# REGIONAL VARIATION OF MESOSCALE PRECIPITATION SYSTEM DURING PRE-MONSOON PERIOD IN BANGLADESH

MASTER OF PHILOSOPHY IN PHYSICS

JAHANARA BEGUM

DEPARTMENT OF PHYSICS

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY,

DHAKA-1000, BANGLADEH

September' 2011

# REGIONAL VARIATION OF MESOSCALE PRECIPITATION SYSTEM DURING PRE-MONSOON PERIOD IN BANGLADESH

A Dissertation Submitted to the Department of Physics,

Bangladesh University of Engineering and Technology, Dhaka,

in Partial Fulfillment for the Requirement of the degree of

Master of Philosophy in Physics

Submitted by

JAHANARA BEGUM

Roll No. 100514001F

DEPARTMENT OF PHYSICS

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY,

DHAKA-1000, BANGLADEH

September’ 2011

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY

DEPARTMENT OF PHYSICS, DHAKA-1000

Certification Of thesis work

The thesis titled "**Regional variation of mesoscale precipitation system during pre-monsoon period in Bangladesh**" submitted by **Jahanara Begum**, Roll No. 100514001F, Session: October 2005 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of philosophy (M. Phil.) in Physics on 17 September, 2011.

BOARD OF EXAMINERS

1. Chairman

Dr. Md Rafi Uddin (Supervisor)
Assistant Professor
Department of Physics, BUET, Dhaka.

2. Member

Dr. A. K. M Akther Hossain (Ex-Offcio)
Professor and Head
Department of Physics, BUET, Dhaka.

3. Member

Dr. Md. Abu Hashan Bhuiyan
Professor
Department of Physics, BUET, Dhaka.

4. Member

Dr. Nasreen Akter
Assistant Professor
Department of Physics, BUET, Dhaka.

5. Member (External)

Mrs. Mehrun Nessa
Chief Scientific officer (CSO), SPARSSO
Ministry of Defense, Mohakash Biggyan Bhaban
Agargoaon, Sher-e-Bangla Nagar, Dhaka-1207

# DECLARATION

It is hereby declared that this thesis or any part of it has been submitted elsewhere for the award of any degree or diploma.

Signature of the candidate

Jahanara Begum

Candidate

Roll No. 100514001F

Session: October 2005

# Table of Contents

**Contents** **Pages**

# List of Tables

# List of Figures

# Acknowledgements

First and for most, I would like to thank, Almighty Allah, who has helped me in everything, I did and do. No achievement in life without Allah could be true. Besides, I owe any measure of success to the array of input from so many. Dr. Md. Rafi Uddin, Assistant Professor, Department of Physics, BUET my talented and excellent supervisor whose relentless pursuit of and patience with me during preparation and delivery of this thesis was a tremendous source of motivation and encouragement. To my honorable teacher, Dr. Md. Nazrul Islam (on leave from BUET) Professor of Meteorology, Department of Meteorology, King Abdulaziz University, Jeddah, Saudi Arabia, I am greatly grateful for his immense deal of help during this painstaking research.

My thanks and gratitude goes to Professor Dr. A. K. M. Akther Hossain, Head, Department of Physics, BUET for his overall compassionate deportment. I also express my thanks to Professor Dr. Mominul Huq (Retired from Department), Professor Dr. Md. Abu Hashan Bhuiyan, Professor Dr. Nazma Zaman, Professor Dr. Jiban Podder, Professor Dr. Md. Feroz Alam Khan, Professor Dr. Mostak hossain, Dr. Afia Begum, Dr. Md. Forhad Mina and all other teachers of the Department of Physics for their encouragement during this work. In this auspices time I would like to special thanks to Dr. Nasreen Akter, Assistant Professor, Department of Physics, BUET.

I acknowledge the authority of Bangladesh University of Engineering and Technology for providing me the Teaching Assistantship provided by Department of Physics. My thanks and gratitude goes to all the staffs of Department of Physics for helping me in providing information regarding to administration that enabled me to pursue my thesis.

I would like to show my appreciation to Bangladesh Meteorological Department (BMD) for allowing me the privilege of sharing data in this research. I thank at last but by no means least, to Md. Mizanur Rahman, Scientist, Theoretical Division, SAARC (South Asian Association for Regional Cooperation) Meteorological Research Centre (SMRC) and Md. Abdul Mannan, Meteorologist, BMD, Dhaka, for help and co-operation they had extended. Proper thanks are due to my dearest colleague Ms Shuchismita Dey, Senior Lecturer, Southeast University, Dhaka and Dr. Arun Kanti Guha, Assistant Professor, Southeast University, Dhaka.

# Abstract

Regional variation of mesoscale precipitation systems is analyzed in and around Bangladesh using six-year (2000-2005) radar data obtained from the Bangladesh Meteorological Department (BMD). Over the study period, regional analysis revealed that the arc, line and scattered types precipitation systems were dominant in the northwest and northeast quadrant during the pre-monsoon period. In monsoon, the arc and line types precipitation systems are dominant in the northwest quadrant and scattered type precipitation systems is dominant in the southeast quadrant. Total 230 arc type precipitation systems are indentified during the study period and classified into 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). During the analysis period, the occurrence frequency of STPS, ATPS, CSATPS and UTPS is 23%, 43%, 21% and 13%, respectively. Seasonal analysis showed that ATPS and STPS is dominated in the pre-monsoon and monsoon period, respectively. Regional analysis of different arc type systems indicate that at the mature stage of their life cycle, STPS, ATPS, and CSATPS is dominated in southwest (northwest), northeast (southeast) and northwest (northwest) quadrants during pre-monsoon (monsoon) period. The maximum occurrence frequency of UTPS is found in the northeast and southwest quadrant during pre-monsoon and in the southwest quadrant during the monsoon season. The statistical analysis of diurnal variation of precipitation systems showed double peaks: primary peak at 03-06 LST (morning) and secondary maximum at 12-15 LST (afternoon). In addition, case study showed that the quantitative comparison between BMD radar retrieve rainfall and conventional rain-gauge rainfall is not possible.

# Chapter One

# Introduction

## 1.1 Prelude

Bangladesh, a sub-tropical monsoonal country, lies in the Indo-Gangetic plain of South Asia within 20.67° and 26.38° north latitude and 88.05° and 92.74° east longitude. It is bounded by India in the west and northeast, the Himalayas and Tibetan Plateau are in the north, Myanmar in the southeast, and the Bay of Bengal in the south (Figure 1.1.).

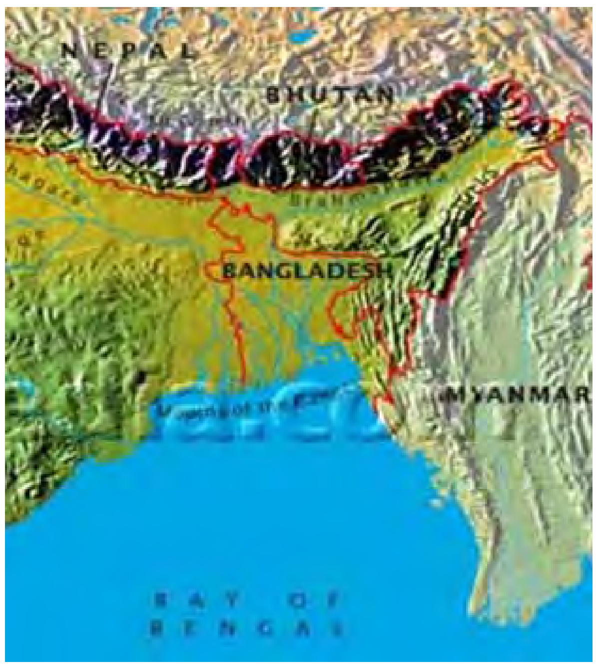



Figure 1.1. Geographical map of Bangladesh.

These special geographical features are very favorable for the development of intense convection in Bangladesh due to the interaction between moist and dry air masses coming from the Bay of Bengal and India, respectively during pre-monsoon period (March to May). The intense convection may occur as isolated cell or as part of large mesoscale convective systems (MCS), which are major contributors to severe weather and precipitation in and around Bangladesh. In pre-monsoon period severe storms, locally called Kalbaishakhi, develop and sometimes associated with tornadoes, damaging hail, strong gust wind, and lightening (Peterson et al., 1995; Yamane et al., 2006; Goldar et al., 2001). Such kind of disturbances during the pre-monsoon season cause severe damage almost every year and lead to extensive agriculture and property damage and the loss of life. The socio economic condition of the people of Bangladesh is greatly depends on the agriculture, which in turn dependent upon rainfall. During the monsoon period (June-September), a large numbers of MCSs develop and produce heavy rainfall in Bangladesh. As an effect, it causes widespread flooding, flash flooding etc and in the other hand its lack lead to drought in the country. MCSs supply precious water resources and sometimes cause severe atmospheric disasters (Karmakar et al., 2005).

Various studies have done about MCS using radar and other mesoscale data to determine the structure of individual convective events (Newton 1950; Fujita 1955; Ligda 1951; Newton and Newton 1959; Pedgley 1962; Sanders and pine 1975; Sanders and Emanuel 1977; Houze 1977; Zipser 1977; Smull and Houze 1985). Maddox (1980) first classified the MCS using satellite image and termed it as mesoscale convective complex (MCC). Bluestein et al., (1983) and Bluestein and Jain (1985) analyzed the evolution of mid-latitude MCSs using radar data and they classified the precipitation structure during the formative stage of mid-latitude squall lines, identifying four common modes of development: broken lines, back building, broken areal, and embedded areal. In later, comprehensive studied on precipitation structure done by Houze et al., (1990) and established the classification of two distinct categories with more common types of organization: symmetric and asymmetric. Although the various researches have done on MCS pattern in several regions in the world, there is much lacking to learn about the precipitation structure in and around Bangladesh. A few numbers of studies have done about the precipitation systems in this region. Islam et al., (2004) studied the characteristics of precipitation area and size of echoes that is related to the cloud activity over Bangladesh using 1 year radar data. They classified the precipitation area into two types: solitary and merged type. Both types again sub-categorized into oval, line and arc type. Rafiuddin et. al., (2010) introduced the details characteristics of precipitation systems based on 6 years radar data during monsoon period in Bangladesh. They classified precipitation systems into arc, line and scattered types according to their shape and found development of these systems is 29%, 15% and 56%, respectively. Rafiuddin et al., (2010) also revealed that arc and scattered type precipitation systems dominate in pre-monsoon and monsoon seasons, respectively. The diurnal characteristics of precipitation are not similar in the different parts of Bangladesh (Islam et al., 2005a). The eastern, southern and northern parts of country are more humid than the central and western parts of Bangladesh. There are two regions in Bangladesh: wet region and dry region (Islam and Uyeda, 2007). The rainfall amount in the wet region is more than the dry region. The northern and southern coastal part of the country received maximum rain from mid-night to early morning (03-06 LST) with an afternoon 18 LST peak in the southeast-southwest region of Bangladesh (Islam et al., 2005a; Islam et al., 2005b). Wahid and Islam (1999) found the morning and afternoon/evening peak in the northeast part (Sylhet) of Bangladesh. The diurnal variation observed by TRMM PR (Tropical Rainfall Measuring Mission Precipitation Radar) informed that precipitation dominates over land and near coast in the afternoon and morning, respectively (TRMM report 2002). In 2002, TRMM also reported that morning precipitation dominant over country in 1998 and 1999 without the afternoon peak. Various studies have done about the diurnal variation of MCSs that produce heavy precipitation during pre-monsoon and monsoon period in Bangladesh (Roy et al., 2007; Ohsawata et al., 2001). Islam et al., (2004) found the morning (evening) maximum precipitation peak at 06 LST (18 LST) dominate in pre-monsoon (monsoon) period. The above studies showed that rainfall characteristics and diurnal variation of rainfall are different in different region of Bangladesh, so development of precipitation systems in different parts of Bangladesh are expecting different. Therefore, it is essential to know the regional and diurnal variations of precipitation systems of their whole life cycle to understand the mechanism of monsoon systems as well for model parameterization.

## 1.2 **Objectives of the Research**

Radar is a useful instrument for observing the mesoscale convective systems over large spatial domains. Its ability to provide detailed information about precipitation patterns is beyond comparable to other operationally used sensors in both time and space.

The prime objectives of this study are:

(i) to determine the regional variation of arc, line and scattered types precipitation systems.

(ii) to classify the dominating arc type precipitation systems such as symmetric, asymmetric , combination of symmetric and asymmetric and unclassified type precipitation type.

(iii) to reveal the regional, annual and intra-seasonal variation of different arc type precipitation system.

(iv) to determine the diurnal variation of different precipitation systems.

(v) to determine the variation between the radar and rain gauge rainfall amount for selective cases.

These results will help to understand the model parameterization, climate research, weather prediction, flood forecasting, the agriculture sector and the water related operational sector.

# Chapter Two

# Literature Review

## 2.1 Precipitation

Precipitation, from a weather point of view, is the condensation of water from the air around us. Precipitation is all the rain, snow, sleet, drizzle, hail, etc. that comes from the sky and give moisture to earth, helping all plants and animals, and people as well. Then, the water cycle starts all over again, with Evaporation, then Condensation, and back to Precipitation.

Precipitation, which comes from the cloud, controls our social, economical and daily life. In order to understand the organization mechanism of the precipitation cycle system we need to analyze the detail internal structure throughout lifetime. The general characteristics of the clouds and cloud cluster are the western pacific warm pool are analyzed by Rahman et al., (1997) The daily variation of maximum cloud zone and inter tropical convergence zone over the Indian latitudes during southwest monsoon are investigated by sikka and Gadgil (1980) Goswcmi et al. (1999) described the characteristics of cloud cluster of summer monsoon experiment (SMONBX) region ($0^0$-$30^0$N, $70^0$-$120^0$E) during June to August 1979 in Manus Island, Papua New Guinea. Some early researchers reported characteristics of cloud clusters over the Pacific, Atlantic and Tropics. The stage of tropical cloud VIZ; formatives, mature and dissipating (Machado and Rossow, 1993) are well known. Wahid et at., (1999) also analyzed the life cycle of single cell and multiple cell cloud developed in and around Bangladesh. In another research, Islam et al., (1994) discussed that some single cell clouds may merge to form a multi-cell cloud, which forms a sub system. There is an intimate relationship between cloud & precipitation. The whole portion of the cloud does not precipitation as rain. Only a fraction of the cloud comes as surface rain. Islam et. al., (1998) reported that 56% of cloud is perceptible and the rest 44% is non perceptible. Furthermore, precipitation is one of the most difficult atmospheric parameters to measure the large variations in space and time (Kummerow et al., 2000)

### 2.1.1 Types of precipitation

There are two basic precipitation generation types, which are dynamic precipitation and convective precipitation. Dynamic precipitation is also known as stratiform precipitation.

Dynamic precipitation results from a forced lifting of air. These forcing mechanisms include processes that cause low-level convergence and upper level divergence. As unsaturated air rises, the relative humidity of the air will increase. Once the air saturates, continued lifting will produce clouds and eventually precipitation. Dynamic precipitation tends to have a less intense rain rate than convective precipitation and also tends to last longer.

Convective precipitation is also known as thermodynamic precipitation. While dynamic precipitation only needs saturated air and lift, convective precipitation requires an additional component called instability. Uplift due to instability release occurs when the air rises on its own after being lifting to a certain point in the troposphere. Instability is commonly assessed by examining the Lifted Index (LI) and CAPE (Convective Available Potential Energy). Both these indices can be used to assess the acceleration rate of air once air from the lower troposphere is brought to a level in the troposphere where it will rise on its own due to positive buoyancy. Instability causes the air to rise much faster than it would by forced lifting alone. Think of convective precipitation as falling from thunderstorms with strong updrafts while dynamic precipitation falls from a deck of stratus clouds. Convective precipitation tends to have lighting, thunder and heavy rain while dynamic precipitation is more of a gentle long lasting rain with no lightning and thunder.

Cloud droplet growth by condensation cannot produce raindrops alone. The Collision coalescence process is necessary to grow the cloud droplets into raindrops. It requires a family of droplets at different sizes. The growth becomes more frequent as large droplets undergo repeated collision and coalescence with smaller droplets followed by droplet break up.

## 2.2 Thunderstorm

A thunderstorm, known as an electrical storm, a lightning storm, or simply a storm is a form of weather characterized by the presence of lightning and its acoustic effect on the Earth's atmosphere known as thunder (National Weather Service 21 April 2005).The meteorologically-assigned cloud type associated with the thunderstorm is the cumulonimbus. Thunderstorms are usually accompanied by strong winds, heavy rain and sometimes snow, hail, or no precipitation at all. Those which cause hail to fall are known as hailstorms. Thunderstorms may line up in a series or rainband, known as a squall line. Strong or severe thunderstorms may rotate, known as supercells. While most thunderstorms move with the mean wind flow through the layer of the troposphere in which they occupy, vertical wind shear causes a deviation in their course at a right angle to the wind shear direction. Thunderstorms result from the rapid upward movement of warm, moist air. They can occur inside warm, moist air masses and at fronts. As the warm, moist air moves upward, its cools, condenses, and forms cumulonimbus clouds that can reach heights of 10 km. As the rising air reaches its dew point, water droplets and ice form and begin falling the long distance through the clouds towards Earth's surface. As the droplets fall, they collide with other droplets and become larger. The falling droplets create a downdraft of air that spreads out at Earth's surface and causes strong winds associated with thunderstorms.

Thunderstorm occurs in Bangladesh during pre-monsoon period (April and May). This severe storm is associated with strong convective instability. The simulate research of Litta and Mohanty (2008) reported that thunderstorm develop over eastern India by higher instability. Numbers of studies have done to understand the frequency and occurrence of severe thunderstorm over India (Rao and Raman 1961; Raman and Raghaven 1961; Vishwanathan and Fria 1962; Krisnamurthy 1969; Manohar et al., 1999; Kandalgaokar et al.; 2002). Few studies (Koteswaran and Srinivasan 1958; Joseph 1982) have made an attempt to understand the formation and propagation of thunderstorm over the region. Peterson and Metha (1981, 1995) examined tornado activity in Bangladesh and northeastern India and found the highest monthly occurrence frequency in April. Choudhury and De (1995) reported that the frequency of thunderstorms and amount of precipitation were the largest in the month of May in Bangladesh during the pre-monsoon period. Yamane and Hayashi (2006) used reanalysis data to show that combination of high convective activity in available potential energy (CAPE) and moderate shear are favorable for the occurrence of severe local storms during monsoon period in Bangladesh and northeastern India. These local storms develop mainly due to merging of cold dry northeasterly winds with warm moist southerly low-level winds from the Bay of Bengal. These leads to flooding, high wind flow, hail, lighting, destruction of properties and even death.

### 2.2.1 Types of thunderstorms

#### 2.2.1.1 Single Cell Storms

Thunderstorms can consist of just one ordinary cell that transitions through its life cycle and dissipates without additional new cell formation. However, true single cell storms are relatively rare since even the weakest of storms usually occur as multicell updraft events. Single cell storms seem quite random (perhaps because of our lack of understanding) in the production of brief severe events such as hail, some heavy rainfall, and occasional weak tornadoes.

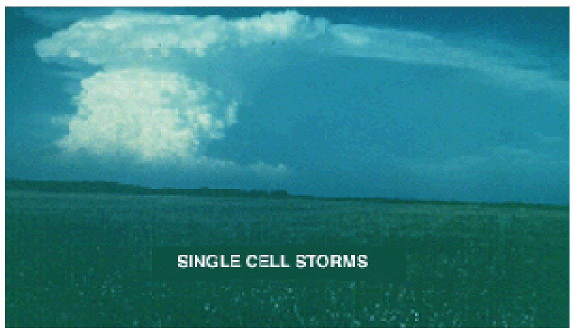
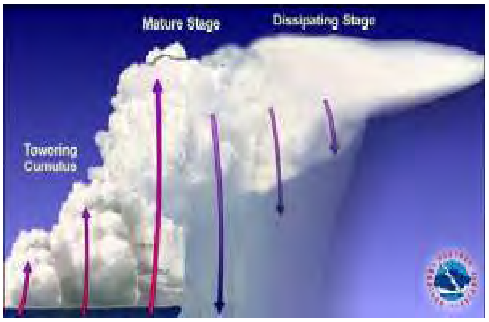



Figure 2.1. Single cell storms. (Source: website).

#### 2.2.1.2 Multicell Storms

Thunderstorms often form in clusters with a group of cells moving as a single unit, with each cell in a different stage of the thunderstorm life cycle. Generally these storms are more potent than single cell storms, but considerably less so than supercells. Unlike ordinary single cells, cluster storms can last for several hours producing large hail, damaging winds, flash flooding, and isolated tornados.



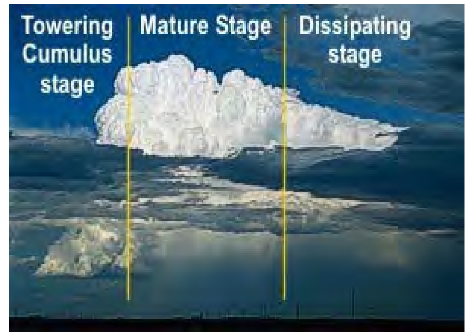




Figure 2.2. An airflow diagram of the towering cumulus stage, mature stage, dissipating stage. (Source: Website)

### 2.2.1.3 Multicell Lines (Squall Lines)

Sometimes thunderstorms will form in a line which can extend laterally for hundreds of miles. These "squall lines" can persist for many hours and produce damaging winds and hail. A squall line is a line of thunderstorms that have a common lifting mechanism. Lifting mechanisms tend to occur in bands. The rain cooled air or "gust front" spreading out from underneath the squall line acts as a mini cold front, continually lifting warm moist air to fuel the storms. Examples of banded lifting mechanisms include fronts, large outflow boundaries, gravity waves, etc.

The classic squall line will develop out ahead of and parallel to a cold front or dry line boundary. The storms first develop where there is the best combination of moisture, instability and lift. The storms will continue to evolve and new cells will develop (commonly toward the south and east).

The squall line will sustain itself by producing its own lift due to outflow boundaries. As long as instability and moisture remain present out ahead of the squall line, the squall line will continue to propagate. Often along the leading edge of the line a low hanging arc of cloudiness will form called the shelf cloud. Gusty, sometimes damaging outflow winds will spread out horizontally along the ground behind the shelf cloud.

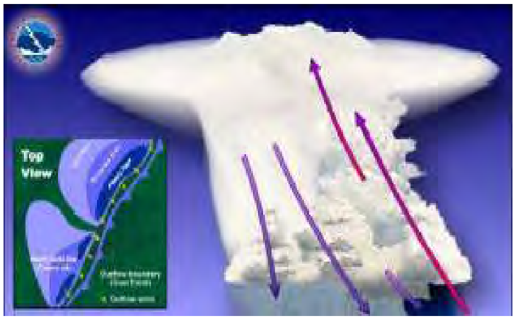




Figure 2.3. Schematic of a squall line (left) and accompanying photograph (right). (source: www.srh.weather.gov).

Downburst winds are the main threat, although hail as large as golf balls and gust, tornadoes can occur. Flash floods occasionally occur when the squall line decelerates or even becomes stationary, with thunderstorms moving parallel to the line and repeatedly across the same area.

### 2.2.1.4 Supercell Thunderstorms

Supercell thunderstorms are a special kind of single cell thunderstorm that can persist for many hours. They are responsible for nearly all of the significant tornados produced in the U.S. and for most of the hailstones larger than golf ball size. Supercells are also known to produce extreme winds and flash flooding.

Figure 2.4. Schematic of a supercell thunderstorm (left) and accompanying photograph (right). (source: www.srh.weather.gov).

They are characterized by a rotating updraft (usually cyclonic) which results from a storm growing in an environment of significant vertical wind shear. Wind shear occurs when the winds are changing direction and increasing with height. The ideal conditions for supercells occur when the winds are veering or turning clockwise with height. For example, in a veering wind situation the winds may be from the south at the surface and from the west at 15,000 feet. Beneath the supercell, the rotation of the storm is often visible as well.

### 2.2.2 Life Cycle of Thunderstorm

A basic thunderstorm (single cell) goes through three phases during its lifetime: cumulus, mature, and dissipating. This can last between 30 minutes to an hour. The life of a typical non-severe thunderstorm goes through three stages: Cumulus, Mature, and Dissipating. In the first stage (cumulus), we see the cloud that will become the thunderstorm starting to form and grow due to the rising thermal (or updraft). The rising updraft of air will begin to cool and condense as it rises, and in the case of thunderstorms, the thermal can travel tens of thousands of feet up before it finally stops! During this stage, small raindrops may begin to form and try to fall; however, the wind flow in the updraft can push the raindrops higher into the cloud rather than letting them fall out. At that level the raindrops collide and join into larger droplets due to the churning turbulence in the cloud.

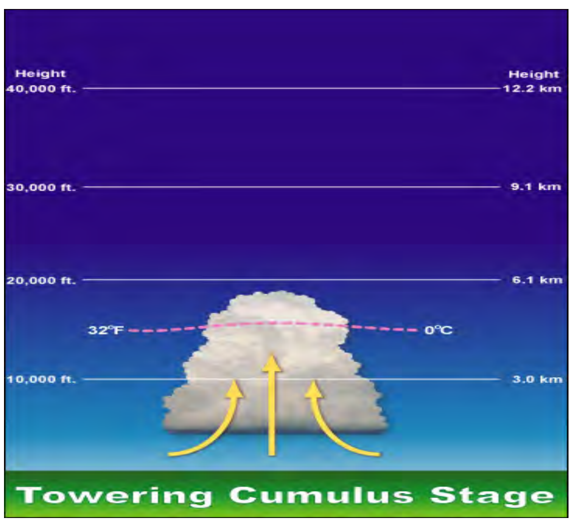



Figure 2.5. An airflow diagram of the cumulus stage. (source: http://severewx.pbworks.com/Thunderstorms).

Eventually, the raindrops will become large and heavy enough to fall from the cloud to the ground. This marks the beginning of the second stage (mature). The term downdraft is used to describe the rain and the cool air that begins to descend from the thunderstorm. You can think of a downdraft as a blob of cool air in the cloud that is heading toward the earth's surface (opposite of an updraft). Downdrafts can change the temperature rapidly in an area in a short amount of time. For example, during a hot, summer afternoon in Sattley, California, the temperature was a blazing 97 degrees at 4:00 P.M. However, after a thunderstorm passed through the area, the downdraft dropped the temperature to a cool 57 degrees by 5:00 P.M., a 40 degree temperature swing in one hour! However, most storms cool things off a more modest 10-15 degrees.

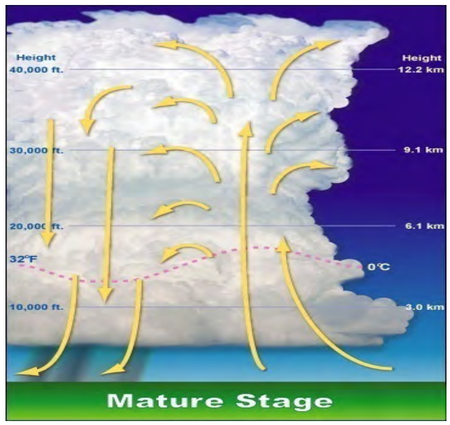



Figure 2.6. An airflow diagram of the mature stage. (source: http://severewx.pbworks.com/Thunderstorms)

When the downdraft hits the ground, it begins to spread out in all directions. When this happens, a gust front can form. The gust front is basically a boundary that separates the rain-cooled air from the surrounding warm air shown in Figure 2.7. Sometimes, a menacing-looking shelf cloud or roll cloud will form along the gust front. As you can imagine, the wind behind the gust front can be very strong, sometimes even reaching severe levels.

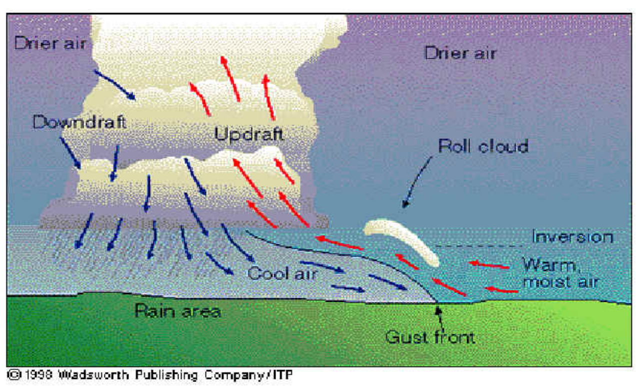



Figure 2.7. A gust front located ahead of approaching thunderstorms. (http://kkd.ou.edu/METR%202603/metr2603lecture14.htm)

During the mature stage, the heaviest rain and (sometimes) hail fall from the storm. As long as the updraft can keep feeding the thunderstorm warm, humid air, it will continue to grow and intensify. However, the downdraft will usually end up killing off the thunderstorm, as it will cut off the updraft's supply of warm, humid air. Once this happens, the storm goes into its last stage (Figure 2.8).

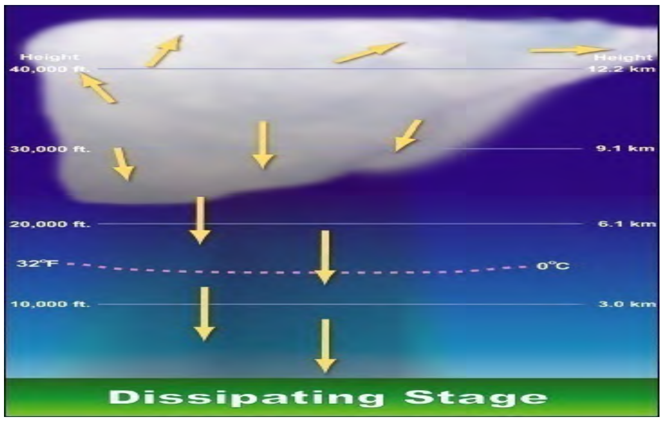



Figure 2.8. An airflow diagram of the dissipating stage.

(http://severe-wx.pbworks.com/Thunderstorms)

During dissipation, the updraft is very weak or non-existent, and the downdraft is the main dominant force in the thunderstorm. The thunderstorm slowly dies out and leaves only wispy clouds behind as evidence of its existence. This whole process usually goes by rather quickly and lasts about 30 minutes to an hour.

In severe thunderstorms, this cycle is extended because of differences in the inflow of warm, moist air into the thunderstorm. If the updraft is slanted, then the rain that falls out of the cloud will not cut off the inflow of the moist air that is the thunderstorm's fuel, allowing it to continue for a much longer time period. Some severe thunderstorms have been known to last for hours and travel at speeds up to 70 miles per hour.

## 2.3 Mesoscale convective system (MCS)

Mesoscale convective systems (MCSs) are an important link between atmospheric convection and the large-scale atmospheric circulation. A number of studies have been performed on MCS in several regions of the world (Augustine and Howard, 1988 Cotten et.

al., 1989). The MCSs produces a boreal range of severe convective weather events (Maddox et. al., 1982, Houze et. al., 1990) that are potentially damaging and dangerous to society in general (Israel et. al., 2003). The organization of MCSs is also important for hazardous weather forecasting and warning. Dosell et. al (1996) showed the relevance of precipitation arrangement to flash flooding associated with MCSs . Leary and Rappaport (1987) investigated the life cycle and internal structure of mesoscele convective complexes over Texas. In and around Bangladesh a number of MCSs developed during the monsoon season that produces heavy precipitation in this region.

There are many definitions of MCSs, depending on the remote sensing system used to identify them or the region of study. Mesoscale Convective system (MCS) is defined as a precipitation system resulting from multicell or squall line systems having a spatial scale of 20-500 km and a temporal scale of 2-12 hours. It includes convection during some part of its lifetime (Hane, 1986, Mesoscale book). Zipser (1982) noted, “The important point is that the MCS evolves form an early intensifying stage in which intense convection is dominant, with a strong net upward motion at low levels, through the mature stage into a decaying stage in which convective rain exists, but becomes less important, while stratiform rain associated with upward motion at high levels becomes predominant”.

Houze (1993) defines a MCS as a cloud system that occurs in connection with an ensemble of thunderstorms and produces a contiguous precipitation area -100 km or more in horizontal scale in at least one direction. They differ from single, simple multicell or discrete lines of thunderstorms in that exhibit a substantial area of stratiform precipitation. Both convective and stratiform precipitation regions are to be in the mesoscale convective systems simultaneously ( Figure 2.9 ) and they develop mesoscale circulation as they get matured. Stratiform regions can extend for hundreds of kilometers and will have precipitation that is less intense and more uniformly spread throughout this region. As per Houze (1993) the stratiform rainfall may account for between a quarter and a half of the total MCS precipitation. Also another radar studies reveal that the stratiform regions of MCSs contribute about 30-60% of the total precipitation of these systems (McGaughey and Zipser 1996). These stratiform regions are characterized by mean ascent above the freezing level and mean descent below the freezing level (McGaughey et al., 1996).

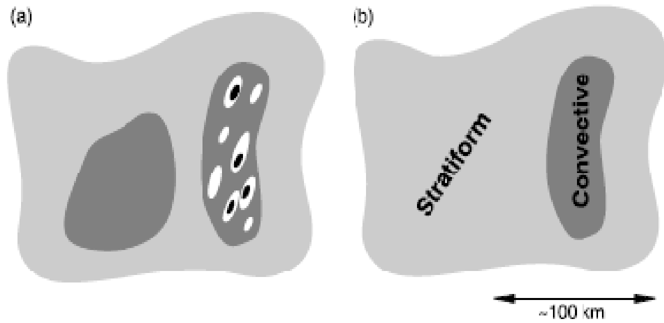



Figure 2.9. Idealization of a horizontal map of radar reflectivity (a) divided into convective and (b) stratiform regions (source: Houze, 1997).

An MCS exhibits deep moist convective overturning contiguous with or embedded within a mesoscale vertical circulation that is at least partially driven by the convective overturning. MCS often forms at or ahead of a surface cold front. The reason why the convection is sustained to develop MCS is shown in Figure 2.10.

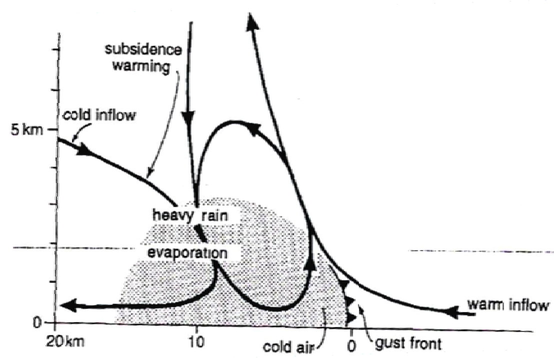



Figure 2.10. Development of convection for MCS.

Warm, moist air is forced to ascend over the gust front and produces deep convective towers, often along a more or less continuous line (often referred to as a squall line). At mid-levels, the frontal system often produces a current of cold, dry air, moving faster than the surface cold front, and this air penetrates into the line of thunderstorms. The snow/rain evaporates as it falls through this descending midlevel rear-to-front current, and as this air reaches the ground, it is cooler than the surrounding air. This cold pool maintains the gust front which sustains continued convection. The convective outflow often stretches to the rear, above the mid-level front-to-rear inflow. The Figure 2.10 above illustrates the airflow through a Baiu MCS. The Baiu (or Meiju) is a long-lived synoptic-scale convective rain-band in Japan and China, (Kawshima et Al. 1995) with some frontal characteristics. The inflow of cold dry air to the rear merges with convective downdrafts, causing divergent outflows at the surface. Evaporation of raindrops in the downdraft creates strong cooling, driving the subsidence and the gust front.

MCS is a significant rain-producing weather system. They account for a large proportion of precipitation in both the tropics and warmer midlatitudes (Houze, 2004). Long-lasting, slow moving MCS is one of the major causes of flooding and these systems often contain hail, strong winds and even tornadoes. MCS over the ocean sometimes evolves into tropical cyclones.

### 2.3.1 Classification of MCS

In producing all these effects discussed above, MCSs can take on a variety of forms. When a particular type of MCS is discussed, the basis upon which system is classified has to be taken into consideration i.e. data used, the lifecycle stages etc.

Since “MCS” does have a general classification, it can be divided into more specific classifications. The most commonly cited illustrations of MCSs include: Squall lines, Bow echoes and Meoscale convective complexes (MCCs).

According to Maddox (1980) Mesoscale Convective Complex (MCC) is a special case of MCS. It is generally round or oval-shaped. MCC normally reaches peak intensity at night.

On the basis of size, shape, and duration i.e. basic cold cloud shield characteristics, it is the easiest way to identify and subsequently classify MCSs. MCS classification scheme based on IR satellite (Jirak et. al., 2003) are:

a. MCC (from Maddox 1980)

b. Persistent elongated convective system (PECS) (from Anderson and Arritt, 1997): eccentricity < 0.7

c. Meso-β circular convective system (MβCCS): cold cloud shield 30,000 $km^2$ for > 3 hrs

d. Meso-β elongated convective system (MβECS): same except eccentricity < 0.7

MCS classification has also been done based on radar characteristics. In this respect two common approaches are organization and development. The first consideration is the organization. These approaches have focused on squall lines but only about half of MCSs have organized convective lines (Jirak, 2003). The classification of MCS organizations established by parker and Johnson and Houze et.al. (parker and Johnson 2000; Houze et.al. 1990 ) are as (i) Trailing stratiform (TS) (ii) Leading stratiform (LS) and (iii) Parallel stratiform (PS). The second type of MCS based on radar characteristics is of developmental or formative stages. Bluestein and Jain (1985) identified common patterns of severs squall line type MCS formation and named as broken line, back building, broken areal and embedded areal pathways. In a later Houze et al., (1990) observed the low altitude radar echo typically associated with the pattern is shown in Figure 2.11. The schematic is based on a study of the mesoscale systems that occurred during the springtime in Oklaoma over a 6 years period. The characteristics of idealized radar echo pattern may be summarized as follows:

The leading convective line has

1. Arc shape (convex toward the leading edge).
2. Generally northeast-southwest orientation (This is variable: sometimes lines are nearly nort-south, while others are nearly east-west. The orientation are undoubtedly determined by local climatology, and the same type of mesoscale systems in another part of the world might have different orientation).
3. Rapid movement with an eastward and/or southward component (<10 m/s in a direction normal to the line orientation).
4. Solid appearance (a series of intense reflectivity cells solidly connected by an echo of more moderate intensity).
5. Very strong reflectivity gradient at leading edge ( i.e., gradient much stronger at the leading edge than the back edge of the convective region).
6. Serrated leading (leading edge of echo is jagged, with forward extending protrusions at an apparent wavelength ~5-10 km).
7. Elongated cells oriented 45-90º with respect to line (elongated leading edge appear to be related to the serrated leading edge).

   The trailing stratiform region has:

8. Large size (>$10^4$ $km^2$ in horizontal area)

9. Notch-like connectivity at rear edge (believe to be associated with mesoscale inflow of dry air that erodes a portion of the stratiform echo).
10. A secondary maximum of reflectivity (separated from the convective line by a narrow channel of lower reflectivity).

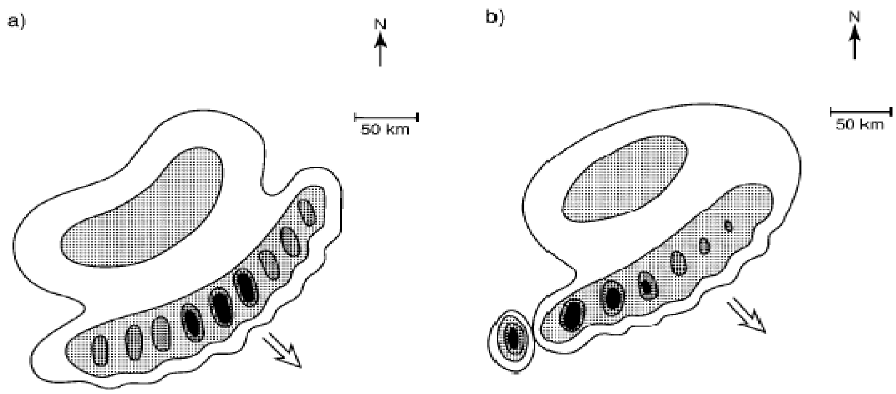



Figure 2.11 Schematic reflectivity of leading line trailing stratiform mesoscale precipitation system: (a) symmetric and (b) asymmetric arc types (Houze et al., 1990).

Two possible manifestations of these 10 characteristics are illustrated by the schematic radar –echo patterns presented in Figure 2.11a and b. The organization shown in Figure 2.11a is referred to as symmetric, while that in Figure 2.11b is referred to as asymmetric.

### 2.3.2 Life cycle of a MCS

The MCS may live as short as a few hours or as long as 2-3 days (Houze 1993). The precipitation area of a MCS exhibits a characteristic life cycle that is divided by Houze (1993) into four stages that are schematically illustrated in Figure 2.12 as they would appear on radar.

The formative stage (Figure 2.12 a) consists of a group of isolated convective cells that may be arranged uniformly in the horizontal or in a line. In the intensifying stage (Figure 2.12 b), the cells grow and merge to form a contiguous rain area in which several relatively intense cores of precipitation are interconnected by lighter precipitation. The mature stage (Figure 2.12c) occurs when a large stratiform region develops from older cells blending together as they begin to weaken. Each convective cell goes through a life cycle, and when it weakens becomes a part of the stratiform region. When several neighboring cells reach this stage, they may become indistinguishable and form an extensive stratiform region as large as 200 km in horizontal direction (Houze 1993)  As clouds and precipitation are detrained from the tops of active cells, the upper-level winds carry the condensate away from the rain area and an overhang of radar echo can form as shown in Figure 2.12 c. In the dissipation stage (Figure 2.12 d), the formation of new convective cells diminishes, and the stratiform area begins to weaken and dissipate.

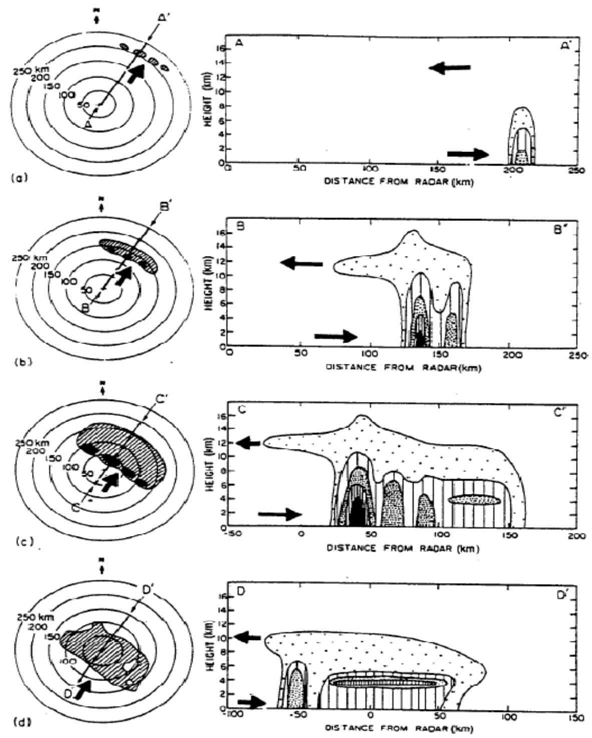


Figure 2.12. Schematic of the life cycle of the precipitation area of a mesoscale convective system as it would appear on radar in horizontal and vertical cross sections during (a) formative, (b) intensifying, (c) mature and (d) dissipating stages. The outside contour of radar reflectivity represents the weakest detectable echo. The inner contours are for successively higher reflectivity values. Heavy arrows indicate the direction of the wind relative to the system (Houze 1993).

## 2.4 Climatology of Bangladesh

Bangladesh is located in the tropical monsoon region and its climate is characterized by high temperature, heavy rainfall, often-excessive humidity, and fairly marked seasonal variations. From the climatic point of view, the rainy season divided into three distinct seasons in Bangladesh-: (i) the pre-monsoon (March-May), (ii) monsoon ( June-September) and (iii) post-monsoon (October-November). (Das 1995, Islam andUyeda 2007). This is the unavoidable influence of the south Asian Indo Gangetic Plane.

The dry season begins first in the west-central part of the country by mid-December, where its duration is about four months, and it advances toward east and south, reaching the eastern and southern margins of the country by mid-march where its duration is about one month.

High temperatures and the occurrence of thunderstorms characterize the pre-monsoon hot season. April is the hottest month when mean temperatures range from 27-28$^0$ C in the east and south to 31-32$^0$ C in the west-central part of the country. In the western part, summer temperature sometimes reaches up to 40$^0$ C. After the month of April, the temperature dampens due to increased cloud cover. The pre-monsoon season is the transition period when the northerly or northwesterly winds of the winter season gradually changes to the southerly or southwesterly winds of the summer monsoon or rainy season (June-September). During the early part of this season, the winds are neither strong nor persistent. However, with the progression of this season wind speed increases, and the wind direction becomes more persistent.

During the early part of the pre-monsoon season, a narrow zone of air mass discontinuity lies across the country that extends from the southwestern part to the northeastern part. This narrow zone lies between the hot dry air coming from the upper Gangetic plane and the warm moist air coming from the Bay of Bengal. As this season progresses, this discontinuity weakens and retreats toward northwest and finally disappears by the end of the season, making room for the onset of the summer monsoon. The rainy season, which coincides with the summer monsoon, is characterized by southerly or southwesterly winds, very high humidity, heavy rainfall and long consecutive days of rainfall, which are separated by short spells of dry days. Rainfall in this season is caused by the tropical depressions that enter the country from the Bay of Bengal.

# Chapter Three

## Data and Methods

### 3.1 Data Utilized

### 3.1.1 Radar Data

Data were obtained from an-S-band weather radar (wavelength ~ 10 cm, beam width 1.7°, elevation angle 0°) placed on a building roof of ~60 m height in the vicinity of Bangladesh Meteorological Department (BMD) office in Dhaka (23°42´0´N and 90°22′30″E). The BMD radar is designed to cover a radius of 400 km that scans 600 km × 600 km area on a regular scanning scheme, which includes almost all of Bangladesh and some neighboring parts of India and Myanmar. The regular scanning scheme is one hour at ‘ON’ and two hours at ‘PAUSE’, and the pixel regulation is 2,5 × 2.5 km. The BMD does not conduct radar operations from 00 to 05 LST (LST=UTC +6 hours). Sometimes it collects the data for few hours without any split. The reflectivity data collected by the BMD radar are automatically converted to the precipitation rate (mm/h), and output is provided only plan position indicator (PPI) in six statuses: 1 (1 mm/h ≤ rain rate < 4 mm/h), 2 (4 mm/h ≤ rain rate < 16 mm/h), 3 (16 mm/h ≤ rain rate < 32 mm/h), 4 (32 mm/h ≤ rain rate < 64 mm/h), 5 (64 mm/h ≤ rain rate < 128 mm/h), 6 (128 mm/h ≤ rain rate).

Because of radar data availability issues, analysis is made only for the pre-monsoon and monsoon periods. The BMD did not properly archive radar data for March and post-monsoon months during the analysis period. Thus, April and May data are analyzed to represent the pre-monsoon period. All 91,673 PPI scans from April to September 2000-2005 (no data are available for April 2001 and 2005, August 2002, and September 2000, 2001 and 2003) are analyzed.

### 3.1.2 Rain Gauge Data

Rain gauge is very common instrument used by meteorologists and hydrologists to collect and measure the amount of liquid precipitation over a set period of time. Most rain gauges generally measure the precipitation in millimeters. The level of rainfall is sometimes reported as inches or centimeters. BMD has 35 rain-gauge stations all over the country. Out of them 33 rain-gauges are used. The locations of these 33 rain gauges are shown in Figure 3.1. In the current study, 3 hourly rain gauge data collected by BMD are utilized and analyzed for comparison in order to radar collected the precipitation systems developed in and around Bangladesh.

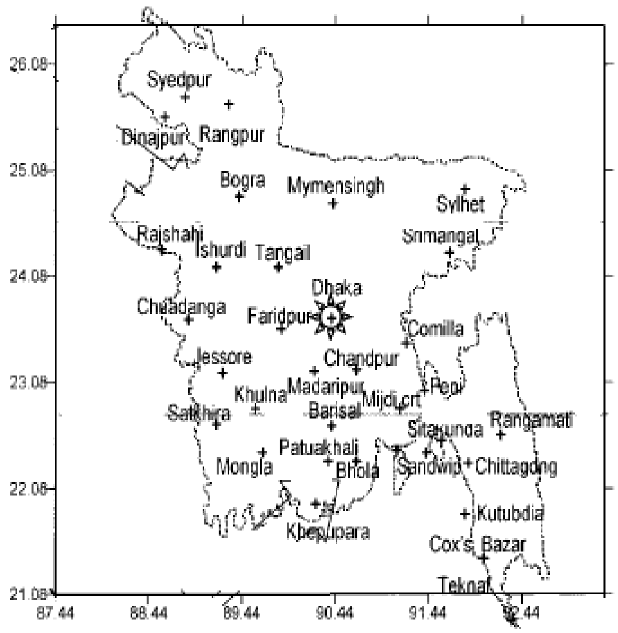



Figure 3.1. Rain-gauge stations of Bangladesh.

### 3.1.3 NCEP/NCAR data

The NCEP/NCAR Reanalysis Project is a joint between the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR). The resolution of the global Reanalysis Model is T62 (209 km) with 28 vertical sigma levels. There are 80 different variables, (including geopotential height, temperature, relative humidity, U and V component, etc) in several different coordinate systems, such as 17-pressure level on 2.5 × 2.5 degree grids. The NCEP/NCAR Reanalysis data is a data set suitable short and long-term climate research. A state of art data assimilation is used. Observation from land surface, ship, rawinsode, pibal, aircraft, satellite and other data are quality controlled and assimilated into the model, the model/data assimilation procedure has remain essentially unchanged during the project; data assimilation includes SSM/I surface winds and tropospheric and stratospheric temperature retrieved from TOVS (Kalnay et al.. 1996).

## 3.2 Method of analysis

The study area is shown in Figure 3.2, this area is subdivided into four quadrants such as northwest (NW), northeast (NE), southwest (SW) and southeast (SE). Some part of northeast and southeast quadrant has high elevation.

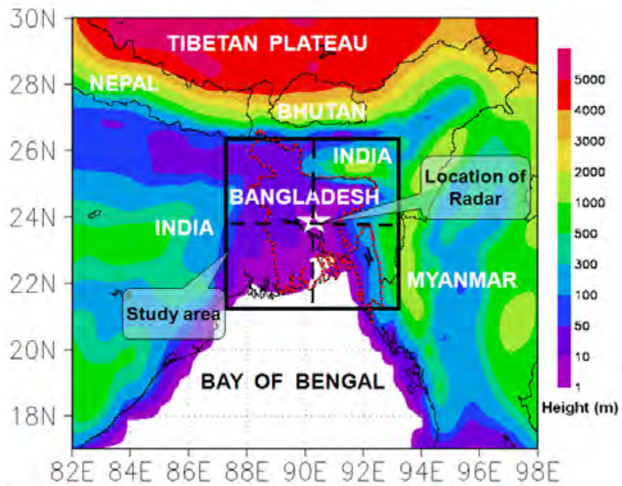



Figure 3.2. Regional map showing the BMD radar coverage of 600 km × 600 km (solid rectangle). The star indicates the location of the BMD radar. The radar coverage is divided into northwest (NW), northeast (NE), southwest (SW) and southeast (SE) quadrant. The topography is shown by color shading.

Precipitation systems which developed within study area and having lifetime equal to or longer than 3 hours and a dimension equal to or longer than 100 km (at least in one direction) are considered for analysis. According to Rafiuddin et al., (2010) precipitation systems are classified into three types: arc, line and scattered type based on their shape when they appeared in mature stage.

i) Arc-type systems, having an arc-shaped with strong leading edge and a stratiform (weak echo) region behind, resemble the squall-line type shown by Houze (1993). Examples of arc-type systems are shown in Figure 3.3. (a).

ii) Line-type systems have linearly shaped echoes and are sometimes embedded within weak echoes, as shown by Bluestein and Jain (1985) Figure 3.3b the example of line-type systems.

iii) Scattered-type systems are composed of groups of poorly organized small individual echoes, with less than 50 km as the maximum distance between echoes.

Figures 3.3 (a, and b), shows the examples of the scattered type. Actually, a scattered-type system could be composed of many small isolated echoes. Some scattered-type systems extend over relatively small areas (Figure 3.3(c)). However, other scattered-type systems have wide areal coverage, named (SWAC.) (Figure 3.3(d)).

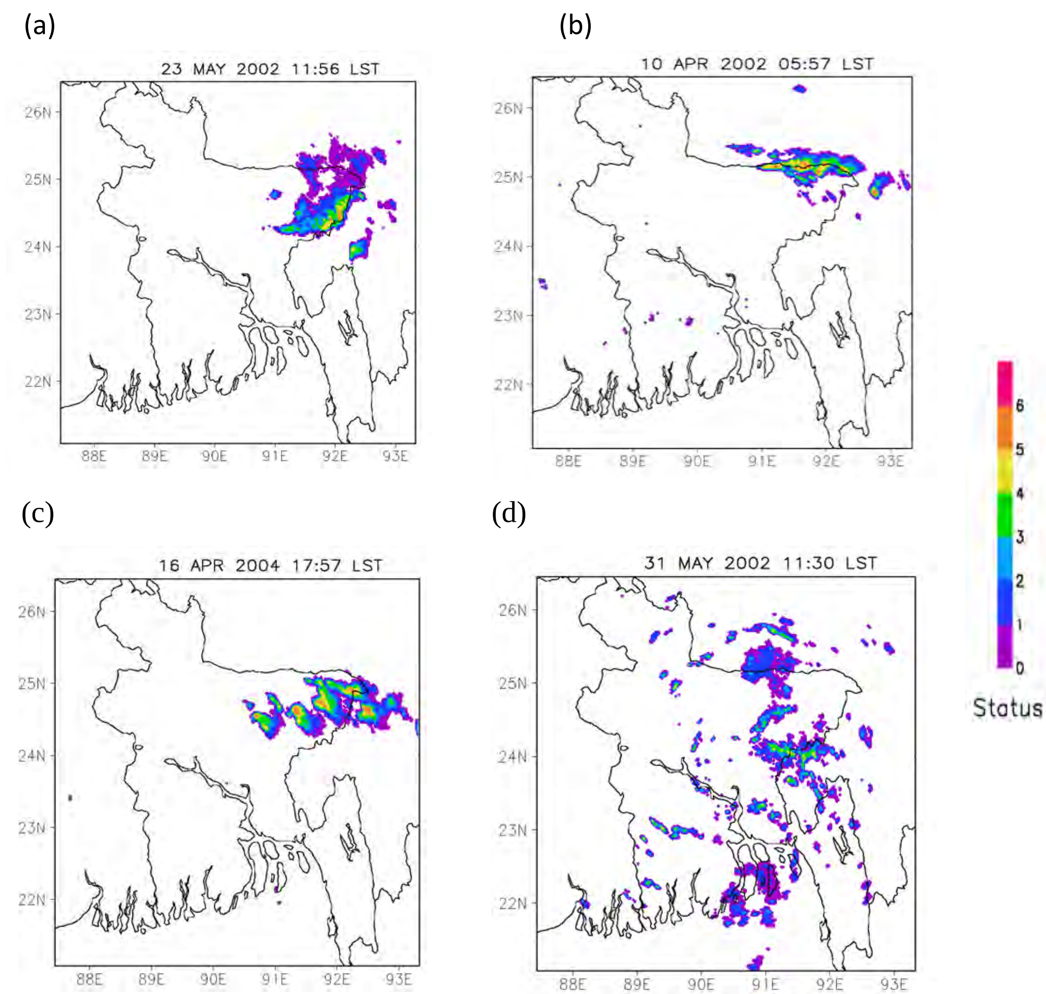



Figure 3.3. Example of different type precipitation systems: (a) arc type, (b) line type, and (c and d) scattered type precipitation systems.

There are four stages of life cycle of MCS: formative-, intensifying/developing-, mature- and decaying- stage. The formative stage is considered when a group of isolated convective cells that may be arranged uniformly in the horizontal or in a line (Figure 3.4a). The intensifying/developing stage is considered when cells grow and merge to form a contiguous rain area in which several relatively intense cores of precipitation are interconnected by lighter precipitation (Figure 3.4b). The highest intensity of the rain rate and longest length of the systems are considered to indicate the mature stage (Figure 3.4c). In mature stage, a large stratiform region develops from older cells blending together as they begin to weaken. In the dissipation stage, the formation of new convective cells diminishes, and the stratiform area begins to weaken and dissipate (Figure 3.4d).

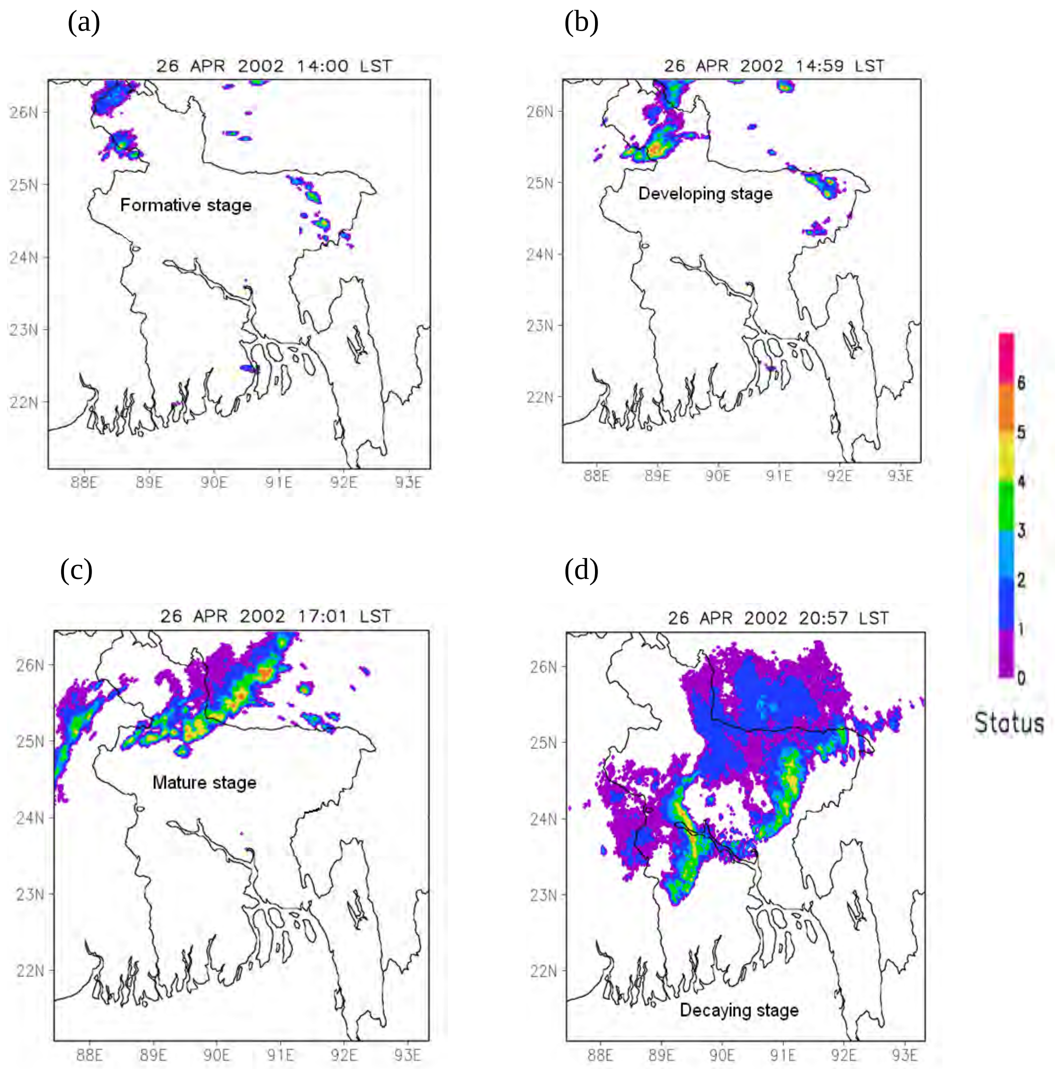



Figure 3.4. Example of different stages of the life cycle of MCS: (a) formative stage, (b) intensifying stage, (c) mature stage and (d) decaying stage.

Arc type precipitation systems are dominant in the pre-monsoon period in Bangladesh (Rafiuddin et al. 2010). This system is classified into four sub-categories: symmetric, asymmetric and combination of symmetric and asymmetric, and unclassified type precipitation systems according to Houze et al., (1990).

(i) Symmetric type precipitation system: there is no preferential particular location for the most intense convective cells along the leading edge of the line and the trailing stratiform region has located directly behind the center of convective line (Figure 3.5).

(ii) Asymmetric type precipitation system: the most intense convective cell preferentially occurs towards the southern, southwestern, or western end of the line, while weaker, dying cells on the verge of becoming stratiform are found toward the other end of the line and located toward the north, northeast, or east end of the line, rather than centroied behind the line (Figure 3.6).

(iii) Combination of symmetric and asymmetric type precipitation system: symmetric and asymmetric both patterns are observed during different stages of the entire life cycle of a system. For instance, from mature stage to dissipating stage of a system, some PPI scans of mature stage were similar to the pattern of symmetric system and some of PPI scans of dissipating stage with the asymmetric system and *vice versa* (Figure 3.7).

(iv) Unclassified type precipitation system: Without these three categories, the remaining systems labeled unclassified type precipitation system (Figure 3.8). Actually, this system is not belonged to the structure of symmetric and asymmetric systems. For example, in some cases when they appear to be mature stage there was no stariform region and some other cases the convective lines were not similar to the asymmetric characteristics and stratiform regions with symmetric characteristics and *vice versa*.

(a)

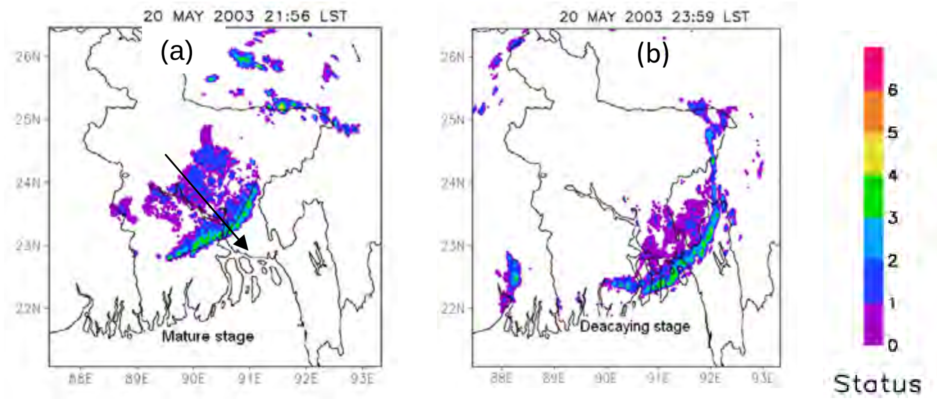



Figure 3.5. An example of different stages of a symmetric type precipitation system on 20 May 2003. (a) Mature stage and (b) decaying stage.

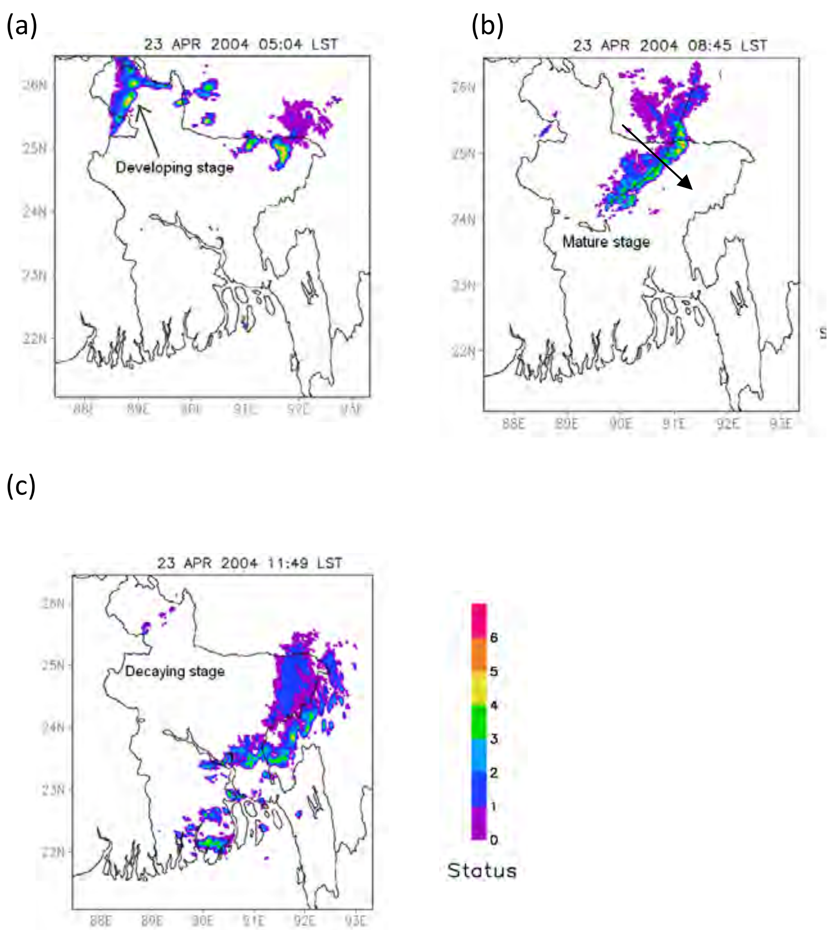



Figure 3.6. An example of different stages of an asymmetric type precipitation system on 23 April, 2004. (a) Developing stage, (b) mature stage and (c) decaying stage.

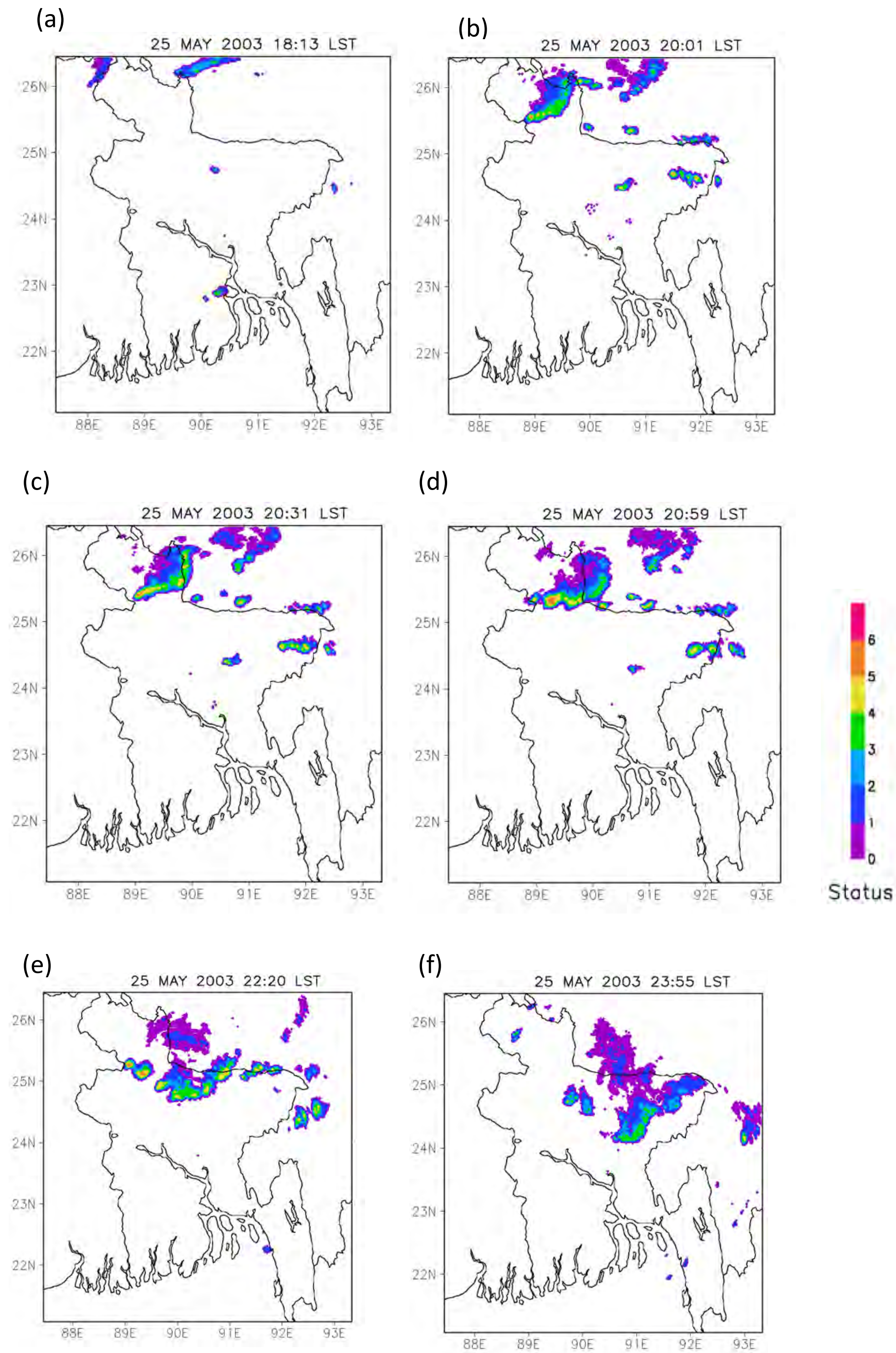



Figure 3.7. An example of different stages of a combination of symmetric and asymmetric type precipitation system on 25 May 2003. Developing stage [a and b (asymmetric pattern)], Mature stage[c (symmetric pattern) and d (asymmetric pattern), Decaying stage [e (symmetric pattern) and f (asymmetric pattern)].

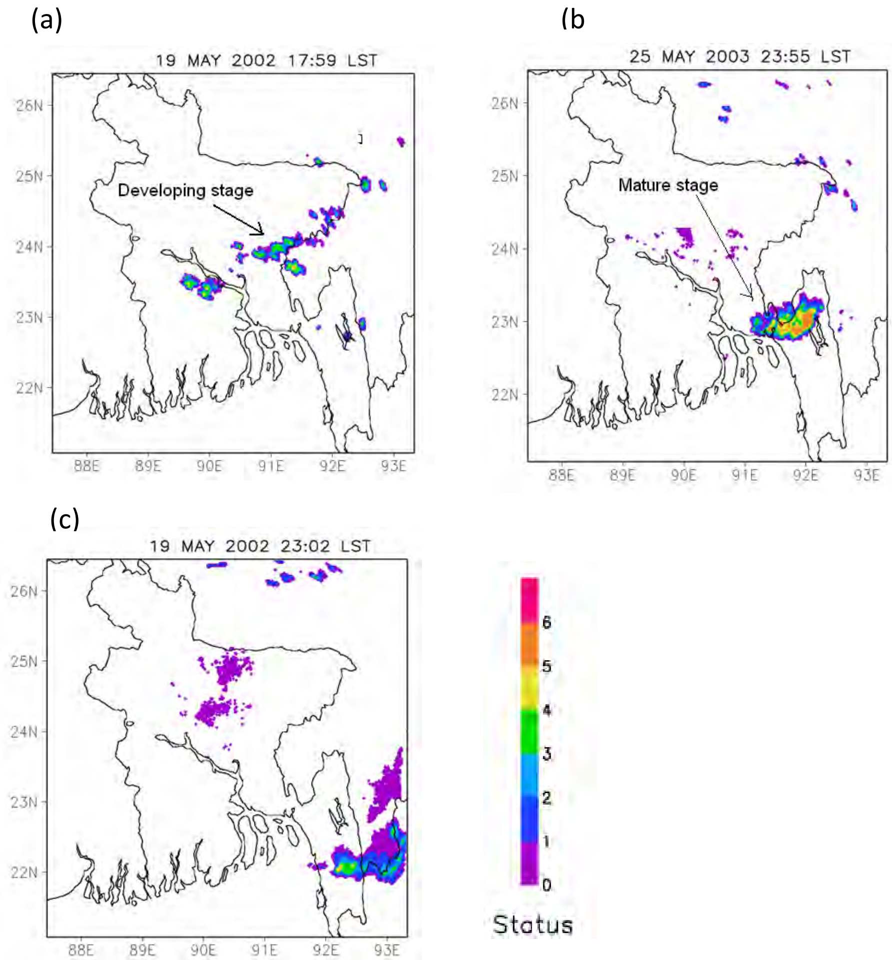



Figure 3.8. An example of different stages of an unclassified type precipitation system on 19 May 2002. (a) Developing stage, (b) mature stage, and (c) decaying stage.

The above classifications are made subjectively after careful observation of the pattern of a system during their life cycle. However, during the formative and intensifying stages the stratiform region is not present and cell tend to be more intense (Houze et al., 1990). Relatively weak echo intensity (status ~ 2) is considered a stratiform region of the system. The propagation speed and direction of the precipitation systems are obtained subjectively from PPI scans at 2–3 min intervals. The propagation speed of a system is calculated from the movement of the convective line at the mature stage (Rafiuddin et al., 2010). The convective line is drawn along the stronger rain band between two subsequent times greater than 30 min. Lines AA' and BB' in Figure 3.9 (a) and (b) are examples of convective lines of arc-type systems. A perpendicular line is drawn for the minimum distance between the convective lines (Figure 3(b)). Latitude and longitude measurements of two intersection points are used to calculate the exact distance and direction of propagation using the formula of Bowring (1996). There are 160 cases of arc type system in pre-monsoon and 70 cases in monsoon period are found during 2000-2005.

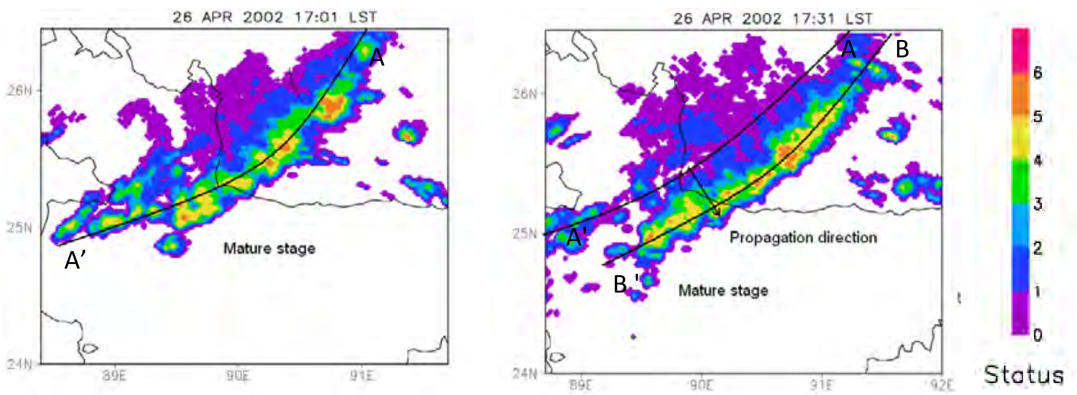



Figure 3.9. Two PPI scan of a system during mature stage on 26 April 2002.

The all types of precipitation systems are separated into four quadrants when they appeared to be in developing and mature stages. Developing stage was not available in some cases due to the lack of radar data. The numbers of lacking data at developing stage are given in the following Table 3.1 and Table 3.2.

**Table 3.1.** Different types of precipitation systems developed in Bangladesh.

| Type of systems | Seasons | Total systems | | SWAC | Number of available data at developing stage | Number of missing data at developing stage |
|---|---|---|---|---|---|---|
| Arc | Pre-monsoon | 230 | 160 | ……. | 123 | 37 |
| | Monsoon | | 70 | ……. | 45 | 25 |
| Line | Pre-monsoon | 117 | 55 | ……. | 39 | 16 |
| | Monsoon | | 62 | …….. | 31 | 31 |
| Scattered | Pre-monsoon | 442 | 80 | 8 | 48 | 32 |
| | Monsoon | | 362 | 236 | 215 | 147 |

*Regional variation of SWACs is not included.

**Table 3.2.** Different types of arc type precipitation systems developed in Bangladesh

| Type of systems | Seasons | Total systems | | Number of available data at developing stage | Number of missing data at developing stage |
|---|---|---|---|---|---|
| Symmetric | Pre-monsoon | 53 | 27 | 22 | 5 |
| | Monsoon | | 26 | 16 | 10 |
| Asymmetric | Pre-monsoon | 98 | 76 | 55 | 21 |
| | Monsoon | | 22 | 14 | 8 |
| Combination of symmetric and asymmetric | Pre-monsoon | 49 | 31 | 24 | 7 |
| | Monsoon | | 18 | 12 | 6 |
| Unclassified | Pre-monsoon | 30 | 26 | 23 | 3 |
| | Monsoon | | 4 | 4 | 0 |

In this research, a normalized technique is used to find the relative frequency of occurrence of system, which is completely different method from Rafiuddin et al. (2010). This simplified normalized technique is based on the idea proposed by Aragoa et al. (2000) for irregular PPI scan (time of observation). The relative frequencies of each type were separately obtained for each month, season, and year, based on the formula.

Relative number of systems $(RNS)_x$(m) = $\frac{Absolute\ number\ of\ system(ANS)_x}{Total\ PPI\ in\ the\ month\ (m)}$ ………..…….. (1)

Relative frequency of system $(RFS)_x$ (m) = $\frac{Relative\ number\ of\ system\ (RNS)_{x\,(m)}}{Total\ relative\ number\ of\ system(TRNS)_x(p)} \times 100\%$ …………….... (2)

Where, x = type of system, m = month, and p = total period

The diurnal variation of arc, line, scattered and different types of arc systems (STPS, ATPS, CSATP, and UTPS) are shown at the developing and mature stages only due to limitation of PPI scan at decaying stage.

To see the comparison between rain gauge and radar rainfall, two cases are considered as a case study. For instance, 21 May 2003 as a STPS and 23 April 2004 as ATPS. The precipitation rate is retrieved from the precipitation status using the following equations. The hourly precipitation rate *HPR* is defined as

$$HPR = \frac{1}{N}\sum_{I=!}^{I=N} R_I \text{ ...............(3)}$$

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

$$R_I = \frac{1}{A}\sum_{r=1}^{r=6} S_r A_{R,r} \text{ .................(4)}$$

where *A* is the grid area (100km² in this analysis), $S_r$ the status precipitation rate averaged from the possible values in a status, and $A_r$ the rainy area corresponding to each status in the 10km grid box. For *r =1, 2, 3, 4, 5*, and *6* the respective possible status values are 1-4, 5-16, 17-32, 33-64, 65-128, and 129 mm/h. The respective $S_r$ values obtained are 2.5, 10.5, 24.5, 48.5, 96.5, and 129 for *r =1, 2, 3, 4, 5*, and *6*. As stated, BMD radar usually stores data continuously for one hour with a two hour interval in operation. Sometimes the radar is operated for several hours without a break. There are about 20 PPI data scans (2-3 minutes interval) available during each hour of operation. Radar data are sampled in each PPI scan, and all the available PPI scans per hour are used to obtain the hourly value. Contours of reflectivity are plotted on the radar charts as a colour coded display the six colours.

Table 3.3. BMD Radar intensity ranges.

| Color | Reflectivity (dBZ) | Status | Rain Rate (mm/hr) | Precipitation Description |
|---|---|---|---|---|
| Violet | 0 | 1 | ≤4 | Light |
| Blue | 10 | 2 | ≤16 | Moderate |
| Sky Blue | 20 | 3 | ≤32 | Strong |
| Yellow | 30 | 4 | ≤64 | Very Strong |
| Green | 35 | 5 | ≤128 | Intense |
| Orange | >35 | 6 | >128 | Extreme |

# Chapter Four

# Results

## 4.1 Regional variation of precipitation systems

The main focus of this study to understand the influence of the occurrence of different precipitation systems in different region over Bangladesh. In this subsection, the occurrence frequency of different types of precipitation systems during developing and mature stages will be shown.

### 4.1.1 Developing stage

Figure 4.1 shows the regional variation of relative frequency of occurrence (RFO) of arc, line and scattered type precipitation systems at developing stage of their life cycle in different region of Bangladesh during pre-monsoon (March to May) and monsoon (June to September) periods. During the pre-monsoon period, the RFO of arc (47.96%) and line (43.58%) type precipitation systems is dominant in the northwest quadrant. The occurrence frequency of arc type precipitation system is very less (4.88%) in southeast quadrant during pre-monsoon period. The RFO of scattered type systems is very high (65.96%) in the northeast quadrant compared to the other quadrants. From Figure 4.1(a), it is also clear that the tendency of arc and line type precipitation systems decline according to their quadrant (NW→ NE→ SW→ SE). During the monsoon period, the arc and line type precipitation systems dominant in the northwest quadrant but the scattered type precipitation systems are dominant in the northeast and southeast quadrants. The occurrence of scattered type system is very less (2.08%) in northwest quadrant during monsoon period.

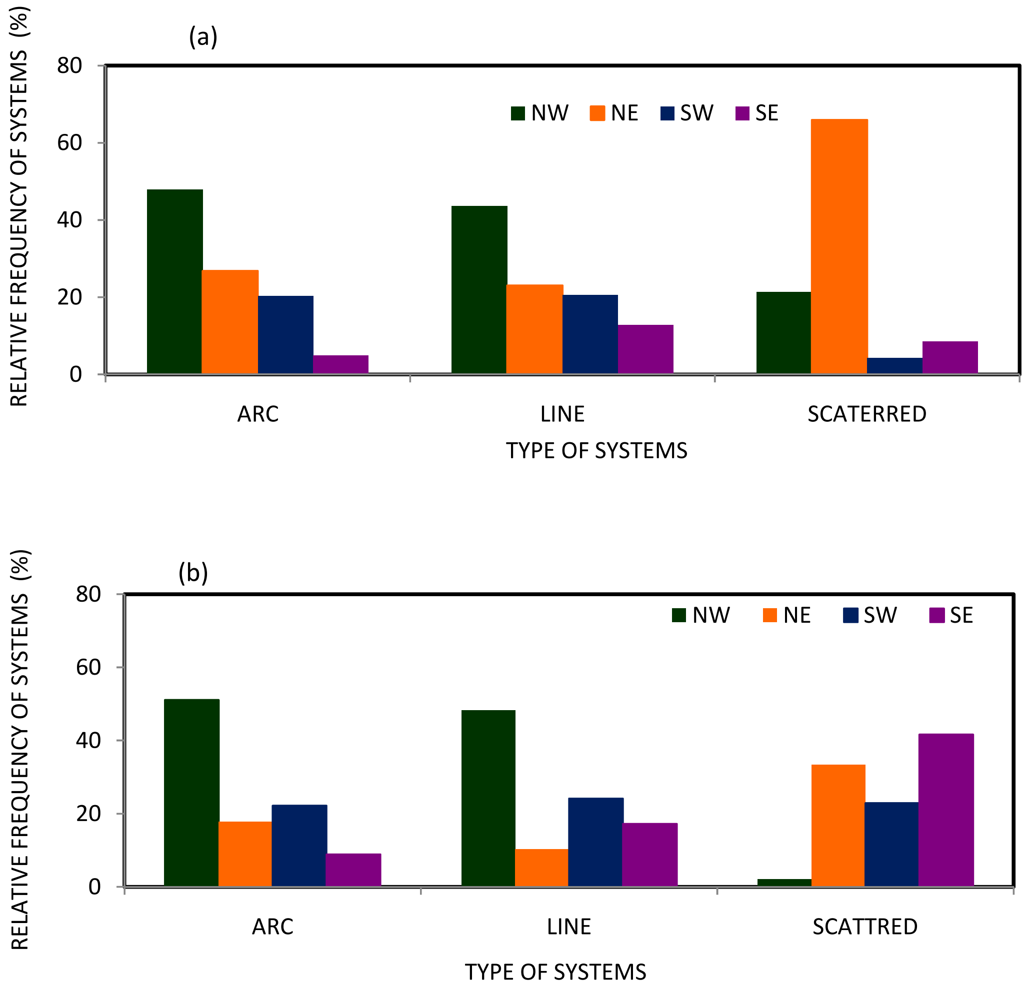



Figure 4.1. Relative frequency of arc, line and scattered types systems by quadrant at developing stage: (a) pre-monsoon and (b) monsoon. The total percentage of each type of precipitation systems is assumed to be 100%.

### 4.1.2 Mature stage

Figure 4.2 shows the regional distribution of the arc, line, and scattered type precipitation systems at mature stage during pre-monsoon and monsoon periods. The RFO of arc type precipitation system is high in the northeast and northwest quadrants during the pre-monsoon and monsoon periods respectively. The highest occurrence frequency of line type precipitation system is found in the northwest quadrant in both periods. The RFO of scattered type systems is very high (66.67%) in the northeast quadrant during pre-monsoon period. At the mature stage, the regional variation of scattered type system in all quadrants shows the similar tendency as developing stage during pre-monsoon season (Figure 4.1 (a)). During monsoon period, the highest occurrence frequency of arc (42.86%) type precipitation system is found in northwest quadrant. During the monsoon period, the scattered type systems are dominant in the northeast and southeast quadrants but the difference between these quadrants is very less and systems occurrence pattern same as developing stage.

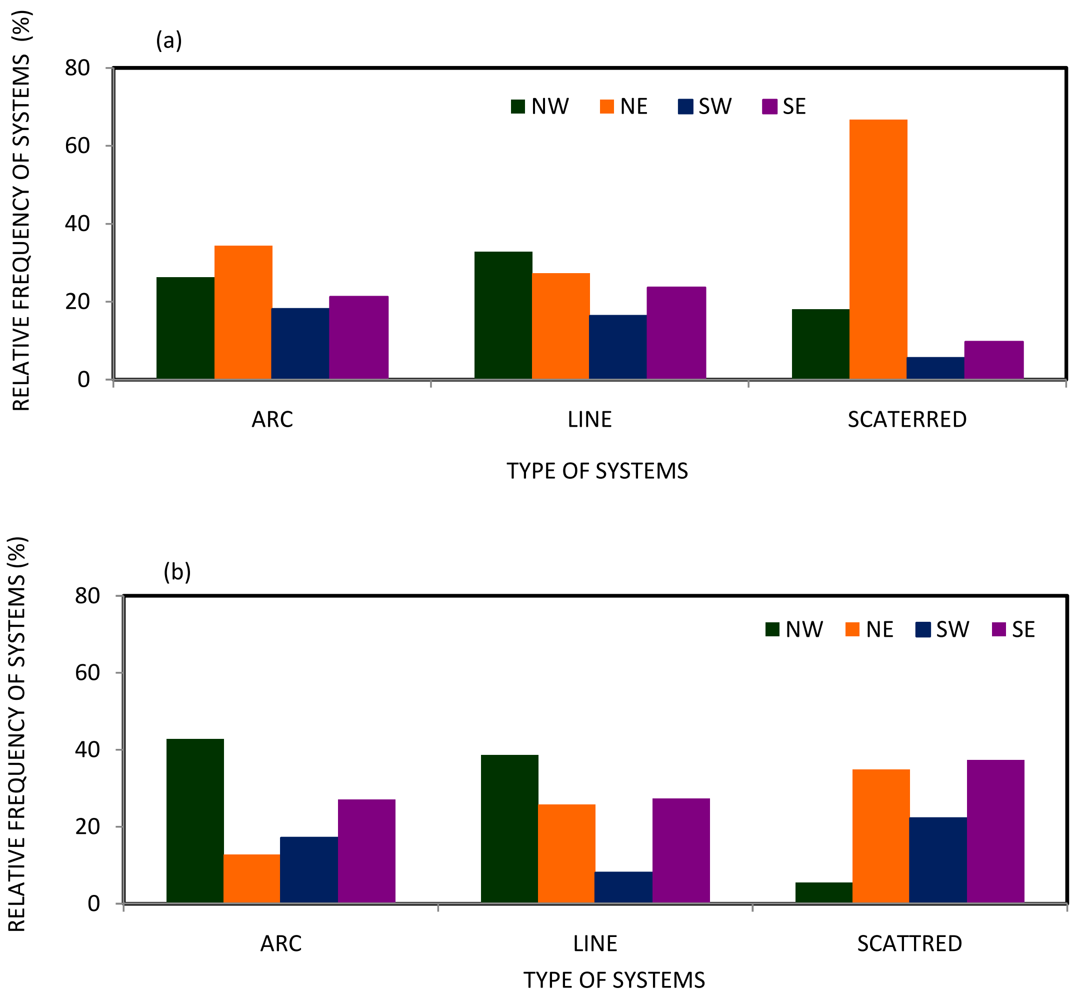



Figure 4.2. Relative frequency of arc, line and scattered types systems by quadrant at mature stage: (a) pre-monsoon and (b) monsoon. The total percentage of each type of precipitation system is assumed to be 100%.

### 4.1.3 Seasonal variation of precipitation systems

Figure 4.3 shows the RFO of precipitation systems at the developing and mature stage during pre-monsoon and monsoon season for combined all types of precipitation systems. The pre-monsoon and monsoon system are dominant in the northwest quadrant at developing.

The pre-monsoon systems is very less (7.70%) in southeast quadrant at developing stage. At mature stage the pre-monsoon system (monsoon system) is high in the northeast (southeast) quadrant

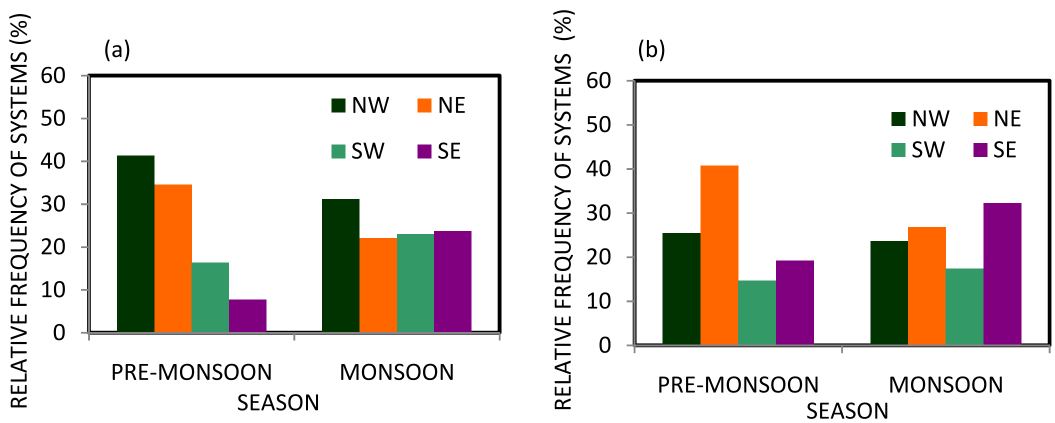



Figure 4.3. The seasonal variation of relative frequency of precipitation systems by quadrant during the study period: (a) developing stage and (b) mature stage. The total percentage of four quadrants is assumed to be 100% for a particular season.

### 4.1.4 Regional variation of precipitation systems at different stage

Figure 4.4 shows the regional variation of combined all types precipitation systems at different stage during study period (2000-2005). The RFO of precipitation systems is high in the northwest (northeast) quadrant at developing stage (at mature stage). The southeast quadrant (13.64%) shows the lowest occurrence frequency of systems at developing stage

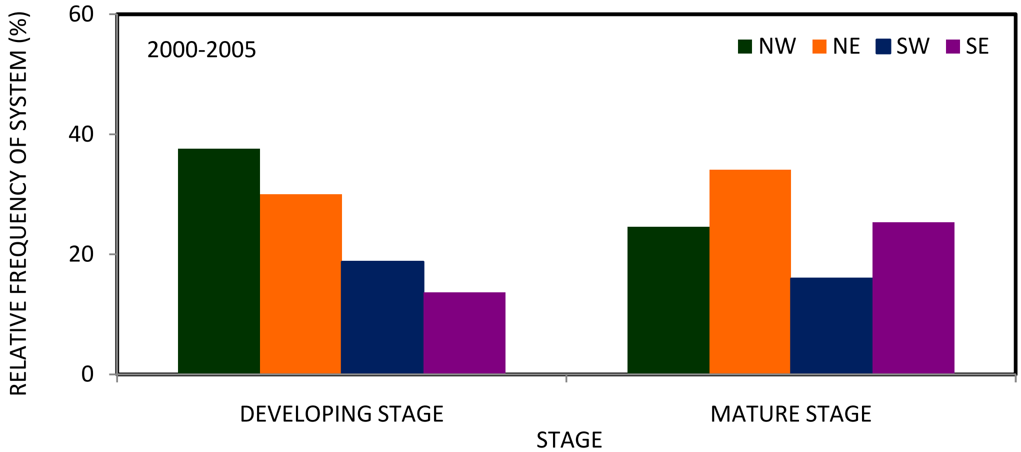



Figure 4.4. The variation of relative frequency of precipitation systems by quadrant at the developing and mature stage during 2000-2005. The total percentage of four quadrants is assumed to be 100%.

### 4.1.5 Distribution of different types precipitation systems by quadrant

Figure 4.5 illustrates the distribution of different types precipitation systems by quadrant at the developing and mature stage for the entire period of study. At the both stage, the highest frequency of occurrence of the arc type precipitation systems is found in the northwest and southwest quadrants while the scattered type system is dominant in the northeast and southeast quadrants. The highest contribution of line type precipitation systems is found in the northwest quadrant. At the mature stage the difference of occurrence frequency of arc and scattered type systems is not significant in southeast quadrant

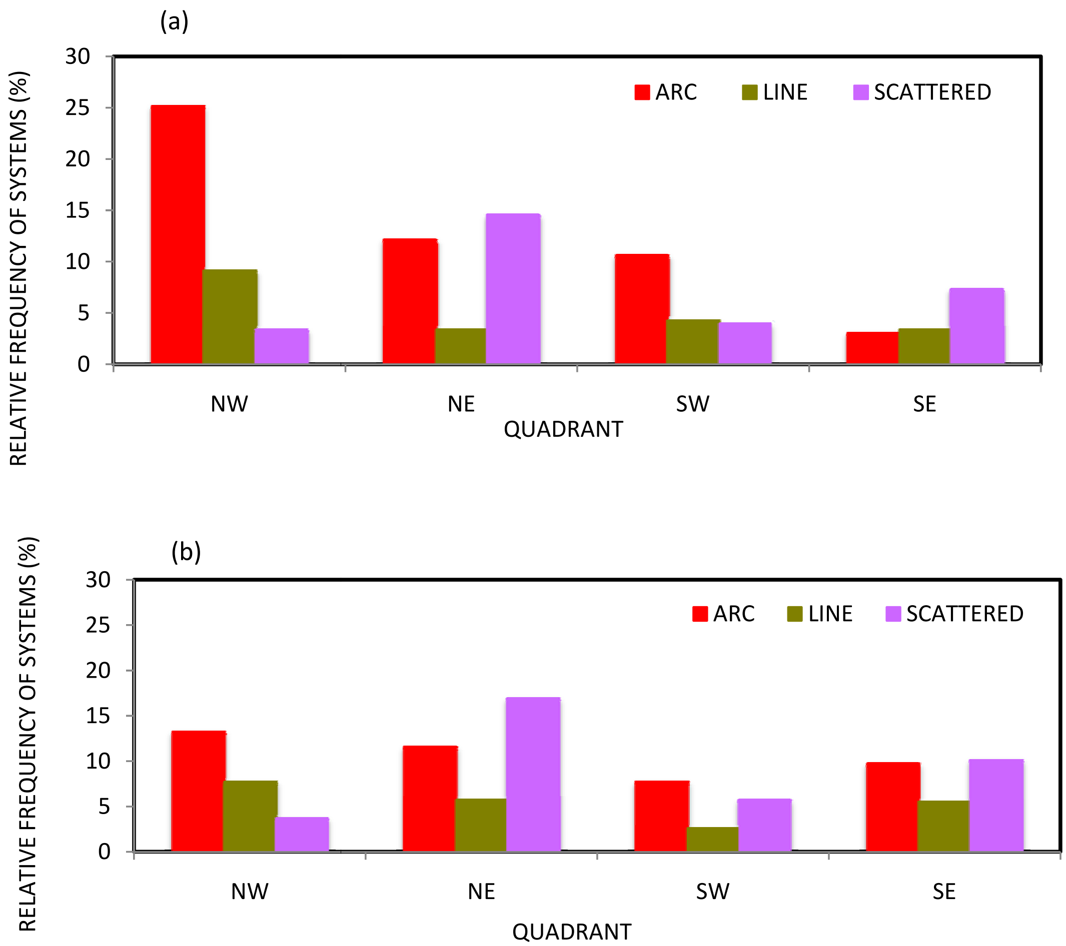



Figure 4.5. The variation of relative frequency of different precipitation systems by quadrant: (a) developing stage and (b) mature stage. The total percentage of the three patterns combined is assumed to be 100% over study period.

## 4.2 Classification of radar observed Arc type precipitation systems

The dominating arc type precipitation systems are classified into four basic types: i) symmetric, ii) asymmetric, iii) combination of symmetric and asymmetric and iv) unclassified type precipitation systems. In total 230 arc type precipitation systems are found during the study period from 2000 to 2005.

### 4.2.1 Symmetric type precipitation system

Figure 4.6 shows the monthly occurrence frequency of symmetric type precipitation system (STPS) during 2000-2005. The STPS is dominant in the month of May of the year

2001, 2003 and 2004. In 2000, and 2002, the RFO of STPS is highest in the month April (57.53%) and July (47.80%), respectively. In 2005, STPS is found only in the monsoon months and maximum occurrence is found in the month of June (65.43%).

### 4.2.2 Asymmetric type precipitation system

Figure 4.7 shows the monthly RFO of asymmetric type precipitation system (ATPS) during 2000-2005. The contribution of ATPS is highest in the pre-monsoon months than the monsoon except the month of June 2003 (Figure 4.7 (d)). The ATPS is dominant in the month of May in pre-monsoon months.

### 4.2.3 Combination of symmetric and asymmetric type precipitation system

During 2000-2005, the monthly RFO of combination of symmetric and asymmetric type precipitation system (CSATS) is shown in Figure 4.8. The occurrence frequency of CSATPS is dominant in the pre-monsoon months (especially in April) except the year 2003 and 2005. In 2003 and 2005, the maximum RFO of CSATPS is found in the month of June. In 2001, CSATS was inactive in each month throughout the year in and around Bangladesh.

### 4.2.4 Unclassified type precipitation system

Figure 4.9 shows the monthly RFO of unclassified type precipitation system (UTPS) during 2000-2005. The occurrence frequency of UTPS is high in the month of pre-monsoon months (Figure 4.4). In pre-monsoon, the higeast RFO of UTPS is found in the month of May. The occurrence of UTPS is not significant in the monsoon months.

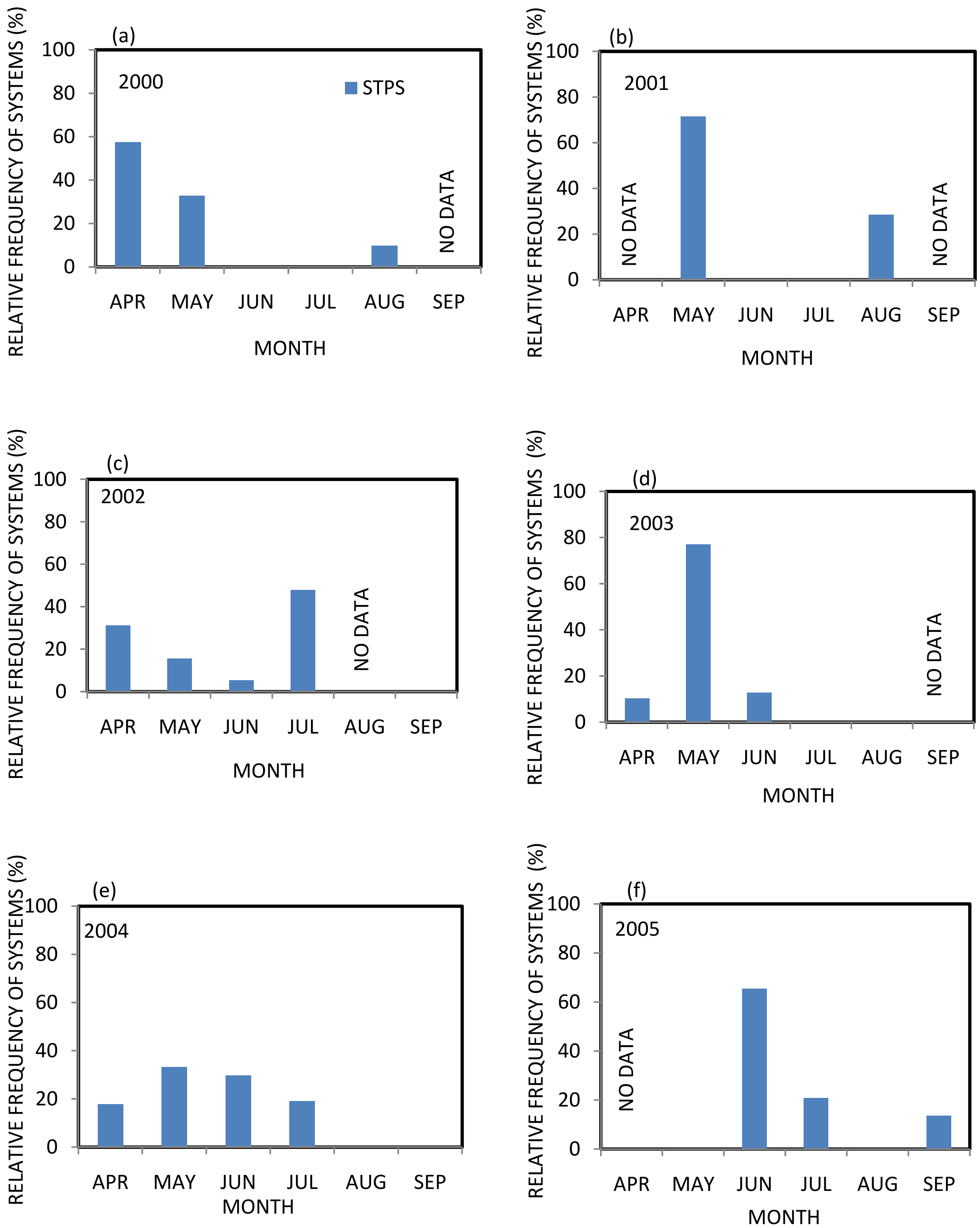



Figure 4.6. Relative frequency of symmetric type precipitation systems in different year. The total percentage of STPS is assumed to be 100%.

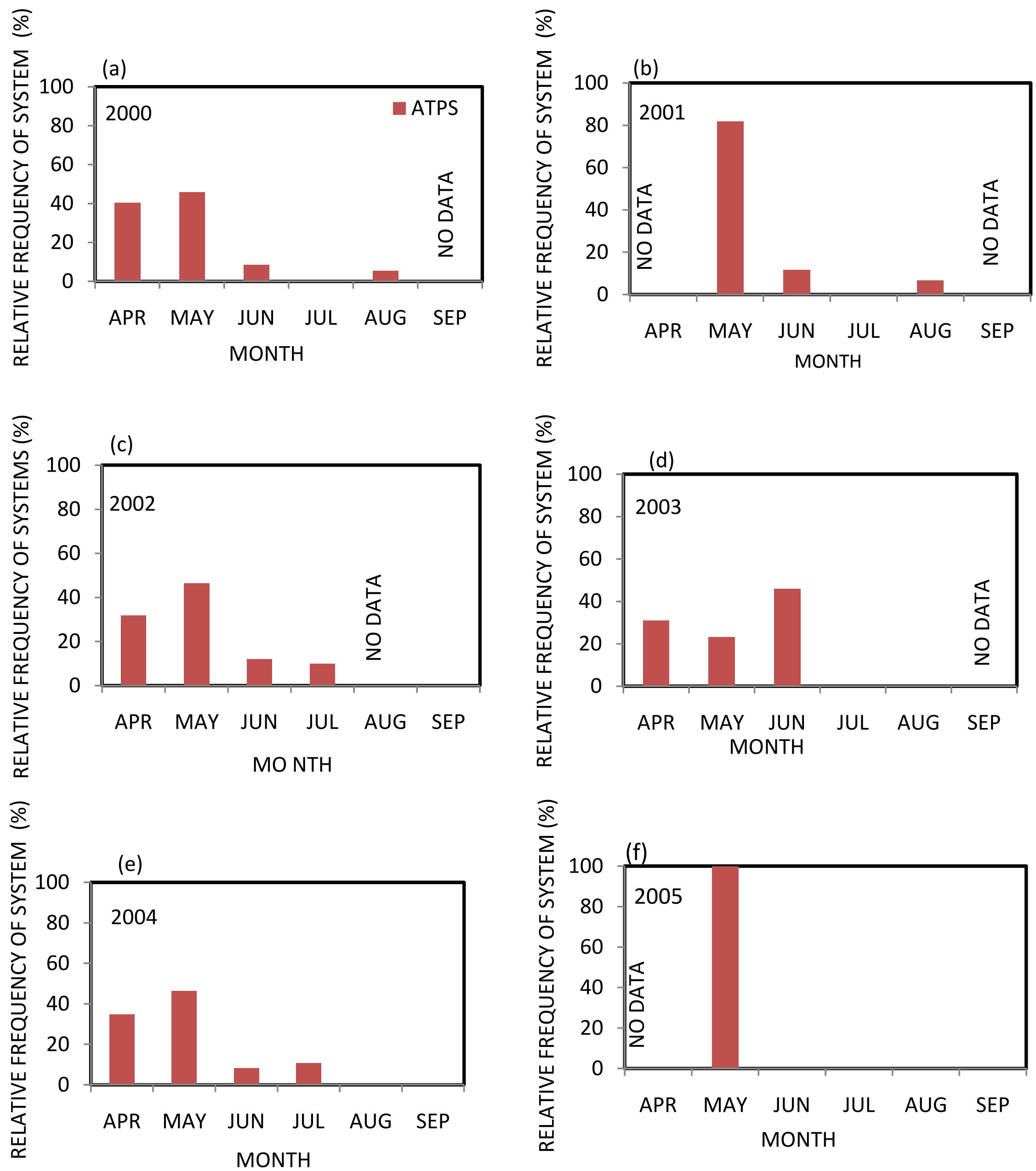



Figure 4.7. Relative frequency of asymmetric type precipitation systems in different year. The total percentage of ATPS is assumed to be 100%.

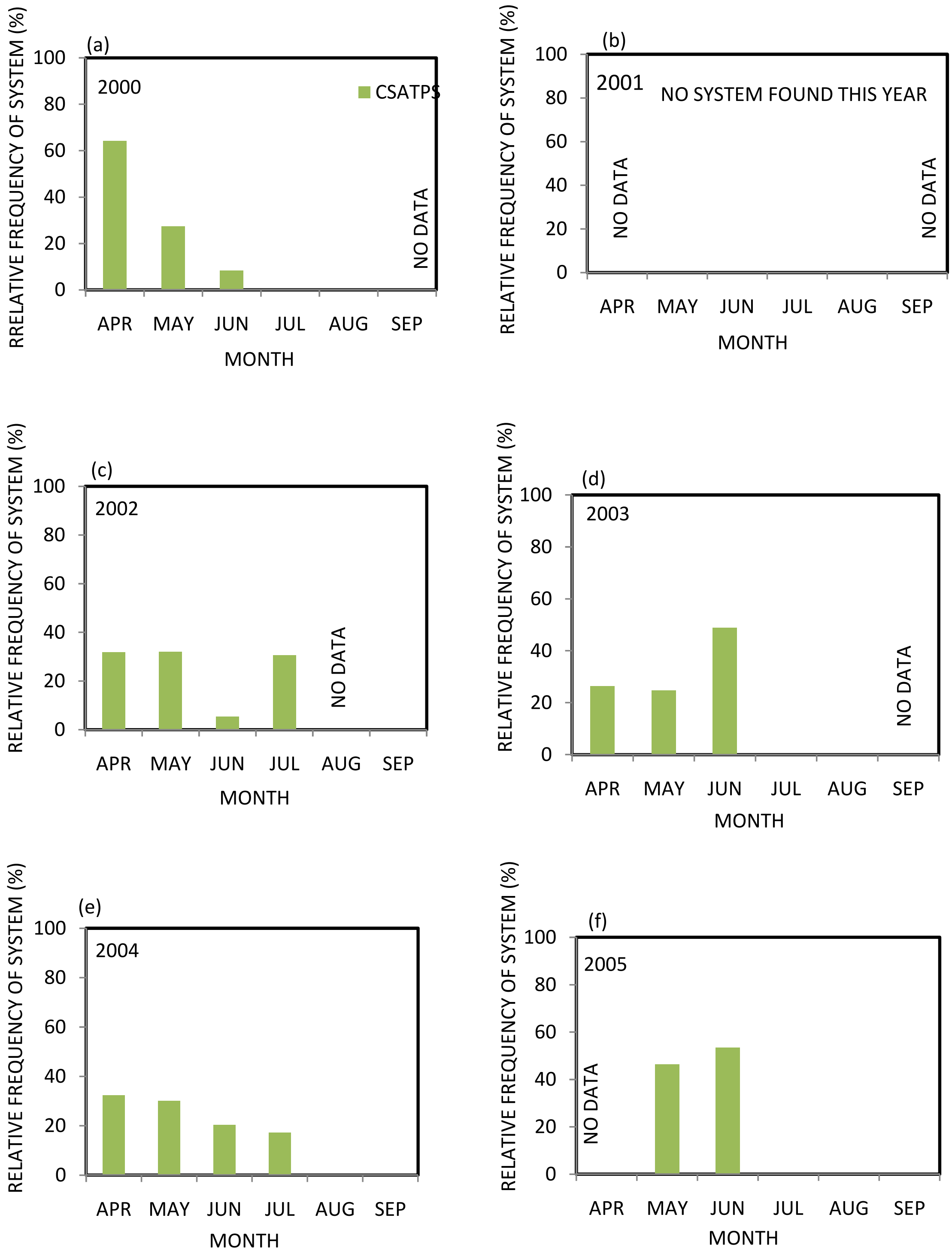



Figure 4.8. Relative frequency of combination of symmetric and asymmetric type precipitation system in different year. The total percentage of CSATPS is assumed to be 100%.

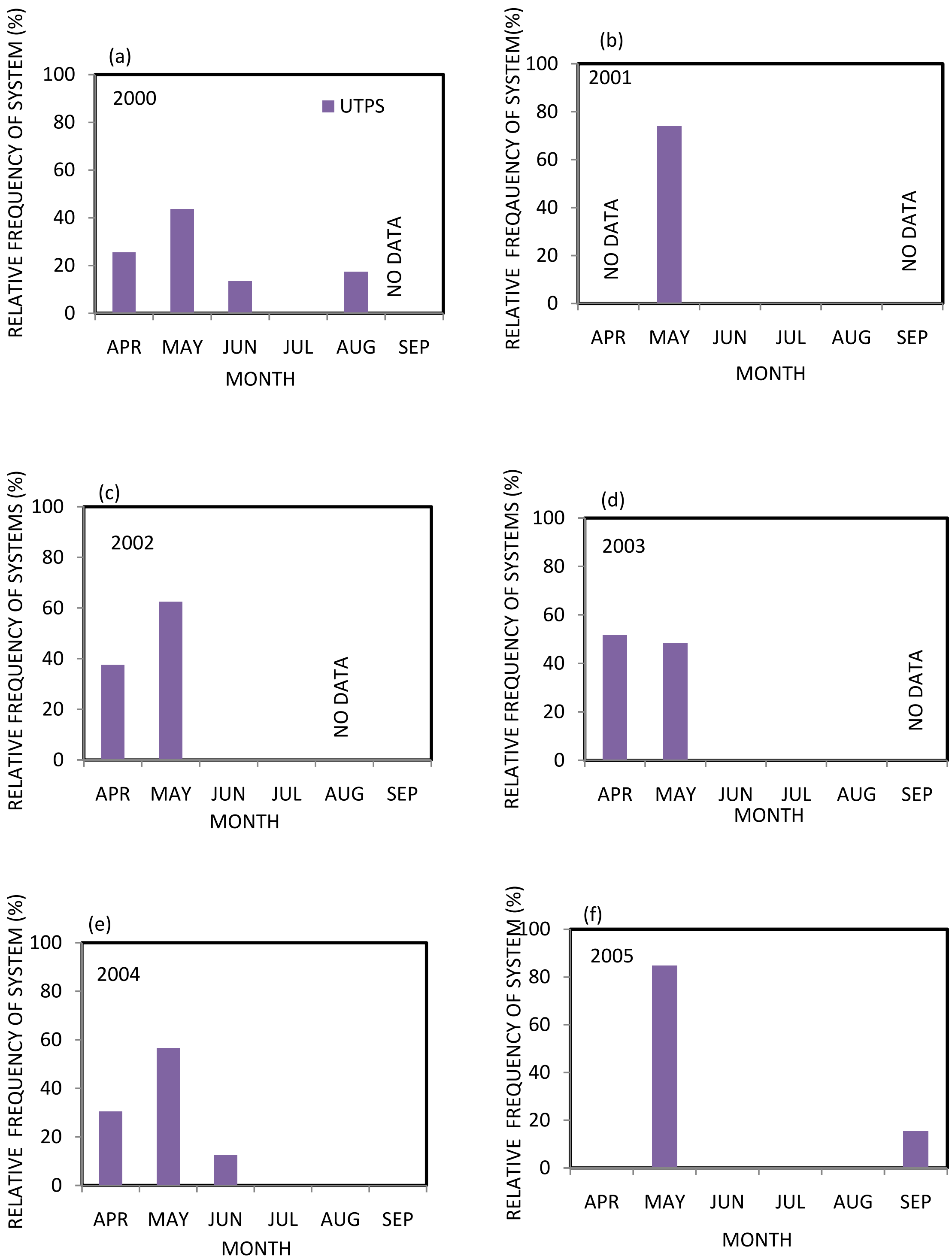



Figure 4.9. Relative frequency of unclassified type precipitation systems in different year. The total percentage of UTPS is assumed to be 100%.

## 4.2.5 Regional variation of different arc type precipitation systems

### 4.2.5.1 Developing stage

Figure 4.10 represents the RFO of STPS, ATPS, CSATPS and UTPS at developing stage during pre-monsoon and monsoon periods. In pre-monsoon all the system types is dominant in the northwest quadrant .The RFO of STPS is same in northwest and southwest quadrants. The occurrence frequency of all system types in the southeast quadrant is not significant during pre-monsoon period. During monsoon, the maximum occurrence frequency of STPS, ATPS, CSATPS and UTPS is found in the northwest, northeast, northwest and southwest quadrant respectively.

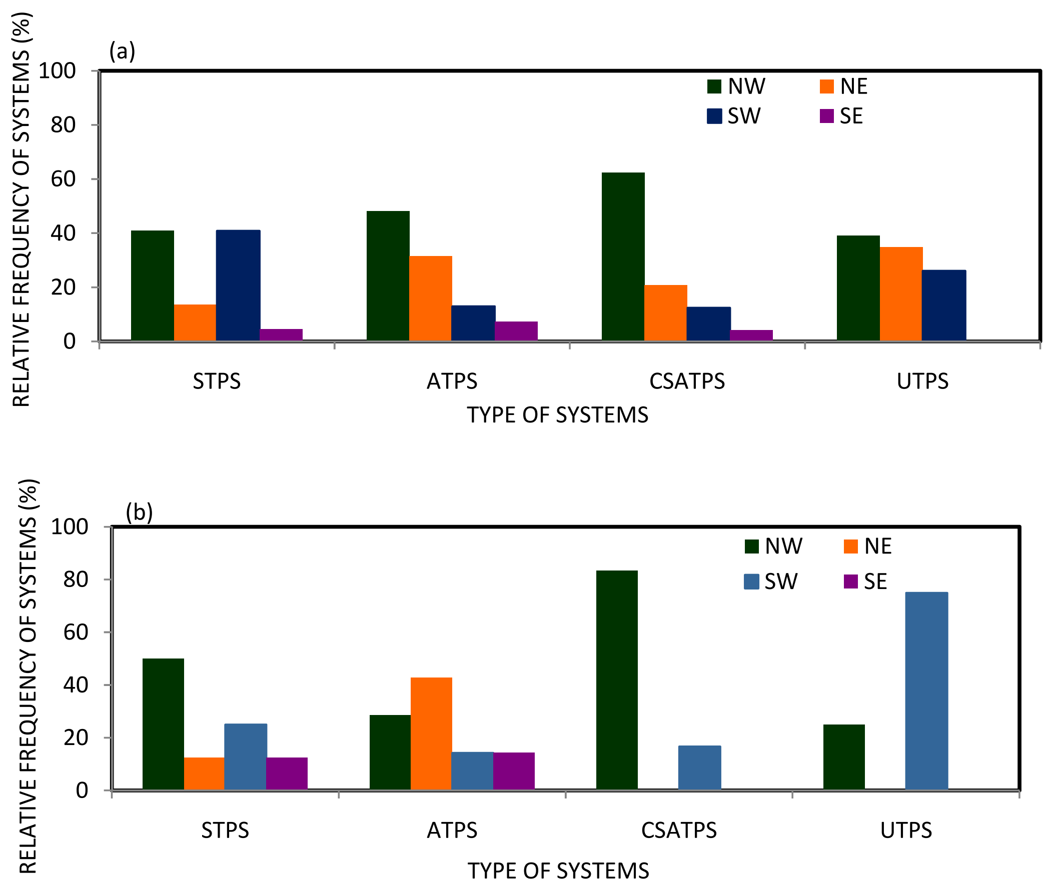



Figure 4.10. The variation of relative frequency of different arc type precipitation systems by quadrant at developing stage: (a) pre-monsoon and (b) monsoon. The total percentage of each type system is assumed to be 100%.

### 4.2.5.2 Mature stage

Figure 4.11 shows the RFO of different arc types systems at mature stage during pre-monsoon and monsoon period. During pre-monsoon period, the maximum occurrence frequency of STPS, ATPS, CSATPS and UTPS is found in the southwest, northeast northwest, and northeast quadrants respectively. The RFO of UTPS in the northeast and southwest quadrants is same. During monsoon period, the maximum occurrence frequency of STPS, ATPS, CSATPS and UTPS is found in the northwest, southeast, northwest and southwest quadrants respectively.

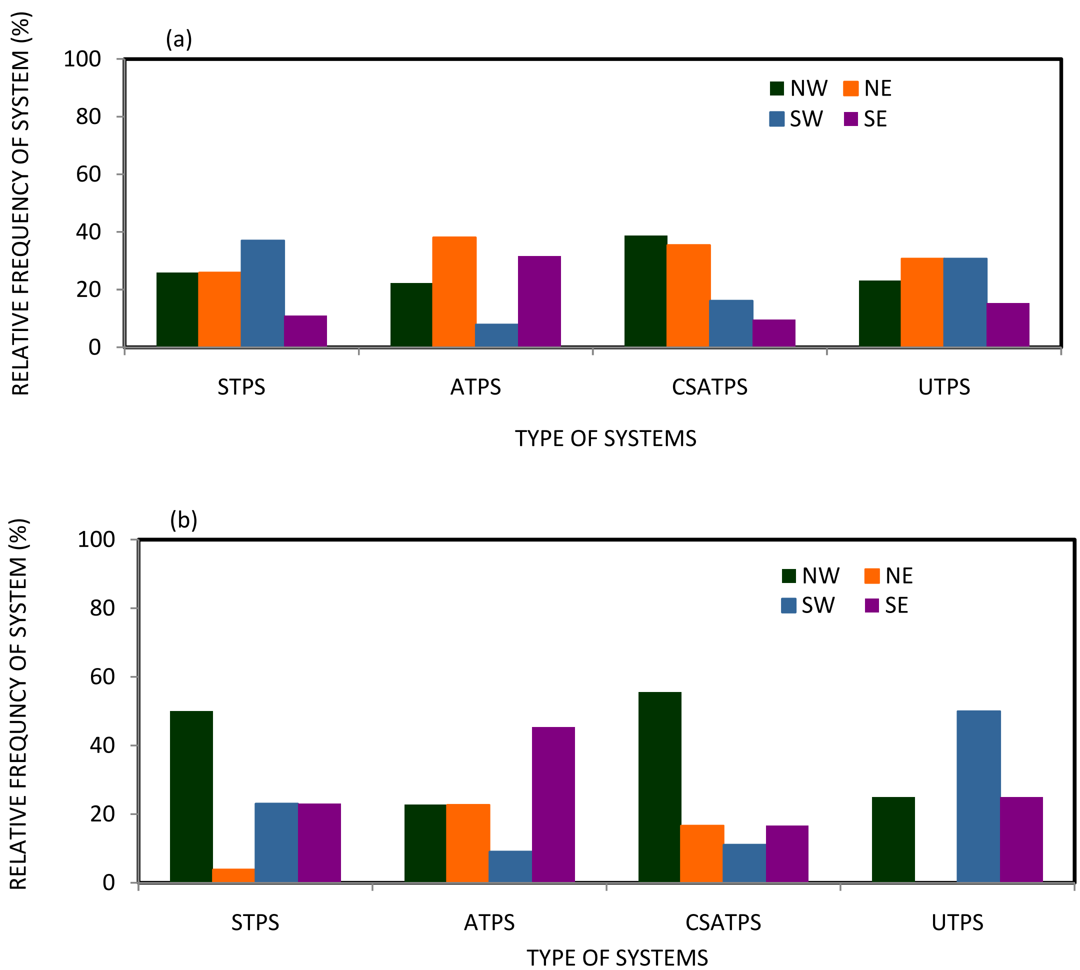



Figure 4.11. The variation of relative frequency of different arc type precipitation systems by quadrant at mature stage: (a) pre-monsoon and (b) monsoon. The total percentage of each type is assumed to be 100%.

### 4.2.6 Regional variation of different arc types precipitation systems at different stages

Figure 4.12 represents the RFO of various arc types precipitation systems at developing and mature stages during study period. During developing stage, the highest occurrence frequency of STPS, ATPS, CSATPS and UTPS is found in the northwest quadrant. Few number of systems are found in the southeast quadrant at the developing stage. At the mature, the maximum occurrence frequency of STPS, ATPS, CSATPS and UTPS is found in the northwest, northeast, northwest and southwest quadrants respectively. The occurrence of ATPS in the northeast and southeast quadrants is same.

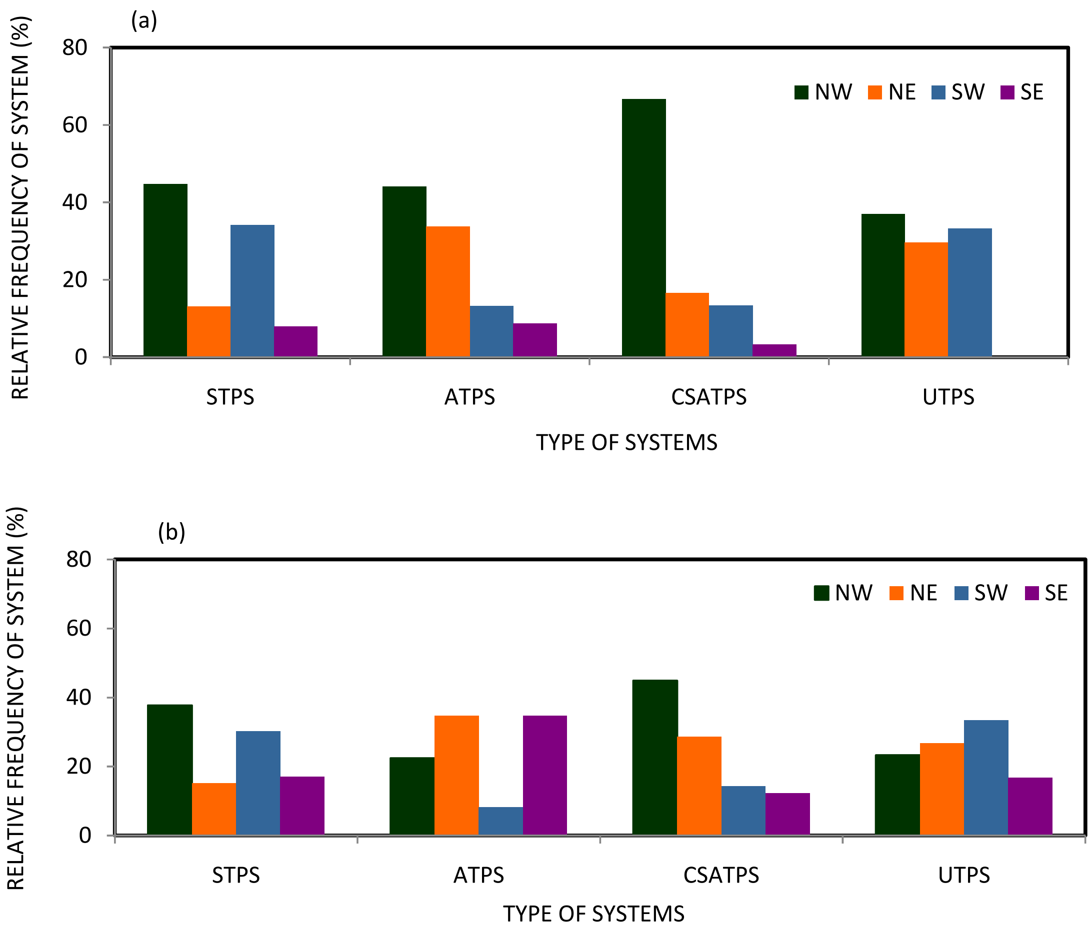



Figure 4.12. The variation of relative frequency of different arc type precipitation systems by quadrant during study period: (a) developing stage and (b) mature stage. The total percentage of each type is assumed to be 100%.

### 4.2.7 Distribution of different arc type precipitation systems by quadrant

Figure 4.13 shows the distribution of STPS, ATPS, CSATPS and UTPS by quadrant at the developing and mature stage for the entire period of study. At the developing stage, the maximum RFO of ATPS is found in the northwest, northeast, and southeast quadrants. The STPS is dominant in the southwest quadrant. At the mature stage occurrence of the ATPS is maximum in the northwest, northeast, and southeast quadrants. The difference of occurrence frequency between ATPS and CSATPS is not significant in the northwest quadrant. The STPS is dominant in the southwest quadrant.

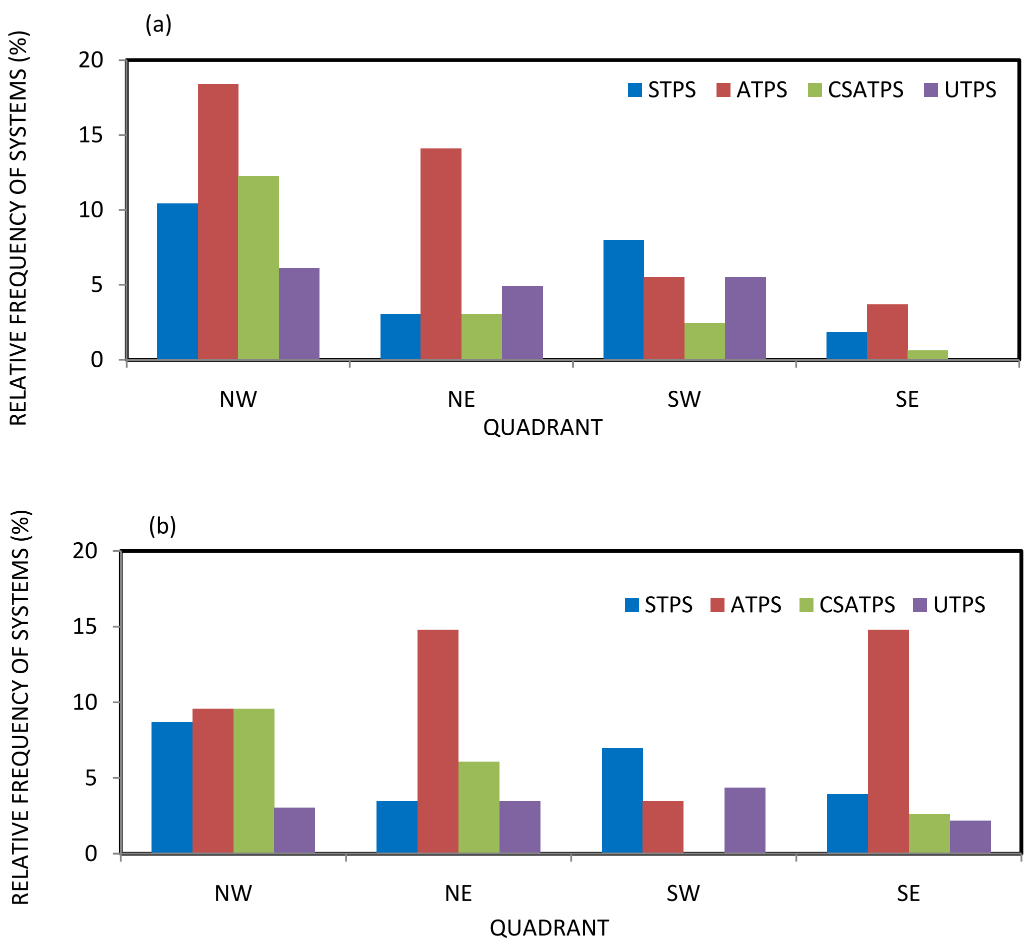



Figure 4.13. The variation of relative frequency of different arc type precipitation systems by quadrant: (a) developing stage and (b) mature stage. The total percentage of the four patterns combined is assumed to be 100%.

### 4.2.8 Monthly variation of STPS, ATPS, CSATPS and UTPS

The monthly variation of RFO of all types of precipitation systems is shown in Figure 4.14. The occurrence frequency of STPS shows highest peak in month April (31.36%) and afterward this frequency decrease almost exponentially. However, exception in month June and July reflect the same value. ATPS and UTPS start to develop from the beginning of the pre-monsoon month of April, peak in May, and radically decrease in the months of monsoon. In the highest month May, the occurrence frequency of ATPS and UTPS is 47.34% and 53.12%, respectively. Figure 4.14 also indicates the highest peak of CSATPS (44.76%) in month of April same as STPS and with the progression of monsoon, the frequency of CSATPS deceases significantly. There is no CSATPS is found in the month of August and September during the study period 2000-2005.

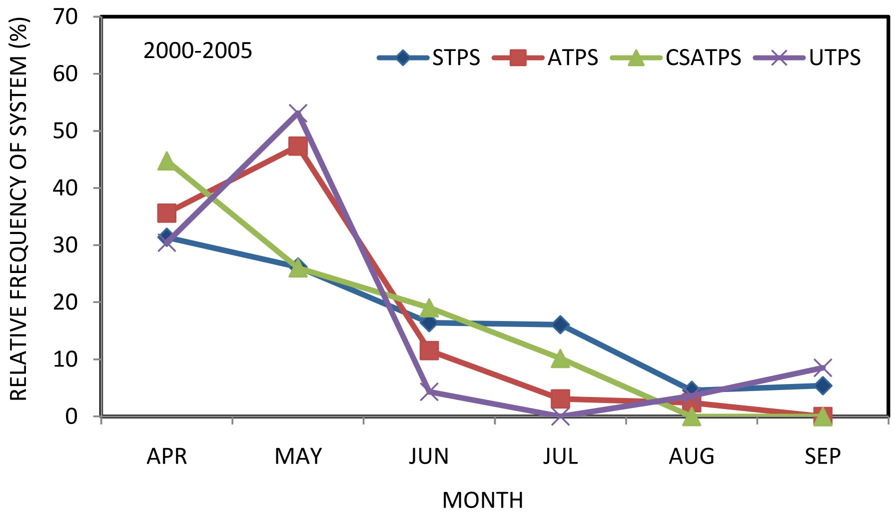



Figure 4.14. Monthly relative frequency of occurrence of STPS, ATPS, CSTPS and UTPS from 2000-2005. The total percentage of each type is assumed to be 100%.

### 4.2.9 Inter-annual variation of STPS, ATPS, CSATPS and UTPS

Figure 4.15 shows the inter-annual variation of STPS, ATPS, CSATPS and UTPS. The RFO of all type systems is found highest peak in the year 2002. The occurrence frequency of STPS, ATPS, and UTPS is very less in 2001 compare with the other year and the CSATPS is very inactive throughout the year (Figure 4.12(b)). The RFO of all types of systems shows strong intra-annual variation, especially STPS and CSATPS.

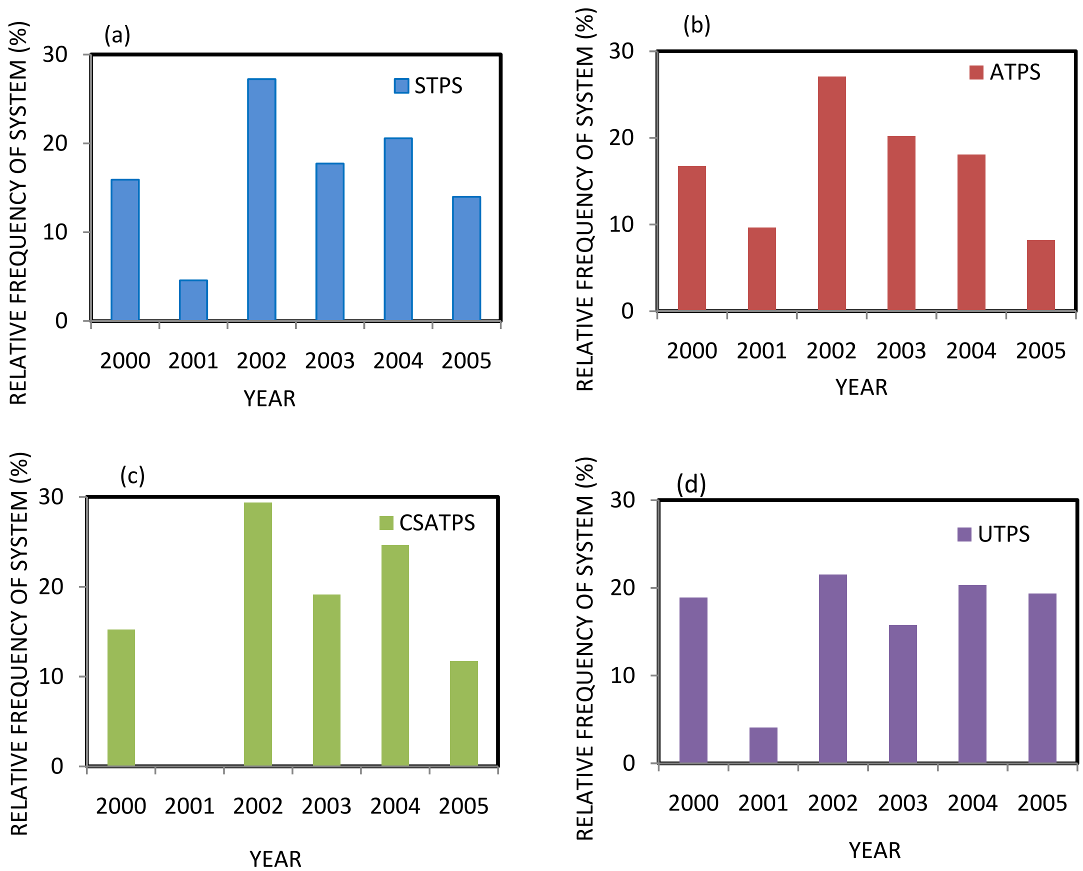



Figure 4.15. Inter annual-variation of the relative frequency of different arc type precipitation systems: (a) STPS, (b) ATPS, (c) CSTPS and (d) UTPS from. The total percentage of each type is assumed to be 100%.

### 4.2.10 Intra-seasonal variation of STPS, ATPS, CSATPS and UTPS

Figure 4.16 shows the intra-seasonal variation of occurrence frequency of STPS, ATPS, CSATPS and UTPS from 2000-2005. It is observed from the figure that there have strong intra-seasonal variations of precipitation systems in different year. The occurrence of all types of systems is very strong in the pre-monsoon than monsoon season. The occurrence frequency of different arc type system is large of the year 2002 during monsoon period except UTPS. It is found that a few number of UTPS (4) observed in monsoon during study period.

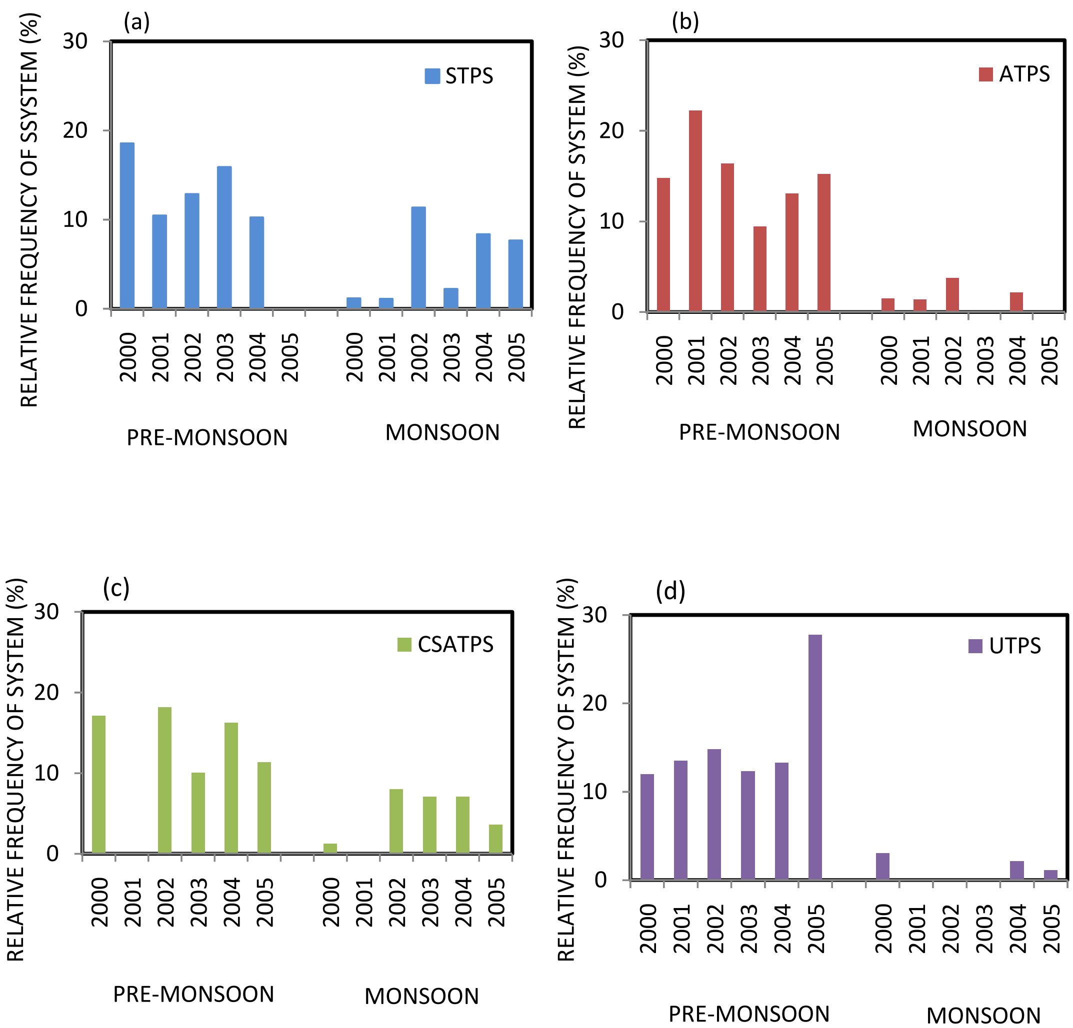



Figure 4.16. The intra-seasonal variation of the relative frequency of different arc precipitation systems in different year: (a) STPS, (b) ATPS, (c) CSTPS and (d) UTPS. The total percentage of each type is assumed to be 100%.

### 4.2.11 Relationship between propagation direction and propagation speed

Figure 4.17 represents the relation between propagation speed and direction of different arc type precipitation systems in different season. Almost all type of arc systems propagate toward southeast in pre-monsoon and monsoon seasons. A few exceptions are observed during both seasons. All types of pre-monsoon systems are moving faster than the monsoon systems. The average propagation speed of STPS, ATPS, CSATPS and UTPS is 13.04 m/s (9.62 m/s), 12.01m/s (8.63 m/s), 13.05m/s (10.64 m/s), and 12.24m/s (6.6 m/s) in pre-monsoon (monsoon), respectively. This finding is consistence with the result by Islam et al., (2004) and Rafiuddin et al., (2010).

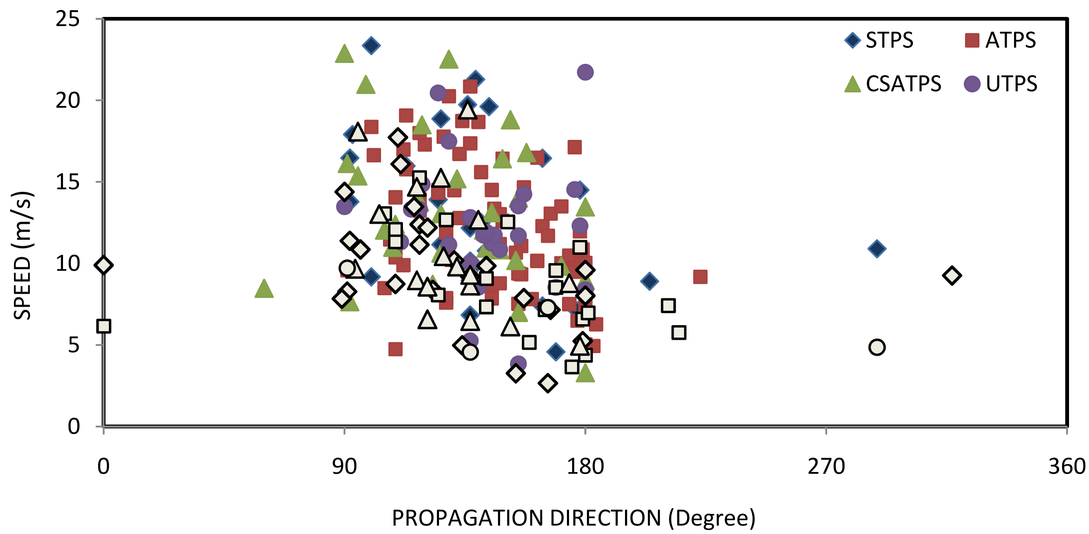



Figure 4.17. Propagation speed and direction of different arc type precipitation systems (STPS, ATPS, CSATPS and UTPS). Color symbol represent the pre-monsoon and colorless symbols represent the monsoon systems.

### 4.3 Diurnal variation of mesoscale precipitation systems

#### 4.3.1 Developing stage

Figure 4.18 shows the diurnal variation of arc, line and scattered types precipitation systems during pre-monsoon and monsoon periods at developing stage. During pre-monsoon period, the arc, line and scattered types precipitation systems show the maximum peak at 15-18 LST (evening), 03-06 LST (morning) and 03-06 LST (morning), respectively. In general, the total relative frequency of all types of precipitation systems shows the morning maximum peak at 03-06 LST with the secondary maximum peak at 15-18 LST. During the monsoon, the arc, line and scattered types precipitation systems show the peak at 15-18 LST, 09-15 LST and 09-12 LST, respectively. In general, the total relative frequency of all types of precipitation systems shows the maximum peak at 09-12 LST.

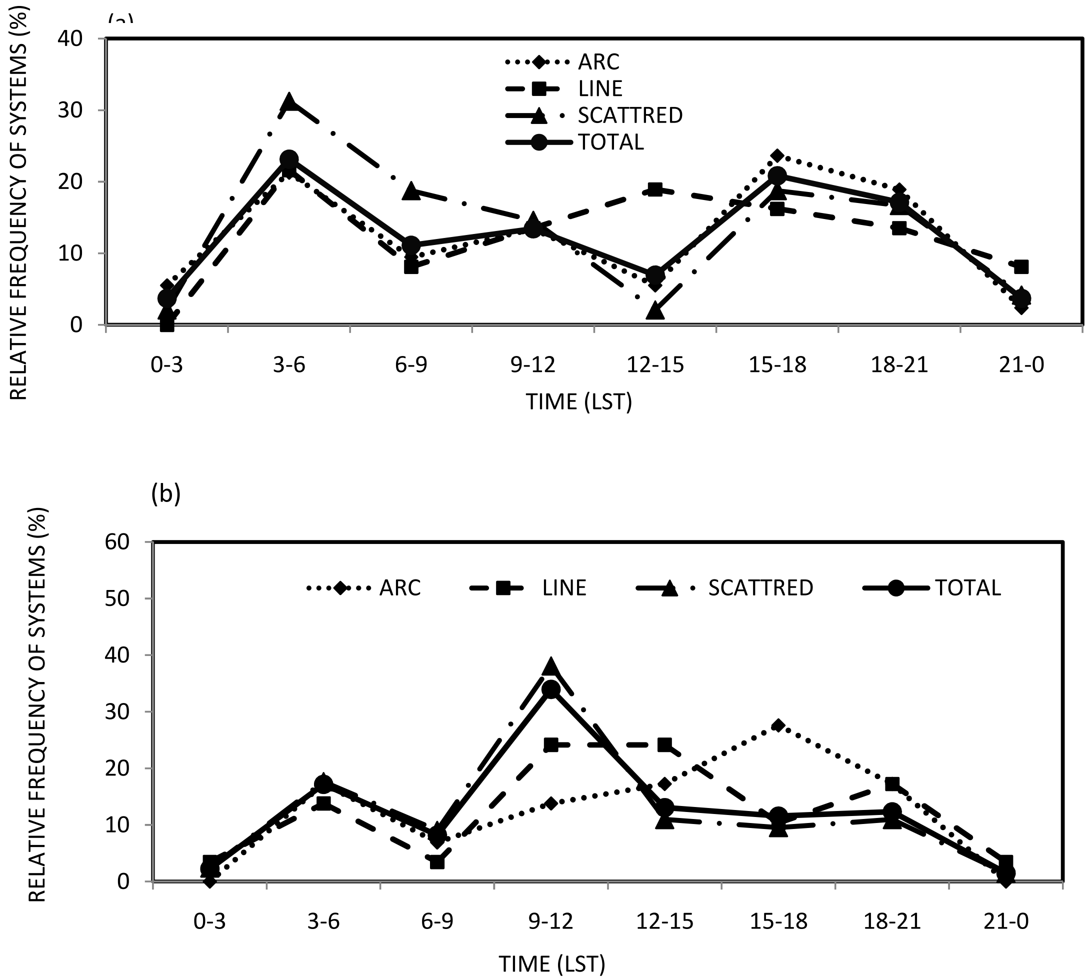
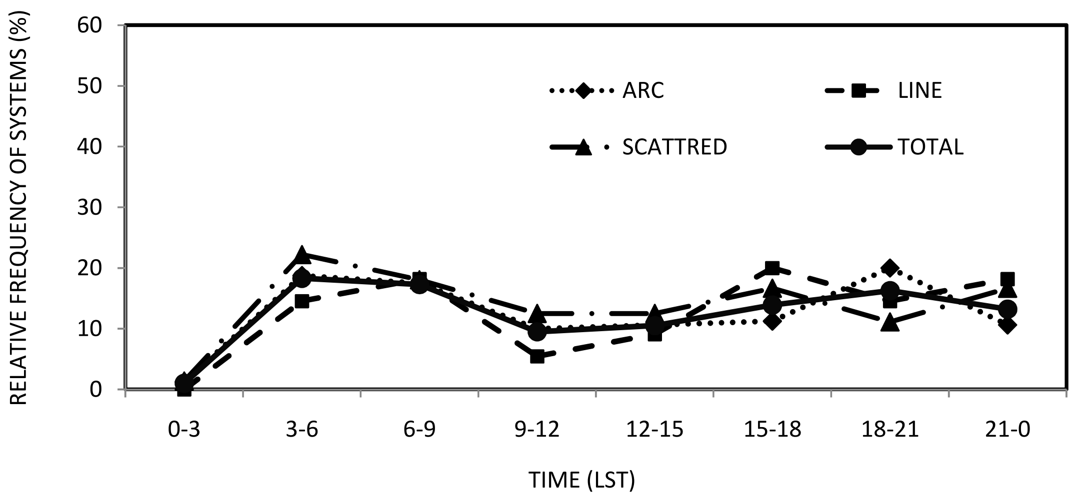



Figure 4.18. Diurnal variation of relative frequency of arc, line and scattered systems at developing stage: (a) pre-monsoon and (b) monsoon. The total percentage of each type of systems is assumed to be 100%

### 4.3.2 Mature stage

Figure 4.19 depicts the diurnal variation of RFO of precipitation systems at mature stage during pre-monsoon and monsoon periods. It is apparent from the figure that during the pre-monsoon period, the arc type precipitation system shows maximum evening peak (20%) at 18-21 LST with a secondary peak (18%) at 03-09 LST. The line type precipitation systems shows the maximum occurrence frequency (20%) at 15-18 LST with the secondary peaks (18%) at 06-09 and 21-00 LST. The occurrence frequency of scattered system shows peak (22%) at 03-06 LST. The total occurrence frequency of all types of precipitation systems shows the maximum peak at 03-09 LST. However, in monsoon, the maximum occurrence frequency of arc, line and scattered types precipitation systems show peak at 03-06 LST, 03-06 LST and 12-15 LST, respectively. The total occurrence frequency of all types of precipitation systems shows the dual maximum peaks at 03-06 LST and 12-15 LST during monsoon period.



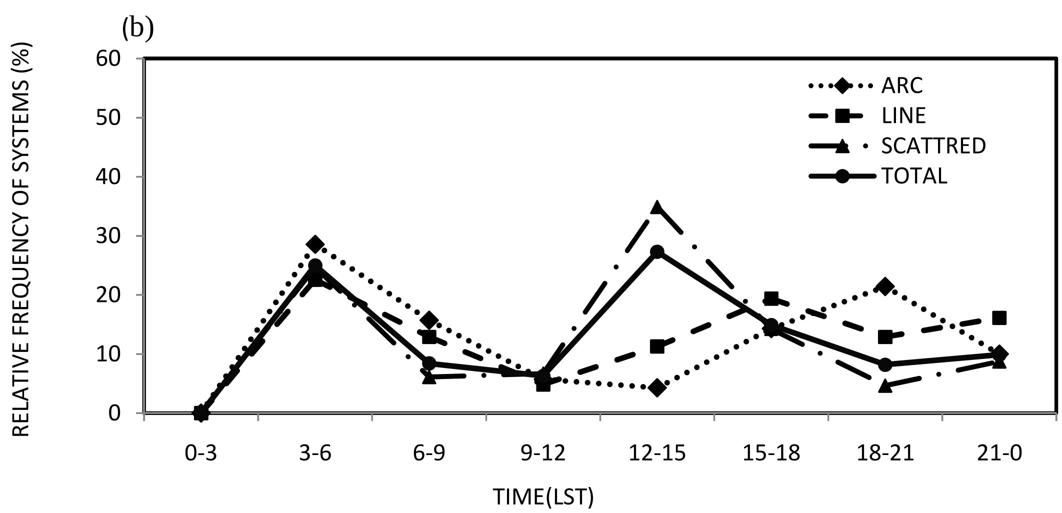




Figure 4.19. Diurnal variation of relative frequency of arc, line and scattered systems at mature stage: (a) pre-monsoon and (b) monsoon. The total percentage of each type of systems is assumed to be 100%

### 4.3.3 Diurnal variation of arc, line and scattered type precipitation at developing and mature stage

Figure 4.20 shows the diurnal variation of RFO of arc, line and scattered type precipitation systems at developing and mature stage over the period 2000-2005. At the developing stage, arc, line, and scattered type precipitation systems shows the peak at 15-18 LST (evening), 12-15 LST (afternoon) and 09-12 LST (noon), respectively. The secondary maximum peak is found at 03-06 LST for all type of systems. The total occurrence frequency shows the maximum (secondary maximum) morning (noon) peak at 03-06 LST (09-12 LST) At the mature stage, maximum (secondary maximum) occurrence frequency of arc, line, and scattered type precipitation systems is found 03-06 LST (18-2 LST), 03-06 LST (15-18 LST) and 12-15LST (03-06 LST), respectively. The total occurrence frequency shows the maximum (secondary maximum) peak at 03-06 LST (12-15 LST).

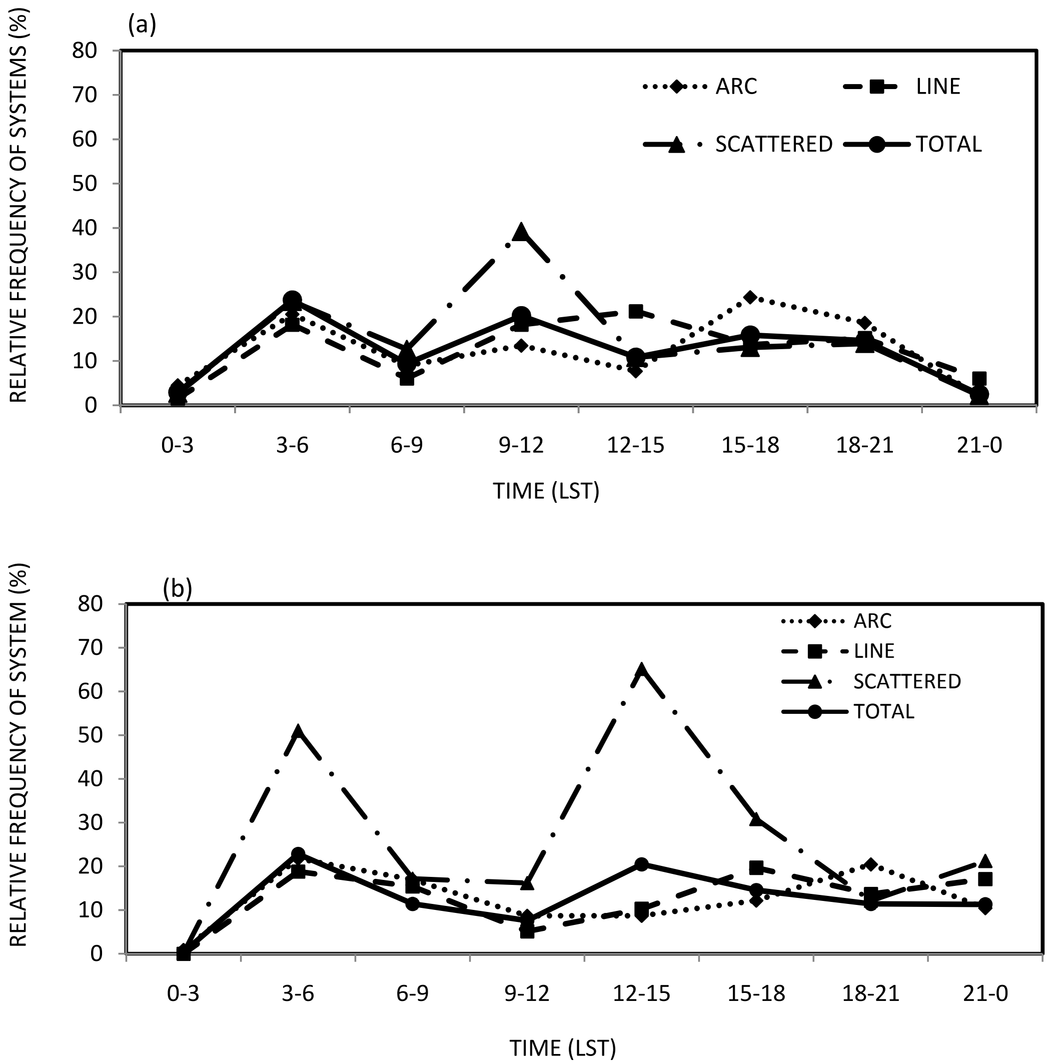



Figure 4.20. Diurnal variation of relative frequency of arc, line and scattered types systems: (a) developing stage and (b) mature stage. The total percentage of each type of systems is assumed to be 100%.

### 4.3.4 Monthly diurnal variation of arc type precipitation systems at mature stage

Figure 4.21 represents the monthly diurnal variation of RFO of arc type system. From the Figure 4.20b, it is observed that arc type precipitation systems shows the morning and midnight peak at 03-06 LST and 18-21 LST during the study period from 2000-2005 ( April to September) but the individual month of different year shows the different peak. April month shows the midnight peak (18-21 LST) in all years except the evening peak at 15-18 LST for the year of 2000. The month of April 2004 also shows another maximum peak at 03-06 LST. In month of May, the RFO of arc type precipitation systems shows the morning peak at 03-06 LST and evening at 15-18 LST randomly from year to year. The month of June shows clear morning peak at 03-06 LST except the year 2000 (18-21 LST) and 2002 (18-21 LST). The month of July shows the peak at 06-09 LST, for the year 2002 and 2004 and 15-21 LST in the year 2005. August 2000 shows the peak at 06 LST while the year 2001 shows the 21 LST and September shows same maximum peak at 15-18 LST and 21-00 LST.

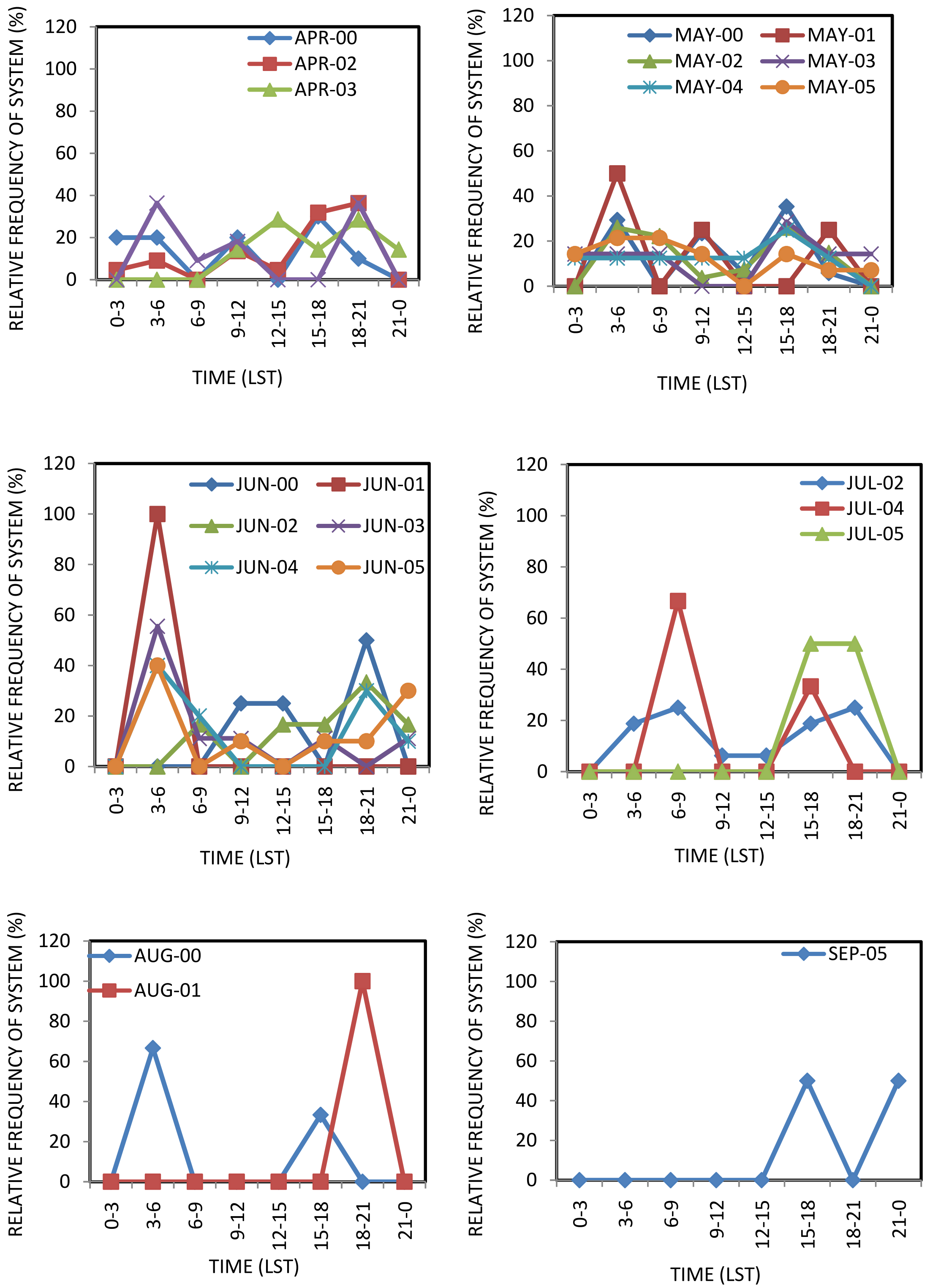



Figure 4.21. Monthly diurnal variation of arc type precipitation systems. The percentage of each month is assumed to be 100%.

### 4.3.5 Diurnal variation of STPS, ATPS, CSATPS, and UTPS

#### 4.3.5.1 Developing stage

Figure 4.22 shows the diurnal variation of RFO of different arc type precipitation systems at developing stage during pre-monsoon and monsoon periods. During the pre-monsoon period, the STPS, ATPS, CSATPS and UTPS show the peak at 15-18 LST, 03-06 LST, 18-21 LST and 15-18 LST, respectively. During the monsoon, the STPS, ATPS, and CSATPS show the same peak value as pre-monsoon. The RFO of CSATPS shows the double peak at 3-6 LST and 18-21 LST. The UTPS shows the maximum peak at 12-18 LST.

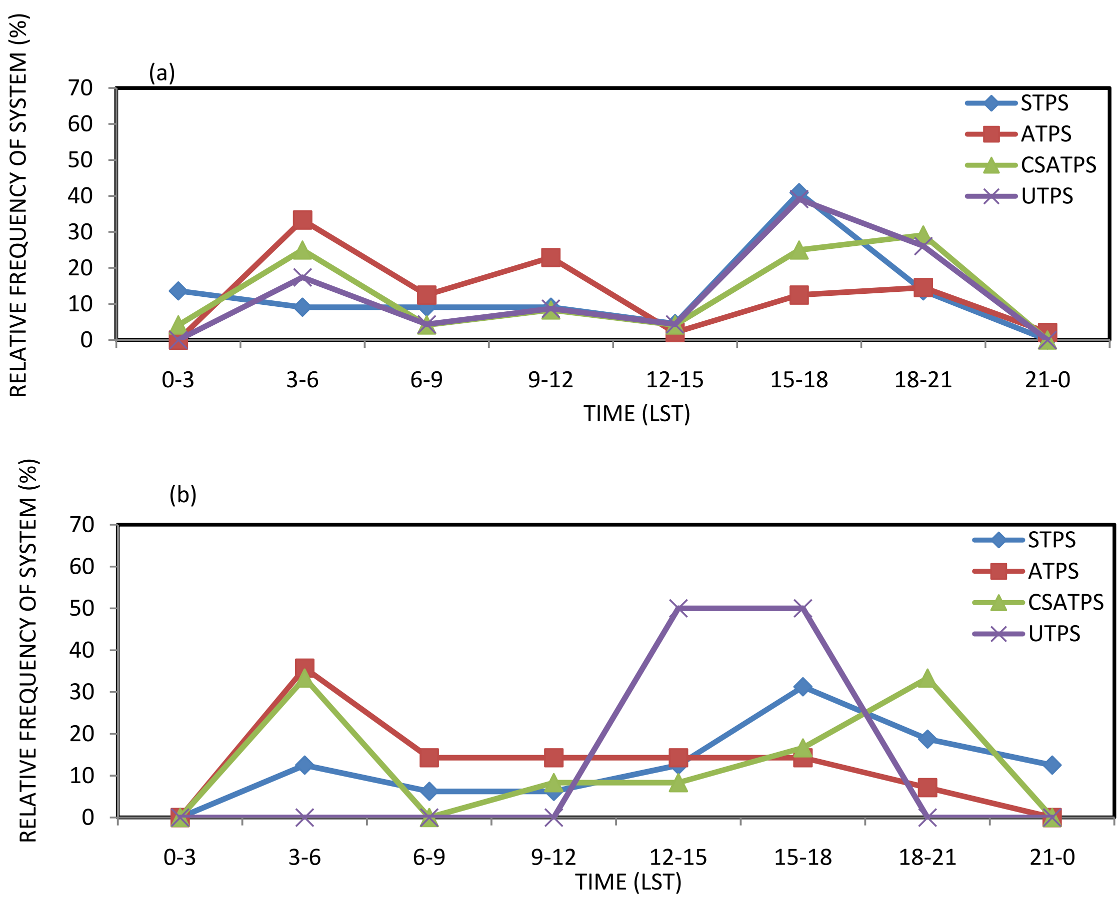



Figure 4.22. Diurnal variation of relative frequency of STPS, ATPS, CSATPS and UTPS at developing stage in different seasons: (a) pre-monsoon (b) monsoon. The total percentage of each type of systems is assumed to be 100%.

### 4.3.5.2 Mature stage

Figure 4.23 shows the diurnal variation of RFO of different type of arc systems at mature stage during pre-monsoon and monsoon period. During the pre-monsoon period, the maximum occurrence frequency of STPS, ATPS, CSATPS and UTPS is found at 15-18 LST, 03-06 LST, 18-21 LST and 18-21 LST, respectively. During the monsoon, the STPS shows the peak at 18-21 LST, while the CSATPS shows the peak at 03-09 LST. The ATPS shows the peak at 03-06 LST same as pre-monsoon. The UTPS shows the peak at 15-21 LST.

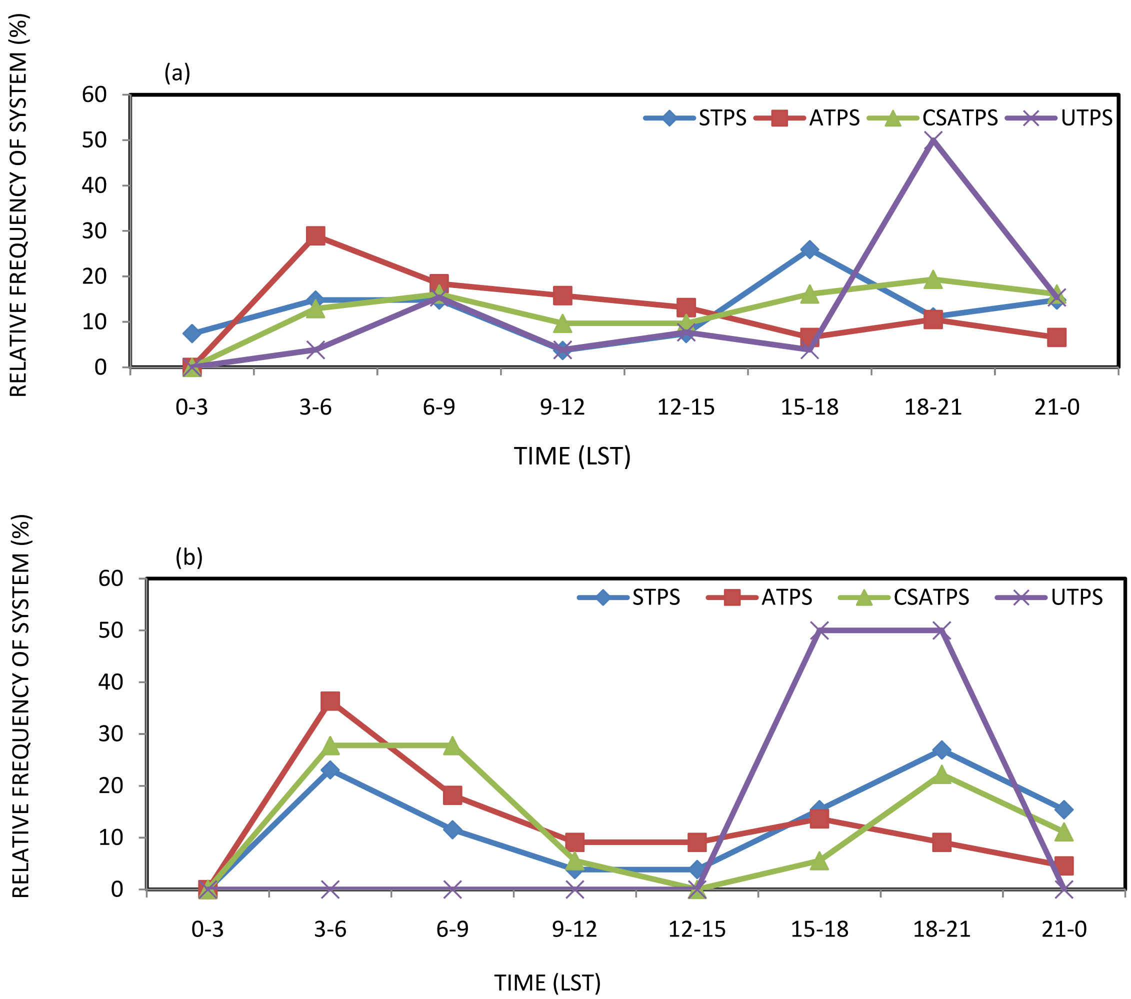



Figure 4.23. Diurnal variation of relative frequency of STPS, ATPS, CSATPS and UTPS at mature stage during different seasons: (a) pre-monsoon (b) monsoon. The total percentage of each type of systems is assumed to be 100%.

### 4.3.6 Diurnal variation of STPS, ATPS, CSATPS, and UTPS at developing and mature stage

Figure 4.24, shows the diurnal variation of different arc type systems at developing and mature stage are observed over the study period from 2000-2005. At developing stage, the maximum occurrence frequency of STPS, ATPS, CSATPS and UTPS is found at 15-18 LST, 03-06 LST, 18-21 LST and 15-18 LST, respectively. At the mature stage, the maximum occurrence frequency of STPS, ATPS, CSATPS and UTPS is found at 15-18 LST, 03-06 LST, 18-21 LST and 18-21 LST, respectively. The CSATPS shows another maximum peak at 06-09 LST.

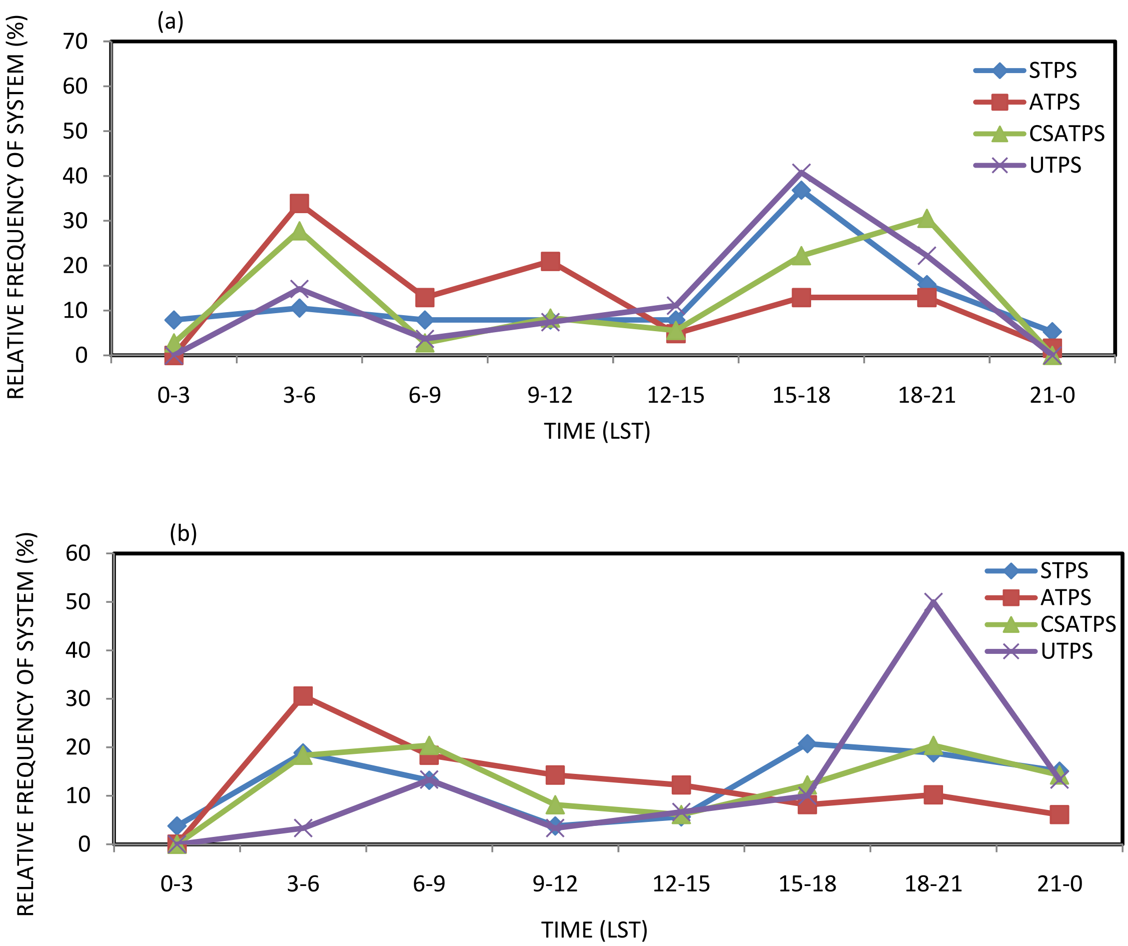



Figure 4.24. Diurnal variation of relative frequency of STPS, ATPS, CSATPS and UTPS during study period (pre-monsoon to monsoon): (a) developing stage and mature stage. The total percentage of each type of systems is assumed to be 100%.

## 4.4 Quantitative analysis of the symmetric and asymmetric types systems

Two cases have been selected for detail quantitative analysis between radar retrieve hourly rainfall and rain-gauge rainfall.

### 4.4.1 Case Study 1: Symmetric type precipitation system, 20 and 21 May 2003

Figure 4.25 shows examples of radar retrieve rainfall of a symmetric type precipitation system on 20 and 21 May 2003. The lifetime, speed and length of this system is ~3 hour, 13 m/s and 372 km, respectively. The system propagates toward the southeast direction. The hourly rain rate (mm/h) is retrieved using equation (3). At a specific hour, rainfall is averaged from all PPI scans available in that hour; say for 22 LST, all PPI scans from 21.01 LST to 21.59 LST are used. The maximum hourly rainfall is observed more than 33 mm/h during the entire life cycle of the system. The maximum rainfall at 22 LST, 23 LST, and 00 LST is 14 mm/h, 33 mm/h and 14 mm/h, respectively (Figure 4.26). Fortunately, the continuous PPI scans are found for this system during mature to decaying stages but the developing stage is not found due to the lack PPI scans.

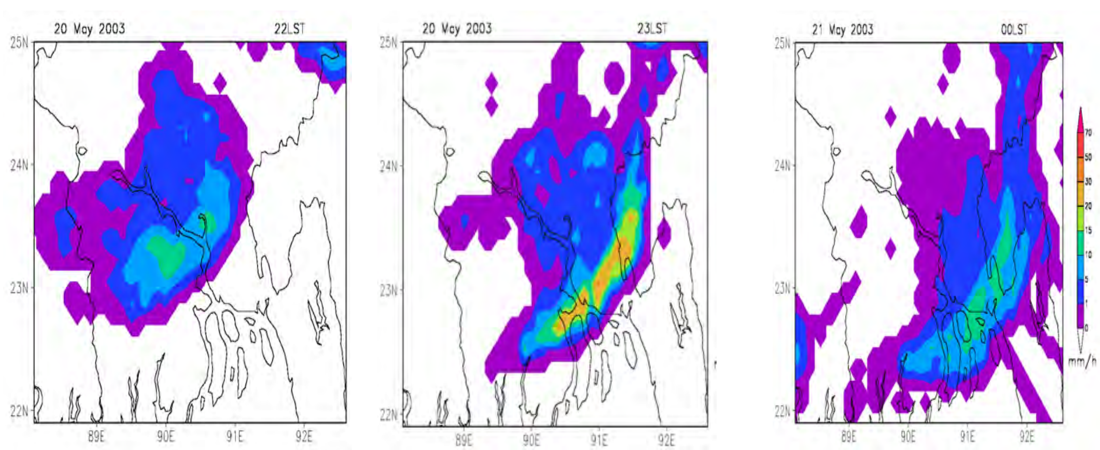



Figure 4.25. Example of the distribution of hourly rainfall (mm/h) at 22 LST and 23 LST of 20 May 2003, and 00 LST of 21 May 2003.

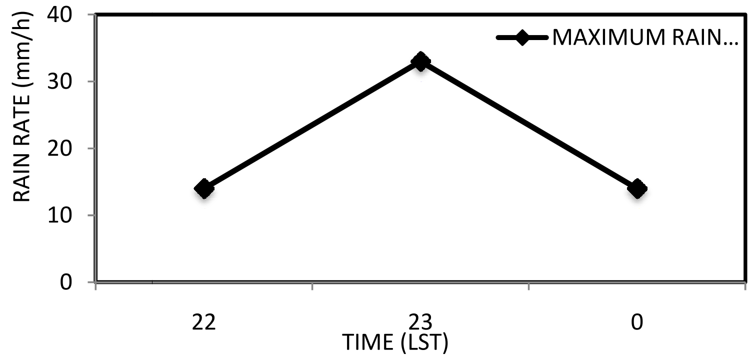



Figure 4.26. Maximum rain rate at 22 LST and 23 LST of 20 May 2003, and 00 LST of 21 May 2003.

Figure 4.27 shows the comparison between the radar retrieve rainfall and rain gauge rainfall for 23 stations at 00 LST on 21 May 2003. The radar retrieve hourly rainfall is obtained from a 10 km x 10 km grid box at each rain gauge location. Figure shows the amount of radar retrieve rainfall and rain gauge observed rainfall is not similar at different stations. As for example, the rainfall 7 mm/h is observed by rain gauge at Bogra station but radar shows 0 mm/h at same location, *vice versa*.

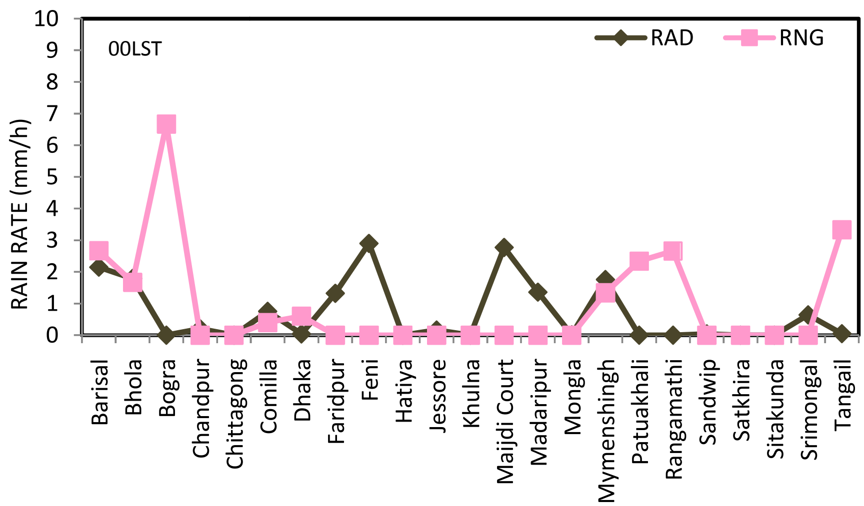



Figure 4.27. Radar (RAD) retrieved rainfall and rain gauge (RNG) rainfall at 23 stations on 00 LST 21 May 2003 over Bangladesh.

### 4.4.2 Case Study 2: Asymmetric type precipitation system, 23 April 2004

Figure 4.28 shows an example of radar retrieve rainfall of asymmetric type precipitation system on 23 April 2004. The lifetime, speed and length of this system are ~9.5hours, 14 m/s and 263 km, respectively. The system propagates toward the southeast direction. The hourly rain rate (mm/h) is retrieved using equation (3). At a specific hour, rainfall is averaged from all PPI scans available in that hour; say for 06 LST, all PPI scans from 05 LST to 5.59 LST are used. The maximum hourly rainfall is observed more than 30 mm/h during the entire life cycle of the system. The maximum rainfall at 06, 09, 12, and 15LST are 20 mm/h, 27 mm/h, 14 mm/h, and 30 mm/h (Figure 4.29).

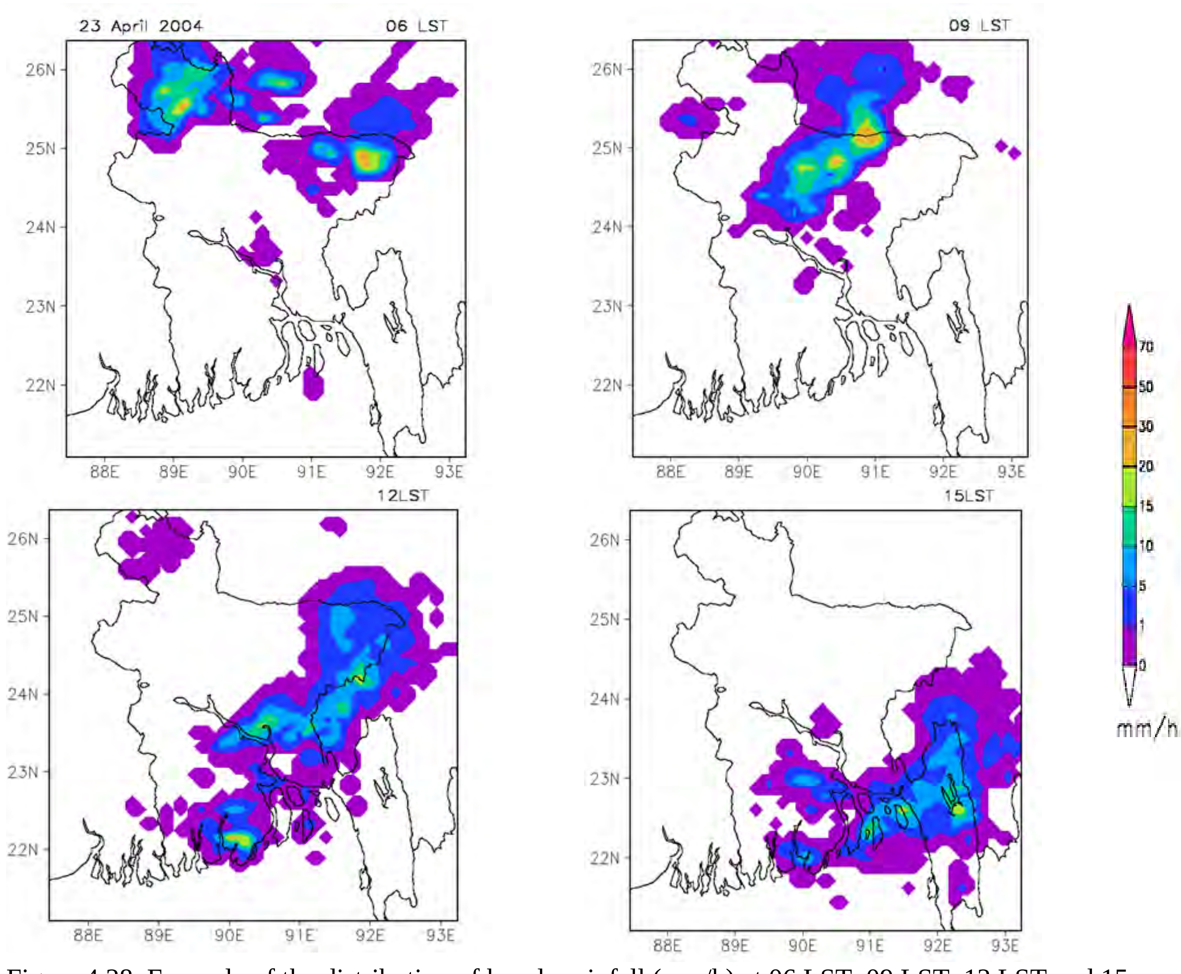



Figure 4.28. Example of the distribution of hourly rainfall (mm/h) at 06 LST, 09 LST, 12 LST and 15 LST on 23 April 2004.

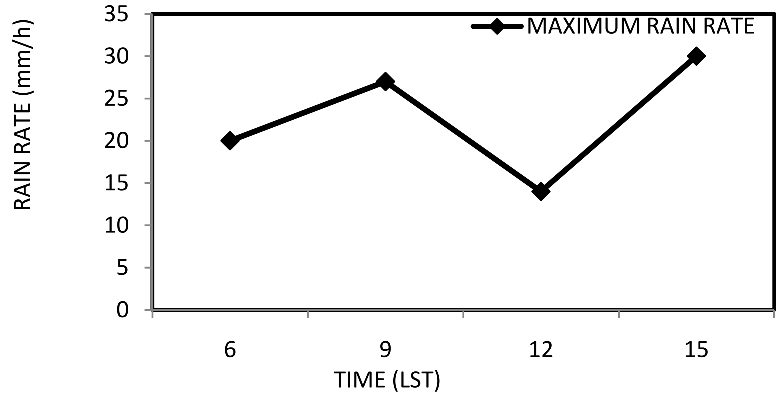



Figure 4.29. Maximum rain rate at 06, 09, 12, and 15 LST on 23 April 2003.

Figure 4.30 shows the comparison of the radar retrieve rainfall obtained from radar & rain gauge for 33 stations on 23 April 2004 at different hour. The radar retrieve hourly rainfall is obtained from a 10 km x 10 km grid box at each rain gauge location. Figure shows the amount of radar retrieve rainfall and rain gauge observed rainfall is not similar at different stations. As for example, the rainfall 17 mm/h is observed by rain gauge at Dhaka station but radar shows 0 mm/h at same location, and *vice versa*.

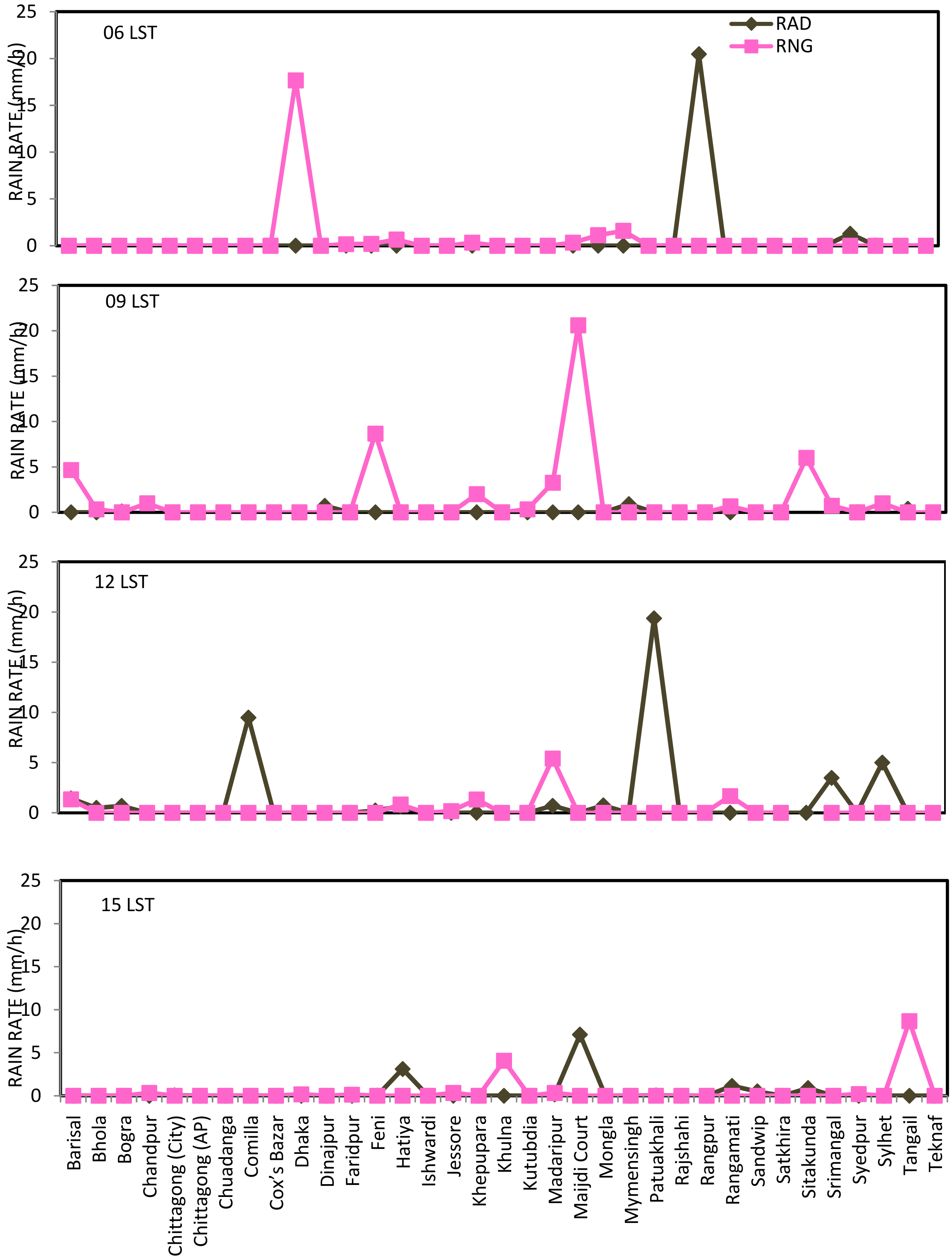



Figure 4.30. Radar (RAD) retrieved rainfall and rain gauge (RNG) rainfall at 33 stations on 23 April 2004 over Bangladesh at different hour: (a) 05 LST (b) 09 LST (c) 12 LST and (d) 15 LST.

# Chapter Five

# Discussion

## 5.1 Regional appearance of mesoscale precipitation systems

The regional variation of mesoscale precipitation systems is analyzed that developed in and around Bangladesh. As explained in subsection 4.1.1, during the pre-monsoon season, the arc, line and scattered types systems are dominant in northwest and northeast quadrants. The pre-monsoon is the transition period from the winter monsoon to summer monsoon circulations. The insolation is very intense which helps to develop a heat low over the subcontinent. Bangladesh and its adjoining regions are under the influence of a low-pressure system (or extended trough of low pressure). The subtropical seasonal high shifts to the Bay of Bengal during this period. In general, the low level winds are southerly or southwesterly which lead to a well marked shallow inflow of moisture from the Bay of Bengal into the Bangladesh, while in the mid upper troposphere a moderate to strong westerly flow, often associated with westerly jet, continuous over the northeastern parts of Indian subcontinent (Bangladesh) (Weston 1972 and Lohar and Pal 1995). Sanderson and Ahmed (1979) also noted that during the pre-monsoon, the mountains around northeastern Bangladesh cause orographic uplifting and conventional overturning of low-level moist air from the Bay of Bengal. The mentioned conditions of northeastern part of Bangladesh may be enhanced the systems population in that region.

As explained in subsection 4.1.2, during the monsoon season the arc and line types systems dominant in northwest quadrant and scattered type in the northeast and southeast quadrants. During monsoon period, Ohsawa et al. (2000) mention that rainfall increases when the monsoon trough is located at the foot of the Himalayas, because synoptic-scale convective activity is much more vigorous to the south of the monsoon trough axis than to the north of it. In addition, the strong southwesterly wind to the south of the monsoon trough intensifies local convective activity owing to the effects of the orography to the north and east of Bangladesh.

## 5.2 Characteristics of different arc type precipitation systems

In this study, the dominating 230 arc type precipitation systems are examined during the analysis period (2000-2005). As explained in subsection 4.2 arc type precipitation systems are classified as STPS, ATPS, CSATPS, and UTPS. Within classifiable systems, the occurrence frequency of STPS, ATPS, and CSATPS is 27%, 49%, and 24%, respectively. These results differ with Houze et al., (1990), who studied the 63 MCS from Oklahoma city and found approximately two by third is classifiable and remaining unclassifiable. Within the classified systems, they found 26%, 35% and 38% is symmetric, asymmetric, and intermediate combination of symmetric and asymmetric, respectively. From the above results, it is clear that ATPS is dominated in and around Bangladesh whereas intermediate combination of symmetric and asymmetric type systems is dominated in the Oklahoma (mid latitude).

In this analysis, it is observed that the occurrence frequency of ATPS is dominant (48%) in pre-monsoon season and STPS is dominant (38%) in monsoon season (Figure 5.1). The genesis mechanism of ATPS is due to the interaction between moisture and warm air in presence of strong vertical wind shear (Maddox and Doswell 1982, Madden 1983, Houze et al., 1990, Brandes 1990, Trier and Parsons 1993). In and around Bangladesh during the pre-monsoon period, the average low-level wind is southwesterly or southerly and mid-level wind is strong westerly or northwesterly (Figure 6.1 (a, b)). The vertical wind shear is strong between the low-level and mid-level (Figure 6.1 (a, b)). These environmental conditions are helped for the development of ATPS during pre-monsoon period. From climate condition of Bangladesh, it is well known that precipitation system is usually associated with intense convective thunderstorm in pre-monsoon. Severe weather form of hail and tornadoes is more common with asymmetric systems, in which new cell formation is preferred on one (typically south) end of the line, and decaying cells accompanied by a larger stratiform region are found in other end (Jewett et al., 1998). Houze et al., (1990) mentioned that STPS is organized in an environment of weak low to mid tropospheric shear with low-level jet. During the monsoon period, the average low-level wind is strong southerly or southwesterly and the mid-level wind is southerly or southwesterly and the vertical wind shear is very small (Figure 6.2 (d, e)). These monsoonal environmental conditions enhanced the development of STPS during monsoon period. The horizontal structure of STPS is an important factor in determining the distribution of rainfall and the possibility of flooding. All other things being equal, locations receiving both stratiform and convective rainfall have a greater risk of flooding than a location receiving only stratiform or convective rainfall (Deswell et al. 1996). The characteristics of ATPS and STPS is help to produce gusty wind, damaging hail and tornadoes, and heavy rainfall (flash flood) in Bangladesh during pre-monsoon and monsoon periods, respectively.

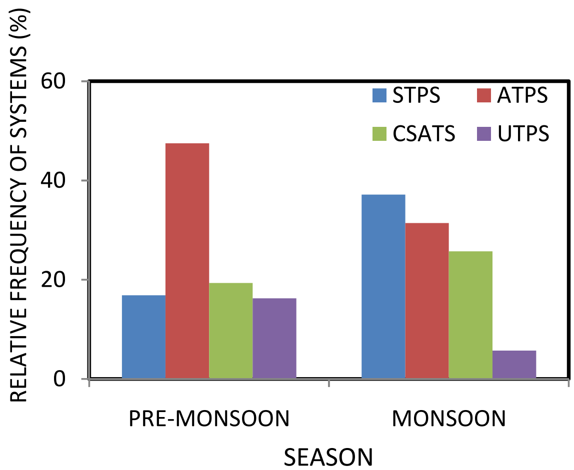



Figure 5.1. Seasonal variation of different arc type systems. The total percentage of the four patterns is assumed to be 100% for each season.

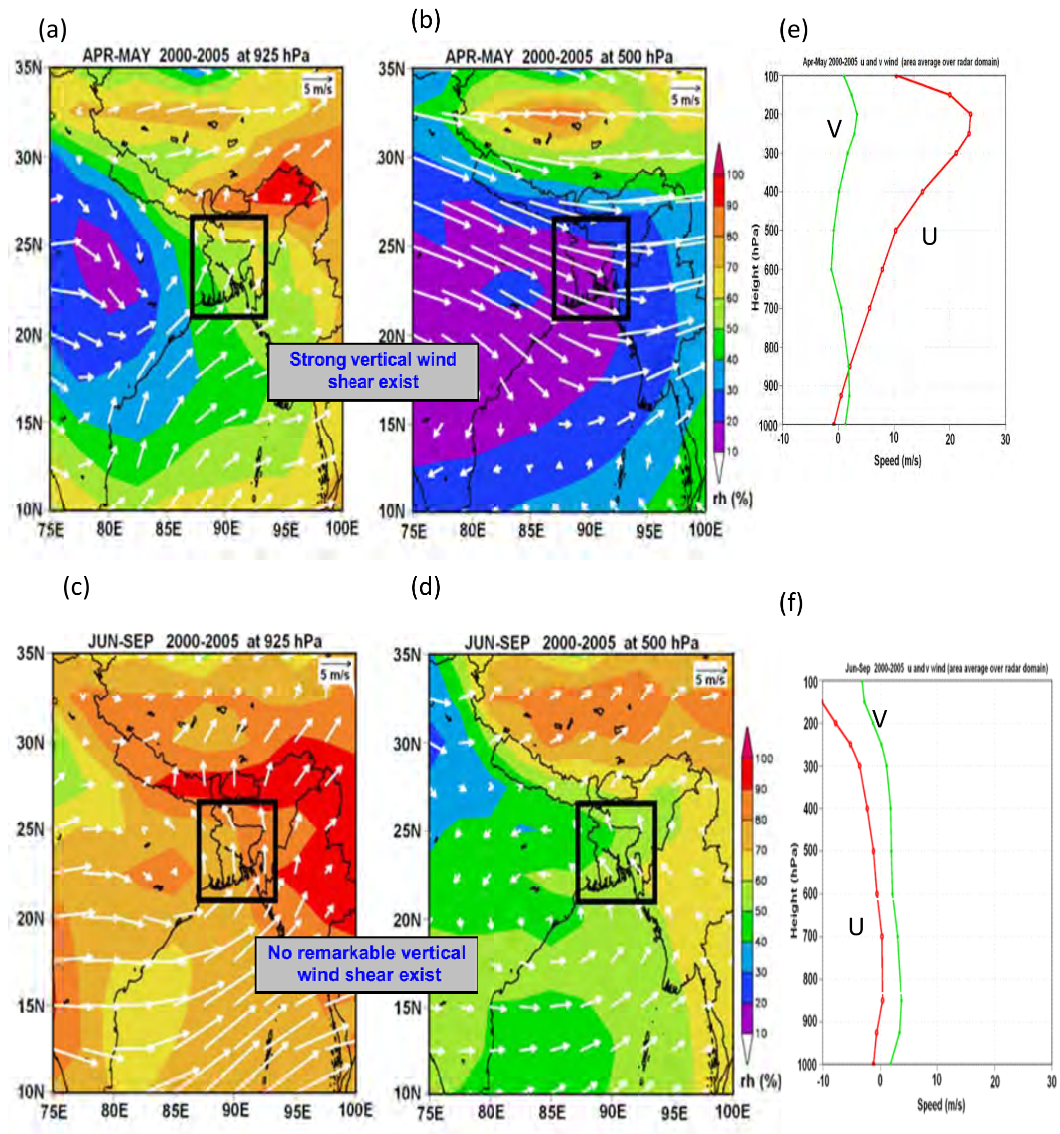



Figure 5.2. Average seasonal variation of relative humidity (color shading) and wind field (arrow) for (a-b) pre-monsoon and (c-d) monsoon periods at 925 and 500 hPa levels.

## 5.3 Monthly variation of different arc types precipitation systems

As explained, in subsection 4.2.9, systems population is found higher in 2002 compared to the other years. The contribution of July 2002 is particularly high (Figure 4.9 (c) Figure 4.11 (c )). El Nino Southern Oscillation occurred in 2002 (NOAA 2000), accordingly, environmental condition differed from other years, favoring the development of STPS and CSTAS (Figure 4.1and Figure 4.3) in 2002. The presence of a weak low-level jet and penetration of strong mid-latitude westerlies (Kalsi et al., 2006) in July may help to promote the STPS and CSTAS.

## 5.4 Diurnal variation of MCS

As explained in the subsection 4.3.2 and 4.3.3, the diurnal variation of precipitation systems in pre-monsoon period showed maximum peak at 03-06 LST and secondary peak at 18-21 LST. The diurnal variation of precipitation systems in monsoon period showed secondary peak at 03-06 LST with a maximum peak at 12-15 LST.

The diurnal variation of total all types of precipitation systems during 2000-2005 (from April to September) showed the double peaks: maximum peak at 03-06 LST and secondary maximum at 12-15 LST. These results are consistence with the results of Islam et al. (2004) who analyzed rainfall amount over Bangladesh and showed that the pre-monsoon and monsoon rainfall is dominant at 06 LST and 15 LST, respectively. The morning maximum rainfalls at 03-06 LST in Bangladesh are different from that of the Indian subcontinent or of the mountain area where, generally maximum rainfall occur in the afternoon (Islam et al. 2004). Bangladesh is one of the places where maximum rainfall comes at morning (Ohsawa et at., 2001; Prasad, 1974).

## 5.5 Comparison between rain–gauge and radar rainfall

As mentioned in subsection 4.4, the radar retrieve rainfall and rain-gauge rainfall are different a particular station. The discrepancy between the rainfall estimation based on the BMD radar and rain-gauge systems is due to the flowing reasons: i) radar rainfall is estimated from the areal average of 100km$^2$ grid boxes, whereas rain gauge indicate point values; ii) there is inconsistency in the temporal and spatial averaging of the radar and rain gauge data; iii) rain status is calculated based on a single Z-R relationship, details of spatial variation in the precipitation in Bangladesh are discussed in Islam et. al. (2005a). It is also found that sometimes rain gauge cannot recognize the intense convection where radar data can detect (Islam et al., 2005b) and sometimes a few amount of rainfall collected by rain-gauge is evaporated in infrequently. Quantitative analysis is not possible using the existing BMD radar systems and convectional rain-gauge in Bangladesh.

# Chapter Six

## Summary and Conclusions

Regional variation of mesoscale precipitation systems is analyzed in and around Bangladesh using six-year (2000-2005) radar data. The data were obtained from the BMD. Over the study period, regional analysis revealed that the arc, line and scattered types precipitation systems are dominant in northwest and northeast quadrant during the pre-monsoon period. The interaction between moist, warm air from the Bay of Bengal and dry air from India at northwest parts and the orography of northeastern part of Bangladesh enhanced to develop the systems in that region during pre-monsoon period. In monsoon, the arc and line type precipitation systems are dominant in northwest quadrant and scattered type precipitation systems is dominant in southeast quadrant. During the monsoon period, the system is usually associated with the occurrence of monsoonal depressions, low pressure systems and cyclonic circulation.

There are 230 arc type precipitation systems are indentified during the study period and are classified into STPS, ATPS, CSATPS and UTPS. During the analysis period, the occurrence frequency of STPS, ATPS, CSATPS and UTPS is 23%, 43%, 21% and 13%, respectively. Seasonal analysis showed that the ATPS and STPS is dominant in pre-monsoon and monsoon period, respectively. During the pre-monsoon period, the ATPS develop through interaction with moisture and warm air presence of strong vertical wind shear between the low levels southwesterly or southerly wind and mid level strong westerly or northwesterly wind. During the monsoon period, the STPS associated with the environment of small vertical wind shear which is developed interaction between the low level strong southerly or southwesterly wind and mid level southerly and southwesterly wind.

Regional analysis of different arc type systems indicate that at the mature stage of their life cycle, STPS, ATPS, and CSATPS is dominated in southwest (northwest), northeast (southeast) and northwest (northwest) quadrants during pre-monsoon (monsoon) period. The maximum occurrence frequency of UTPS is found in the northeast and southwest quadrant during pre-monsoon and in the southwest quadrant during the monsoon season.

The statistical analysis of diurnal variation of different types of precipitation systems suggests that the most likely time of maximum occurrence of arc, line and scattered type precipitation systems dominant at 18-21 LST (03-06 LST), 15-18 LST (03-06 LST), and 03-06 LST (12-15 LST) during the pre-monsoon (monsoon) period, respectively. The secondary maximum of arc, line and scattered type systems is found at 03-06 LST (03-06 LST), 06-09/21-00 LST (15-18 LST) and 06-09 LST (03-06) during pre-monsoon (monsoon) period, respectively. Since the different types of precipitation system show the different peak but in total the occurrence frequency of all types of precipitation systems show the double peaks: maximum at 03-06 LST and secondary maximum at 12-15 LST. This double peak may be link to the solar heating of the surface, local effects such as complex terrain and sea breeze circulation, or the long nocturnal life cycle of mesoscale convective systems. The diurnal variation of STPS, ATPS, CSATPS and UTPS systems show that the maximum occurrence frequency is observed at 15-28 LST (15-18 LST), 03-06 LST (03-06 LST), 18-21 LST (03-06 LST) and 15-18 LST (12-18 LST) during pre-monsoon (monsoon) period.

In addition, analyzed case studies suggest that the quantitative analysis is not possible with the existing radar data and conventional rain-gauge rainfall. In future, if the continuous reflectivity data are available from the radar observation, it may be possible to make the quantitative analysis between the radar data and conventional rain-gauge rainfall data.

# References


Agustine JA and Howard KW, 1988: Mesoscale convective complexes over the United States during 1985. Mon Wea. Rev. 116: 685-701.

Aragao SMR, Correia MF, Araujo HA, 2000: Characteristics of C-band meteorological radar echoes at Petrolina, northeast Brazil. International Journal of Climatology 20: 279-298.

Bluestein HB, Jain MH, 1985: Formation of mesoscale lines of precipitation: Severe squall lines in Oklahoma during the spring. J. Atmos. Sci. **42:** 1711–1732.

Bluestein HB, Parks CR, 1983: Synoptic and photographic climatology of low precipitation severe thunderstorms in the southern plains. Mon. Wea. Rev. **111:** 2034–2046.

Bowring BR, 1996: Total inverse solutions for the geodesic and great ellipetic. Survey Review 33 (261): 461-476.

Brandes EA, 1990: Evaluation and structure of the 6-7 May 1985 mesoscale convective systems and associated vortex. Mon. Wea. Rev. 118: 109-197.

Chouwdhury MAM and De UK, 1995: Pre-monsoon thunderstorm activity over Bangladesh from 1983 to 1992. TAO. 6(4): 591-606.

Cotton WR, Lin MS, McAnelly RL and Tremback CJ, 1989: A composite model of mesoscale convective complexes. Mon. Wea. Rev. 117: 765-783.

Das PK, 1995: The monsoons: 3$^{rd}$ edn. Natinal Book Trust , published by the Director: New Delhi

Doswell CA III, Brooks HE, and Maddox RA, 1996: Flash flood forcasting: An ingredients based methodoKalsilogy . Wea. Forcasting . 11: 560-581.

Doswell CA, III, Brooks HE and Maddox RA, 1996: Flash Flood Forecasting : An ingredients-based methodology. Wea. Forcasting . 11: 560-581.

Fujita T, 1955: Results of detailed synoptic studies of squall lines. Tellus. 7: 405-436.

Goldar RN, Banerjee SK, Debnath GC, 2001: Tornado in India and neighborhood and its predictability. Sci. Rep. 2/2001, 21 pp, Indian Meteorol. Dep, Pune, India.

Goswami BN, Krishnamurthy V and Annamalai H, 1999: A broad-scale circulation index for the interannual variability of the Indian summer monsoon. Quart. J. Roy. Meteor. Soc. 125B: 611–633.

Hane CE, 1986: Extratropical squall lines and rainbands. Mesoscale Meteorology and Forecasting, Ray, P., Ed., Amer. Meteor. Soc., 359-389.

Houze RA, 2004: Mesoscale convective systems. Reviews of Geophysics. 42: 1-43.

Houze RA. Jr, 1993; Cloud dynamics. Academic Press, 573pp.

Houze RA. Jr, Smull BF, Dodge P, 1990: Mesoscale organization of springtime rain storms in Oklahoma. Mon. Wea. Rev. 118: 613-654.

Houze RA. Jr, 1997: Structure and dynamics of a tropical squall-line system. Mon. Wea. Rev. 105: 1540-1567.

Islam M. Nazrul, Ugeda H, Kikuchi K. 1998: Convective and stateroom component of tropical cloud clusters in determining radar adjusted satellite rainfall during the TOGA-COARE IOP, j. Fac. Sci. Hokkaido Uni. Japan, ser VII. II (1): 265-200.

Islam MN, Hayashi T, Terao T, Uyeda H, KiKuchi K, 2005a: Charecteristics of precipitation system analyzed from radar data over Bangaldesh, Journal of Natural Disaster Science. 27(1): 17-23.

Islam MN, Hayashi T, Uyeda H, Terao T, Kikuchi K, 2004: Diurnal variations of cloud activity in Bangladesh and north of the Bay of Bengal in 2000. Remote Sensing of Environment **90**: 378–388, DOI:10.1016/j.rse.2004.01.011.

Islam MN, Terao T, Uyeda H, Hayashi T, Kikuchi K, 2005b: Spatial and Temporal Variations of Precipitation in and around Bangladesh, Journal of the Meteorological Society Japan. 83(1): 23-41.

Islam MN, Uyeda H, 2007. Use of TRMM in determine the climatic charecteristics of all over Bangladesh. Remote sensing of Environment. 108: 264-274, DOI: 10.1016/j.rse2006.11.001.

Islam MN, Uyeda H, Takahashi N, Kikuchi O and Kikuchi K, 1994.” Behavior of sub-system of cloud clusters in the tropics during the TOGA-COARE IOP, pre-prints: conference of Met. Soc. Japan. 40: 50-51.

Israel LJ, Cotton WR and McAnelly RL, 2003: Sattelite and radar survey of mesoscale convective systems development. Mon. Wrea. Rev. 131: 2428-2449.

Jewett, BF and Wilhelmson RB, 1998: Numerical study of back building squall line. Preceding of 19th conference on severe local storms, Minneapolis, Minnesota , USA , 371-372.

Joseph PV, 1982: A tentative model for Aandi . MAUSUM. 33.417.

Kadalgaokar SS, Tinmaker MIR, Kulkami MK and Nath A, 2002: Thunderstrom activity and sea surface temperature over the Islam stations and along the east and west coast of India. MAUSAM. 53, 245.

Kalney E, co-authors (many), 1996: The NCEP/ NCAR 40 years reanalysis project. Bull. Amer. Meteor. Soc. 77: 437-471.

Kalsi SR, Jenamani RK, Hatwar HR, 2006: Meteorology features associated with project Bull Amer. Meteor Soc. 77: 437-471.

Karmakar S, Alam MM, 2005: On the Sensible heat energy, latent heat energy & potential energy of the trosphere over Dhaka before the occurence of Norwester in Bangladesh during the pre-monsoon season. Mausam. 56: 671-680.

Kawasima M, Tsuboki K and Asai T, 1995: Miantenance mechanism and thermodynanics of a Baiu frontal rainband. J. Metor. Soc Japan. 73: 717-735.

Kirsnamurthy V, 1965: A statistical study of thunderstorm over Poona. Indian J. Meteorol. Geophys, 16, 484

Koteswaran Pand Srinivasan V, 1058: Thunderstrom over Gangatic West Bengal in the pre-monsoon season and the synoptic factors favorable for their formation. Indian .J. Meteorol. Geophys. 09, 301.

Kummerow C, Simpson J, Thiele O, Barnes W, Chang ATC, Stocker E, Adler RF, Hou A, Kakar R, Wentz F, Ashcroft P, Kozu T, Hong Y, Okamoto K, Iguchi T, Kuroiwa H, Im E., Haddad Z, Huffman G, Ferrier G, Olson WS, Zipser E, Smith EA, Wilheit TT, North G, Krishnamurti T, Nakamura K, 2000; The Status of the Tropical Rainfall Measuring Mission (TRMM) after Two Years in Orbit, J. Appl. Meteor., 39, 1965–1982.

Leary CA and Rappaport EN, 1987: The life cycle and internal structure of a Mesoscale Convective Complexes. Mon. Weath Rev, 115: 1503- 1527.

Ligda MGH, 1951: Radar storm observation. Compendium of Meteorology. TF. Malone, Ed. Amer. Meteor. Soc. 1265-1282

Litta AJ and Mohanty MC, 2008: Simulation of a severe thunderstorm event during the field experiment of STROM programme 2006, using WRF-NMM model. Current sience. 95(2): 204-215

Lohar D and Pal B , 1995: The effect of irrigation on pre-monsoon season precipitation over the west Bengal . India J. Climate. 8: 2567-2570.

Machaddo LAT and Rossow WB, 1993: Structural characteristics and Radioactive properties of cloud clusters". Mon. Wea. Rev., 121. 324-3261.

Maddox RA and Doswell CA III, 1982: An examination of jet stream configurations, 500-mb vorticity advection and low level thermal advection patterns during extended periods of intense convection . Mon. Wea. Rev. 110: 184-197.

Maddox RA, 1983: Large-scale meteorological conditions associated with midlatitude mesoscale convective complexes. Mon. wea. Rev. 111: 1475-1493.

Maddox RA, Roger DM and Howar KW, 1982: Mesoscale convective complexes over the United States during 1981-An annual summary. Mon. Wea. Rev. 110: 1510-1514.

Maddox RA. 1980: Mesoscale convective complexes. Bull. Amer. Meteor. Soc. 61:1374-1387.

Manhor GK, Kandalgaokar SS and Tinmaker MIR, 1999: Thu derstrom activity in Indian and Indian southwest monsoon. J. Geophys. Res. 104, 4169.

McGaughey, G., and E.J. Zipser, 1996: **Passive** microwave observations of the stratiform regions of two tropical oceanic mesoscale convective systems. J. Appl. Meteor., 35, in press.,

McGaughey, G., E.J. Zipser, R.W. Spencer, and R.E. Hood, 1996: High resolution passive microwave observations of convective systems over the tropical Pacific ocean. J. Appl. Meteor., 35, in press. Sci. 43, 1559—1573..

National Weather Service (21 April 2005). "Weather Glossary - T". National Oceanic and Atmospheric Administration. Retrieved 2006-08-23.

Newton CW, 1950: Structure and mechanism of the pre-frontal squall line. J. Meteor. 7: 210-222.

Newton CW. Newton HR, 1959: Dynamic interactions between large convective clouds and environments with vertical shear. J. Meteor. 16: 483-496.

Ohsawata T, Hayashi T, Mitsuta Y, Matsumoto J, 2000: Intra-seasonal variation of monsoon activities associated with the rainfall over Bangladesh during the 1995 summer monsoon season. J. Geophy. Res. 105(D24): 29445-29459.

Ohsawata T, Ueda H, Hayashi T, Watanabe A, Matsamoto J, 2001: Diurnal variations of convective activity and rainfall in tropical Asia. J. Meteor. Soc. Japan,, 79:333-352.

Parker MD and Jonson RH, 2000: Ordanizational modes of midlatitude mesoscale convective systems. Mon. Weather Rev. 128: 3413-3436.

Pedgley DE, 1962: A Meso-Synoptic Analysis of the Thunderstorms of 28 August1958. Geophysical Memoirs. Vol.14. Brit. Meteor. Office. 74 pp.

Peterson RE and Metha KC, 1981: Climatology of tornadoes of India and Bangladesh. Arch. Met. Geoph. Biokl. Ser. B. 29: 345-356.

Peterson RE, Mehta KC, 1995: Tornadoes of the Indian subcontinent. $9^{th}$ International Conference on Wind Engineering, Int. Assoc. of Wind Eng., New Delhi, India.

Prasad B , 1974: Diurnal variation of rainfall in Brahmaputra Valley. Indian Journal of Meteorology and Geophysics. 25: 245-250

Rafiuddin M, Uyeda H, Islam MN, 2010: Characteristics of monsoon precipitation systems in and around Bangladesh, International Journal of Climatology. 30: 1024-1055. DOI:10.1002/joc.1949.

Rahman R, Islam N and Alam S, 1997 "Application of remote sensing technology to rainfall forcasting". Final report, Japan Bangladesh joint society report, BUET, Dhaka.

Raman PK and Raghaven K, 1961: Diurnal variation of thunderstorm in India in different seasons. Indian J. Meteorol. Geophys. 12, 115-130.

Rao KN and Raman PK, 1961: Frequency of days of thunder in India. Indian J. Meteorol. Geophys., 16, 103-108.

Roy SN, Balling RC Jr, 2007: Diurnal variations in summer season precipitation in India. Int. J. Climatol., 27: 969-976. DOI: 10.1002/joc. 1458

Sanders E, Emanul KA, 1977: The momentum budget and temporal evolution of a mesoscale convective system. J. Atmos. Sci. 34: 322-330.

Sanders F, Paine RJ, 1975: Structure and thermodynamics of an intense mesoscale convective storm in Oklahoma. J. Atmos. Sci. 32: 1563-1579.

Sanderson M and Ahmed R, 1979: Pre-monsoon rainfall and its variability in Bangladesh : a trend surface analysis. Hydrological Sciences Bulletin des Sciences Hydrologiques. 24(3): 277-287.

Sikka DR, Gadgil S, 1980. On the maximum cloud zone and the ITCZ over India longitude during the Southwest monsoon. Mon.Weather Rev. 108:1840–53.

Smull BF, Houze RA, Jr. 1985: Amidlatitude squall line with a trailing region of stratiform rain: radar and satellite observations. Mon. Wea. Rev., 113:117-133.

Trier SB and Parson DB, 1993: Evalution of environmental conditions preceding the development of a nocturnal mesoscale convective complex. Mon. Wea. Rev. 121: 1078-1098.

TRMM report, 2002: Rain as seen from space, Edited by "rain as seen from space" production committee, published by Japan Advanced plan co., Inc. First edition, 31 May 2002.

Vishwanathan TR and Faria JF, 1962: Climatological study of thunderstorm at Bombay airport. Indian J. Meteorol. Geophys. 13. 377.

Wahid CM and Islam MN, 1999: Patterns of rainfall in the northern part of Bangladesh. Bang. J. Sci. Res., 17 (1): 115-120.

Wahid CM, Rahman R and Islam MN. 1999: Single cell and multi cell clouds analyzed with satellite data in and around Bangladesh, MAUSAM. 50(20): 177-180.

Weston KJ, 1972: The dry line of northern India and its role in cumulonimbus convection. Quart JR Met. Soc . 98: 519-531

Yamane Y, Hayashi T, 2006: Evaluation of environmental conditions for the formation of severe local storms across the Indian subcontinent. Geophys. Res. Lett. 33: L17806. doi: 10.1029/2006GL026823.

Zipser EJ, 1977: Mesoscale and of convective downdrafts as distinct components of squall line circulation. Mon. Wea. Rev. 105: 1568-1589.

Zipser KA, 1982: Use of a conceptual model of the life cycle of mesoscale convective systems to improve very-short- range forecasts. Nowcasting K Browing Ed. Academic press, 191-204.