities are promoted by the Japan Aerospace Exploration Agency (JAXA) Precipitation Measuring Mission (PMM) Science Team. Moreover, the dataset produced by GSMaP product can be downloaded from their server or website; **ftp://rainmap:Niskur+1404@hokusai.eorc.jaxa.jp** (Last access: May 2017). It provides global precipitation map with high spatial (0.1 degree) and temporal (1 hour) resolution using Kalman filter technique and coverage domain is 60°N-60°S. It offer hourly global rainfall maps in near real time (about four hours after observation) using the combined MW-IR algorithm with TRMM TMI, Aqua/ AMSR-E, ADEOS-2/ AMSR, DMSP series SSM/I and Geostationary Infrared ( IR) data. The newly developed algorithm for the Global Precipitation Measurement (GPM) mission (GPM-GSMaP Ver.6) is used to retrieve rain rate, and product is the same to the GPM Global Rainfall Map product distributed from the JAXA G-Portal (<https://www.gportal.jaxa.jp>). GPM-

GSMaP version 6 is the latest algorithm developed by the Global Satellite Mapping of Precipitation (GSMaP) project. It also offer cloud and typhoon images are globally merged IR data produced by NOAA Climate Prediction Center (CPC), using IR data observed by JMA's MTSAT satellite(Japan Meteorological Agency, Multi-functional Transport Satellite), NOAA's GOES satellites and EUMETSAT's(European Organization for the Exploitation of Meteorological Satellites) Meteosat satellites.

The main feature of the GSMaP algorithm is utilization of various attributes derived from TRMM PR that is the first space borne precipitation radar. Data Directory and File description is given below: Hourly Rain Rate data;

Directory: /standard/v5/hourly/YYYY/MM/DD/  
File Name: gsmmap\_mvk.YYYYMMDD.HHNN.vP.RSK.I.dat.gz

Where,

YYYY: 4-digit year  
MM: 2-digit month  
DD: 2-digit day  
HH: 2-digit hour  
NN: 2-digit minute (currently fixed as 00)  
P: Product version  
R: Version of microwave imager algorithm (reset when P is updated)  
S: Version of microwave sounder algorithm (reset when P is updated)  
K: Version of microwave-IR combined algorithm  
I: Inclement number of reprocessing

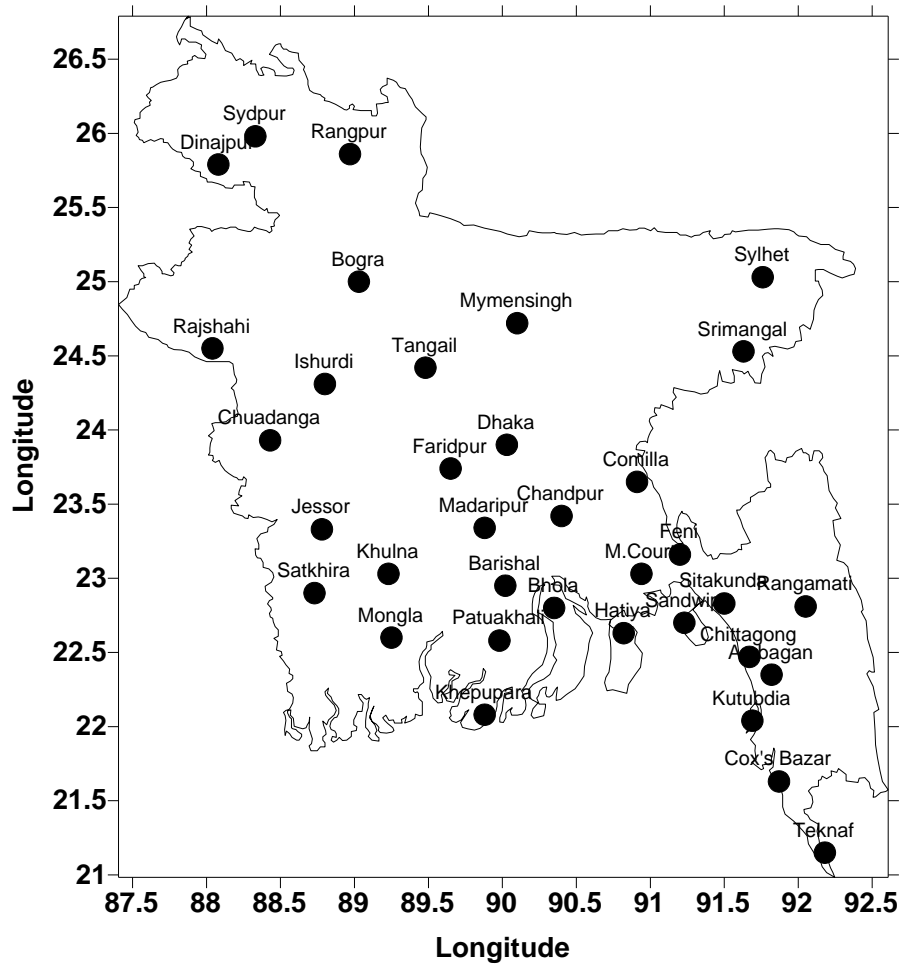
In this study, GSMaP\_MVK hourly rainfall data from 2001 to 2015 are being used for the analysis of diurnal variation of rainfall in Bangladesh.

### **3.2.2 Rain Gauge Data and its limitation in Bangladesh**

Rain gauge is very common instrument used by meteorologists and hydrologists to collect and measure the amount of liquid precipitation over a period of time. Most rain gauges generally measure the precipitation in millimeters. The level of rainfall is



sometimes reported as inches or centimeters. BMD has only 35 rain gauge stations all over the country. The locations of these 35 rain gauges are shown in Figure 3.1. In the current study, 3 hourly rain gauge data collected by BMD are utilized and analyzed for comparison to GSMaP products over Bangladesh.



**Figure 3.1:** Locations of the 35 rain gauge stations of Bangladesh Meteorological Department (BMD).

The information obtained from the low density rain gauge network is not always suitable for the quantification of the correct amount of the precipitation from small cloud. For accurate estimation of precipitation a dense rain gauge network is required. On the other hand, the location of the formation of the cloud, its shape and size, propagation speed

and the direction of motion are not obtainable from rain gauge data, but these are very much important for weather modeling and forecasting. GSMaP data may be useful for all kind of observation and research especially in data spare region such as remote mountainous area, over ocean etc. It is one of the exigent purposes of this research to find out the correlation between GSMaP and rain gauge data over Bangladesh.

### 3.3 Method

The Grid Analysis and Display System (GrADS) script was used to extract GSMaP data at 35 BMD rain gauge station locations. GSMaP products are hourly rainfall data whereas BMD rain gauge data is 3-Hourly. So, for harmonic analysis daily rainfall data has been calculated by adding the data at 00, 03, 06, 09, 12, 15, 18, and 21 LST. Then monthly, seasonal and yearly rainfall was calculated on the basis of daily rainfall. Year to year diurnal variation of rainfall during different season are evaluated in this research. From this process daily, monthly, seasonal and annual diurnal variation of rainfall is analyzed. MS-Excel is used for statistical and arithmetic calculation in this study to compare and justify both GSMaP and BMD rain gauge observed rainfall in Bangladesh. Spatial distributions of seasonal and average diurnal variations of rainfall are displayed using mapping software tool Surfer for both dataset.

#### 3.3.1 Correlation Coefficient

The formula for the correlation (r) is

$$r = \frac{1}{(n-1)} \left( \frac{\sum \sum (x - \bar{x})(y - \bar{y})}{S_x S_y} \right)$$

Where n is the number of pairs of data  $\bar{x}$  and  $\bar{y}$  are the sample means of all the x-values and all the y-values, respectively;  $S_x$  and  $S_y$  are the sample standard deviations of all the x-value and y-values, respectively.

### 3.3.2 Root Mean Square Error (RMSE)

The RMSE (also called the root mean square deviation, RMSD) is a frequently used measure of the difference between values predicted by a model and the values actually observed from the environment that is being modeled. These individual differences are also called residuals, and the RMSE serves to aggregate them into a single measure of predictive power.

The RMSE of a model prediction with respect to the estimated variable  $X_{model}$  is defined as the square root of the mean squared error:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (X_{obs,i} - X_{model,i})^2}{n}}$$

Where  $X_{obs}$  is observed values and  $X_{model}$  is modeled values at time/place  $i$ .

The calculated RMSE values will have units. In this study, BMD data is observed values and rain gauge data is modeled/reference values. The unit of RMSE is millimeter in this study.

However, the RMSE values can be used to distinguish model performance in a calibration period with that of a validation period as well as to compare the individual model performance to that of other predictive models.

### 3.3.3 Standard deviation

In statistics, the standard deviation (SD, also represented by the Greek letter sigma  $\sigma$  or the Latin letter  $s$ ) is a measure that is used to quantify the amount of variation or dispersion of a set of data values. A low standard deviation indicates that the data points tend to be close to the mean (also called the expected value) of the set, while a high standard deviation indicates that the data points are spread out over a wider range of values.

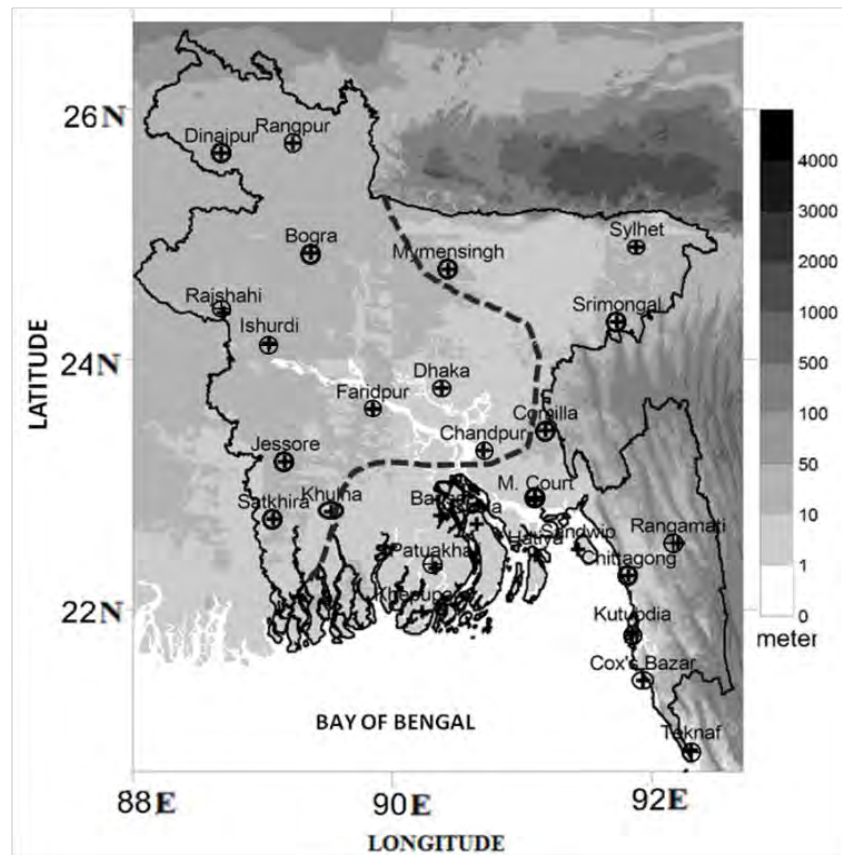
The formula for standard deviation (SD) is

$$SD = \sqrt{\frac{\sum (x - \bar{x})^2}{n}}$$

Where  $\sum$  means sum of,  $x$  is a value in the data set,  $\bar{x}$  is the mean of the data set, and  $n$  is the number of data points.

### 3.3.4 Regional classification

For detail analysis the whole country was divided into two regions named: wet and dry regions (Figure 3.2), based on humidity anomalies as proposed by Islam and Uyeda [61]



**Figure 3.2:** The names of the BMD observational site over Bangladesh are shown above the station location. The left side of dash line is dry region and right side is wet region. Topography is shown by grey shading.

### **3.3.5 Classification of season of Bangladesh**

In meteorological point of view Bangladesh has four seasons, such as,

- Pre-monsoon (March – May)
- Monsoon (June – September)
- Post-monsoon (October – November)
- Winter (December – February)

In this study, different criteria of diurnal variation of rainfall are studied in and around Bangladesh using GSMaP data and rain gauge on the basis of this classification of season.

### **3.3.6 Different types of diurnal variation of rainfall**

There are two main types of diurnal variation of rainfall: (a) continental or inland type, and (b) maritime or coastal type [4, 5]. The main dominant feature of the diurnal cycle is a rainfall maximum in late-evening or Early-morning (LE-EM) hours in oceanic area, while over land the dominant maximum occurs in the mid- to late-afternoon (MLA).

In the study of station-wise diurnal variation of rainfall, the station which shows maximum rainfall at Late-evening or Early-morning (LE-EM) hours is as considered Maritime type station whereas the station shows maximum rainfall at mid- to late-afternoon (MLA) hours is as considered Continental type station.

# CHAPTER FOUR

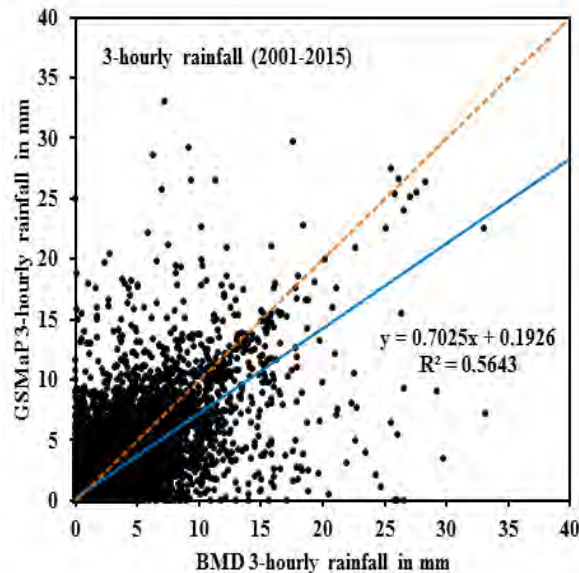
## RESULTS AND DISCUSSION

### 4.1 Data Validation

So far our knowledge this is the first attempt to use GSMaP data in Bangladesh, for this reason we validated GSMaP data with BMD rain gauge data. It is found GSMaP data are highly correlated with BMD rain gauge data. The 3-hourly, daily, monthly and yearly correlation coefficients between BMD rain gauge and GSMaP data are found 0.71, 0.74, 0.82, and 0.66, respectively. We also checked the average daily rainfall trend of BMD rain gauge and GSMaP data during study period (2001-2015).

#### 4.1.1 Scattered plot of 3-hourly rainfall

Figure 4.1 represents scatter plot of 3-hourly rainfall between GSMaP and BMD rain gauge for the period 2001-2015.



**Figure 4.1:** Scatter plot of 3-hourly rainfall between GSMaP and rain gauge from 2001-2015.

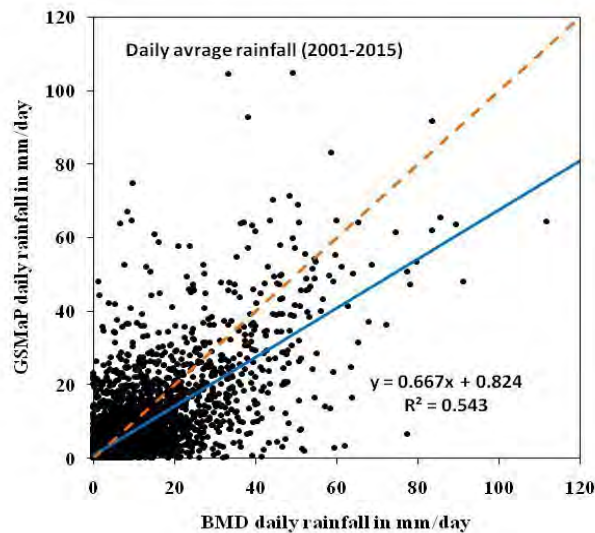
The dashed line is a 1:1 line and blue solid line represents linear fit ( $Y=a+bX$ ).

The value of  $R^2$  (The Value of determinant) between GSMaP and rain gauge is found 0.5643, which means that 56% of GSMaP data can be explained by the BMD rain gauge data. The Standard Deviation (SD, which is the measure of dispersion of a set of data from its mean) of 3-hourly rainfall for GSMaP and rain gauge data are found 1.96 mm and 2.10 mm, respectively. The Root Mean Square Error (RMSE) between both dataset is 4.56 mm.

In this figure, the dashed line (1:1) is above the blue solid line (linear fit), suggesting the negative (GSMaP < rain gauge) systematic difference is significant for higher rainfall rate. The systematic difference is small for low rainfall rate. The performance of GSMaP data is found better in detecting the low rainfall rate (< 5 mm/h) than that of higher rainfall (> 5 mm/h).

#### 4.1.2 Scattered plot of daily average rainfall

Figure 4.2 represents scatter plot of daily average rainfall between GSMaP and BMD rain gauge during the period 2001-2015.



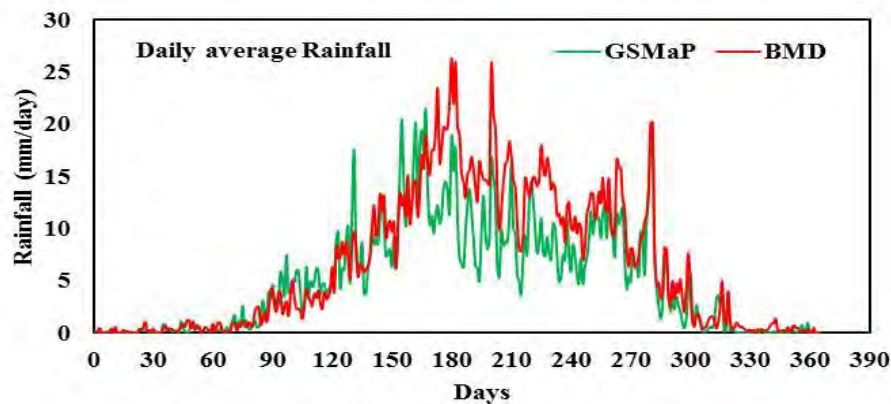
**Figure 4.2:** Scatter plot of daily average rainfall between GSMaP and rain gauge from 2001-2015. The dashed line is a 1:1 line and blue solid line represents linear fit ( $Y=a+bX$ ).

The value of  $R^2$  between GSMaP and rain gauge is found 0.5435. The Standard Deviation (SD) of daily GSMaP and rain gauge data are found 10.78 mm and 9.76 mm, respectively. The RMSE is 7.62 mm.

In the above figure, the dashed line (1:1) is above the blue solid line (linear fit), suggesting the negative (GSMaP < rain gauge) systematic difference is significant for higher rainfall rate whereas systematic difference is small for low rainfall rate.

### 4.1.3 Daily rainfall variation

Figure 4.3 showed the 15-years daily average variation of rainfall measured by rain gauge and GSMaP. It is found that the average daily rainfall during study period measured by GSMaP is well correlated with rain gauge observation. The correlation coefficient between GSMaP and rain gauge is found 0.93. The GSMaP and rain gauge measured 5.14 mm and 6.47 mm rainfall per day, respectively. It is found from figure that active and break phases of rainfall trend are well matched between GSMaP and rain gauge.



**Figure 4.3:** Variation of daily average rainfall from 2001 to 2015 over Bangladesh measured by GSMaP and rain gauge.

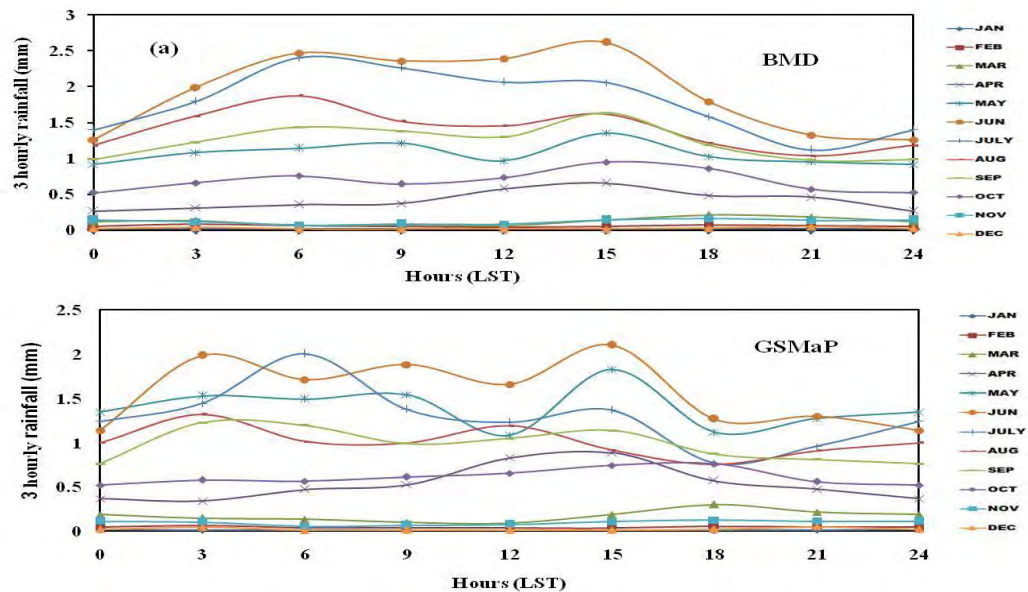
Prasad et al. [45] explain the primary cause of these active and break spells are fluctuations (i.e. intensity and position) of the seasonal monsoon trough. Monsoon trough is an extended trough of low seasonal pressure which runs across the Gangetic plains of north India and also over northwest India and Pakistan, eastern end emerging



into the Bay of Bengal. In the meantime, the axis of this trough runs from Ganganagar in Rajshahi to Kolkata via Allahabad. Figure.4.3 also showed that during monsoon period (around days of 160-270) GSMaP underestimated and during pre-monsoon period (around days of 65-160) GSMaP overestimated.

#### 4.2 Monthly diurnal variation of rainfall

Monthly diurnal variations of rainfall during study period are shown in Figure 4.4 which detected by (a) BMD rain gauge and (b) GSMaP. Most of the months show two major rainfall peaks.



**Figure 4.4:** Monthly diurnal variation of rainfall during study period (a) BMD rain gauge and (b) GSMaP.

In January and February, maximum rainfall found at 0000 and 0300 LST by both BMD rain gauge and GSMaP. Both datasets observed two well matched maximum rainfall peak at 1500 LST and 2100 LST during March to May. BMD rain gauge data showed maximum rainfall vertex at 0060 LST and 1500 LST during June to August. On other hand GSMaP showed these peaks at 0030 LST and 1500 LST except July. In July, GSMaP found maximum rainfall at 0060 LST and 1500 LST. In October, maximum

rainfall observed at 1200 LST and 1500 LST by both datasets. In November and December, both datasets found maximum rainfall at 0300 LST and 2100 LST.

### **4.3 Seasonal diurnal variation of rainfall**

Seasonal diurnal variation of rainfall during pre-monsoon (March-May), monsoon (June-September), post-monsoon (October-November) and winter (December-February) seasons are described below.

#### **4.3.1 Diurnal variation of rainfall during pre-monsoon season**

Figure 4.5 represented the diurnal variation of rainfall during pre-monsoon. In this season both BMD rain gauge and GSMaP are found well matched two maximum rainfall peaks at 1500 LST (primary peak) and 2100 LST (secondary peak). Rainfall dominates from afternoon to early night during pre-monsoon season. Though GSMaP is well captured the rainfall peaks but the amount was overestimated than that of BMD rain gauge. Thunderstorms which is known as „Kalbaisakhi“ or „Nor“westers in Bangladesh, is the main source of pre-monsoon rainfall [46]. Norwesters mainly come from the north westerly direction (and hence the name) which is land based phenomena. This Thunderstorm season begins in the northeastern and eastern parts of the country by the first week of March during post noon period of the day. These thunderstorm season activities gradually move westward, and become significant in the western part of the country before the advent of the summer monsoon in late May or early June [47]. In this season, daytime heating triggers by high temperatures and towering clouds build up which is mainly tall, high echo top and deep convection clouds such as cumulonimbus, cumulus, that is more vertical in nature and mostly come up during late afternoon and early evening or night hours and form often an arc-shape squall line type and intense rainfall which usually gets the thunderstorms after the post-noon period [48]. So, ideally a day will begin with a clear sky and summer like temperature but from the afternoon, these pre-monsoon rain will start occurring and strong rain with squally cooled winds (sometime along with hail) will cause decrease in the temperatures, which help to procreate a diurnal cycle of rainfall during this season. It is synonymous with heat and

humidity with uncomfortable conditions throughout the day and night [49]. Besides these, various weather systems (say troughs) bring in moisture and thermal instability during this season due to condensation which is also responsible to afternoon's maxima of rains" [50].

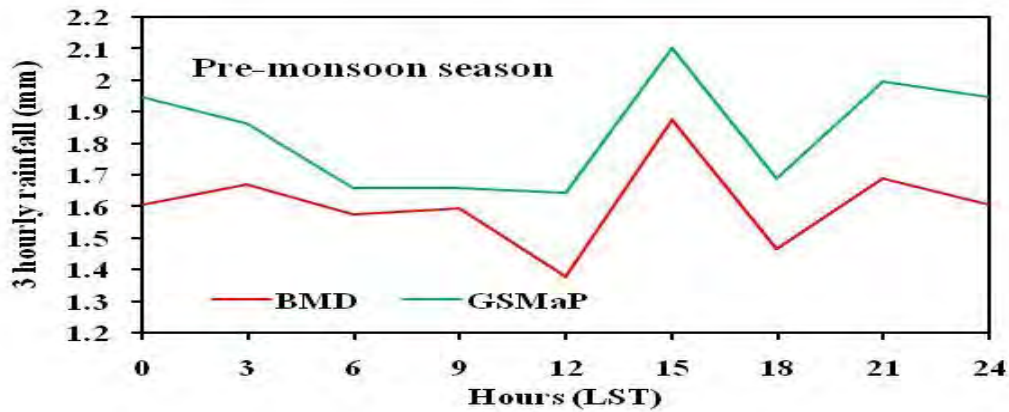
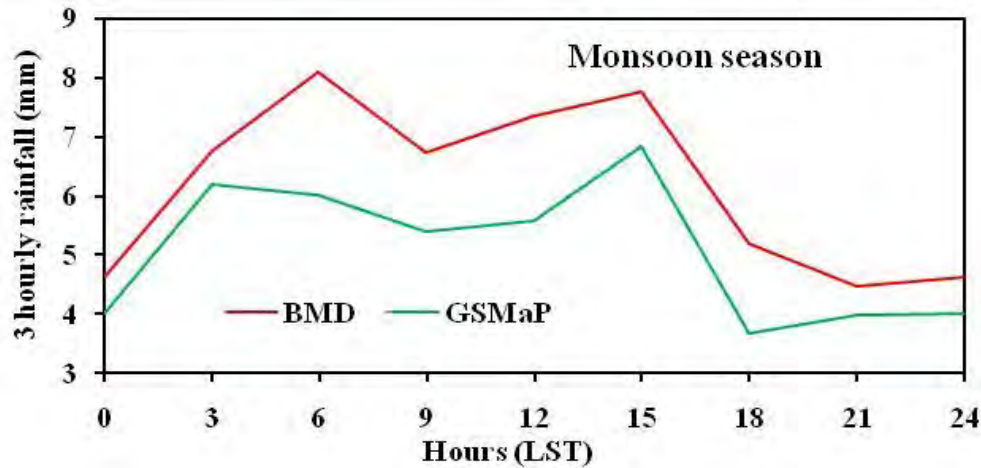


Figure 4.5: Diurnal variation of rainfall of pre-monsoon during study period between BMD rain gauge and GSMaP.

### 4.3.2 Diurnal variation of rainfall during monsoon season

Figure 4.6 showed the diurnal variation of rainfall of monsoon during study period. It is observed by BMD rain gauge measured dual peaks of rainfall at 0600 LST (primary peak) and 1500 LST (secondary peak). On other hand, GSMaP found this twin peaks at 0300 LST and 1500 LST. These findings are almost similar to yearly average sketch of diurnal variation of rainfall. So it is clear, monsoon rainfall has a strong effect on the annual rainfall in Bangladesh. The quantity of rainfall which measured by GSMaP is underestimated than that of BMD rain gauge. In the monsoon season, rain can commence any time of the day, generally the preferred time of maximum rainfall at late night to early morning and late noon. During this monsoon, the atmosphere over Bangladesh is highly unstable due to the massive amount of moisture present in the lower troposphere, and only a small perturbation is often enough to produce formation of low-level clouds mainly nimbostratus and stratiform clouds which are mainly widespread or continuous layers of clouds [49, 51]. Depths of these clouds are less but

the layers are thick and moisture laden which contain a very big amount of water droplets and result in precipitation especially rain which mainly occur after post noon session. This is why, during monsoon days“ most afternoons experience heavy rainfalls [49].

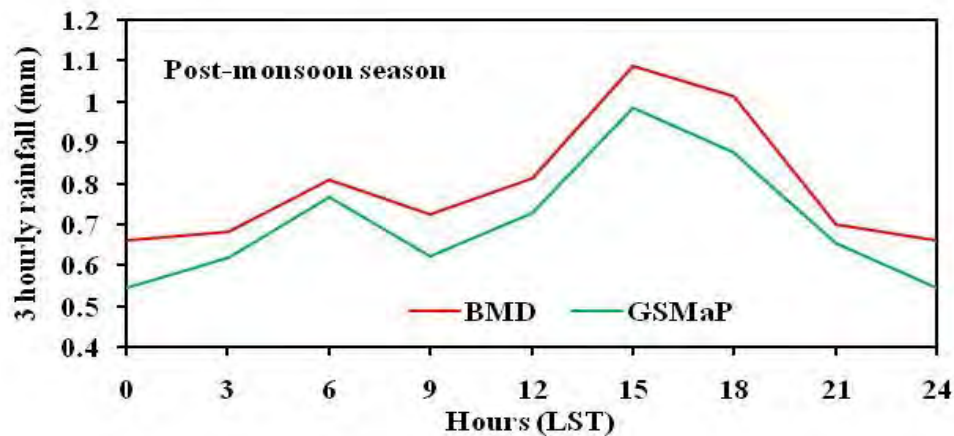


**Figure 4.6:** Diurnal variation of rainfall of monsoon during study period between BMD rain gauge and GSMaP.

In addition, the mesoscale circulations like land–sea breezes, katabatic-anabatic winds, mountain valley winds, etc. can modulate the rain regime and propagate a diurnal cycle [52]. Actually, the dominant forcing for diurnal variation in convection and rain over land during the monsoon is ground heat provided by insolation. Occasionally, convective cells forming over sea drift inland under suitable synoptic wind conditions leading to a maximum in rain in the late night or early morning. Terao et al., [53] investigated that over Bangladesh especially in the northeastern part of country, where the total monsoon rainfall peak appears at 0030 to 0060 local time. In the lower troposphere, the southeasterly accelerates in the evening, and the wind direction exhibits a clockwise change at night. This feature corresponds with the nocturnal jet, which can be a cause of the midnight-early morning rainfall peak in the northeastern part of Bangladesh through the increased wind blowing against the southern edge of the Meghalaya Mountains. Besides this, post-noon tidal water of rivers may accountable to these phenomena, because during this time huge water moisture come or grow from river water.

### 4.3.3 Diurnal variation of rainfall during post- monsoon season

Figure 4.7 showed the diurnal variation of rainfall of post-monsoon season during study period. BMD rain gauge and GSMaP observed a secondary peak at 0600 LST and primary peak at 1500 LST. So, it reveals that in post-monsoon season maximum rainfall occurred at afternoon and early night. The diurnal pattern of rainfall determined by both GSMaP and rain gauge is almost similar. These findings are relevant with the result of Islam et al. [54]. During post-monsoon, high temperature and low pressure in the Bay of Bengal causes to bring dry, cool, and dense air masses to large parts of Bangladesh. Winds spill across the Himalayas and flow to the southwest and north-easterly direction across the country [55], resulting in clear, sunny skies and sometimes depression or cyclone form in the Bay of Bengal resulting the evening hour with a significant amount rainfall. The mean rainfall decreases sharply from October to November and slowly from November to December. The gradients of mean monthly rainfall are maximum over the northeastern and southwestern parts of Bangladesh during evening period [56].

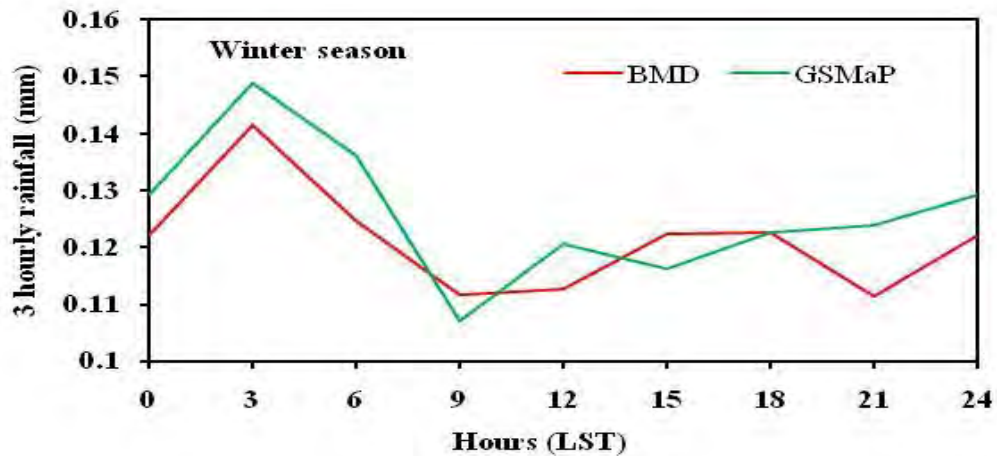


**Figure 4.7:** Diurnal variation of rainfall of post-monsoon season during study period between BMD rain gauge and GSMaP.

### 4.3.4 Diurnal variation of rainfall during winter season

Figure 4.8 represented the diurnal variation of rainfall of winter season of the study period. The maximum rainfall is found at 0300 LST by both GSMaP and rain gauge.

Since Bangladesh is a rainfall dominated climate country and maximum rainfall occur during monsoon season, only 2% or less rainfall of the annual occurs during winter season [57]. In winter, the solar radiation falls obliquely which may not to conducive making a remarkable to generate the thermal properties of sea and land let alone to create a diurnal cycle of rainfalls. During the winter season, a centre of high pressure lies over the northwestern part of India including Bangladesh. A stream of cold and dry air flows eastward from this high pressure and enters our country through its northeast corner by changing its course clockwise, almost right-angle. This wind is the part of the winter monsoon circulation of the South Asian subcontinent. Wind inside the country generally has a northerly component (flowing from north or northwest) [57] which are not helpful creating a significant rainfall during this season.



**Figure 4.8:** Diurnal variation of rainfall of winter season during study period between BMD rain gauge and GSMaP.

#### 4.4 Yearly diurnal variation of rainfall

Figure 4.9 (a & b) represented yearly diurnal rainfall variation of BMD rain gauge and GSMaP data for different years. Most of the years found two vertex of maximum rainfall

peak. BMD rain gauge observed two maximum rainfall peak at 0600 LST and 1500 LST except 2004, 2007, 2010, 2013. In 2004 and 2010 found these peak at 0300 LST and 1500 LST but 2007 and 2013 maximum rainfall peak found at 0900 LST and 1500 LST. On other hand GSMaP found maximum rainfall peak at 0300 LST and 1500 LST except 2004, 2005 and 2013. In 2004 and 2005 maximum rainfall peak are found at 0600 LST and 1500 LST. In 2013 maximum rainfall peak observed at 0900 LST and 1500 LST.

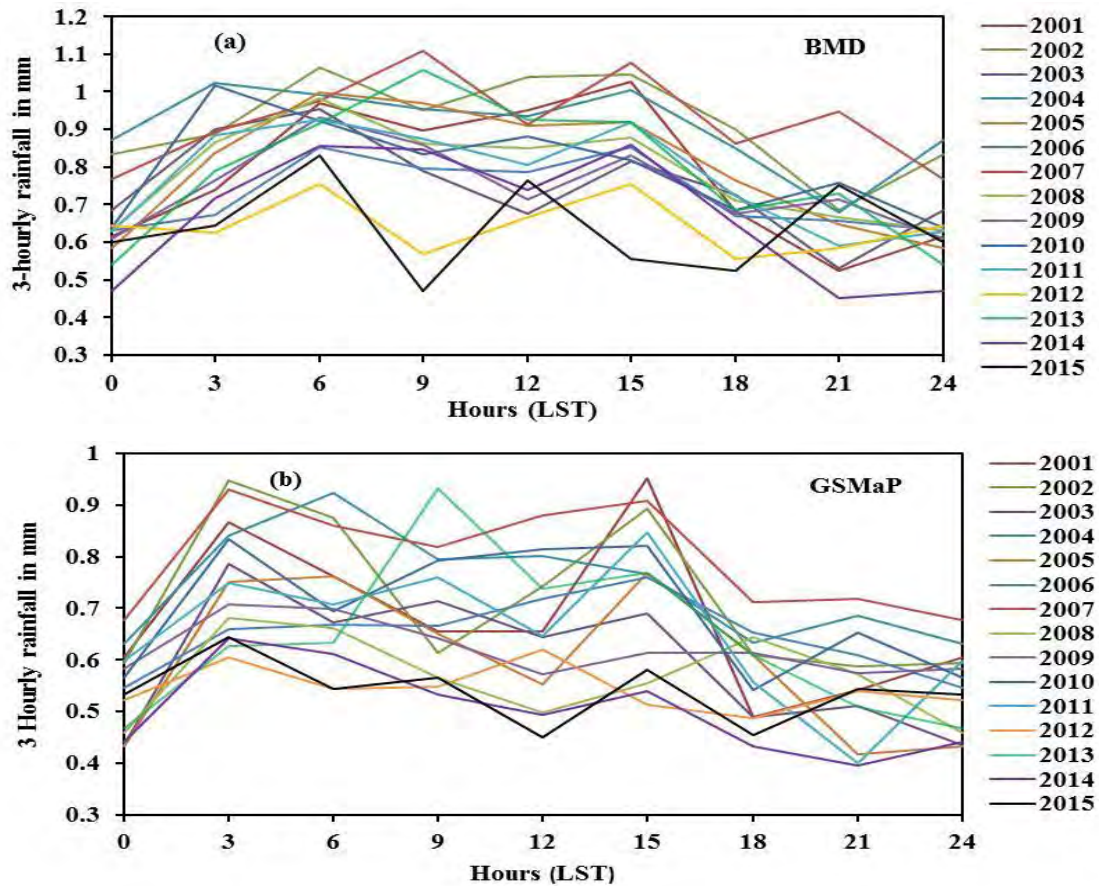


Figure 4.9: Yearly diurnal variation of rainfall detected by (a) BMD rain gauge and (b) GSMaP during study period.

#### 4.5 Diurnal variation of rainfall of yearly average

Figure 4.10(a) represented the average yearly diurnal variation of rainfall which is measured by BMD rain gauge and GSMaP. BMD rain gauge detects a primary peak at early morning (0600 LST) and a secondary peak at afternoon (1500 LST). On other hand

GSMaP also measured dual peaks; one at late night (0300 LST) and other in the afternoon (1500 LST). Due to available of hourly data of GSMaP, we also sampled the hourly diurnal variation of rainfall which represents in Figure 4.10(b). From this figure, it is found four peaks rainfall but distinctly twin maxima of rainfall; one at 0400 LST another at 1500 LST. Using Radar data from BMD, Islam et al. [58] observed rainfall echoes exhibit two peaks, one in the morning (~0600 LST) and other in the afternoon (~1500 LST). On contrary using Japanese Geostationary Meteorological Satellite (GMS-5) they also found two peaks at morning (~0300 LST) and afternoon (~1700 LST). Bhuiyan et al. [59] also showed dual maxima of three hourly rainfall which occur during noon to afternoon (1200 LST-1500 LST) and late night to early morning (0300 LST-0600 LST) periods over Bangladesh. Our studies also show that BMD rain gauge measured; daytime's rainfall is 48.42 % and nighttime's rainfall is 51.58%. On other hand GSMaP measured the daytime's and nighttime's rainfall is 48.25% and 51.65%, respectively. Thus it is clear that in Bangladesh more rainfall occurs in nighttime than daytime.

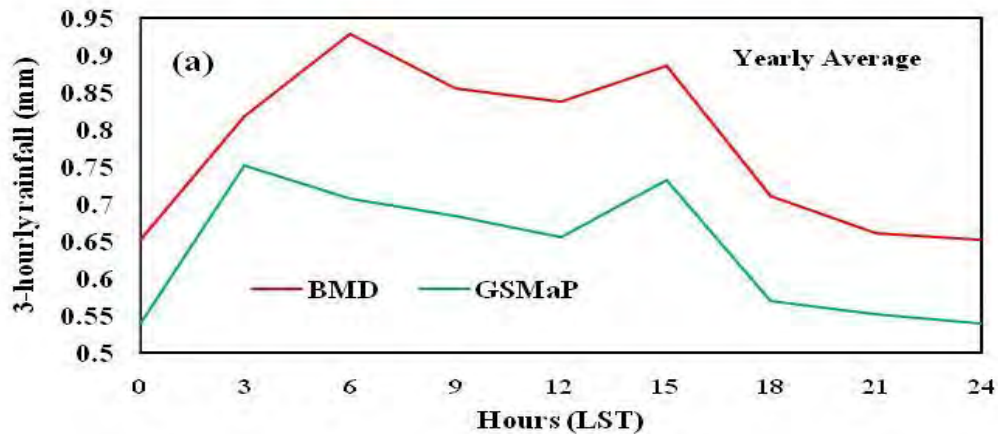


Figure 4.10 :( a) Diurnal variation of rainfall of yearly average during study period.



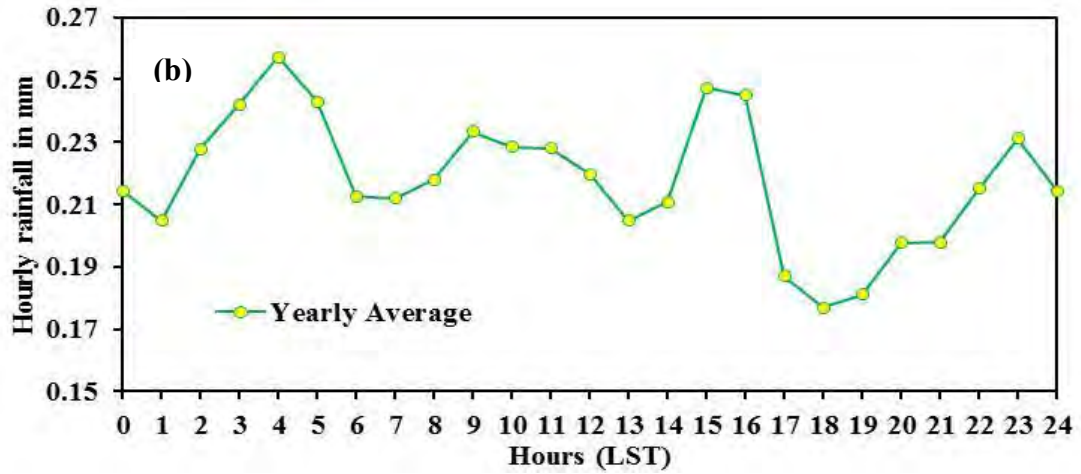
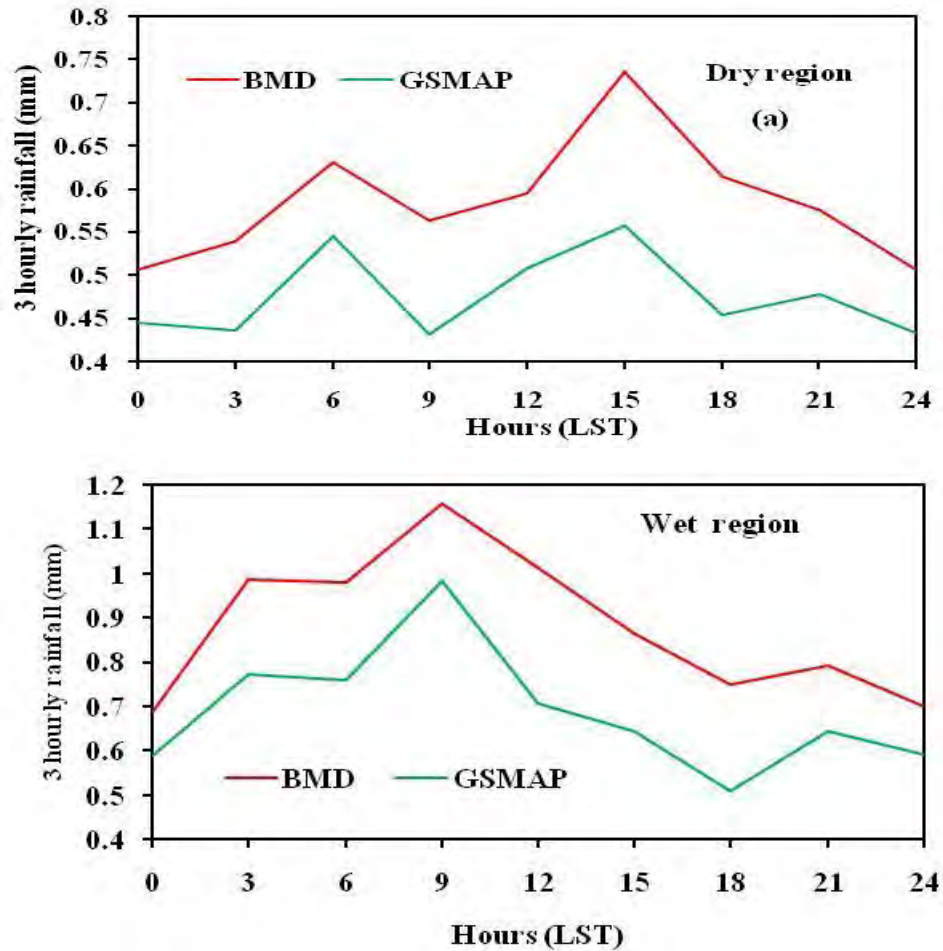


Figure 4.10 :( b) Diurnal variation of rainfall of yearly average of GSMaP hourly data.

#### 4.6 Diurnal variation of rainfall in dry and wet region

On the basis of excess and deficit of humidity Bangladesh are divided into dry and wet regions [60]. Among 35 BMD rain gauge stations, 16 stations are located in the dry region and 19 stations are in the wet region. Dry region stations are Rangpur, Dinajpur, Bogra, Rajshahi, Ishurdi, Dhaka, Faridpur, Jessore, Chandpur, Khulna, Sathkhira, Mongla, Madaripur, Sydpur, Tangail, Chuadanga, and wet region stations are Mymensingh, Sylhet, Srimongal, M.Court, Comilla, Patuakhali, Barishal, Cox-Bazar, Teknaff, Chittagong, Sandwip, Khepupara, Hatia, Rangamati, Bhola, Feni, Sitakunda, Kutubdia, Ambagan. The diurnal variation of rainfall in dry and wet region are shown in Figure 4.11 (a & b). In dry region maximum rainfall peak measured by BMD rain gauge and GSMaP are well matched. In dry region, the primary rainfall peak is found 1500 LST and secondary peak is at 0600 LST. This is the continental or inland type feature of diurnal cycle of rainfall which leads to mid to late afternoon peaks due to thermal properties. Most of the big rivers such as Padma, Meghna, Jamuna, Brammaputra are admixed the land behavior of dry region. These rivers are source of moisture in the dry region which characterized the thermal properties of surface on other hand, in wet region, the primary peak is observed at 0900 LST and secondary peak at 0300 LST by both data sets, which are similar to maritime type of diurnal cycle of rainfall. Most of the

stations in the wet regions are in hilly area and some of it is adjacent to Bay of Bengal. Lots of moisture carries from Bay of Bengal and topography may cause of excess rainfall of the wet region in the morning.

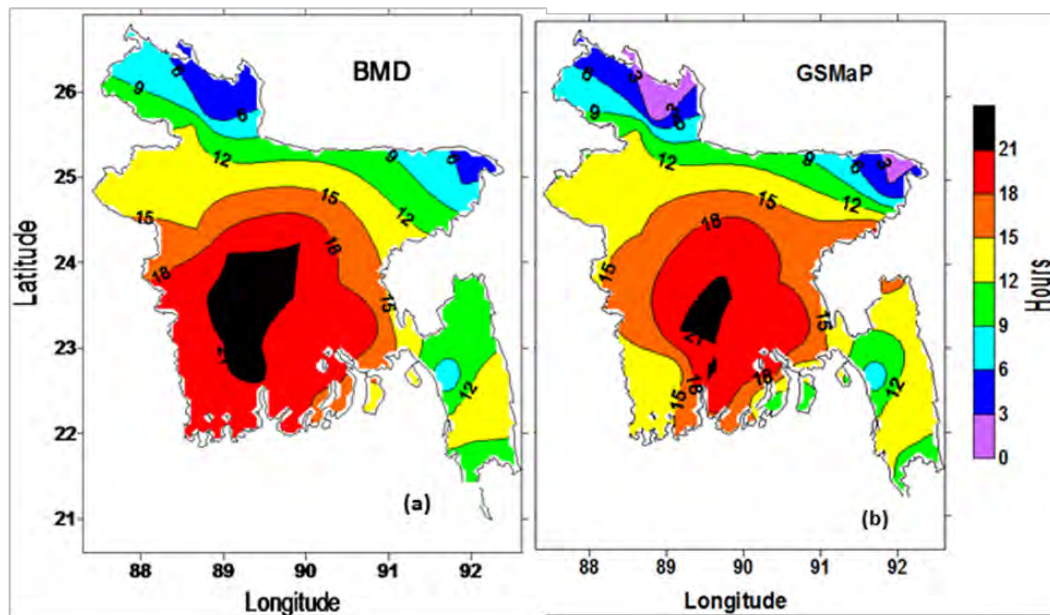


**Figure 4.11:** Diurnal variation of rainfall of dry (a) and wet (b) region measured by BMD rain gauge and GSMaP.

#### 4.7 Spatial distribution of occurrence time of maximum seasonal rainfall

##### (a) Pre-monsoon

In Bangladesh, the pre-monsoon rainfall is small in comparison to monsoon rainfall. During the pre-monsoon season; its climate is characterized by high temperatures and the occurrence of thunderstorms. April is the hottest month. Temperatures of this month range from 27°C along the northeastern foothills to 30°C along the western border [61]. Figure 4.12 (a & b) represents the spatial distribution of occurrence of maximum pre-monsoonal rainfall observed by BMD rain gauge and GSMaP during study period (2001-2015).



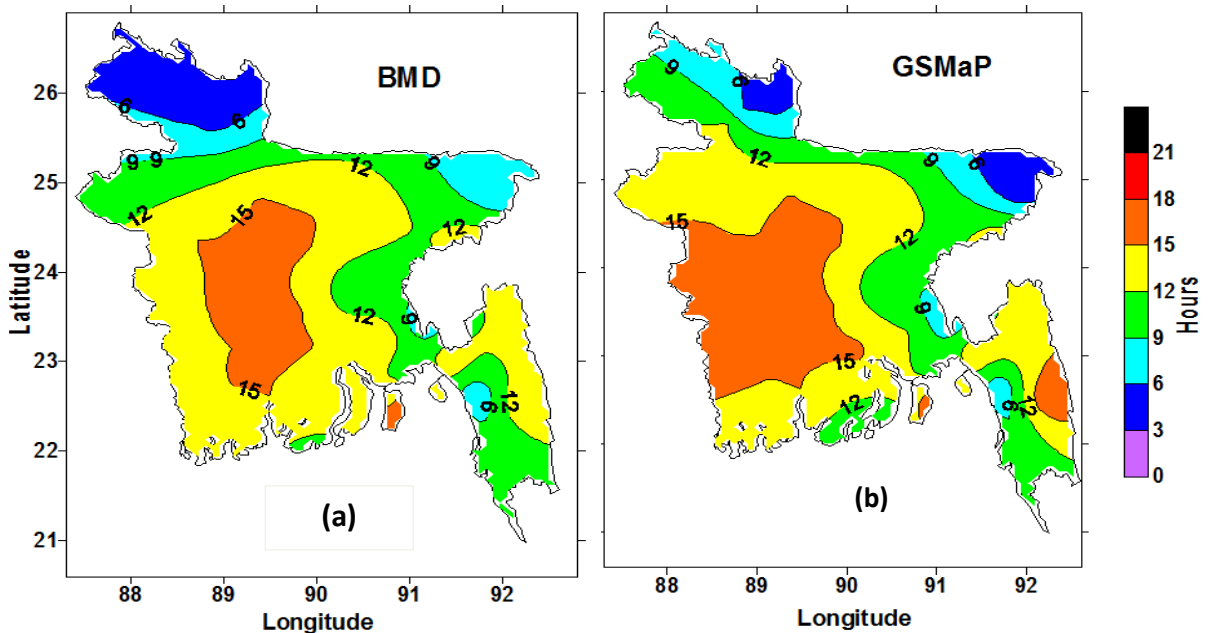
**Figure 4.12:** Spatial distribution of maximum occurrence time of pre-monsoon rainfall from 2001-2015 measured by (a) rain gauge and (b) GSMaP.

From this figure it is clear that the maximum rainfall occurrence time gradually shifted from 0300 to 1800 LST from north-eastern part of the country to the southern part but in the central part the maximum rainfall occurred at 2100 LST. Northern and eastern sides of the country are bounded by Meghalya and Assam hills which are favorable for uplifting of the moist air mass. When the moist air lift upward it gradually loses its

temperature to condense enough to form cloud [60]. This is one of the main reasons of the high intensity of rainfall in and around at Sylhet region. Most of the part of the country experiences maximum rainfall at daytime due to local circulation but in and around Dhaka or central part of the country at early night (2100 LST) which may be the effect of excessive air pollution, aerosol particle, Greenhouse gas, rapid industrialization etc. which causes late cooling of rain composing particles [62].

**(b) Monsoon**

Figure 4.13 showed the spatial distribution of occurrence of monsoonal maximum rainfall in Bangladesh. The occurrence of the maximum monsoon rainfall time is observed at 0900-1200 LST in coastal region and hilly part of the country except in and around Dhaka. In and around Dhaka experiences the maximum rainfall at 1500 LST. North-western and north-eastern parts of the country experiences maximum rainfall at 0300~0600 LST.

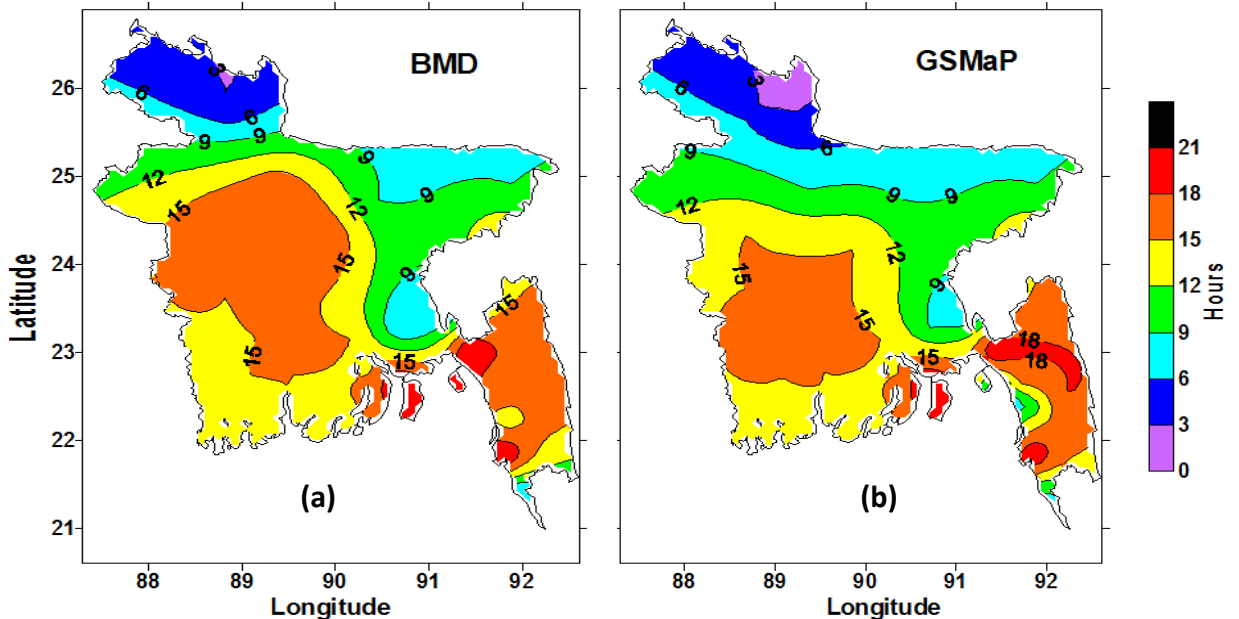


**Figure 4.13:** Spatial distribution of maximum occurrence time of monsoon rainfall from 2001-2015 measured by (a) rain gauge and (b) GSMaP.

The rainfall of Bangladesh is mainly governed by the activities of south-western summer monsoon system (i.e., position and intensity of monsoon trough), tropical cyclonic disturbances, local land origin weather systems (land depressions, thunderstorms and mesoscale convective systems) and sub-tropical western disturbances [63]. Monsoon progress from southeastern to northeastern part and monsoon withdraw in the reverse direction. The Khasi-Jaintia-Garo hill complex and the plateau of Shillong and Arakan Mountains as well as Mizo hills play important role in modifying the rainfall pattern in northeast and southeast part of the country. For this different fact Bangladesh experiences highest amount of country average monsoon and annual rainfall among SAARC countries [64].

**(c) Post-monsoon**

The spatial distribution of occurrence of maximum post-monsoonal rainfall in Bangladesh measured by BMD rain gauge and GSMaP is shown in Figure 4.14.

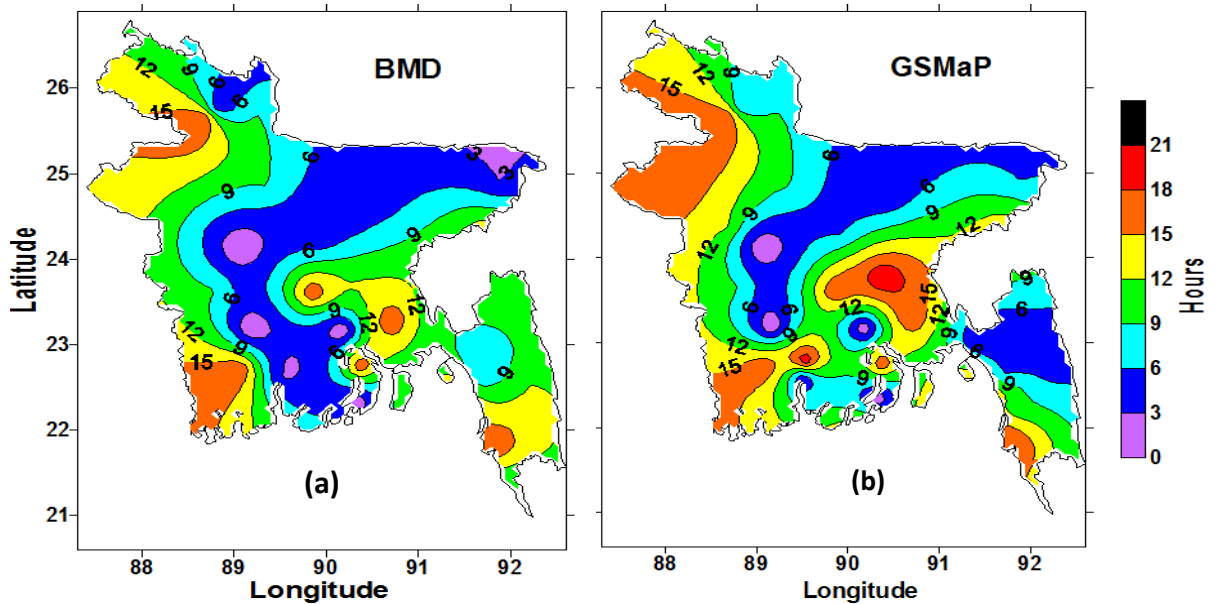


**Figure 4.14:** Spatial distribution of maximum occurrence time of post-monsoon rainfall from 2001-2015 measured by (a) rain gauge and (b) GSMaP.

Figure showed that north-western and eastern part of the country experiences maximum rainfall at 0600-0900 LST. In the middle part of the country and Chittagong region experience the maximum rainfall at 1500~1800 LST. Coastal and south-eastern part of the country observed maximum rainfall time at 1200 LST. This maximum rainfall variation pattern is followed a periodicity from north-eastern part from southern and other part of the country which associated to trade wind and its moves from land to sea.

**(d) Winter**

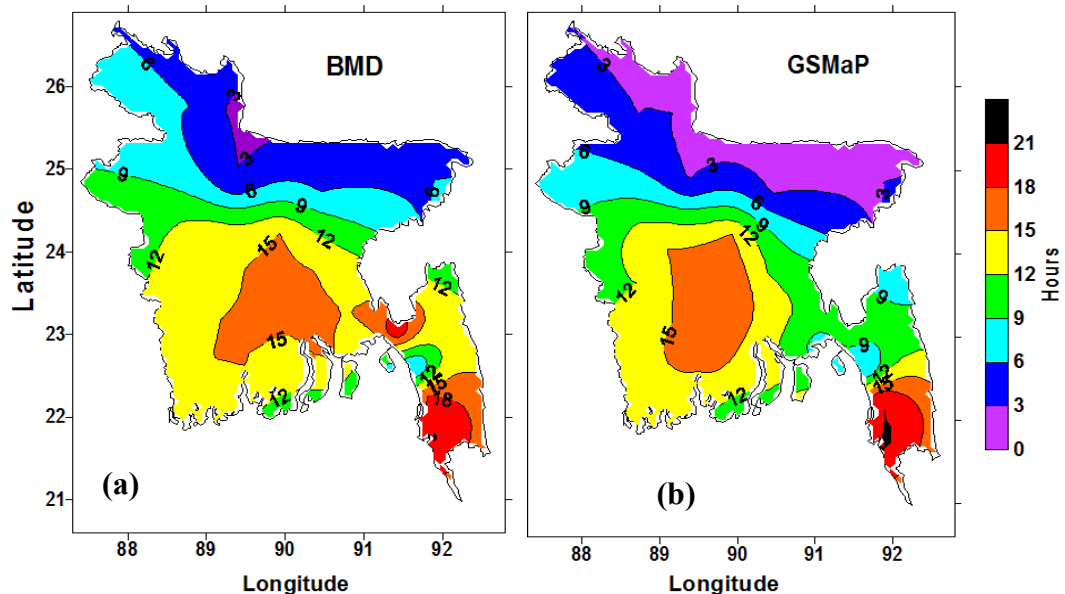
Spatial distribution of occurrence of maximum rainfall during winter season over Bangladesh displayed is shown in Figure 4.15. In both figures there has a periodicity of maximum rainfall time from North-eastern to middle then onward to south and coastal part of the country. North-eastern and north-western part of the country experiences maximum rainfall at 0300~0600 LST and some parts at 1200~1500 LST of these regions. In and around of the Dhaka maximum rainfall observed at 0600~900 LST.



**Figure 4.15:** Spatial distribution of maximum occurrence time during winter season of study period measured by (a) rain gauge and (b) GSMaP.

#### 4.7.1 Spatial distribution of occurrence time of maximum yearly average rainfall during study period

Spatial distribution of occurrence of maximum yearly rainfall measured by BMD rain gauge and GSMaP is shown in Figure 4.16. The pattern of distribution of time of maximum rainfall of BMD and GSMaP is almost same. BMD rain gauge showed the northern part of the country experiences maximum rainfall at 0600 LST and central part of the country experiences maximum rainfall at 1500 LST. Whereas, GSMaP observed the maximum rainfall in the northern part at 0300 LST and in the central part of the country at 1500 LST. Islam et al. [65] divided the total radar coverage area into nine sectors and showed that the north part and northeastern part of the Bangladesh experiences the maximum rainfall at 0000-0600 LST, which is the influence of the Shillong hill. The maximum rainfall occurred in the western part at 0900-1200 LST, which may be the influence of the land characteristics of the India especially Meghalaya. Rainfall at 1200-1500 LST is dominated in the coastal region of the south and southeastern part.



**Figure 4.16:** Spatial distribution of maximum occurrence time of yearly average over Bangladesh between BMD (a) and GSMaP (b).

The eastern part of Bangladesh shows the maximum rainfall in the morning at 0300-0600 LST, which is different from the Indian subcontinent and mountain regions. Northern, some part of eastern region observed much amount of rainfall from 0300-0600 LST, which is possibly linked to the local many effects, such as complex terrain or sea and land breeze circulations, the long, nocturnal life cycle of mesoscale convective systems [66]. Over land and near coastlines the thermal properties of the land surface and the land-sea-breeze circulation induced by the contrast between the land and ocean surfaces can explain much of the diurnal cycle of clouds and precipitation. Bangladesh is one of the places where maximum rainfall comes at morning and at its northern parts received maximum rain from mid-night to early morning [67]. Ohsawa et al. [68] and Prasad [45] proposed the amount of rainfall depends on the moisture content of the air and its ascent rate. The ascent rate is controlled by the low-level convergences, which is reflected by local orographic features. Terao et al. [53] suggested that the lower troposphere wind acceleration can be responsible for the development of convective systems over northeastern part of the country in the midnight-early morning.



#### 4.8 Station wise diurnal variation of rainfall during study period

Following table shows the summary of diurnal variation of rainfall of 35 BMD rain gauge stations.

**Table 4.8.1:** Station wise diurnal properties analysis

	Number of maritime type station	Number of continental type station
Pre-monsoon	16	19
Monsoon	22	13
Post-monsoon	17	18
Winter	27	08
Yearly average	21	14

From this table it confirms that during pre-monsoon and post-monsoon seasons Bangladesh dominated the continental type diurnal properties of rainfall but during monsoon and winter seasons maritime type diurnal properties of rainfall.

Details study of diurnal properties of 35 BMD rain gauge stations are given below.

**Barishal**

In figure 4.17 (a), (b), (c) and (d) represent the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter seasons, respectively during study period of Barishal station. Both dataset detected twin peaks of maximum rainfall. BMD rain gauge found maximum rainfall peak of these seasons at 2100 LST, 1500 LST, 1500 LST and 1800 LST, respectively. On other hand GSMaP observed these peaks at 2100 LST, 1200 LST, 1500 LST and 1800LST. Figure 4.17 (e) represented the diurnal variation of rainfall during study period or yearly average. BMD found the peak at 0600 LST and 1500LST. Elsewhere GSMaP found at 0300 LST and 1200 LST.

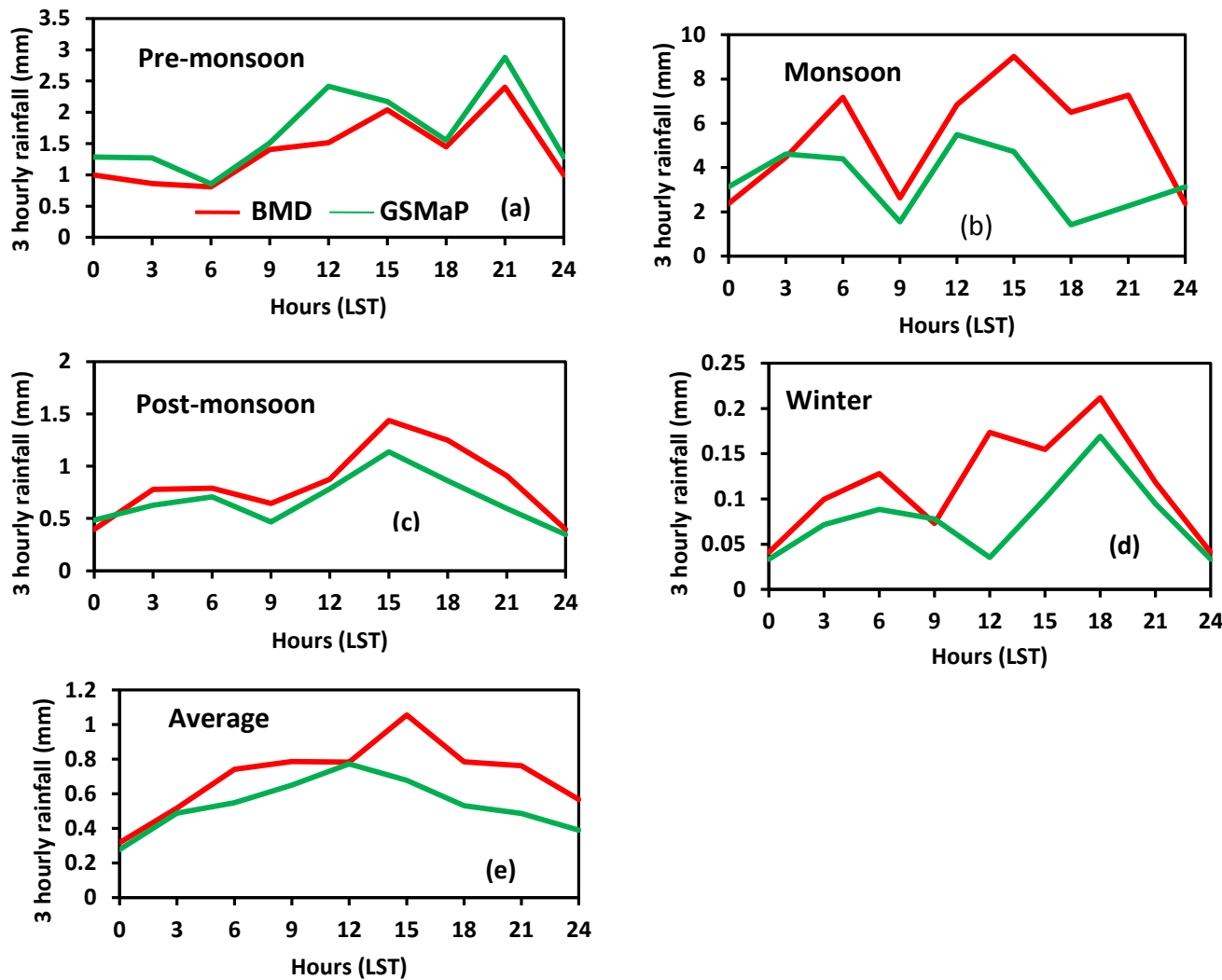


Figure 4.17: Seasonal and yearly average diurnal variation of rainfall of Barishal.

## Bhola

In figure 4.18 (a), (b), (c) and (d) represents the diurnal variation of pre-monsoon rainfall, monsoon rainfall, post-monsoon rainfall and winter rainfall, respectively during study period and also found maximum rainfall peak of these seasons by rain gauge at 1500 LST, 1500 LST, 2100 LST and 0900 LST, and GSMaP at 1200 LST, 1500 LST, 2100 LST, 0900 respectively. Figure 4.18 (e) represented the diurnal variation of

rainfall of Bhola during study period or yearly average. Rain gauge observed at 0600LST and 1500 LST elsewhere, GSMaP at 0600 LST and 1200 LST.

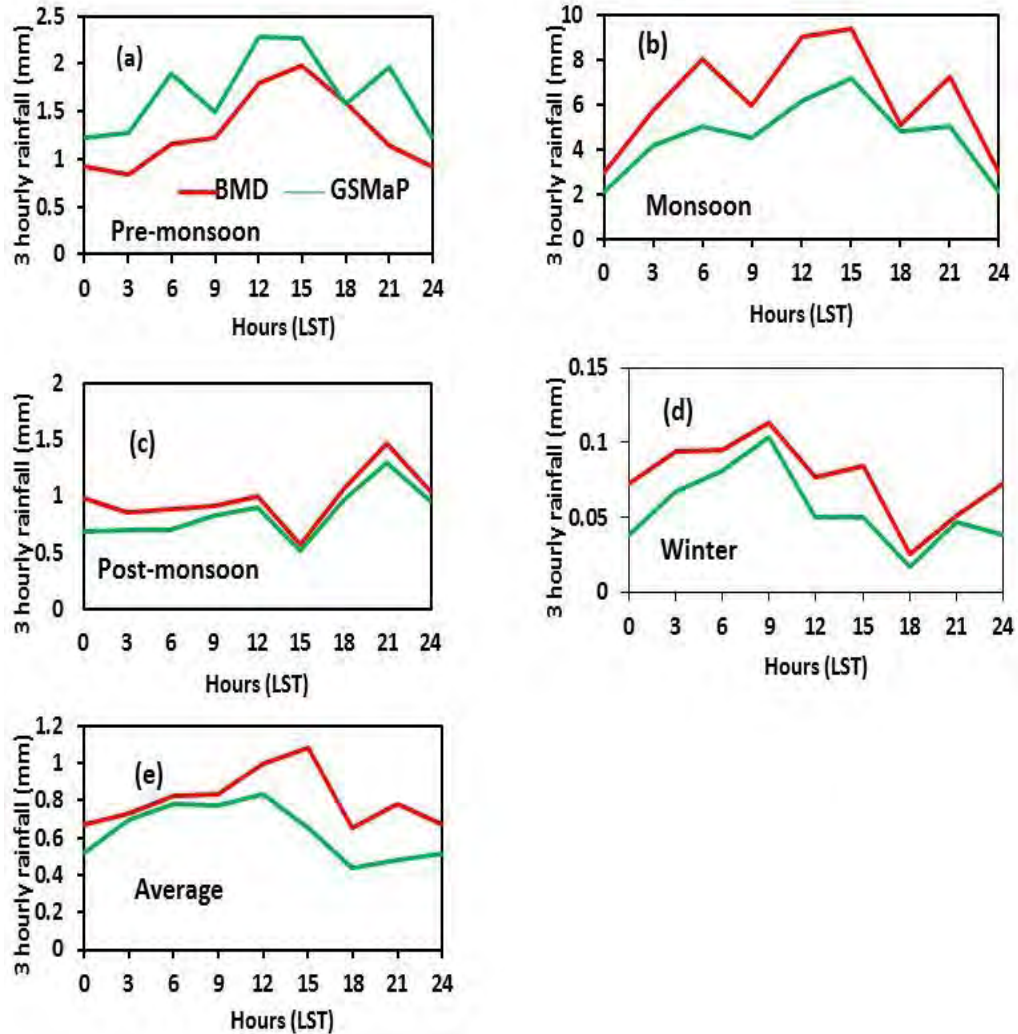
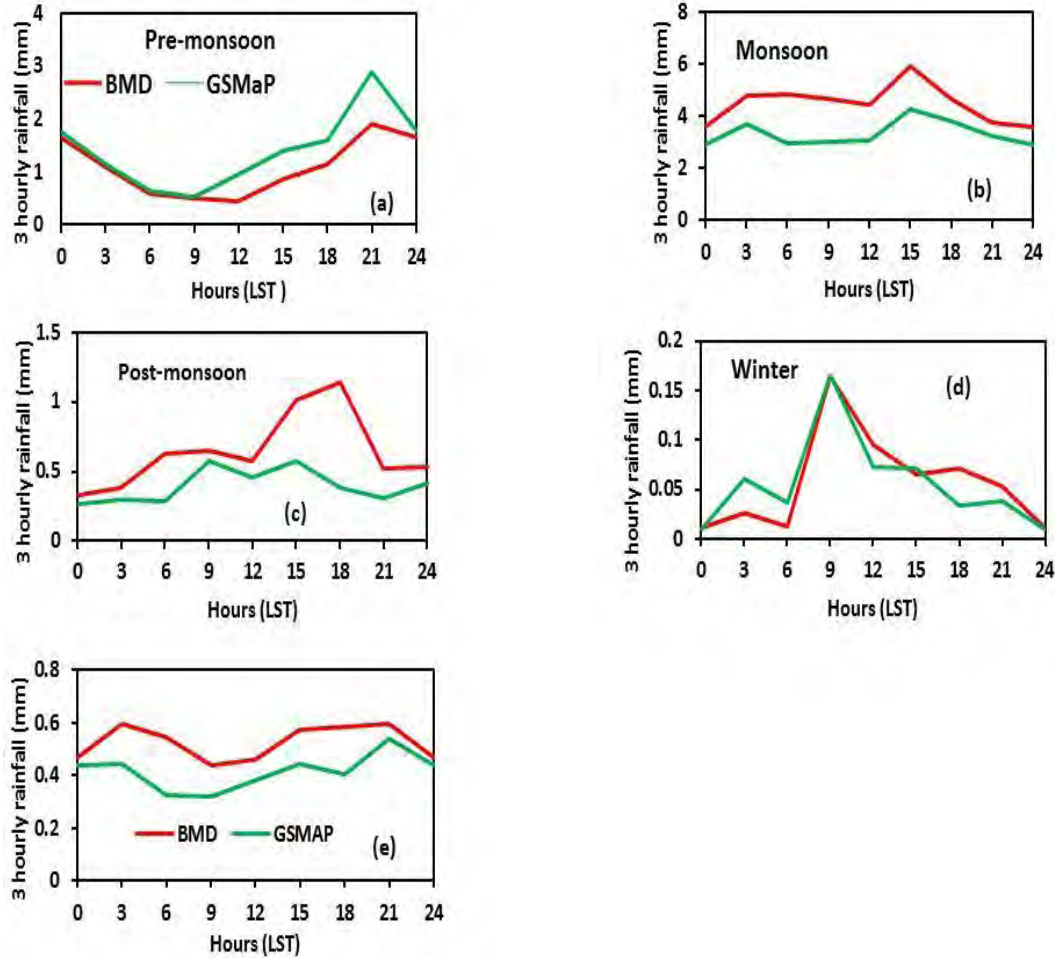


Figure 4.18: Seasonal and yearly average diurnal variation of rainfall of Bhola.

### Bogra

In figure 4.19 (a), (b) (c) and (d) represents the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter season during study period. Both rain gauge and GSMaP found well matched maximum rainfall occurring time at 2100 LST, 1500 LST and 0900 LST during pre-monsoon, monsoon and winter except post-monsoon. Rain gauge and GSMaP detected post-monsoon rainfall peak at 1800 LST and 1500 LST, respectively. In Figure 4.19 (e) represents the diurnal variation of rainfall of Bogra

during study period or yearly average. Both dataset found two well matched maximum rainfall peak at 0300LST and 2100 LST.



**Figure 4.19:** Seasonal and yearly average diurnal variation of rainfall of Bogra.

### Chandpur

In figure 4.20 (a), (b), (c) and (d) represents the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter rainfall during the study period. It is found well matched maximum rainfall occurring time at 2100 LST, 0600 LST and 1800 LST during pre-monsoon, post-monsoon and winter except monsoon. In monsoon rain gauge detected two peaks at 1500 LST and GSMaP at 1200 LST. In Figure 4.20 (e) represents the diurnal variation of rainfall during study period or yearly average of Chandpur. Both

dataset detected twin peak of maximum rainfall. Rain gauge found at 1200LST and 2100 LST, whereas GSMaP at 1200 LST and 1500 LST.

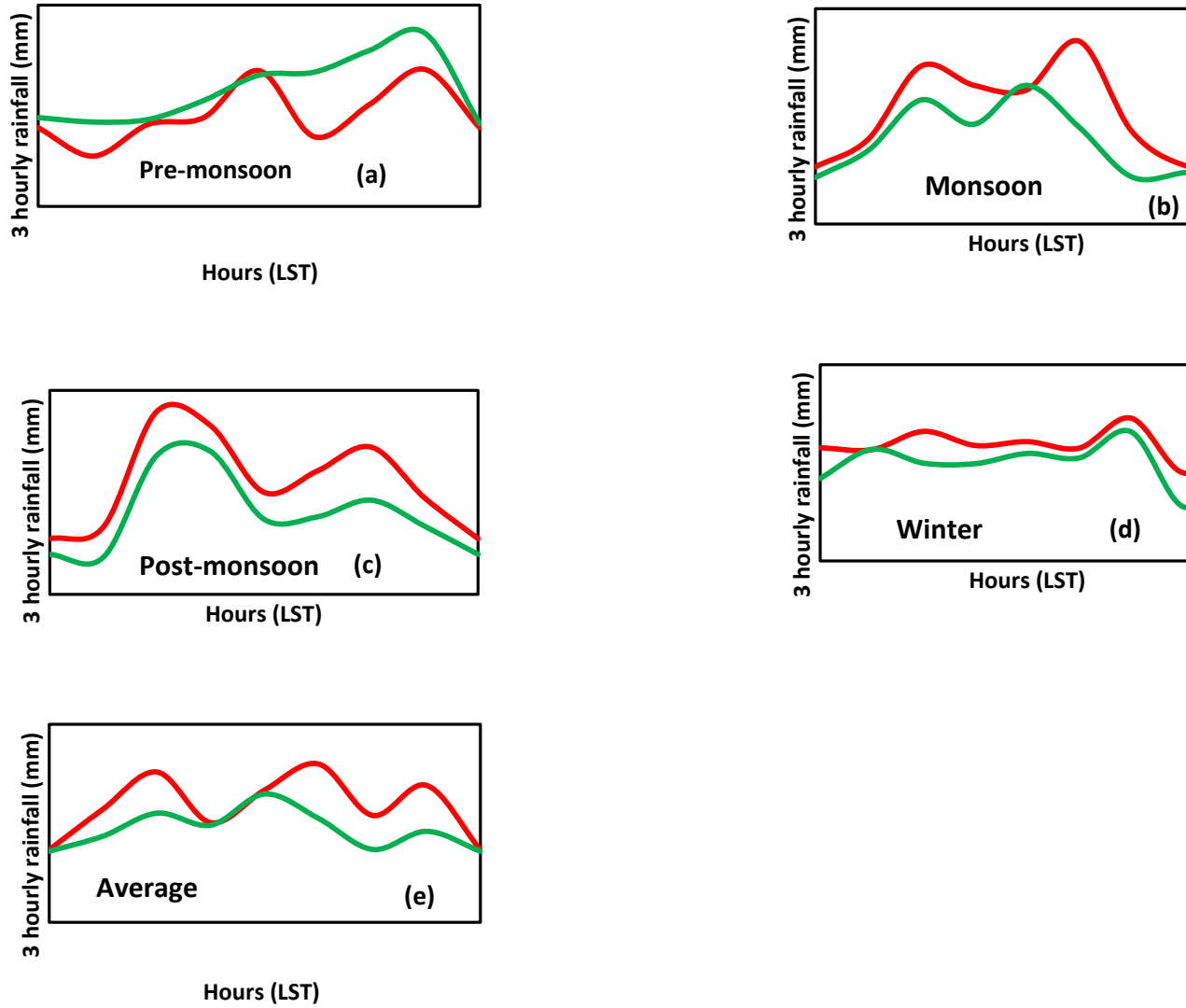
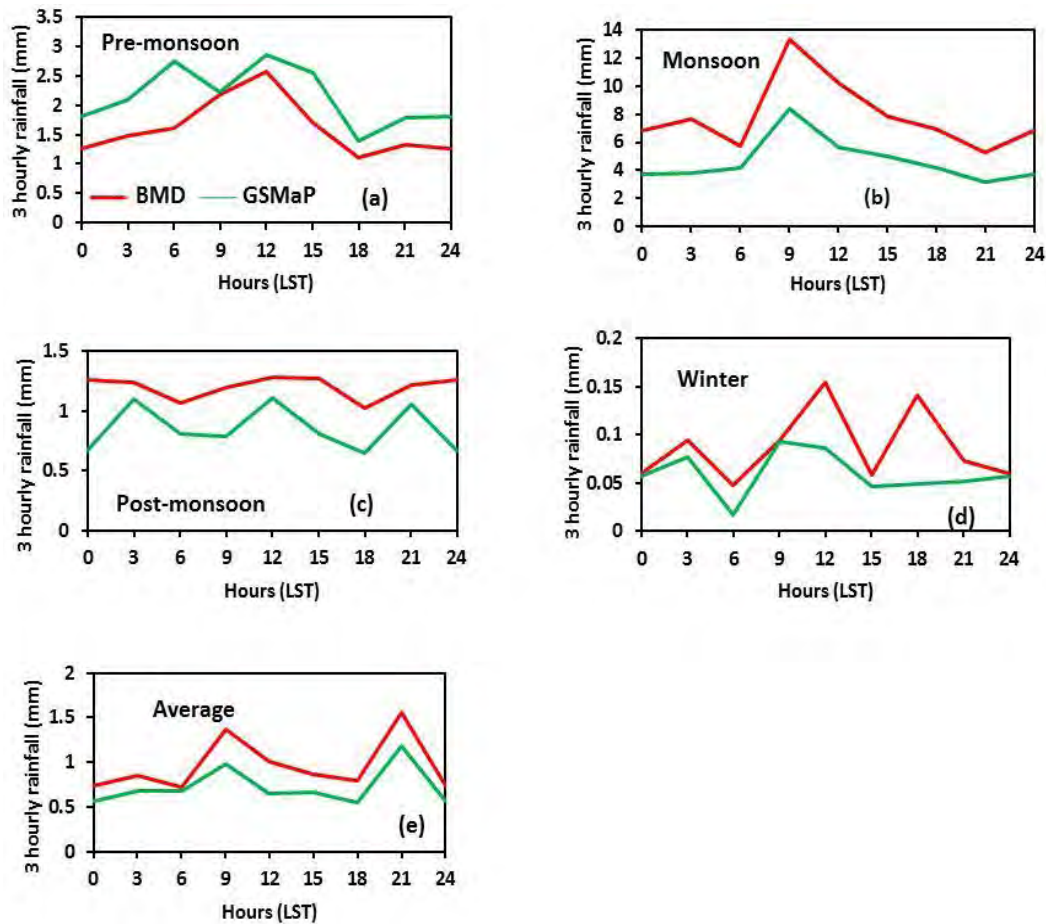


Figure 4.20: Seasonal and yearly average diurnal variation of rainfall of Chandpur.

### Chittagong

In figure 4.21 (a), (b), (c) and (d) represents the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter season during study period. It is found sharp

matched maximum rainfall of these seasons at 1200 LST, 0900 LST, and 1200 LST, during pre-monsoon, monsoon, and post-monsoon except winter season by both dataset. In winter rain gauge detects the peak at 1200 LST and by GSMaP at 0900 LST. In Figure 4.21 (e) shown the diurnal variation of rainfall during study period or yearly average of Chittagong. Both dataset detected dual peak of maximum rainfall at 2100LST and 0900 LST.



**Figure 4.21:** Seasonal and yearly average diurnal variation of rainfall of Chittagong.

### Chuadanga

In figure 4.22 (a), (b), (c) and (d) represents the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter season during the study period. Rain gauge found maximum rainfall time at 2100 LST, 1500 LST, 1800 LST and 2100 LST during pre-

monsoon, monsoon, post-monsoon and winter, respectively. GSMaP detects these peaks at 1800 LST, 1800 LST, 1500 LST, 2100 LST, respectively. In Figure 4.22 (e) represents the diurnal variation of rainfall during study period or yearly average of Chuadanga. Both dataset detected a couple peak of maximum rainfall. Rain gauge observed at 0300 LST and 1800LST whereas GSMaP found at 0600 LST and 2100 LST.

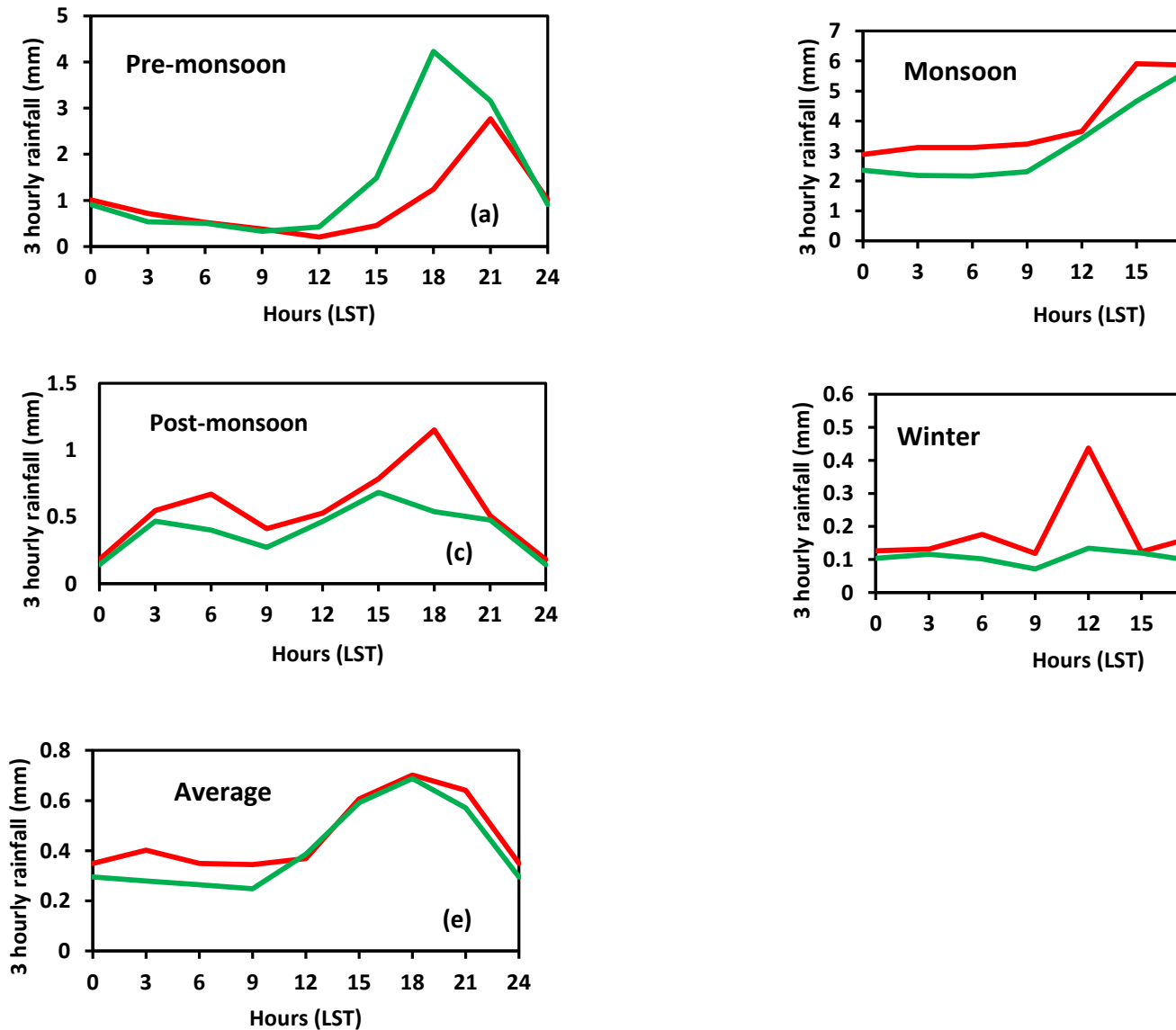


Figure 4.22: Seasonal and yearly average diurnal variation of rainfall of Chuadanga.

## Comilla



In figure 4.23 (a), (b), (c) and (e) represents the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter season during study period. Rain gauge and GSMaP found well matched maximum rainfall time at 1200 LST, 0600 LST, 0600 LST and 0900 LST during pre-monsoon, monsoon, post-monsoon and winter, respectively. In Figure 4.24 (e) represents the diurnal variation of rainfall during study period or yearly average of Comilla. Both dataset detected well matched twin peaks of maximum rainfall at 0900LST and 1500 LST.

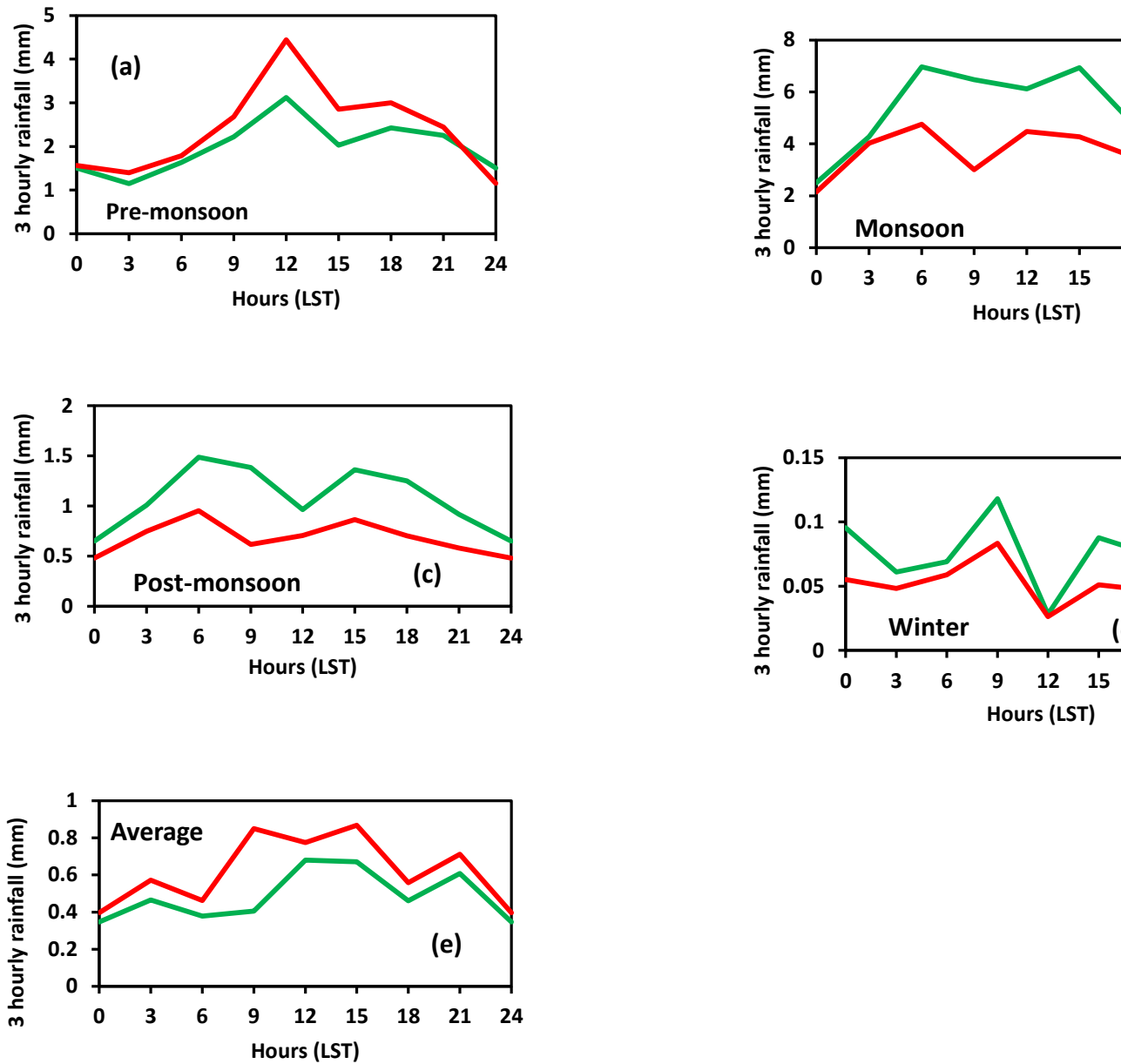
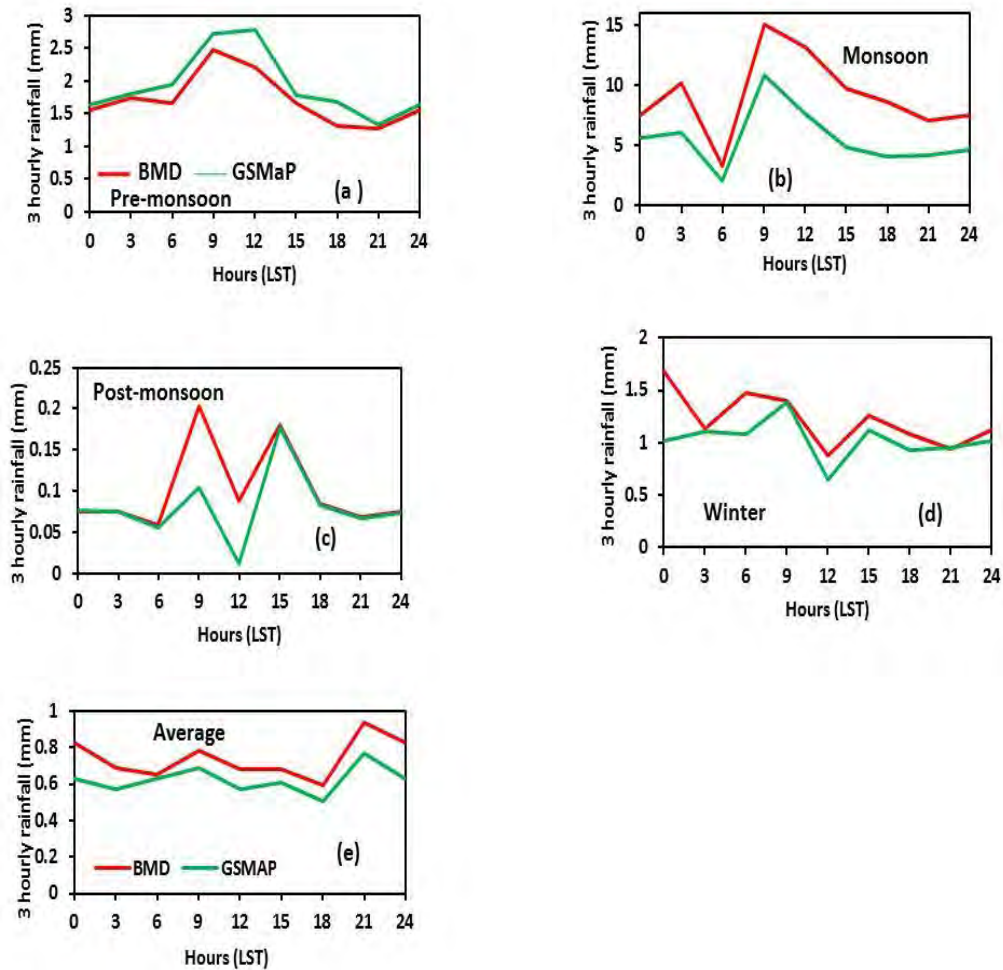


Figure 4.23: Seasonal and yearly average diurnal variation of rainfall of Comilla.

### Cox's-Bazar

In figure 4.24 (a), (b), (c) and (d) represents the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter season during study period. Rain gauge found maximum rainfall of these seasons at 0900 LST, 0900 LST, 0000 LST and 0900 LST

during pre-monsoon, monsoon, post-monsoon and winter respectively whereas GSMaP detects these peaks at 2100 LST, 1200 LST, 0900 LST and 0900 LST, respectively. In Figure 4.25 (e) shown the diurnal variation of rainfall during study period or yearly average of Cox-Bazaar. Both dataset detected well matched twin peak of maximum rainfall at 2100LST and 0900 LST.



**Figure 4.24:** Seasonal and yearly average diurnal variation of rainfall of Cox's-Bazaar.

### Dhaka

In figure 4.25 (a), (b), (c) and (d) represents the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter season during the study period. Rain gauge found maximum rainfall of these seasons at 1800 LST, 0900 LST, 1500 LST and 1200 LST,

respectively and GSMaP detects these peaks at 1800 LST,0900 LST,1500 LST and 1500 LST. In Figure.4.26 (e) represents the diurnal variation of rainfall during study period or yearly average of Dhaka. Both dataset detected well matched twin peak of maximum rainfall at 0000LST and 1200 LST.

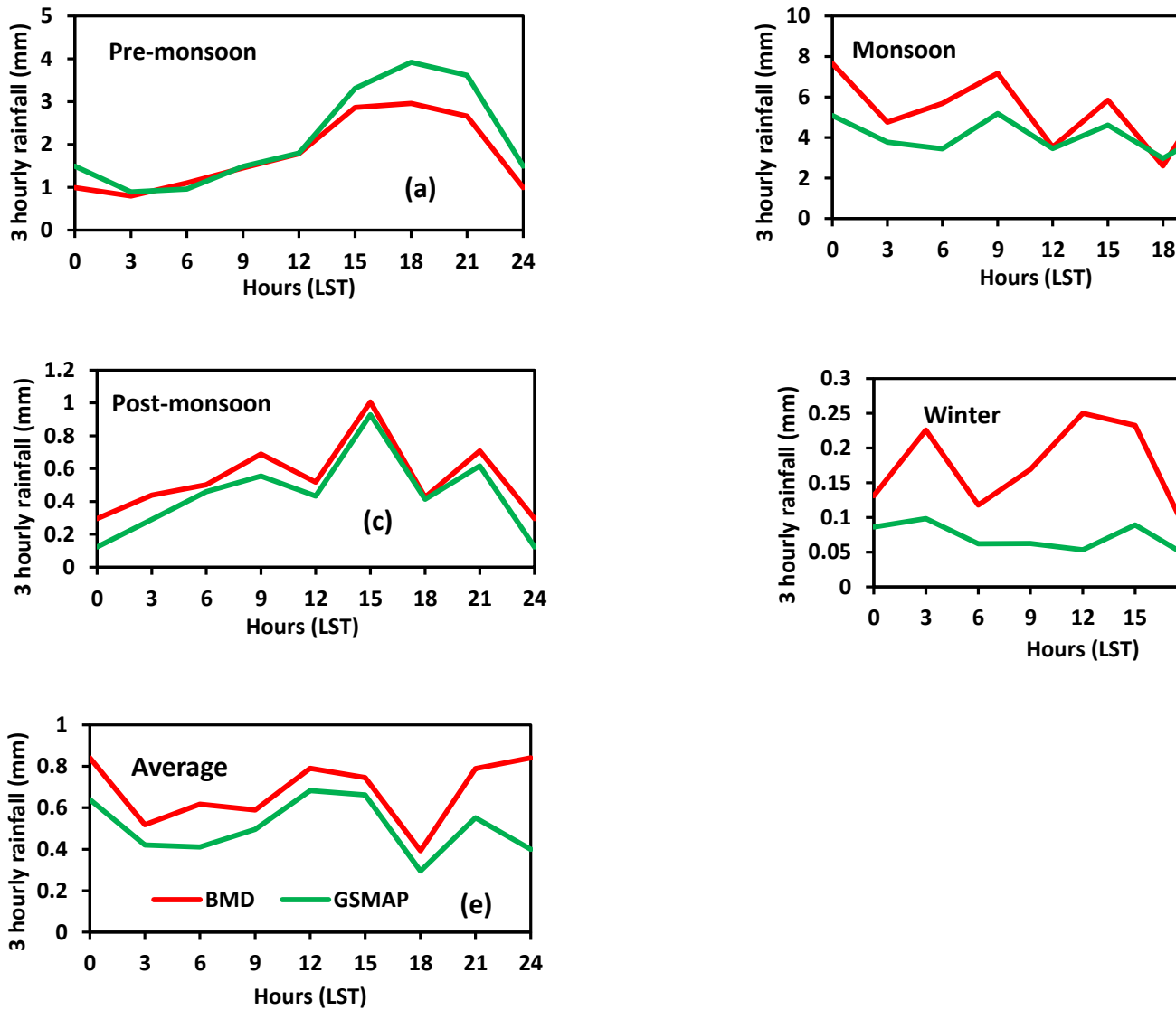
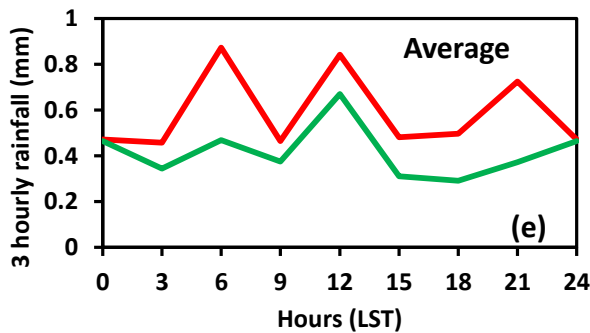
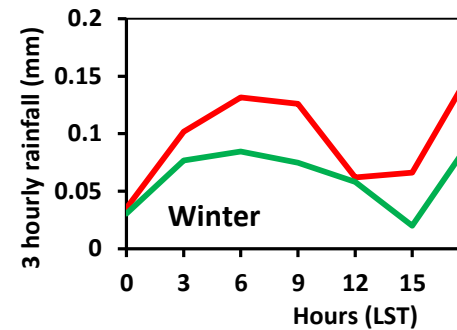
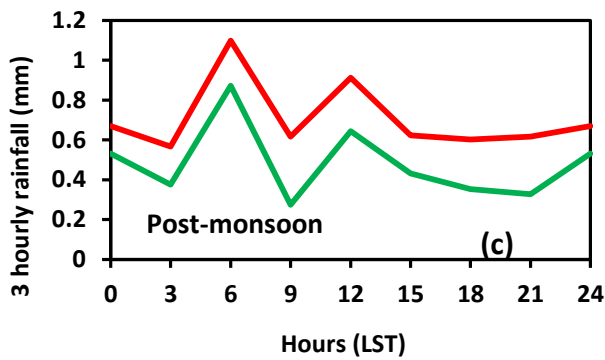
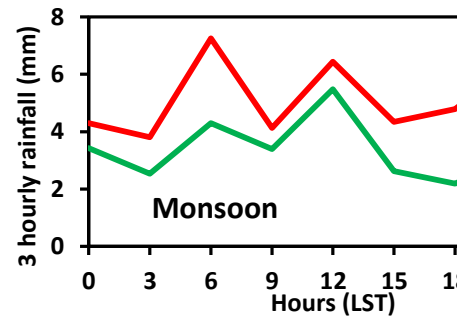
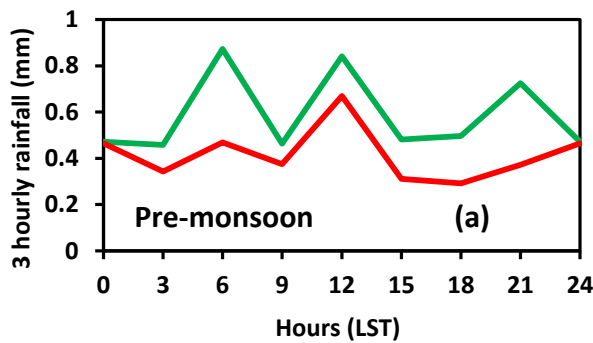


Figure 4.25: Seasonal and yearly average diurnal variation of rainfall of Dhaka.

## Dinajpur

In figure 4.26 (a), (b), (c) and (d) represents the diurnal variation of pre-monsoon , monsoon, post-monsoon and winter season during study period .Both Rain gauge and GSMaP found sharp matched maximum rainfall at 1200 LST, 0600 LST,1800 LST during pre-monsoon, post-monsoon and winter, respectively. In monsoon, rain gauge observed maximum rainfall at 0600 LST whereas GSMaP at 1200 LST. In Figure.4.27 (a) represents the diurnal variation of rainfall during study period or yearly average. Both dataset detected twin peak of well-matched maximum rainfall at 1200LST and 0600 LST.



**Figure 4.26:** Seasonal and yearly average diurnal variation of rainfall of Dinajpur.

**Faridpur**

In figure 4.27 (a), (b), (c) and (d) represents the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter season during study period. Rain gauge and GSMaP found well matched maximum rainfall peak at 1500 LST, 1500 LST, and 1800 LST during monsoon, post-monsoon and winter, respectively. In pre-monsoon rain gauge observed the peak at 2100 LST and GSMaP at 1800 LST. In figure 4.28 (e) represents the diurnal variation of rainfall during study period or yearly average of Faridpur. A couple peak of maximum rainfall found at similar time (1500 LST and 0900 LST) detected by both dataset.

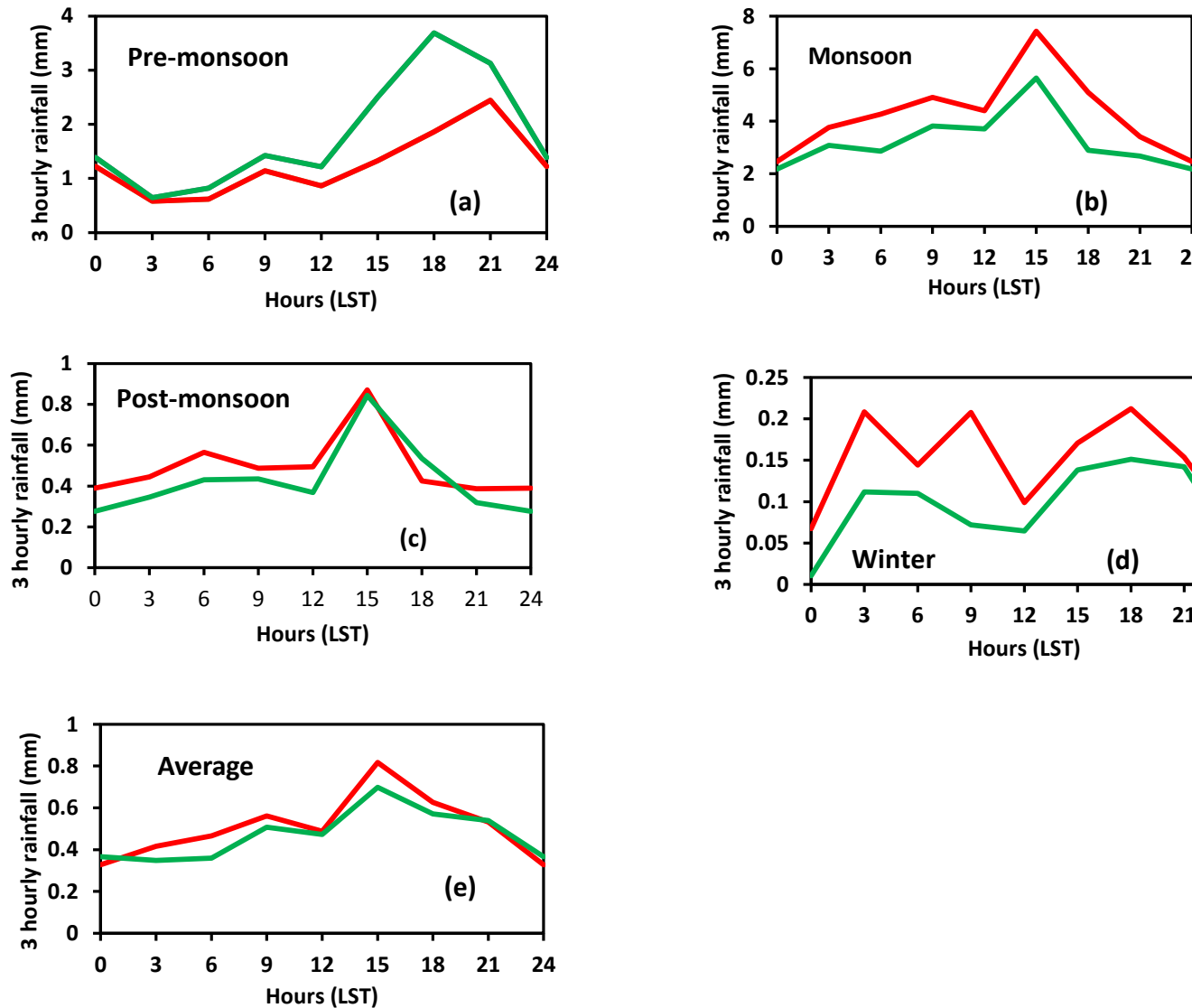


Figure 4.27: Seasonal and yearly average diurnal variation of rainfall of Faridpur.

### Feni

In figure 4.28 (a) (b) (c) and (d) represents the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter season during study period. Rain gauge found maximum rainfall vertex of these seasons at 1200 LST, 2100 LST, 2100 LST and 0900 LST, respectively. On other hand GSMaP observed at 1200 LST, 1200 LST, 2100 LST and 0600 LST respectively. In figure 4.29 (e) represents the diurnal variation of rainfall

in during study period or yearly average of Feni. Both datasets detected well matched twin peak of maximum rainfall at 2100LST and 1200 LST.

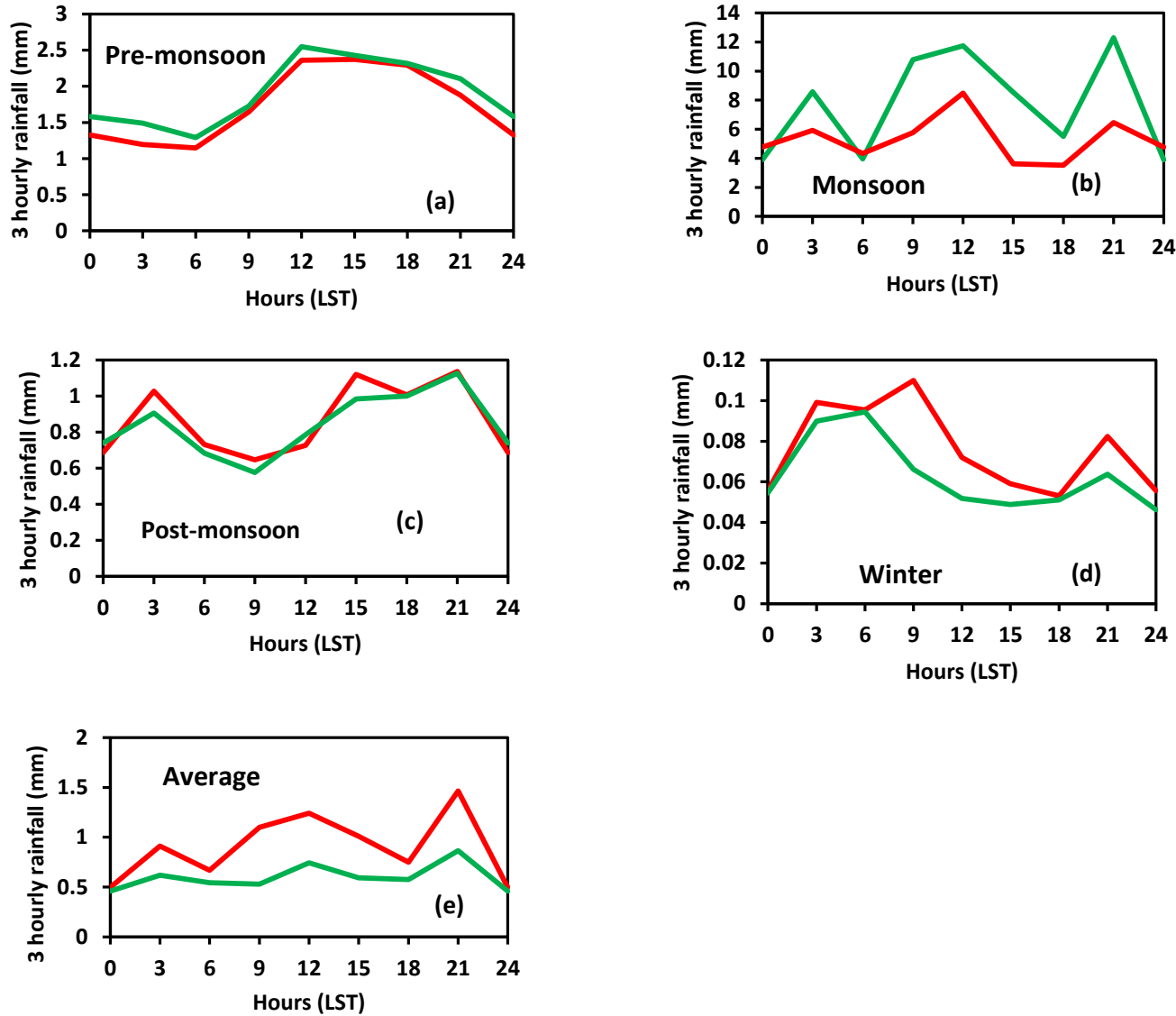


Figure 4.28: Seasonal and yearly average diurnal variation of rainfall of Feni.

**Hatia**

In figure 4.29 (a), (b), (c) and (d) represents diurnal variation of pre-monsoon, monsoon, post-monsoon and winter season during study period. Rain gauge found maximum



rainfall of these seasons at 1500 LST, 2100 LST, 2100 LST and 1500 LST, respectively. On other hand GSMaP detects these vertex at 1200 LST, 2100 LST, 2100 LST and 1800 LST, respectively. In figure 4.30 (e) represents the diurnal variation of rainfall during study period or yearly average of Hatia. Both datasets detected well matched twin peak of maximum rainfall at 0900LST and 1500 LST

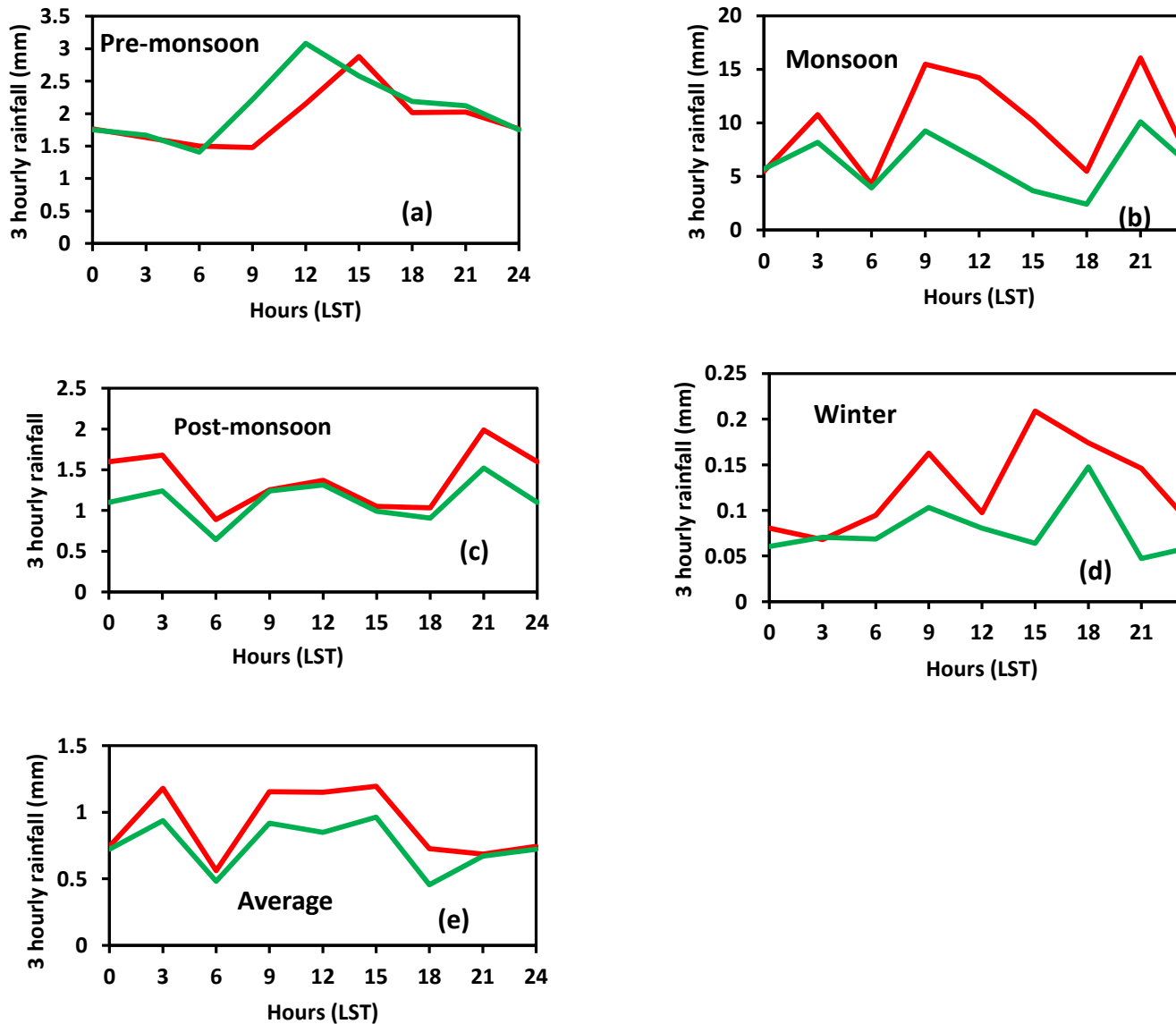
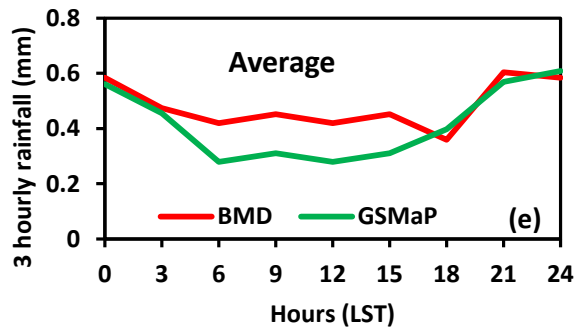
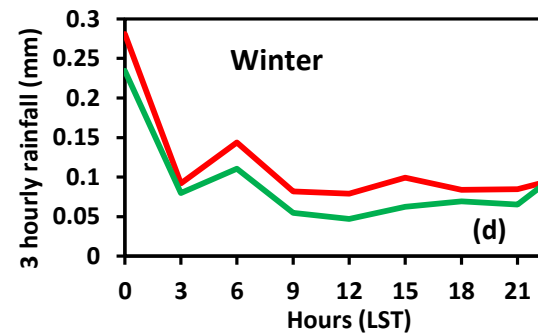
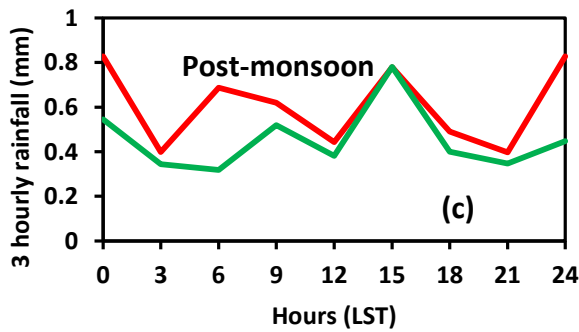
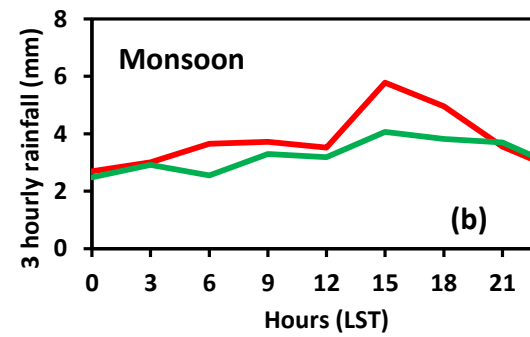
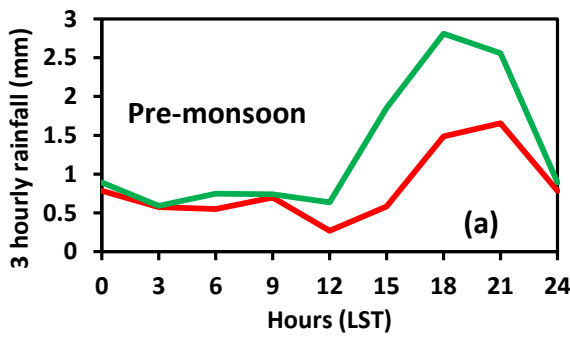


Figure 4.29: Seasonal and yearly average diurnal variation of rainfall of Hatia.

**Ishurdi**

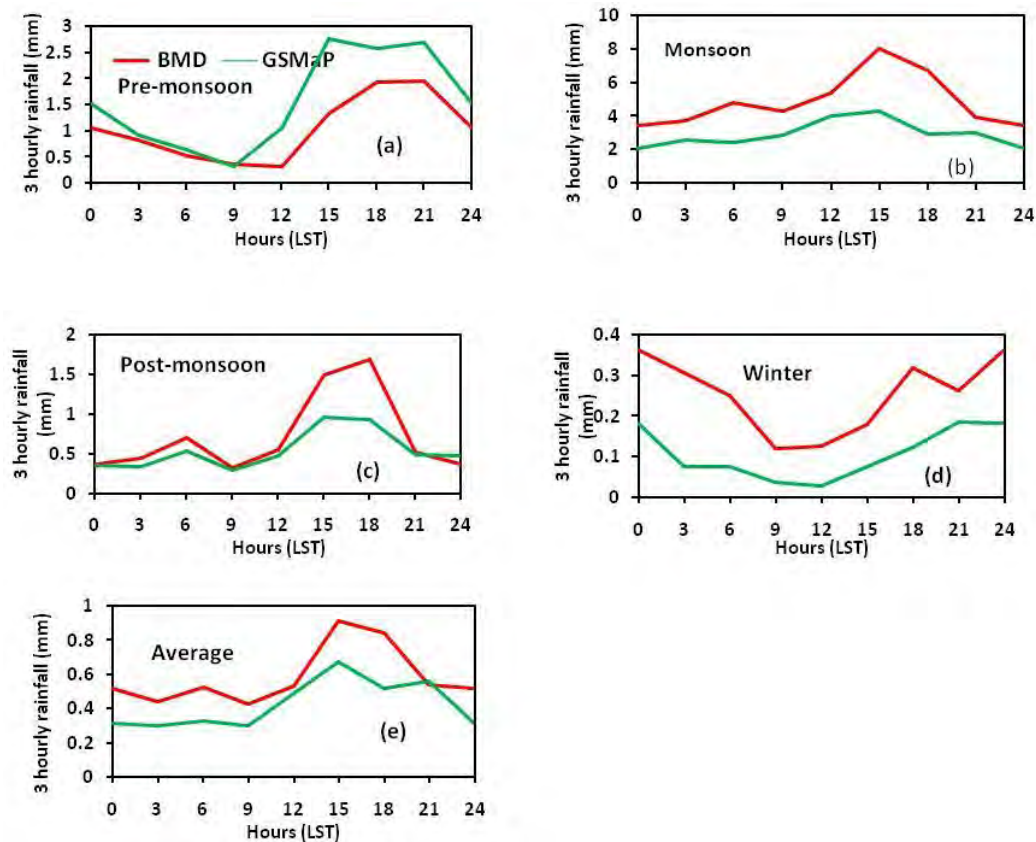
In figure 4.30 (a), (b), (c) and (d) represents the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter season. Rain gauge found maximum rainfall of these seasons at 2100 LST, 1500 LST, 1500 LST and 0000 LST, respectively whereas GSMaP detected these peaks at 1800 LST, 1500 LST, 1500 LST and 0000 LST, respectively. In figure 4.31 (e) represents the diurnal variation of rainfall of Ishurdi during study period. Both datasets detected well matched twin peak of maximum rainfall at 2100LST and 0000 LST.



**Figure 4.30:** Seasonal and yearly average diurnal variation of rainfall of Ishurdi

**Jessore**

In figure 4.31 (a) (b) (c) and (e) represents the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter season. Rain gauge found maximum rainfall of these seasons at 2100 LST, 1500 LST, 1800 LST and 0000 LST, respectively and GSMaP found these vertex at 1500LST, 1500 LST, 1500 LST and 2100 LST, respectively. In figure 4.31 (e) represents the diurnal variation of rainfall during study period or yearly average of Jessore. Both datasets detected twin peak of maximum rainfall. Rain gauge found at 1500 LST and 1800 LST elsewhere GSMaP observed at 1500 LST and 2100 LST.



**Figure 4.31:** Seasonal and yearly average diurnal variation of rainfall of Jessore.

**Khepupara**

In figure 4.32 (a) (b) (c) and (d) represents the diurnal variation of pre-monsoon , monsoon, post-monsoon and winter season during study period and also found well matched maximum rainfall of these seasons at 1800 LST, 0900 LST,1500 LST and 1800 LST, respectively. In Figure.4.32 (e) represents the diurnal variation of rainfall during study period or yearly average of Khepupara. Rain gauge observed twin peak of maximum rainfall at 0900LST and 1200 LST whereas GSMaP found at 0600 and 0900 LST.

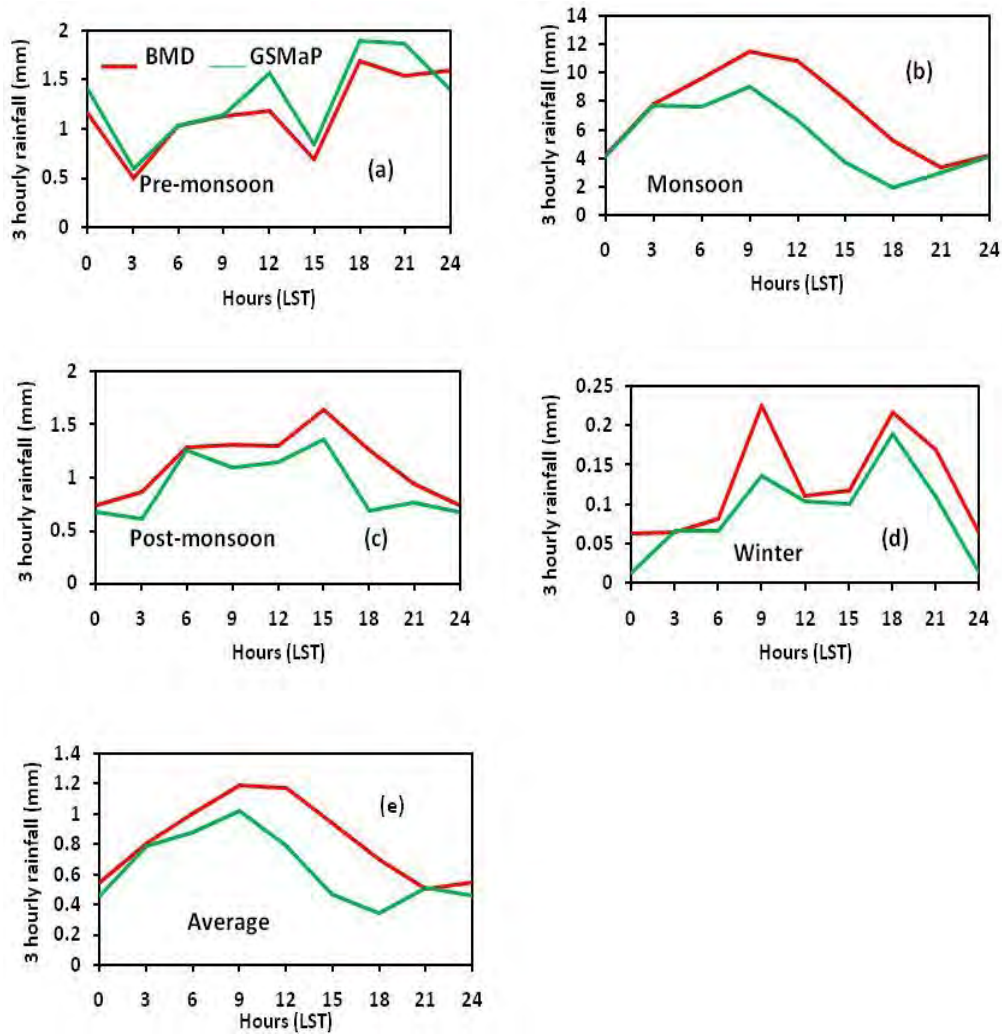


Figure 4.32: Seasonal and yearly average diurnal variation of rainfall of Khepupara.

### Khulna

In figure 4.33: (a), (b), (c) and (d) represent the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter season during the study period. Both datasets found well matched maximum rainfall at 2100 LST, 1500 LST, 1500 LST during pre-monsoon, monsoon and post-monsoon respectively. In winter rain gauge found at 0300 LST and GSMaP at 2100 LST. In figure 4.33 (e) represents the diurnal variation of rainfall during study period or yearly average of Khulna. Rain gauge detected twin peak

of maximum rainfall at 1500LST and 1800 LST elsewhere GSMaP also found two peaks at 1200 LST and 1500 LST.

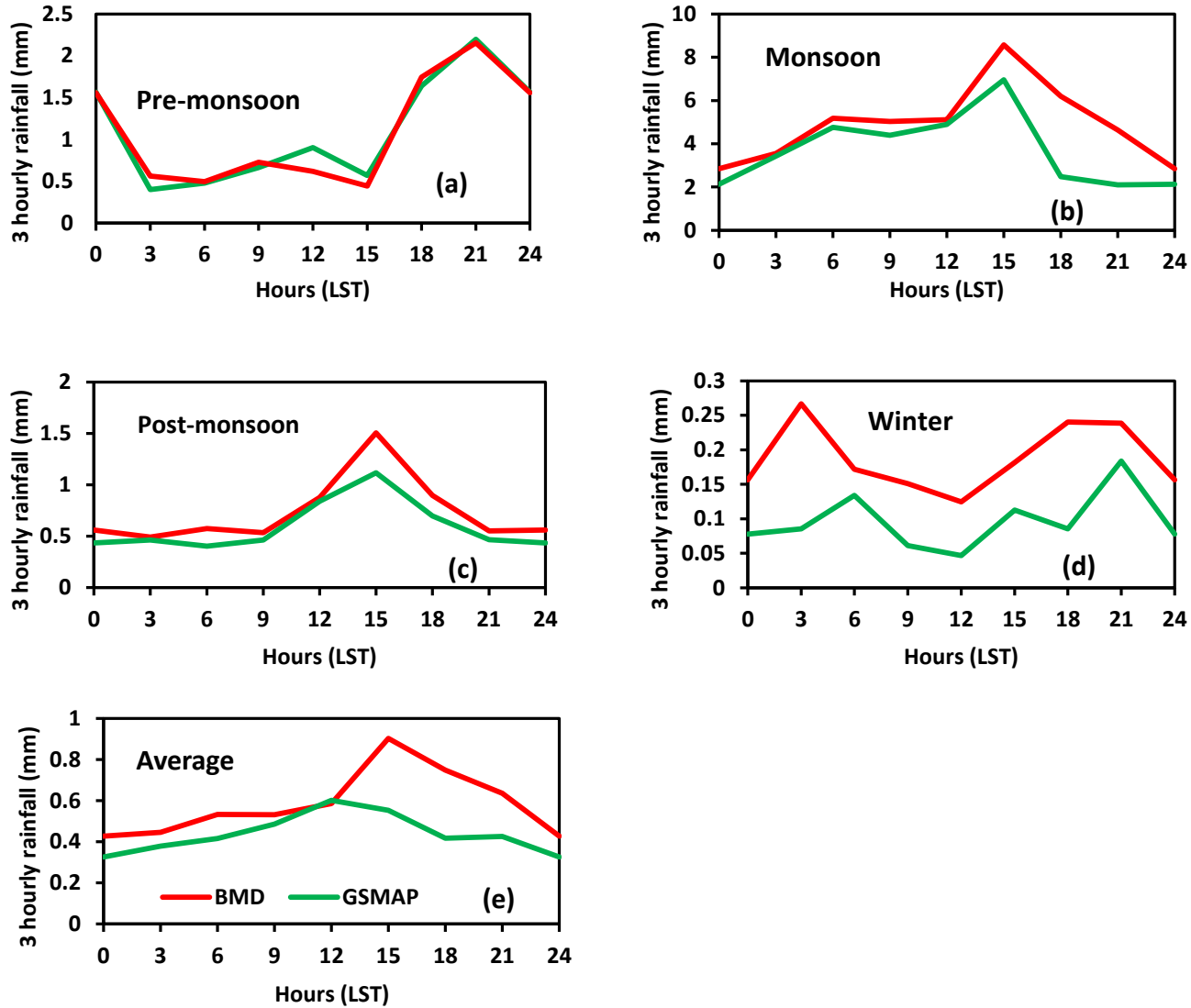


Figure 4.33: Seasonal and yearly average diurnal variation of rainfall of Khulna.

### Kutubdia

In figure 4.34 (a), (b), (c) and (d) represents the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter season during the study period and also found same maximum rainfall vertex of these seasons at 1200 LST, 0900 LST, 2100 LST and 1800

LST, respectively by both datasets. In figure 4.34 (e) represents the diurnal variation of rainfall in during study period. It is observed by BMD rain gauge and GSMaP. Both datasets detected well matched a couple peak of maximum rainfall at 2100LST and 0900 LST.

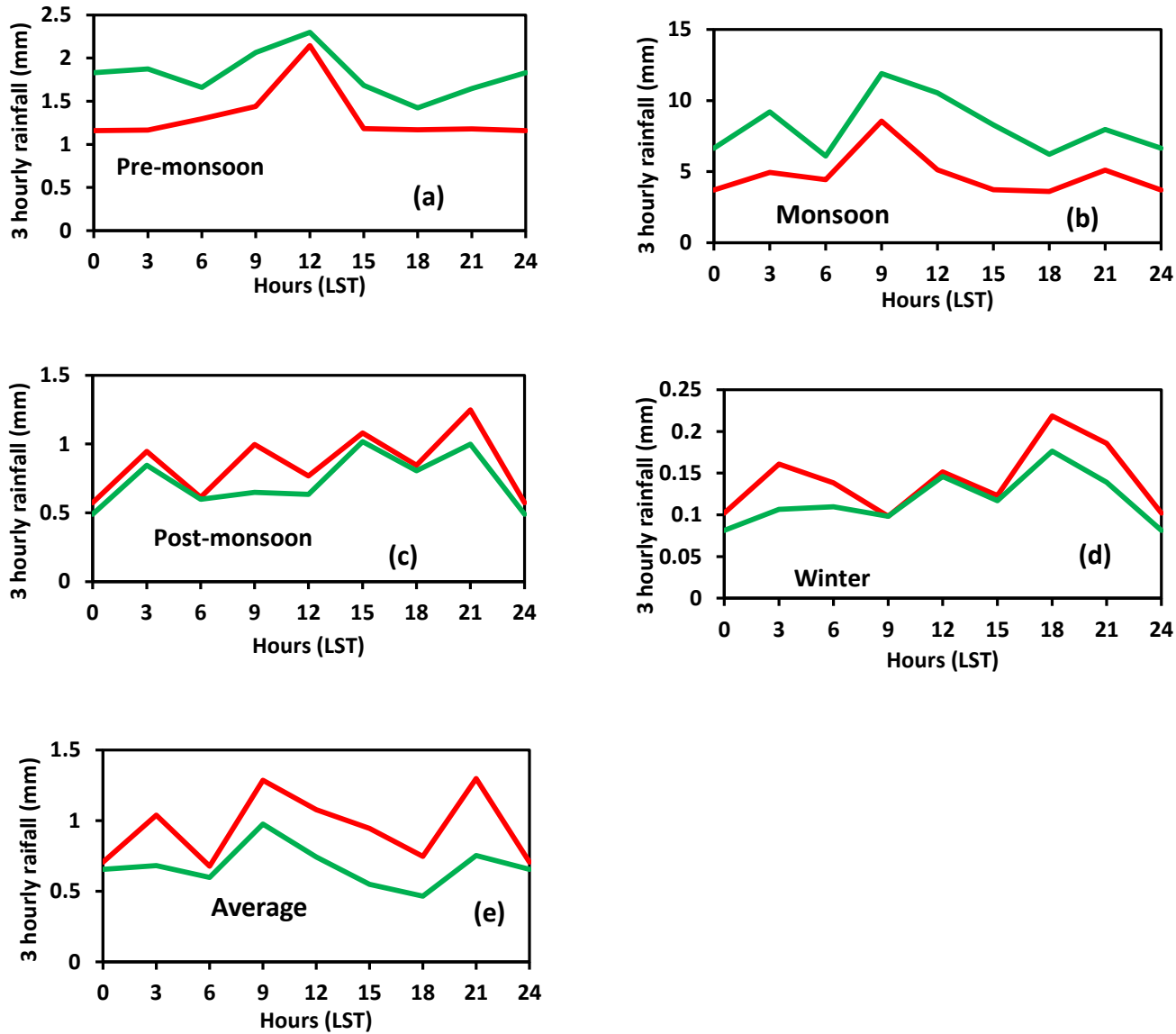
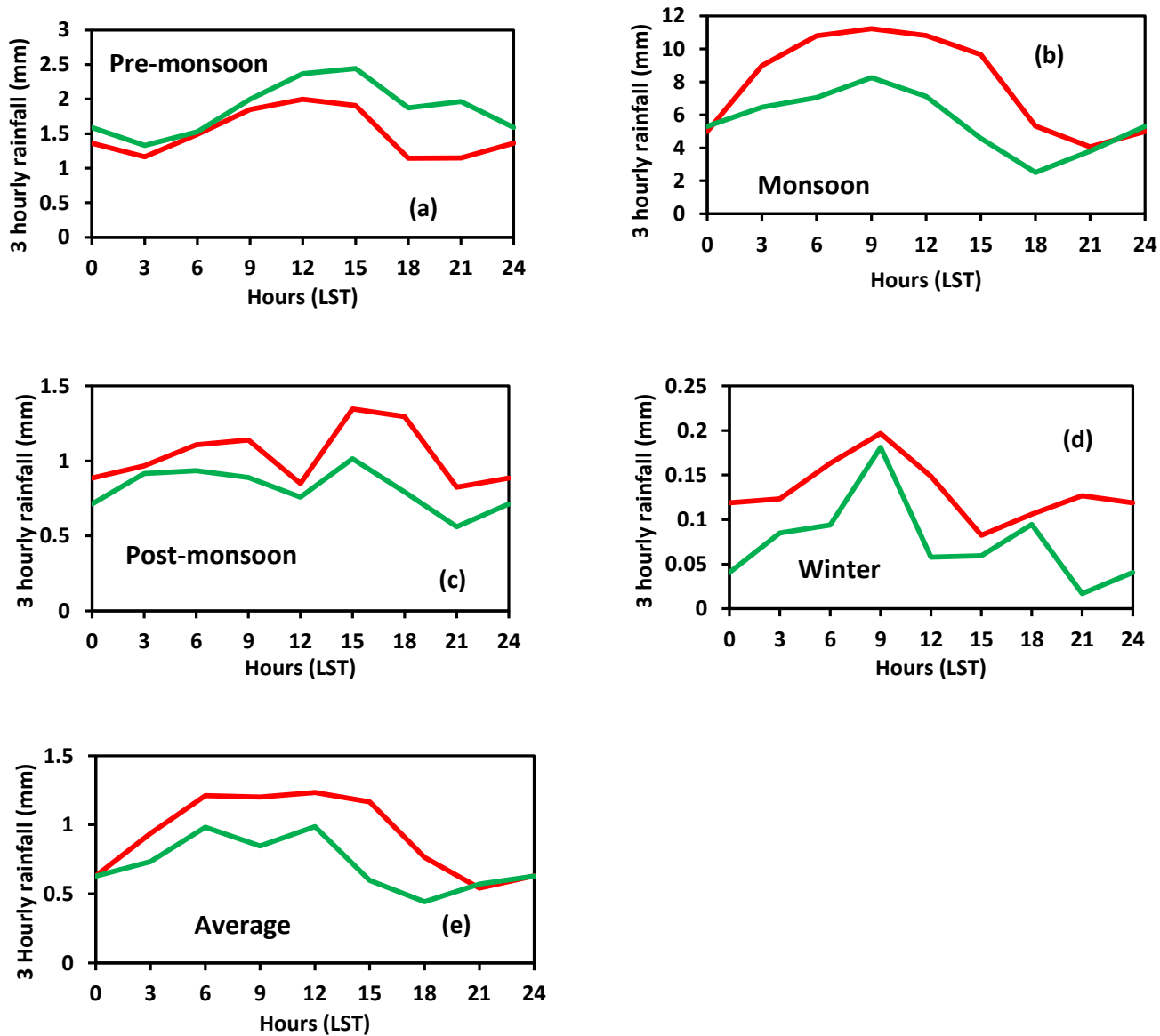


Figure 4.34: Seasonal and yearly average diurnal variation of rainfall of Kutubdia.

**M.Court**

In figure 4.35 (a), (b), (c) and (d) represents the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter season during the study period and also found maximum rainfall of these seasons at 1500 LST, 0900 LST, 1500 LST and 0900 LST, respectively. In Figure 4.35 (e) represents the diurnal variation of rainfall during study period or yearly average. Both datasets detected well matched twin peak of maximum rainfall at 0900LST and 2100 LST.



**Figure 4.35:** Seasonal and yearly average diurnal variation of rainfall of M.Court.



**Madaripur**

In figure 4.36 (a), (b), (c) and (d) represents the diurnal variation of pre-monsoon rainfall, monsoon rainfall, post-monsoon rainfall and winter rainfall during study period. Rain gauge found maximum rainfall of these seasons at 1800 LST, 1500 LST, 1500 LST and 0000 LST, respectively. On other hand GSMaP found these peaks at 2100 LST, 1500 LST, 1500 LST and 0000 LST, respectively. In Figure 4.36 (e) represents the diurnal variation of rainfall during study period or yearly average of Madaripur. Both datasets detected well matched a couple of maximum rainfall at 1500LST and 1200 LST.

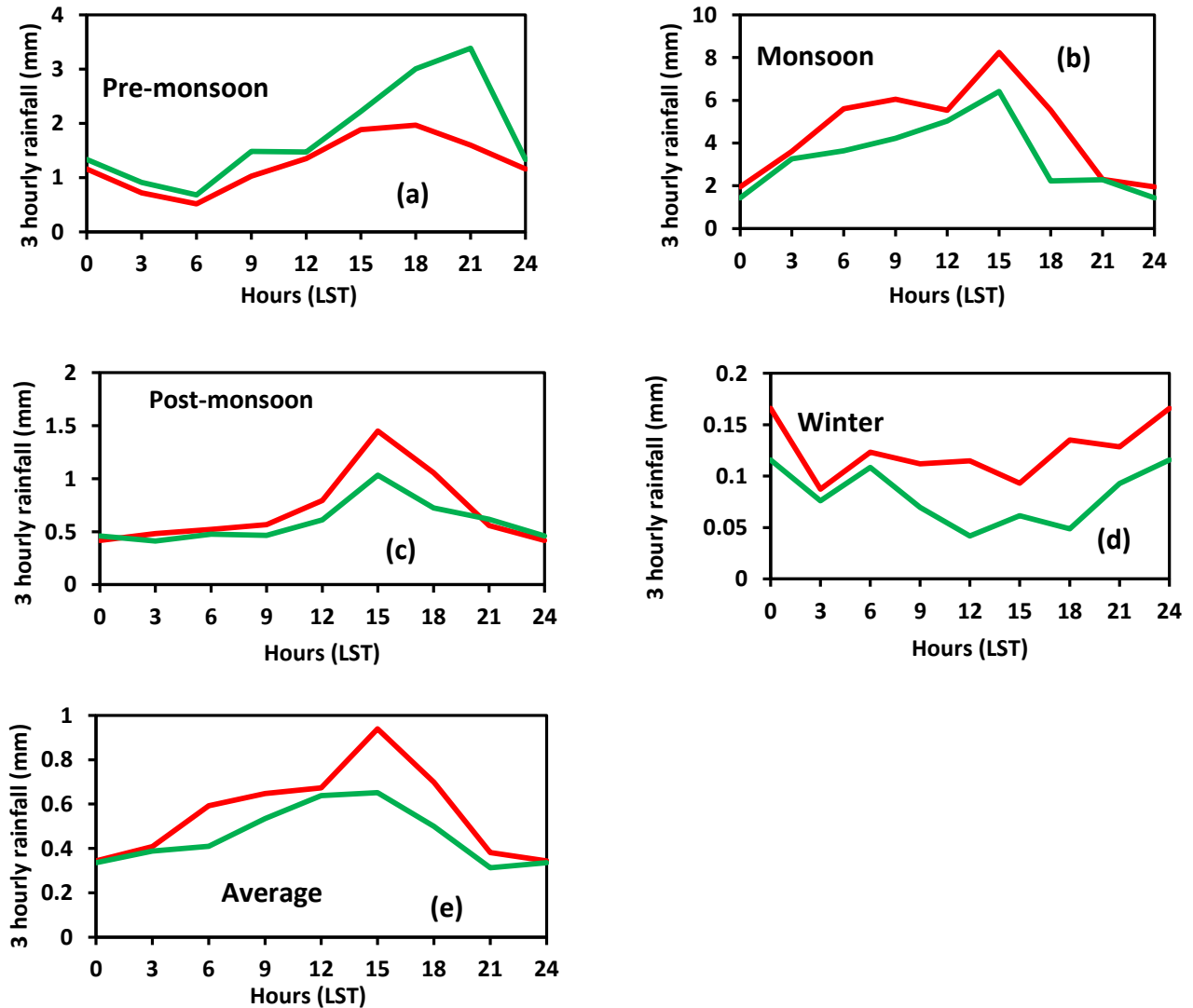


Figure 4.36: Seasonal and yearly average diurnal variation of rainfall of Madaripur.

### Mongla

In figure 4.37 (a), (b), (c) and (d) represents the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter season during the study period and also found same maximum rainfall of these seasons at 2100 LST, 1500 LST, 1500 LST and 0300 LST, respectively. It is observed by BMD rain gauge and GSMaP in Figure 4.37 (e) represents

the diurnal variation of rainfall during study period or yearly average of Mongla. Both datasets detected a couple peak of maximum rainfall at 1500LST and 1200 LST.

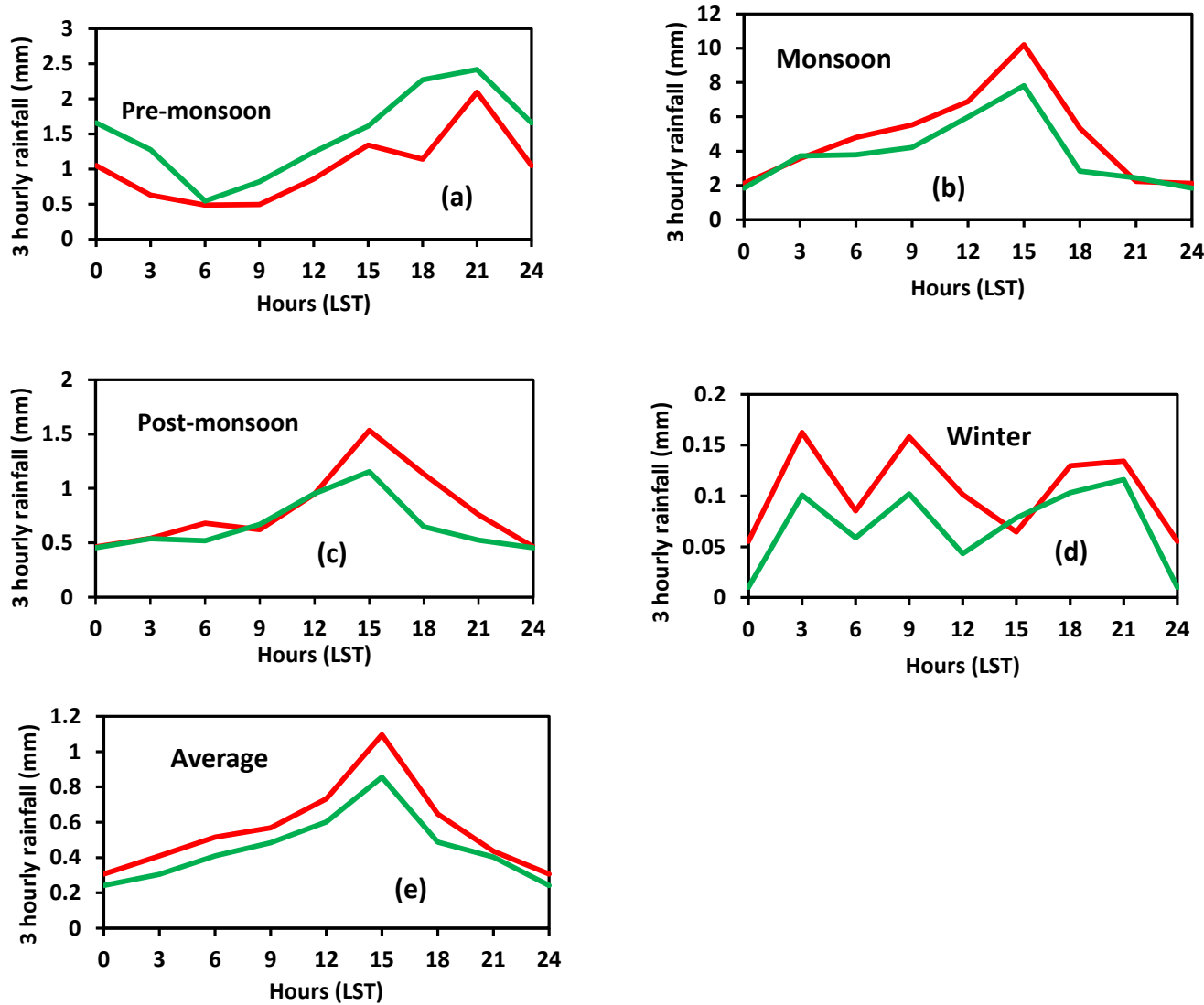


Figure 4.37: Seasonal and yearly average diurnal variation of rainfall of Mongla.

### Mymensingh

In figure 4.38 (a), (b), (c) and (d) represents the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter season during the study period and also found

similar maximum rainfall of these seasons at 0900 LST, 1500 LST, 0900 LST and 0300 LST, respectively. It is observed by BMD rain gauge and GSMaP. In figure 4.38 (e) represents the diurnal variation of rainfall during study period or yearly average of Mymensingh. Both datasets detected mismatched twin peak of maximum rainfall at 0600LST and 0900 LST by rain gauge whereas GSMaP found these peaks at 0300 and 1500 LST.

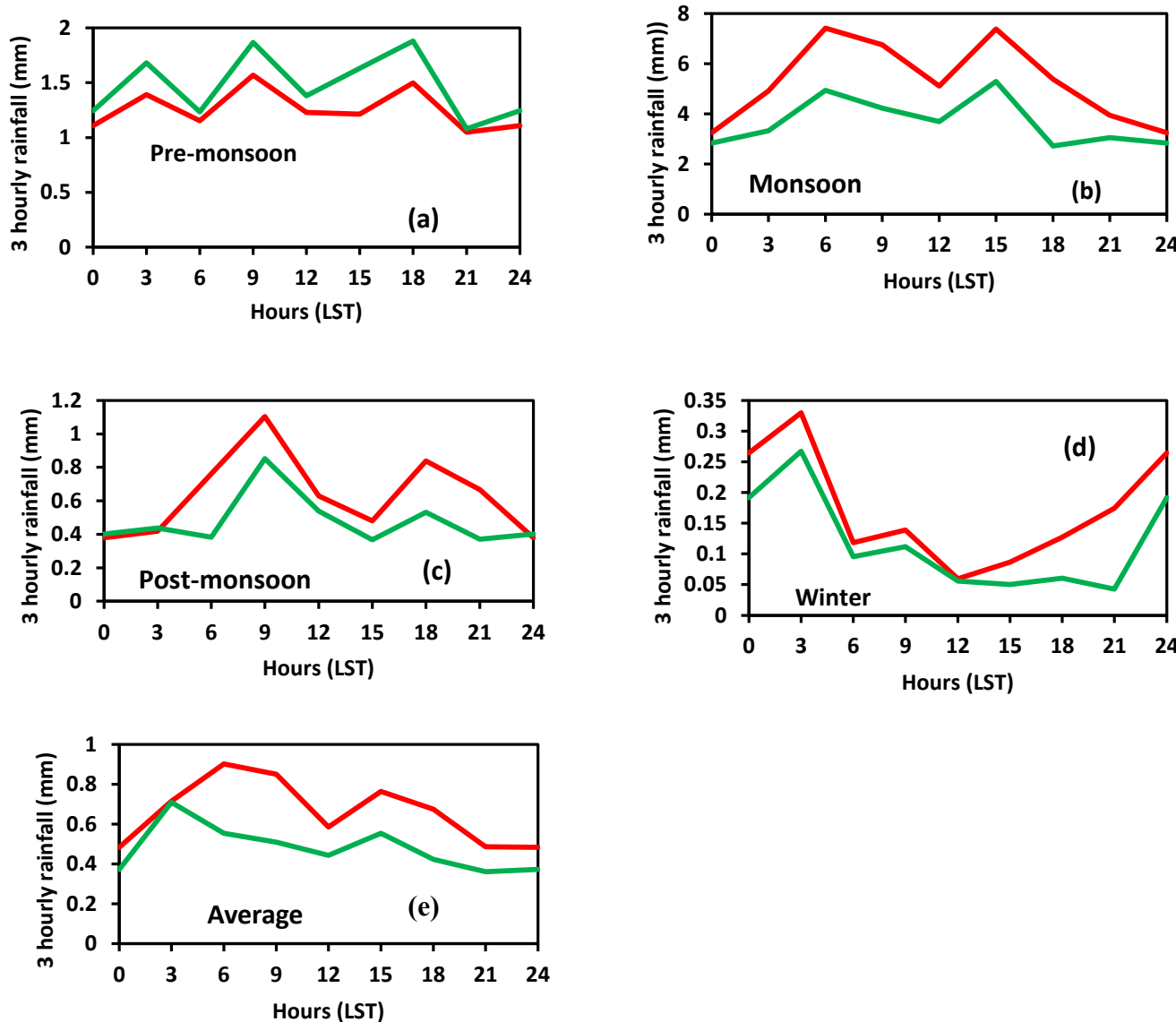
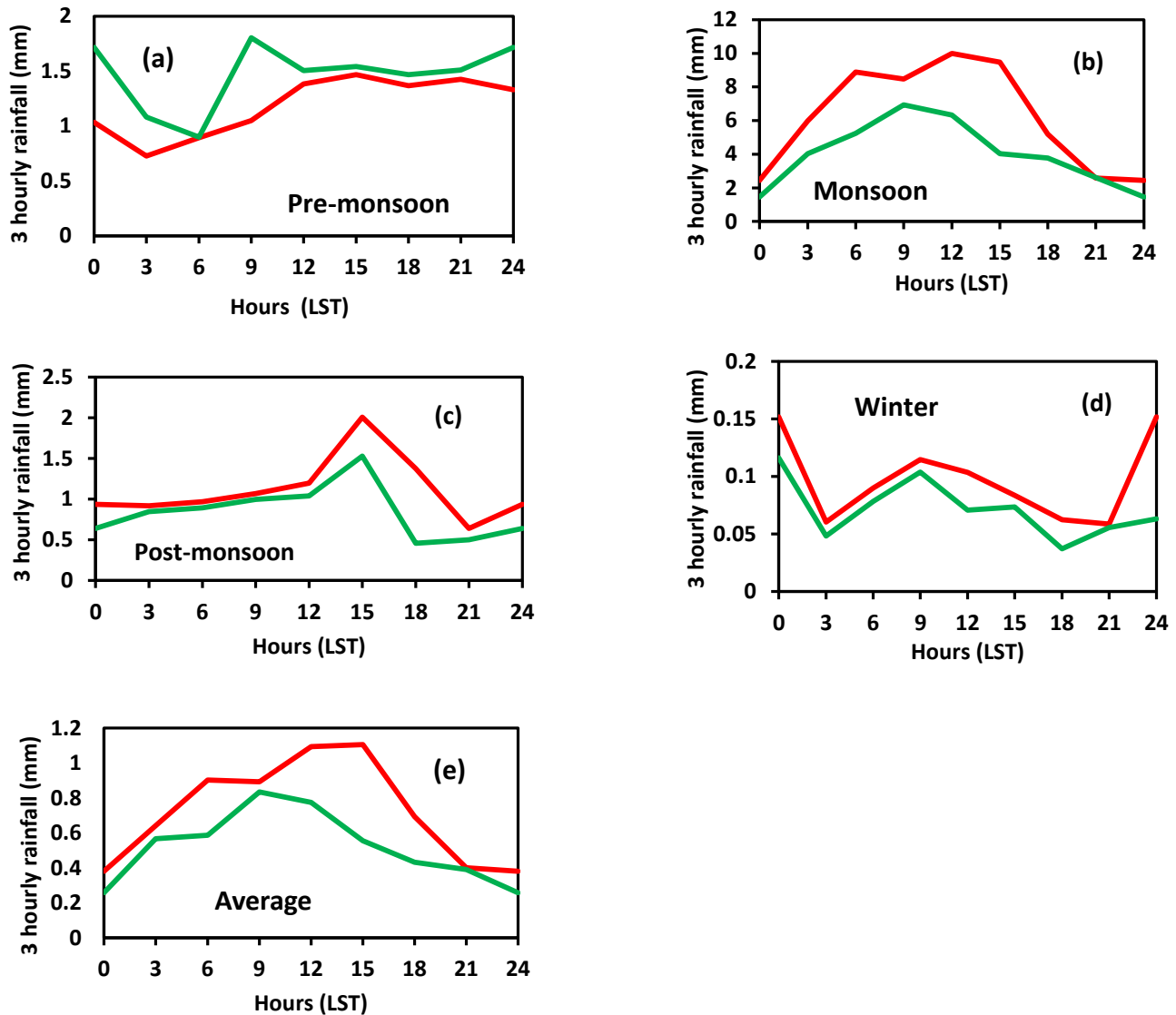


Figure 4.38: Seasonal and yearly average diurnal variation of rainfall of Mymensingh.

**Patukhali**

In figure 4.39 (a), (b), (c) and (d) represents the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter season during study period. It is observed by BMD rain gauge and GSMaP Rain gauge found maximum rainfall of these seasons at 0900 LST, 1200 LST, 1500 LST and 0000 LST, respectively. On other hand GSMaP found these peaks at 1500 LST, 0900 LST, 1500 LST and 0000 LST, respectively. In figure 4.39 (e) represents the diurnal variation of rainfall during study period or yearly average of Patakhali. Rain gauge detected a peak of maximum rainfall at 1500LST whereas GSMaP found at 1200 LST.



**Figure 4.39:** Seasonal and yearly average diurnal variation of rainfall of Patuakhali

### Rajshahi

In figure 4.40 (a), (b), (c) and (d) represents the diurnal variation peak of pre-monsoon rainfall, monsoon rainfall, post-monsoon rainfall and winter rainfall during the study period or yearly average. Rain gauge found maximum rainfall of these seasons at 1800 LST, 1500 LST, 1800 LST and 0600 LST, respectively. On other hand GSMaP found these peaks at 2100 LST, 1500 LST, 1500 LST and 1200 LST, respectively. In figure

4.40 (e) represents the diurnal variation of rainfall during study period of Rajshahi. It is observed by BMD rain gauge and GSMaP. Both dataset detected a peak of maximum rainfall. Rain gauge observed at 1800LST whereas GSMaP found at 1500 LST.

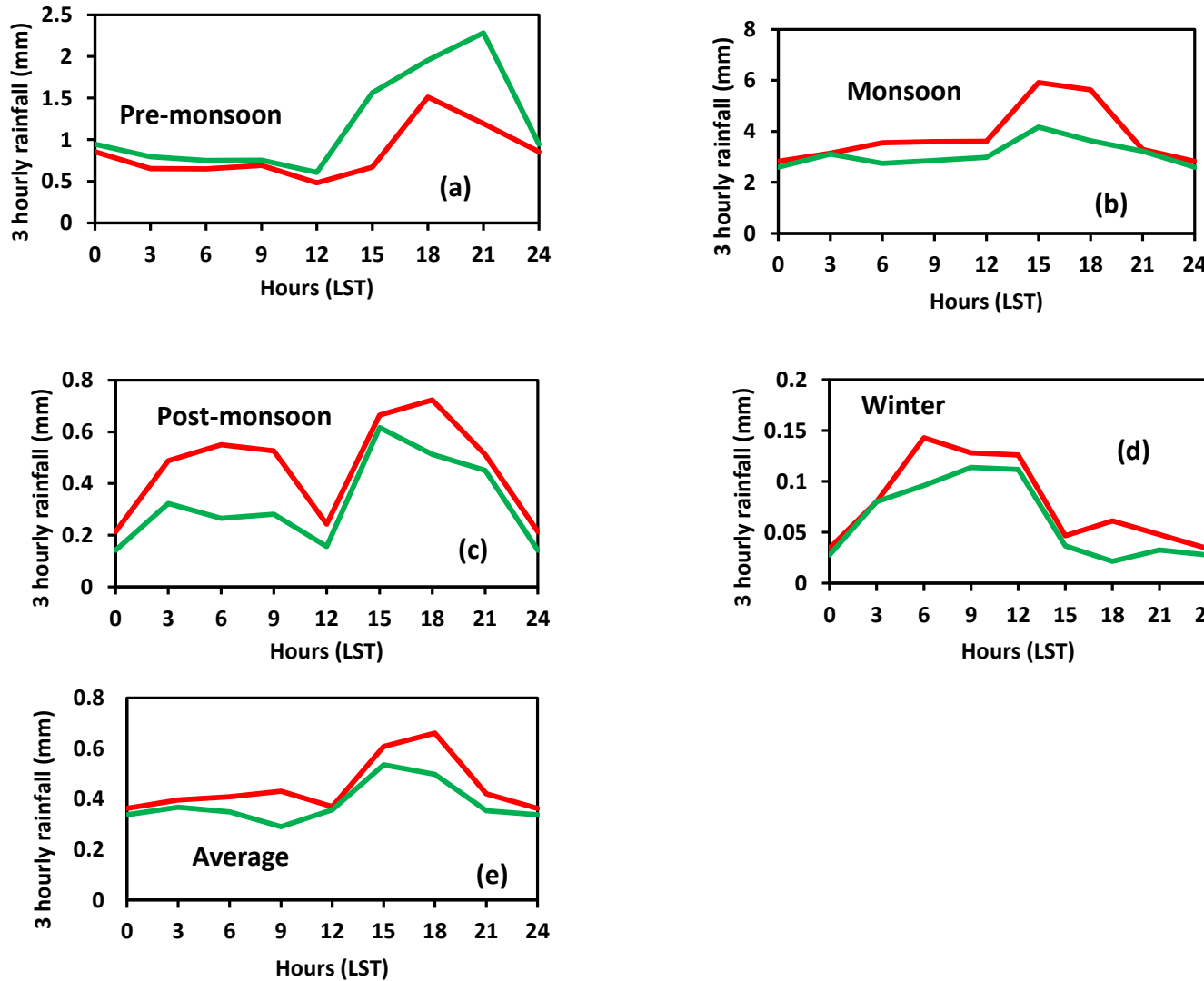


Figure 4.40: Seasonal and yearly average diurnal variation of rainfall of Rajshahi.

### Rangpur

In figure 4.41 (a), (b), (c) and (d) represents the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter season during study period. Rain gauge found

maximum rainfall of these seasons at 0300 LST, 0600 LST, 2100 LST and 0900 LST, respectively. On other hand GSMaP detected these peaks at 0000 LST, 0600 LST, 2100 LST and 0900 LST, respectively. In figure 4.41 (e) represents the diurnal variation of rainfall during study period or yearly average of Rangpur. It is observed by BMD rain gauge and GSMaP. Rain gauge detected a peak of maximum rainfall at 0600LST whereas GSMaP observed the peak at 0300 LST.

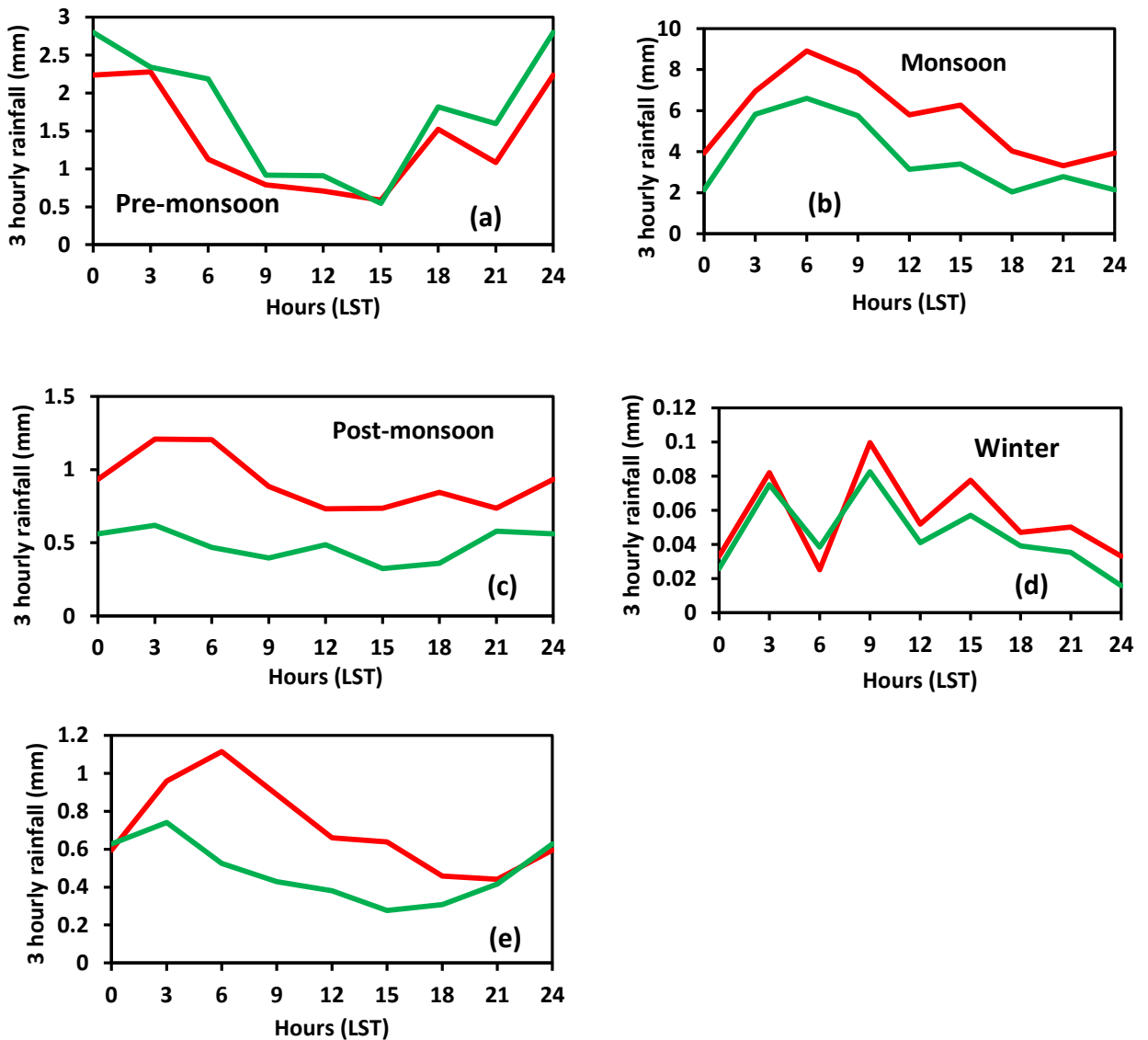
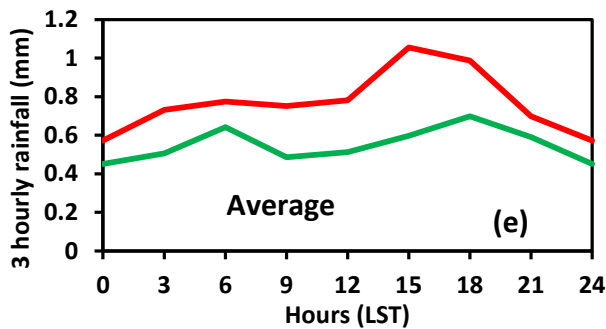
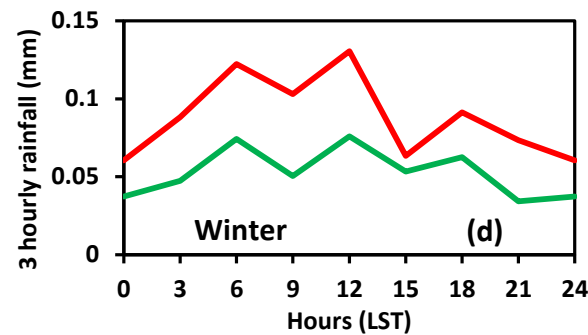
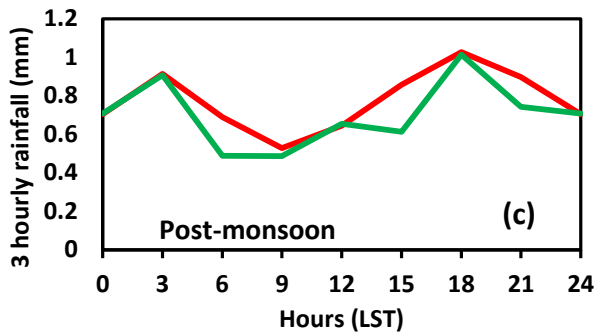
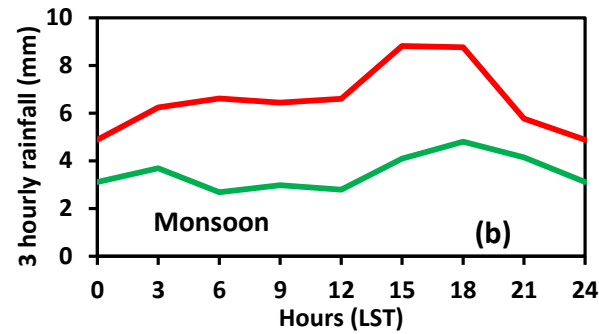
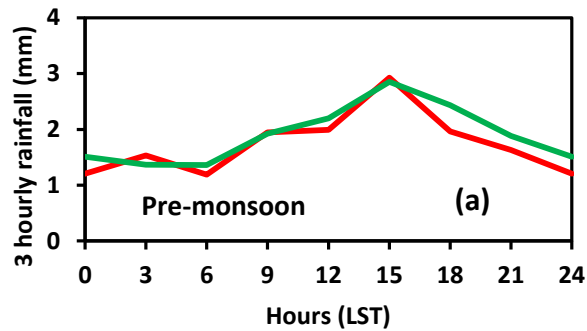


Figure 4.41: Seasonal and yearly average diurnal variation of rainfall of Rangpur.



**Rangamati**

In figure 4.42 (a), (b), (c) and (e) represents the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter during study period or yearly average and also found well matched maximum rainfall of these seasons at 1500 LST, 1800 LST, 1800 LST and 1200 LST, respectively. In figure 4.42 (e) represents the diurnal variation of rainfall during study period of Rangamati. It is observed by BMD rain gauge and GSMaP. Rain gauge detected twin peak of maximum rainfall at 1200LST and 1800 LST whereas GSMaP found these peaks at 2100 LST and 0600 LST.



**Figure 4.42:** Seasonal and yearly average diurnal variation of rainfall of Rangamati.

**Sandwip**

In figure 4.43: (a), (b), (c) and (d) represent the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter season during study period. Rain gauge found maximum rainfall of these seasons at 1200 LST, 1200 LST, 2100 LST and 1500 LST, respectively. On other hand GSMaP observed these peaks at 1200 LST, 1200 LST, 0900 LST and 0600 LST, respectively. In figure 4.43 (e) represents the diurnal variation of rainfall during study period or yearly average. It is observed by BMD rain gauge and GSMaP .Rain gauge observed twin peak of maximum rainfall at 0600LST and 0300 LST whereas GSMaP found these peaks at 0900 LST and 0600 LST.

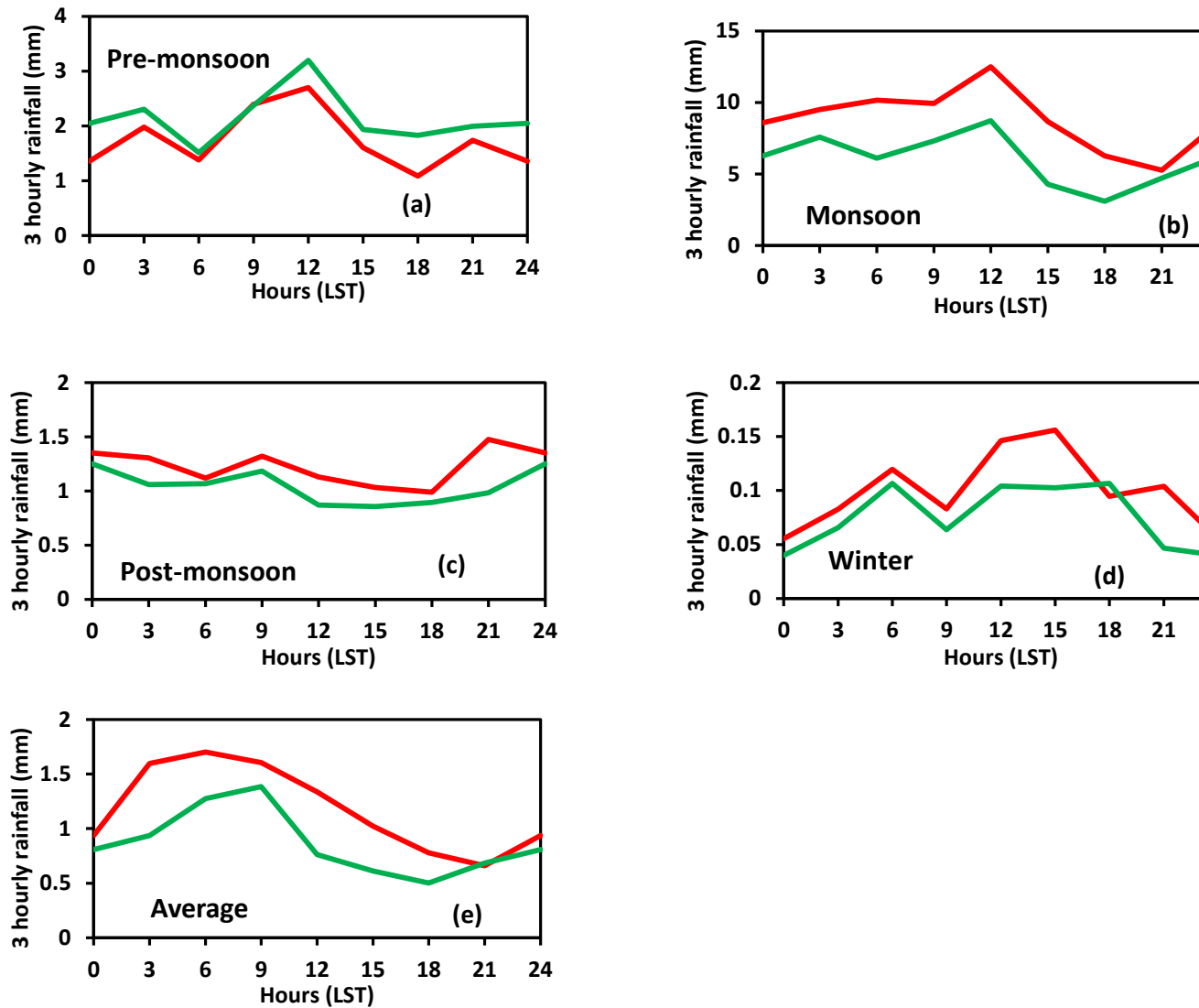


Figure 4.43: Seasonal and yearly average diurnal variation of rainfall of Sandwip.

### Sathkhira

In figure 4.44 (a), (b) (c) and (d) represents the diurnal variation of pre-monsoon rainfall, monsoon rainfall, post-monsoon rainfall and winter rainfall during study period. It is observed by BMD rain gauge and GSMaP Rain gauge found maximum rainfall of these seasons at 2100 LST, 1500 LST, 0300 LST, 1500 LST, and 1800 LST, respectively. On

other hand GSMaP found these peaks at 2100 LST, 1500 LST, 1500 LST and 1800 LST, respectively. In figure 4.45 (e) represents the diurnal variation of rainfall of Sathkhira during study period. or yearly average Rain gauge detected twin peak of maximum rainfall at 0000LST and 0900 LST whereas GSMaP observed these peaks at 0000 LST and 1800 LST.

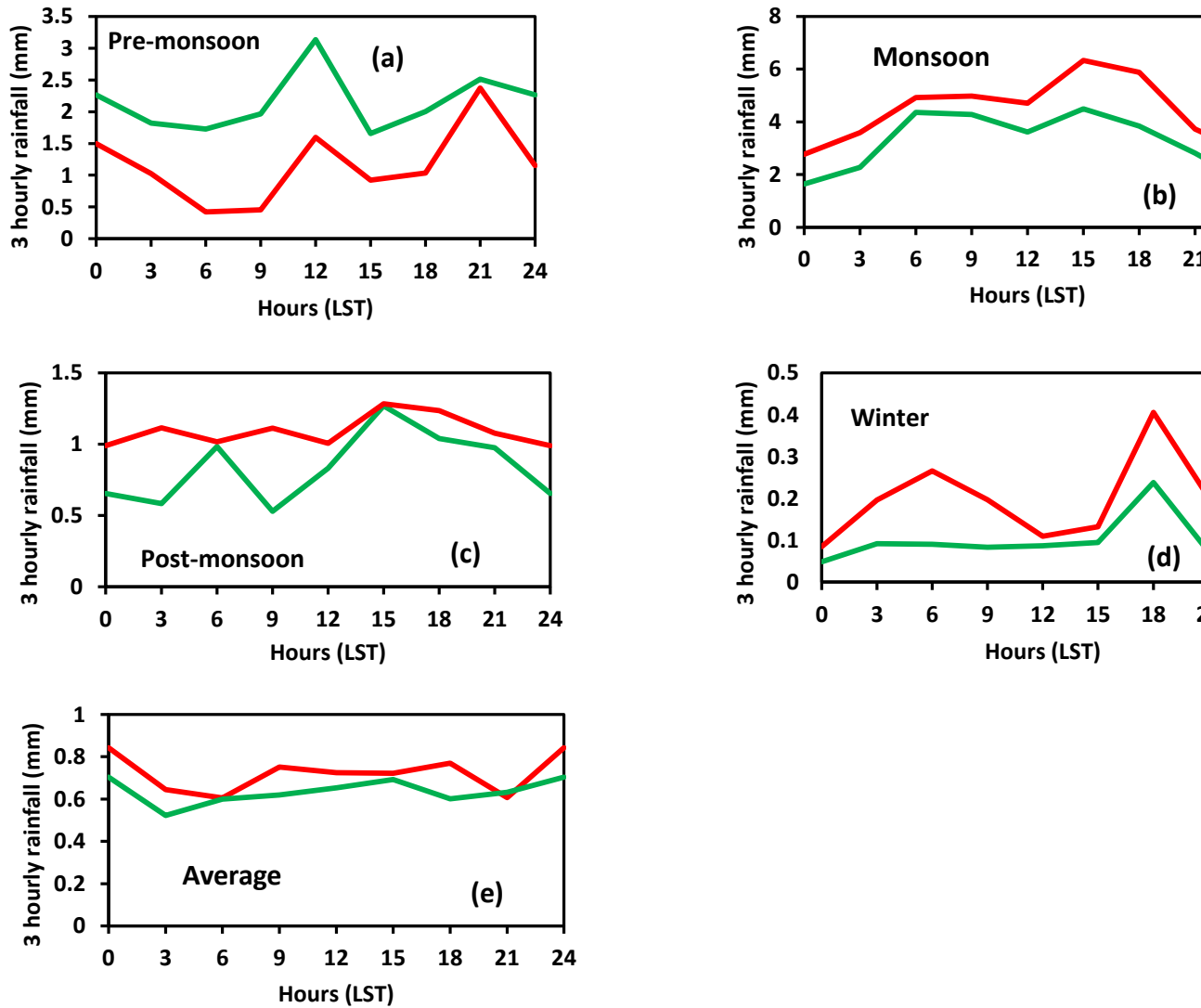


Figure 4.44: Seasonal and yearly average diurnal variation of rainfall of Sathkhira.

### Sitakunda

In figure 4.45 (a), (b), (c) and (d) represent the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter season during study period. It is observed by BMD rain gauge and GSMaP Rain gauge found maximum rainfall of these seasons at 0600 LST, 0600 LST, 1500 LST and 0600 LST, respectively. On other hand GSMaP detected these peaks at 1500 LST, 0600 LST, 1500 LST and 0600 LST, respectively. In figure 4.46 (e) represents the diurnal variation of rainfall during study period of study period or yearly average. Both datasets found well matched detected a peak of maximum rainfall at 0600LST.

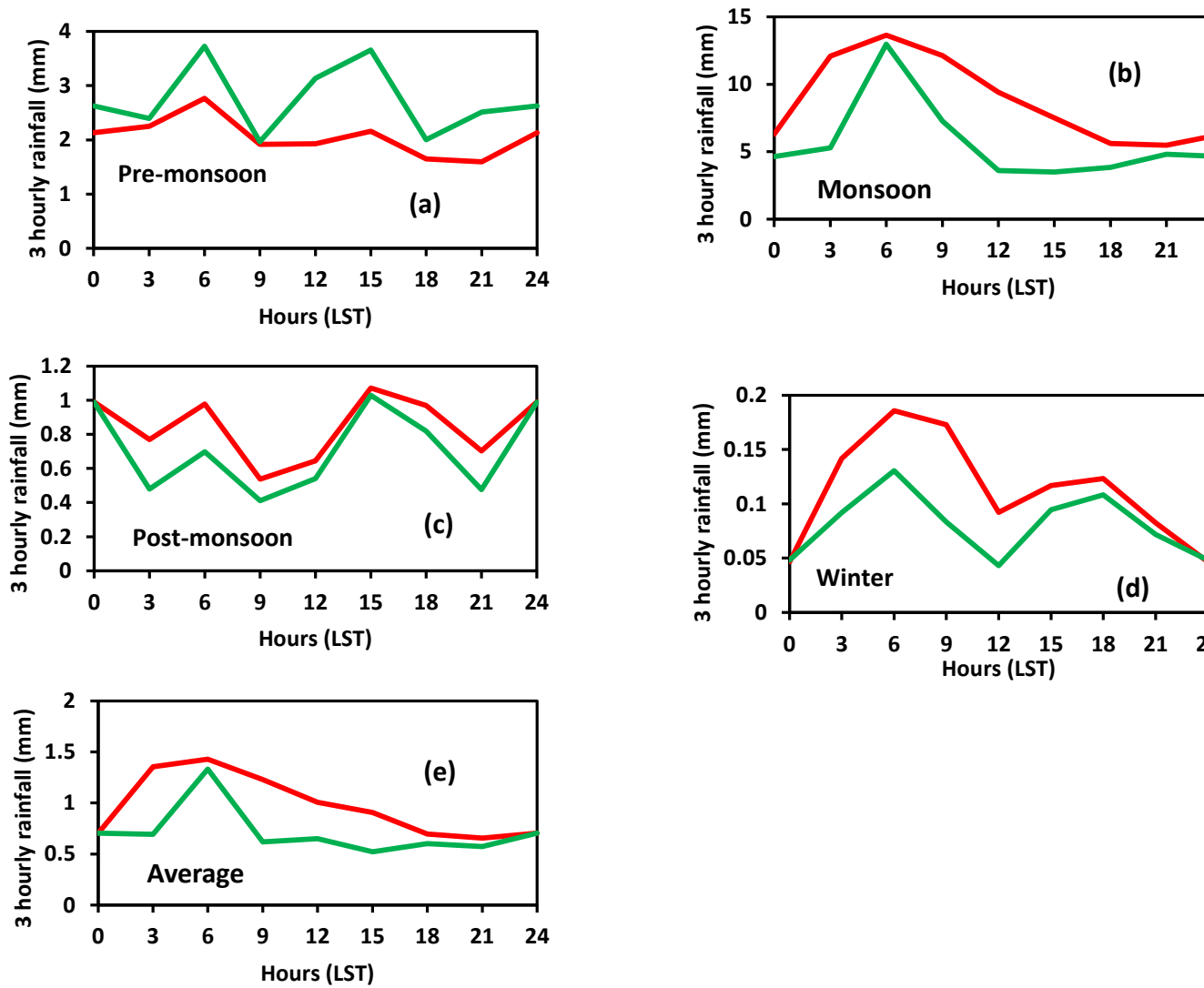
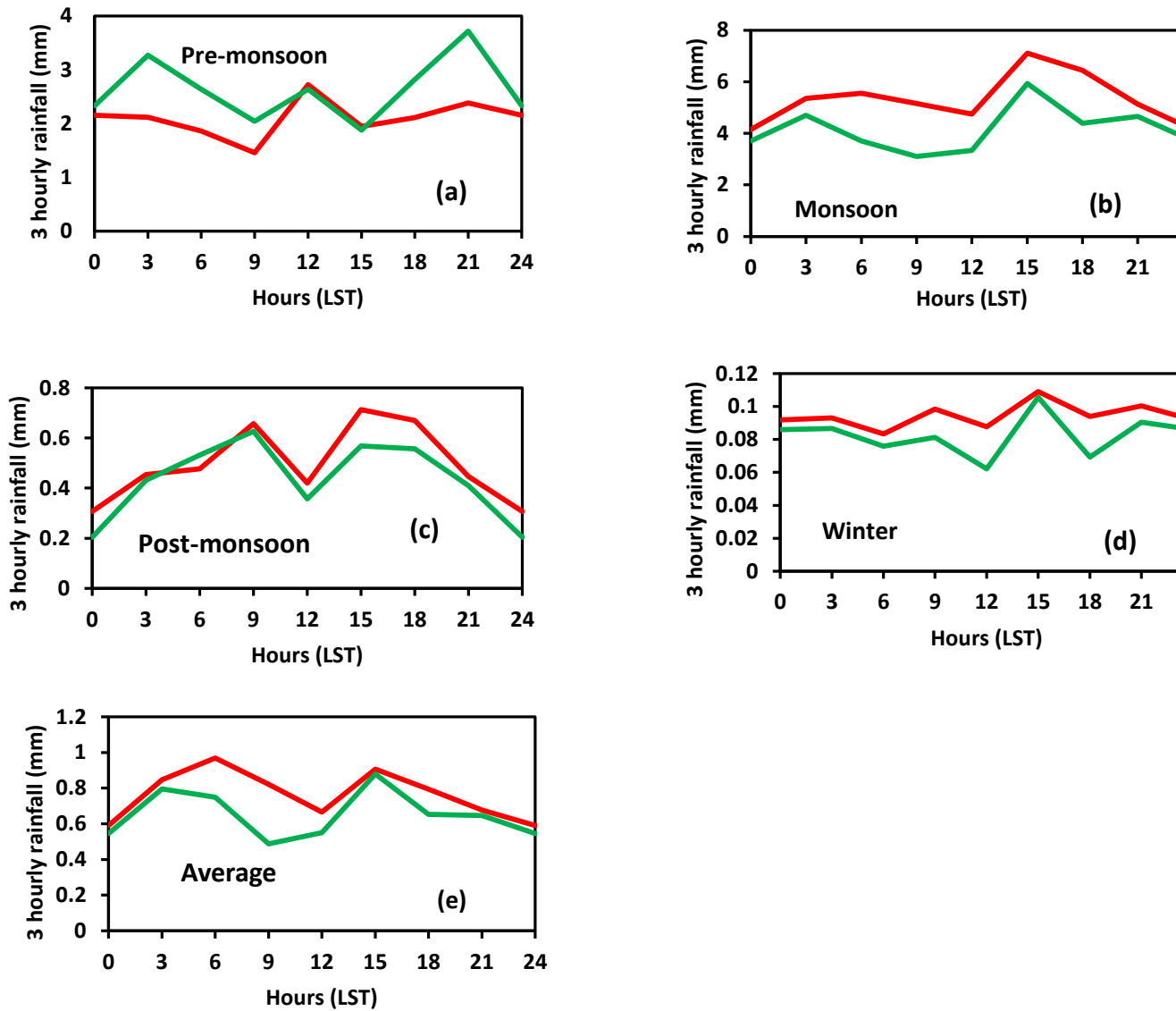


Figure 4.45: Seasonal and yearly average diurnal variation of rainfall of Sitakunda.

**Srimongal**

In figure 4.46 (a), (b), (c) and (d) represents the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter season during study period. It is observed by BMD rain gauge and GSMaP Rain gauge found maximum rainfall of these seasons at 2100 LST, 1500 LST, 1500 LST and 1500 LST, respectively. On other hand GSMaP detected these peaks at 1200 LST, 1500 LST, 0900 LST and 1500 LST, respectively. In figure 4.47 (e) represents the diurnal variation of rainfall during study period or yearly average of Srimongal. Rain gauge detected twin peak of maximum rainfall at 1500LST and 0600 LST whereas GSMaP found these peaks at 1500 LST and 0300 LST.



**Figure 4.46:** Seasonal and yearly average diurnal variation of rainfall of Srimongal.

### Sydpur

In figure 4.47 (a), (b), (c) and (e) represents the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter season during study period. It is observed by BMD rain gauge and GSMaP. Rain gauge found maximum rainfall of these seasons at 0000 LST, 0600 LST, 0300 LST and 0600 LST, respectively. On other hand GSMaP detected these peaks at 0900 LST, 0300 LST, 0300 LST and 0600 LST. In figure 4.48 (e)

represents the diurnal variation of rainfall during study period or yearly average of Sydpur. Both datasets detected well matched twin peak of maximum rainfall at 0000LST and 0600 LST.

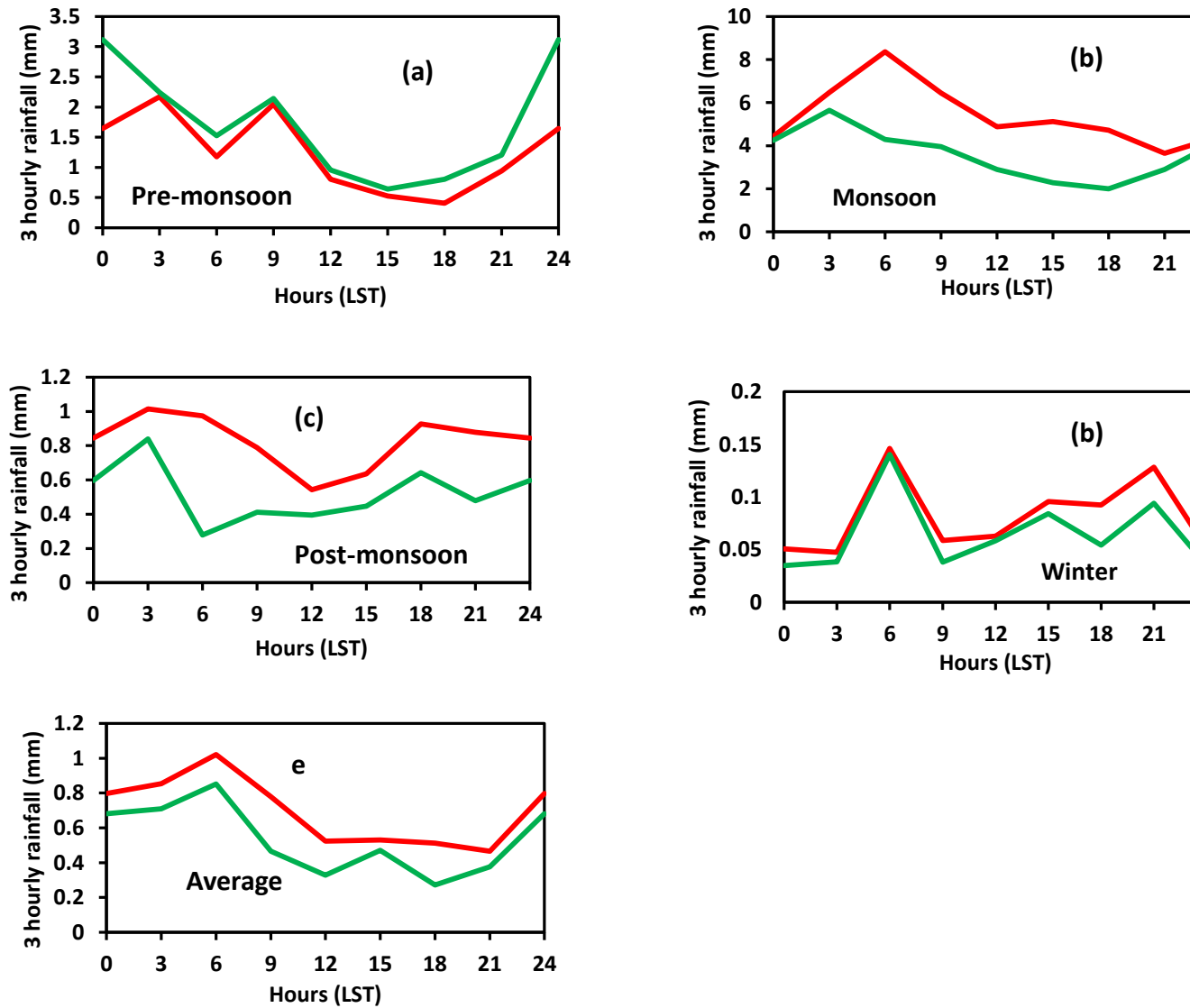


Figure 4.47: Seasonal and yearly average diurnal variation of rainfall of Sydpur.

### Sylhet

In figure 4.48 (a), (b), (c) and (d) represents the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter season during the study period. It is observed by



BMD rain gauge and GSMaP. Rain gauge found maximum rainfall of these seasons at 0000 LST, 0300 LST, 0900 LST and 1200 LST, respectively. On other hand GSMaP observed these peaks at 2100 LST, 0300 LST, 0900 LST and 1200 LST, respectively. In Figure 4.49 (e) represents the diurnal variation of rainfall of Sylhet during study period or yearly average. Rain gauge detected dual peak of maximum rainfall at 0600LST and 0300 LST whereas GSMaP detected these peaks at 0000 LST and 0300 LST.

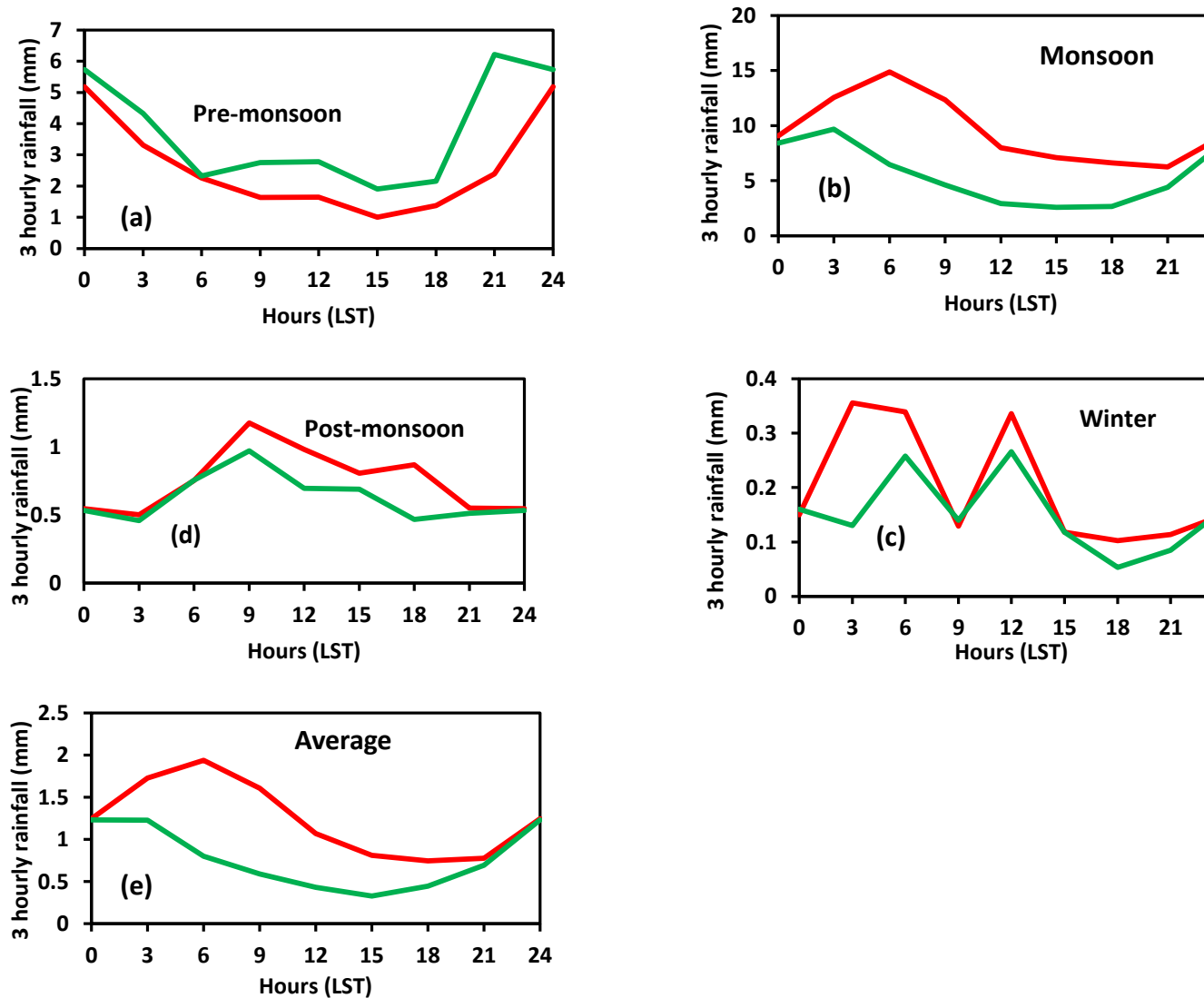


Figure 4.48: Seasonal and yearly average diurnal variation of rainfall of Sylhet.

### Tangail

In figure 4.49 (a), (b), (c) and (d) represents the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter season during study period. Rain gauge found maximum rainfall of these seasons at 2100 LST, 1500 LST, 1500 LST and 1800 LST, respectively. On other hand GSMaP observed these peaks at 2100 LST, 1500 LST, 1500 LST and 1800 LST, respectively. In Figure 4.50 (e) represents the diurnal variation of rainfall during study period or yearly average of Tangail. Rain gauge detected a couple peak of maximum rainfall at 1500LST and 0600 LST whereas GSMaP observed these peaks at 1800 LST and 1500 LST.

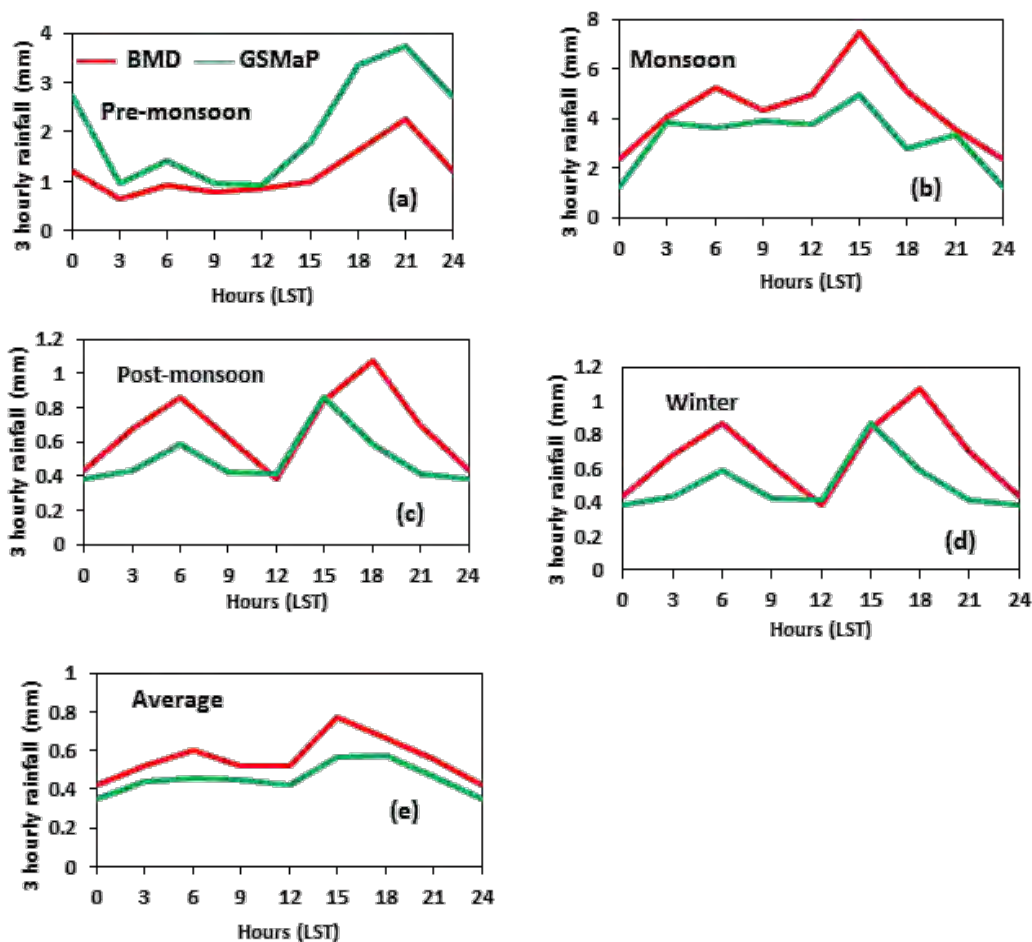
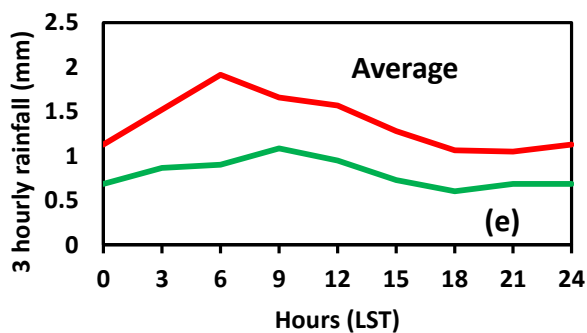
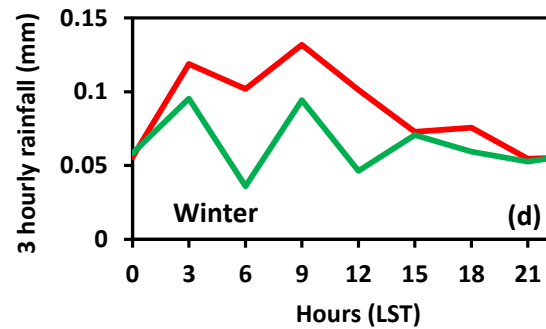
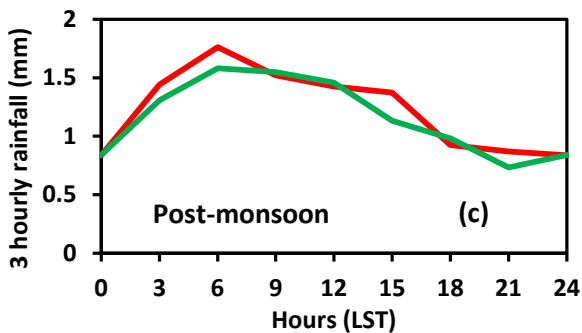
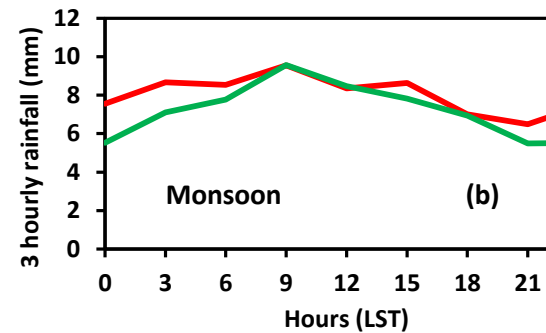
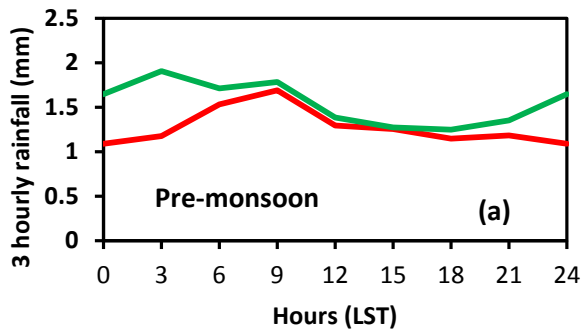


Figure 4.49: Seasonal and yearly average diurnal variation of rainfall of Tangail.

**Teknaf**

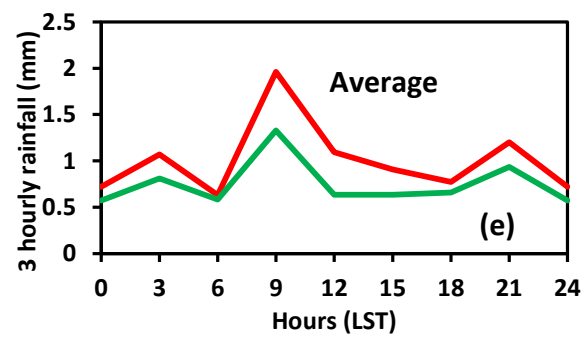
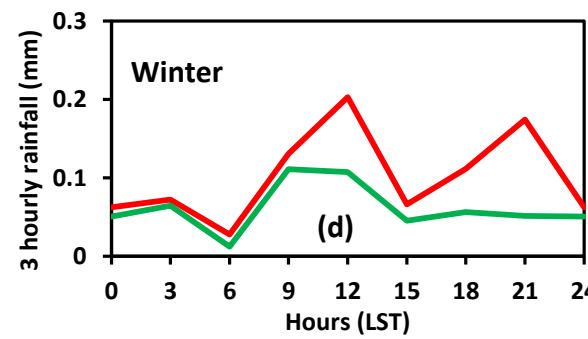
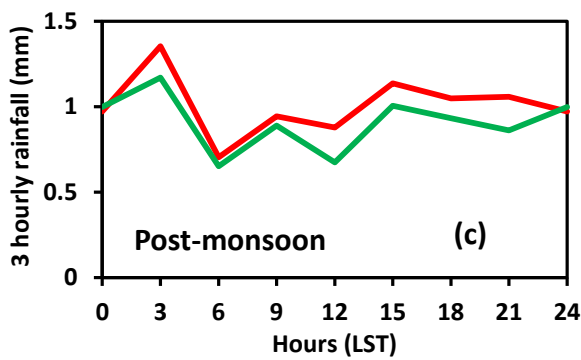
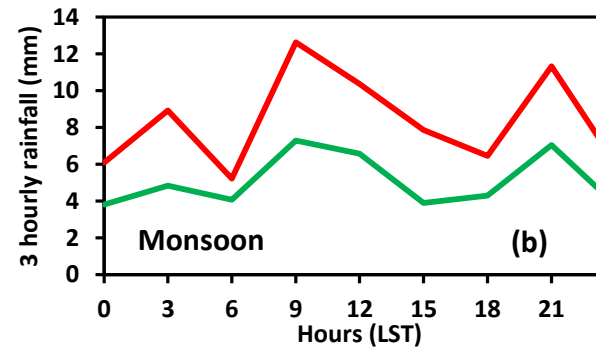
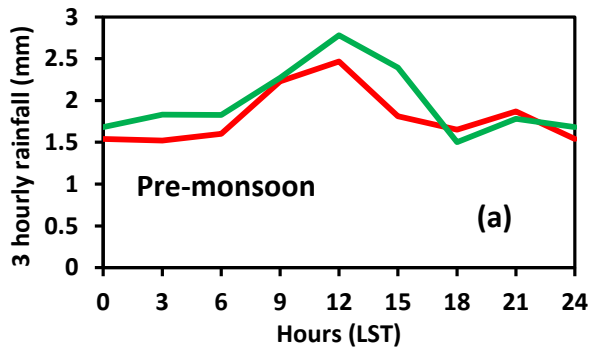
In figure 4.50(a), (b), (c) and (d) represents the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter season during the study period. Rain gauge found maximum rainfall of these seasons at 0900 LST, 0600 LST, 0900 LST and 0900 LST, respectively. On other hand GSMaP observed these peaks at 0300 LST, 0900 LST, 0600 LST and 0900 LST, respectively. In Figure 4.51 (e) represents the diurnal variation of rainfall during study period or yearly average of Teknaf. It is observed by BMD rain gauge and GSMaP. Rain gauge detected dual vertex of maximum rainfall at 0600LST and 1200 LST whereas GSMaP found these vertex at 0900 LST and 0300 LST.



**Figure 4.50:** Seasonal and yearly average diurnal variation of rainfall of Teknaf.

**Ambagan**

In figure 4.51 (a), (b), (c) and (d) represents the diurnal variation of pre-monsoon, monsoon, post-monsoon and winter during the study period and also found well matched maximum rainfall of these seasons at 1200 LST, 0900 LST, 0300 LST and 1200 LST, respectively. It is observed by BMD rain gauge and GSMaP. In figure 4.52 (e) represents the diurnal variation of rainfall during study period or yearly average of Ambagan. Both dataset detected twin peak of maximum rainfall at 0900 LST and 2100 LST.



**Figure 4.51:** Seasonal and yearly average diurnal variation of rainfall of Ambagan.

From 35 rain measurement station, it is found most of the station shows Maritime or coastal type of diurnal variation of rainfall which associated to generate the maximum rainfall at late-evening to early morning hours. Elsewhere, a very few stations such as Bogra, Chuadanga, Comilla, Dhaka, Dinajpur, Rajshahi showed maximum rainfall at noon to post-noon period are identified as Inland or Continental type of diurnal variation of rainfall, which may involve of thermal properties of surface. In Bangladesh most of the rain measurement station is situated at coastal area and also some station at hilly region which leads to originate the Maritime properties of diurnal cycle. Houze et al. [69] discussed the offshore rainfall during early morning, and propose that the onset of offshore rainfall due to a convergence of land breeze and low-level monsoon flow. This mechanism might explain the early morning windward rainfall, although the atmospheric structure was different. Because early morning rainfall was found only over the windward side of the mountain ranges, the mountain breezes may contribute to the local circulation in this region.

Kataoka and Satomura [70] used a three-dimensional cloud-resolving model to suggest a possible mechanism for a nocturnal rainfall system in Bangladesh, although the onset and peak times of their simulated rainfall were somewhat different from the early morning rainfall maxima. The rainfall system in their study developed during the night, due to greater atmospheric instability at night than during the day. The katabatic winds are considered a major candidate for the rainfall mechanism. Our station wise results revealed that the diurnal variations of rainfall over Bangladesh showed two distinct peaks.

## CHAPTER FIVE

### SUMMARY AND CONCLUSIONS

To study the diurnal variation of rainfall and the possibility to use of GSMaP data in and around Bangladesh, hourly GSMaP data of spatial resolution of 0.1 degree by 0.1 degree and three hourly rain gauge data of 35 stations of Bangladesh Meteorological Department (BMD) are analyzed. Daily, monthly, seasonal and yearly diurnal variations of rainfall are studied. The spatial distributions of occurrence of the maximum rainfall for different seasons are also studied during the period 2001-2015.

It is found that GSMaP data is well correlated with BMD rain gauge data. The 3-hourly, daily, monthly and yearly correlation coefficients between GSMaP and rain gauge data are 0.71, 0.74, 0.82 and 0.66, respectively. The standard deviation of 3-hourly, daily, monthly and yearly data of BMD rain gauge data is 2.01 mm, 10.87 mm, 201.44 mm and 233.20 mm, respectively on other hand GSMaP found this value 1.92 mm, 9.77 mm, 156.67 mm and 297.03 mm. The Root Means Square Error of 3-hourly, daily, monthly and yearly data between both dataset is 4.56 mm, 7.62 mm, 91.08 mm and 492.04 mm, respectively.

Daily average rainfall analysis showed that GSMaP overestimated during pre-monsoon and underestimated during monsoon compared to BMD rain gauge for the period 2001-2015.

Monthly diurnal variation of rainfall during study period between GSMaP and BMD rain gauge showed that maximum rainfall occurred in late night (0300 LST) during January and February whereas March to May maximum rainfall peak found between 1200 LST to 1500 LST by both datasets. Rain gauge observed two maximum rainfall peak from June to September; one in the morning (0600 LST) other at afternoon (1500 LST) whereas GSMaP observed at late night (0300 LST) and afternoon (1500 LST). In October, maximum rainfall peak found between 1200 to 1500 LST by both datasets. In

November and December maximum rainfall peak found by both datasets at 0300 LST. It is may be a periodicity of rainfall in and around Bangladesh.

From seasonal diurnal variation of rainfall it is found well matched twin peaks of the maximum rainfall at 1500 LST and 1800 LST by both datasets in the pre-monsoon season. During monsoon season rain gauge detected two maximum rainfall peaks at 0600 LST and 1500 LST elsewhere GSMaP at 0300 LST and 1500 LST. In post-monsoon season, both datasets found well matched dual peaks at 0600 LST and 1500 LST. In winter season, both datasets detected only one peak of maximum rainfall at 0300 LST.

Diurnal variation of yearly rainfall during study period showed two peaks of maximum rainfall. Rain gauge detected maximum rainfall at 0600 LST and 1500 LST whereas GSMaP found these peaks at 0300 LST and 1500 LST but hourly data of GSMaP showed the peaks of rainfall at 0400 LST and 1500 LST.

In dry region, both datasets found well matched maximum rainfall at 0600 LST and 1500 LST. On other hand in wet region, both datasets found well matched maximum rainfall at 0300 LST and 0900 LST.

From spatial analysis of pre-monsoon season; central, coastal and southern part of the country experiences maximum occurrence time of rainfall from 1200 to 1500 LST elsewhere eastern and north eastern at 0600 to 0900 LST. In monsoon and post-monsoon season central, coastal and southern part of country receives maximum rainfall from 1200 to 1500 LST whereas eastern and north eastern at 0600 to 0900 LST. Spatial analysis of rainfall during study period showed that the maximum rainfall occur in the north and northeastern part of the country at 0300 to 0600 LST. Central, coastal and southeastern of the country receive maximum rainfall at 1500 LST, 1200 LST and 1800 LST, respectively. From Yearly average it is found that north and north-eastern part of the country experienced maximum rainfall at 0300-0600 LST whereas central and southern part of the country at 1200-1500 LST but coastal part of Chittagong at 1800 LST.



From station wise diurnal variation of rainfall we found, most of the stations observed two maximum rainfall vertex and a few stations found one peak of maximum rainfall during study period. Most of station showed continental type during pre-monsoon and post-monsoon season whereas during monsoon and winter season most of the station shows maritime type diurnal properties.

Several types of analysis between GSMaP and BMD rain gauge data over Bangladesh shows that GSMaP has lower bias. So, GSMaP data might be useful for different meteorological purpose in Bangladesh.

## REFERENCE

- [1] Matsunoto, J., “Synoptic features of heavy monsoon rainfall on 1987 related to the severe floods in Bangladesh”, *Bulletin of the Department of Geography*, University of Tokyo, Vol. 20, pp. 43-56, 1988.
- [2] Yin, S., Chen, D., and Xie, Y., “Diurnal variations of precipitation during the warm season over China”, *International Journal of Climatology*, Vol. 29 (8), pp. 1154-1170, doi: 10.1002/joc, 2008.
- [3] Basu, B. K., “Diurnal Variation in Precipitation over India during the Summer Monsoon Season: Observed and Model Predicted”, *Monthly Weather Review*, Vol. 135, pp. 2155-2167, doi: 10.1175/MWR3355.1, 2007.
- [4] <http://www.publishyourarticles.net/knowledge-hub/articles/brief-notes-on-diurnal-variation-of-precipitation/2993>, last access time: at 10 pm on 20 May 2017.
- [5] Yang, S. and Smith, E. A., “Mechanisms for Diurnal variability of Global Tropical Rainfall observed TRMM”, *Journal of Climate*, Vol. 19, pp. 5190-5226, 2006.
- [6] Iliston, B. G., Basara, J. B. and Crawford, K. C., “Seasonal to Inter-annual Variations of Soil Moisture Measured in Oklahoma”, *International Journal of Climatology*, Vol. 24, pp. 1883-1996, 2004.
- [7] Souza, B. B. D. and Rocha, E. J. P. D., “Diurnal variation of rainfall in Braganca-PA (Eastern Amazon) during rainy season: mean characteristics and extreme events”, *Revista Brasileira de Meteorologia*, Vol. 21, pp. 142-152, 2006.
- [8] Warner, T. T., Mapes, R. E. and Xu, M., “Diurnal patterns of rainfall in northwestern South America. Part II: Model simulations”, *Monthly Weather Review*, Vol. 131, pp. 813-829, 2003.
- [9] Nesbitt, S. W. and Zipser, E. J., “The diurnal cycle of rainfall and convective intensity according to three years of TRMM measurements”, *Journal of Climate*, Vol. 16, pp. 1456-1475, 2003.
- [10] Islam, M. N., Hayashi, T., Terao, T., Uyeda, H., and Kikuchi, K., “Characteristics of precipitation system analyzed from radar data over Bangladesh”, *Journal of Natural Disaster Science*, Vol. 27, pp. 17-23, 2005.

- [11] Wahid, C. M. and Islam, M. N., “Patterns of rainfall in the northern part of Bangladesh”, *Bangladesh Journal of Science and Research*, Vol. 17 (1) pp. 115-120, 1999.
- [12] Azam, A. T. M. S., “Study of Extreme rainfall in Bangladesh using Tropical Rainfall Measuring Mission Data”, M. Phil Thesis, June 2015, BUET, Bangladesh.
- [13] Bhuiyan, M. T. H., Bhuyan, M. D. I., Chowdhury, M. N., Wahid, C., and Faruque, S. B., “Characteristics of Diurnal Variation of Summer Monsoon Rainfall over Bangladesh and its Adjacent Areas”, *Journal of Emerging Trends in Engineering and Applied Sciences*, Vol. 5(3), pp. 217-221, 2014.
- [14] Terao, T., Islam, M. N., Hayashi, T., and Oka, T., “Nocturnal jet and its effects on early morning rainfall peak over northeastern Bangladesh during summer monsoon season”, *Geographical Research Letters*, Vol. 33, pp. L18806, doi: 10.1029/2006GL026156, 2006.
- [15] Islam, M. N., Hayashi, T., Uyeda, H., Terao, T., and Kikuchi, K., “Diurnal variation of cloud activity in Bangladesh and north of the Bay of Bengal in 2000”, *Remote Sensing and Environment*, Vol. 90, pp. 378-388, 2004.
- [16] Sing, P., and Nakamura, K., “Diurnal variation in summer monsoon precipitation during active and break periods over central India and southern Himalayan foothill”, *Journal of Geophysical Research*, Vol. 115, pp. D12122, doi: 10.1029/2009JD012794, 2010.
- [17] Chen, S. S. and House, R. A., “Diurnal variation and life-cycle of deep convective systems over the tropical Pacific warm pool”, *Quarterly Journal Royal Meteorology Society*. Vol.123, pp. 357-388, 1997.
- [18] Kataoka, A., and Satomura, T., “Numerical simulation on the diurnal variation of precipitation over northeastern Bangladesh: A case study of an active period 14-21 June 1995”, *Scientific Online Letters on the Atmosphere*, Vol. 1, pp. 205–208, 2005.
- [19] Deshpande, N. R. and Goswami, B. N., “Modulation of the diurnal cycle of rainfall over India by intra-seasonal variations of Indian summer monsoon”, *International Journal of Climatology*, Vol. 34(3), pp. 793-807, doi:10.1002/joc.3719, 2013.
- [20] Shrestha, D., and Deshar, R., “Spatial Variations in the Diurnal Pattern of Precipitation over Nepal Himalayas”, *Nepal Journal of Science and Technology*, Vol. 15, pp. 57-64, 2014.

- [21] Ray, K., Warsi, A. H., Warsi, S. C. and Jaswal, A. K., “Diurnal variations in rainfall over Indian region using self-recording rain gauge data”, *Current Science*, Vol.110, pp. 682-686, 2016.
- [22] Bharti, V., and Singh, C., “Diurnal variations of seasonal rainfall over the state of Himachal Pradesh as observed by Satellite data”, *Asian Journal of Geoinformatics*, Vol. 16, pp. 1-7, 2016.
- [23] Sahany, S., Venugopal, V., and Nanjundiah, R. S., “Diurnal-scale signatures of monsoon rainfall over the Indian region from TRMM satellite observations”, *Journal of Geophysical Research*, Vol. 115, pp. D02103, and DOI: 10.1029/2009JD012644, 2010.
- [24] Limsakul, A., Humphries, U., Wangwongchai, A., Chitsuphaphan, T and Wongwises, P., “ Diurnal Variations in Summer Monsoon Precipitation over Thailand and Its Vicinity Observed from Ten Years of TRMM Data”, *Journal of Sustainable Energy & Environment*, Vol. 5, pp. 13-19, 2014.
- [25] Yu, R., Zhou, T., Xiong, A., Zhu, Y. and Li. J., “Diurnal variations of summer precipitation over contiguous China”, *Geophysical Research Letters*, Vol. 34, pp. L01704, doi: 10.1029/2006GL028129, 2007.
- [26] Mori, S., Jun-chu, H., Tauhid, Y. I., and Yamanka, M. D., “Diurnal Land–Sea Rainfall Peak Migration over Sumatera Island, Indonesian Maritime Continent, Observed by TRMM Satellite and Intensive Rawinsonde Soundings”, *Monthly Weather Review*, Vol. 21, pp. 2021-2039, 2004.
- [27] Begum, S., and Alam, M. S., “Climate Change Impact on Rainfall over Bangladesh for Last Decades”, *International Journal of Open Scientific Research*, Vol. 1(4), pp. 1-8, 2013.
- [28] Takahashi, H. G., Fujinami, H., Yasunari, T., and Matsumoto, J., “Diurnal rainfall pattern observed by Tropical Rainfall Measuring Mission Precipitation Radar (TRMM-PR) around the Indochina peninsula”, *Journal of Geophysical Research*, Vol. 115, D07109, doi: 10.1029/2009JD012155, 2010.
- [29] Saha, U., “Diurnal Rainfall Variation of Bangalore HAL Airport”, *The International Journal of Innovative Research in Science, Engineering and Technology*, Vol. 4, (9), pp. 63-68, 2015.

- [30] Zardi, D., and Whiteman, C. D., “Diurnal mountain wind systems, Mountain Weather Research and Forecasting”, *Springer Atmospheric Sciences publications*, doi: 10.1007/978-9 007-4098-3 2, 2012.
- [31] Barros, A. Joshi, P., Putkonen, J. M., and Burbank, D. W., “A study of the 1999 monsoon rainfall in a mountainous region in central Nepal using TRMM products and rain gauge observations”, *Geophysical Research Letters*, Vol. 27(22), pp. 3683-3686, 2000.
- [32] Barros, A., Joshi, P., and Lang, T., “Monitoring the monsoon in the Himalayas: Observations in central Nepal”, *Monthly Weather Review*, Vol. 131, pp. 1408–1427, 2003.
- [33] Bhatt, B. C., and Nakamura, K., “Characteristics of Monsoon Rainfall around the Himalayas Revealed by TRMM Precipitation Radar”, *Monthly Weather Review*, Vol.133 (1), pp. 149-165, 2005.
- [34] Varikoden, H., Preethi, B., and Revadekar, J. V., “Diurnal and spatial variation of Indian summer monsoon rainfall using tropical rainfall measuring mission rain rate”, *Journal of Hydrology*, Vol. 475, pp. 248–258, 2012.
- [35] Houze Jr., R. A., “Orographic effects on precipitating clouds”, *Review of Geophysics*, Vol. 50, pp. 365-412, doi: 10.1029/2011RG000365, 2012.
- [36] Lang, T., and Barros, A. P., “An investigation of the onsets of the 1999 and 2000 monsoons in Central Nepal,” *Monthly Weather Review*, Vol.130, pp.1299–1316, 2002.
- [37] Biasutti, M., Yuter, S. E., Burleyson, C. D., and Sobel, A. H., “Very high resolution rainfall patterns measured by TRMM precipitation radar: seasonal and diurnal cycles”, *Climate Dynamics*, Vol. 39, pp. 239–258, doi: 10.1007/00382-011-1146-6, 2012.
- [38] Dai, A., “Global Precipitation and Thunderstorm Frequencies. Part I: Seasonal and Interannual Variations”, *Journal of Climate*, Vol. 14, pp. 1092–1111, 2011.
- [39] Liu, X., Bai, A., and Liu, C., “Diurnal variations of summertime precipitation over the Tibetan Plateau in relation to orographically induced regional circulations”, *Environment Research Letter*, Vol. 4, pp. 045203-045203, doi:10.1088/1748-9326/4/4/045203, 2009.
- [40] Yin, S., Li, W., Chen, D., Jeong, J. H., and Guo, W., “Diurnal variations of summer precipitation in the Beijing area”, *Advance Atmospheric Science*, Vol. 28(4), pp.725–734, doi: 10.1007/s00376-010-9240-y, 2011.

- [41] Nesbitt, S. W., and Zipser, E. J., “The Diurnal Cycle of Rainfall and Convective Intensity according to Three Years of TRMM Measurements”, *Journal of Climate*, Vol. 16, pp.1456–1475, 2003.
- [42] [http://en.banglapedia.org/Geography\\_of\\_Bangladesh](http://en.banglapedia.org/Geography_of_Bangladesh), last access time: at 11pm on 20 May 2017.
- [43] Rashid, H. E., 1991, “Geography of Bangladesh (*Second Revised Edition*)”, *The University Press Ltd.*, Dhaka, Bangladesh.
- [44] Devkota, L. P., “Rainfall over SAARC region with special focus on tele-connections and long range forecasting of Bangladesh monsoon rainfall, monsoon forecasting with a limited area numerical weather prediction system,” *Published by SAARC Meteorological Research Centre*, Report No-19, Dhaka, Bangladesh, 2006.
- [45] Prasad, K., “Monsoon Forecasting using Numerical Weather prediction Guidance”, SAARC Meteorological Research Centre, Report No. 11, 2005.
- [46] Shahid, S., “Rainfall variability and the trends of wet and dry periods in Bangladesh”, *International Journal of Climatology*, Vol. 30, pp. 2299–2313, 2010.
- [47] Sanderson, M., and Ahmed, R., “Pre-monsoon rainfall and its variability in Bangladesh: a trend surface analysis”, *Hydrological Sciences-Bulletin-des Sciences Hydrologique*, Vol. 24(3), pp. 277 – 287, 1979.
- [48] <https://www.skymetweather.com/content/weather-news-and-analysis>, last access time: at 03 pm on 21 May 2017.
- [49] <https://www.quora.com/What-are-pre-monsoon-showers-and-what-are-its-features>, last access time: at 04 pm on 21 May 2017.
- [50] [www.panahon.tv/blog/2014/09](http://www.panahon.tv/blog/2014/09), last access time: at 05 pm on 21 May 2017.
- [51] Basu, B. K., “Diurnal Variation in Precipitation over India during the Summer Monsoon Season: Observed and Model Predicted”, *Monthly Weather Review*, Vol. 135, pp.2155-2167, doi: 10.1175/MWR3355.1, 2007.
- [52] Woolnough, S. J., J. M. Slingo, and Hoskins, B. J., “The diurnal cycle of convection and atmospheric tides in an aqua-planet GCM”, *Journal of Atmospheric Science*, Vol. 61, pp. 2559–2573, 2004.
- [53] Terao, T., Islam, M. N., Hayashi, T., and Oka, T., “Nocturnal jet and its effects on early morning rainfall peak over northeastern Bangladesh during summer monsoon season”,

- Geographical Research Letters*, Vol. 33, pp. L18806, doi: 10.1029/2006GL026156, 2006.
- [54] Islam, M. N. and Uydea, H., “Vertical variation of rain intensity in different rainy periods in and around Bangladesh”, *International Journal of Climatology*, Vol. 30, pp. 1024-1055, doi: 10.1002/joc.1585, 2008.
- [55] Banglapedia, “National Encyclopaedia of Bangladesh”, *Asiatic Society of Bangladesh: Dhaka*, 2003.
- [56] Rana, M., Shafee, S and Karmaker, S., „Estimation of rainfall in Bangladesh by using Southern Oscillation Index”, *Journal of Meteorology*, Vol. 4 (7), pp. 7-23, 2007.
- [57] Islam, M. N. and Uydea, H., „Comparison of TRMM 3B42 products with surface rainfall over Bangladesh”, In *Preprints in the Proceedings of International Geoscience and Remote Sensing Symposium*, Seoul, South Korea, July 25-29, 2005.
- [58] Islam, M. N., and Uyeda, H., “Use of TRMM in determines the climatic characteristics of all over Bangladesh”, *Remote sensing of Environment*, Vol. 108, pp. 264-274, doi: 10.1016/j.rse.2006.11.001, 2007.
- [59] Bhuiyan, M. T. H., Bhuyan, M. D. I., Chowdhury, M. N., Wahid, C., and Faruque, S. B., “Characteristics of Diurnal Variation of Summer Monsoon Rainfall over Bangladesh and its Adjacent Areas”, *Journal of Emerging Trends in Engineering and Applied Sciences*, Vol. 5(3), pp. 217-221, 2014.
- [60] Islam, M. N., and Uyeda, H., “Use of TRMM in determines the climatic characteristics of all over Bangladesh”, *Remote sensing of Environment*, Vol. 108, pp. 264-274, DOI: 10.1016.11.001, 2007.
- [61] Choudury, M. A., “Climate of Bangladesh”, Space Research and Remote Sensing Organization publications, Dhaka, Bangladesh.
- [62] Li, X. X., Koh, T. Y., Panda, J., and Norford, N. L., “Impact of urbanization patterns on the local climate of a tropical city Singapore: an ensemble study”, *Journal of Geophysical Research*, Vol. 121 (9), pp. 4386-4403 doi: 10.1002/2015JD024452, 2016.
- [63] Ahsan, M. N., Chowdhary, M. A. M., and Quadir, D. A., “Variability and Trends of Summer Monsoon Rainfall over Bangladesh”, *Journal Hydrology Meteorology*. Vol. 7, pp. 1-17, 2010.

- [64] Islam, A. K. M. S., and Hasan, M. A., “Climate induces changes of precipitation extremes over Bangladesh,” *Proceedings of 3<sup>rd</sup> International Conference on Environmental Aspects of Bangladesh*, ID 110, A3-01, Dhaka, Bangladesh, 13-14 October, 2012.
- [65] Islam, M. N. and Uydea, H., “Vertical variation of rain intensity in different rainy periods in and around Bangladesh”, *International Journal of Climatology* Vol. 30, pp. 1024-1055, doi: 10.1002/joc.1585, 2008.
- [66] Chen, S. S. and Houze, R.A., “Diurnal variation and life-cycle of deep convective systems over the tropical Pacific warm pool”, *Journal of Royal Meteorology Society*, Vol. 123, pp. 357-388, 1997.
- [67] Islam, M. N., Hayashi, T., Uyeda, H., Terao, T., and Kikuchi, K., “Diurnal variation of cloud activity in Bangladesh and north of the Bay of Bengal in 2000”, *Remote Sensing and Environment*, Vol. 90, pp. 378-388, 2004.
- [68] Oshawa, T., Hayashi, T. and Mitsuta, Y., “Interseasonal variation of monsoon activities associated with the rainfall over Bangladesh during the 1995 summer monsoon season”, *Journal of Geophysical Research*, Vol. 105, pp 29445-29459, 1998.
- [69] Houze, R., Jr., Geotis, S., Marks, F. Jr., and West, A., “Winter monsoon convection in the vicinity of North Borneo. Part I: Structure and time variation of the clouds and precipitation,” *Monthly Weather Review*, Vol. 109, pp. 1595–1614, 1981.
- [70] Kataoka, A., and Satomura, T., “Numerical simulation on the diurnal variation of precipitation over northeastern Bangladesh: A case study of an active period 14–21 June 1995,” *Scientific online letters on the atmosphere*, Vol. 1, pp. 205–208, 2005.



## **APPENDIX-1**

### **Diurnal variation of rainfall using hourly GSMaP data**

### Monthly diurnal variation of rainfall

In figure A-1 showed that monthly diurnal variation of rainfall during study period (2001-2015). Most of the rainy month especially June to September observed two rainfall maxima at 0300-0400 LST and 1500-1600 LST by GSMaP. In October and November found at 0400 and 1600 LST whereas in December, January and February observed maximum rainfall at 0000 and 2300 LST. During March and April maximum rainfall found at 1500-1600 and 2300 LST and in May at 0500 and 2300 LST.

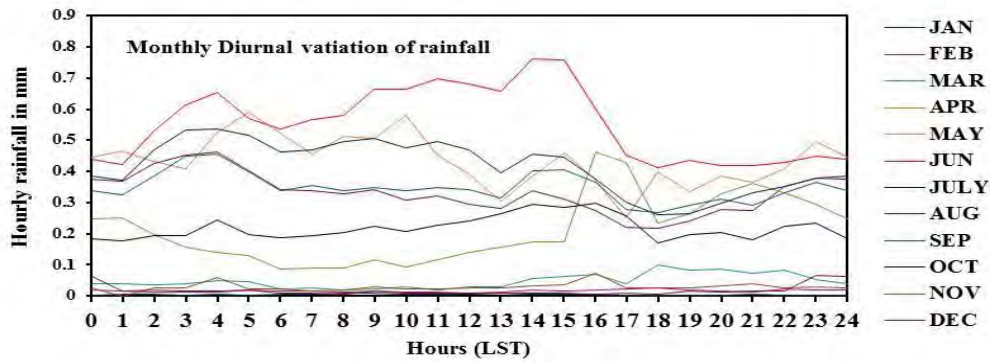


Figure A-1: Monthly diurnal variation of rainfall during study period of hourly data GSMaP.

### Seasonal diurnal variation of rainfall

Seasonal diurnal variation of rainfall during study period is represented in figure A-2 which is observed by GSMaP. In pre-monsoon season maximum rainfall occurring time at 1600 and 2300 LST. During monsoon season maximum rainfall found at 0400 and 1500 LST. Elsewhere in post-monsoon season found at 0500 and 1700 LST. In winter season at 0000 and 0500 LST.

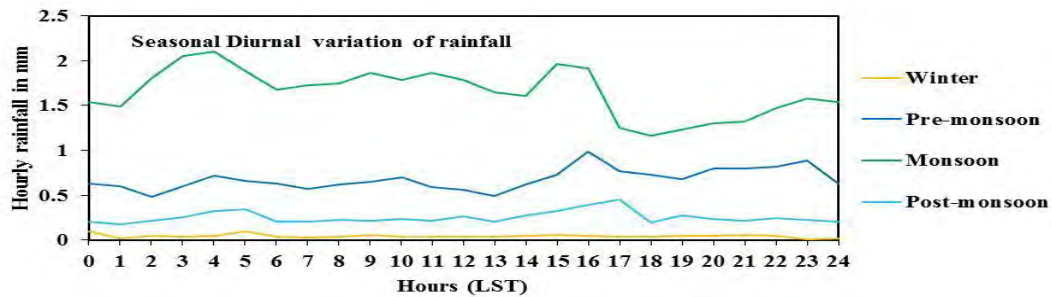


Figure A-2: Seasonal diurnal variation of rainfall during study period of hourly data of GSMaP.

### Yearly diurnal variation of rainfall

Different years of study period showed that maximum rainfall found at 0300-0400 and 1500 LST except some years which represented at figure A-3. In 2001 found at 0400 and 1800 LST. In 2004 found at 0500 and 0900 LST. In 2005 observed at 0400 and 1800 LST. In 2011, captured the peaks at 0400 and 2000 LST whereas in 2015 at 1000 and 2100 LST. The deep blue line represents the average of different years of the study period which captured maximum rainfall vertex at 0400 and 1500 or 1600 LST.

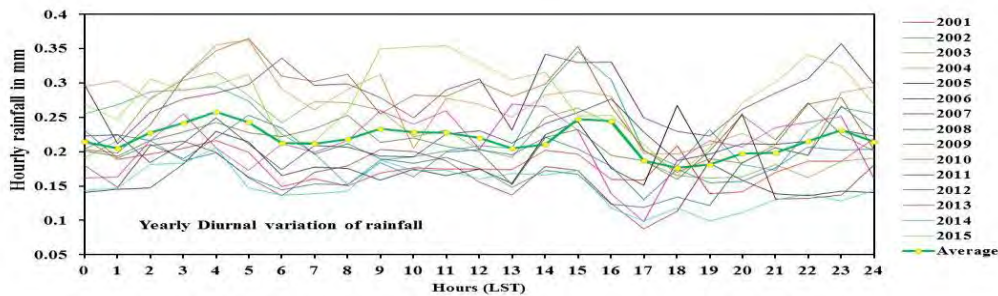


Figure A-3: Different years and yearly average of diurnal variation of rainfall during study period of hourly data of GSMaP.

### Station wise diurnal variation of rainfall of hourly data of GSMaP

## Barishal

In figure A-4 showed that diurnal variation of rainfall in Barishal which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon, winter and average of study period of Barishal station found maximum rainfall peak at 2100, 1200 1500, 1800, and 1200 LST respectively.

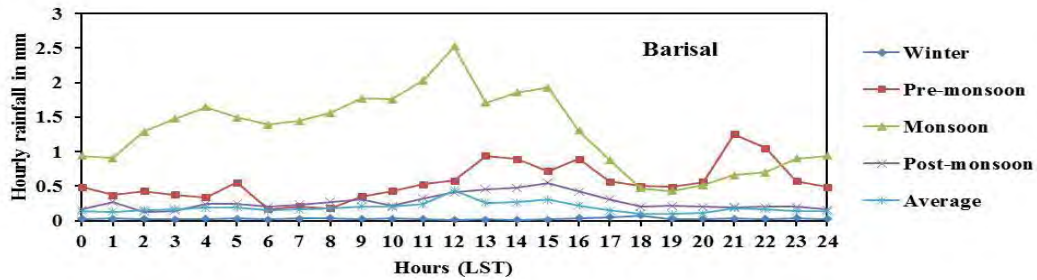


Figure A-4: Seasonal and yearly average diurnal variation of rainfall in Barishal of hourly data of GSMaP.

## Bhola

In figure A-5 showed that diurnal variation of rainfall in Bhola which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon winter and average of study period of Bhola station found maximum rainfall peak at 2200, 1500 1400, 1900, and 1300 LST respectively.

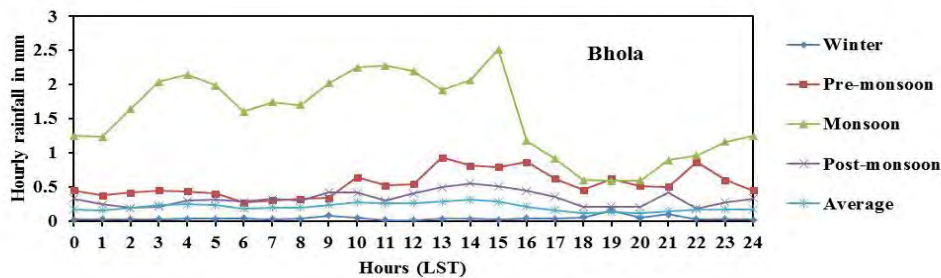
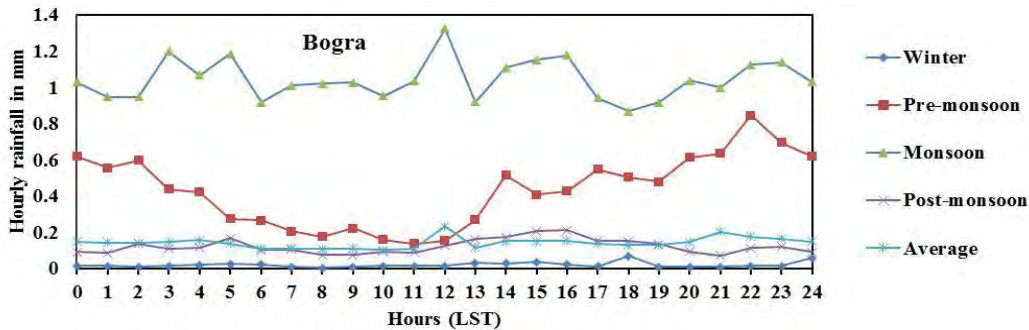


Figure A-5: Seasonal and yearly average diurnal variation of rainfall in Bhola of hourly data of GSMaP.

## Bogra

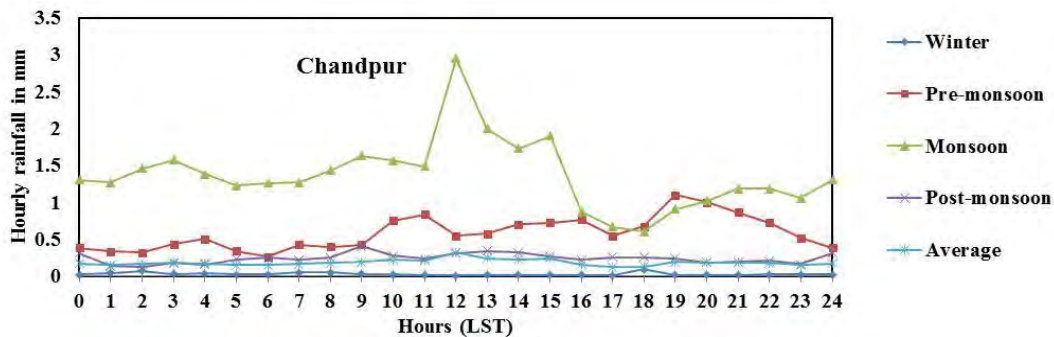
In figure A-6 showed that diurnal variation of rainfall in Bogra which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon winter and average found maximum rainfall peak at 2200, 1200 1600, 1800 LST, and 1200 LST respectively.



**Figure A-6:** Seasonal and yearly average diurnal variation of rainfall in Bogra of hourly data of GSMaP.

## Chandpur

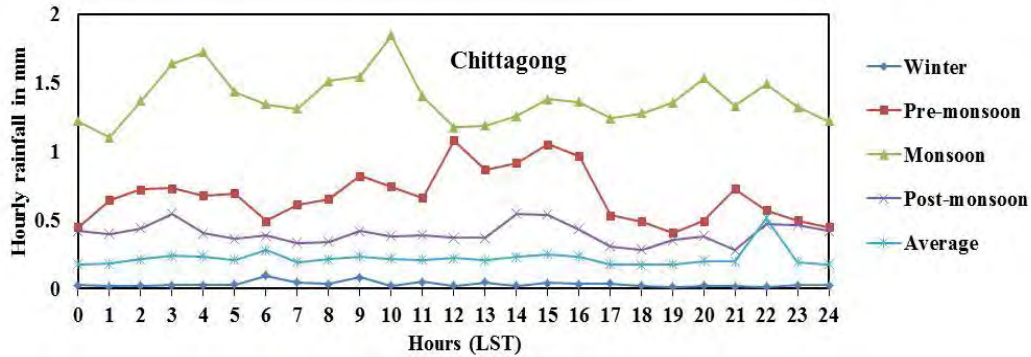
In figure A-7 showed that diurnal variation of rainfall in Chandpur which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon winter and average found maximum rainfall peak at 2200, 1200 1600, 1800 and 1200 LST, respectively.



**Figure A-7:** Seasonal and yearly average diurnal variation of rainfall in Chandpur of hourly data of GSMaP.

### Chittagong

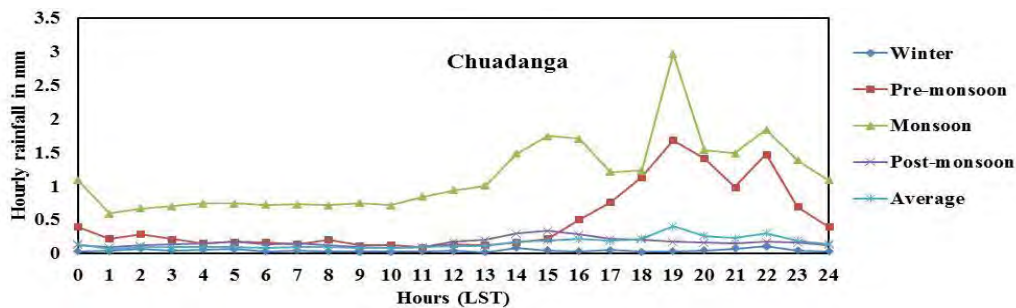
In figure A-8 showed that diurnal variation of rainfall in Chandpur which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon winter and average found maximum rainfall peak at 1200, 1000 1300, 1600 and 2200 LST, respectively.



**Figure A-8:** Seasonal and yearly average diurnal variation of rainfall in Chittagong of hourly data of GSMaP.

### Chuadanga

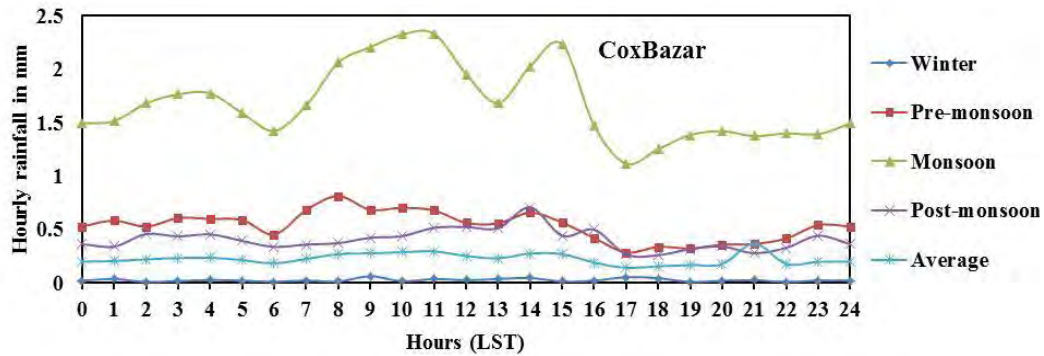
In figure A-9 showed that diurnal variation of rainfall in Chudanga which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon winter and average of study period of Chandpur found maximum rainfall peak at 1900, 1900 1400, and 1900 LST, respectively.



**Figure A-9:** Seasonal and yearly average diurnal variation of rainfall in Chuadanga of hourly data of GSMaP.

### Cox-Bazar

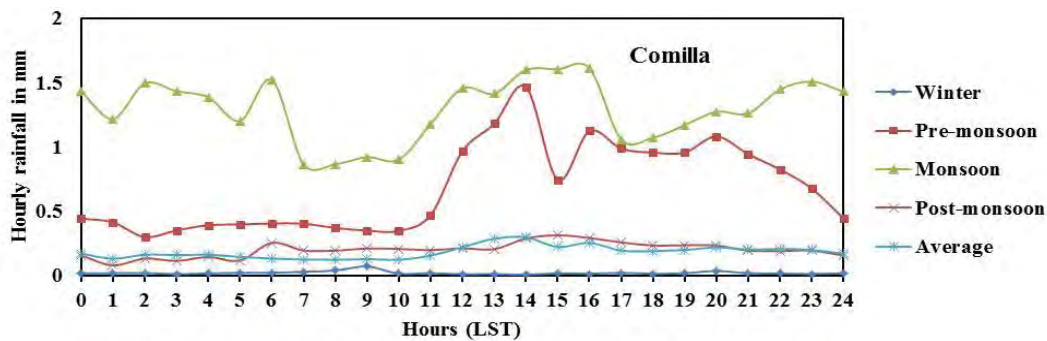
In figure A-10 showed that diurnal variation of rainfall in Cox-Bazar which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon winter and average 2100 LST found maximum rainfall peak at 0800, 1000 1400, and 1700 LST, respectively.



**Figure A-10:** Seasonal and yearly average diurnal variation of rainfall in Cox Bazaar of hourly data of GSMaP.

### Comilla

In figure A-11 showed that diurnal variation of rainfall in Comilla which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon winter found and average of study period of Comilla station maximum rainfall peak at 1400, 1600 1400, 1700 LST, and 1400 respectively.



**Figure A-11:** Seasonal and yearly average diurnal variation of rainfall in Comilla of hourly data of GSMaP.

## Dhaka

In figure A-12 showed that diurnal variation of rainfall in Dhaka which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon, winter and average of the study period of Dhaka station found maximum rainfall peak at 1900, 1400, 1500, 1700, and 1500 LST, respectively.

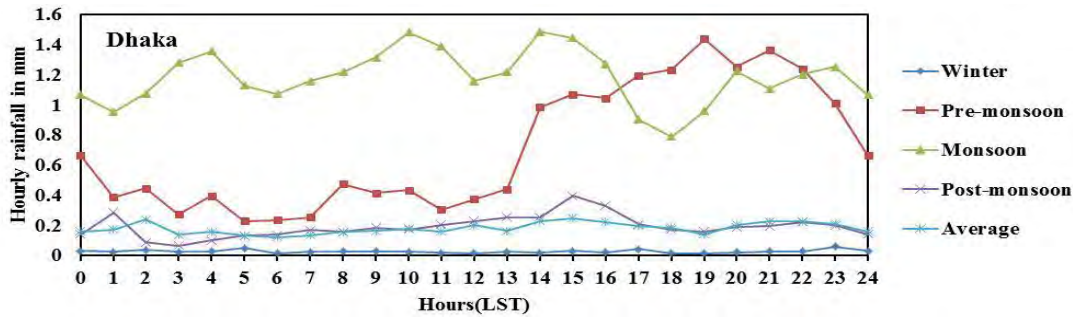


Figure A-12: Seasonal and yearly average diurnal variation of rainfall in Dhaka of hourly data of GSMaP.

## Dinajpur

In figure A-13 showed that diurnal variation of rainfall in Dinajpur which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon and winter found maximum rainfall peak at 1200, 1200 1200, 1700 and 1200 LST, respectively.

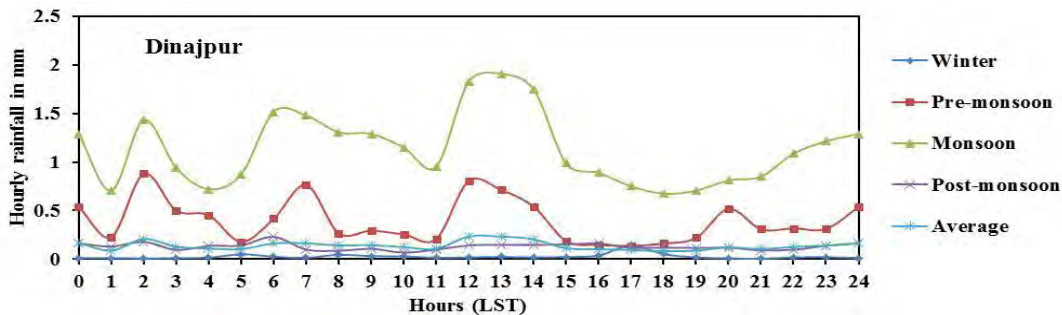
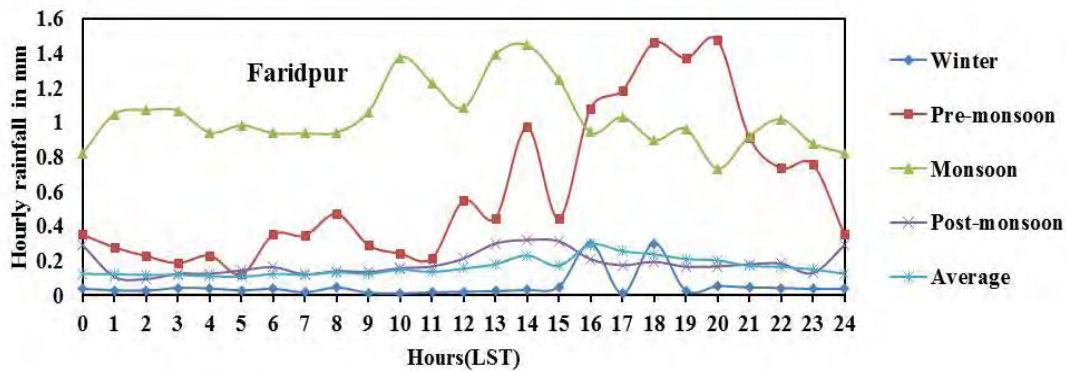


Figure A-13: Seasonal and yearly average diurnal variation of rainfall in Dinajpur of hourly data of GSMaP.



## Faridpur

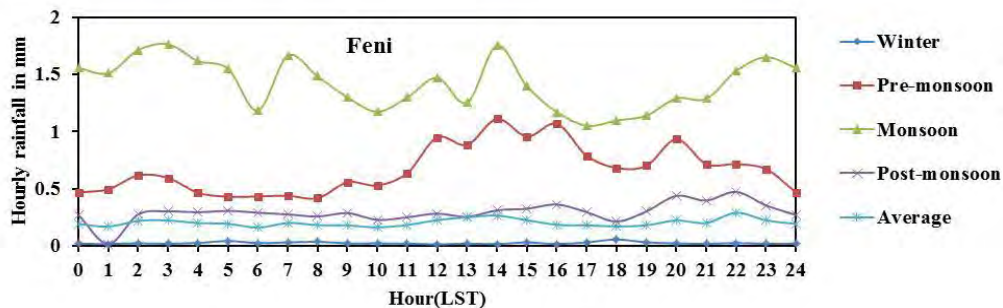
In figure A-14 showed that diurnal variation of rainfall in Faridpur which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon and winter found maximum rainfall peak at 2000, 1400 1500, 1800 and 1600 LST, respectively.



**Figure A-14:** Seasonal and yearly average diurnal variation of rainfall in Faridpur of hourly data of GSMaP.

## Feni

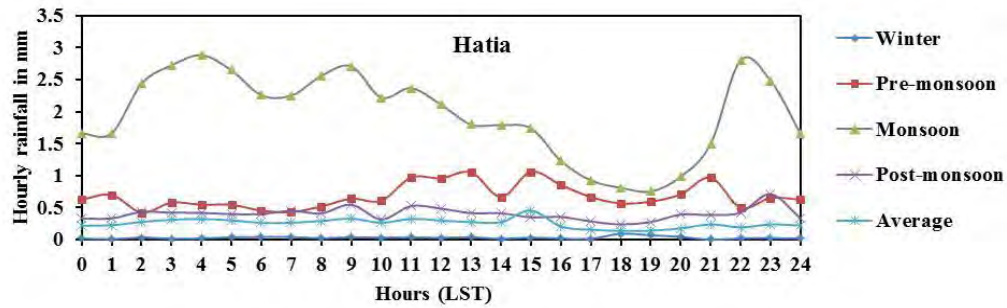
In figure A-15 showed that diurnal variation of rainfall in Feni which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon and winter found maximum rainfall peak at 1400, 1400 2200, 1800 and 2200 LST, respectively.



**Figure A-15:** Seasonal and yearly average diurnal variation of rainfall in Feni of hourly data of GSMaP.

## Hatia

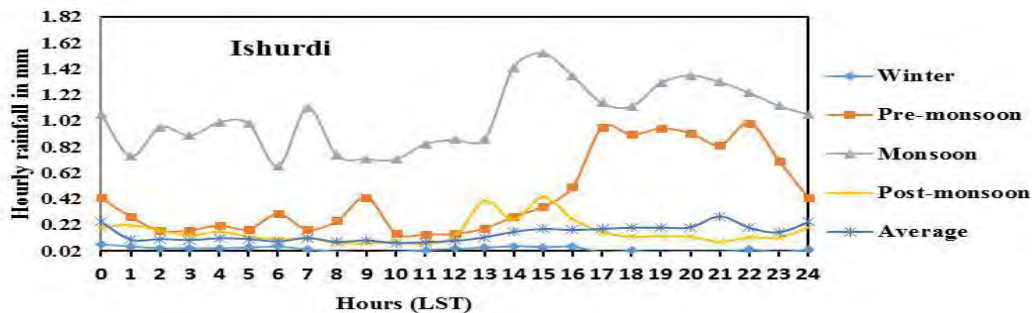
In figure A-16 showed that diurnal variation of rainfall in Hatia which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon and winter found maximum rainfall peak at 2100, 2200 2300, 1800 and 1500 LST, respectively.



**Figure A-16:** Seasonal and yearly average diurnal variation of rainfall in Hatia of hourly data of GSMaP.

## Ishurdi

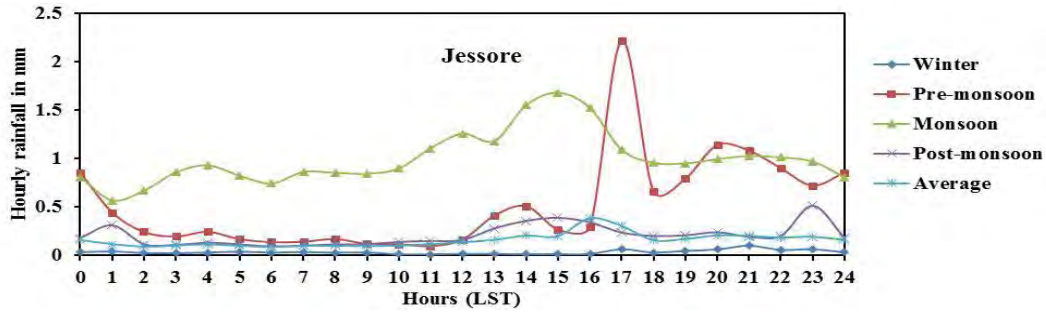
In figure A-17 showed that diurnal variation of rainfall in Ishurdi which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon and winter found maximum rainfall peak at 1500, 2200 1500, 0600 and 2100 LST, respectively.



**Figure A-17:** Seasonal and yearly average diurnal variation of rainfall in Ishurdi of hourly data of GSMaP.

## Jessore

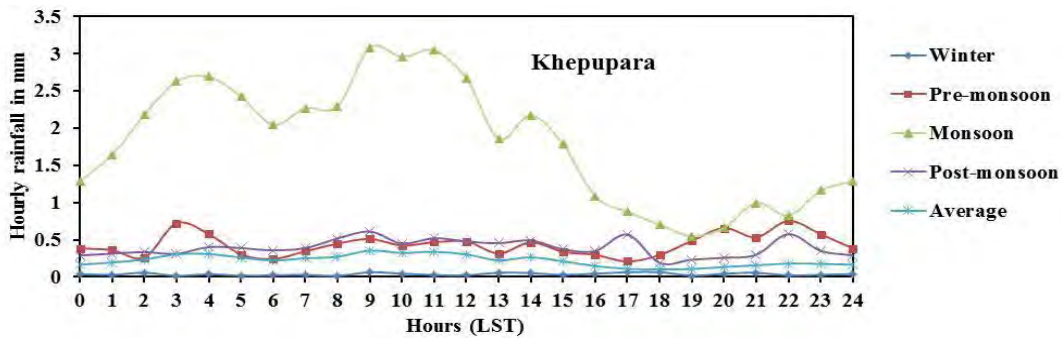
In figure A-18 showed that diurnal variation of rainfall in Jessore which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon and winter found maximum rainfall peak at 1700, 1500 2300, 2100 and 1600 LST, respectively.



**Figure A-18:** Seasonal and yearly average diurnal variation of rainfall in Jessore of hourly data of GSMaP.

## Khepupara

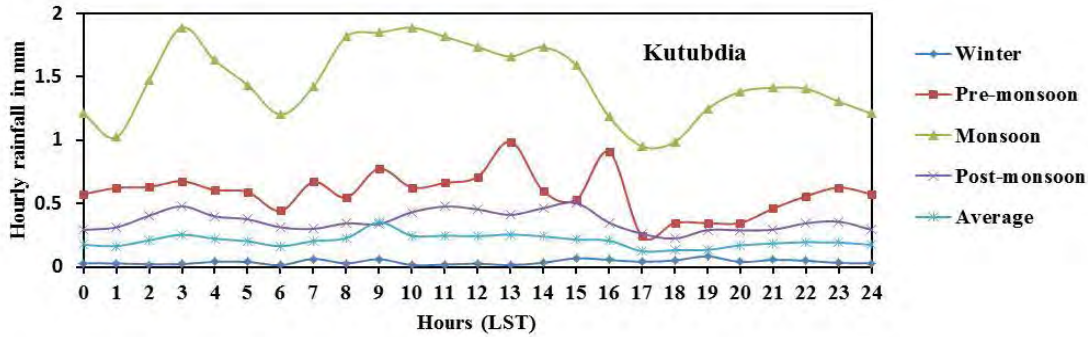
In figure A-19 showed that diurnal variation of rainfall in Khepupara which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon and winter found maximum rainfall peak at 0900, 2200 1700, 1800 and 9000 LST, respectively.



**Figure A-19:** Seasonal and yearly average diurnal variation of rainfall in Khepupara of hourly data of GSMaP.

### Kutubdia

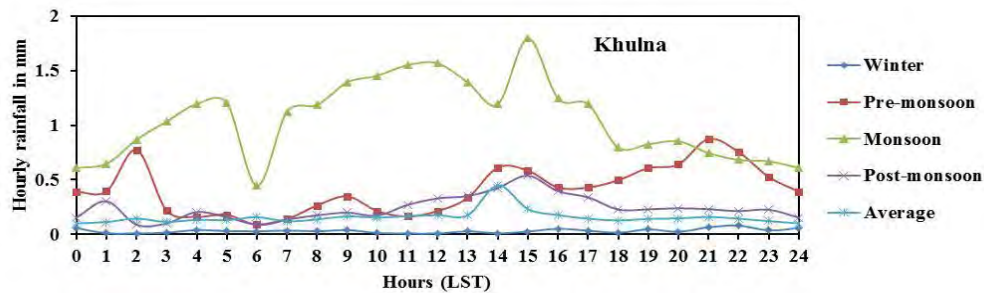
In figure A-20 showed that diurnal variation of rainfall in Kutubdia which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon and winter found maximum rainfall peak at 0300, 1600 1500, 1900 and 9000 LST, respectively.



**Figure A-20:** Seasonal and yearly average diurnal variation of rainfall in Kutubdia of hourly data of GSMaP.

### Khulna

In figure A-21 showed that diurnal variation of rainfall in Khulna which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon and winter found maximum rainfall peak at 2100, 1500 1500, 2200 and 14000 LST, respectively.



**Figure A-21:** Seasonal and yearly average diurnal variation of rainfall in Khulan of hourly data of GSMaP.

## M. Court

In figure A-22 showed that diurnal variation of rainfall in M.Court which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon and winter found maximum rainfall peak at 1600, 1100 1600, 1700 and 14000 LST, respectively.

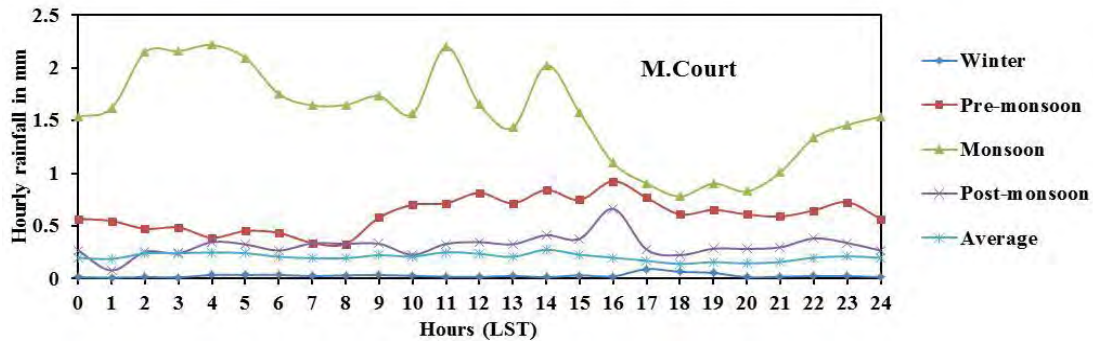


Figure A-22: Seasonal and yearly average diurnal variation of rainfall in M.Court of hourly data of GSMaP.

## Madaripur

In figure A-23 showed that diurnal variation of rainfall in Madaripur which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon and winter found maximum rainfall peak at 2200, 1500 1500, 0000 and 14000 LST, respectively.

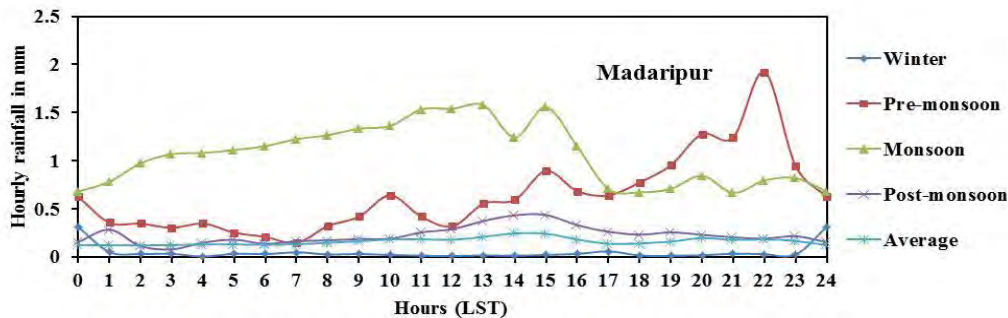
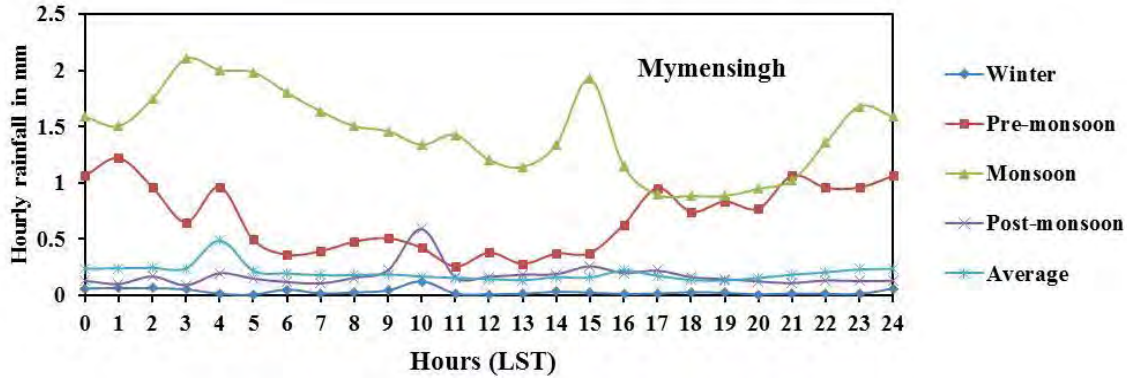


Figure A-23: Seasonal and yearly average diurnal variation of rainfall in Madaripur of hourly data of GSMaP.

## Mymensingh

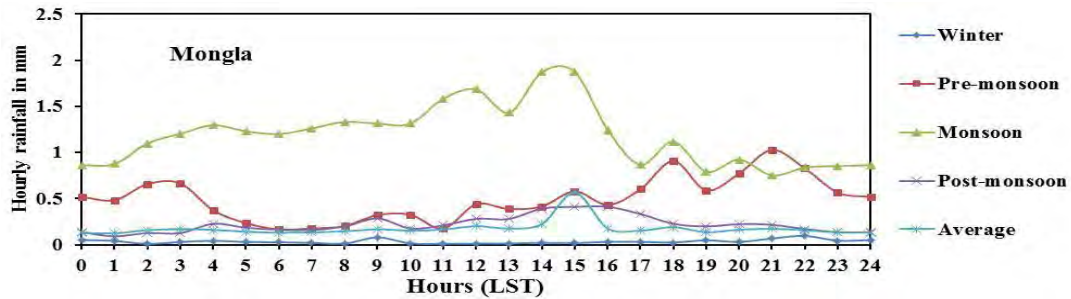
In figure A-24 showed that diurnal variation of rainfall in Mymensingh which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon and winter found maximum rainfall peak at 2100, 1500 1000, 1000 and 0400 LST, respectively.



**Figure A-24:** Seasonal and yearly average diurnal variation of rainfall in Mymensingh of hourly data of GSMaP.

## Mongla

In figure A-25: showed that diurnal variation of rainfall in Mongla which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon and winter found maximum rainfall peak at 2100, 1500 1500, 900 and 1500 LST, respectively.



**Figure A-25:** Seasonal and yearly average diurnal variation of rainfall in Mongla of hourly data of GSMaP.

### Rajshahi

In figure A-26 showed that diurnal variation of rainfall in Rajshahi which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon and winter found maximum rainfall peak at 2100, 1500, 1500, 0600 and 1500 LST, respectively.

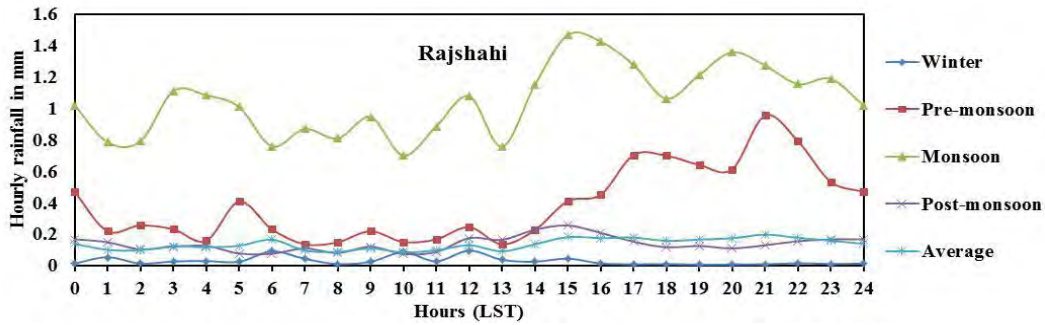


Figure A-26: Seasonal and yearly average diurnal variation of rainfall in Rajshahi of hourly data of GSMaP.

### Patuakhali

In figure A-27 showed that diurnal variation of rainfall in Patuakhali which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon and winter found maximum rainfall peak at 1900, 0900, 1300, 1900 and 0900 LST, respectively.

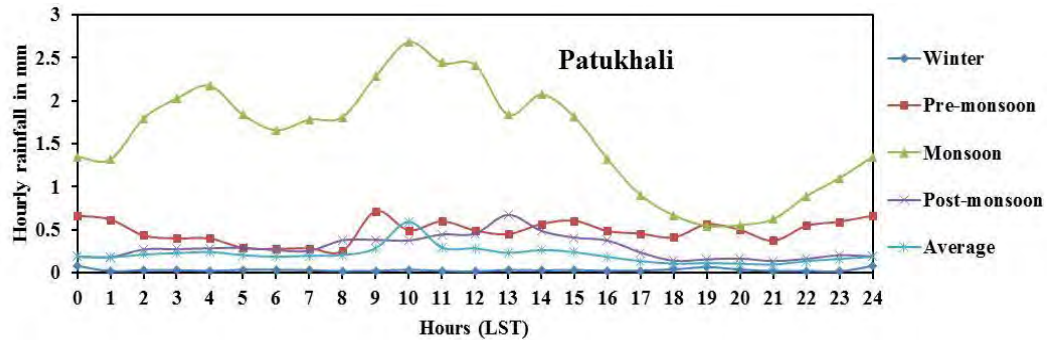
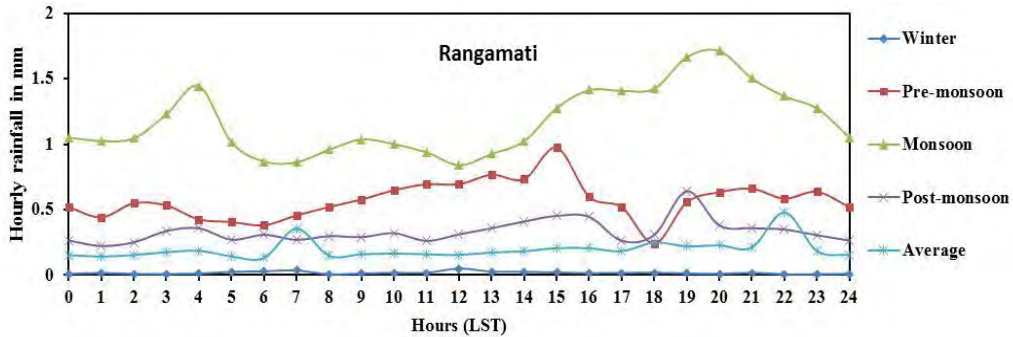


Figure A-27: Seasonal and yearly average diurnal variation of rainfall in Patuakhali of hourly data of GSMaP.

## Rangamati

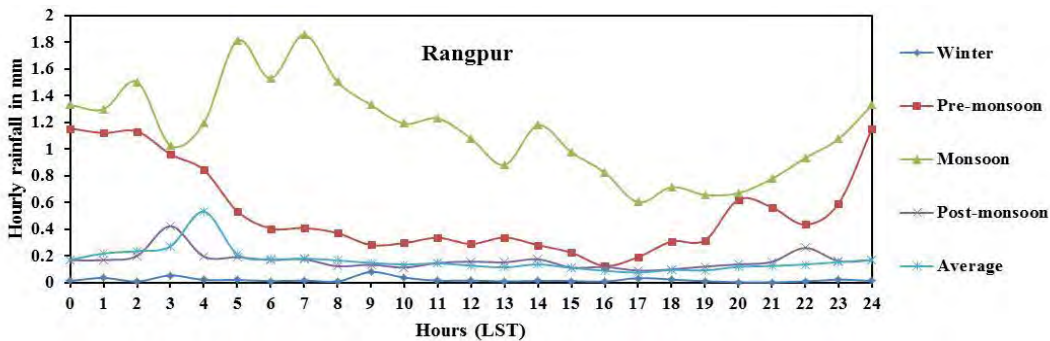
In figure A-28 showed that diurnal variation of rainfall in Rangamati which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon and winter found maximum rainfall peak at 1500, 2000 1900, 1200 and 2200 LST, respectively.



**Figure A-28:** Seasonal and yearly average diurnal variation of rainfall in Rangamati of hourly data of GSMaP.

## Rangpur

In figure A-29 showed that diurnal variation of rainfall in Rangpur which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon and winter found maximum rainfall peak at 0000, 0500 0300, 0300 and 400 LST, respectively.

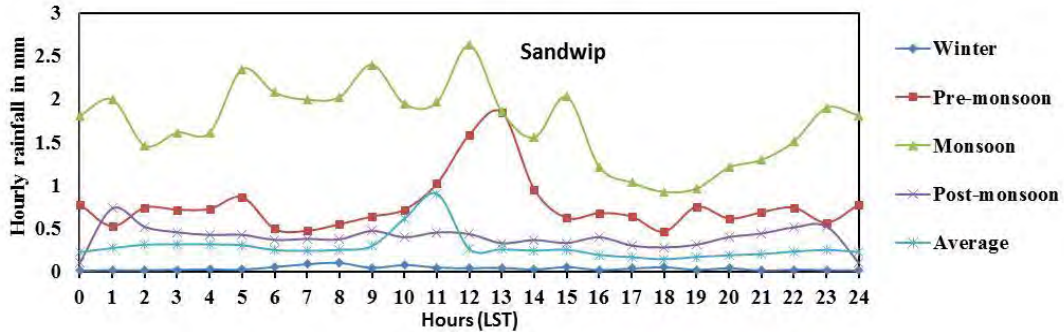


**Figure A-29:** Seasonal and yearly average diurnal variation of rainfall in Rangpur of hourly data of GSMaP.



## Sandwip

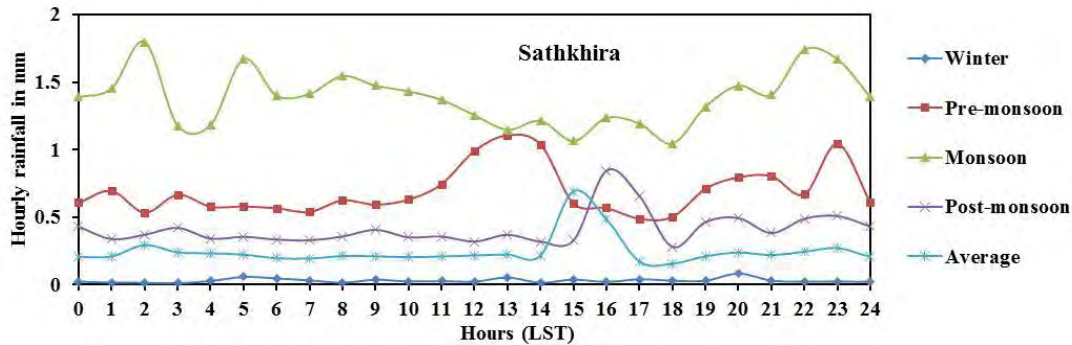
In figure A-30 showed that diurnal variation of rainfall in sandwip which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon and winter found maximum rainfall peak at 1300, 1200 0100, 0800 and 1100 LST, respectively.



**Figure A-30:** Seasonal and yearly average diurnal variation of rainfall in Sandwip of hourly data of GSMaP.

## Sathkhira

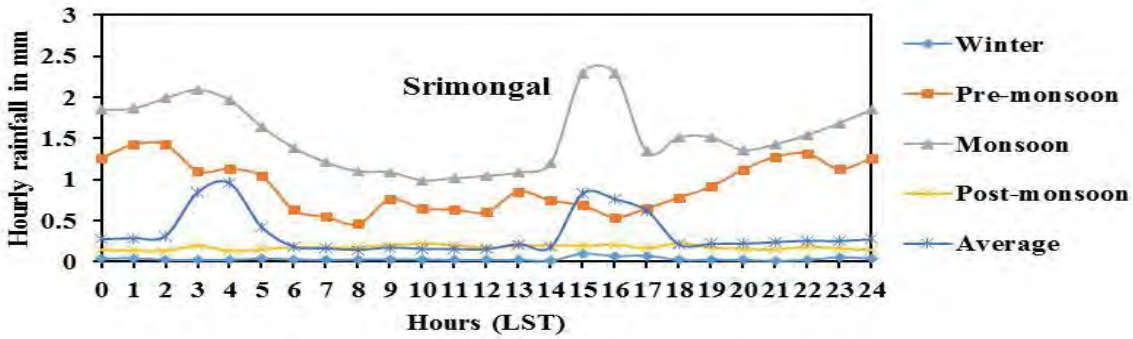
In figure A-31 showed that diurnal variation of rainfall in Sathkhira which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon and winter found maximum rainfall peak at 2200, 2300 1600, 2000 and 1500 LST, respectively.



**Figure A-31:** Seasonal and yearly average diurnal variation of rainfall in Sathkhira of hourly data of GSMaP.

### Srimongal

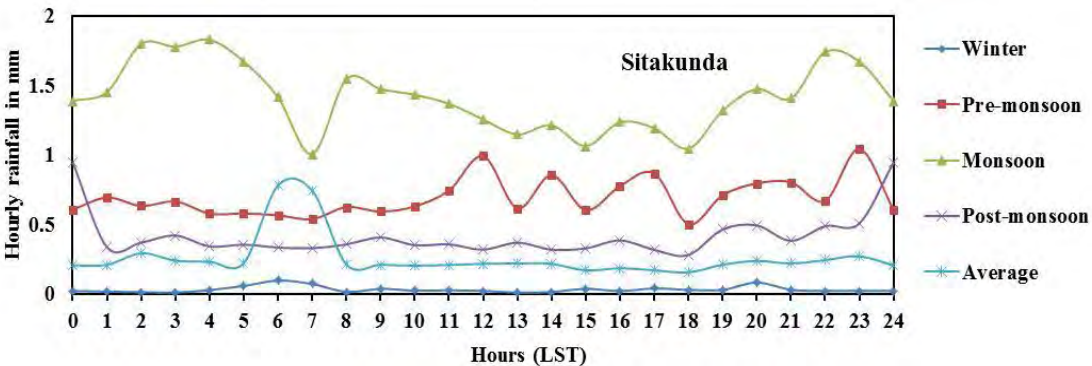
In figure A-32 showed that diurnal variation of rainfall in Srimongal which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon and winter found maximum rainfall peak at 2200, 1600 1500, 1500 and 0400 LST, respectively.



**Figure A-32:** Seasonal and yearly average diurnal variation of rainfall in Sri-mongal of hourly data of GSMaP.

### Sitakunda

In figure A-33 showed that diurnal variation of rainfall in Sitakunda which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon and winter found maximum rainfall peak at 0400, 2200 0000, 0600 and 0600 LST, respectively.



**Figure A-33:** Seasonal and yearly average diurnal variation of rainfall in Sitakunda of hourly data of GSMaP.

## Sydpur

In figure A-34 showed that diurnal variation of rainfall in Sydpur which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon and winter found maximum rainfall peak at 0100, 0400 0400, 0600 and 0700 LST, respectively.

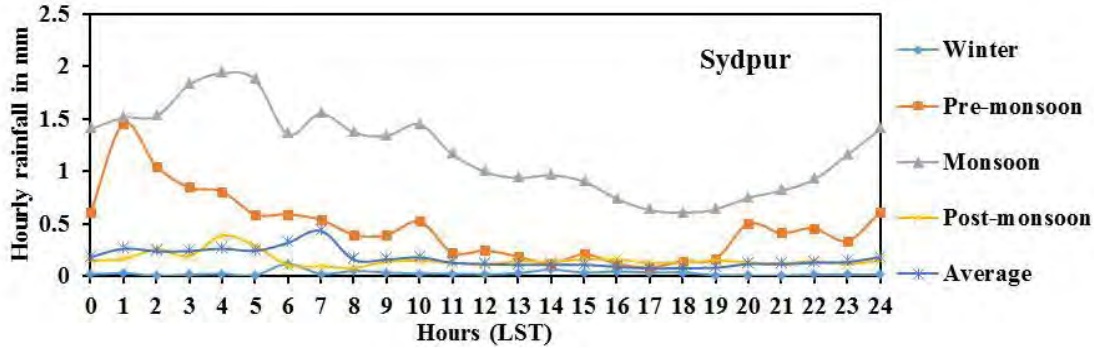


Figure A-34: Seasonal and yearly average diurnal variation of rainfall in Sydpur of hourly data of GSMaP.

## Sylhet

In figure A-35 showed that diurnal variation of rainfall in Sylhet which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon and winter found maximum rainfall peak at 2300, 0400 1000, 1200 and 0500 LST, respectively.

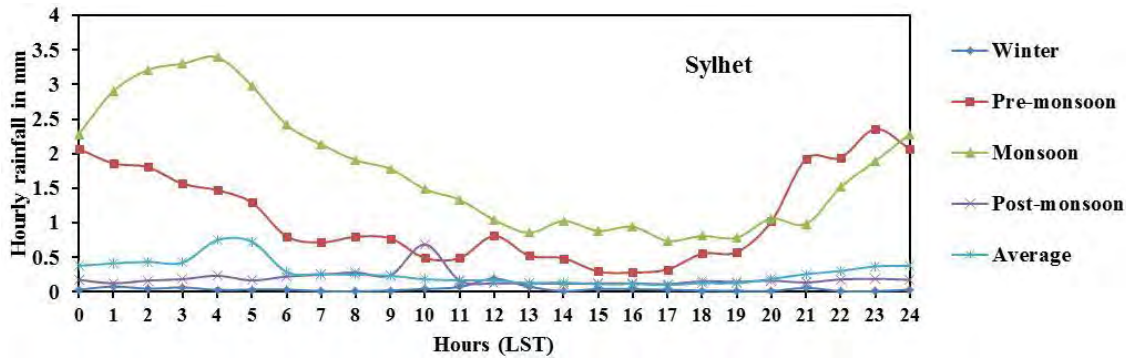
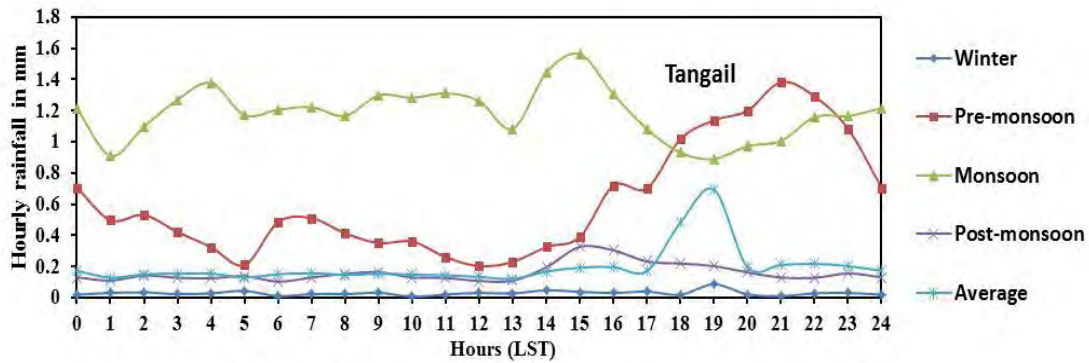


Figure A-35: Seasonal and yearly average diurnal variation of rainfall in Sylhet of hourly data of GSMaP.

## Tangail

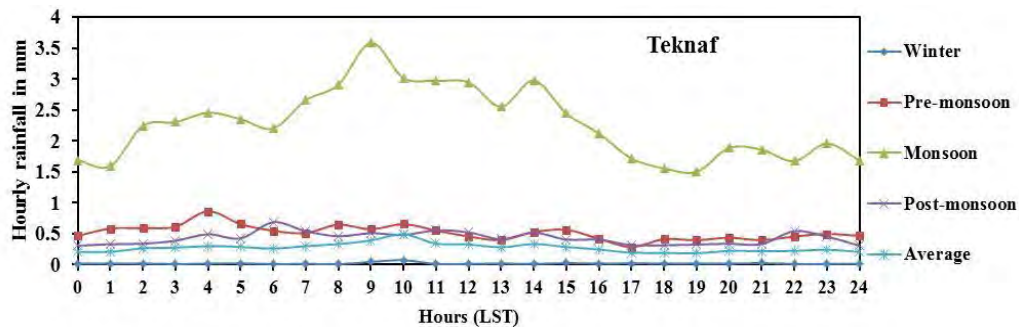
In figure A-36 showed that diurnal variation of rainfall in Tangail which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon and winter found maximum rainfall peak at 2100, 1500 1500, 1900 and 1900 LST, respectively.



**Figure A-36:** Seasonal and yearly average diurnal variation of rainfall in Tangail of hourly data of GSMaP.

## Teknaf

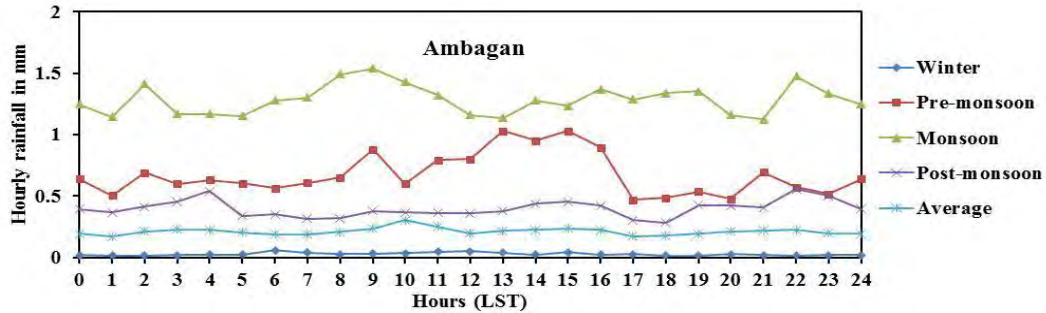
In figure A-37 showed that diurnal variation of rainfall in Teknaf which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon and winter found maximum rainfall peak at 0400, 0900 0600, 1000 and 1000 LST, respectively.



**Figure A-37:** Seasonal and yearly average diurnal variation of rainfall in Teknaf of hourly data of GSMaP.

## Ambagan

In figure A-38 showed that diurnal variation of rainfall in Ambagan which is measured by GSMaP hourly rainfall data of study period. During pre-monsoon, monsoon, post-monsoon and winter found maximum rainfall peak at 1300, 2100 0400, 0600 and 1000 LST, respectively.



**Figure A-38:** Seasonal and yearly average diurnal variation of rainfall in Ambagan of hourly data of GSMaP.

It is found that most of stations among 35 rain measurement station found coastal or maritime type diurnal variation of rainfall. From harmonic analysis of 3-hourly data between GSMaP and BMD rain gauge found at early or evening rainfall peak. But from hourly station wise analysis showed the these peaks hold one or two hour late than that of harmonic analysis of datasets i. e if 3-hourly analysis data found a peak at 1500 LST whereas this peak catch 1600 or 1700 LST. Some inland station showed continental type of diurnal variation of rainfall.

## APPENDIX-2

### List of Conference papers

- 1. J. Hossain**, A. T. M. S. Azam and M. Rafiuddin, “Study of diurnal variation of rainfall in Bangladesh using GSMaP data”, Abstract in the National Conference on Physics, 5-7 January, 2017, Dhaka, Bangladesh, pp.88-90, 2017.
- 2. J. Hossain**, A. T. M. S. Azam, M. A. Khatun and M. Rafiuddin, “Study of heavy rainfall events in Bangladesh using Global Satellite Mapping of Precipitation data”, Submitted abstract for Physics for Sustainable Development and Technology, “ICPSDT-2017”, Conference will be held on December 10-11, 2017, CUET, Chittagong - 4349, Bangladesh (Accepted).

## **STUDY OF DIURNAL VARIATION OF RAINFALL IN BANGLADESH USING GSMaP DATA**

**J. Hossain, A. T. M. S. Azam and M. Rafiuddin**

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Email: ahmed.sohel.7.bd@gmail.com

### **Abstract**

To study the diurnal variation of rainfall and possibility to use of Global Satellite Mapping of Precipitation (GSMaP) data in Bangladesh, GSMaP hourly data of spatial resolution of 0.1 degree by 0.1 degree and three hourly rain gauge data of 35 stations of Bangladesh Meteorological Department (BMD) are used. Daily, monthly, seasonal and yearly diurnal variation of rainfall and their spatial distribution are studied during the period 2001-2015. It is found that GSMaP data is highly correlated with rain gauge data. The correlation coefficients between GSMaP and BMD rain gauge for daily, monthly and yearly rainfall are found 0.90, 0.96 and 0.66, respectively. From this study, it is found that GSMaP measured daily maximum rainfall over Bangladesh at 0300 LT (Local Time) with a secondary maximum peak at 1500 LT whereas rain gauge observed primary peak at 0600 LT with a secondary peak at 1500 LT. The seasonal primary peak of GSMaP is well matched with rain gauge observation during winter, pre-monsoon and post-monsoon. Whereas the primary peaks of GSMaP and rain gauge are found at 1500 and 0600 LT during monsoon season. The seasonal secondary peaks observed by GSMaP are not well match with observation except winter season. Daily maximum rainfall of southern, western, eastern and central regions of the country is occurred during 1200-1500 LT on the other hand southeastern regions of Bangladesh is found during 0600-0900 LT. In the northwestern and northeastern regions of the country the maximum rainfall is found during 0300-0600 LT.

## **Study of heavy rainfall events in Bangladesh using Global Satellite Mapping of Precipitation data**

**J. Hossain, A. T. M. S. Azam, M. A Khatun and M. Rafiuddin**

Department of Physics, Bangladesh University of Engineering and Technology, Dhaka  
Email: robi.buet.phy@gmail.com

### **Abstract**

Flood or flash flood monitoring and forecasting is a complicated tasks in densely inhabited and low-lying topography areas like Bangladesh. Recently, flash flood showed its hazardous and devastating affect in the northeastern part of the country especially Sumamganj, Kishoreganj, Netrokona etc. due to heavy rainfall in those area and upper catchment area in India. Due to lack of rainfall data of upper catchment area in India, flash flood forecasting was not possible. Global Satellite Mapping of Precipitation (GSMaP) data can be used for flash flood forecasting. GSMaP is a high spatiotemporal resolution ( $0.1^\circ \times 0.1^\circ$ ; 1 hourly) data and available four hour later after the observation. To validate GSMaP data, 3-hourly data of 35 rain gauge stations of Bangladesh Meteorological Department (BMD) used for the study period 2001-2015. Several statistical analyses showed that GSMaP data are well correlated with rain gauge data. The correlation coefficients between GSMaP and BMD rain gauge for 3-hourly, daily, monthly and yearly are found 0.71, 0.74, 0.82 and 0.66, respectively. The Standard Deviation (SD) of 3-hourly rainfall for GSMaP and rain gauge data are found 1.96 and 2.10 mm, respectively. According to BMD, there are five types of threshold rainfall events such as Very Heavy Rainfall (VHR  $> 88$  mm in 24 hour), Heavy Rainfall ( $88 \geq HR \geq 43.5$  mm in 24 hour), Moderate Heavy Rainfall ( $43.5 > MHR \geq 22.5$  mm in 24 hour), Moderate rainfall ( $22.5 > MR \geq 10.5$  mm in 24 hour) and Light rainfall ( $10.5 > LR \geq 2.5$  mm in 24 hour). The yearly occurrence of VHR, HR, MHR, MR and LR events are found 4.1, 11.7, 17.9, 23.5 and 35.4 for BMD rain gauge data and 2.30, 8.03, 14.13, 22.56, and 42.58 for GSMaP data, respectively. The performance of GSMaP data to detect the events is 97%. So GSMaP data may be used to predict for flash flood, especially in areas where rain gauge data are limited.