STUDY ON PRE-MONSOON THUNDERSTORM FREQUENCY AND ITS RELATION WITH RAINFALL IN BANGLADESH DURING 1990-2017

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AVANTIKA JAYATI DHALI

Roll No: 0417142502 F

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CANDIDATE'S DECLARATION

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

Signature of the Candidate

Avantika Jayati Dhali

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Avantika Jayati Dhali

Dedicated to,

My Parents and Teachers

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LIST OF ABBREVATIONS

BMD: Bangladesh Meteorological Department

MCS: Multicell Storms

LST: Local Standard Time

PBL: Planetary Boundary Layer

CAPE: Convective Available Potential Energy

WAA: Warm Air Advection

UTC: Universal Time Coordinated

LI: Lifting Index

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ABSTRACT

Thunderstorm is a short-lived and violent weather phenomenon which synchronizes with rain, lightning, hail or gusty wind. In this study, pre-monsoon (March-May) thunderstorm frequency and its relation with rainfall are carried out for 28 years (1990-2017) using Bangladesh Meteorological Department (BMD) 34 stations data. BMD archived the thunderstorm as gusty, squall and hail types. The thunderstorms are also further classified into severe (> 64 km/h) and non-severe (≤64 km/h) based on their wind speed. Inthe present study the highest thunderstorm frequency is found at 12 UTC (18 LST) in May. The maximum occurrence of thunderstorm is found 12-18 UTC (18-24 LST) during 1990-2017. The occurrence of squall type thunderstorm is found maximum (54%). The occurrence of severe and non-severe thunderstorms is found maximum in the month of May in 1993 and March in 2004, respectively. Strong yearly variation of different types of thunderstorms is found during pre-monsoon season in Bangladesh. Spatial distribution showed the maximum occurrence of thunderstorm is found central and northeastern part of Bangladesh and minimum in Teknaf, Maijdee Court and Feni. During pre-monsoon wind speed of thunderstorm is found maximum in May. The highest average wind speed of thunderstorm is found in Teknaf in May is 98 km/h and lowest in Hatiya in March is 38 km/h. On average, about 26% thunderstorm is found to propagate southeastward during pre-monsoon season. The highest number of thunderstorm day is found in the month of May. During pre-monsoon season maximum average rainfall occurs in May and minimum in March. The highest amount of rain is found at Srimangal in the month of May. Daily rainfall is showed increasing trends as the monthly progress during pre-monsoon season. Generally, the thunderstorm frequency as well as average rainfall is highest in May. The correlation coefficient of thunderstorm occurrence and rainfall is found 0.45, 0.57 and 0.61 for the month of March, April and May, respectively. This study reveals that rainfall increases with increase of thunderstorms in Bangladesh during pre-monsoon season.

CHAPTER ONE

INTRODUCTION

1.1 Prelude

Bangladesh is geomorphologically and geographically a low-lying riverine country. In the north-west there are large land masses of India; north-east sides of the country there are foot hills of Meghalaya which are east-west oriented; in the south, there is the Bay of Bengal and in the south-east, there lie mountain ranges of Myanmar which are north-south oriented. This country is the utmost outcome of the fluvio-deltatic sediment accumulated in the Bengal Basin from the Ganges (Padma), Meghna, Jamuna and their tributaries. Bangladesh is located in the tropical monsoon region where extensive variations in rainfall, temperature and humidity exist. Bangladesh is called land of rivers. These rivers and their branches and canals are widely spread throughout the country. They have large impact on the weather and climate of the country.

In Bangladesh there are four prominent seasons. They are: a) Pre-monsoon (March-May) b) Monsoon (June-September) c) Post-Monsoon (October-November) d) Winter (December-February). Among these seasons the pre-monsoon is a transition phase from cold, dry winter to warm moist monsoon (Chowdhury et *al.*, 1995).

During pre-monsoon convective uplift take place due to high surface temperature and abundant of moisture comes from the Bay of Bengal. Weston (1972) mentioned that during the pre-monsoon period, hot, dry air masses from India interact with warm, moist, low-level (~1 km) air from the Bay of Bengal and create unstable conditions favorable for the development of convection. Sanderson and Ahmed (1979) also noted that mountains around northeastern Bangladesh cause orographic uplifting and convectional overturning of low-level moist air from the Bay of Bengal. This environmental condition helps to develop thunderstorms in Bangladesh during pre-monsoon season. In Bangladesh, one of the most hazardous weather phenomena is the outburst of severe local convective storms (thunderstorms) that develop in the north-west part and propagate southeastward, commonly known as ‗nor‘westers‘‘ and locally called ‗Kal-baishakhi‘‘.

According to Houze et *al.* (1993) development of thunderstorms can be divided into three stages: Initial, Mature and Dissipation stage. The stages may take anywhere in Bangladesh and stay about 20 minutes to several hours. Initial stage consists of vigorous, in which hydrometers are growing rapidly. The updraft velocity increases with height. Mature stage has both an active updraft and downdraft, latter coinciding with a downpour of precipitation. The heaviest rain occurs in this stage and it is the most violent stage among the three stages. During mature stage, thunderstorms synchronize with strong lightning, squall, hail and wind gusts; and every year such storms lead to extensive agricultural and property damage and the loss of human and animal lives (Sanderson et al., 1978). These cause great economic damage for Bangladesh. In the dissipating stage the downdraft takes over entire cloud.

Pre-monsoon is the hot weather period in Bangladesh (Choudhury et *al.*, 2008). In pre-monsoon the activity of thunderstorms is generally high (Chowdhury et *al.*, 1995; Chaudhury et *al.*, 1961). Recently many violent thunderstorms occur in Bangladesh and make lot of casualties and property damage. Although of this huge amount of losses appears in case of lives and property, these thunderstorms also provide major valuable rainfall during pre-monsoon season and origin of rains till the setting of southwest monsoon. (Sen et *al.*, 1961; Begum et *al.*, 2013; Wapler et *al.*, 2015; Parsons, 2015; Doswell et *al.*, 2005). This mesoscale weather phenomenon is important to meteorologists and perilous for aviation (Awadesh et *al.*, 1992; Litta et *al.*, 2012). Thunderstorm also has important impact on the climate of Bangladesh.

For better understanding merits and demerits of thunderstorm, the economical and agricultural importance has to be considered. These severe local storms often include thunder, lightning, intense rain, hail, wind gusts and tornado, and every year such storms lead to extensive agricultural and property damage and the loss of human life. These cause great economic damages for Bangladesh. Excessive rainfall can damage foods and crops (Sanderson et *al.*, 1978).

On the other hand, this pre-monsoon rainfall plays an important role in the socioeconomic development of the agricultural-dependent country of Bangladesh. The growth of crops generally depends on rainfall. Sufficient rainfall can produce good amount of crops. For harvesting rice especially (Boro) this pre-monsoon rainfall is very important (Buffes et *al.*, 2001). Summer vegetables- lady's finger, Indian spinach, sweet gourd, bitter gourd, squash, teasel gourd, yard long bean, brinjal, and summer tomato greatly depends on pre-monsoon rainfall. Major ‗Rabi crops' grows in the country such as wheat, maize, mustard, sesame, groundnut, sunflower, chickpea etc. during pre-monsoon (Islam, 2001; Quddus et *al.,* 2004).

Chowdhury et al. (1995) showed that the frequency of thunderstorms and amount of precipitation were the greatest in the month of May in Bangladesh during the pre-monsoon season for the year 1983-1992. In central part of Bangladesh thunderstorm is found at early afternoon or evening, while the north it is night or early morning. Begum et al. (2012) studied the diurnal variation of mesoscale precipitation systems in Bangladesh using six year radar data and showed that the asymmetric type arc shape precipitation systems dominate during pre-monsoon season. Saha et al. (2014) showed a decreasing trend for the pre-monsoon rainfall and an increasing trend in the monsoon rainfall amounts over the Gangetic West Bengal. Saha et al. also showed a significant positive correlation for all types of thunderstorm (severe, ordinary and total) events with pre-monsoon rainfall. These studies showed thunderstorm activity, but so far there is no work in Bangladesh which shows thunderstorm related wind propagation direction and speed; gusty, squall, and hail thunderstorm and the number of thunderstorm and non-thunderstorm days. To clarify pre-monsoon thunderstorm frequency and its relation with rainfall, this present study shows the sub-daily, daily, monthly and yearly thunderstorm frequency; the spatial (regional) variation of thunderstorm frequency; propagation speed and direction; gusty, squall, and hail thunderstorm; thunderstorm and non-thunderstorm days over Bangladesh for 28 years (1990-2017).

Since the convective phenomena play an important role in generation of thunderstorm activities in Bangladesh, as the pre-monsoon rainfall is associated with convection, it is intended to study the association of rainfall with thunderstorm activities.

1.2 Objectives of the Research

The specific objectives of the present research work are:

1. To study the sub-daily, daily, monthly and yearly variations of thunderstorm frequency in Bangladesh during pre-monsoon season.
2. To observe the regional variation of thunderstorm frequency.
3. To observe variation of different types of thunderstorms.
4. To observe the propagation speed, direction of thunderstorm.
5. To study relationship between thunderstorm frequency and rainfall during pre-monsoon season in Bangladesh.

The results of this research work will be helpful to understand the climatological characteristics of thunderstorm and its relation with rainfall in Bangladesh. Results of this research work will help to reduce the thunderstorm related disasters (e.g. Lightning deaths, crop and property damage etc.) in Bangladesh. This work will also provide valuable information to the national climate and weather forecasting service agency.

CHAPTER TWO

LITERATURE REVIEW

2.1 Review

There are many studies related to thunderstorm frequency and its relationship with rainfall using rain gauge data.

Chowdhury et *al.* (1995) reported that the frequency of thunderstorms and amount of precipitation were the greatest in the month of May in Bangladesh during the pre-monsoon period. They showed that thunderstorm occurrence had wide variation in terms of both space and time. In their study Maijdee had 10% precipitation for per thunderstorm day where Sylhet had 50% precipitation during pre-monsoon. For central part of Bangladesh highest thunderstorm occurrence during late afternoon or early evening where, in the northern part the occurrence was highest during night or early morning.

Saha et *al.* (2014) studied the thunderstorm which associated with strong convective activity in the Gangetic West Bengal, is one of the most prominent weather phenomena in the atmosphere. The occurrences of severe thunderstorms were decreasing, although the number of ordinary thunderstorms occurring in this period has an increasing trend. A decrease in Convective Available Potential Energy (CAPE), Vertical Wind Shear (VWSH), Deep Layer Shear (0–6 km AGL) and an increase in Lifted Index (LI) might be an indicator for the suppression of the severity of thunderstorms over the urban location. There was also a decreasing trend for the pre-monsoon rainfall and an increasing trend in the monsoon rainfall amounts over the region. A further study indicated a significant positive correlation for all the types of thunderstorm (severe, ordinary and total) events with the pre-monsoon rainfall amount. On the other hand, a significant anti-correlation was observed between the severe thunderstorm frequencies with the monsoon rainfall amount for the same period. The decrease in the severity of the thunderstorm events was accompanied by an increase of pre-monsoon cloud Liquid Water Content (LWC) with Integrated Water Vapor (IWV). Hence, there was an expected strong association of the thunderstorm frequency with the pre-monsoon and monsoon rainfall amounts at this tropical location.

Rafiuddin et al. (2013) showed using fifty years (1950-1999) daily rainfall data of 13 meteorological stations of Bangladesh Meteorological Department (BMD). Variations of rainy days were studied during pre-monsoon, monsoon, post-monsoon, winter, and yearly consideration. Three threshold rainy days named moderated heavy (22 - 44 mm/day), heavy (45 - 88 mm/day) and very heavy (greater than 88 mm/day) are also studied. During premonsoon period in Bangladesh except Srimongal all the stations show increasing trend of rainy days. In monsoon all the stations show increasing trend of rainy days except Dkaka, Chittagong, Cox‘s Bazar, Srimongal and Rangpur. Dkaka, Chittagong, Srimongal and Bogra stations show negative trend of rainy days during post-monsoon period, all other stations show positive trend. During winter season all stations show positive trend. Yearly variation of rainy days for all stations showed positive trend except Srimongal during 1950-1999. All the stations showed increasing trend of moderate heavy rainy days except Srimongal and Comilla during 1950-1999. For heavy rainy days except Comilla and Satkhira, all other stations showed positive trend. For very heavy rainy days except Mymensing, Rangpur, Bogra and Dinajpur, all other stations showed positive trend. The increasing tendency of rainy days in dry region is higher than wet region. The country averaged seasonal, yearly and decadal variation of rainy days as well as three threshold rainy days showed positive trend. The yearly averaged increase of rainy days was found 0.36 days/year.

Avotniece et *al.* (2017) found that, thunderstorms are the most hazardous meteorological phenomena in the summer season. They studied the spatial and temporal distribution of thunderstorms during the period 1960–2015 by using surface observation data from 14 major weather stations. To assess the severity of thunderstorms and suitability of the existing warning system, the frequency and distribution of thunderstorm intensities according to the national warning and hazard criteria was analyzed. The results of this analysis showed significant decrease in thunderstorm frequency in Latvia since 1960; however indicators of an increase in thunderstorm severity were also found which reveals and emphasizes the complex nature of convective atmospheric phenomena also on climatic scales.

Islam et al. (1994) showed that the single cell clouds may merge to form a multiple cell cloud developed in and around Bangladesh. There was an intimate relationship in cloud and precipitation. The whole portion of cloud did not cause rain. Only fraction of cloud caused surface rain.

Hoque et al. (2011) studied the climate characteristics of monsoon in Bangladesh using Japanese 25-years re-analysis data and BMD data. The highest rainfall occurred in the northeast region (Sylhet) during pre-monsoon season and during monsoon highest rainfall found in southeast region (Teknaf). The central west region (Ishurdi) got less rainfall during in all seasons. In the post-monsoon rainfall amount did not vary in stations.

Begum et *al*. (2012) studied the diurnal variation of mesoscale precipitation systems in and around Bangladesh using six year (2000-2005) radar data. The data were obtained from Bangladesh meteorological department. Over the study period diurnal variation of precipitation systems revealed that arc, line and scattered shaped precipitation systems show maximum peak at 18-21 LST (03-06 LST), 15-18 LST (03-06 LST) and 03-06 LST (12-15 LST), respectively during the pre-monsoon (monsoon) period. Dominating pre-monsoon arc shaped precipitation systems are classified as symmetric type precipitation systems (STPS), asymmetric type precipitation systems (ATPS), combination of symmetric and asymmetric type precipitation systems (CSATPS) and unclassified type precipitation systems (UTPS). The maximum occurrence frequency of STPS, ATPS, CSATPS and UTPS showed the peak at 15-18 LST (18-21 LST), 03-06 LST (03-06 LST), 18-21 LST (03-09 LST) and 18-21 LST (15-21 LST) respectively during the pre-monsoon (monsoon) period. Overall, the occurrence frequency of precipitation systems showed double peaks: primary maximum at 03-06 LST and secondary maximum at 12-15 LST. The primary maximum dominated in pre-monsoon while secondary maximum dominated in monsoon season.

Litta et *al.* (2012) showed that thunderstorm, resulting from vigorous convective activity, is one of the most spectacular weather phenomena in the atmosphere. A common feature of the weather during the pre-monsoon season over the Indo-Gangetic Plain and northeast India is the outburst of severe local convective storms, commonly known as ‗Nor'westers'(as they move from northwest to southeast). The severe thunderstorms associated with thunder, squall lines, lightning and hail cause extensive losses in agricultural, damage to structure and also loss of life. In this paper, sensitivity experiments had been conducted to test the impact of three microphysical schemes in capturing the severe thunderstorm event occurred over Kolkata on 15 May 2009. Litta et *al.* showed that the WRF model with Ferrier microphysical scheme appeared to reproduce the cloud and precipitation processes more realistically than other schemes. Also, they had made an attempt to diagnose four severe thunderstorms that occurred during pre-monsoon seasons of 2006, 2007 and 2008 through the simulated radar reflectivity fields and validated the model results with Kolkata Doppler Weather Radar (DWR) observations.

2.2 Geography of Bangladesh

Bangladesh is a South Asian country located between 20.67°N to 26.63°N latitude and 88.05°E to 92.72° E longitude. The country has an area of 147,610 square kilometers and extends 820 kilometers north to south and 600 kilometers east to west. Bangladesh is bordered on the west, north, and east by a 4,095 kilometers land frontier with India and, in the southeast 193 kilometers with Burma (Myanmar). The delta plain of the Ganges (Padma), Brahmaputra (Jamuna), and Meghna Rivers and their tributaries occupy 79 percent of the country. The geographical position of Bangladesh is shown in Figure 2.1.

Figure 2.1: Geographical map of Bangladesh (Source: https://www.researchgate.net/Geographical_map_of_Bangladesh_png)

Geologically, Bangladesh is a part of the Bengal Basin. The territorial waters of Bangladesh extend 12 nautical miles (22 km). Roughly, 80% of the landmass is made up of fertile alluvial lowland called the Bangladesh Plain. The plain is part of the larger Plain of Bengal, which is sometimes called the Lower Gangetic Plain. Although altitudes up to 105 meters (344 ft.) above sea level occur in the northern part of the plain, most elevations are less than 10 meters (33 ft.) above sea level; elevations decrease in the coastal south, where the terrain is generally at sea level. With such low elevations and numerous rivers, water—and concomitant flooding—is a predominant physical feature. From physiographic point of view, about 80% of the land is floodplains with very low mean elevation above the sea level with rest made up hills and elevated lands (Rahman et *al*., 1994).

Topography of the country is characterized by very low differences in the elevation between adjoining ridge tops and depression centers. The only exceptions to Bangladesh's low elevations are the Chittagong hills in the southeast, the Low hills of Sylhet in the northeast, and highlands in the north and northwest. The Chittagong hills constitute the only significant hill system in the country and, in effect, are the western fringe of the north-south mountain ranges of Burma and eastern India. The Chittagong hills rise steeply to narrow ridge lines, generally no wider than 36 meters (118 ft.), with altitudes from 600 to 900 meters (2,000 to 3,000 ft.) above sea level. Fertile valleys lay between the hill lines, which generally run north-south. West of the Chittagong hills is a broad plain, cut by rivers draining into the Bay of Bengal, that rises to a final chain of low coastal hills, mostly below 200 meters (660 ft.) that attain a maximum elevation of 350 meters (1,150 ft.). West of these hills is a narrow, wet coastal plain located between the cities of Chittagong in the north and Cox's Bazar situated in the south. Tertiary hills have elevation over 1000 meters above sea level (Rashid, 1991).

Bangladesh is situated between two different environments: a) Himalayas to the north and b) Bay of Bengal to the south. Because of the geographical position Bangladesh experience highest amount of country average monsoon and annual rainfall among SAARC countries. Bangladesh is one of the highest flood-prone countries in due to its geographic position (Devkota, 2006; Banglapedia, 2003).

2.3 Seasons of Bangladesh

Bangladesh contains a humid, warm, tropical climate. Its climate is sharply dominant by monsoon. The south-west monsoon originates over the Indian Ocean and carries moist, warm and unstable air. In Bangladesh there are four prominent seasons. They are:

a) Pre-monsoon (March-May)
b) Monsoon (June-September)
c) Post-Monsoon (October-November)
d) Winter (December-February)

The general climate characteristics of these seasons are as follows:

a) Pre-monsoon:

Pre-monsoon is actually hottest season of the year and during this period there is some rainfall accompanied by Nor'wester and hailstorm, gusty winds and often with recurrence of tornadoes. The mean temperature during summer months remains within 23 to 30° C. April and May are the hottest months. The highest temperature ranging from 44 to 45°C is attained in the northern and northwestern districts. Over rest of the country, it ranges from 41 to 43° C (Choudhury, 2008). The rainfall during the pre-monsoon is about 15% though it varies from region to region.

Figure 2.2: Pre-monsoon in Bangladesh

b) Monsoon:

Monsoon is hot and humid and brings heavy rainfall throughout the country. The average maximum temperature is about 30° C during day where at night temperature is about 25° C. The temperature difference between land and ocean is the main factor of the Asian monsoon, which causes seasonal scale sea breeze circulation. The mean monsoon temperature is higher in the western districts than eastern districts. The rainfall during the monsoon is about 75% of the yearly total. The rains are most abundant in the south-east (Chittagong, Cox‘s Bazar) and north-east areas (Sylhet).

Figure 2.3: Monsoon in Bangladesh (Source: https://www.en.banglapidia.org/monsoon)

c) Post-monsoon:

The post-monsoon is a short living season. In this season months of October and November are transition months from summer to winter and it is quite hot in October. During the post-monsoon, there is a gradual decrease in rainfall and lowering night-time temperature. Moderate rainfall occurs at this time. The rainfall during post-monsoon period is about 5% though it may be more if there is a depression or cyclone.

Figure 2.4: Post-monsoon in Bangladesh

d) Winter:

During winter, days are warm and dry and nights are cool. In the northern part of the country (Sayedpur, Rangpur) in January, coldest month and temperature is about 11° C. It becomes quite warm from the middle of the February. Rainfall over the country during winter is very scanty and does not exceed 5% of the yearly total. The driest month of the season is December when the northern and the western districts get hardly 3-10 mm of rainfall; the coastal districts of Barisal, Noakhali, Chittagong and Chittagong Hill Tracts get 15-30 mm of rain. With the progress of the season, the rainfall increases over the whole of the country (https://www.climatetestotravel.com/climate/Bangladesh).

Figure 2.5: Winter in Bangladesh

2.4 Thunderstorm

2.4.1 Definition of Thunderstorm

Thunderstorm is a storm characterized by the presence of lightning and its acoustic effect on the earth atmosphere. It is also known as thundershower. It occurs from cumulonimbus cloud. They are accompanied by strong winds, heavy rain and sometimes hail, sleet, snow, in contrast no rain at all. Thunder is caused by the sudden heating (and therefore expansion) of air due to lightning, so it is not possible to have thunder without lightning having occurred first. Thunderstorm results from rapid movement of moist, warm air, sometimes along a front. It can form and develop in any geographic location but mostly at mid-latitude, where moist, warm air collides with cooler polar air. Most commonly, thunderstorms last between 30 and 90 minutes (https://www.en.m.wikipedia.org/thunderstrom). Thunderstorm develops in Bangladesh during pre-monsoon. This severe storm is associated with convective instability. Litta et *al.* (2008) reported that thunderstorm develop due to high instability. Thunderstorms are responsible for the development of great weather phenomena. Thunderstorms and the phenomena which occur with them cause great hazards. Strong thunderstorms can cause tornados and waterspouts.

Figure 2.6: Thunderstorm

2.4.2 Types of thunderstorm

Thunderstorm variation depends on atmospheric profiles, especially those concerned with vertical wind shear, defined as the change in wind velocity (speed or direction) with height, or dV/dZ. There are four types of thunderstorms:

a) Single-cell
b) Multicell cluster
c) Multicell lines (Squall lines)
d) Supercell

a) Single-cell storms:

Single-cell thunderstorm is a common and usually non-severe phenomenon that forms away from frontal systems or other synoptic-scale disturbances. They form where moist and unstable conditions exist in the atmosphere.

Single-cell thunderstorms are usually produced in areas of very little vertical shear. It moves with mean environmental wind over 5-7 km. Its duration is 30- 60 minute. Rainfall can be moderate to heavy, small hail is possible. Single cell thunderstorms, in their pure sense, are rare. Most thunderstorms are at least weakly multicellular. Single cell storms usually indicate thunderstorms that form in very weak shear environments with new storms forming in an unorganized manner.

Figure 2.7: Single-cell storms

b) Multicell cluster storms:

Multicell storms (MCS) have series of evolving cells, forming on right or right rear flank about every 15-30 minutes. New cells eventually dominate. Motion may deviate from mean winds due to new cell regeneration. New cells form where the low-level mesoscale convergence is strongest. Precipitation is moderate to heavy; hail is usually present; short-lived tornadoes may form along the gust front or underneath rapidly developing updrafts. An MCS, or mesoscale convective system, is a cluster of thunderstorms that persist and evolve like multicells. MCS's generally move with the mean 700-500 mb layer wind.

Figure 2.8: Multicell cluster storms

c) Multicell lines (Squall lines):

A squall line is a group of storms arranged in line, often accompanied by ―squall" of high wind and heavy rain. Squall lines pass quickly. They are less prone to produce tornados than are supercells. Squall line is a line of thunderstorms that have common lightning mechanism. They can be 100 miles long. But normally occurs as only 10 to 20 miles. The _gust front' underneath squall line acts as a mini front. The classic squall line wills develop ahead of and parallel to cold front or at dry line boundary. The storms first develop where there is the best combination of moisture, lift and instability. The storms will continue to evolve and new cell will develop.

Figure 2.9: Squall lines

d) Supercell storms:

Supercell storms are most dangerous because of strong winds, hail and long-lived or multiple tornadoes. A single supercell can last several hours. The updraft has a continuous feed of inflow air. Wind shear vector typically veers (turns clockwise) with height in the boundary layer. Propagation is continuous rather than discreet. The storm usually travels slower and to the right of the mean wind. Research found average maximum size of multicell hailstone of 1.9 cm, while supercell is 5.3 cm. Average hail swath is 10 km and 20.2 km for the multicell and supercell storms, respectively. The supercell is resulting from an intense, moist, convective updraft.

Figure 2.10: Supercell storms

2.4.3 Life Cycle of Thunderstorm

A basic thunderstorm (single-cell) goes through three phases during its life time. They are:

a. Initial stage
b. Mature stage
c. Dissipating stage

These stages last between 30 minutes to an hour.

a. Initial Stage:

Initial stage starts with a warm plume of rising air. Single grows cloud-filled with updraft. The updraft velocity increases with height. Entrainment pulls outside air into the cloud. Super-cooled water droplets are carried far above freezing level. Usually there is a little if any rain during this stage. This stage lasts about 10 minutes. Occasional lightning occurs in this stage. No downdraft occurs in this stage.

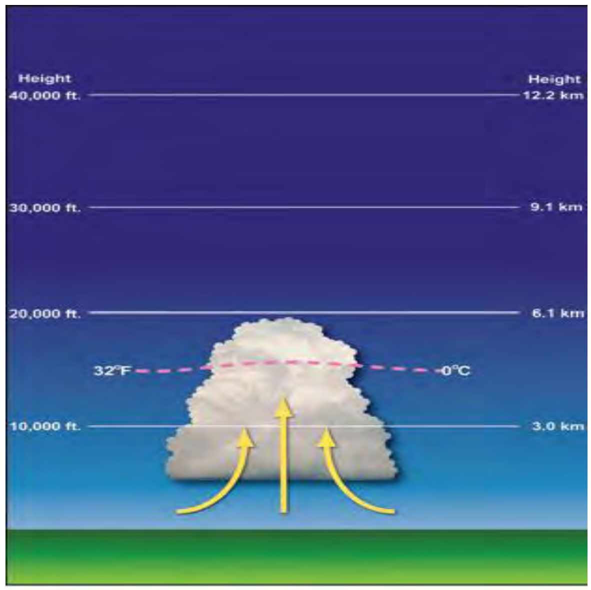


Figure 2.11: Initial stage

b. Mature Stage:

In mature stage the heaviest rains occur. Most likely hail, heavy rain, frequent lightning, strong winds, and tornadoes occur. Storm occasionally has a black or dark green appearance. Lasts an average of 10 to 20 minutes but some storms may last much longer.

Large raindrops/ice particles fall from updraft. They drag air down with them to form downdraft.

Evaporative cooling leads to negative buoyancy. Weight of raindrops and cooling by evaporation of rain keep downdraft air heavy as it plummets to ground. Updraft reaches max height at top of conditionally unstable layer at tropopause, spreads as anvil of ice crystals.

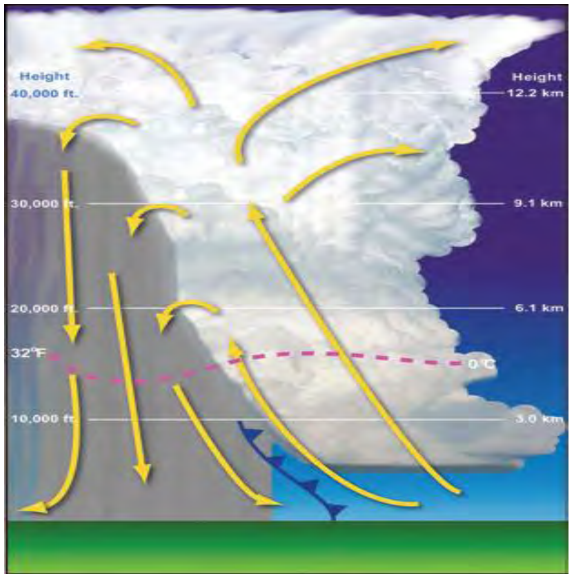


Figure 2.12: Mature stage

c. Dissipating Stage:

In this stage the downdraft takes over entire cloud. Downdrafts, downward flowing air, dominate the storm. Downdraft chokes off low-level updraft. Low-level cloud evaporates to leave only anvil. The storm deprives itself of supersaturated updraft air. After the cloud evaporates, rainfall decreases in intensity. But still produce a burst of strong winds. Lightning remains a danger.

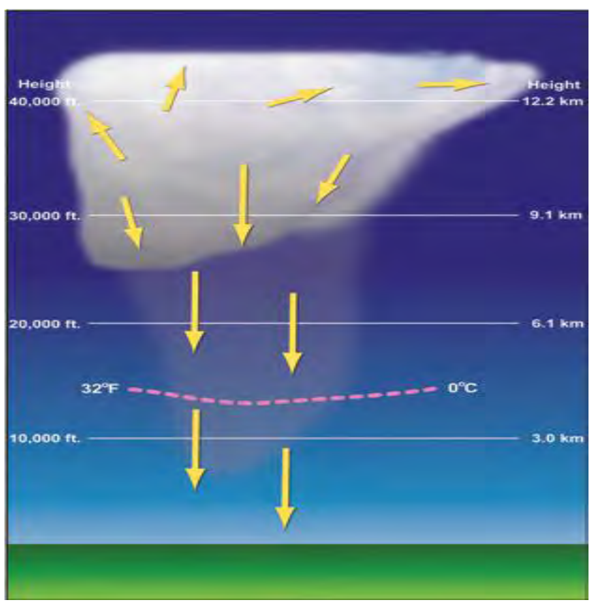


Figure 2.13: Dissipating stage

2.5 Environment for Thunderstorm Occurrence

As a general rule, surface based thunderstorm occurrence is the surface dew point needs to be 12.778 degrees Celsius or greater. A dew point of less than this is unfavorable for thunderstorms because the moist adiabatic lapse rate has more stable parcel lapse rate at colder dew points. Dew points at the surface can be less than 12.778 degrees Celsius in the case of elevated thunderstorms. According to meteorologist Jeff Haby, there are three ingredients that must be present for a thunderstorm to occur. They are:

1. Moisture
2. Instability
3. Lifting

Additionally, there is a fourth ingredient (Wind shear) for severe thunderstorms and each is covered separately and in-depth farther down:

1. **Moisture**:

A thunderstorm will form first and develop toward the region that has the best combination of: high PBL moisture, low convective inhibition, CAPE and lifting mechanisms. Low level moisture is assessed by examining boundary layer dew points. Severe thunderstorms are more likely when the surface dew point is 12.778° C or higher, all else being equal. Low dew point values inhibit sufficient latent heat release and significantly reduce the tornado threat. While a lack of moisture in the lower troposphere reduces the severe storm threat, a lack of moisture in the middle troposphere is helpful to the severe storm threat if there is abundant moisture in the lower troposphere.

2. **Instability**:

Instability also decreases as low-level moisture decreases. Instability occurs when a parcel of air is warmer than the environmental air and rises on its own due to positive buoyancy. Instability is often expressed using positive CAPE or negative LI values.

Instability is what allows air in the low levels of the atmosphere to rise into the upper levels of the atmosphere. Without instability, the atmosphere will not support deep convection and thunderstorms. Instability can be increased through daytime heating.

Very often, instability will exist in the middle and upper levels of the troposphere but not in the lower troposphere. Low level stability is often referred to as negative CAPE, convective inhibition, or the cap.

3. **Lifting**:

It is lift that allows air in the low levels of the troposphere to overcome low level convective inhibition. Lift is often referred to as a trigger mechanism.

There are many lift mechanisms. A list of many of them follows: fronts, low level convergence, low level WAA, low level moisture advection, mesoscale convergence boundaries such as outflow and sea breeze boundaries, orographic upslope, frictional convergence, vorticity, and jet streak. All these processes force the air to rise. The region that has the greatest combination of these lift mechanisms is often the location that storms first develop.

2.6 Rainfall

2.6.1 Definition of Rainfall

Rainfall is a form of moisture falls to the earth. Rainfall occurs when water vapor cools. When air reaches the saturation point water vapor condenses and formed tiny droplet of water. These tiny droplets of water produce clouds. Complex forces cause water droplets to fall as rainfall.

2.6.2 Causes of Rainfall in Bangladesh

There are many causes of rainfall in Bangladesh. Few important causes are given below:

a. Convection
b. Relative humidity
c. Orographic effects

a. **Convection**:

Rainfall occurs due to convection when the sun heats the water source to the point that the water turns into vapor and rises. By the time it reaches the condensation level, the vapor cools enough to turn back into water and falls in the form of rain. Most rainfall in Bangladesh occurs due to convection.

b. **Relative humidity**:

Relative humidity is the amount of moisture in the air compared to what the air can hold at that time i.e. indicates how most the air is. Relative humidity = (Actual vapor density/ Saturation vapor density) × 100%

c. **Orographic effect**:

The orographic effect is the changes in the atmosphere conditions caused in elevation, primarily due to mountains. In Bangladesh south-east part (Chittagong) and north-east part (Sylet) shows this kind of effect.

CHAPTER THREE

DATA AND METHODS

3.1 Data Sources and Duration

In this study, the thunderstorms and rainfall data from 34 stations of Bangladesh Meteorological Department (BMD) is used for the pre-monsoon period.

Study Period: 28 years (1990-2017)

3.2 Data Description

3.2.1 Stations Data for Thunderstorm Measurement

For measuring thunderstorm occurrence frequency, Bangladesh Meteorological Department (BMD) 34 stations data in pre-monsoon season is used [no data are available for March 1992, 1993 and 2011 and stations (Bhola, Sayedpur, Kutubdia, Maijdee Court, Sandwip, Teknaf) during March (1990-2017)]. Bangladesh Meteorological Department (BMD) archived data for thunderstorm frequency as date; time in UTC, events (gusty, squall and hail), wind speed in kts/kph and direction of the thunderstorms.

3.2.2 Rain Gauge Data

Rain gauge is a meteorological device which determines the depth of precipitation (usually in mm) that occurs over a unit area (usually one meter square) over a set period of time. In this way rainfall amount is measured. The level of rainfall sometimes reported in centimeters or inches. BMD used recording type rain gauge. BMD has 34 rain-gauges all over the country. These stations are (Dhaka, Feni, Chandpur, Chattogram, Bhola, Sylhet, Sayedpur, Khulna, Kutubdia, Cox's Bazar, Hatiya, Jashore, Barishal, Patuakhali, Khepupara, Bogura, Rangpur, Rajshahi, Mongla, Ishurdi, Faridpur, Mymensingh, Tangail, Dinajpur, Maijdee Court, Sandwip, Teknaf, Srimangal, Satkhira, Rangamati, Cumilla, Sitakunda, Madaripur, Chuadanga). The locations of these 34 stations are shown in Figure 3.1. In this study, 3-hourly rain-gauge data is used to analyze and comparison of rainfall. Rain-gauges have some limitations. Only localized area rainfall can be measured by rain-gauge. Data have been collected from BMD, Agargaon, Dhaka.

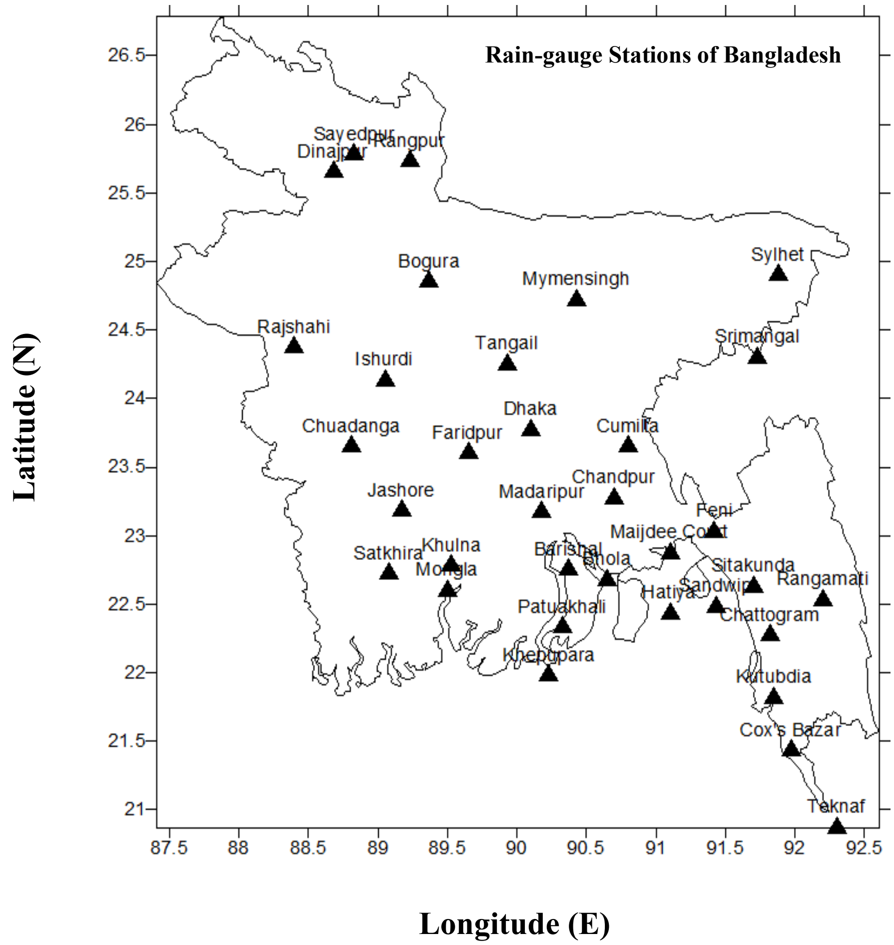


Figure 3.1: Locations of 34 rain-gauge stations of Bangladesh Meteorological Department (BMD)

3.3 Methods of Analysis

The sub-daily, daily, monthly and yearly thunderstorm frequency was extracted from the Bangladesh Meteorological Department station data during 1990 to 2017 over Bangladesh.

Details analysis of variation of pre-monsoon thunderstorm frequency will be carried out using statistical method. From station data, the spatial (regional) variation of thunderstorm frequency, average wind speed and propagation direction was also studied.

According to propagation speed, the thunderstorm occurrences was categorized into two types—Severe (horizontal wind speed >64 km/h) and Ordinary (horizontal wind speed ≤ 64 km/h) as proposed by Saha et *al.* (2014) for Kolkata and Gangatic West Bengal. Categorization of these two types of thunderstorms comes primarily from the wind profile in conjunction with the instability condition of the atmosphere was shown by Saha et *al.* (2014). The thunderstorm and non-thunderstorm days in Bangladesh will be evaluated from the BMD data during pre-monsoon season. Daily thunderstorm frequency will further be correlated with BMD daily rainfall data using statistical method.

Microsoft Excel software was used for statistical analysis. Result was displayed using a variety of graphical technics (e.g. Line and bar graphs, shaded contours, vectors, grid boxes etc.). For spatial analysis Surfer software was used.

3.3.1 Hourly Variation of Thunderstorm Frequency

During pre-monsoon season hourly variation (00, 01, 02, 03, 04, 05, 06, 07, 08, 09, 10, 11, 12, 13, 14, 15 ,16 , 17, 18, 19, 20, 21, 22, 23 UTC) (LST+6 hours) of thunderstorm occurrence frequency can be found by below commands.

For March, to get hourly variation the command AVERAGE was used. Similarly for April and May the same commands were used. But the ranges of numbers are different for each case.

For pre-monsoon season the command AVERAGE was used also. This showed the summation of these three months for the years 1990-2017.

3.3.2 3-hourly Occurrence Frequency of Thunderstorms

In this study, 3-hour interval (00-03, 03-06, 06-09, 09-12, 12-15, 15-18, 18-21 and 21-23) thunderstorm frequency is measured for 28 years.

For 3-hour interval showed the change in thunderstorms for each three hours of the day. Like hourly case same method was used here. The command AVERAGE was used to know the thunderstorm frequency.

3.3.3 Daily Variation of Thunderstorm Frequency

In this present study, daily thunderstorm frequency for March (1-March to 31-March), for April (1-April to 30-April), for May (1-May to 31-May) has been measured.

For March, the summation of thunderstorm frequency measured from 1-March to 31-March and the AVERAGE command was used for 28 years. Similar methods were used for April and May.

During pre-monsoon same command was used but it showed the variation in these months.

3.3.4 6-hourly Thunderstorm Frequency

There are 34 meteorological stations considered in the study. The 6-hour interval (00-06, 06-12, 0-12-18, 18-23) thunderstorm frequency measured in this research during (1990-2017). For measuring this commands in below were used:

Like hourly, 3-hour interval and daily measurement of thunderstorm frequency for 6-hour interval the AVERAGE commands were used for March, April and May.

But it was slightly different from above cases. Because this data was measured individual 34 stations where the above cumulatively data for overall Bangladesh was used.

3.3.5 Gusty, Squall and Hail Thunderstorm's Variation

3.3.5.1 Yearly Variation of Gusty, Squall and Hail Thunderstorms

During the thunderstorm sometimes gusty or squall or hail occurs simultaneously. In the study, with observation of thunderstorm these three types of hazards are also measured.

- The gusty wind is measured by averaging over the months of March, April and May from 1990 to 2017.
- The squall is measured by averaging over the months of March, April and May from 1990 to 2017.
- The hail is measured by averaging over the months of March, April and May from 1990 to 2017.

3.3.5.2 Station-wise Variation of Gusty, Squall and Hail Thunderstorms

Bangladesh Metrological Department sub-categorizes their thunderstorms data in the following types:

a. Gusty:

Gusty is one kind of wind with short-bursts with high speed. The average wind speed is about 33 km/h.

b. Squall:

Squall is sharp and sudden increase in wind speed that is usually associated with active weather, such as rain shower, thunderstorm. The average wind speed is about 48 km/h.

c. Hail:

Hail is large, layered ice particles, often spherical in shape, which produced by thunderstorm and has tilted, strong updraft and wind speed is very high (https://www.weatherquestion.com). Often hail occurs in the presence of storms (Bielec et *al*. 2003).

For 34 meteorological stations gusty, squall and hail were measured. From station data the precise change in these events can be measured. By using this method showed which station had different events more or less. For station-wise variation below commands were used.

During pre-monsoon season, for gusty wind, squall and hail the command were used=AVERAGE with mention the starting to end number.

3.3.6 Wind Speed Associated with Thunderstorms

3.3.6.1 Yearly Variation of Wind Speed of Thunderstorms

For yearly variation in average wind speed (km/h) is measured precisely for 1990-2017.

By averaging the wind speed is measured for the month of March. Similarly for April and May the same command were used. For pre-monsoon average wind speeds showed the AVERAGE of three months with starting and ending number range.

3.3.6.2 Severe and non- Severe Thunderstorms

Yearly severe and non-severe thunderstorms were found by using AVERAGE command.

3.3.6.3 Station-wise Variation of Wind Speed of Thunderstorms

For stations- wise average propagation wind speed for 34 stations over Bangladesh were considered. By averaging wind speed of these stations wind speed of March, April and May were found for 1990-2017.

For March, April and May AVERAGE commands were used.

3.3.7 Variation of Wind Propagation Direction of Thunderstorms

In the study, for better understanding thunderstorm frequency the wind propagation directions (Northerly, North-westerly, North-easterly, Southerly, Easterly, Westerly etc.) were used for 28 years.

In the present study 13 wind propagation directions were indicated.

For each wind direction the AVERAGE command was used which showed variation in wind direction throughout the pre-monsoon season.

3.3.8 Counting of Thunderstorm Day and Non-thunderstorm Day

For counting thunderstorm day and non- thunderstorm commands were used,

For Thunderstorm Day:

For counting thunderstorm days the COUNT command was for March, April and May

For Non-thunderstorm Day:

For non-thunderstorm day the same COUNT was used. But the numbers of non-thunderstorm days were contrast of thunderstorm day.

3.3.9 Variation in Daily Average Rainfall

3.3.9.1 Yearly Variation of Daily Average Rainfall

In this study, daily average rainfall measurement also shown for same time period (1990-2017). The commands were used,

For measuring average rainfall in mm/day, the AVERAGE command was used throughout the pre-monsoon season.

3.3.9.2 Station-wise Variation in Monthly Average Rainfall

Station-wise variation in daily average rainfall was similar to yearly variation. The only difference was it consider for stations with 28 years variation.

The AVERAGE commands were used for the three months March, April and May.

3.3.10 Correlation Coefficient Formula

The correlation of coefficient measures the degree of linear relations between two variables say X and Y. Karl Pearson denoted it as ‗r‘.

$$r = \frac{\sum(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum(X_i - \bar{X})^2 \sum(Y_i - \bar{Y})^2}}.$$

Where, ≤X and ≤Y are the mean values of all X and Y respectively (https://uregina.ca>~gingrich> corr.).

3.3.11 General Equation of Straight Line

The general equation of a straight line is,

y= mx+ c

Where m is the gradient, and y= c is the value where the line cuts the y-axis. The number c is the intercept of the y-axis.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Variation in Pre-monsoon Thunderstorm Frequency

Variation of pre-monsoon thunderstorm occurrence frequency and its relation with rainfall during 1990-2017 over Bangladesh is discussed in this section.

4.1.1 Hourly Variation of Thunderstorm Frequency

In pre-monsoon there is great variation in hourly thunderstorm frequency. Figure 4.1 shows hourly thunderstorm frequency for the month of (a) March (b) April (c) May during 1990-2017. In March the maximum thunderstorm frequency (hourly occurrence number 2.27) is found on 14 UTC (LST+6 hours). The lowest (occurrence number 1.00) number of events is found on 00 UTC. In April maximum thunderstorm frequency (occurrence number 3.34) occurs on 15 UTC. The lowest thunderstorm frequency (occurrence number 1.60) is found on 00 UTC. In May the highest thunderstorm frequency (occurrence number 4.00) is found on 12 UTC and the lowest (occurrence number 1.67) on 00 UTC.

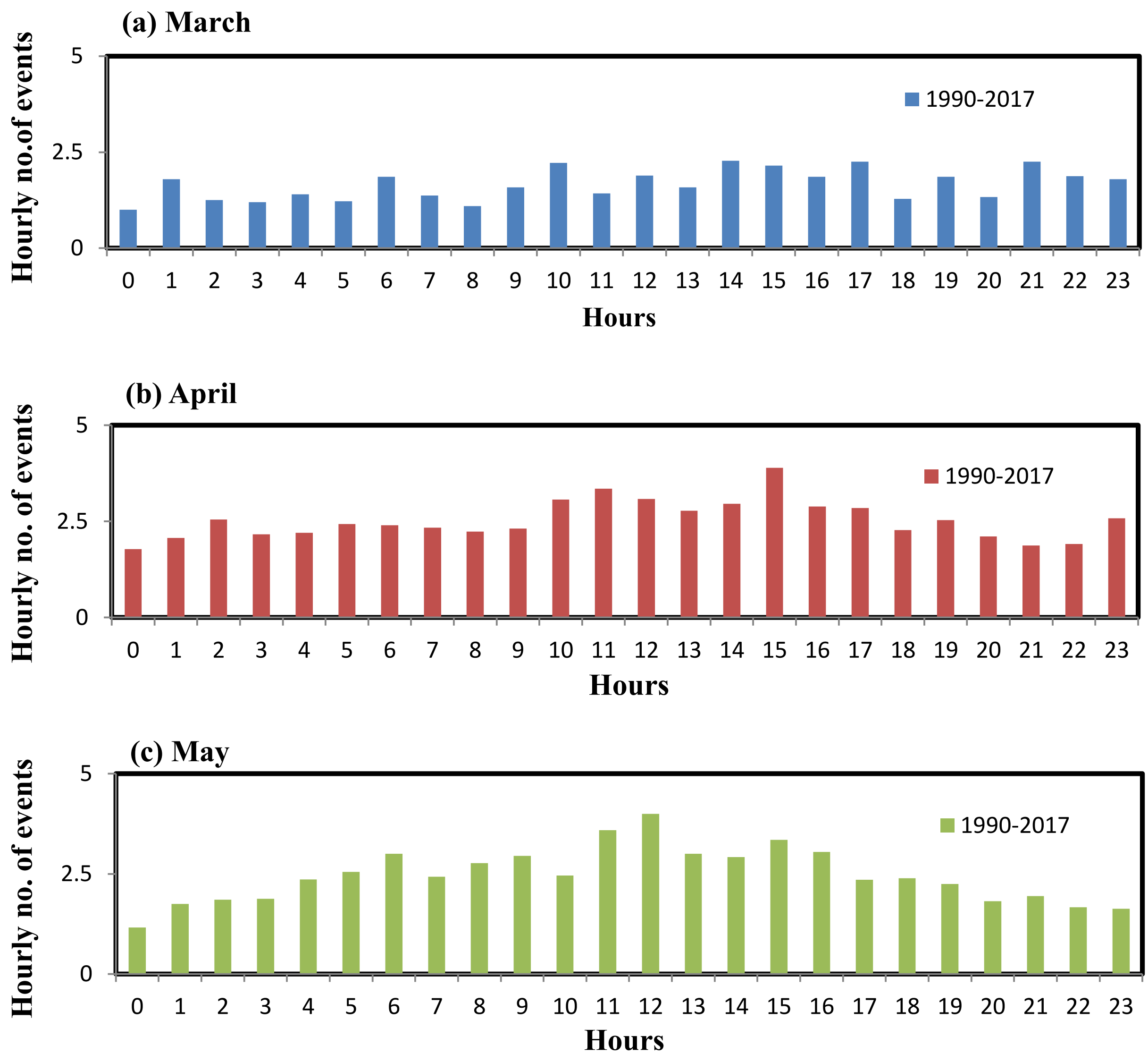


Figure 4.1: Hourly thunderstorm frequency during 1990-2017: (a) March (b) April (c) May

Figure 4.2 shows the hourly comparison of thunderstorm frequency for the months of March, April and May. Maximum thunderstorm (occurrence number 4.00) occurs in May at 12 UTC and minimum thunderstorm (occurrence number 1.00) is found in March at 00 UTC. Among the three months, the maximum occurrence is found in the month of May and minimum in March. This is quite expected as sun becomes more overhead from March to May. For this reason temperature increases (Chowdhury et *al*. 1995). Convection starts to develop and maximum occurrence is found around this time.

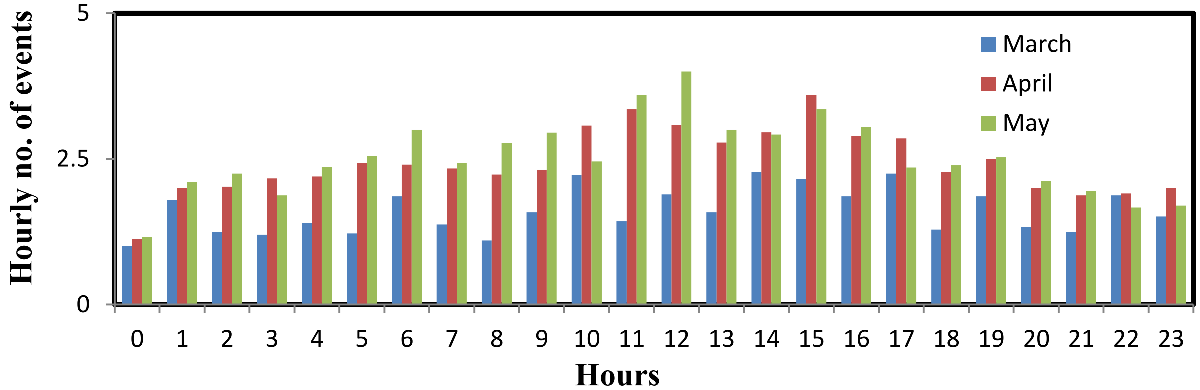


Figure 4.2: Comparison of monthly variation in thunderstorm during 1990-2017

4.1.2 3-hourly Occurrence Frequency of Thunderstorms

The three hourly occurrence frequencies of thunderstorms for the months of March, April and May is shown in Figure 4.3. The maximum occurrence of thunderstorm (occurrence number 7.61) for all months is found at 12-15 UTC and minimum occurrence (occurrence number 3.50) is found at 00-03 UTC. Most of the thunderstorms are occurred in May than that of in April and March. In the month of May the low level moist air from Bay of Bengal dominant significantly over Bangladesh, this may enhance occurrence of thunderstorms.

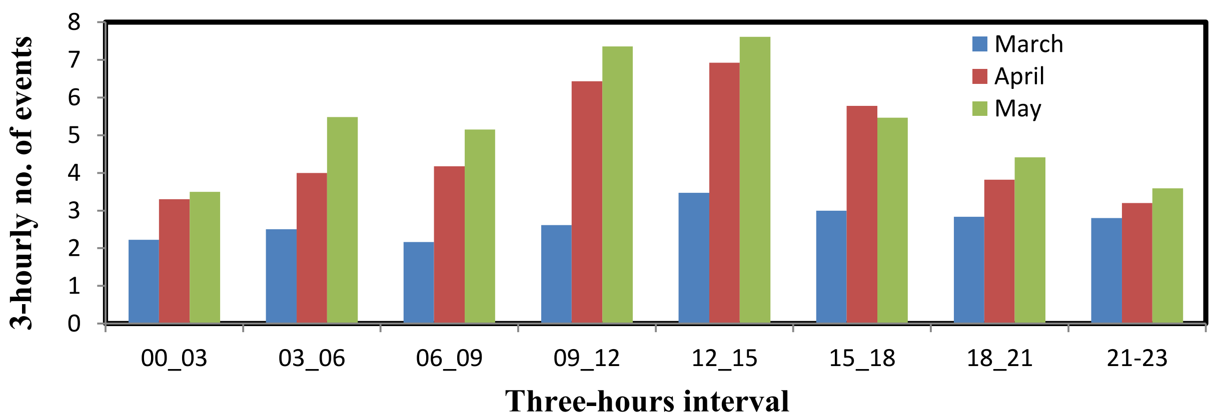


Figure 4.3: Three hourly occurrence frequency of thunderstorms during 1990-2017

4.1.3 Daily Variation of Thunderstorm Frequency

Daily occurrence of thunderstorm for the month of March, April and May is shown in Figure 4.4. Figure 4.4 indicates daily thunderstorm frequency (a) March (b) April (c) May during 1990-2017. In March, thunderstorm occurrence is found minimum for the first half of the month. For

March, after 22nd March thunderstorm activity increases during the study period, because in the starting of March there is an influence of winter seasonal activity. In April, maximum (occurrence frequency 12.11) number of events occur on 22nd April and minimum (occurrence frequency 5.31) on 2nd April. In May, highest (occurrence frequency 12.71) thunderstorm frequency appears on 1st May and the lowest (occurrence frequency 3.75) on 31st May. During last week of May the monsoonal activity starts to develop and hence, thunderstorm activity decreases.

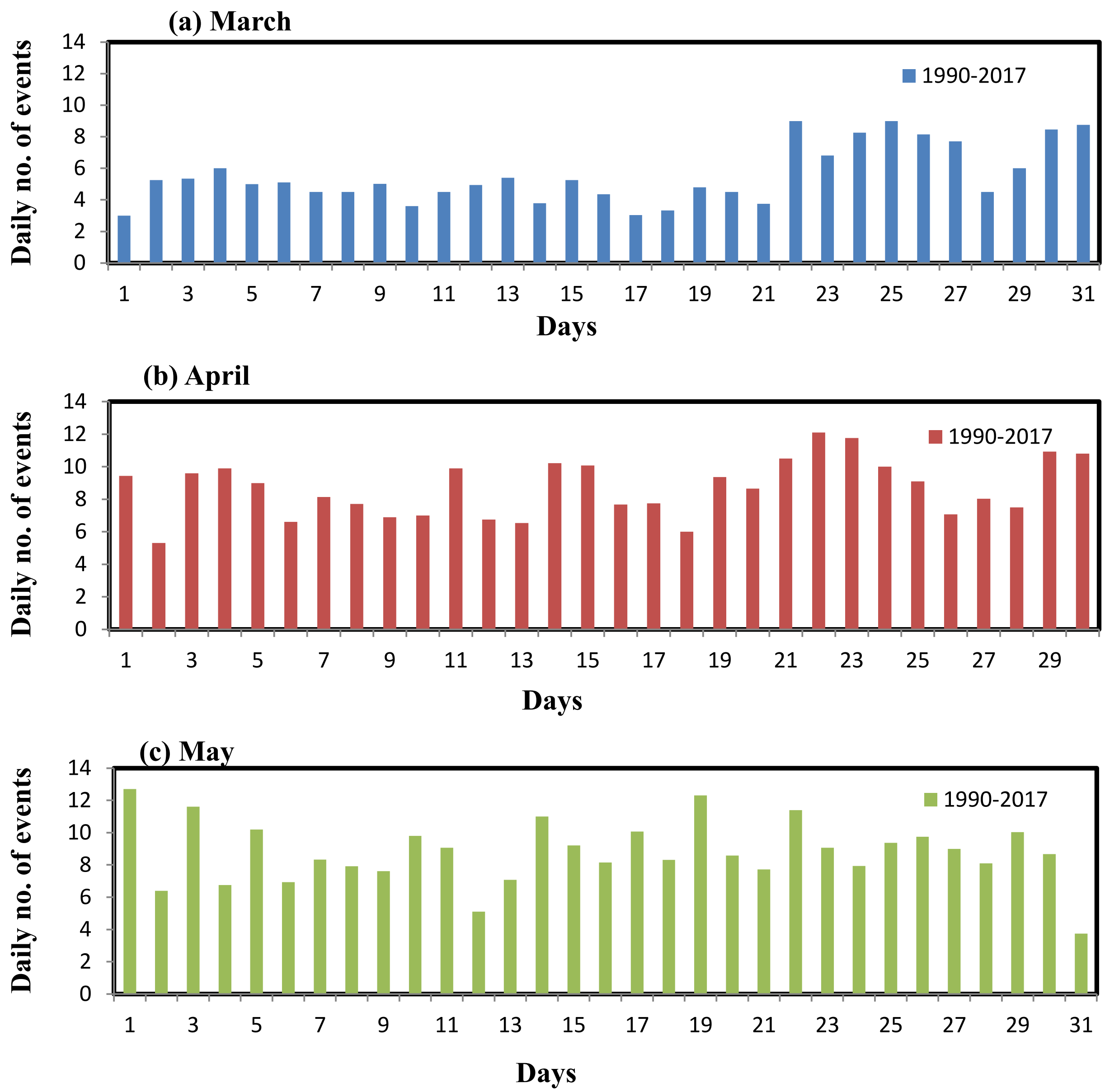


Figure 4.4: Daily thunderstorm frequency during 1990-2017: (a) March (b) April (c) May

Figure 4.5 indicates comparison of daily number of thunderstorms. The highest occurrence of thunderstorm is found in the month of May and lowest is found in the month of March.

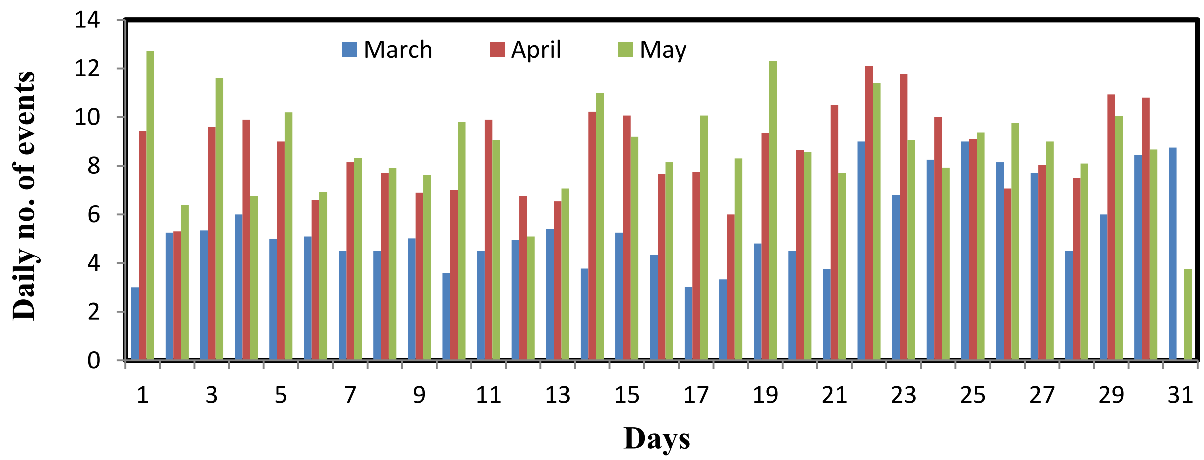


Figure 4.5: Comparison of daily number of thunderstorms during 1990-2017

4.1.4 6-hourly Thunderstorm Occurrence

Figure 4.6 shows the thunderstorm frequency variation during pre-monsoon season at 6-hour interval for different stations. In this study, maximum (occurrence number 3.14) thunderstorm frequency is found in Dhaka 12-18 UTC and minimum (occurrence number 0.07) is found in Feni and Dinajpur during the pre-monsoon season.

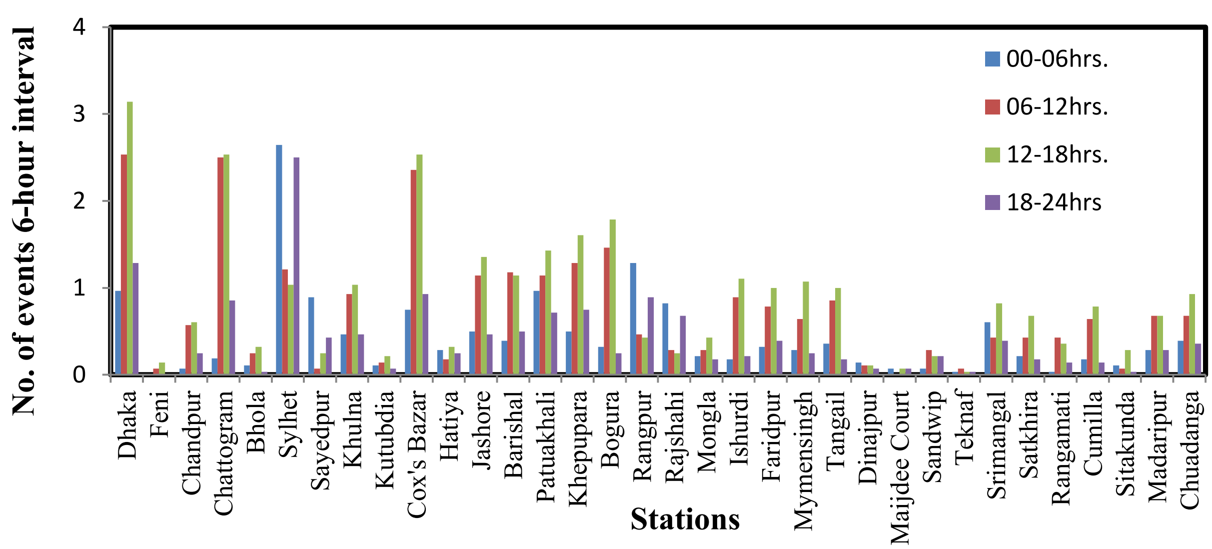


Figure 4.6: 6-hourly station-wise thunderstorm frequency variation during pre-monsoon

Figure 4.7 shows thunderstorm frequency for 6-hour interval during 1990-2017 during pre-monsoon season. In Bangladesh the maximum (occurrence number 9.90) occurrence is found at 12-18 UTC and the minimum (occurrence number 4.82) at 18-23 UTC.

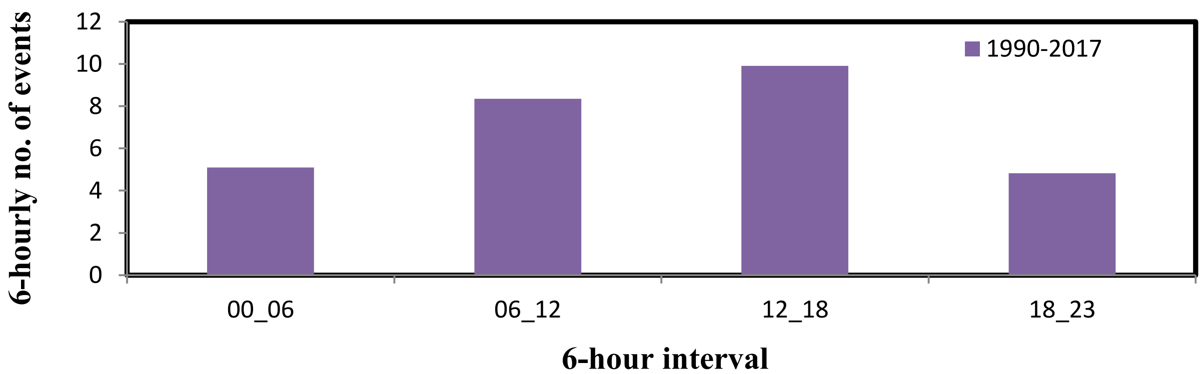


Figure 4.7: Thunderstorms frequency for 6-hour interval during 1990-2017 during pre-monsoon season

4.1.5 Gusty, Squall and Hail Thunderstorms Variation

4.1.5.1 Yearly Variation of Gusty, Squall and Hail Thunderstorms

The total yearly variation of gusty, squall and hail thunderstorms for the month of March, April and May is shown in Figure 4.8. There is strong yearly variation of different types of thunderstorm. In the month of March highest number gusty, squall and hail thunderstorm are found in the year of 2005 and lowest in 1990 and 1991, in April, the maximum events occurs in 2000 and minimum in 1991, and in May, maximum events appears in 2005 and lowest 1993.

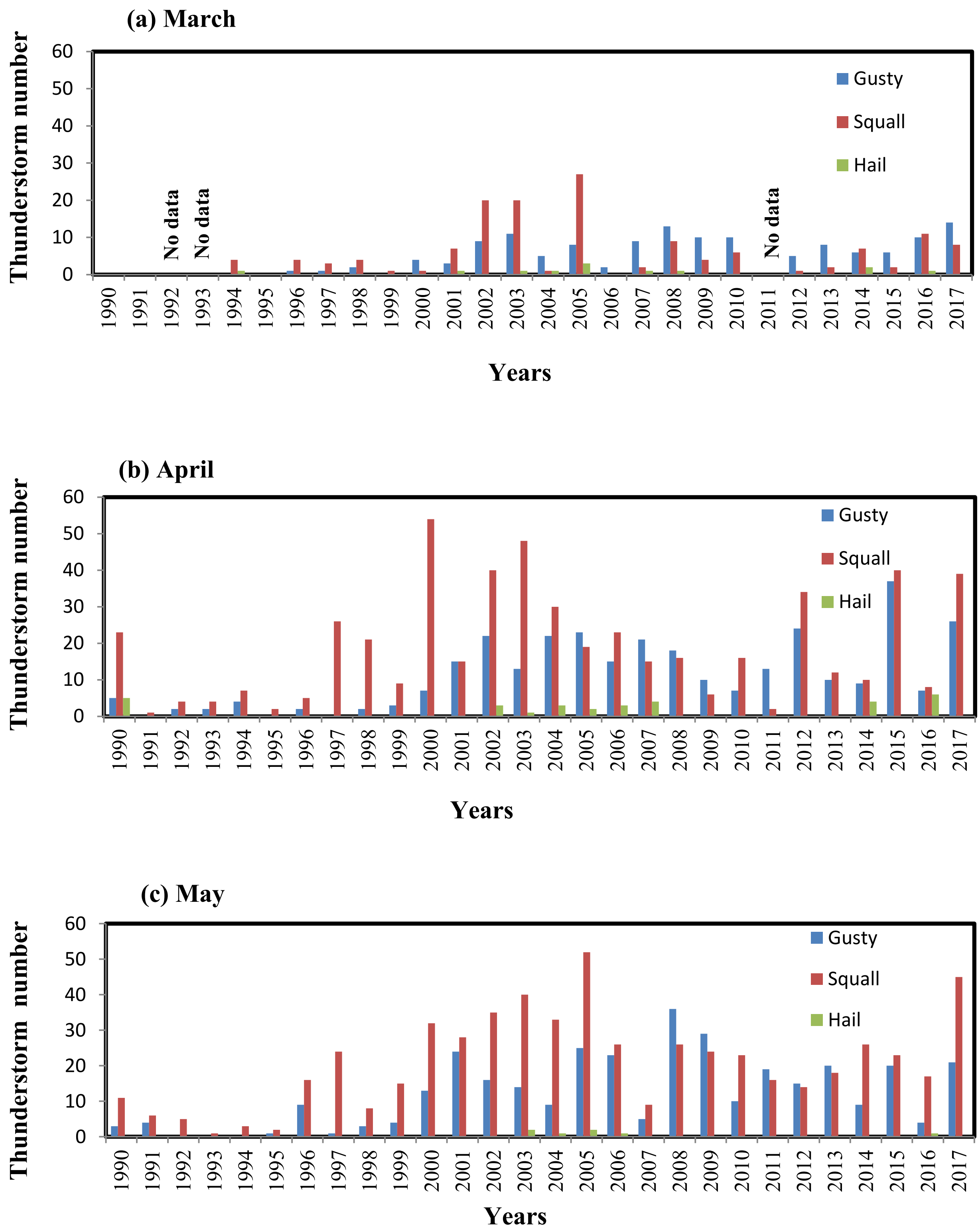


Figure 4.8: Yearly variation of gusty, squall and hail thunderstorms during 1990-2017: (a) March (b) April (c) May

Occurrence number of different type of thunderstorms during pre-monsoon is shown in Figure 4.9. In Bangladesh it is found that about 54% of thunderstorms are squall type, 39% gusty and remaining 7% are hail type during pre-monsoon. The percentage of squall is highest in May because the sun is more overhead compare to March and April, so temperature increases and deep convection develops. This helps to increase number of squall. Bangladesh is covered by many water bodies. For this reason moisture support also increases in May which causes squall type thunderstorm (Chowhury et *al*. 1995). Hail type thunderstorm is found more in the month of April.

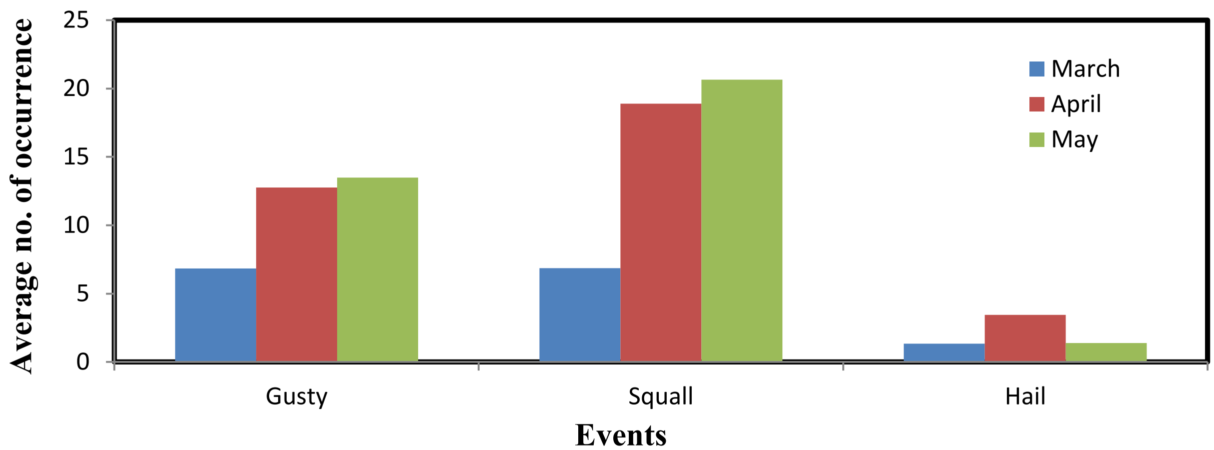


Figure 4.9: Variation of gusty, squall and hail thunderstorms during 1990-2017: (a) March (b) April (c) May

4.1.5.2 Station-wise Variation of Gusty, Squall and Hail Thunderstorms

The station-wise averagely variations of gusty, squall and hail type thunderstorms for different months are shown in Figure 4.10. During March maximum 51% squall type thunderstorms are found in Dhaka and lowest events are found in Feni, Dinajpur and Rangamati. In April, the number of gusty, squall and hail increases in each station than that of March. About 59% events are found in Dhaka station. During May, the number of gusty and squalls rises. But hail occurrence deceases than April. The highest events found in Dhaka and minimum in Feni, Teknaf and Maijdee Court.

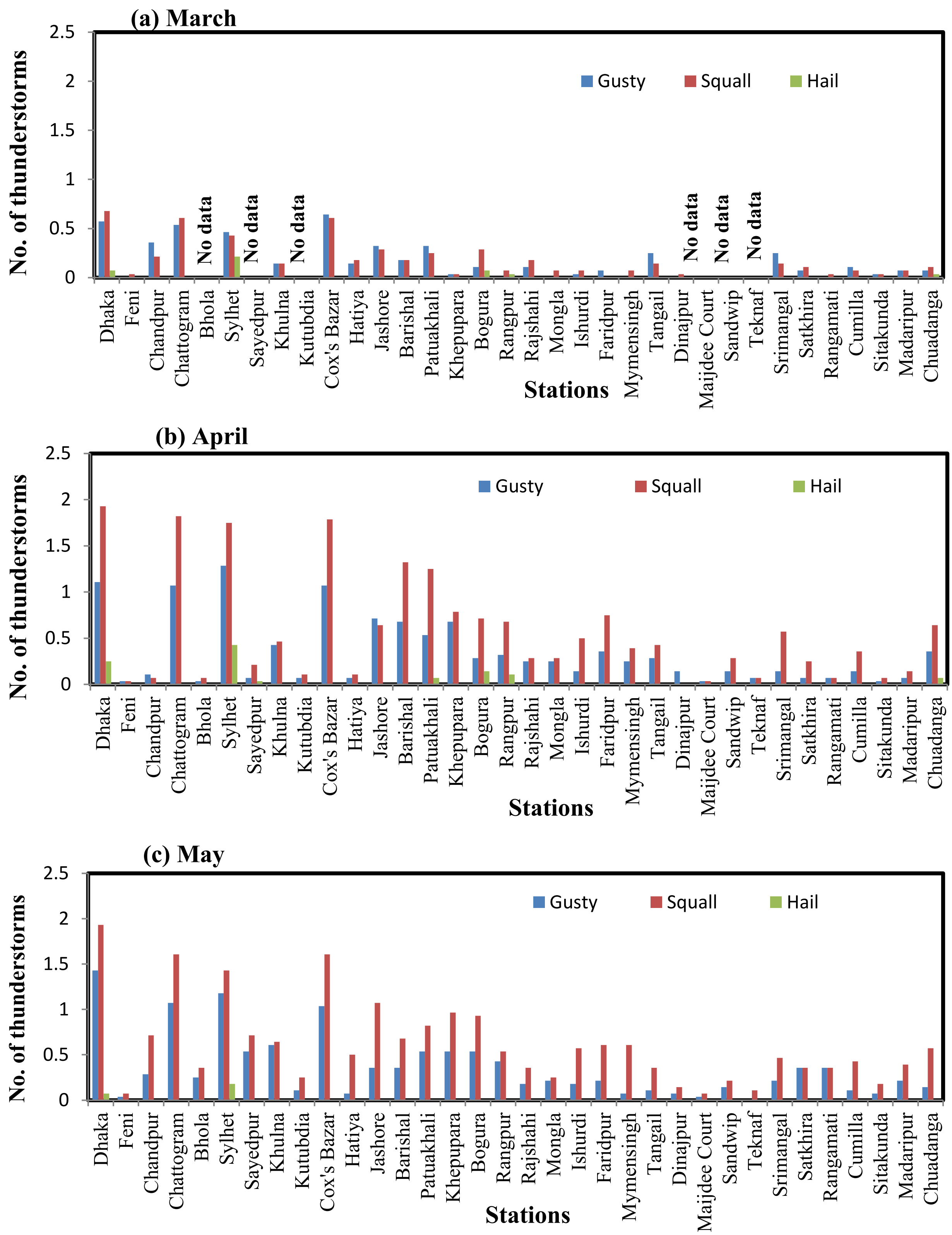


Figure 4.10: Station-wise variation of gusty, squall and hail thunderstorms during 1990-2017: (a) March (b) April (c) May

The Figure 4.11 indicates the variation of gusty, squall and hail type thunderstorm during pre-monsoon. During pre-monsoon maximum events occurs at Dhaka about 10% and minimum events occurs at Feni, Teknaf and Maijdee Court about 1%.

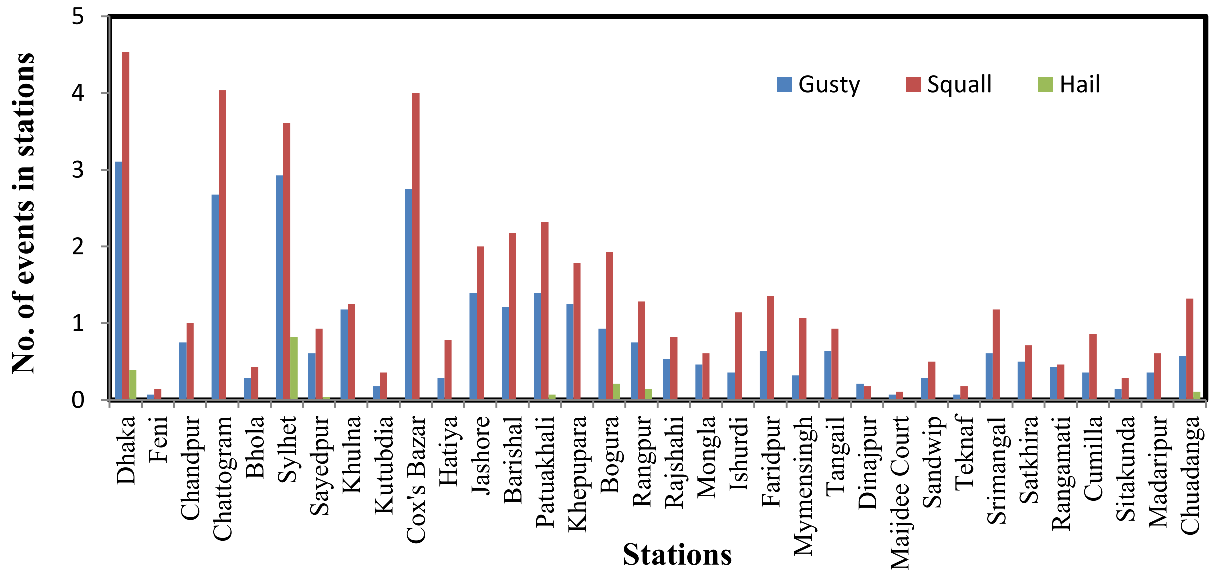


Figure 4.11: Station-wise variation in gusty, squall and hail during pre-monsoon season during 1990-2017

4.1.6 Spatial Distribution of Thunderstorms

Figure 4.12 shows spatial distribution of thunderstorms occurrence in the month of (a) March (b) April (c) May. During March highest thunderstorm occurrence is found in central part of Bangladesh (Dhaka) whereas lowest in Feni and Dinajpur. In April, maximum thunderstorm occurrence is found in Dhaka and Sylhet and minimum in Teknaf. In May, the highest thunderstorm founds in Dhaka and lowest in Feni, Teknaf and Maijdee Court. In general, the maximum occurrence is found in the northeastern (Sylhet) part of Bangladesh. Orography of the northeastern part of country plays important role for thunderstorm occurrence (Chowdhury et *al.* 1995). In addition, eastern and north-eastern part of country is more humid and hence convection develops.

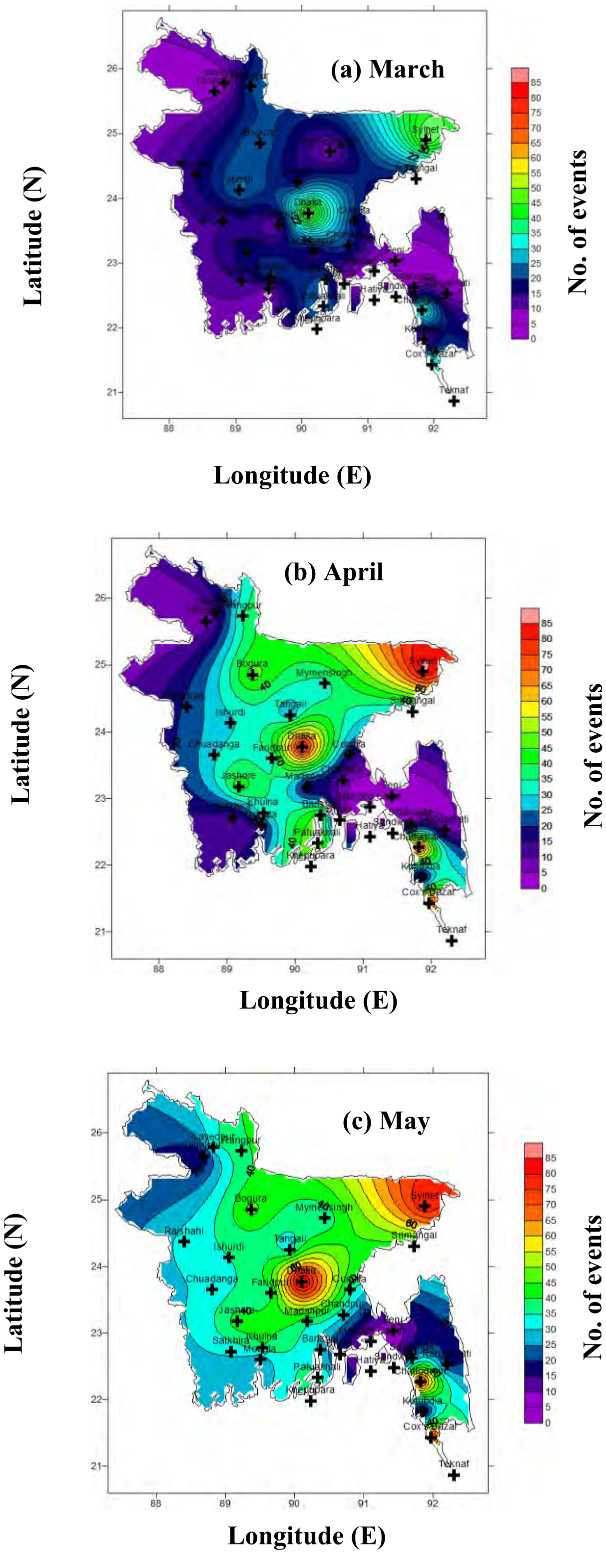


Figure 4.12: Spatial distribution of thunderstorms occurrence during 1990-2017: (a) March (b) April (c) May

The Figure 4.13 shows spatial distribution of thunderstorm during pre-monsoon season. During the pre-monsoon season the highest thunderstorm frequency occurs in central Bangladesh and northeastern part of the country.

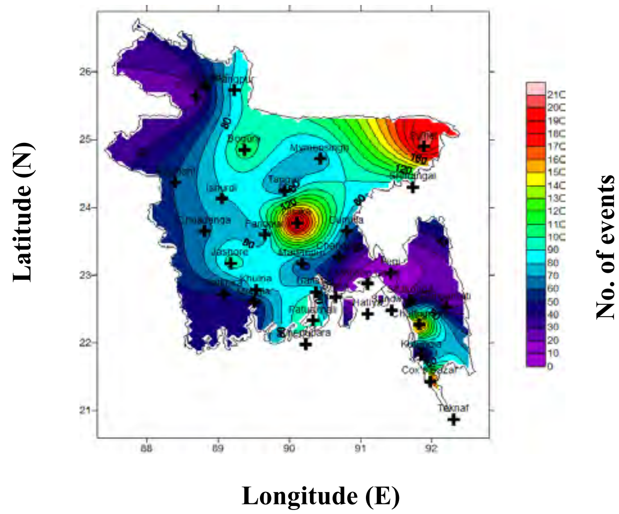


Figure 4.13: Spatial distribution of thunderstorm during pre-monsoon

4.1.7 Wind Speed Associated with Thunderstorms

4.1.7.1 Yearly Variation of Wind Speed in Thunderstorm

Figure 4.14 shows yearly variation of wind speed in thunderstorm for the month of (a) March (b) April (c) May. The yearly variation of wind speed in thunderstorms is very less except in 1991,1994 and 1993,1997 for the month of April and May, respectively. On the other hand, relatively, significant variation of wind speed of thunderstorms is found in the month of March.

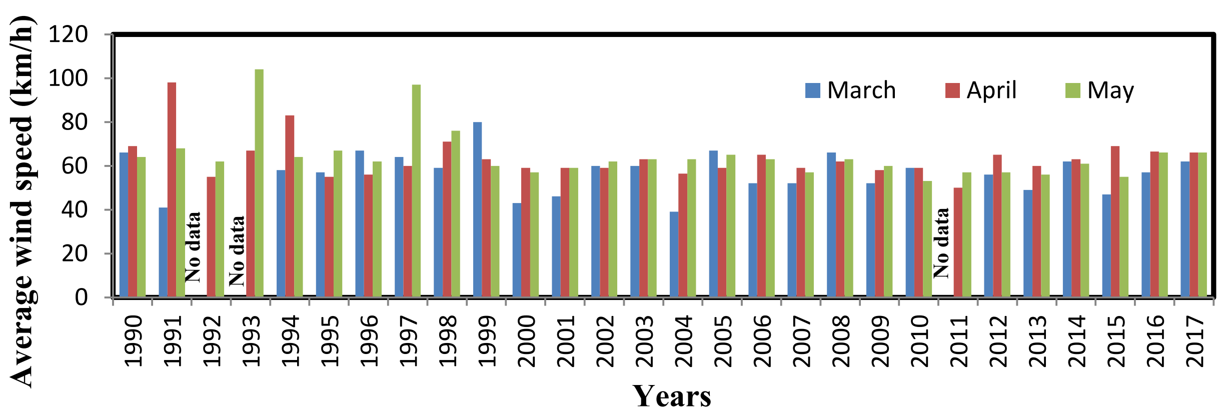


Figure 4.14: Yearly variation of wind speed associated with thunderstorm in (a) March (b) April (c) May

Figure 4.15 shows average wind speed associated with thunderstorm during pre-monsoon months. The wind speed of thunderstorm increases as the month progress. The increasing trend of wind speed is significant with coefficient of determination R^2= 0.9674. The monthly average wind speed of thunderstorms is found 57 km/h, 63 km/h, and 67 km/h, for the month of March, April and May, respectively. The average wind speed of thunderstorm in pre-monsoon is found 62 km/h.

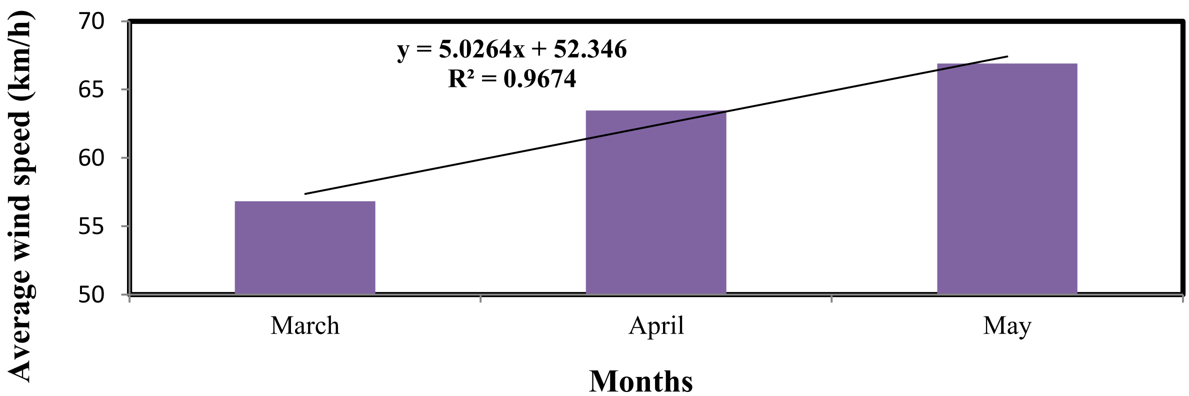


Figure 4.15: Average wind speed during pre-monsoon

4.1.7.2 Severe and Non- severe thunderstorms

Figure 4.16 shows yearly variation of severe and non-severe thunderstorms for the month of (a) March (b) April (c) May. In present study, the thunderstorms are classified into severe (> 64 km/h) and non-severe (≤ 64 km/h) based on their wind speed according to Saha et *al.* (2014). The occurrence of severe and non-severe thunderstorm is found maximum in the month of May in 1993 and March in 2004, respectively.

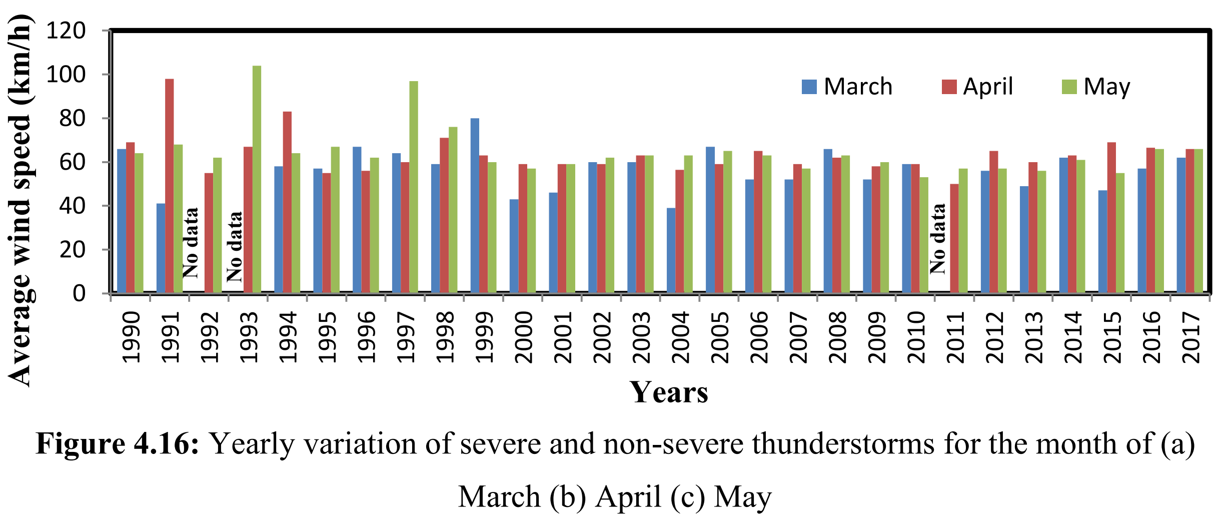


Figure 4.16: Yearly variation of severe and non-severe thunderstorms for the month of (a) March (b) April (c) May

4.1.7.3 Station-wise Variation of Wind Speed in Thunderstorms

Figure 4.17 shows station-wise of average wind speed in thunderstorms in (a) March (b) April (c) May. In March, maximum average wind speed in Mongla is 93 km/h. The lowest wind speed at Hatiya 38 km/h. In April, maximum average wind speed is 96 km/h in Teknaf and the lowest in Satkhira is 45 km/h. In May, maximum average wind speed is 98 km/h in Teknaf. The lowest in Cumilla is 47 km/h.

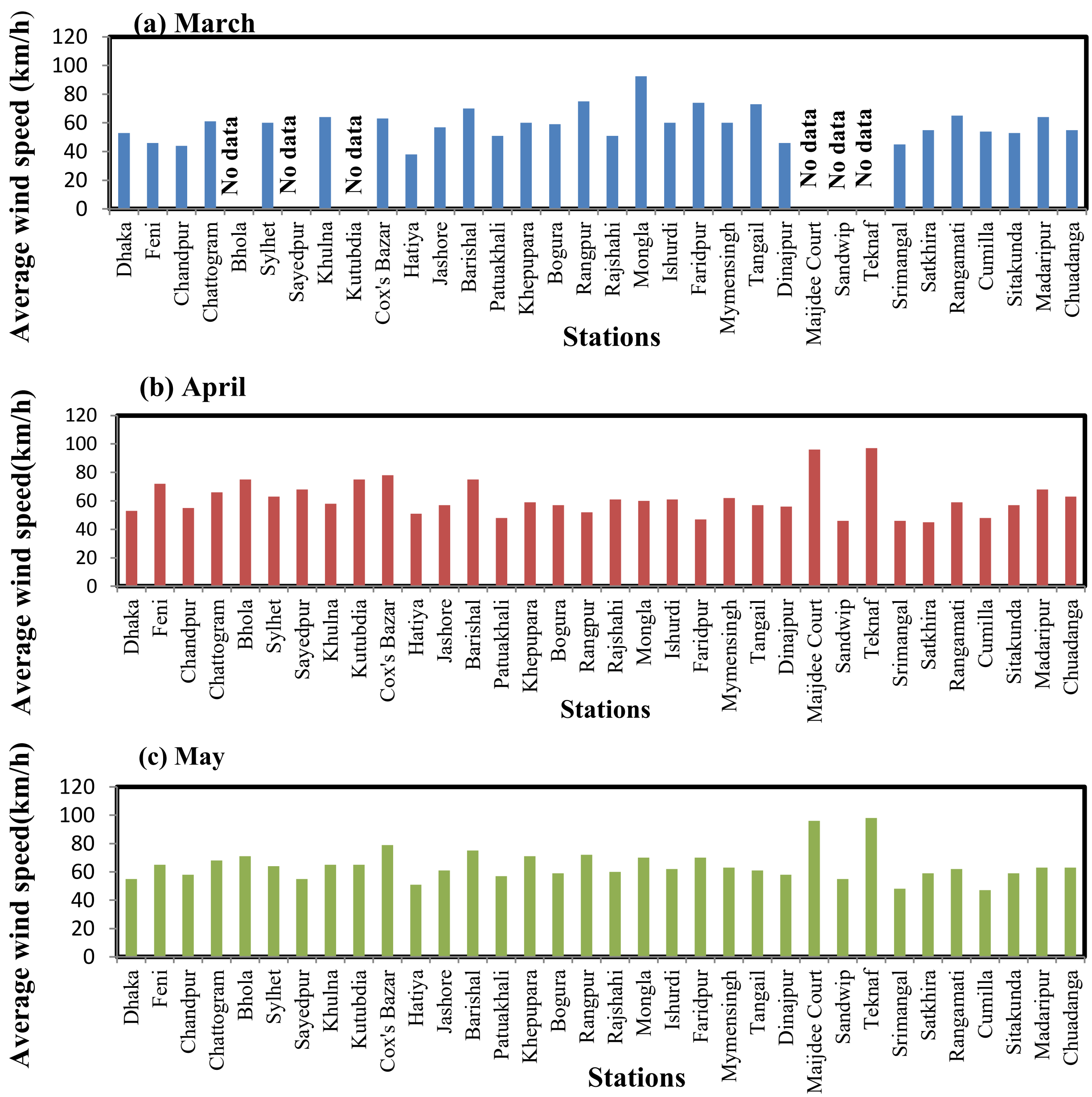


Figure 4.17: Station-wise variation of average wind speed of thunderstorms during 1990-2017: (a) March (b) April (c) May

Figure 4.18 indicates variation in average wind speed in thunderstorms in different stations during pre-monsoon. During pre-monsoon season the maximum average wind speed is found in May , medium in April and minimum in March. The highest average wind speed Teknaf in May is 98 km/h and lowest in Hatiya in March is 38 km/h.

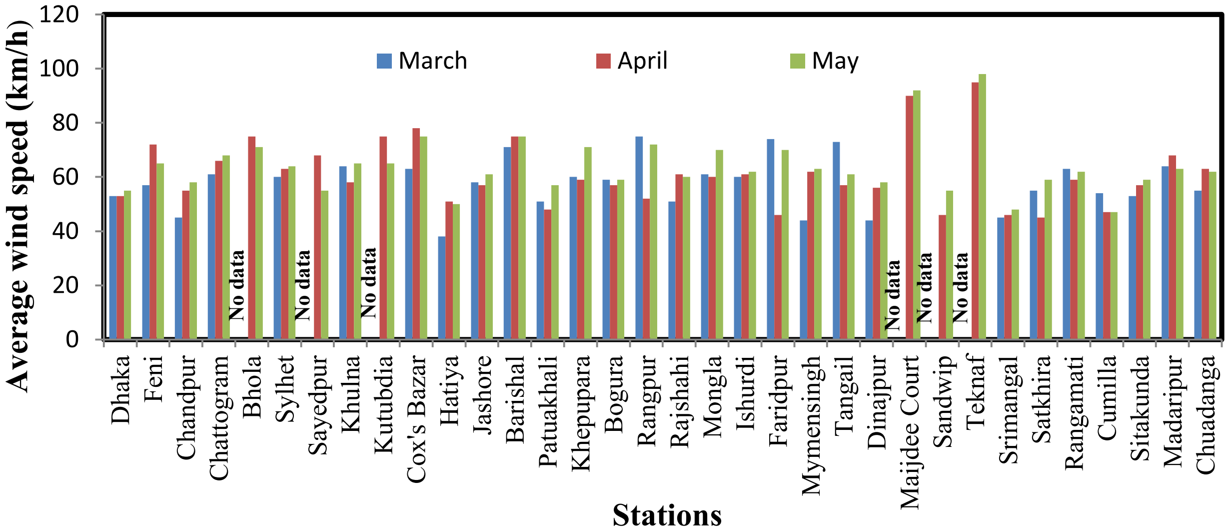


Figure 4.18: Station-wise variation in average wind speed of thunderstorms during pre-monsoon

4.1.8 Percentage of Propagation Direction of Thunderstorms during Pre-monsoon

Figure 4.19 shows the percentage of monthly propagation direction of thunderstorms during this period. In this study, propagation directions divided in 13 directions. They are northerly (N), north-westerly (NW), north-easterly (NE), northly/north-westerly (N/NW), northly/north-easterly (N/NE), southerly (S), south-westerly (SW), south-easterly (SE), westerly (W), westerly/north-westerly (W/NW), easterly (E),north-northeasterly (NNE), north-northwesterly (NNW) and west-northwesterly (WNW).

During March, the maximum thunderstorm propagates NW direction which is 18% (occurrence number 5). The lowest numder of thunderstorm propagates E, WNW, W/NW and N/NW. In April, the maximum thunderstorm propagates NW direction which is 29% (occurrence number 13). The minimum numder of thunderstorm propagates NNE, N/NE, WNW and W/NW. In May, the maximum thunderstorm propagates NW direction which is 31% (occurrence number 16). The mininum numder of thunderstorm propagates N/NW, WNW, W/NW and NNE.

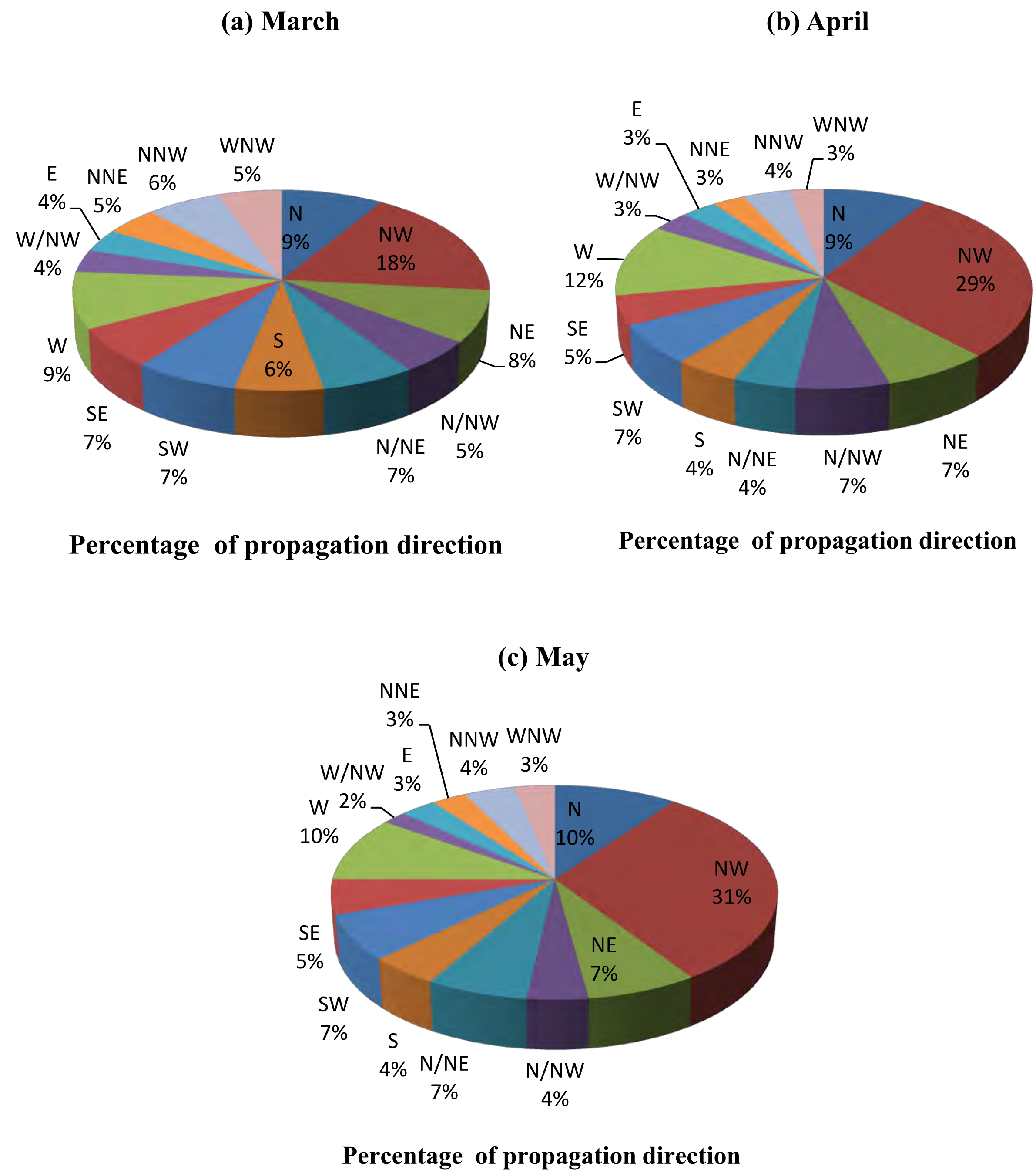


Figure 4.19: Percentage of propagation direction of thunderstorms during 1990-2017: (a) March (b) April (c) May

Figure 4.20 shows variation in propagation direction of thunderstorm during pre-monsoon. During pre-monsoon, the maximum (31%) thunderstorm comes from northwest. Which is called

Nor'westers or Kal-baishakhi. The minimum number (2%) of thunderstorm propagates W/NW. The number of thunderstorms propagate W, NE, N direction is 10%, 7% and 10% respectively.

In pre-monsoon, the midlevel wind is northwesterly, and in this season, thunderstorms are deep (Rafiuddin et *al.* 2013) and its propagation is partly controlled by this midlevel wind. Therefore, most of thunderstorm propagate southeastward.

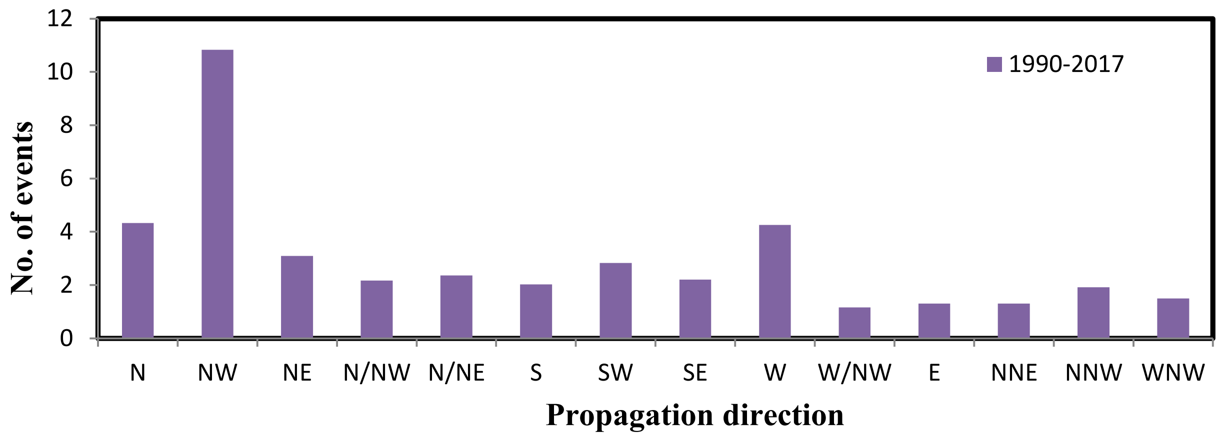


Figure 4.20: Variation of propagation direction of thunderstorms during pre-monsoon during 1990-2017

4.1.9 Variation of Thunderstorm Day and Non-thunderstorm Day

Figure 4.21 shows yearly variation of thunderstorm day and non-thunderstorm day for the month of (a) March (b) April (c) May. There is strong yearly variation of thunderstorm and non-thunderstorm days. It is found that thunderstorm days are increasing as the month progress from month of March. For all three months it is found that thunderstorm days show increasing trends.

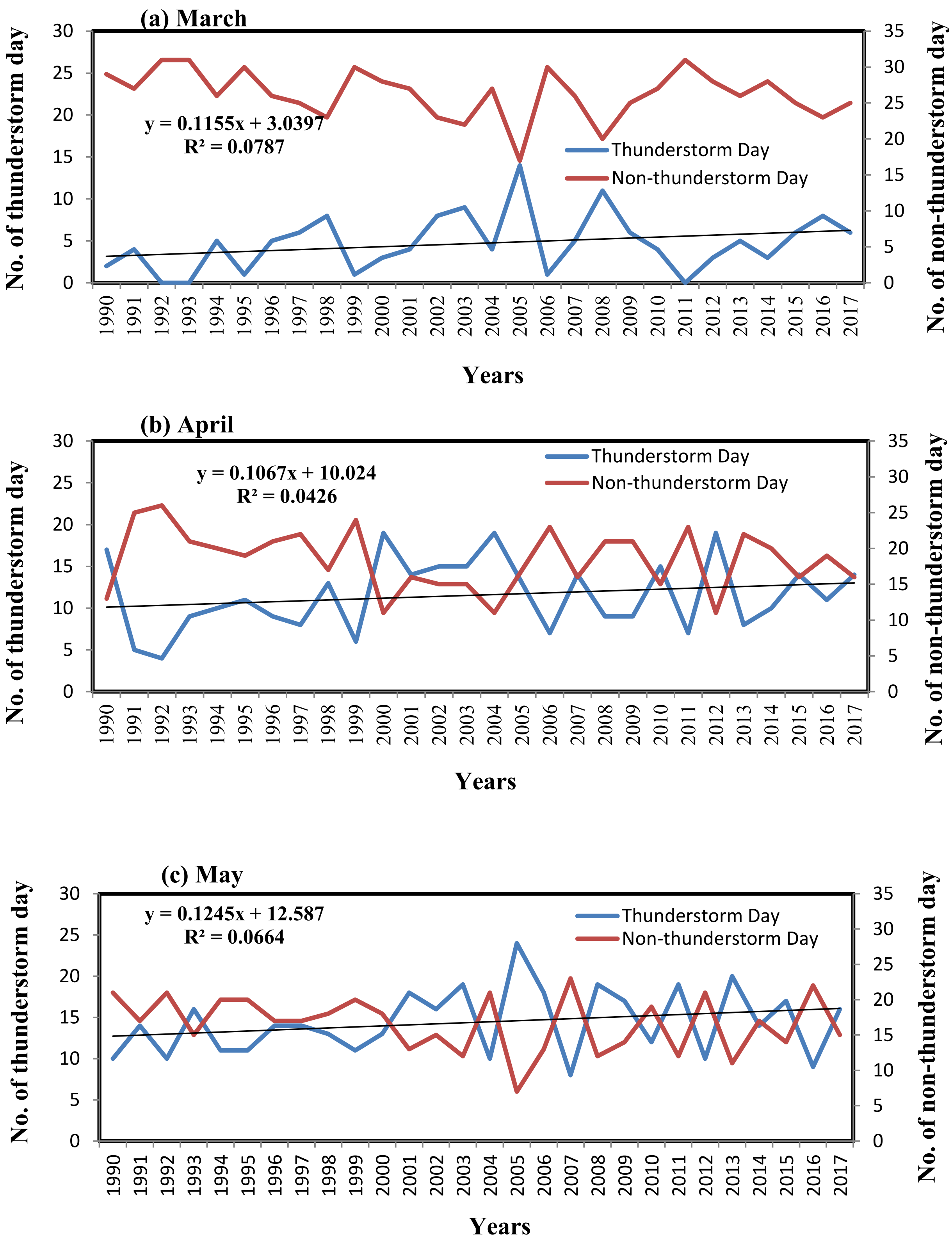


Figure 4.21: Yearly variation of thunderstorm day and non-thunderstorm day for the month of (a) March (b) April (c) May

Figure 4.22 shows total number of thunderstorm and non-thunderstorm days during the year 1990-2017. The number of thunderstorm days is highest in May (occurrence number 14), medium in April (occurrence number 12) and minimum in March (occurrence number 5). In contrast, the number of non-thunderstorm days is greatest in March, medium in April and minimum in May. The number of non-thunderstorm day decrease gradually through May to March. On the other hand, the number of non-thunderstorm day increase gradually through March to May.

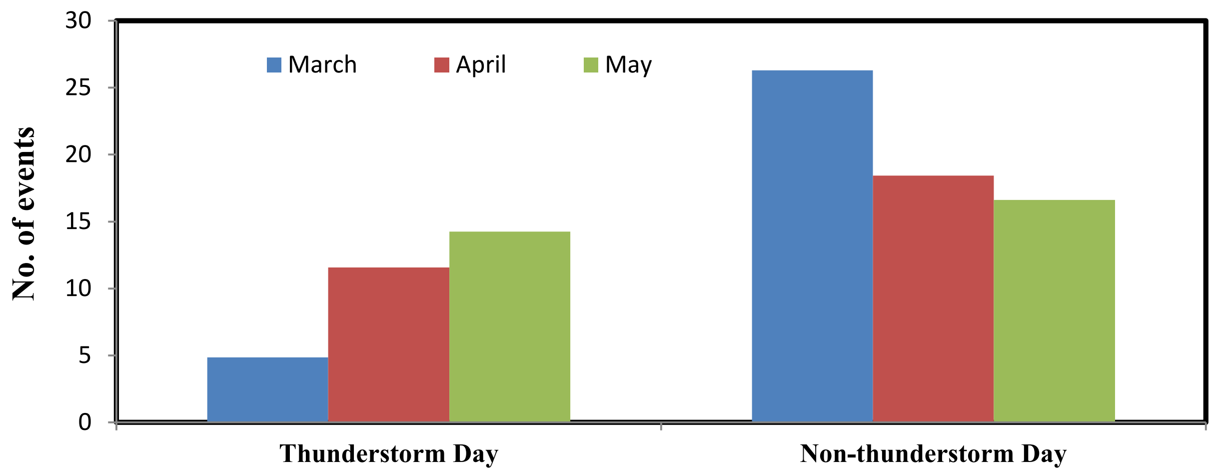


Figure 4.22: Number of thunderstorm and non-thunderstorm day during 1990-2017

4.1.10 Variation in Daily Average Rainfall

4.1.10.1 Yearly Variation of Daily Rainfall

Figure 4.23 shows trend in daily rainfall during 1990-2017 for the month of (a) March (b) April (c) May. Among the three months, increasing trend of daily rainfall is high in the month of March. The average amount daily rainfall of this month is found 2.90 mm. The maximum (4.76 mm) and minimum (0.07 mm) is found on 31st and 3rd March, respectively. In April, the average amount of daily rainfall is 5.43 mm. The maximum (6.91 mm) and minimum (3.33 mm) is found on 14th and 7th April, respectively. In May, the average amount of daily rainfall is 6.56 mm. The maximum (8.77 mm) and minimum (4.09 mm) is found on 20th and 4th May, respectively.

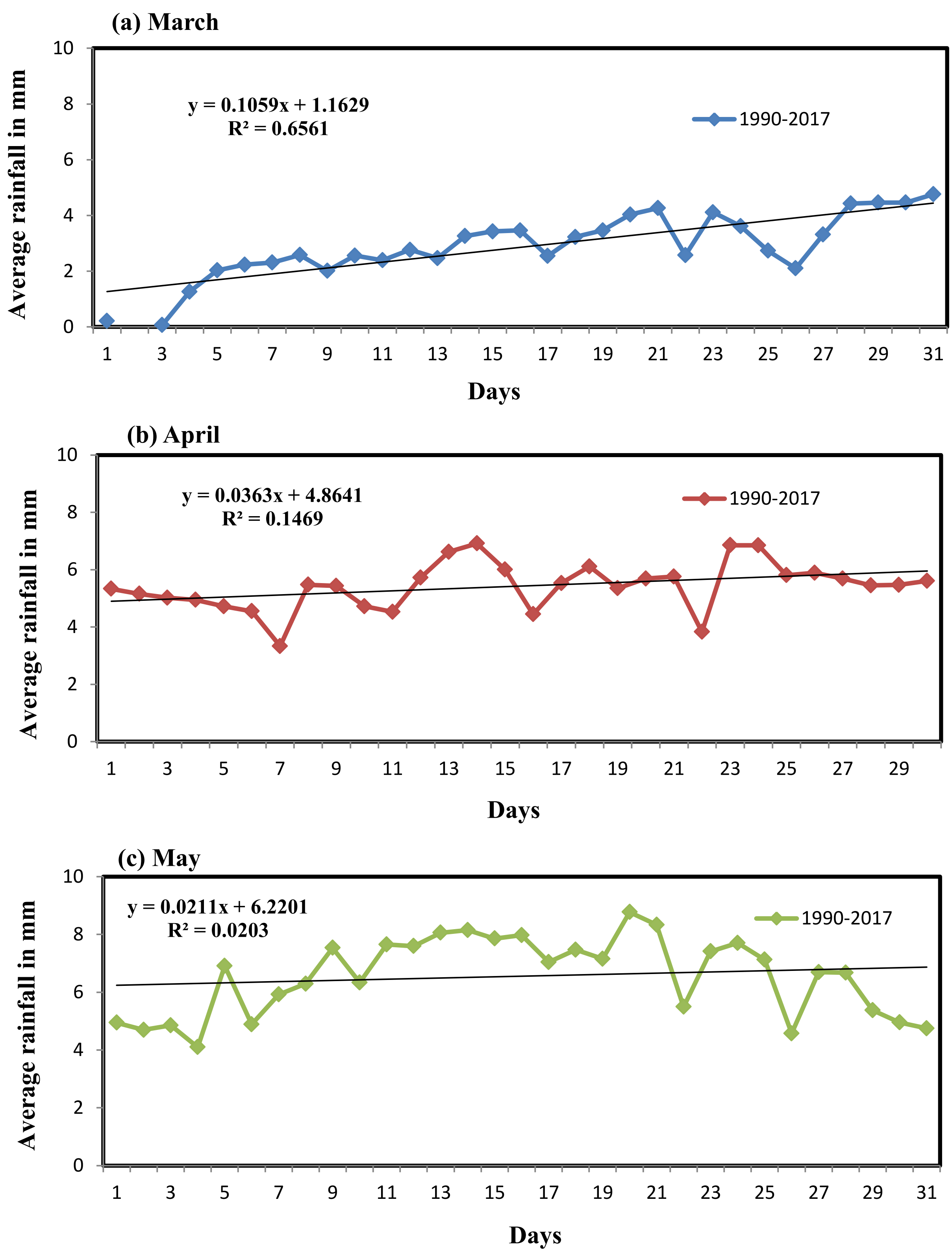


Figure 4.23: Trend in daily average rainfall during 1990-2017: (a) March (b) April (c) May

Figure 4.24 shows the monthly average rainfall variation during pre-monsoon season. The maximum (203 mm) amount of monthly average rainfall is found in the month of May and the minimum amount of (87 mm) monthly average rainfall is found in the month of March.

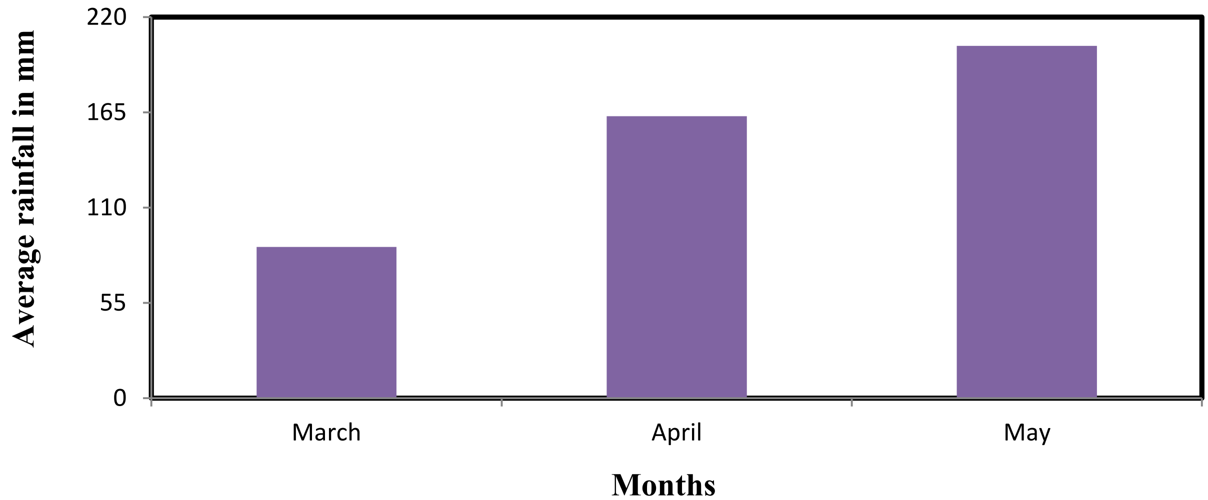


Figure 4.24: Average rainfall during pre-monsoon season

4.1.10.2 Station-wise Variation in Monthly Average Rainfall

Figure 4.25 shows station-wise variation in monthly average rainfall during 1990-2017. In March, maximum average rainfall is found at Srimangal is about 90 mm. Minimum in Sandwip is about 19 mm. In April, maximum average rainfall is found at Srimangal is about 164 mm and minimum in Rangamati is about 32 mm. In May, maximum average rainfall is found at Srimangal is about 207 mm and minimum in Teknaf is about 35 mm.

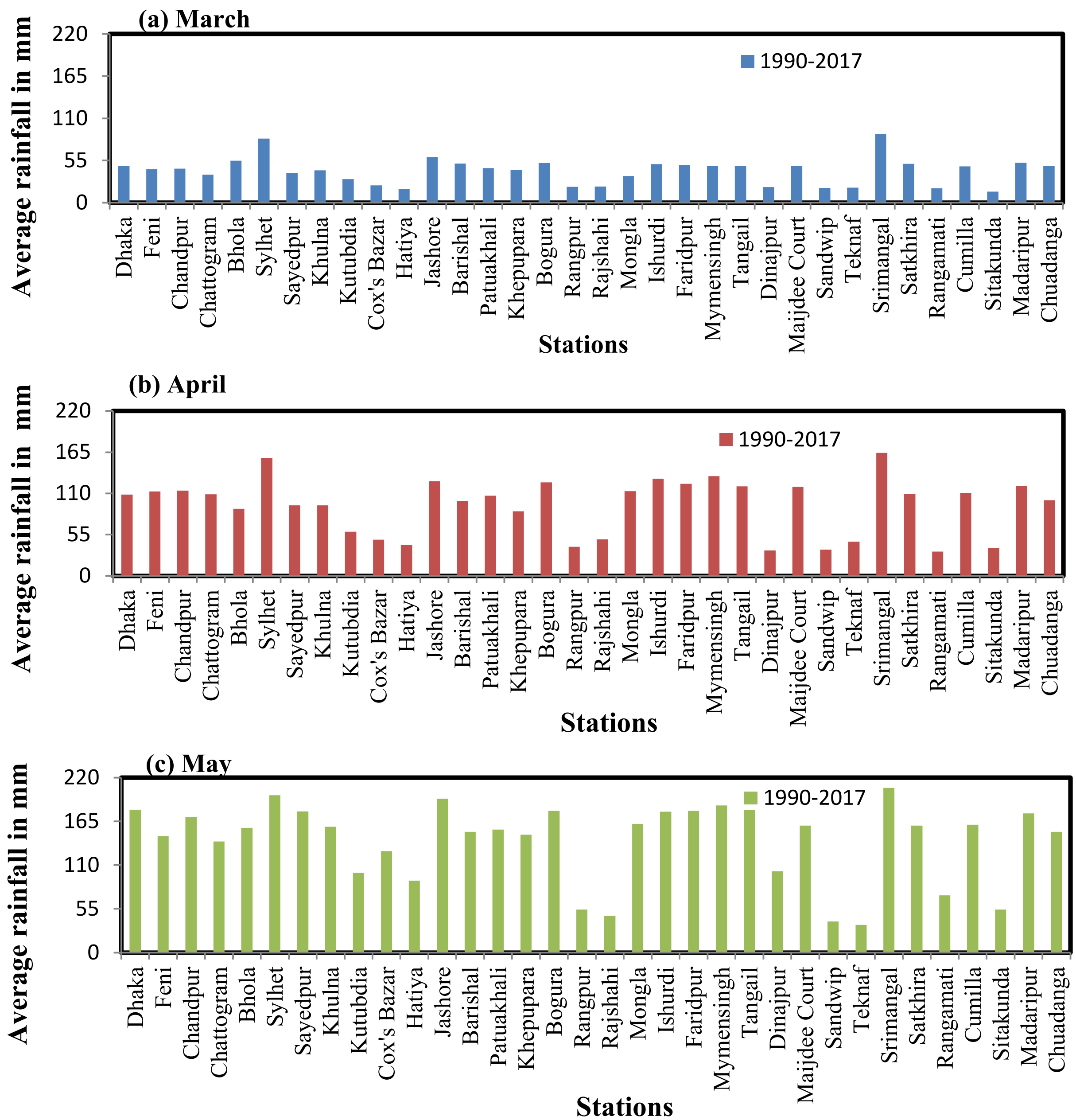


Figure 4.25: Station-wise variation in monthly average rainfall during 1990-2017

4.1.11 Trends of Thunderstorm Frequency and Rainfall

4.1.11.1 Trends of Daily Average Thunderstorm Frequency and Average Rainfall in 34 Stations

- **Dhaka**

Figure 4.26 shows trends of daily average thunderstorm frequency and average rainfall during

1990-2018 for the month of (a) March (b) April (c) May for Dhaka station. The increasing trend for rainfall in March is strong compared to April and May.

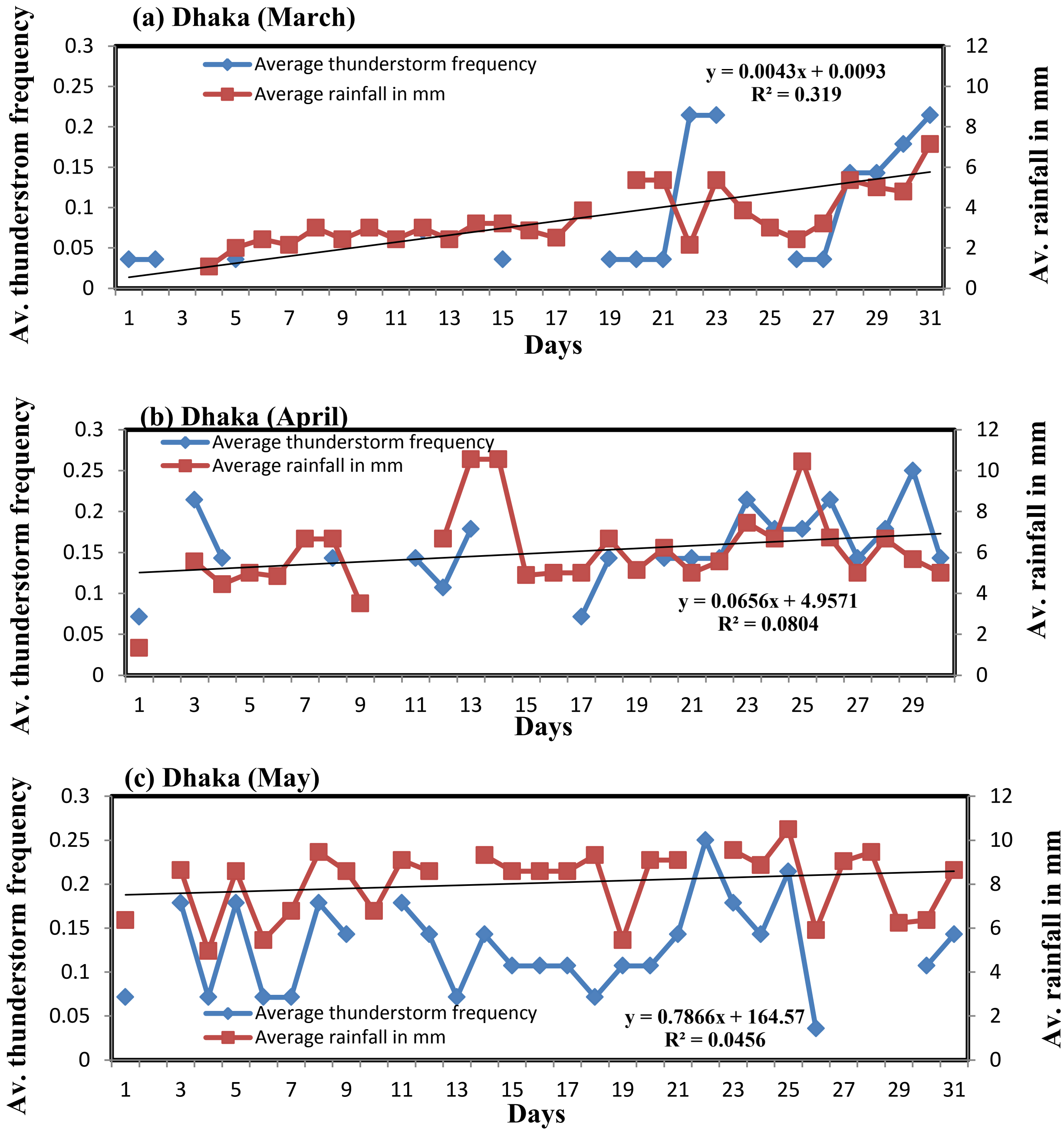


Figure 4.26: Trends of daily average thunderstorm frequency and average rainfall for Dhaka station during 1990-2017: (a) March (b) April (c) May

- **Feni**

Figure 4.27 shows trends of daily average thunderstorm frequency and average rainfall during

1990-2018 for the month of (a) March (b) April (c) May for Feni station. The increasing trend for rainfall in March is strong compared to April and May. Coefficients of determinations R^2 are 0.3677, 0.0034 and 0.0844 during March, April and May, respectively.

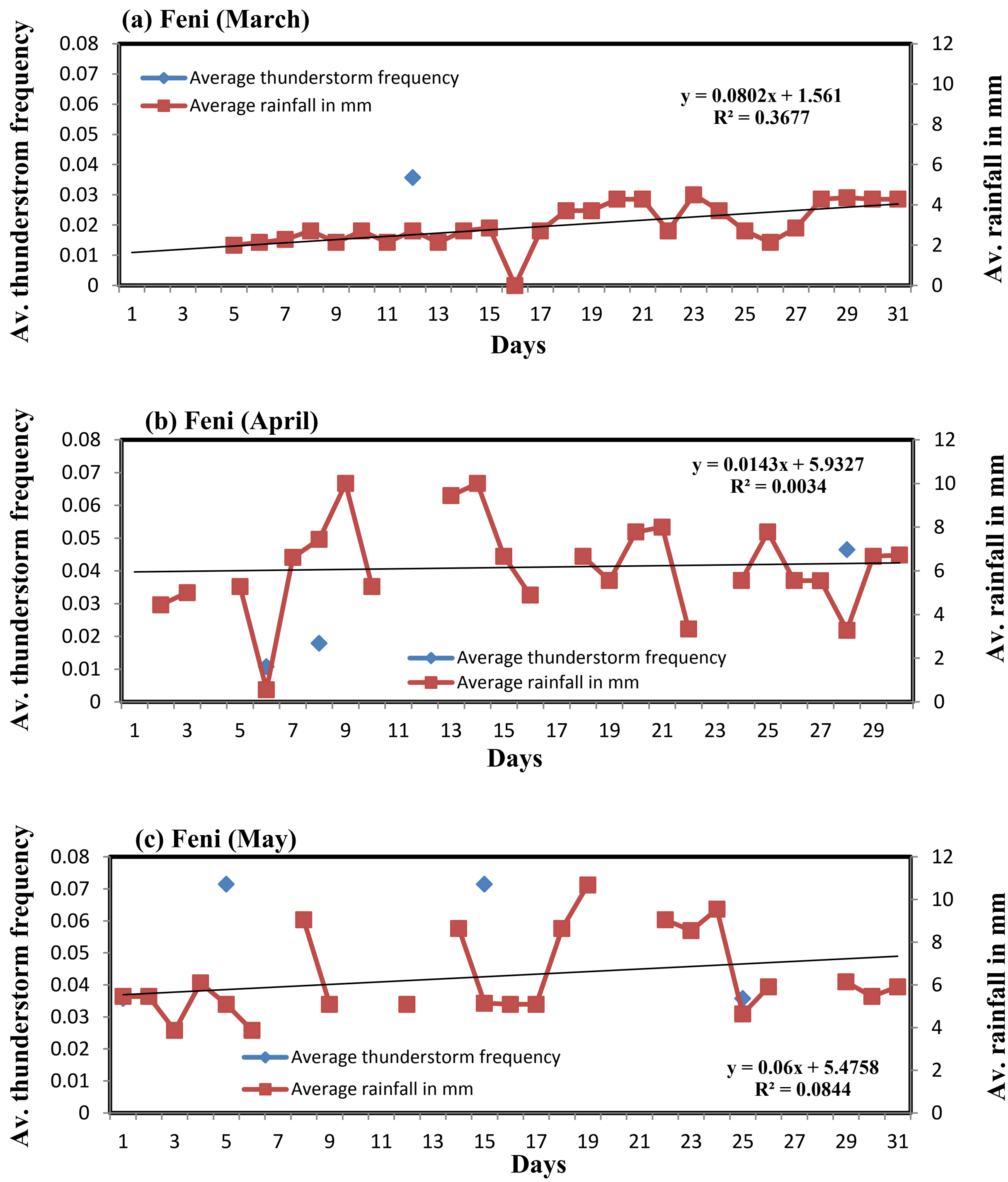


Figure 4.27: Trends of daily average thunderstorm frequency and average rainfall for Feni station during 1990-2017: (a) March (b) April (c) May

- **Chandpur**

Figure 4.28 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Chandpur station. The increasing trend for rainfall in March is strong compared to April and May.

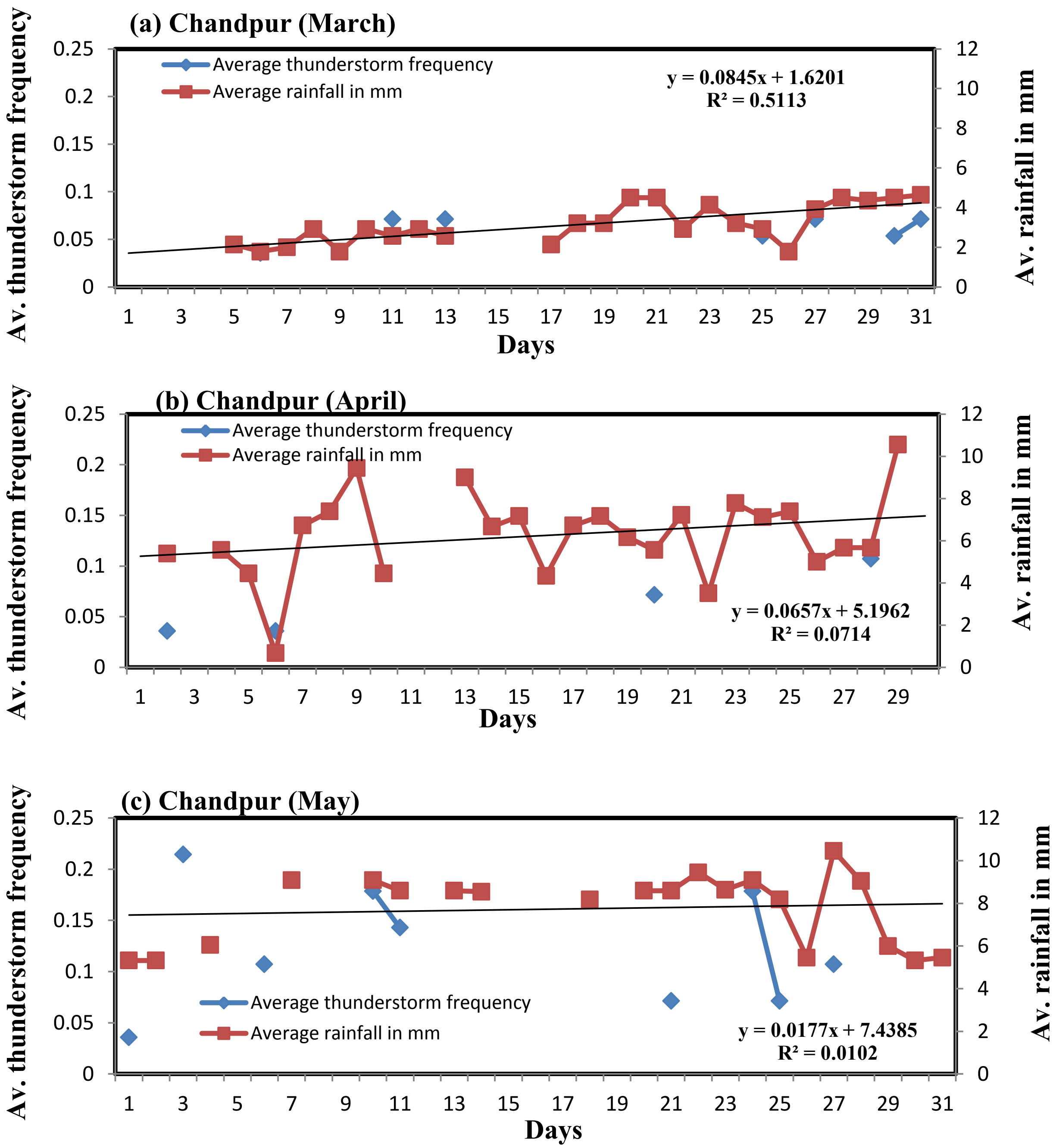


Figure 4.28: Trends of daily average thunderstorm frequency and average rainfall for Chandpur station during 1990-2017: (a) March (b) April (c) May

- **Chattogram**

Figure 4.29 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Chattogram station. The increasing trend for rainfall in March is strong compared to April and May. Coefficients of determinations R^2 are 0.4009, 0.2296 and 0.0014 during March, April and May, respectively.

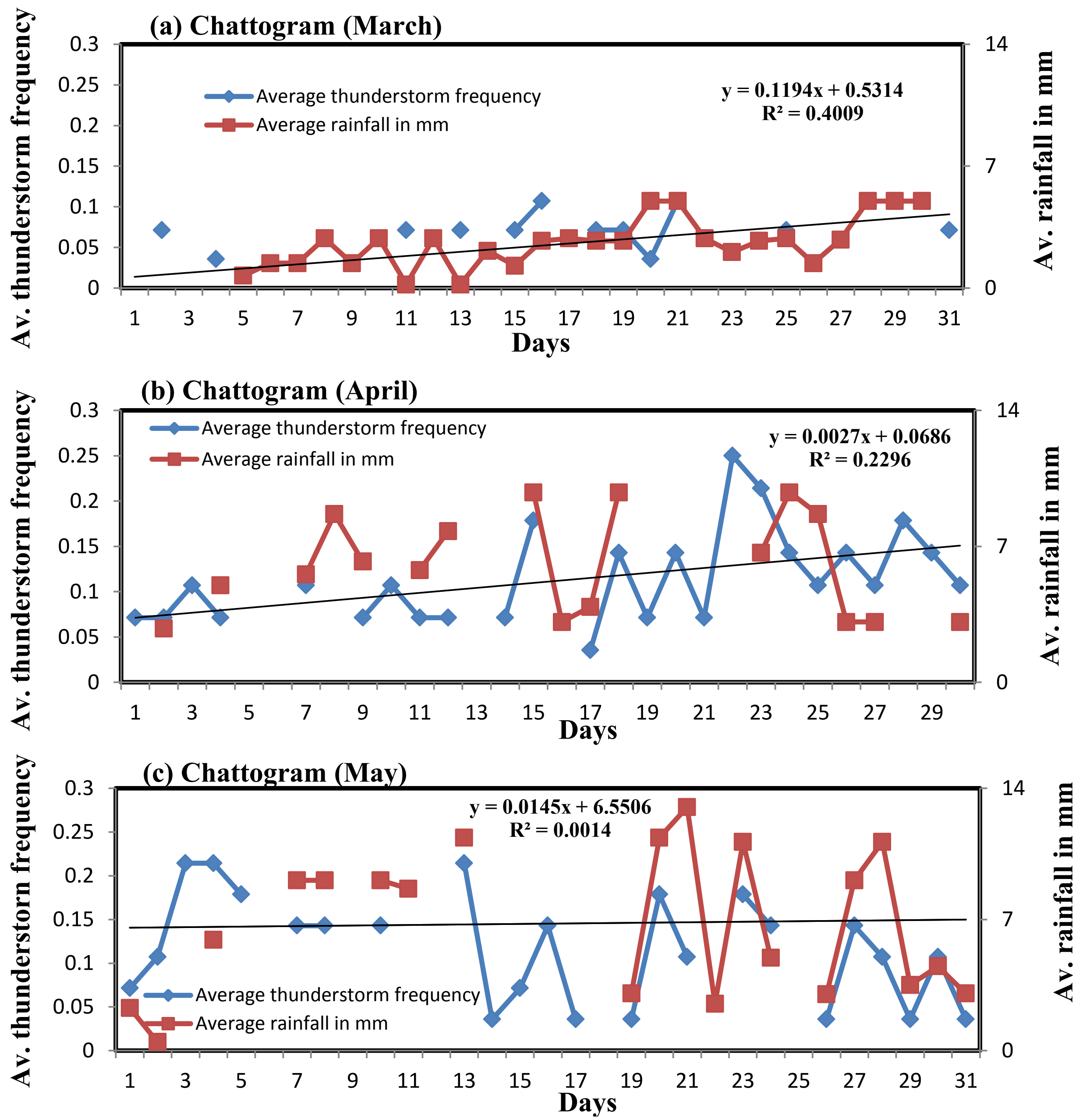


Figure 4.29: Trends of daily average thunderstorm frequency and average rainfall for Chattogram station during 1990-2017: (a) March (b) April (c) May

- **Bhola**

Figure 4.30 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Bhola station. There are increasing trends during pre-monsoon for average rainfall. Coefficients of determinations R^2 are 0.4945, 0.0512 and 0.0193 during March, April and May, respectively.

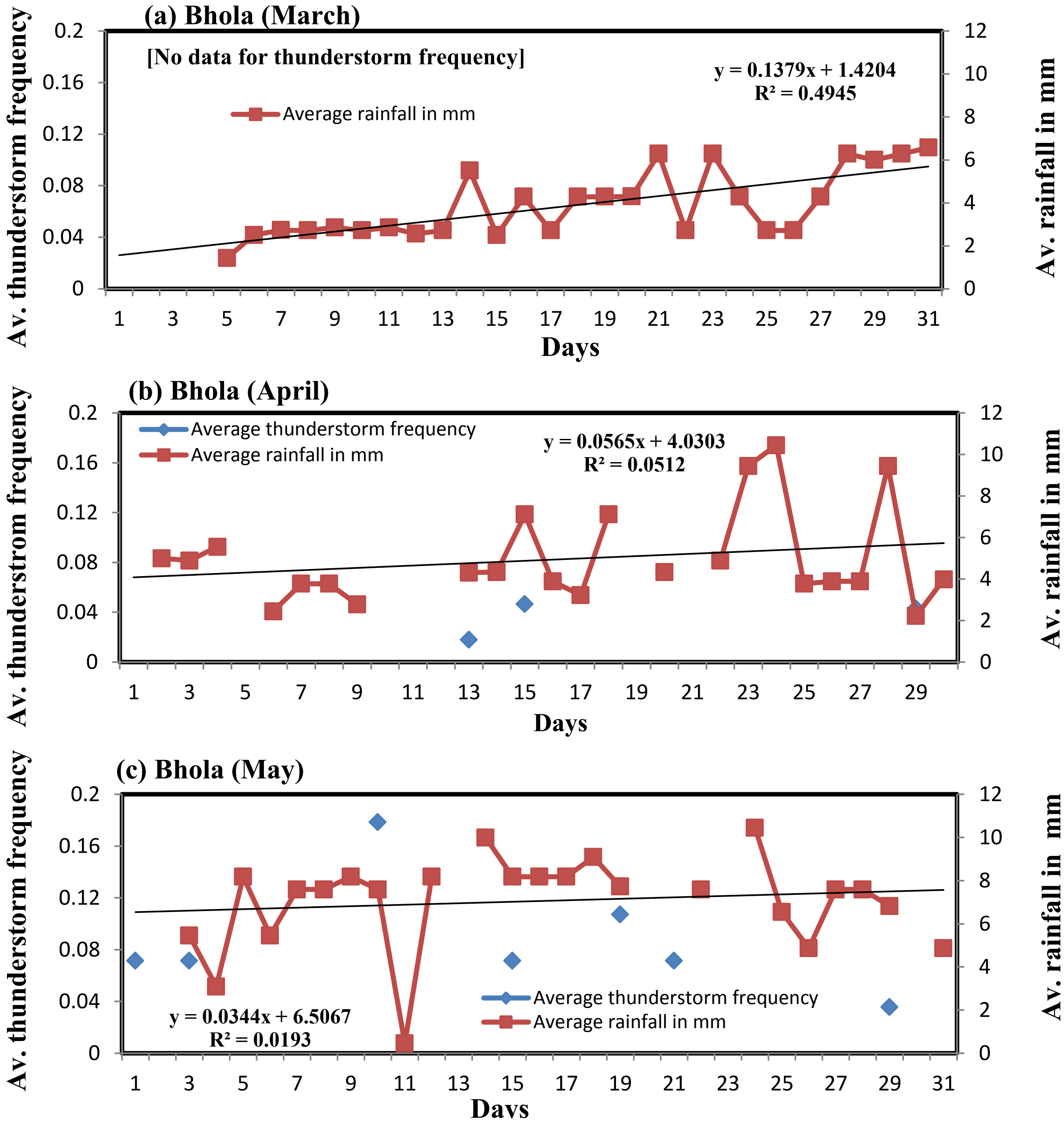


Figure 4.30: Trends of daily average thunderstorm frequency and average rainfall for Bhola station during 1990-2017: (a) March (b) April (c) May

- **Sylhet**

Figure 4.31 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Sylhet station. The increasing trend for rainfall in March is strong compared to April and May.

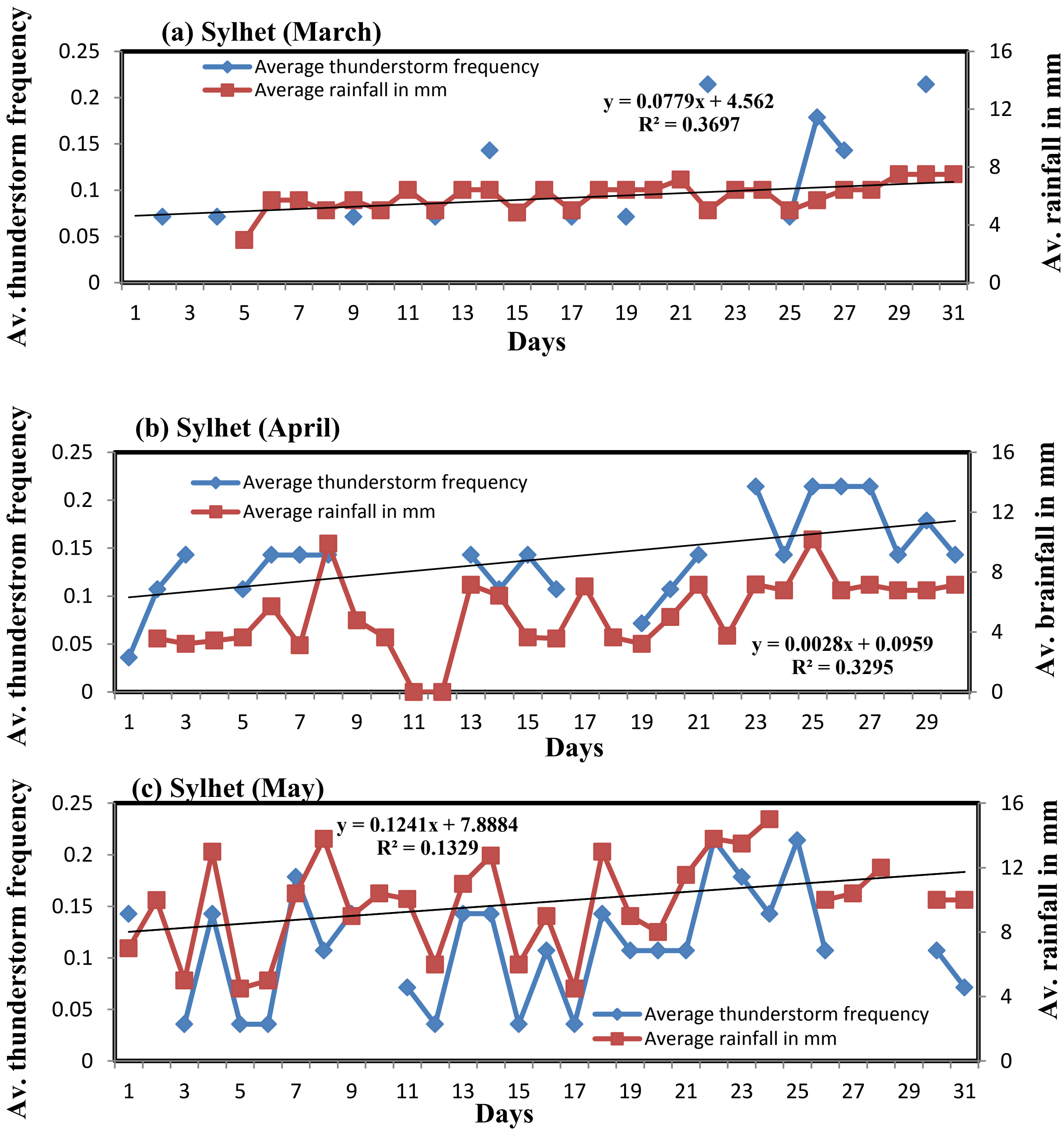


Figure 4.31: Trends of daily average thunderstorm frequency and average rainfall for Sylhet station during 1990-2017: (a) March (b) April (c) May

- **Sayedpur**

Figure 4.32 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Sayedpur station. The increasing trend for rainfall in March is strong compared to April and May. Coefficients of determinations R^2 are 0.3934, 0.1446 and 0.0205 during March, April and May, respectively.

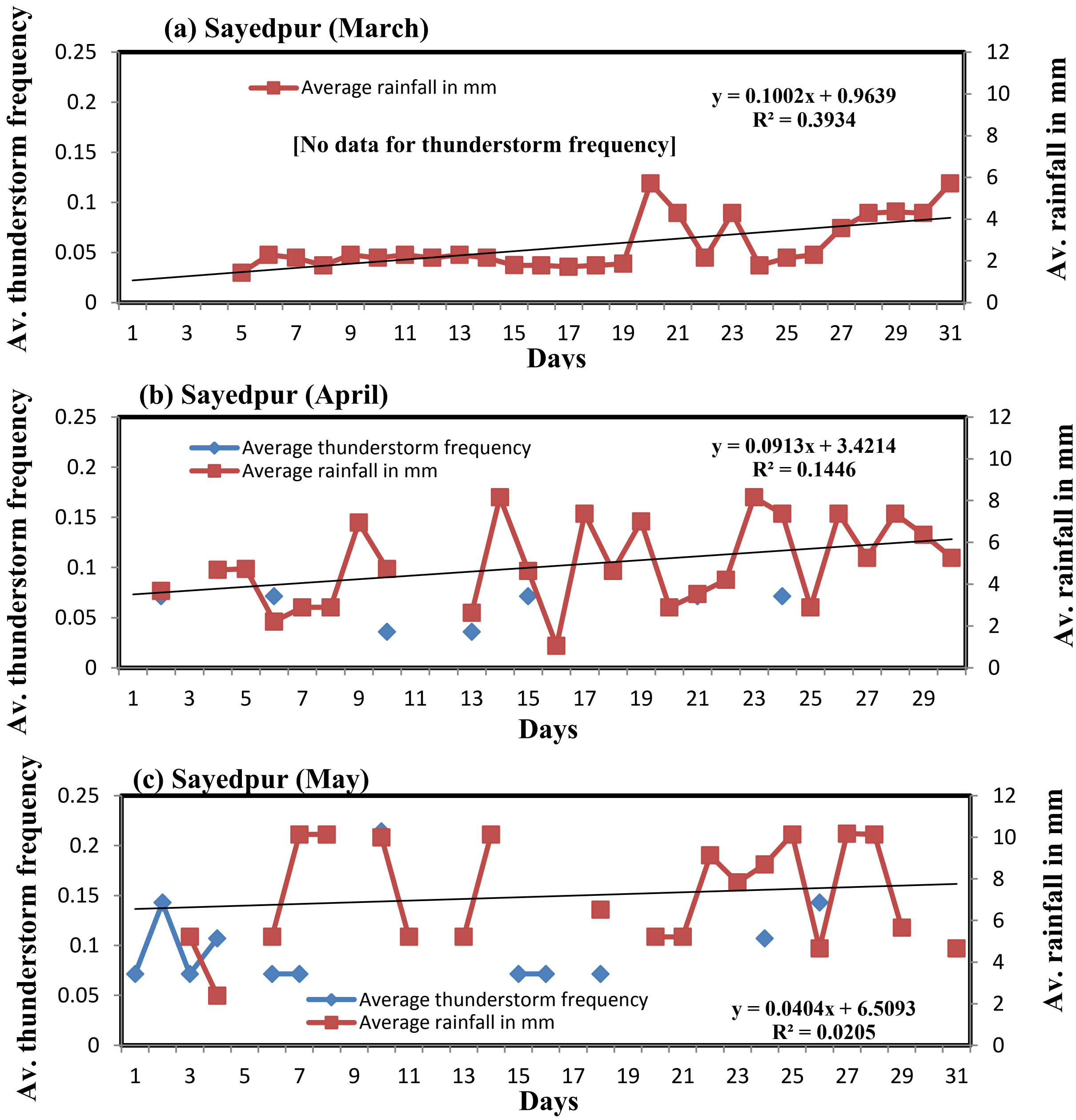


Figure 4.32: Trends of daily average thunderstorm frequency and average rainfall for Sayedpur station during 1990-2017: (a) March (b) April (c) May

- **Khulna**

Figure 4.33 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Khulna station. The increasing trend for rainfall in March is strong compared to April and May.

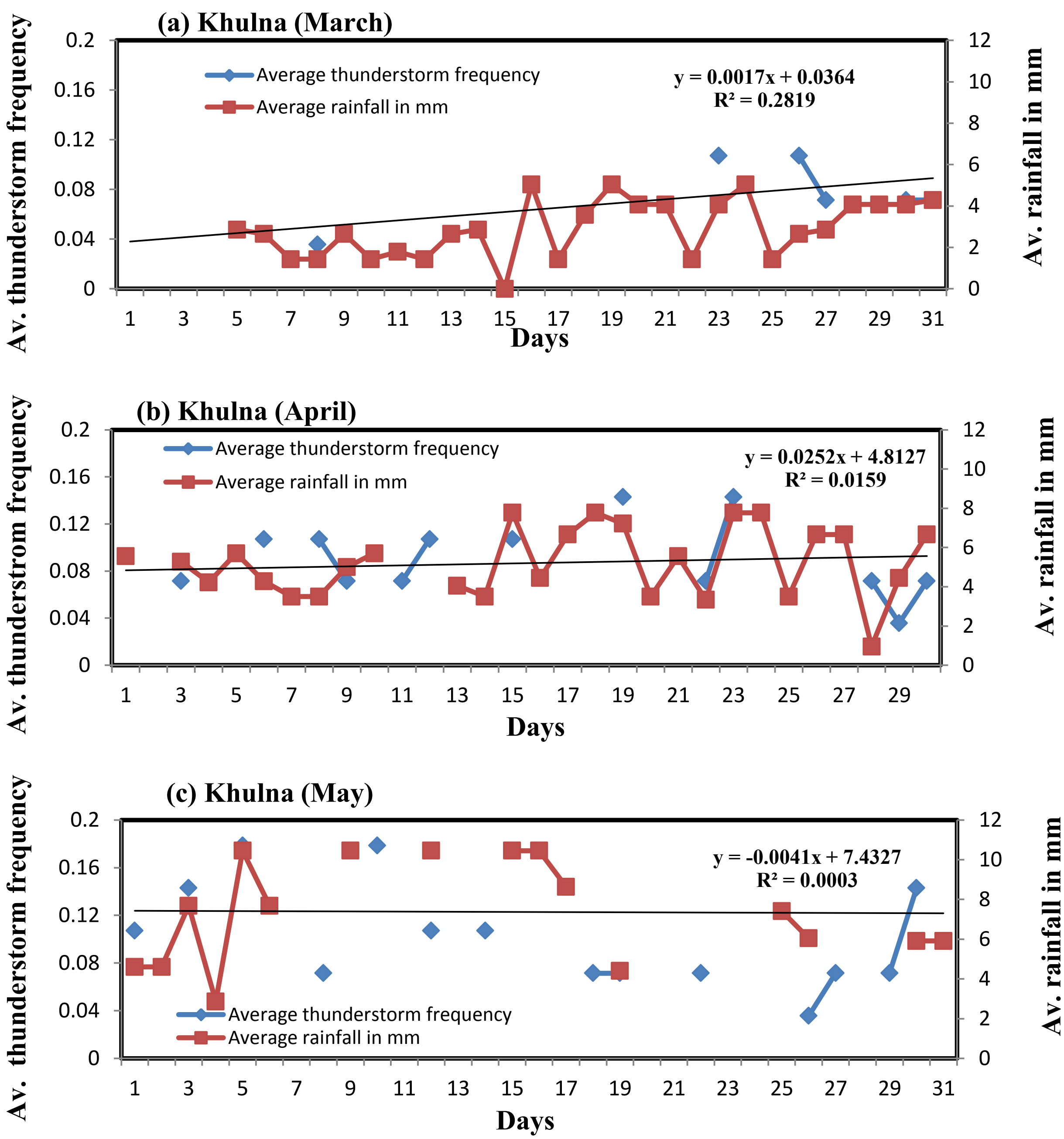


Figure 4.33: Trends of daily average thunderstorm frequency and average rainfall for Khulna station during 1990-2017: (a) March (b) April (c) May

- **Kutubdia**

Figure 4.34 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Kutubdia station. The increasing trend for rainfall in March is strong compared to April and May. Coefficient of determination R^2 is 0.0057, 0.1387 and 0.0021 during March, April and May, respectively.

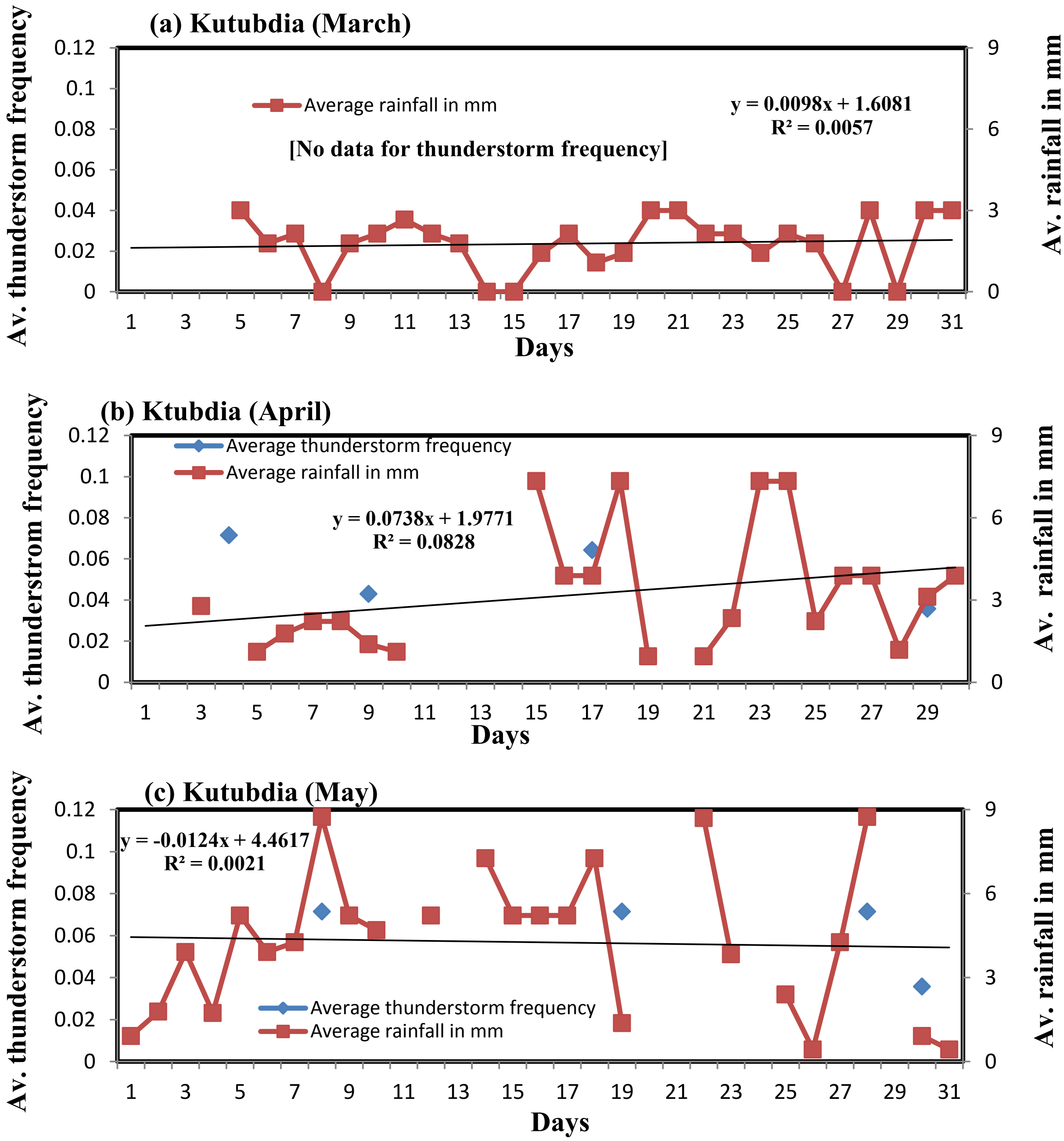


Figure 4.34: Trends of daily average thunderstorm frequency and average rainfall for Kutubdia station during 1990-2017: (a) March (b) April (c) May

- **Cox's Bazar**

Figure 4.35 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Cox‘s Bazar station. The increasing trend for rainfall in March is strong compared to April and May.

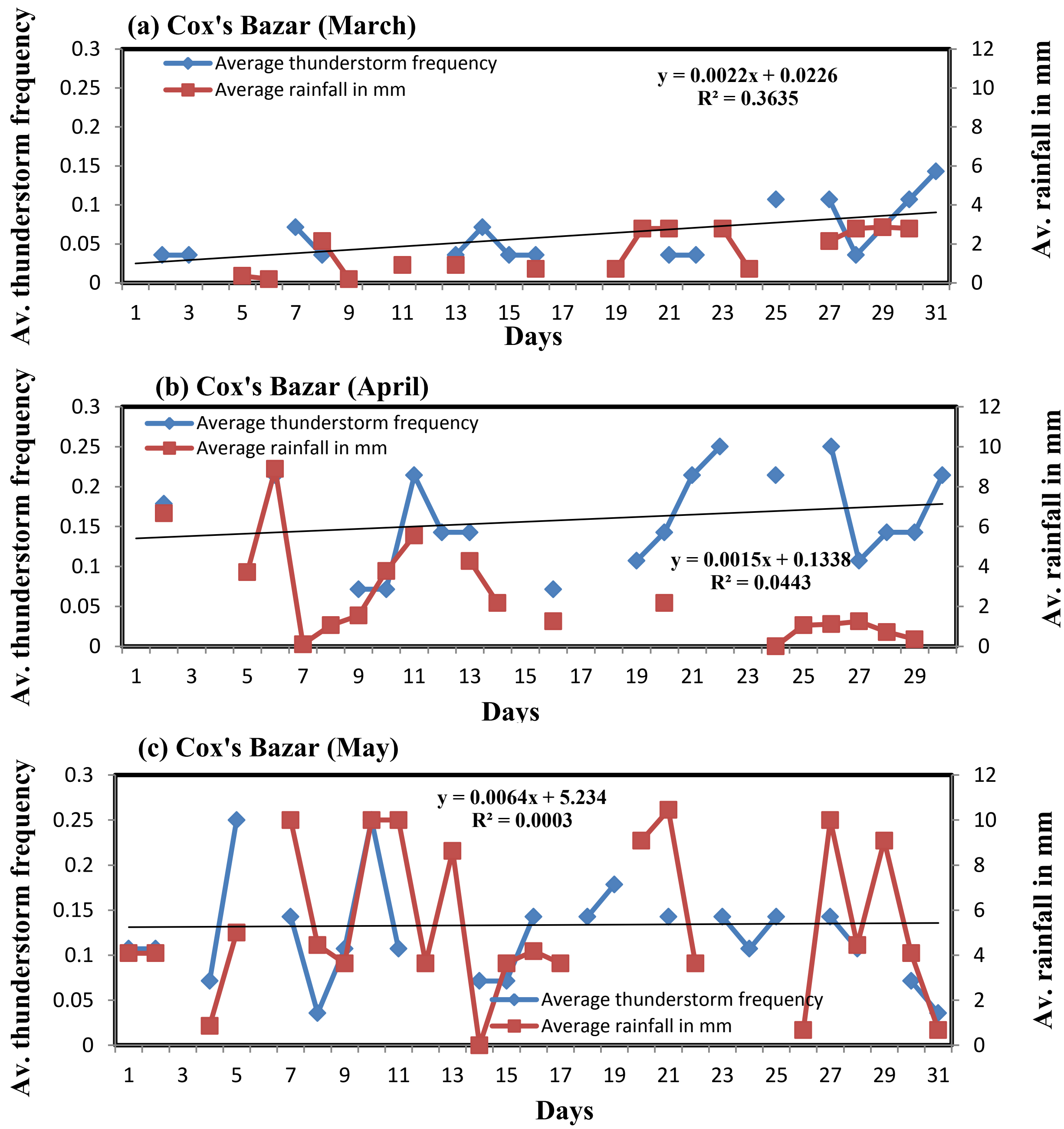
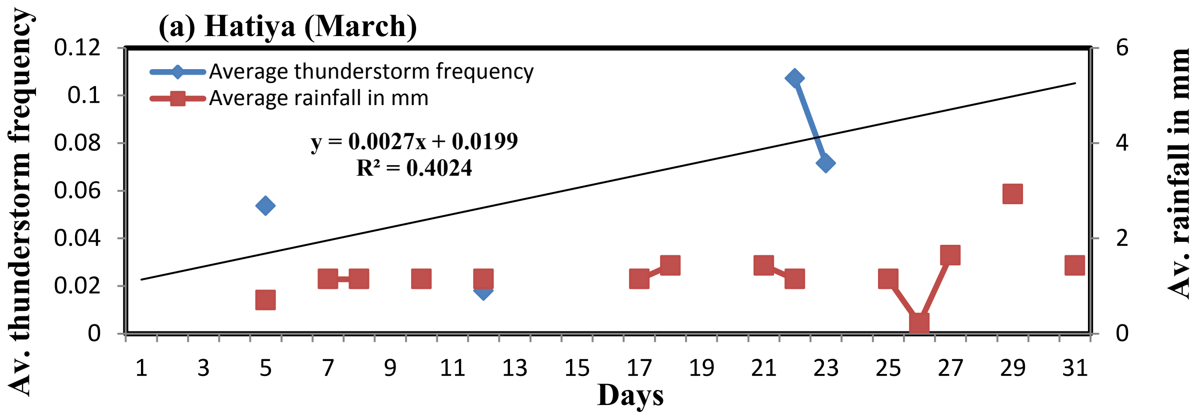
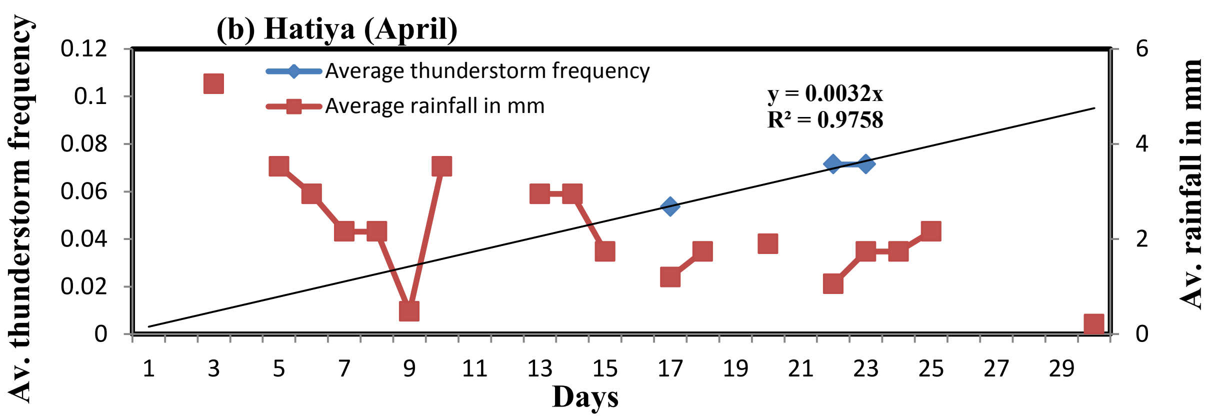


Figure 4.35: Trends of daily average thunderstorm frequency and average rainfall for Cox‘s Bazar station during 1990-2017: (a) March (b) April (c) May

- **Hatiya**

Figure 4.36 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Hatiya station. The increasing trend for rainfall in April is strong compared to March and May. The coefficient of determinations R^2 are 0.4024, 0.9758, 0.2617 and during March, April and May, respectively.





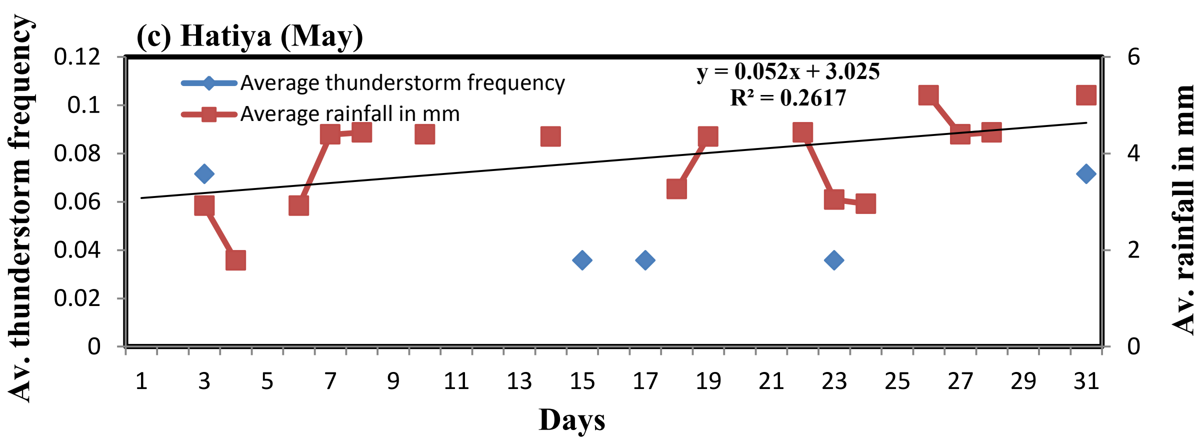


Figure 4.36: Trends of daily average thunderstorm frequency and average rainfall for Hatiya station during 1990-2017: (a) March (b) April (c) May

- **Jashore**

Figure 4.37 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Jashore station. The increasing trend for rainfall in March is strong compared to April and May. Coefficients of determinations R^2 are 0.4544, 0.1226 and 0.0091 during March, April and May, respectively.

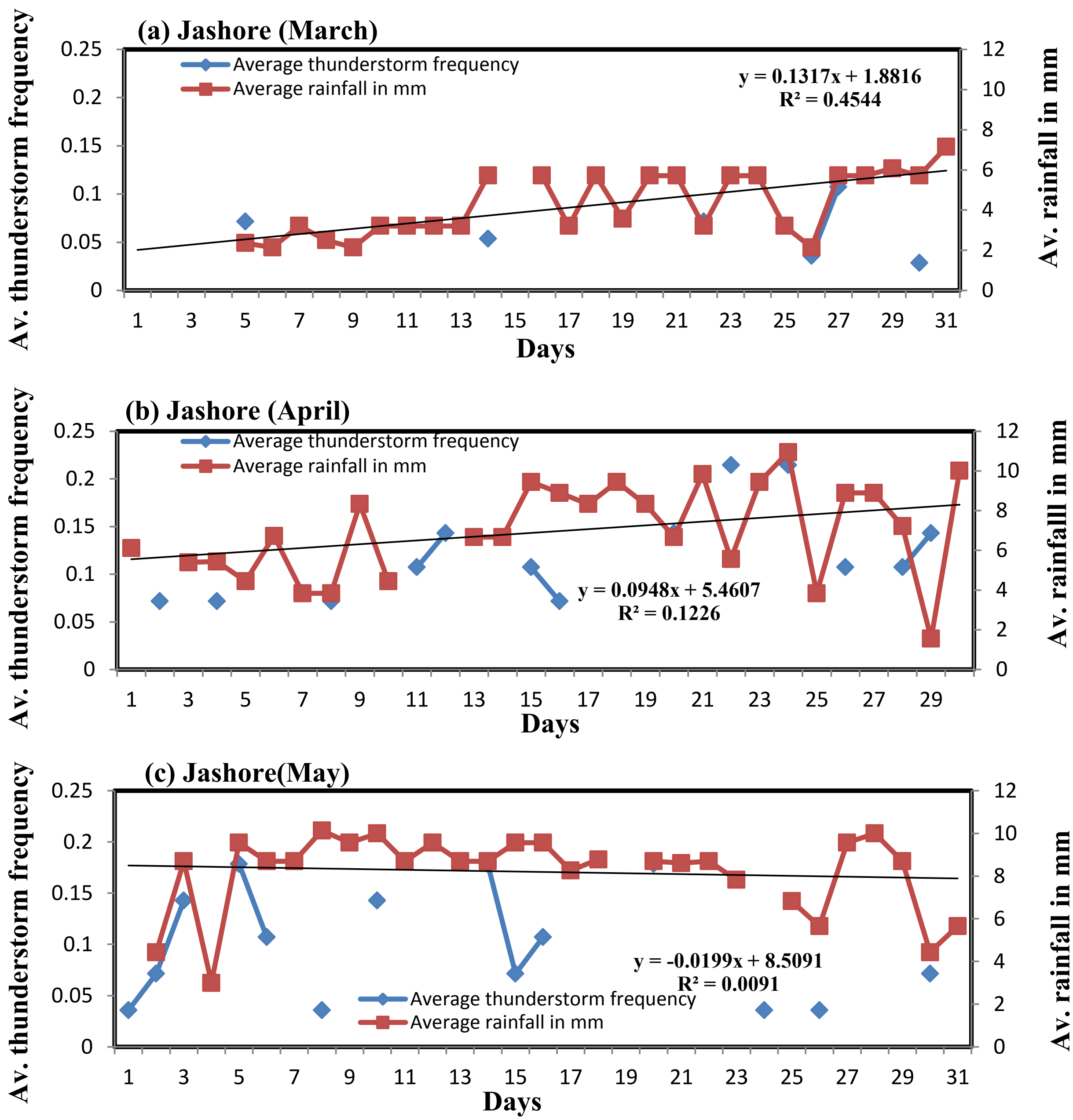


Figure 4.37: Trends of daily average thunderstorm frequency and average rainfall for Jashore station during 1990-2017: (a) March (b) April (c) May

- **Barishal**

Figure 4.38 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Barishal station. The increasing trend for rainfall in March is strong compared to April and May. Coefficients of determinations R^2 are 0.4796, 0.1297 and 0.0007during March, April and May, respectively.

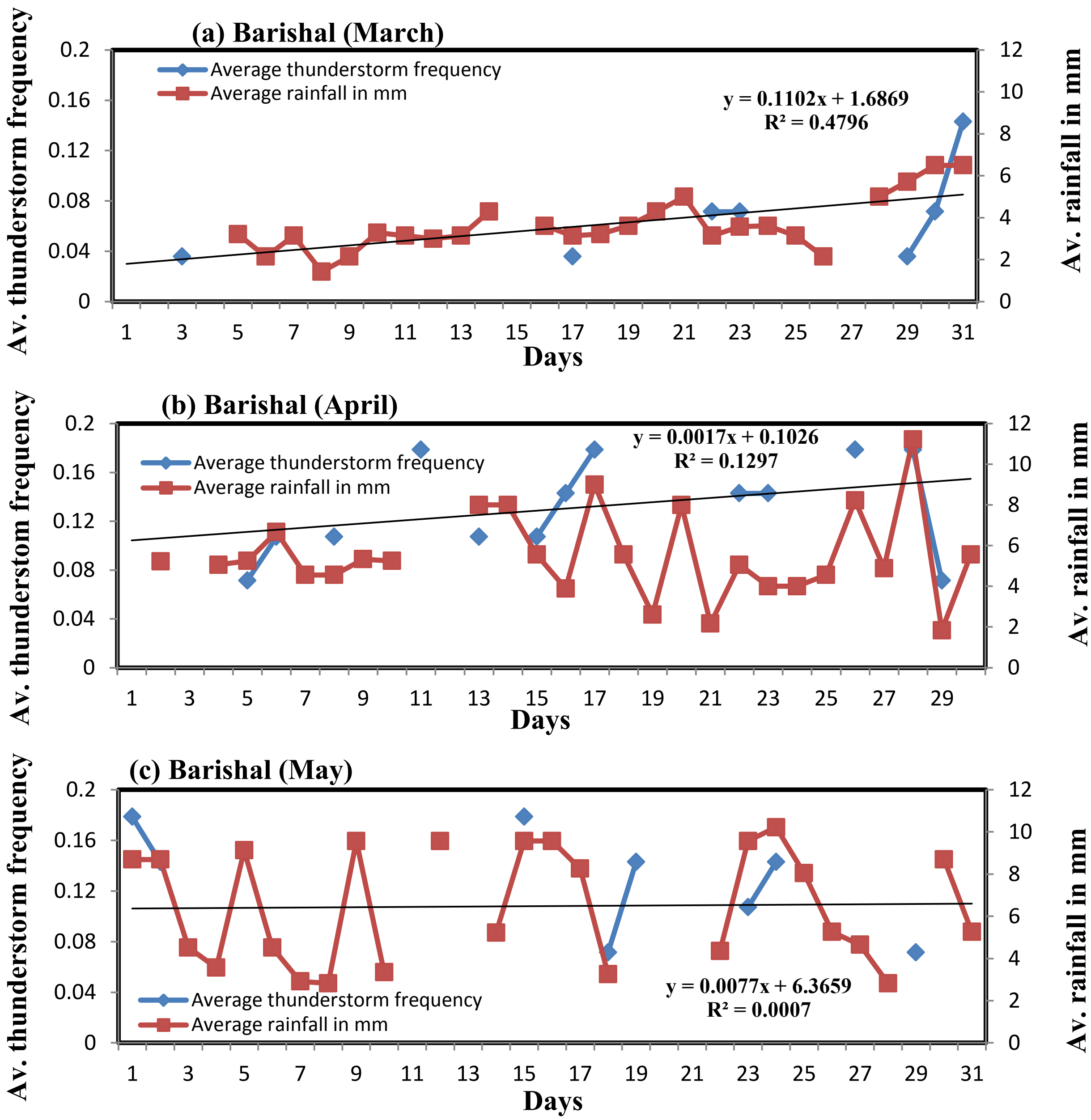


Figure 4.38: Trends of daily average thunderstorm frequency and average rainfall for Barishal station during 1990-2017: (a) March (b) April (c) May

- **Patuakhali**

Figure 4.39 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Patuakhali station. The increasing trend for rainfall in March is strong compared to April and May. Coefficients of determinations R^2 are 0.5408, 0.1416 and 0.0037 during March, April and May, respectively.

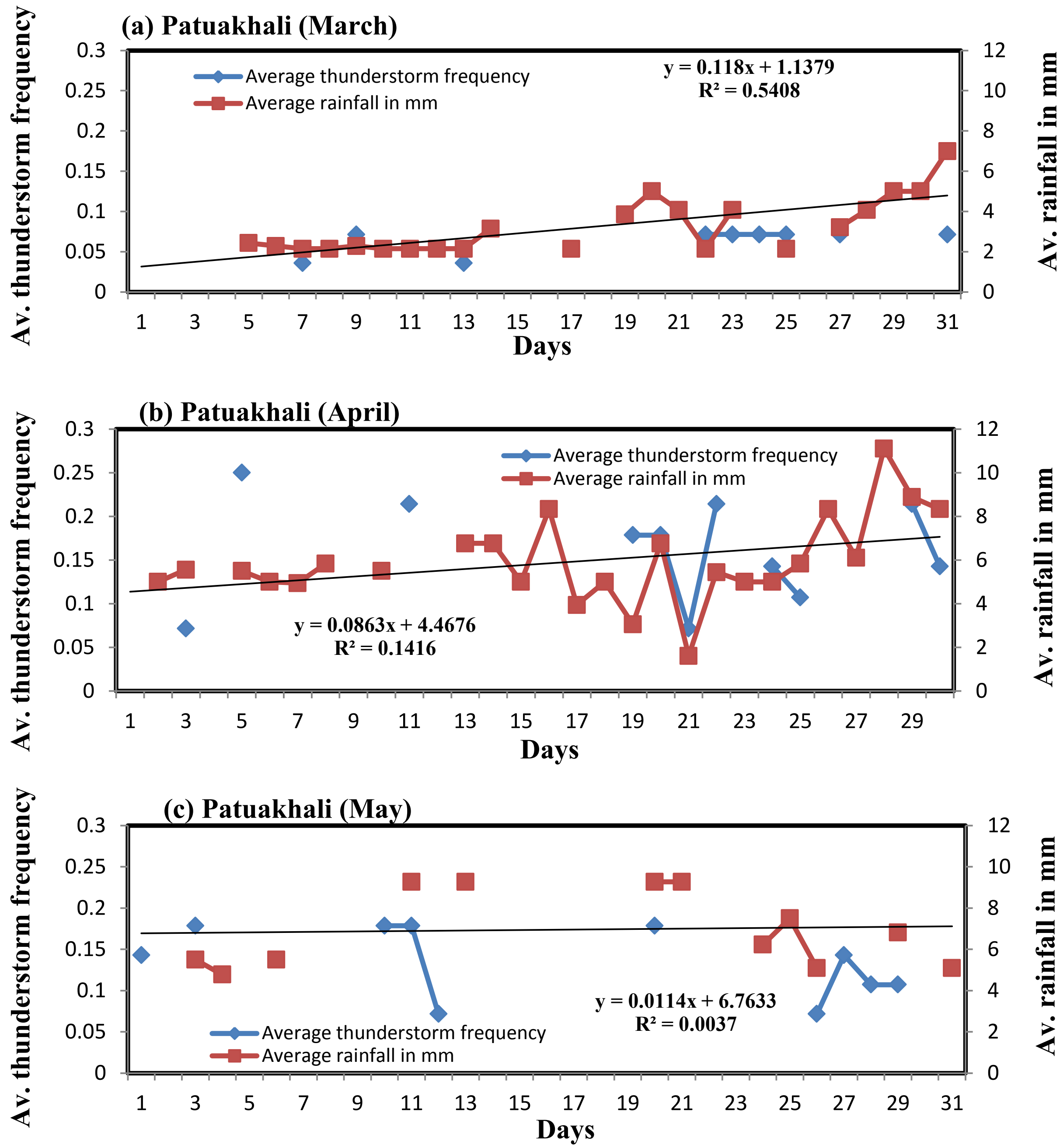


Figure 4.39: Trends of daily average thunderstorm frequency and average rainfall for Patuakhali station during 1990-2017: (a) March (b) April (c) May

- **Khepupara**

Figure 4.40 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Khepupara station. The increasing trend for rainfall in March is strong compared to April and May. Coefficients of determinations R^2 are 0.2666, 0.0221 and 0.0218 during March, April and May, respectively.

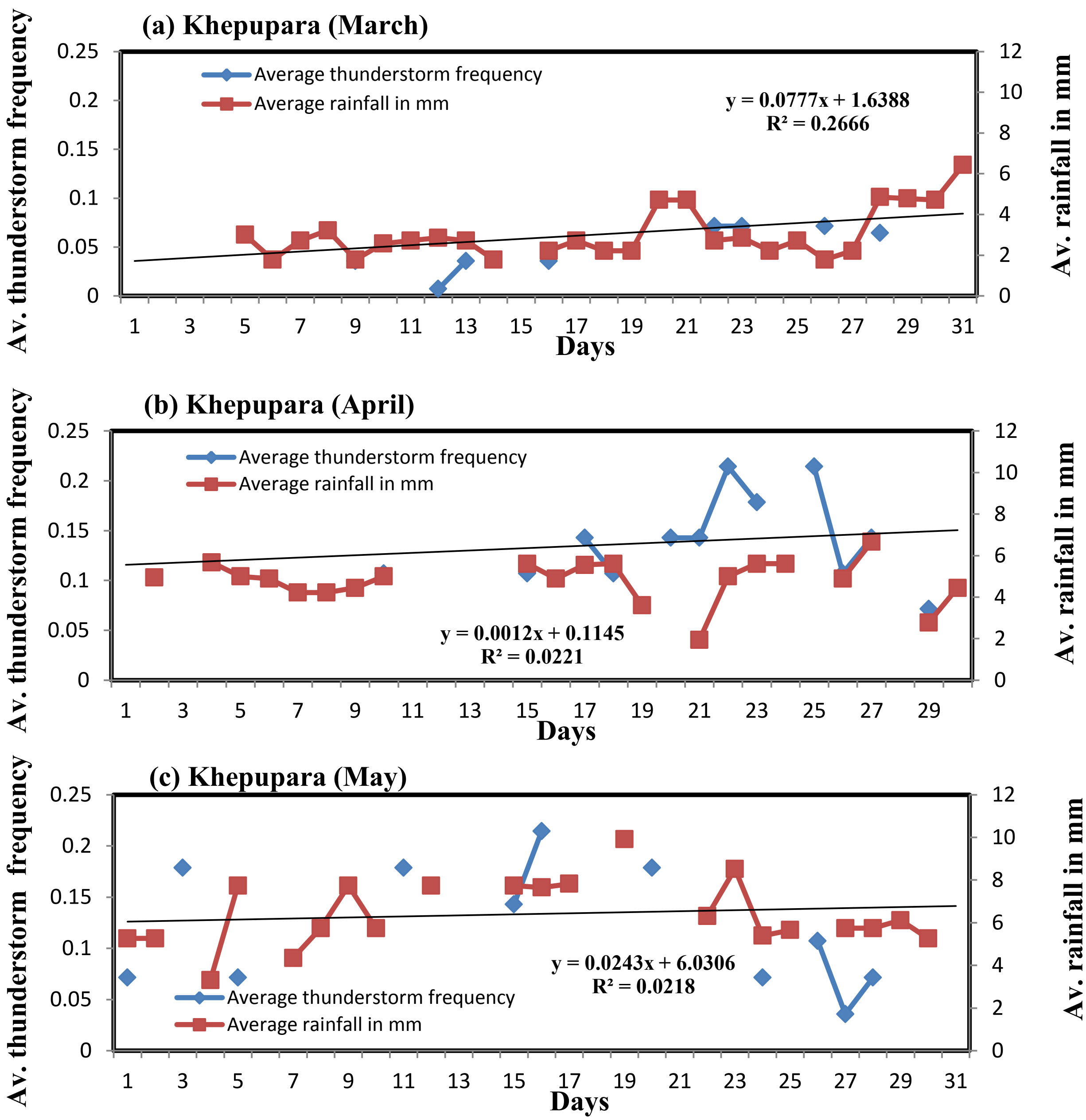


Figure 4.40: Trends of daily average thunderstorm frequency and average rainfall for Khepupara station during 1990-2017: (a) March (b) April (c) May

- **Bogura**

Figure 4.41 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Bogura station. The increasing trend for rainfall in March is strong compared to April and May. Coefficients of determinations R^2 are 0.4549, 0.3275 and 0.0347 during March, April and May, respectively.

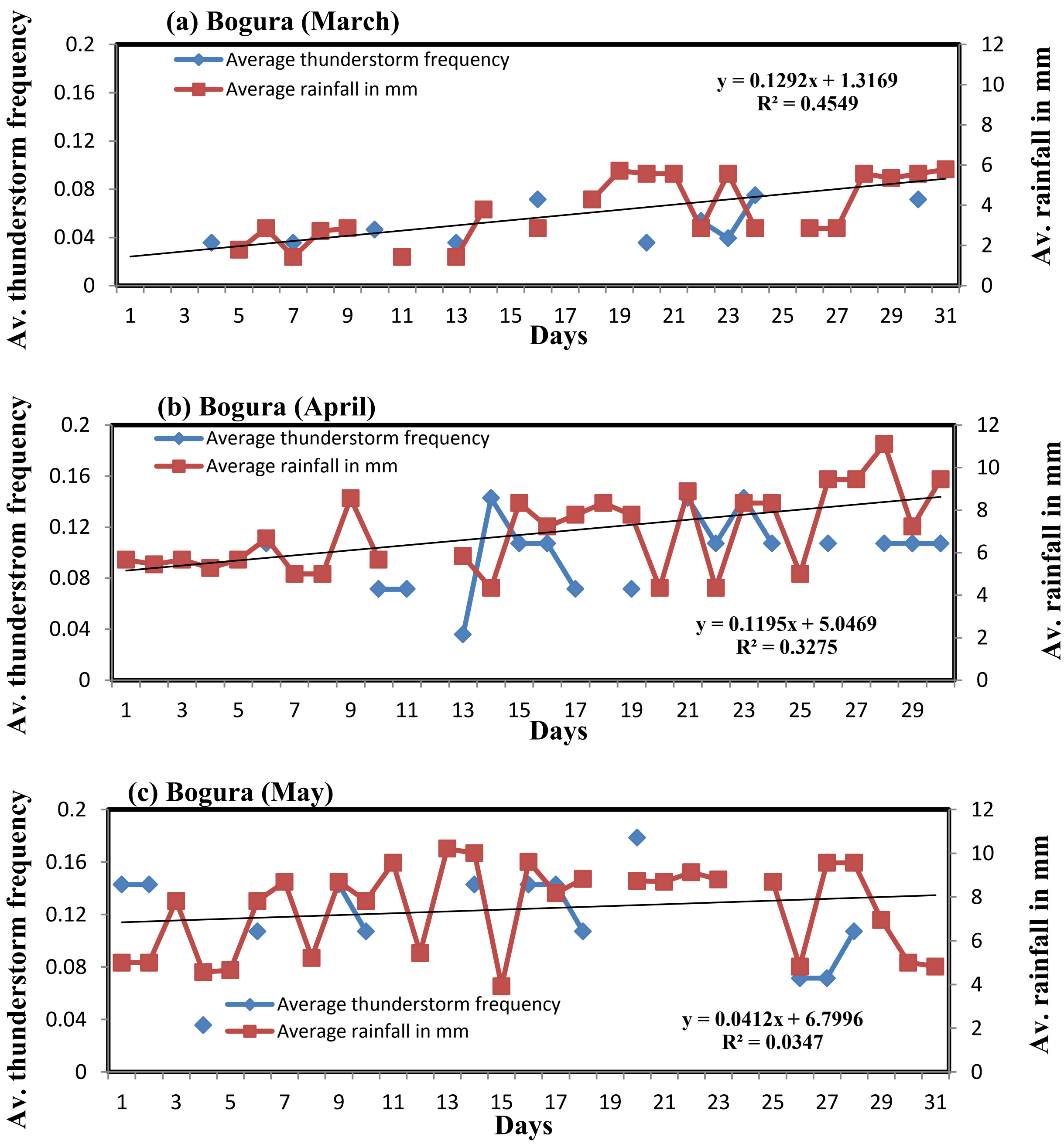


Figure 4.41: Trends of daily average thunderstorm frequency and average rainfall for Bogura station during 1990-2017: (a) March (b) April (c) May

- **Rangpur**

Figure 4.42 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Rangpur station. Coefficients of determinations R^2 are found 0.1489, 0.0302 and 0.005 for the month March, April and May, respectively.

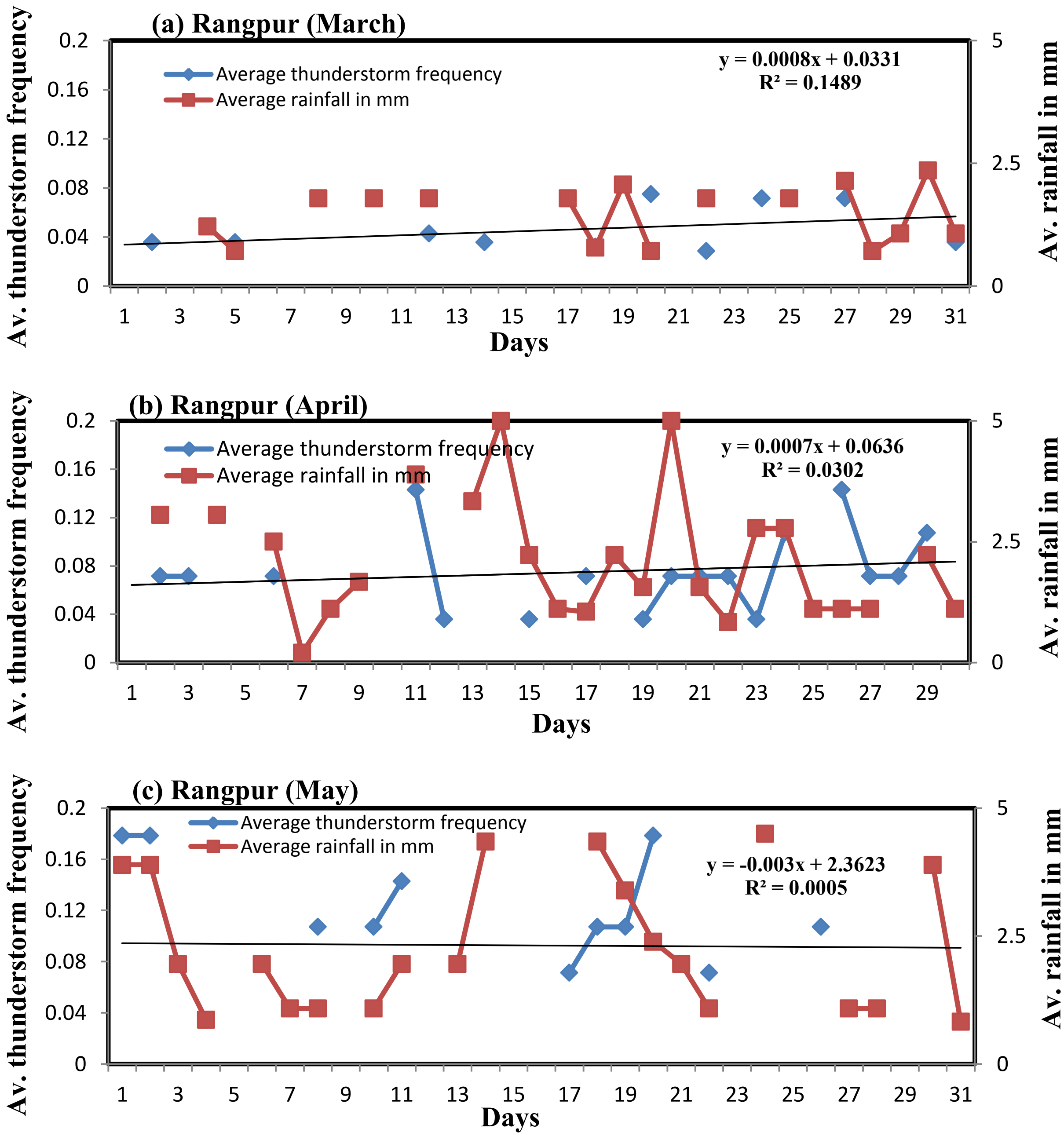


Figure 4.42: Trends of daily average thunderstorm frequency and average rainfall for Rangpur station during 1990-2017: (a) March (b) April (c) May

- **Rajshahi**

Figure 4.43 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Rajshahi station. The increasing trend for rainfall in March is strong compared to April and May. Coefficients of determinations R^2 are 0.2508, 0.0046 and 0.1159 during March, April and May, respectively.

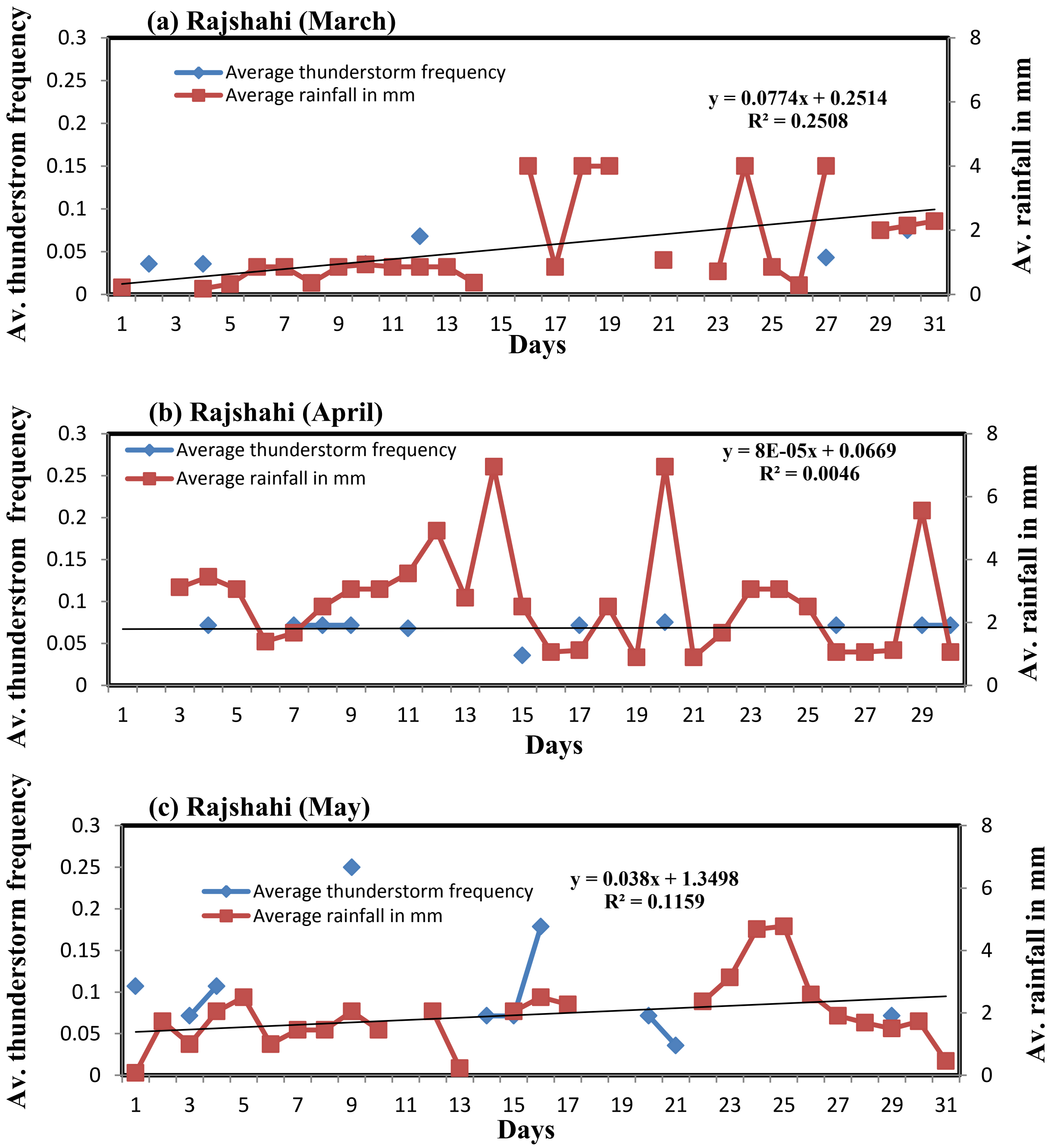


Figure 4.43: Trends of daily average thunderstorm frequency and average rainfall for Rajshahi station during 1990-2017: (a) March (b) April (c) May

- **Mongla**

Figure 4.44 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Mongla station. The increasing trend for rainfall in March is strong compared to April and May. Coefficients of determinations R^2 are 0.4724, 0.1172 and 0.0169 during March, April and May, respectively.

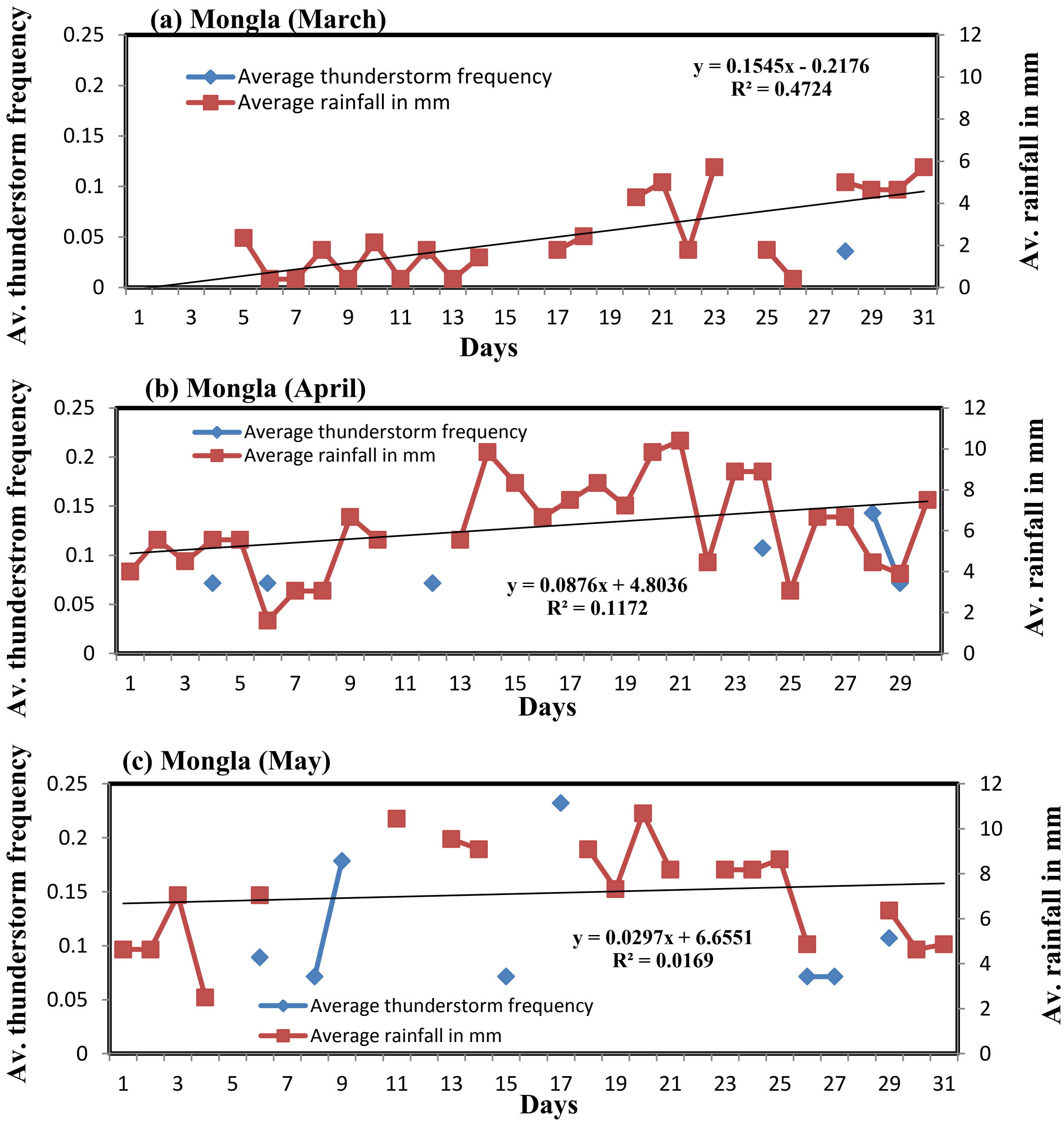


Figure 4.44: Trends of daily average thunderstorm frequency and average rainfall for Mongla station during 1990-2017: (a) March (b) April (c) May

- **Ishurdi**

Figure 4.45 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Ishurdi station. The increasing trend for rainfall in March is strong compared to April and May. Coefficients of determinations R^2 are 0.5481, 0.2937 and 0.0458 during March, April and May, respectively.

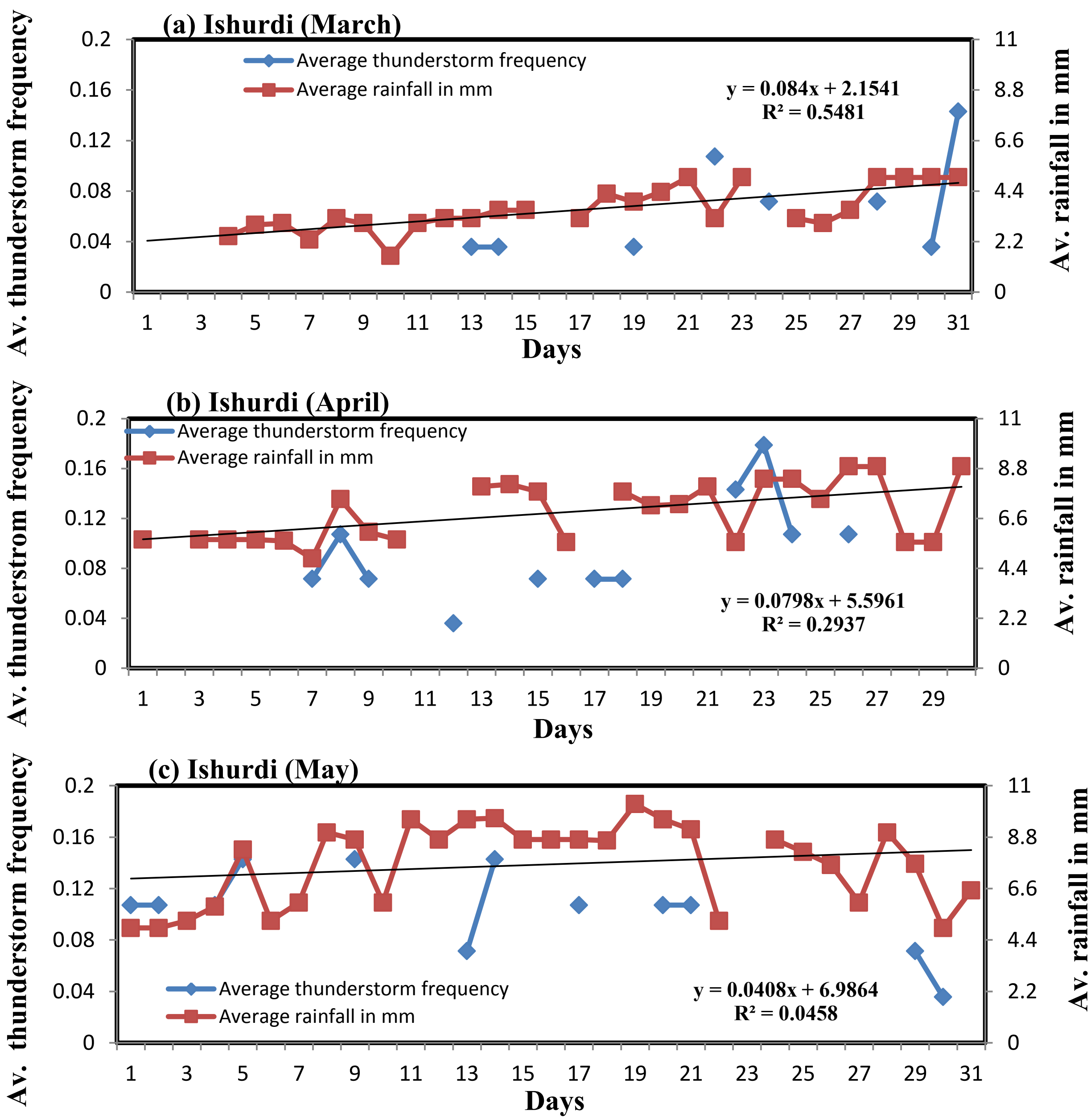


Figure 4.45: Trends of daily average thunderstorm frequency and average rainfall for Ishurdi station during 1990-2017: (a) March (b) April (c) May

- **Faridpur**

Figure 4.46 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Faridpur station. The increasing trend for rainfall in March is strong compared to April and May. Coefficients of determinations R^2 are 0.4148, 0.0061 and 0.0672 during March, April and May, respectively.

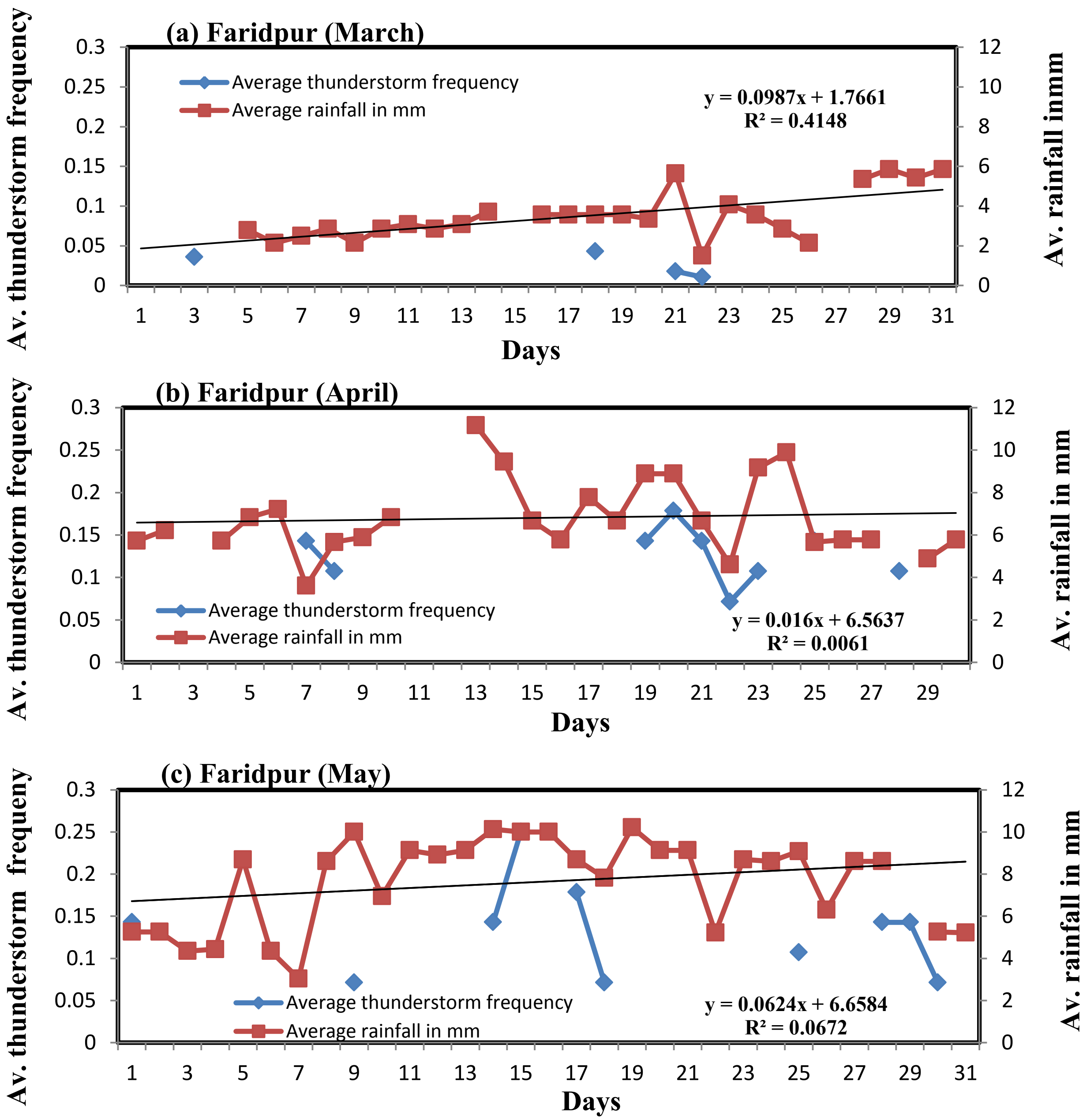


Figure 4.46: Trends of daily average thunderstorm frequency and average rainfall for Faridpur station during 1990-2017: (a) March (b) April (c) May

- **Mymensingh**

Figure 4.47 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Mymensingh station. The increasing trend for rainfall in March is strong compared to April and May.

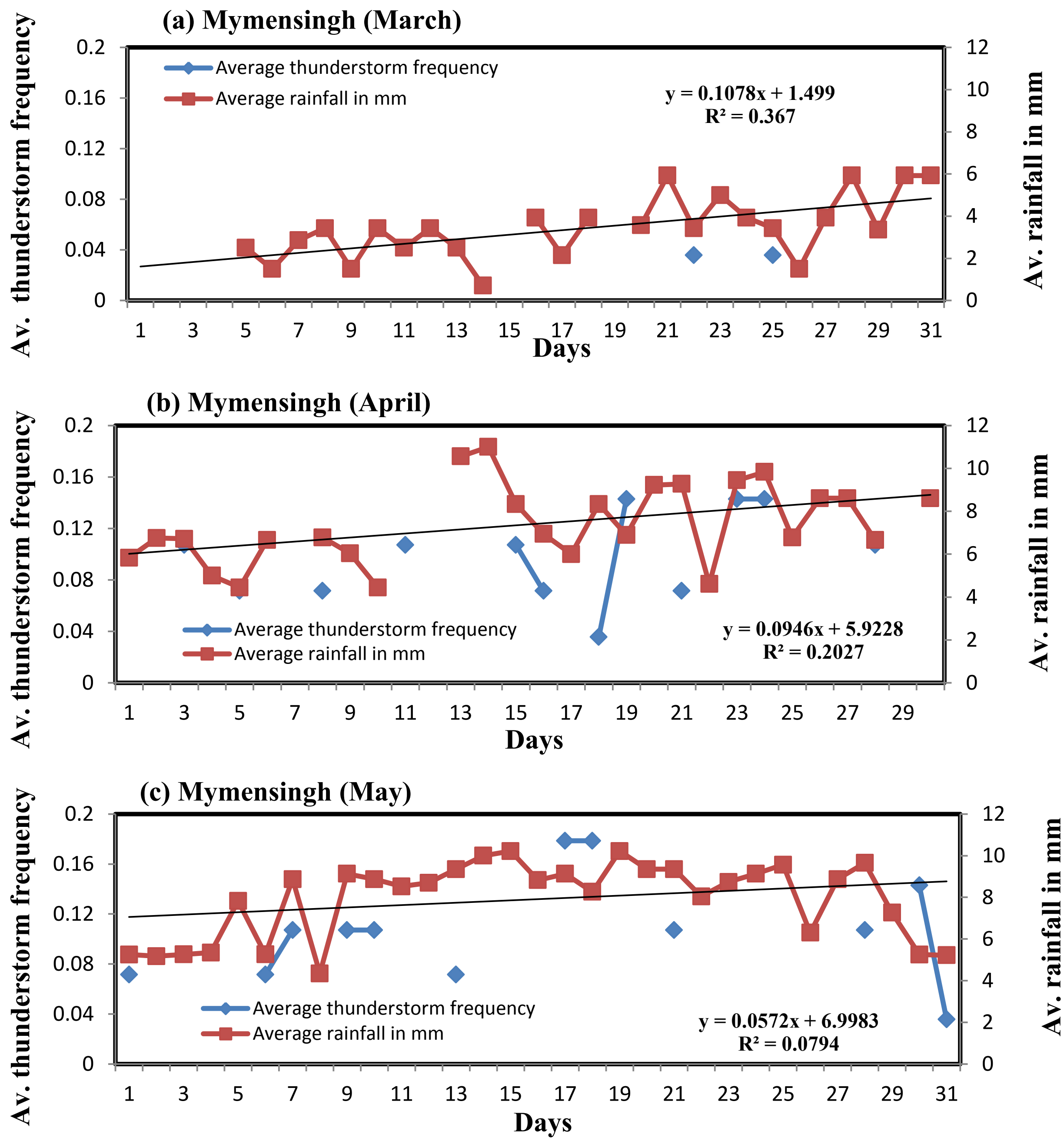


Figure 4.47: Trends of daily average thunderstorm frequency and average rainfall for Mymensingh station during 1990-2017: (a) March (b) April (c) May

- **Tangail**

Figure 4.48 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Tangail station. The increasing trend for rainfall in March is strong compared to April and May. Coefficients of determinations R^2 are 0.2551, 0.0859 and 0.1556 during March, April and May, respectively.

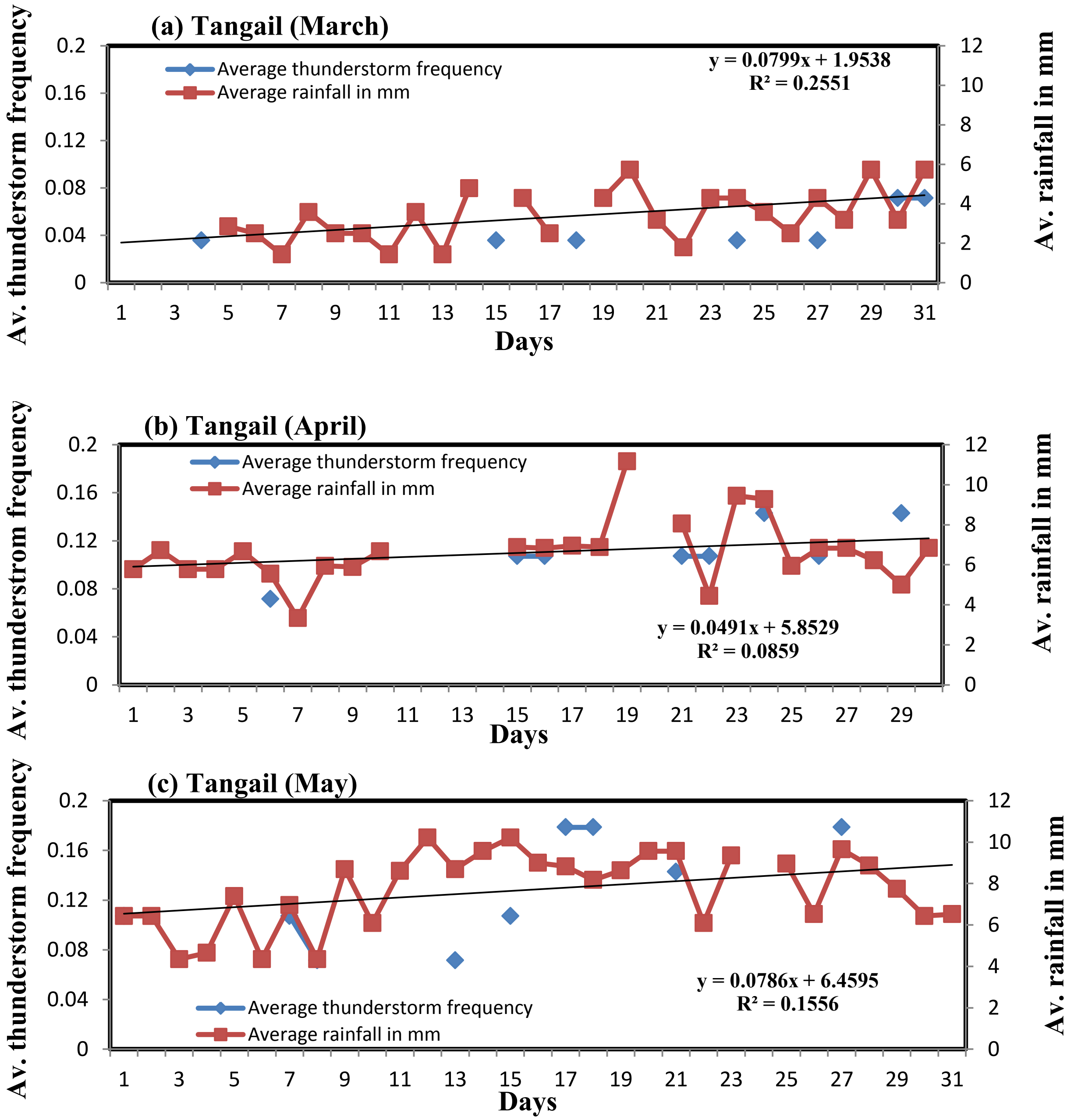


Figure 4.48: Trends of daily average thunderstorm frequency and average rainfall for Tangail station during 1990-2017: (a) March (b) April (c) May

- **Dinajpur**

Figure 4.49 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Dinajpur station. The increasing trend for rainfall in March is strong compared to April and May. Coefficients of determinations R^2 are 0.0237, 0.0009 and 0.0012 during March, April and May, respectively.

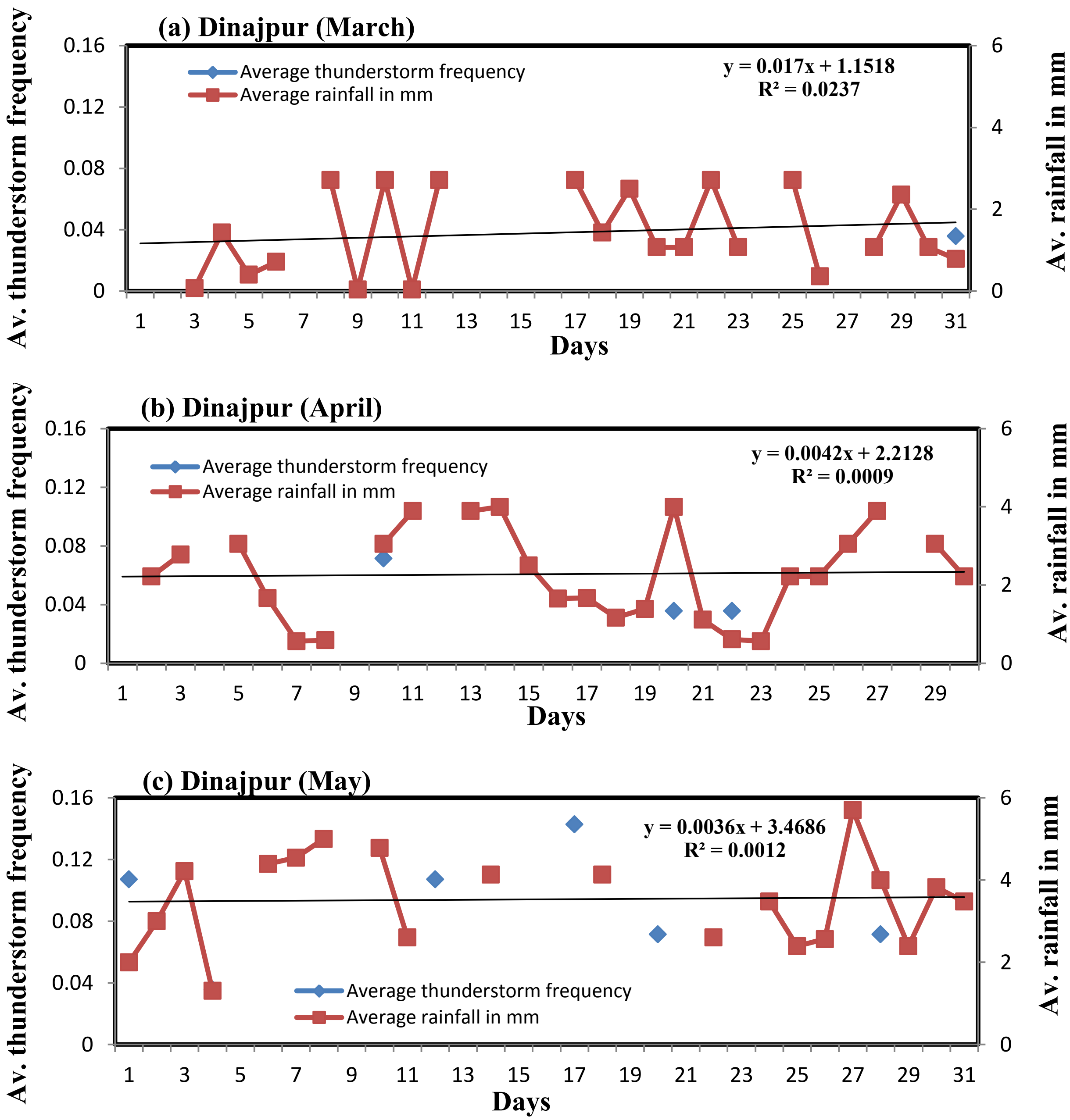


Figure 4.49: Trends of daily average thunderstorm frequency and average rainfall for Dinajpur station during 1990-2017: (a) March (b) April (c) May

- **Maijdee Court**

Figure 4.50 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Maijdee Court station. The increasing trend for rainfall in March is strong compared to April and May. Coefficients of determinations R^2 are 0.3427, 0.0013 and 0.0119 during March, April and May, respectively.

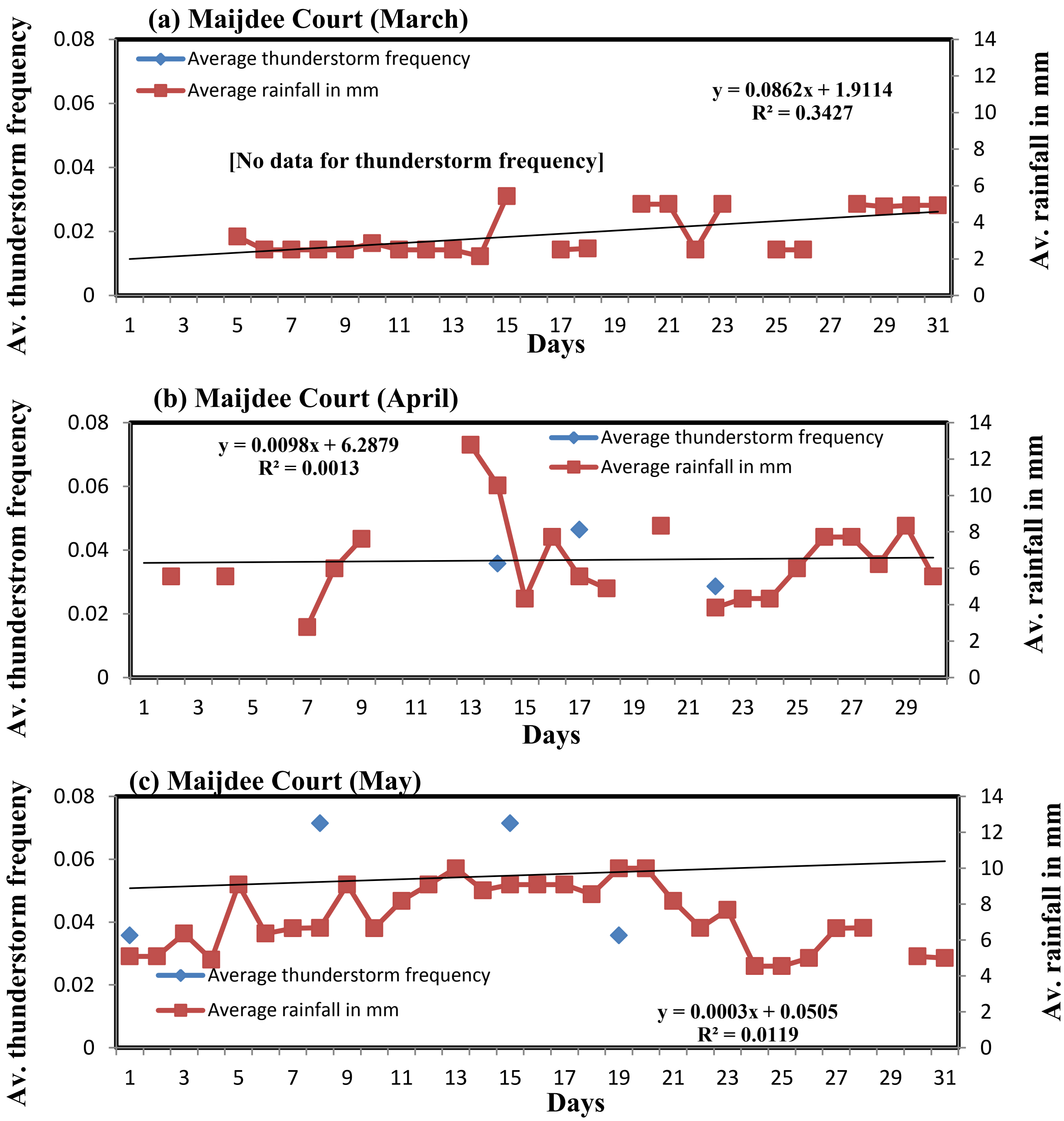


Figure 4.50: Trends of daily average thunderstorm frequency and average rainfall for Maijdee Court station during 1990-2017: (a) March (b) April (c) May

- **Sandwip**

Figure 4.51 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Sandwip station. The increasing trend for rainfall in March is strong compared to April and May. Coefficients of determinations R^2 are 0.0366, 0.0016 and 0.001 during March, April and May, respectively.

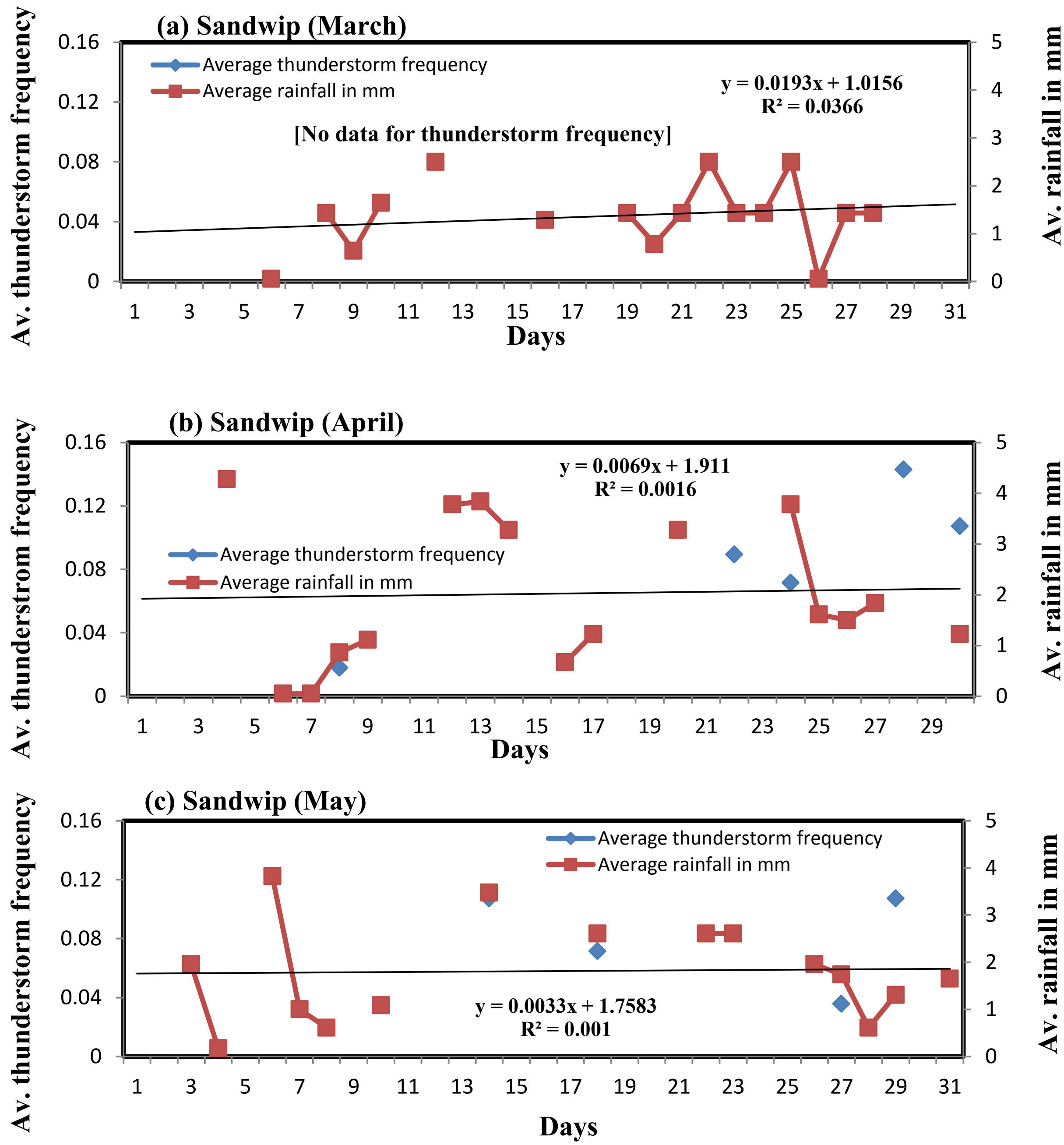


Figure 4.51: Trends of daily average thunderstorm frequency and average rainfall for Sandwip station during 1990-2017: (a) March (b) April (c) May

- **Teknaf**

Figure 4.52 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Teknaf station. The increasing trend for rainfall in March is strong compared to April and May. Coefficients of determinations R^2 are 0.7489, 0.0035 and 0.0014 during March, April and May, respectively.

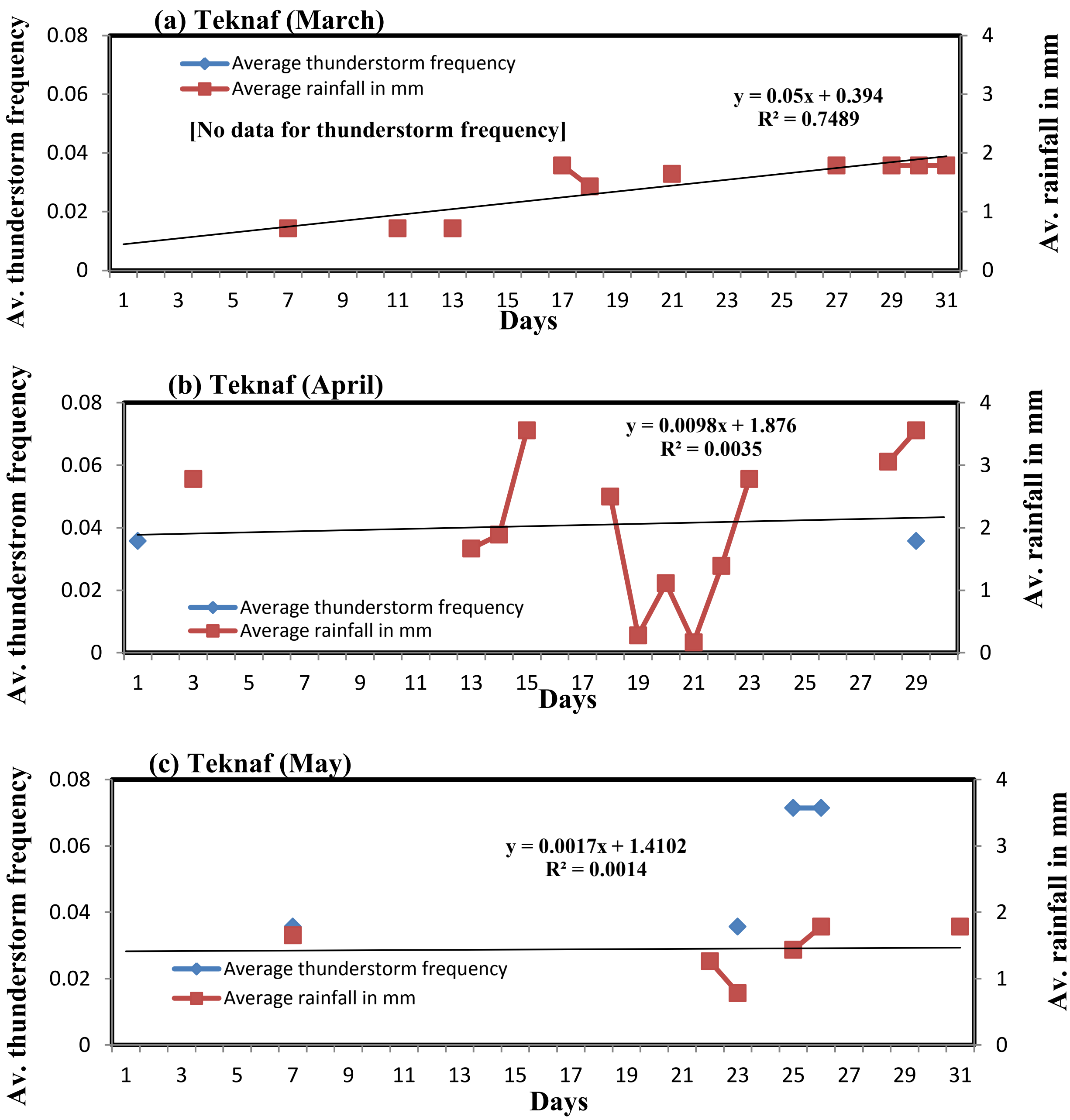


Figure 4.52: Trends of daily average thunderstorm frequency and average rainfall for Teknaf station during 1990-2017: (a) March (b) April (c) May

- **Srimangal**

Figure 4.53 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Srimangal station. The increasing trend for rainfall in March is strong compared to April and May. Coefficients of determinations R^2 are 0.4284, 0.2641 and 0.311 during March, April and May, respectively.

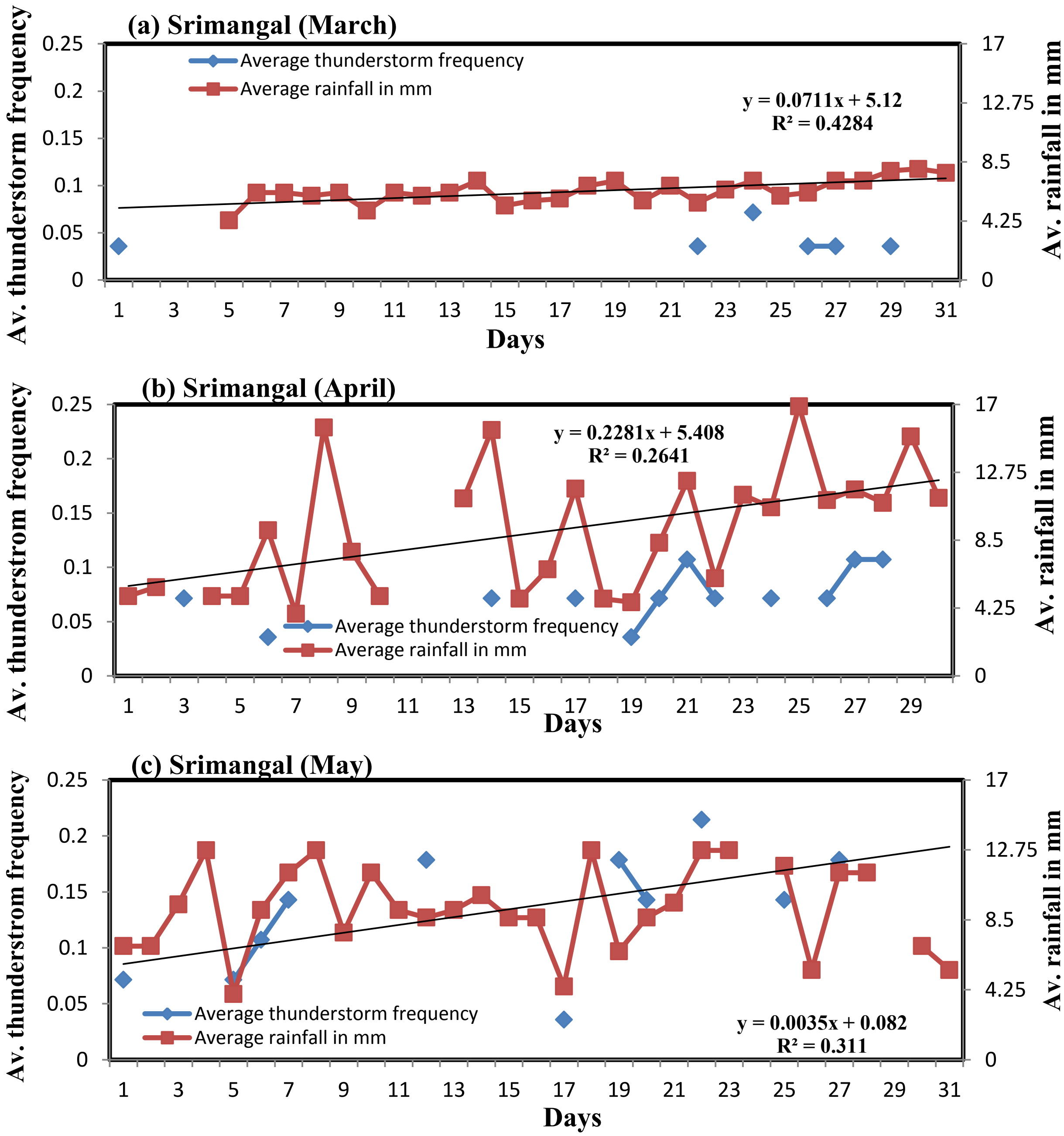


Figure 4.53: Trends of daily average thunderstorm frequency and average rainfall for Srimangal station during 1990-2017: (a) March (b) April (c) May

- **Satkhira**

Figure 4.54 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Satkhira station. The increasing trend for rainfall in March is strong compared to April and May. Coefficients of determinations R^2 are 0.423, 0.312 and 0.1413 during March, April and May, respectively.

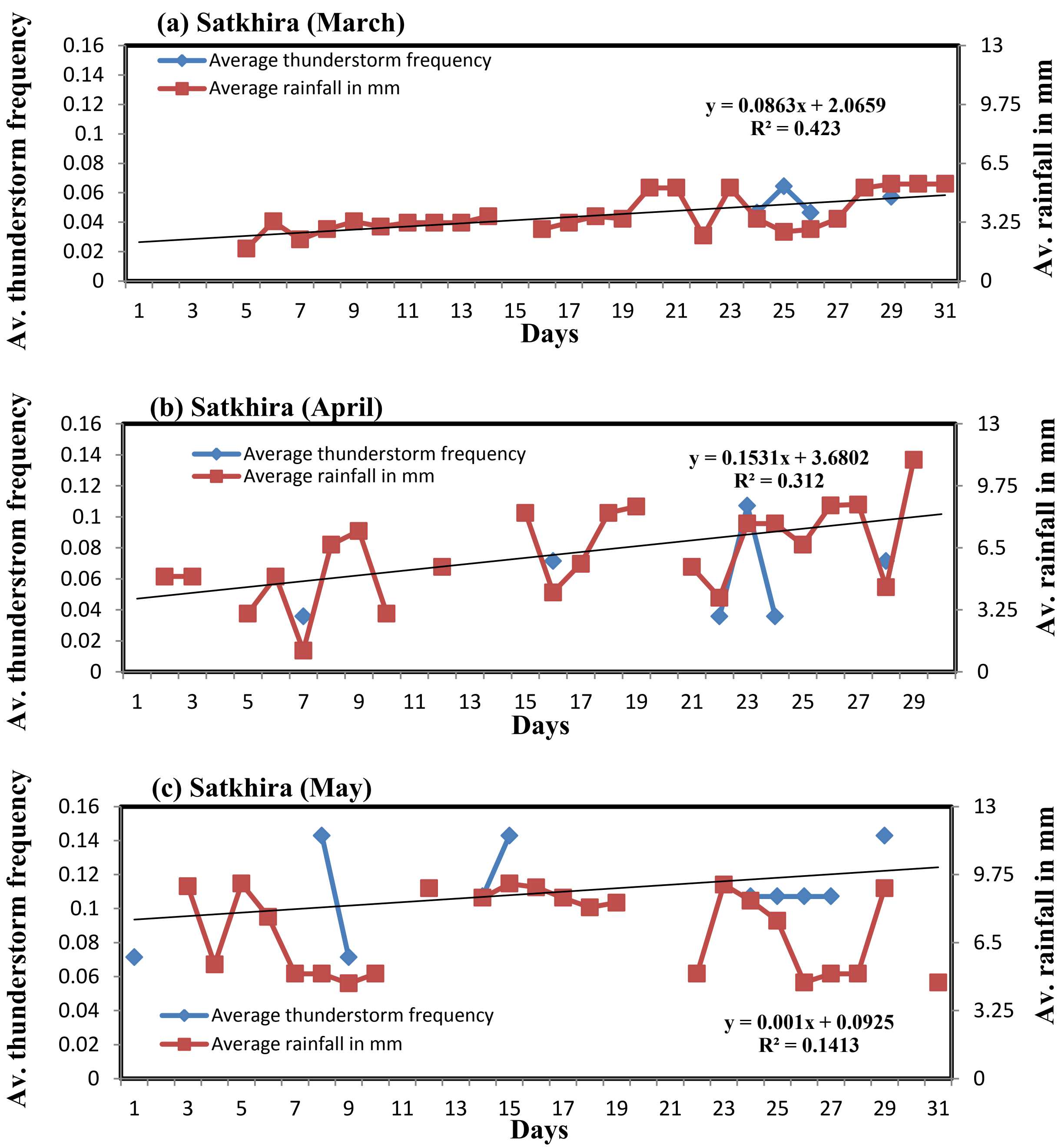


Figure 4.54: Trends of daily average thunderstorm frequency and average rainfall for Satkhira station during 1990-2017: (a) March (b) April (c) May

- **Rangamati**

Figure 4.55 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Rangamati station. The increasing trend for rainfall in March is strong compared to April and May. Coefficients of determinations R^2 are 0.3604, 0.0395 and 0.0272 during March, April and May, respectively.

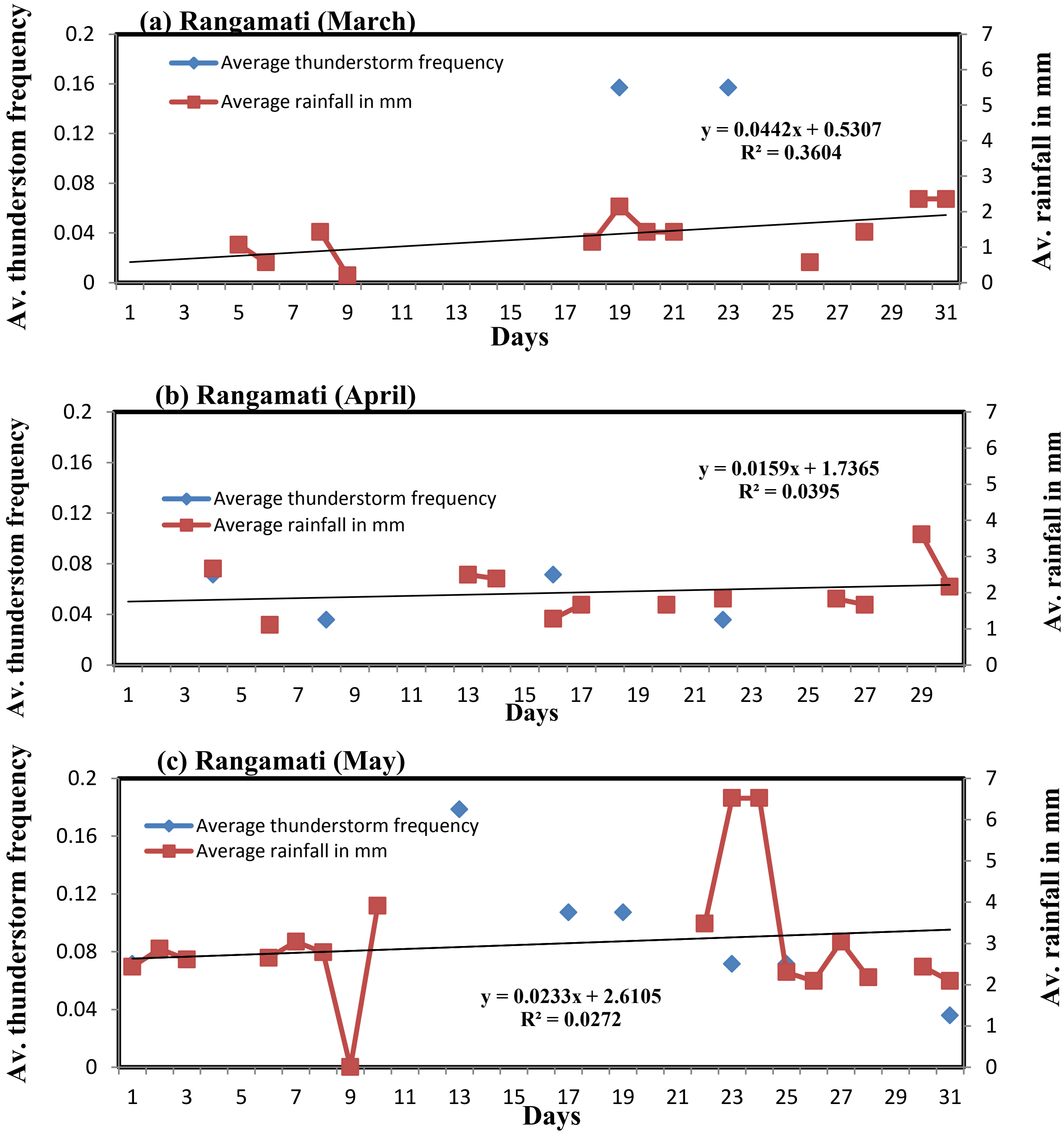


Figure 4.55: Trends of daily average thunderstorm frequency and average rainfall for Rangamati station during 1990-2017: (a) March (b) April (c) May

- **Cumilla**

Figure 4.56 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Cumilla station. The increasing trend for rainfall in March is strong compared to April and May. Coefficients of determinations R^2 are 0.2469, 0.0068 and 0.0013 during March, April and May respectively.

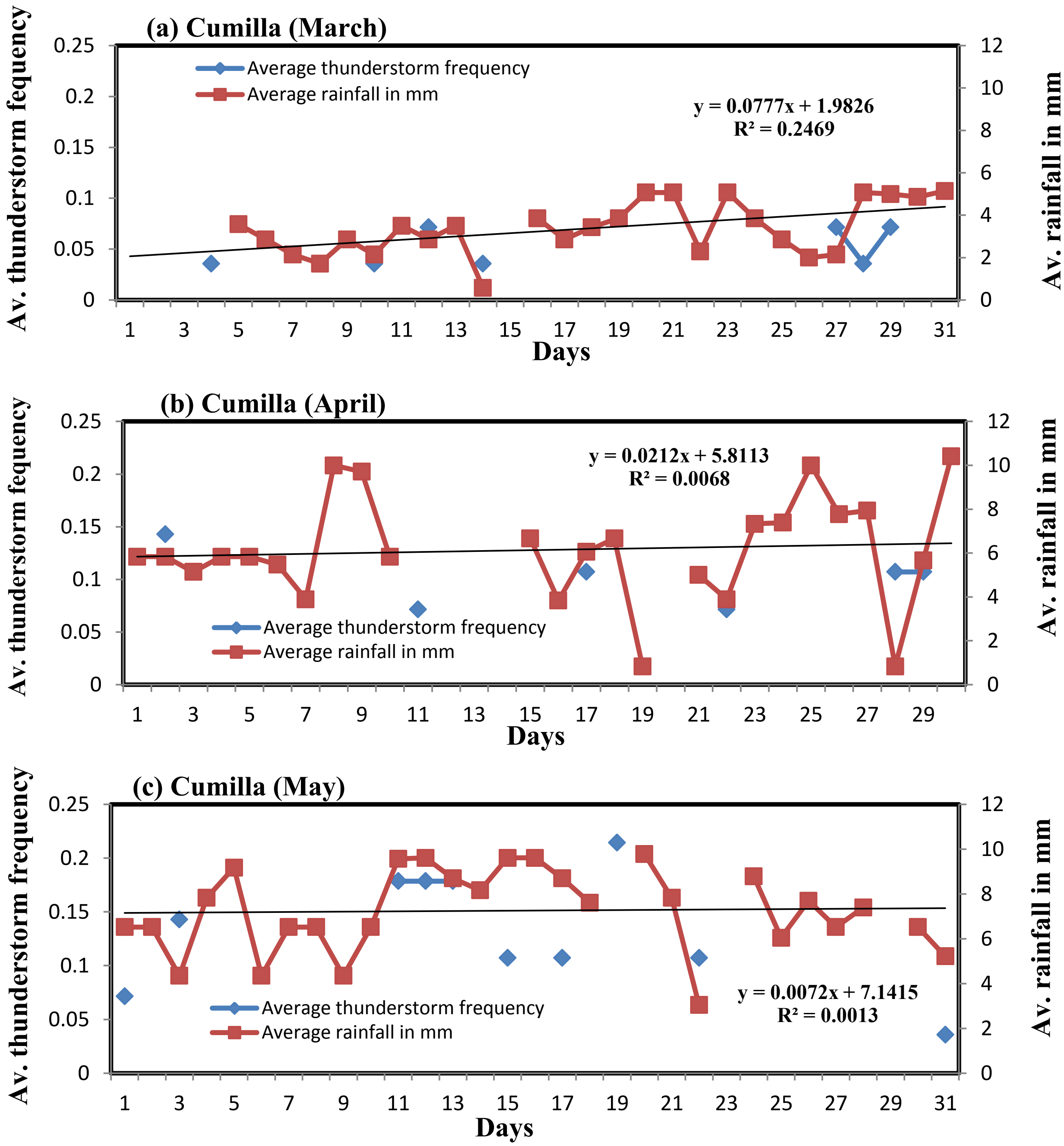


Figure 4.56: Trends between average thunderstorm frequency and average rainfall for Cumilla station during 1990-2017: (a) March (b) April (c) May

- **Sitakunda**

Figure 4.57 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Sitakunda station. The increasing trend for rainfall in March is strong compared to April and May.

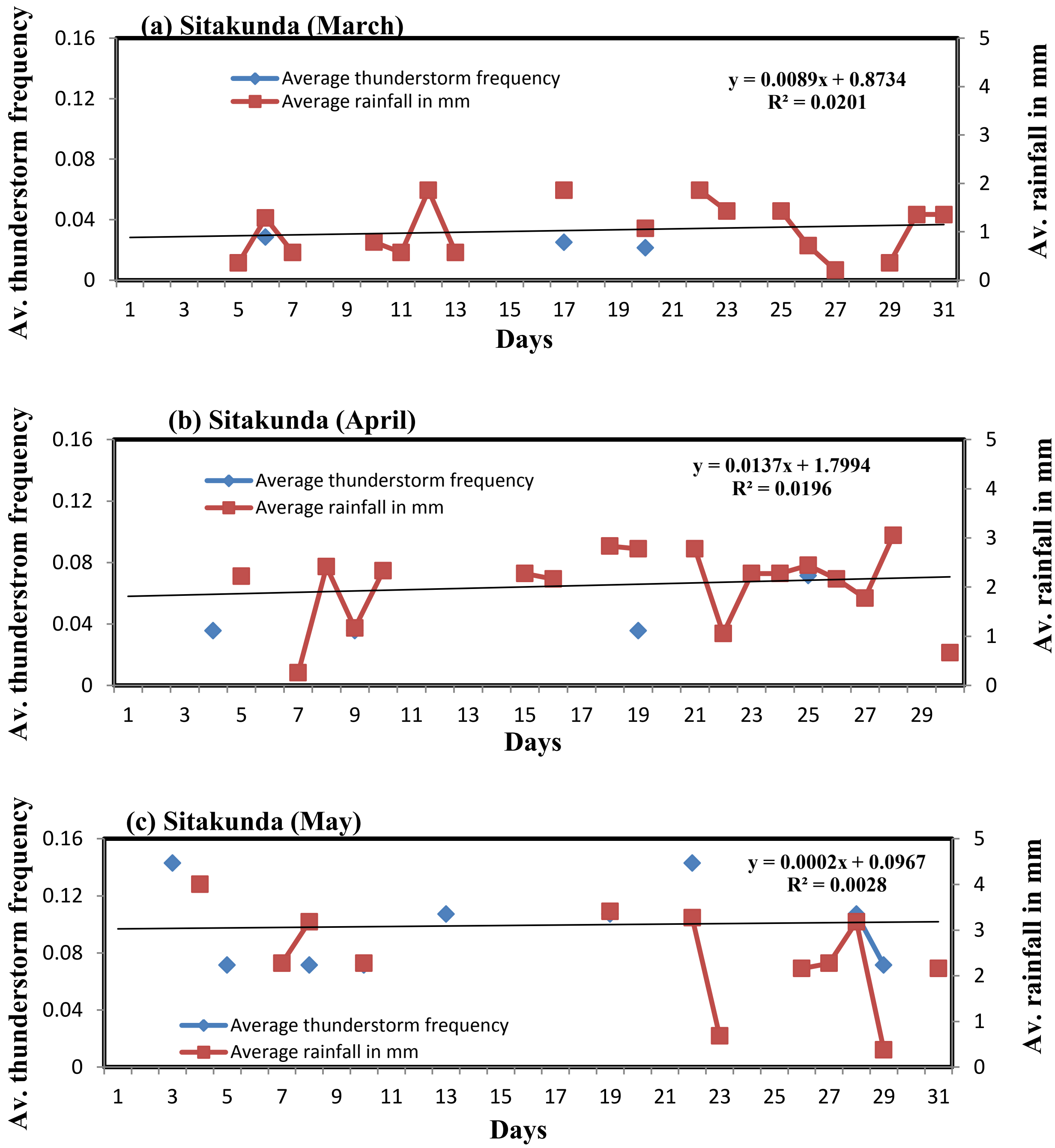


Figure 4.57: Trends of daily average thunderstorm frequency and average rainfall for Sitakunda station during 1990-2017: (a) March (b) April (c) May

- **Madaripur**

Figure 4.58 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Madaripur station. The increasing trend for rainfall in March is strong compared to April and May. Coefficients of determinations R^2 are 0.4554, 0.046 and 0.1832 during March, April and May respectively.

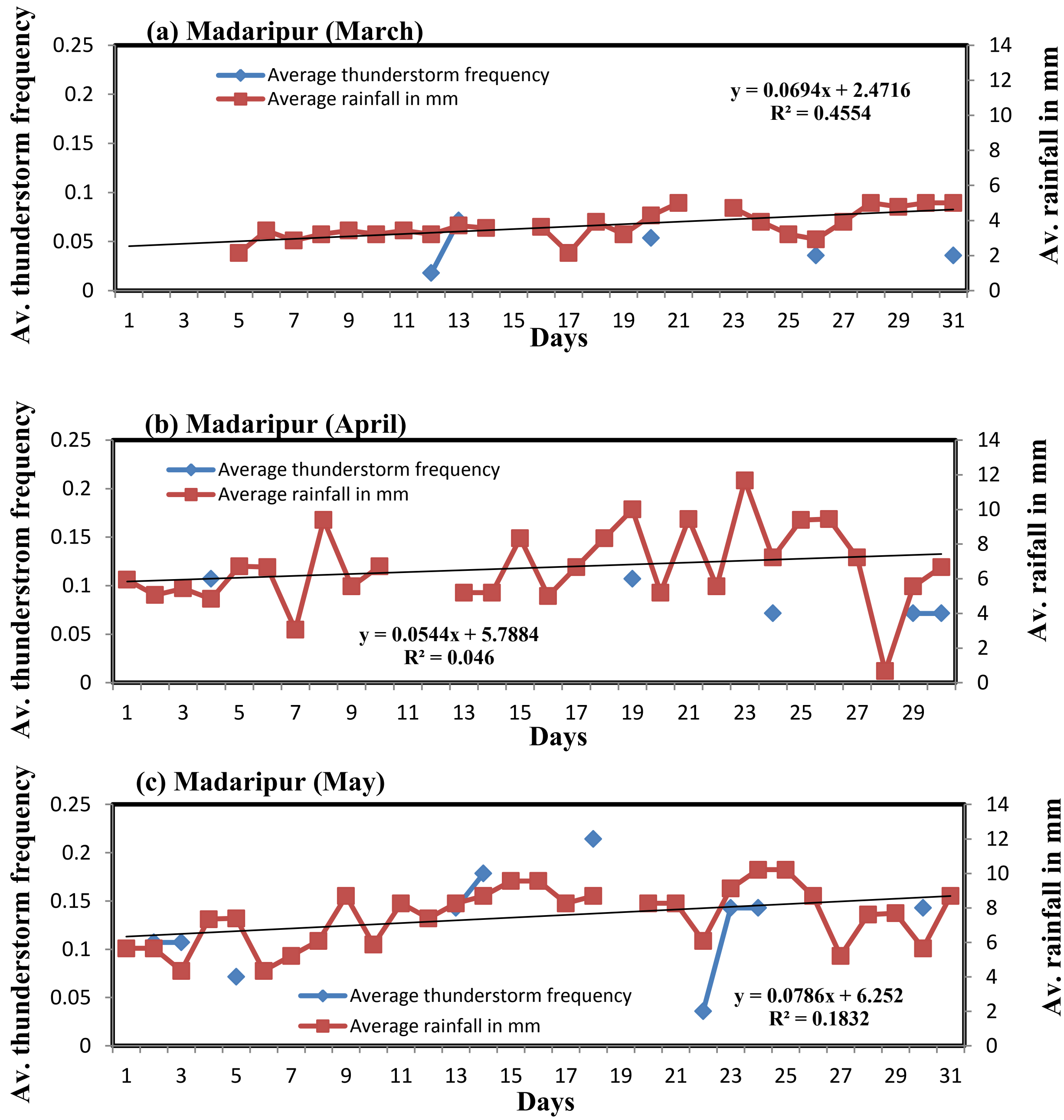


Figure 4.58: Trends of daily average thunderstorm frequency and average rainfall for Madaripur station during 1990-2017: (a) March (b) April (c) May

- **Chuadanga**

Figure 4.59 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May for Chuadanga station. . The increasing trend for rainfall in March is strong compared to April and May. Coefficients of determinations R^2 are 0.2305, 0.0443 and 0.2126 during March, April and May respectively.

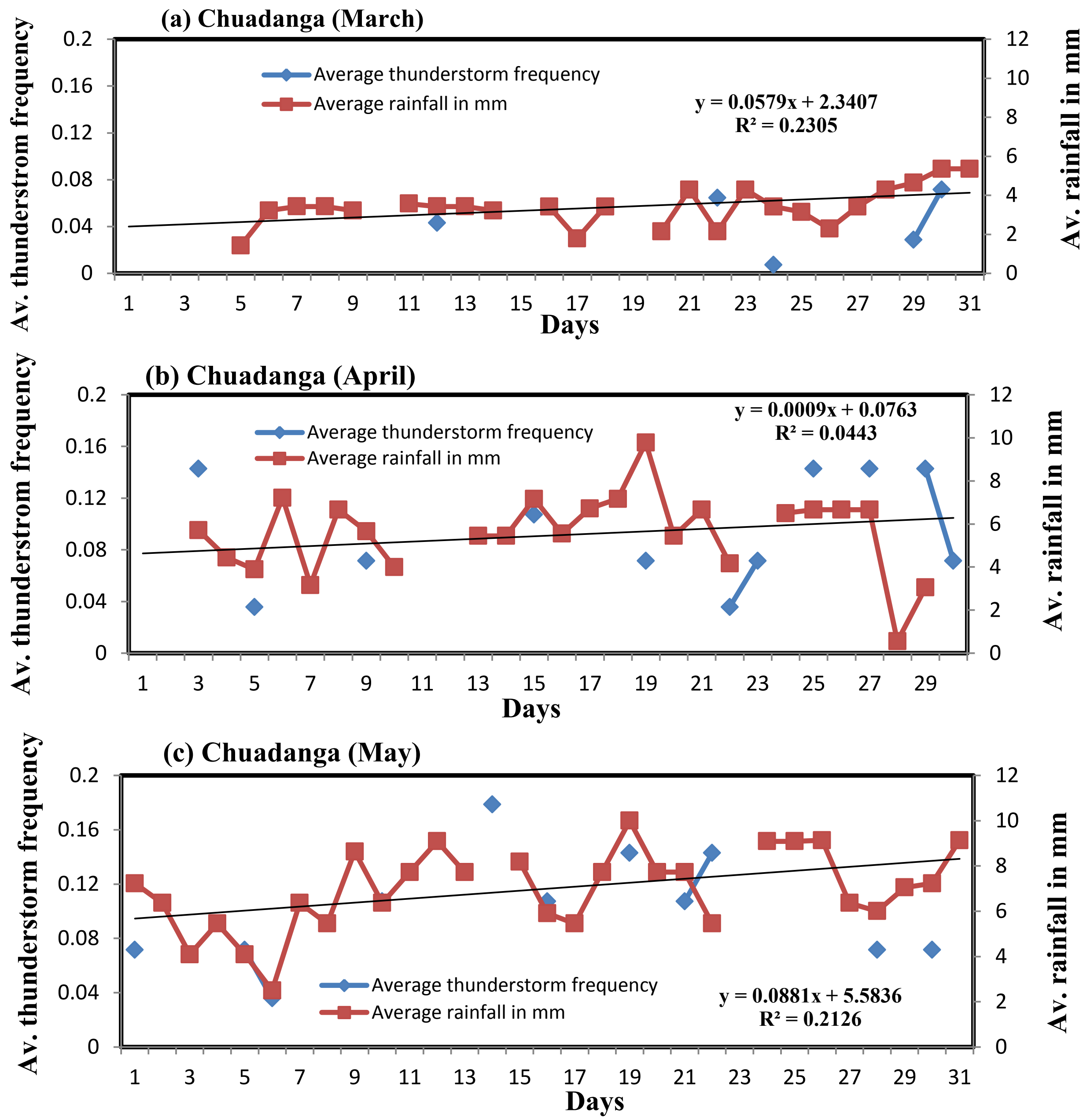


Figure 4.59: Trends of daily average thunderstorm frequency and average rainfall for Chuadanga station during 1990-2017: (a) March (b) April (c) May

4.1.11.2 Trends of Daily Average Thunderstorm Frequency and Average Rainfall over Bangladesh

Figure 4.60 shows trends of daily average thunderstorm frequency and average rainfall during 1990-2018 for the month of (a) March (b) April (c) May over Bangladesh. There are increasing trend of rainfall during pre-monsoon. In comparison, during March most significant increasing positive trend is found than that of April and May. Coefficients of determinations R^2 are 0.6561, 0.1469 and 0.0203 for the month of March, April and May, respectively.

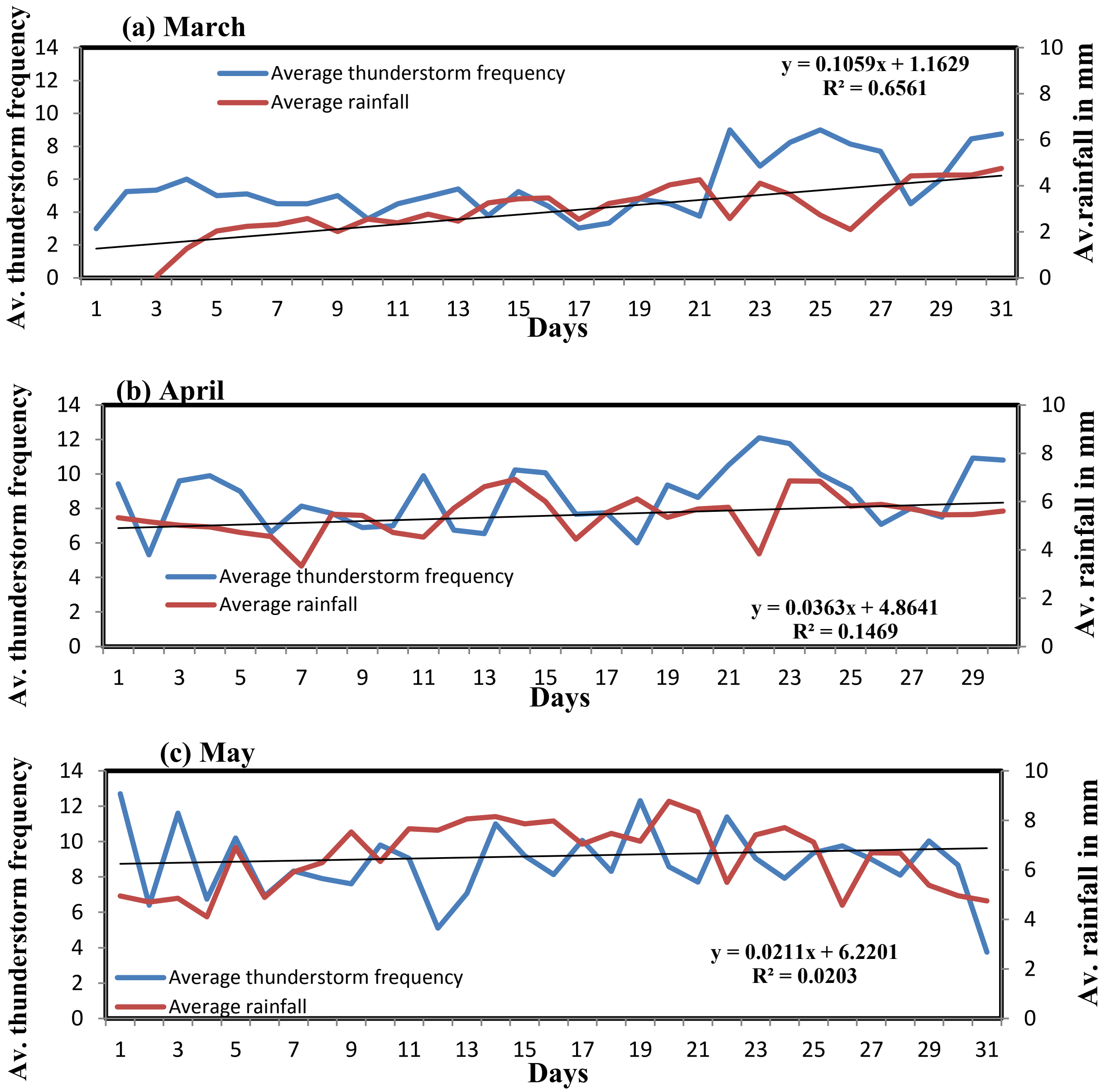


Figure 4.60: Trends of daily average thunderstorm frequency and average rainfall over Bangladesh during 1990-2017: (a) March (b) April (c) May

Figure 4.61 shows trends of daily average thunderstorm frequency and average rainfall during pre-monsoon over Bangladesh. There are increasing trend of average rainfall during pre-monsoon season and coefficients of determinations R^2 is found 0.1892.

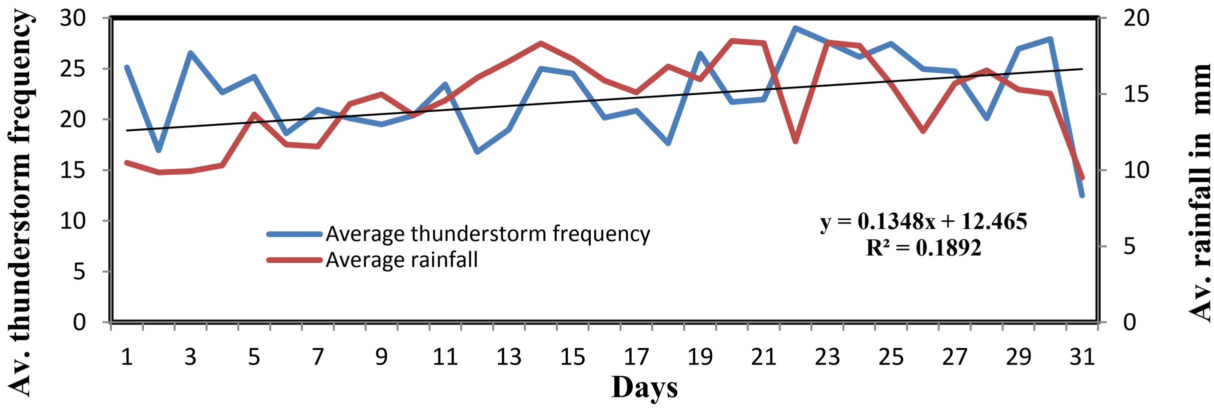


Figure 4.61: Trend of daily average thunderstorm frequency and average rainfall during pre-monsoon over Bangladesh during 1990-2017

4.1.12 Correlation Co-efficient between Thunderstorm Frequency and Rainfall

Stations	March	April	May
Dhaka	0.42	0.46	0.73
Feni	N/ A	0.07	0.12
Chandpur	0.41	0.56	0.61
Chattogram	0.21	0.43	0.67
Bhola	N/ A	0.20	0.34
Sylhet	0.42	0.60	0.83
Sayedpur	N/ A	0.17	0.28
Khulna	0.49	0.52	0.53
Kutubdia	N/ A	0.56	0.56
Cox's Bazar	0.36	0.43	0.55
Hatiya	0.11	0.31	0.48
Jashore	0.13	0.14	0.51
Barishal	0.46	0.64	0.70
Patuakhali	0.36	0.37	0.62
Khepupara	0.17	0.24	0.67
Bogura	0.09	0.17	0.44
Rangpur	0.14	0.11	0.48
Rajshahi	0.11	0.14	0.48

Mongla	N/ A	0.33	0.67
Ishurdi	0.26	0.26	0.40
Faridpur	0.22	0.35	0.55
Mymensingh	N/ A	0.30	0.56
Tangail	0.09	0.30	0.50
Dinajpur	N/ A	0.07	0.40
Maijdee Court	N/ A	0.13	0.19
Sandwip	N/ A	0.23	0.27
Teknaf	N/ A	N/A	0.14
Srimangal	0.22	0.52	0.73
Satkhira	0.10	0.45	0.45
Rangamati	N/ A	0.11	0.39
Cumilla	0.23	0.31	0.53
Sitakunda	0.26	0.32	0.45
Madaripur	0.22	0.26	0.52
Chuadanga	0.08	0.11	0.61

Table 4.1: Correlation co-efficient _r' between average thunderstorm frequency and average rainfall in 34 stations of Bangladesh

N/A: Not applicable

Note: In March 6 stations (Bhola, Sayedpur, Kutubdia, Maijdee Court, Sandwip and Teknaf) thunderstorm data is not available.

Table 4.2 shows the co-relation co-efficient between thunderstorm frequency and rainfall during pre-monsoon season in Bangladesh. The correlation co-efficient increases as month progress. The average correlation co-efficient for pre-monsoon season is found 0.55.

Month	Correlation co-efficient
March	0.45
April	0.57
May	0.61
Pre-monsoon	0.55

Table 4.2: Correlation co-efficient _r' between thunderstorm frequency and rainfall during pre-monsoon over Bangladesh

CHAPTER FIVE

CONCLUSIONS

Thunderstorm is a weather phenomenon occurs with dense cloud, heavy rain, gusty wind, hail and rainfall. To study thunderstorm frequency, Bangladesh Meteorology Department (BMD) station data and rainfall data are used. The sub-daily, daily, monthly and yearly thunderstorm frequency is extracted from the BMD station data during 1990-2017 over Bangladesh. Details analysis of variation of pre-monsoon thunderstorm frequency and its relation with rainfall is carried out using statistical method. From station data, the spatial (regional) variation of thunderstorm frequency, wind speed and direction will be also studied.

In case of hourly thunderstorm frequency, during March the maximum thunderstorm frequency is found at 14 UTC for the month of March. The lowest thunderstorm frequency found on 00 UTC. During April, maximum thunderstorm frequency is found on 15 UTC. The lowest thunderstorm frequency occurs on 00 UTC. During May the highest thunderstorm frequency is observed on 12 UTC and the lowest on 00 UTC.

The maximum occurrence of thunderstorm for pre-monsoon season is found on 12-15 UTC and minimum occurrence is found on 00-03 UTC. The maximum numbers of thunderstorms are found in the month of May.

For 6-hours interval data, the highest thunderstorm frequency is found in Dhaka on 12-18 UTC whereas the minimum frequency is found in Feni, Dinajpur for the month of March. In April, the maximum thunderstorm is found in Dhaka at 12-18 UTC and minimum occurrence is found in Feni and Teknaf. During May, the maximum frequency is found in Dhaka at 12-18 UTC and minimum frequency in Feni, Maijdee Court and Teknaf.

From daily frequency distribution of thunderstorm it is found that, in the first half of the March thunderstorm occurrence is less. From 22nd March it starts to increase. Maximum number of events occurs on last week of March. For the months of April and May thunderstorm activities are found throughout the month. But at end of May thunderstorm frequency starts to decreases, due to initiation of monsoon.

In Bangladesh it is found that about 54% of thunderstorms are squall type, 39% gusty and remaining 7% are hail type during pre-monsoon season. There is strong yearly variation of occurrence frequency of different types of thunderstorms in Bangladesh during pre-monsoon season.

The highest average wind speed 98 km/h is found in Teknaf in the month of May and lowest 38 km/h in Hatiya in March. About 18%, 29% and 31% thunderstorm propagates southeastward direction during March, April and May, respectively.

From spatial analysis, during March highest thunderstorm frequency appears in Dhaka and lowest in Feni and Dinajpur. During April maximum thunderstorm frequency occurs in Dhaka and Sylhet and minimum in Teknaf. The highest frequency appears in Dhaka and lowest in Feni, Teknaf and Maijdee Court. During pre-monsoon season most of the thunderstorm is found in the central and north-eastern part of Bangladesh.

The number of thunderstorm days is highest in May, medium in April and minimum in March. In contrast, the number of non-thunderstorm days is greatest in March, medium in April and minimum in May. The number of non-thunderstorm day decrease gradually through March to May.

Among the three pre-monsoonal months increasing trend of rainfall is maximum for the month of March but amount is less compared to April and May. The average amount of rainfall is found 87 mm, 163 mm and 203 mm for the month of March, April and May during the study period, respectively. There is strong daily variation of rainfall in pre-monsoon season.

The correlation coefficient of thunderstorm occurrence and rainfall is found 0.45, 0.57 and 0.61 for the month of March, April and May respectively. The present study found a good correlation between thunderstorm frequency and rainfall in Bangladesh during pre-monsoon season. This study reveals that rainfall increases with increase of thunderstorms in Bangladesh during pre-monsoon season.

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Appendix-A

Station-wise variation in six-hourly, monthly and yearly thunderstorm frequency

A-1.1 Station-wise variation in six-hourly, monthly and yearly thunderstorm frequency

The figure A-1.1 indicates station-wise six hourly variation in thunderstorm frequency during 1990-2017 for the month of (a) March (b) April (c) May. During March, the highest thunderstorm frequency is found in Dhaka at 12-18 UTC (events no. 0.54). Minimum frequency is found at Feni, Dinajpur. In April, as March maximum thunderstorm occurs at Dhaka at 12-18 UTC (events no. 1.25). The minimum number of thunderstorms is found in Feni and Teknaf. The maximum frequency is in Dhaka at 12-18 UTC (events no. 1.36) and minimum frequency are in Feni, Maijdee Court and Teknaf.

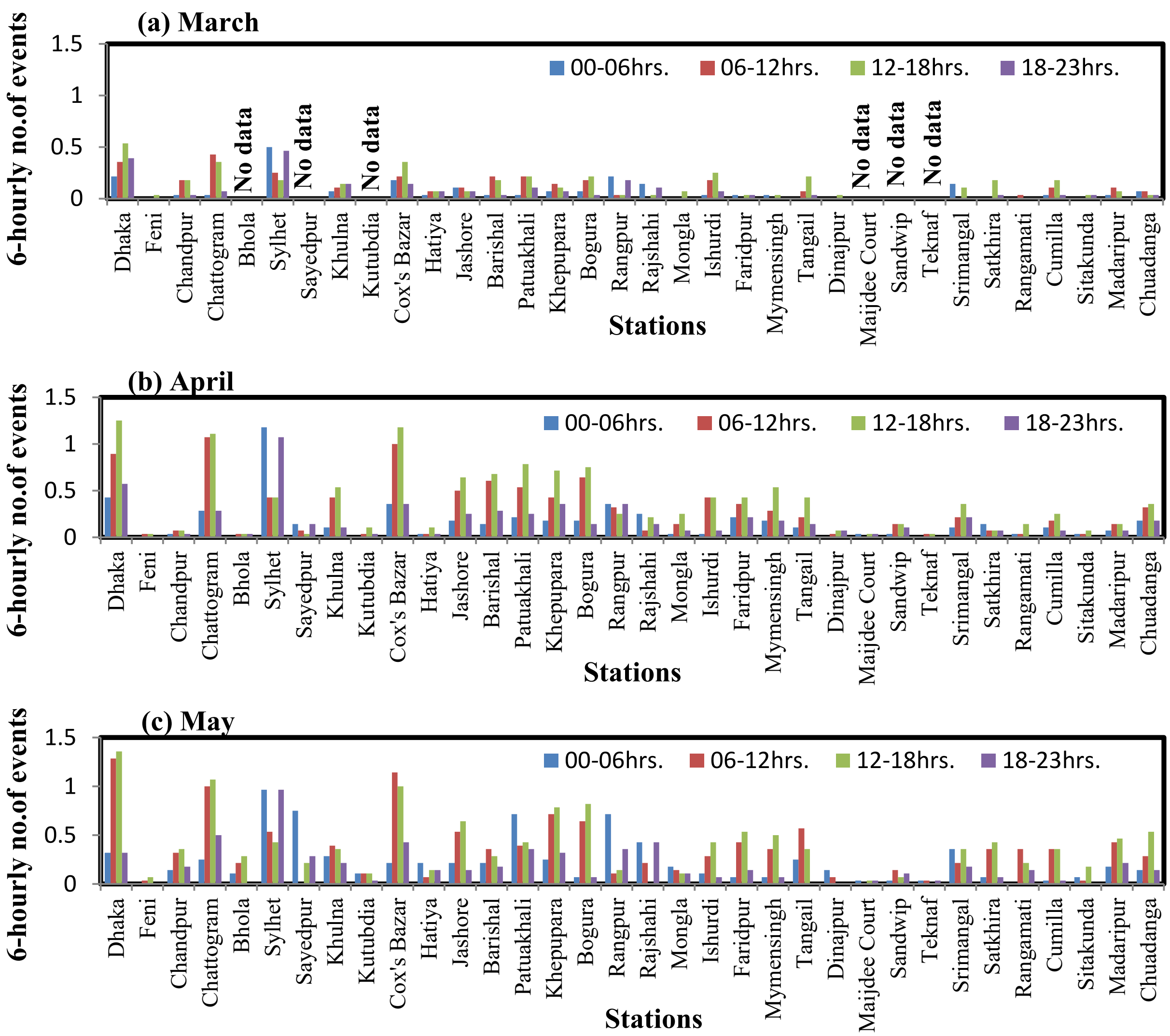

Figure A-1.1: Station-wise six hourly variations in thunderstorm frequency during 1990-2017: (a) March (b) April (c) May

Appendix-B

Conference Abstract

Avantika Jayati Dhali and M. Rafiuddin, ―Study on pre-monsoon thunderstorm frequency and its relation with rainfall in bangladesh during 1990-2017" Abstract in the National Conference on Physics-2019, Bangladesh Physical Society, University of Dhaka, Bangladesh, 07-09 February, 2019.

Abstract in the National Conference on Physics-2019, Bangladesh Physical Society,

University of Dhaka, Bangladesh, 07-09 February, 2019.

STUDY ON PRE-MONSOON THUNDERSTORM FREQUENCY AND ITS RELATION WITH RAINFALL IN BANGLADESH DURING 1990-2017

Avantika Jayati Dhali[1*], M. Rafiuddin[2]

[1] *M. Sc. student, Department of Physics, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh, e-mail: www. avantika1994@gmail.com*

[2] *Department of Physics, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh, e-mail: rafiuddin@phy.buet.ac.bd*

ABSTRACT

In this study, pre-monsoon (March-May) thunderstorm frequency and its relation with rainfall is carried out using 28 years (1990-2017) Bangladesh Meteorological Department (BMD) 34 stations data. BMD achieved the thunderstorm as gusty, squall and hail type. The thunderstorms are also further classified into severe (> 64 km/h) and non-severe (≤64 km/h) based on their wind speed. The maximum occurrence of thunderstorm is found 12-18 UTC (18-24 LST) during 1990-2017. The occurrence of squall is found maximum in the month of May. The occurrence of severe and non-severe thunderstorm is found maximum in the month of May in 1993 and March in 2004 respectively. Spatial distribution showed the maximum occurrence of thunderstorm is found in Dhaka and minimum in Teknaf, M. Court and Feni. In average, about 39% thunderstorm is found to propagate southeastward during pre-monsoon. The highest number of thunderstorm day is found in the month of May. The correlation coefficient of thunderstorm occurrence and rainfall is found 0.42, 0.14 and 0.13 for the month of March, April, May, respectively.

Keywords: Thunderstorm frequency, Rainfall, Bangladesh, Correlation coefficient.