An Investigation of High Resolution Spatio–Temporal Variation of Morphological, Microphysical and Rainfall Properties of Precipitating Systems and its Social Impact: An Integrated Multi Sensor and Multi Institutional Approach

A study under the Research, Innovation & Quality Improvement (RI & QI) component of RUSA

An Annual Progress Report (2016) Submitted by the Leading Institution:

Kohima Science College, Jotsoma, Nagaland, 797002, INDIA

An investigation of high resolution spatio –temporal variation of morphological, microphysical and rainfall properties of precipitating systems and its social impact: An integrated multi sensor and multi institutional approach

Project Progress Report

1st Year (2016)

Submitted to

Ministry of Human Resource Development

(Higher Education)

Rashtriya Uchchatar Shiksha Abhiyan (RUSA)

By

Kohima Science College, Jotsoma,

Kohima, Nagaland, 797002

(The Lead Institution)

Content

Preface

The project entitled "An investigation of high resolution spatio–temporal variation of morphological, microphysical and rainfall properties of precipitating systems and its social impact: An integrated multi sensor and multi institutional approach" was approved in the 9th PAB meeting on 1st December 2015 with a total budget of Rs. 227.34 Lakhs. Kohima Science College an autonomous government post graduate college is a lead institute for the approved project. The main scientific objectives of the approved projects are (i) To study the spatial and temporal (seasonal and diurnal) variability of the morphological, microphysical and rainfall properties of the precipitating systems (ii) To study the extreme weather systems in terms of these properties and atmospheric energetic.(iii) To develop a comprehensive "Precipitation Features & Atmospheric Data Base" with the help of satellite and ground based observations and (iv). To study the social impact of weather related disasters and its socio –psychological response. A total amount of Rs. 113.67 Lakhs, including the state share has been received by the college. At the outset, an eight members expert committee was formed, with Prof. Animesh Maitra, Department of Electronics & Radio Physics, Calcutta University, Kolkata as a chairman. It was followed by appointment of three research scholars and one project assistant and nomination of nine associate members for the project. The formation of expert committee, appointment of project staff and nomination of associate members have government approval. The nominated associate members are faculty members of different government colleges and institutes within and outside Nagaland. The associate members are eligible for access to the data repository developed under the project. They are also eligible for sponsorship to participate in project related academic and research activities. During the last one year, a data repository consisting of satellite data over Indian subcontinent and adjoining ocean and ground reporting of thunderstorms, hail and lightning over north eastern region during 1998-2014 is developed. The data collection work is in progress. The data set is analyzed and a detail scientific progress report is presented along with the annual progress report. Significant spatiotemporal variation in the properties of convective systems is observed over the study region. Few scientific results are published in a reputed journal (*International Journal of Climatology*, a Journal of Royal Meteorological Society UK, published by Wiley International with a impact factor of 3.61). Work is in progress to prepare more manuscripts for submission to scientific journals. Five research papers are also presented in a regional and in a international conference. Project staff including the principal investigator have participated in various training programs. Five associate members of the project are sponsored to participate in a short term course entitled " Landslides and debris flow systems: Prediction, control and reclamation" under the Global Initiatives of Academic Network (GIAN) at Nagaland University Kohima during March 7th -11th, 2017. Two main stations, one at Kohima Science college, Kohima, Nagaland and other at Indian Statistical Institute, Giridih (Jharkhand) and twelve substations at various colleges in Nagaland are identified for placing the instruments. The work on installation of instruments at various locations is in progress. A mutual agreement is signed with Prof. Alexander G Keul, Environmental Psychology, Psychology Department, University of Salzburg, Austria to study the social impact of weather related disasters and its socio –psychological response. A set of questionnaires is developed for the analysis of socio –psychological response. A survey is in progress to collect the data in the state of Nagaland and west Bengal During the last one year, a total of Rs. 79.87 Lakhs have been utilized and balance amount is under commitment. On behalf of all the members of the project I would like to take the opportunity to present a detail progress report of the project. Looking forward for an enriching experience in coming years

Dr. Sanjay Sharma
Principal Investigator
RUSA (Research, Innovation & Quality Improvement) Project
Kohima Science College, Jotsoma, Kohima, Nagaland

General Information		
1	Title of the Project	An investigation of high resolution spatio – temporal variation of morphological, microphysical and rainfall properties of precipitating systems and its social impact: An integrated multi sensor and multi institutional approach
2	Name and address of the Institution	Kohima Science College, Jotsoma, Kohima, Nagaland, 797002 (Lead Institution)
3	Principle investigator with address	Dr. Sanjay Sharma Assistant Prof. (Sr.), Department of Physics Kohima Science College, Jotsoma, Nagaland, 797002
4	Staff under the project	1. Partha Roy (Research Scholar) 2. Rupraj Bishwasharma (Research Scholar) 3. Imolemba (Research Scholar) 4. Vitsiavi Nyuthe (Project Assistant)
5	Nominated Associate members	09 (Please refer Annexure I)
6	Nominated members of expert committee	8 members (Please refer Annexure II)
7	Duration of the project	Three Years
8	Starting date of the project	01-01-2016
9	Total outlay of the Project	Rs. 227.34 Lakhs
10	Amount Received	Rs. 113.67 Lakhs
11	Amount Utilized	Rs. 79.87 Lakhs
12	No of Publications.	01 (Annexure III A)
13.	Paper presented in the conferences.	05 (Annexure III B)
14.	Participation to short term courses/training programs	03 (Annexure III C)

Financial Status for 1st Year (2016)

Fund Received (Rs.) (lakhs)	Expenditure			Remark
	Head	**Item**	**Amount (Rs.) (lakhs)**	
`102.30 11.37	Equipment	• Parsivel Disdrometer (02 units) (Vendor: Sutron Hydromet Systems Pvt. Limited, New Delhi) • Automatic rain gauges (10 units) (Vendor: Sutron Hydromet Systems Pvt. Limited, New Delhi *One unit of Disdrometer and 09 units of rain gauges are delivered at Kohima. The one unit each of Disdrometer and rain gauge is yet to be delivered at Indian Statistical Institute Giridih, Jharkhand.*	19.00	Total 31.04 and balance of 12.04 lakhs to be utilized *(Order placed on Sep 26th, 2016)*
		Lightning detector Sensors (04 Unit) (Vendor : Dhruva Technologies Pvt. Ltd, New Delhi)	8.60	Total 14.10 and balance of 5.5 lakhs to be utilized *(Order placed on Oct 20th, 2016)*
		Micro Rain Radar Vendor: Electrotek International Inc, Chennai)	22.00	Utilized *(Order placed on Oct 20th, 2016)*
		Computers (work station, Laptops) , Printers, UPSs, Short Projectors	9.00	Utilized
	Salary	Three Research scholars and one project Assistant	9.28	Utilized
	Contingency	Travel, data download, Data collection, Stationary	5.45	Utilized
	Institutional Overhead	To the Host Institute	6.54	Utilized
113.67			**79.87**	**Balance amount to be utilized after installation of the instruments : Rs. 17.54 lakhs**

Outcome of Project for the 1st Year

Sl No	Progress	Action Taken
1	Physical Progress	• A government nominated expert committee for the review of the project is formed. • Three Research Scholars and one project Assistant are appointed. • 9 Associated members of the RUSA (RI &QI) project (faculty members from various Colleges/institute) are nominated. • After due process, order for the Instruments have been placed. Custom Duty Exemption (CDE) certificates for the imported instruments are provided to the vendors. • Multi institutional site selection for the installation of the instruments is completed.
2.	Scientific Progress	• Satellite data are down loaded TRMM satellite : 1998-2015 INSAT 3D satellite : 2014-2016 GPM satellite : 2014-2016 • Meteorological Data Hail and Lightning data from IMD* : 1998-2016 *IMD: India meteorological Department • Analysis of the satellite and other collected data is in progress (70 % of analysis is completed). • MOU is signed with the Prof. Alexander Keul Department of Environmental Psychology, Salzburg University, Salzburg, Austria. It resulted in the development of the questionnaires for the survey to asses the psychological response of the people to the severe weather (Please refer Annexure IV for the questionnaires) Survey has already started in Nagaland and West Bengal. In coming days survey will also start in the state of Assam (40% of the sample collection is completed). • One paper is accepted for publication in "International Journal of Climatology (IF:3.61) (A Journal of Royal Meteorological Society, Great Britain, published by Wiley international). • Total 05 papers are presented in the conferences. • Five associate members and one Project Assistant are sponsored to participate in a workshop in Nagaland University • Detail scientific progress report is submitted.

The Scientific Objectives of the Approved Project
(i) To study the spatial and temporal (seasonal and diurnal) variability of the morphological, microphysical and rainfall properties of the precipitating systems. **(ii) To study the extreme weather systems in terms of these properties and atmospheric energetic.** **(iii) To develop a comprehensive "Precipitation Features & Atmospheric Data Base" with the help of satellite and ground based observations.** **(iv). To study the social impact of weather related disasters and its socio –psychological response.**

Executive Summary of the Scientific Results

The basic objective of the presented report is to study the spatial and temporal (seasonal and diurnal) variation of the convective systems in association with the rainfall and hail during the premonsoon and monsoon seasons. The scientific report consists of three parts namely (i) Seasonal and intra-seasonal variation of rainfall contribution by different types of convective systems over the south Asian region (ii). Diurnal variation of the occurrence of convective systems over north eastern part of India and adjoining region (iii) Detection of Hail Features (HFs) by satellite onboard microwave sensors over the north eastern part of India. The study is carried out over the south Asian region in general with special reference to the north eastern part of India and its adjoining area. Broadly study area consists of Indian subcontinent and surrounding oceanic region namely Bay of Bengal, Arabian sea and Indian ocean. The study is carried out by using the space borne sensors on Tropical Rainfall Measuring Mission (TRMM) a polar orbit satellite. The observations from TRMM-Precipitation Radar (PR) and TRMM Microwave Imager (37 GHz channels) are utilized for the present study. The observations by the TRMM sensor are supplemented by the observations from INSAT -3D onboard infrared thermal sensors. To study seasonal change, the premonsoon (March-May) and monsoon (June-September) months are considered. To study intra-seasonal change, the active and break days during the monsoon season are considered. The hail features as detected by the satellite onboard microwave sensors are analyzed during the premonsoon season. Overall results are summarized as follows.

Chapter 1: Seasonal and intra-seasonal variation of rainfall contribution by different types of convective systems over the south Asian region

- Convective systems are classified into three categories namely, Large Convective Systems (LCSs), Deep Convective Systems (DCSs) and intense Convective Systems (ICSs). Rain characteristics from these three systems are studied in terms of rainfall contribution and rain intensity. The analysis is carried out during the premonsoon and monsoon seasons as well as during the active and break periods of the monsoonseason.

- (i). Rainfall contribution by LCSs, in both the seasons, is predominantly over the oceanic region, with maximum over the northern Bay of Bengal and central Arabian Sea. Over the land during the premonsoon its maximum contribution is along the Himalayan foothills and during the monsoon its maximum contribution is over the central India region along with the Himalayan foothills. (ii). Rainfall contribution by DCSs, during the premonsoon, is predominantly over the oceanic region with maximum contribution over the central Bay of Bengal and central Arabian sea, whereas during the monsoon, it is predominantly over the land with maximum contribution over the Sindh region of Pakistan. (iii). Rainfall contribution by ICSs, in both the seasons, is predominantly a land phenomena. During the premonsoon the maximum contribution is over the eastern India and during the monsoon the maximum contribution is over the western Himalaya Indentation region.
- (i). Rainfall contribution by LCSs over the land during the active monsoon days is predominantly over the core monsoon region, whereas during the break days rainfall contribution is shifted towards the Bangladesh plain, north east India and central & eastern Himalaya foothills region. Rainfall contribution by LCSs over ocean region is maximum over Bay of Bengal during the active days, and during the break days , it shifts to equatorial Indian oceanic region (ii). The nature of spatial variation of rainfall contribution by DCSs during active and break days are similar to LCSs. (iii). As far as contribution of rainfall from ICSs during active and break days is concerned, there is no appreciable shift in the region of the maximum rainfall during these days (which is over the northern part of the East Coast of India and Western Himalaya Indentation). The pattern remain same in both the periods albeit with varying rainfall contribution.
- The extreme rain intensity (irrespective of type of convective systems namely LCSs, DCSs and ICSs) is generally higher over the land compared to the ocean. During both the seasons, over the land, the most extreme rain intensity are found over the Himalaya-foothills (particularly eastern Himalaya foothills), northern part of east-coast of India, Gangetic West Bengal, Chota-Nagpur-plateau, Bangladesh-

plain and Meghalaya-plateau albeit with relatively higher values during the premonsoon seasons. Over the ocean the most extreme rain intensity is observed over the Bay of Bengal and Arabian sea.

- The characteristics of ICSs have strong regional variability. The ICSs are stronger during the premonsoon compared to the monsoon seasons and also ICSs over the land are stronger compared to the ocean. Over land, during the premonsoon and monsoon seasons, the maximum radar reflectivity at mixed-phase region (at 7 Km height) are observed over the northern part of East Coast of India (~48dBZ) and Western-Himalaya Indentation (~43dBZ) respectively , Over the ocean, during the premonsson as well as the monsoon season, the maximum radar reflectivity at mixed-phase region are observed over the Bay of Bengal (~ 44 dBZ and ~40dBZ).
- The preferred locations of ICSs are associated with a relatively higher value of the IWC in the upper part of the mixed-phase region. Over the ocean, with insignificant occurrence of ICSs, the parameter has relatively low values in the mixed-phase region.

Chapter 2: Diurnal variation of the occurrence of convective systems over north eastern part of India and adjoining region

- The observation from TRMM as well as INSAT 3D suggests that there is a significant regional variability in the diurnal characteristics of the convective systems over the study region. The foothills region of Himalya including the Assam valley have maximum occurrence during night to morning hours, whereas the plain region of Bangladesh, Gangetic west Bengal, northern part of east coast have maximum occurrence during afternoon to night hours.

Chapter 3: Detection of Hail Features (HFs) by satellite onboard microwave sensors over the north eastern part of India.

- On the basis of threshold value of the Polarization corrected temperature of 37 GHz channels (PCT_{37}), hail features (HFs) are classified into three categories namely, T-1 (with hail detection probability of 24%) , T-2 (with hail detection probability of 45%) and T-3 (with hail detection probability of 70%).

- T-1, T-2, and T-3 HFs have about 35, 45, and 49 dBZ radar reflectivity at 9 Km height (within the mixed-phase region). The nature of vertical structures of reflectivity for T-1, T-2, and T-3 HFs. correlates well with hail reporting at ground. The strongest vertical structure of T-3 HFs indicates the strong updraft and large ice particles presence in the mixed - phase region. It also represents that the strong mixed-phase microphysical processes (i.e., freezing of raindrops and riming) are involved for production of hail/graupel.
- The two stations in the plain region, namely Agartala and Dhubri, detected the maximum occurrence of most severe HFs (type T-3). The stations in the valley regions namely Tezpur, Mohanbari, North Lakhimpur, Pasighat, and Imphal have not detected the most severe HFs. The spatial variability in the HFs is amply supported by the vertical profiles of reflectivity and its value at mixed phase region.
- During the premonsoon, the maximum occurrence of HFs is found in April. The occurrence of HFs is minimum in March.
- HFs show strong diurnal variation. with maximum occurrence during the afternoon hours
- Occurrence of HFs show noticeable year to year variation. There is a decreasing trend during the period 1998 - 2013. The trend values are -0.70, -0.44, -0.14 and -0.10 for T-1, T-2 and T-3 HFs and ground reporting respectively.

Overall significant spatiotemporal variability is observed, with respect to rainfall contribution by different types of convective systems . The study provides a better insight into the spatiotemporal characteristics of convective systems over the region. The present results will be helpful for the better understanding of severe weather and also to improve rainfall estimation from satellite on-board sensors over the region. The study will also be useful for hydro-meteorological applications, particularly for flood forecasting and landslide hazards.

SCIENTIFIC PROGRESS REPORT

(2016)

Chapter 1

Seasonal and intra-seasonal variation of rainfall contribution by different types of convective systems over the south Asian region

Seasonal and intra-seasonal variation of rainfall contribution by different types of convective systems over the south Asian region

1.1 Introduction

Convective systems play a crucial role in the hydrological cycle and energy budget of the planet and influence its climate variability. Spatio-temporal variation of their population, along with their vertical extent and microphysical properties influence the variation in the earth's water cycle and also pose a challenge to parameterize the rainfall processes. Intense convective systems are often associated with strong lightning and hails in the storm updraft region (Dye *et al.*, 1989, Saunders *et al.*, 1991; Ushio *et al.*, 2001; Petersen *et al.*, 2005; Luo *et al.*, 2011; Wiens *et al.*, 2005).

The significant part of the South Asia is affected by hazardous convective systems during the premonsoon season (Zipser *et al*., 2006; Romatschke *et al*., 2010; Choudhury *et al*., 2015). The South-West monsoon system, an ensemble of convective systems, is one of the largest meteorological system (Gadgil, 2003), which affects the socioeconomic condition of a sizeable population of the South Asia. The launch of Tropical Rainfall Measuring Mission (TRMM; Simpson *et al.*, 1988) in 1997 provided a great opportunity to study the properties of convective systems. Significant studies on the properties of these systems have been carried out by using the TRMM observations at a global scale (Nesbitt *et al.*, 2000; Alcala and Dessler, 2002; Nesbitt and Zipser, 2003; Boccippio *et al.*, 2005; Liu and Zipser, 2005; Cecil *et al.*, 2005; Nesbitt *et al.*, 2006; Zipser *et al.*, 2006; Nesbitt and Anders 2009; Liu, 2011; Liu *et al.*, 2011; Liu *et al*., 2012; Xu and Zipser 2012; Houze *et al.*, 2015; Hamada *et al.*, 2014; Hamada *et al.*, 2015). By using the TRMM observations, several studies of this nature have also been carried out over the South Asia. By using the TRMM-PR near surface reflectivity observations, Bhatt and Nakamura (2005) showed that, during the monsoon season large portion of the rainfall is concentrated over the south facing slopes of the Himalaya. Similarly, during the monsoon season, by using the vertical profile of reflectivity from the TRMM-PR over the Himalaya region, Houze *et al*. (2007) reported that 40 dBZ echo top > 10 km and 40 dBZ echo area > 1000 km^2 occurs preferentially in the north western concave Indentation of the barrier. Islam and

Uyeda (2008) studied TRMM-PR derived vertical profile of rain intensity in and around Bangladesh during various rainy seasons. They reported that, the premonsoon rainfall is characterized by higher rain intensity and echo top height compared to the monsoon and post monsoon seasons. With the help of high resolution numerical simulation model and observation from TRMM-PR, Medina *et al.* (2010) studied the terrain and land cover effects on the summer monsoon convection in the Himalaya region. They reported that, intense convective echoes occur in the western Himalaya region, whereas broad stratiform echo occurs in the eastern-Himalaya. Through numerical analysis they showed that these variations are a result of region specific orographically modified flows and land surface flux feedbacks. By using the TRMM-PR data Romatschke *et al.* (2010) reported that the preferred location of deep as well as wide convective cores changes distinctly from India's East-coast in the premonsoon to Western-Himalaya-foothills in the monsoon. By using the same data set and time period, contribution of different size of the convective systems to the precipitation were studied during the premonsoon (Romatschke and Houze, 2011 a) and monsoon (Romatschke and Houze, 2011 b). During the premonsoon, it was reported that over the land, most of the rain falls from the medium sized systems. Over the Bay-of-Bengal, the dominant systems are larger. It was shown that, during the monsoon along the Western-Himalaya, precipitation falls mainly from the small but from the highly convective nature. Medium systems are favoured over the east Arabian-Sea and large systems are favoured over the Bay-of-Bengal. By using the TRMM sensors, Qie *et al.* (2014) reported that DCSs (20 dBZ echo top ≥ 14 km) and IDCSs (40 dBZ echo top ≥ 10 km) are most frequent over the southern Himalayan front (SHF) especially in the western most SHF. The DCSs over the Tibetan-plateau are relatively weak in convective intensity and small in size but occur frequently. The Oceanic DCSs possess the tallest cloud top and the largest in size but their convective intensity is significantly weaker. By using the TRMM observations, Choudhury *et al.* (2015) reported that the most intense MCSs occurs during the premonsoon over the Chota-Nagpur-Plateau and adjoining region with markedly reduced intensity in monsoon. They further pointed out that the Eastern-Himalaya and adjoining area consist of relatively weak MCSs and the region of most intense MCSs is associated with the large ice particles and ice water content compared to the region of weak MCSs. Bhat and Kumar (2015) studied cumulonimbus towers and intense convective cells by using the vertical reflectivity profiles from the TRMM-PR. They reported that the frequency of the occurrence of cumulonimbus towers (CbTs; 20 dBZ radar echo ≥ 12 km height and at least 9 km thick) is highest over the foothills of Himalaya, plain of northern India and Bangladesh and minimum over the Arabian-Sea and equatorial-Indian-ocean. They reported marginal land, ocean contrast for CbTs.

The basic objective of the study is to investigate the f rainfall contribution by various type of convective systems such as large, deep and intense over the South Asian region

1.2 Data and Methodology:

To study the spatio-temporal variability of rainfall contribution of Convective Systems (CSs) over the South Asian region (Figure-1.1),

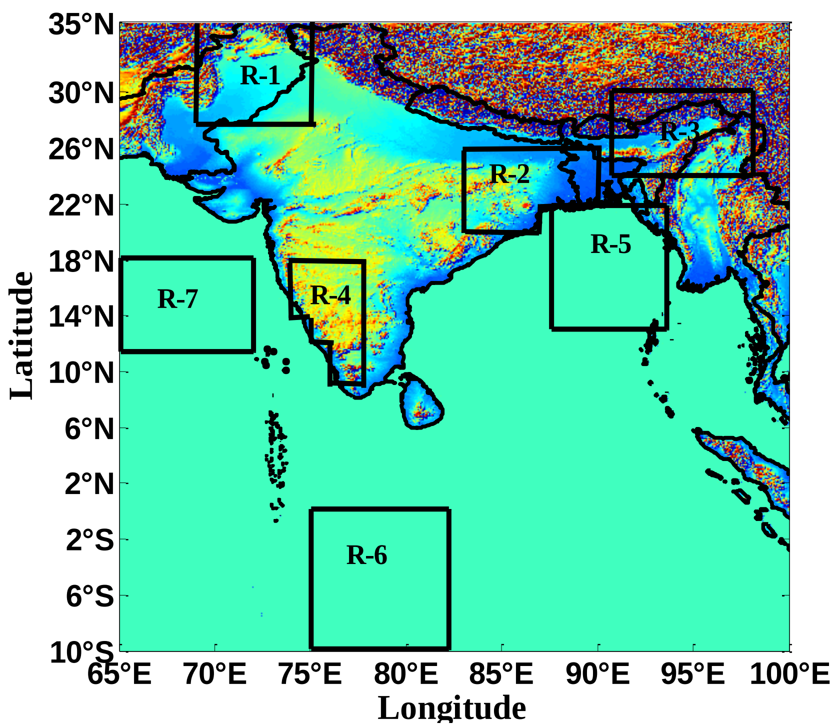


Figure 1.1 : Physiographic map of South Asian region.

For the present work 17 years (1998- 2014) of TRMM precipitation radar (PR) observation during the premonsoon (March - May) and the monsoon (Jun - September) seasons are utilized. Moreover, the intraseasonal change in rainfall characteristics of CSs is examined from the monsoon active days to break days. Total numbers of active days (108) and break days (148) from 1998 to 2014 are collected from as given by Pai et al (2015). PFs are defined by grouping the contiguous pixels with nonzero near-surface rainfall rate from TRMM PR 2A25 v7 data product (Liu et al., 2008).

CSs are categorized as a large, deep and intense. They are defined as follows

(i) Large Convective Systems (LCSs): When near-surface rainfall area of CSs are greater than 10000 Km^2 (Hirose and Nakamura, 2005),

(ii). Deep Convective Systems (DCSs) : When maximum height of 20 dBZ echoes within the CSs are greater than 12 Km (Xu., 2013)

(iii) Intense Convective Systems (ICSs) : When maximum height of 40 dBZ e echoes within the CSs are greater than 7 Km (Xu., 2013) respectively.

Rainfall contribution by each type of CSs are presented in each 2^o x 2^o grid. Rainfalls contributions are calculated by dividing rain volume of each CSs to total rain volume in 2^o x 2^o region.

To study the characteristics of extreme rain intensity from CSs which are defined as CSs in which maximum near-surface rainfall intensity (mm hr^{-1}) are higher than the corresponding 99.9th percentile on a 2^o x 2^o grid.

1.3 Results:

1.3.1 Spatial and seasonal variation of rainfall contribution:

Table- 1.1 shows the regional and seasonal variability of rainfall contribution by each type of CSs. Regionally, LCSs and DCSs both show that a larger proportion of rainfalls come from them over the ocean than over the land. Seasonally, rainfall contribution by LCSs shows a significant seasonal variability over land compared to ocean. Over land, LCSs (DCSs) contribute about 13% (~ 12%) rainfalls during the premonsoon and, it changed to about 18% (~ 16%) during the monsoon. Over ocean, LCSs (DCSs) contributes about 34% (~ 32%) rainfalls during the premonsoon and, it changed to about 34% (~ 22%) during the monsoon. Rainfall contribution by ICSs shows significant regional variability, it is generally higher over land compared to ocean during each seasons. Over the land During the premonsoon and monsoon , about 11% and 9% of rainfall contribution is from ICSs respectively.

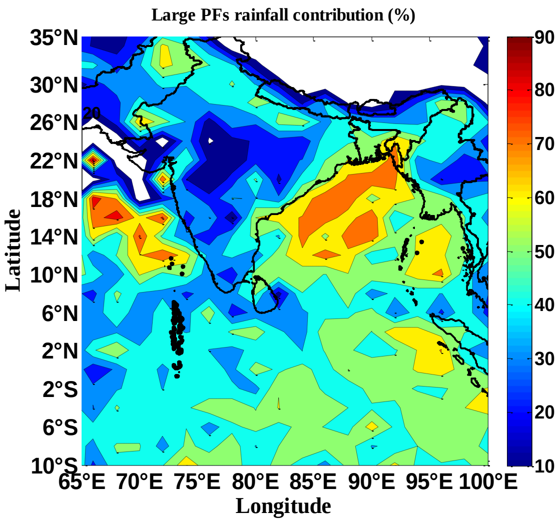
Table-1.1 : Seasonal variation in rainfall contribution by each type CSs over land and ocean.

	Land		Ocean	
	P-M	**M**	**P-M**	**M**
All CSs	796053	1948973	1523190	2220862
LCSs	13.15%	17.68%	34.12%	34.04%
DCSs	11.55%	16.37%	32.13%	21.96%
ICSs	10.64%	8.67%	4.31%	3.41%

P-M: Premonsoon, M: Monsoon

During the premonsoon and the monsoon seasons the spatio-temporal variation of rainfall contribution by LCSs is shown in Figure 1.2 (a, b) respectively. Over land, premonsoon rainfall is mostly dominated by isolated thunderstorm over central-India, but in monsoon significant rainfall comes from organized LCSs. Rainfall contribution by LCSs is increased (decreased) in monsoon over the Meghalaya-plateau, equatorial-Indian-ocean and south-Myanmar-coast (west-coast of India). Over all, it is observed that, LCSs contribute large portion of rainfall over the north Bay-of-Bengal than those in high rainfall regions, such as equatorial-Indian-ocean, Meghalaya-plateau, Eastern-Himalaya-foothills, and west-coast of India during each seasons. It is interesting to see that, over north Arabian-sea (near Gujarat and Karachi coast), rainfall mostly comes from small CSs in the premonsoon and in the monsoon it is from LCSs.

(a) Premonsoon	(b) Monsoon



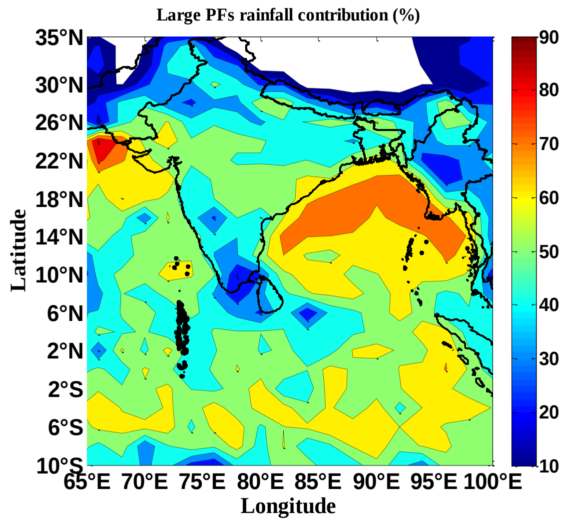
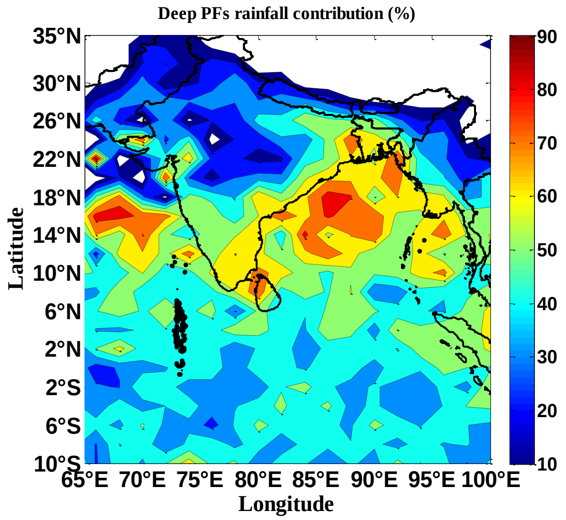


Figure 1.2: shows the spatial variability of rainfall contribution by LCSs (a) during the Premonsoon and (b) during the Monsoon.

During the premonsoon and the monsoon seasons the spatio-temporal variation of rainfall contribution by DCSs is shown in Figure 1..3 (a, b) respectively. Over land, local rainfall received by DCSs shows the significant spatial variability from premonsoon to monsoon seasons. During premonsoon, DCSs contribute most of local rainfall along east-coast of India, Gangetic West Bengal, Chota-Nagpur-plateau and Bangladesh-plain and during the monsoon, there is less rainfall over Thar-desert but most of the rainfall over this region is from few DCSs. Over the ocean, DCSs contribute maximum percentage of local rainfall over north Bay-of-Bengal and central Arabian-sea during premonsoon (Figure 1.3.a) and during monsoon, it is observed over north Arabian-sea (near Gujarat and Karachi coast) (Figure 1.3.b). During premonsoon, over west-coast of India and southeast Bay-of-Bengal (near south-Myanmar-coast) significant proportion of local rainfalls receive from DCSs, but in monsoon it is from shallow CSs.

(a) Premonsoon



(b) Monsoon

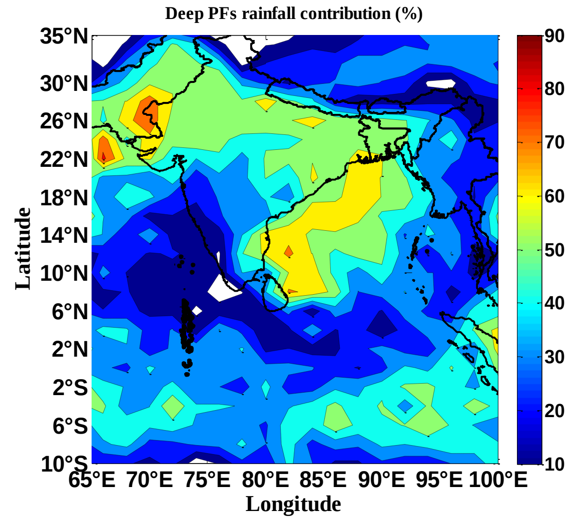


Figure 1.3: shows the spatial variability of rainfall contribution by DCSs (a) during the Premonsoon and (b) during the Monsoon.

During the premonsoon and the monsoon seasons the spatio-temporal variation of rainfall contribution by ICSs is shown in Figure 1.4 (a, b) respectively. The ICSs contribute a larger proportion of rainfall over land than ocean. Over land, in the premonsoon, maximum rainfall contribution is over north of east-coast of India, Chota-Nagpur-plateau, and adjoining Bangladesh-plain (Figure 1.4.a) and in monsoon, which is shifted in western-Himalaya-Indentation region (Figure 1.4.b). It is interesting to see that CSs which are intense but not deep, contribute higher portion of rainfall than CSs those are deep but not intense over western-Himalaya-Indentation region during both seasons.

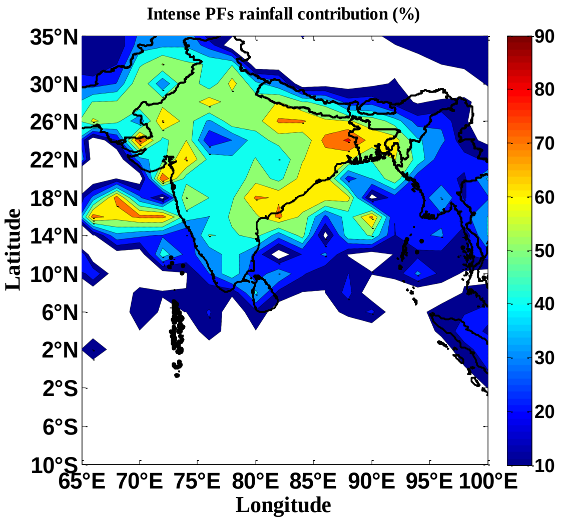
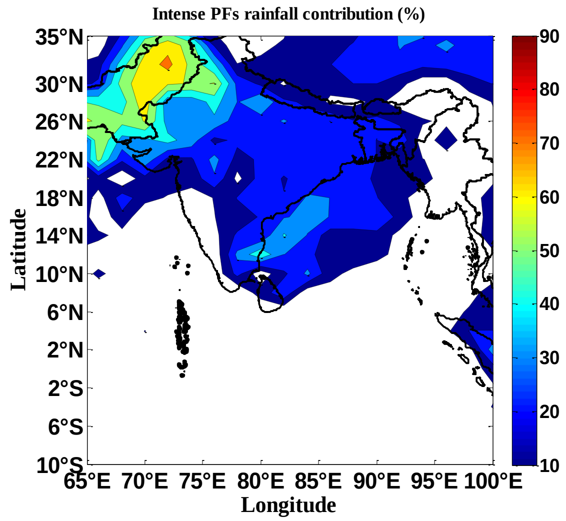
(a) Premonsoon	(b) Monsoon
	

Figure 1.4: shows the spatial variability of rainfall contribution by ICSs (a) during the Premonsoon and (b) during the Monsoon.

Overall it is observed that the rainfall contribution by LCSs, in both the seasons, is predominantly over the oceanic region, with maximum over the northern Bay of Bengal and central Arabian sea. Rainfall contribution by DCSs, during premonsoon, is predominantly over the ocean with maximum contribution over the central Bay of Bengal and central Arabian sea, whereas rainfall contribution by DCSs, during the monsoon, is both over land and ocean albeit with maximum contribution over the land, the Sindh region of Pakistan. Rainfall contribution by ICSs, in both the season, is predominantly over the land with maximum over the eastern India during the premonsoon and maximum over the western Himalaya Indentation region monsoon.

1.3.2. Intra-seasonal variation of rainfall contribution:

The previous section shows clear spatial contrasts in rainfalls contribution from each type of CSs over land and ocean. This section compares rainfall contribution by each type of CSs, during the monsoon active and break days. The Table-1.2 shows the significant intra-seasonal change of rainfall contribution of CSs types over land and ocean. The intra-seasonal change suggests that over the land, larger percentage of rainfall contribution from each type of CSs is observed during the monsoon active days compared to monsoon break days. On the contrary, ocean region experiences an increase in rainfall contribution by LCSs and DCSs during monsoon break days, whereas rainfall contributions by ICSs is relatively larger during the active monsoon days.

Table-1.2: Intra-seasonal variation of rainfall contribution of each type of CSs over land and ocean.

	Land		**Ocean**	
	Active	**Break**	**Active**	**Break**
All PFs	120088	151688	109260	164018
LCSs	23.65%	14.72%	27.72%	34.48%
DCSs	20.80%	14.00%	16.80%	21.20%
ICSs	20.90%	19.00%	6.00%	3.25%

Figure 1.5 (a, b) shows the spatial distribution of rainfall contribution by LCSs during active and break days, respectively. Over land, the central-India and north western part of India experiences the greater decrease in local rainfall contribution by LCSs in break monsoon days. Over Ocean, over south Bay-of-Bengal, south equatorial-Indian-ocean and southeast Arabian-sea (near west-coast), a significant increase in rainfall contribution by LCSs is observed in monsoon break days.

(a) Monsoon (Active days) | **(b) Monsoon (Break days)**

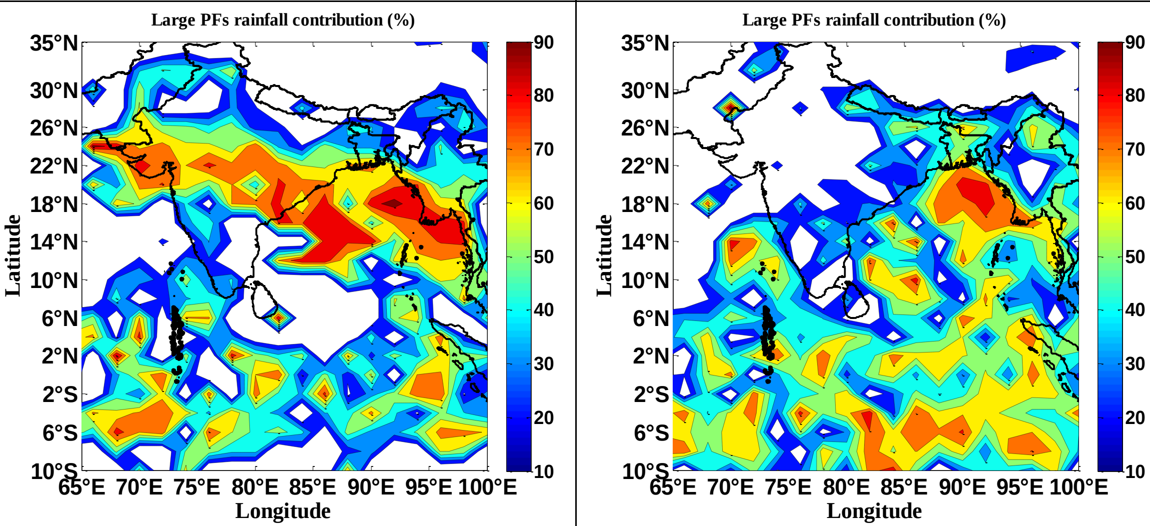


Figure 1.5: shows the spatial variability of rainfall contribution by LCSs (a) during Active days and (b) during Break days.

Rainfall contribution by DCSs during active and break days, are shown in figure 1.6 (a, b) respectively. Over land, the central Himalaya-foothills region experiences much smaller intra-seasonal changes in DCSs rainfall contribution compared to eastern Himalaya-foothills regions. Though, the eastern Himalaya-foothills regions receive maximum rainfall during break monsoon days, rainfall contribution by DCSs is significant in monsoon active days. Even though, during monsoon active days, monsoon trough locates over central-India and north western part of India, DCSs contribute relatively larger portion of local rainfall over the north western part of India.

(a) Monsoon (Active days)	(b) Monsoon (Break days)

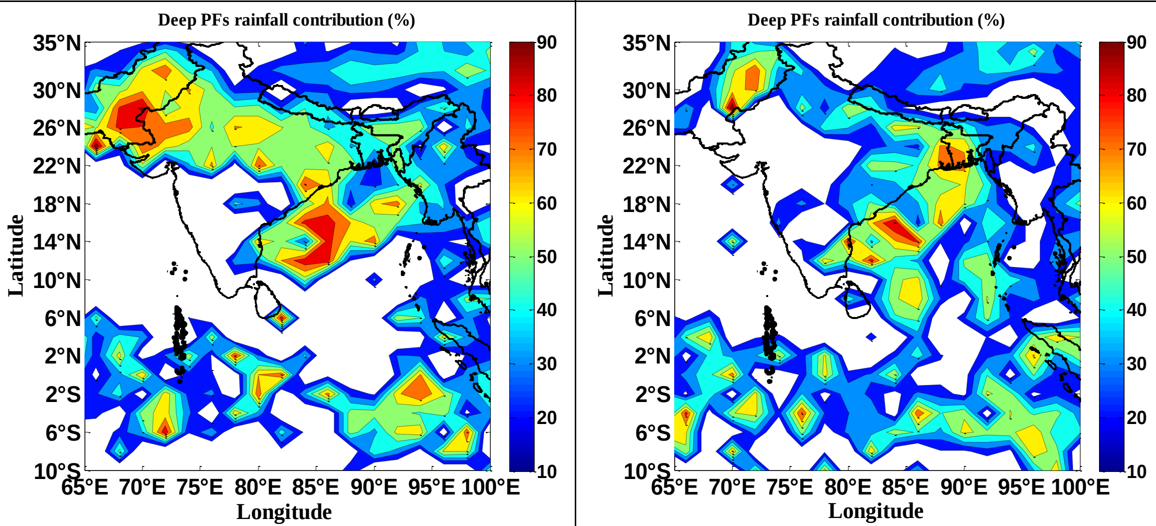


Figure 1.6: shows the spatial variability of rainfall contribution by DCSs during (a) d Active days and (b) Break days.

Rainfall contribution by ICSs during active and break days, are shown in figure 1.7 (a, b) respectively. Spatial distribution on rainfall contribution by ICSs does not show any significant change. Majority of rainfall contribution by ICSs persist over western-Himalaya-Indentation region. Over northern part of east-coast and southeast peninsula experience a reasonably increase in local rainfall contribution by ICSs in break monsoon days.

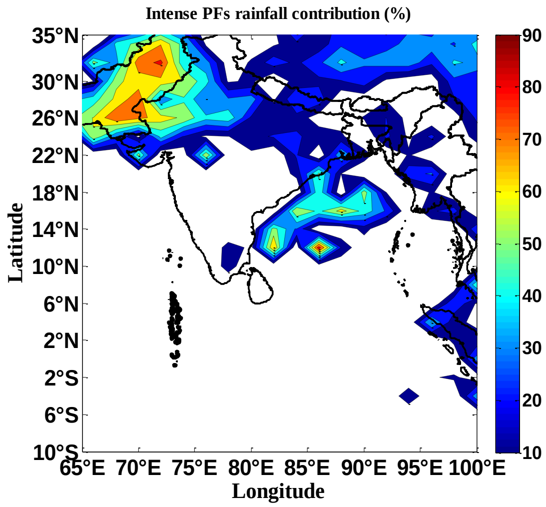
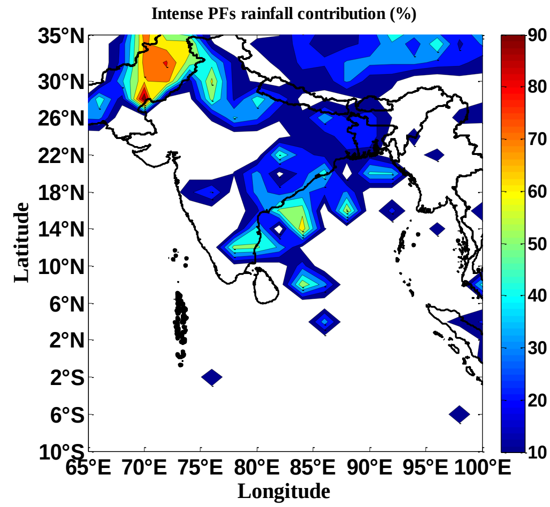
(a) Monsoon (Active days)	**(b) Monsoon (Break days)**
	

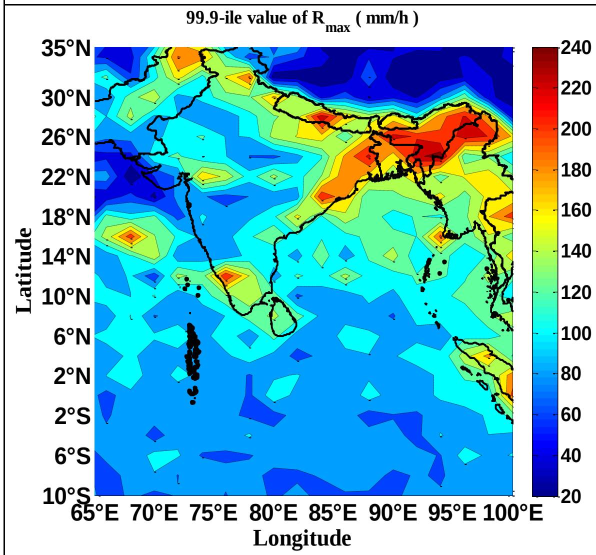
Figure 1.7: shows the spatial variability of rainfall contribution by ICSs (a) during Active days and (b) during Break days.

Overall, the rainfall contribution by LCSs over the land during active monsoon days is predominantly over the core monsoon region, whereas during the break days rainfall contribution is shifted towards the Bangladesh plain, north east India and central & eastern Himalaya foothills region. Rainfall contribution by LCSs over ocean region with maximum at Bay of Bengal during the active days shift to maximum at equatorial Indian ocean during the break days. The nature of spatial variation of rainfall contribution by DCSs during active and break days are similar to LCSs. As far as contribution of rainfall from ICSs during active and break days is concerned, there is no appreciable shift in the region of maximum rainfall during these days.

1.3.3 Spatial and seasonal variation of extreme rain intensity :

Spatial variation of extreme rain intensity (irrespective of the type of convective systems namely LCSs, DCSs and ICSs) during the premonsoon and monsoon seasons are shown in figure 1.8 (a, b) respectively. The extreme rain intensity are generally higher over land compared to ocean. Most extreme rain intensity are found over the land along Himalaya-foothills, northern east-coast, Gangetic West Bengal, Chota-Nagpur-plateau, Bangladesh-plain and Meghalaya-plateau during both seasons. Significant rain intensity is also observed the coastal regions, including south west-coast of India and Myanmar-coast during both the seasons. Extreme rain intensity is higher during the premonsoon compared to the monsoon. Over the ocean, in both the seasons, extreme rainfall is observed mainly over the Bay of Bengal and Arabian sea .

(a) Premonsoon



(b) Monsoon

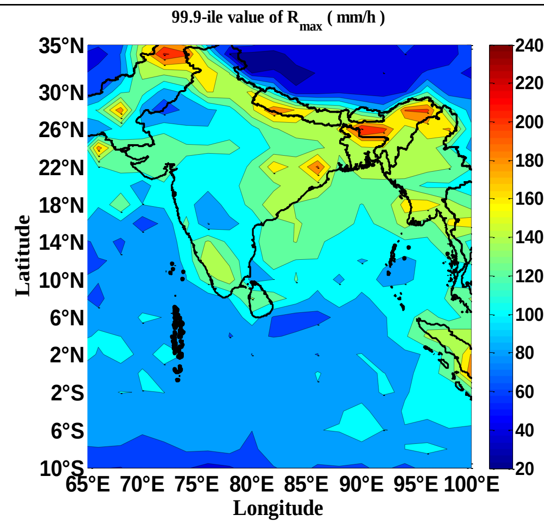


Figure 1.8: shows the spatial variation of extreme rain intensity during the (a) Premonsoon and (b) Monsoon.

The extreme rain intensity is generally higher over the land compared to the ocean. Most extreme rain intensity (irrespective of type of convective systems namely LCSs, DCSs and ICSs) are found over the land along Himalaya-foothills, northern east-coast, Gangetic West Bengal, Chota-Nagpur-plateau, Bangladesh-plain and Meghalaya-plateau during both the seasons albeit with relatively higher values during the premonsoon seasons.

1.3.4 Regional variability of the characteristics of convective systems associated with extreme rain intensity

In this subsection, the characteristics of the convective systems (e.g., size and vertical extent) associated with the extreme rain intensity, are examined in four sub-regions over land and in three sub-regions over ocean (Table-1.3). Over the land the selected sub-regions are (i) R-1 (28^0N – 35^0N & 69^0E – 75^0E) (ii) R-2 (20^0N – 26^0N & 83^0E – 90^0E), (iii) R-3 (24^0N – 30^0N & 91^0E – 98^0E) and (iv) R-4 (9^0N – 18^0N & 74^0E – 79^0E). Over the ocean the selected sub-regions are (i) R-5 (14^0N – 22^0N & 87^0E – 94^0E) (ii) R-6 (10^0S – 0^0N & 75^0E – 82^0E), (iii) R-7 (12^0N – 18^0N & 65^0E – 72^0E).

Over land, during the premonsoon, maximum fraction of extreme rain intensity from the mesoscale convective systems (MCSs; near-surface rainfall area greater than 2000 Km^2) are observed over the R-1 (~ 88%), followed by the R-2 (~ 73%), the R-3 (~ 54%) and the R-4 (~ 40%) and during monsoon, it is observed over the R-3 (~ 68%), followed by the R-4 (~ 61%), the R-2 (~ 56%) and the R-1(~ 48%). Over ocean, during the premonsoon, maximum fraction of extreme rain intensity from MCSs are observed over the R-7 (~ 100%), followed by the R-6 (~ 97%) and the R-5 (~ 91%) and during monsoon, it is observed over the R-5 (~ 98%), followed by the R-7 (~ 95%) and the R-6 (~ 94%).

Over land, during the premonsoon, maximum fraction of extreme rain intensity by storms having strong mixed-phase process (40dBZ echo top > 7 Km, i.e., freezing of raindrops and riming) (Xu and Zipser, 2012) are observed over the R-2 (~ 80%), followed by the R-1 (~ 46%), the R-4 (~ 20%) and the R-3 (~ 12%) and during monsoon, maximum fraction is observed over the R-1 (~ 47%), followed by the R-2 (~ 23%), the R-3 (~ 6%) and the R-4 (~ 2%). Over ocean, during the premonsoon, maximum fraction of extreme CSs by storms involving strong mixed-phase process are observed over the R-7 (~ 64%), followed by the R-5 (~ 59%), and the R-6 (~ 1%) and during monsoon, maximum fraction is observed over the R-5 (~ 40%), followed by the R-7 (~ 16%) and the R-6 (~ 0%).

Table-1.3: Regional variability of extreme PFs properties over the seven sub-regions.

	R-1	R-2	R-3	R-4	R-5	R-6	R-7
			P-M, **M**				
Occurrence	52, **60**	15, **75**	65, **143**	15, **61**	22, **114**	109, **126**	11, **90**
Area> 2000 km^2 (%)	88.5, **48.3**	3.3, **56.0**	53.8, **68.5**	40.0, **60.6**	91.0, **98.2**	97.2, **94.4**	100.0, **95.5**
40dBZ >7 Km (%)	46.1, **46.7**	80.0, **22.7**	12.3, **5.6**	20.0, **1.6**	59.0, **40.3**	1.0, **0.0**	63.6, **15.5**

P-M: Premonsoon, M: Monsoon

The vertical profiles of maximum radar-reflectivity factor for the extreme rain intensity in the sub-regions over land and ocean during the premonsoon and monsoon seasons are shown in figure 1.9 (a, b). Over land, during the premonsoon, maximum radar reflectivity at mixed-phase region (7 Km) are observed over the R-2 (~ 48dBZ), followed by the R-1 (~ 40dBZ), the R-4 (~ 38dBZ) and the R-3 (~ 32dBZ) and during monsoon, it is observed over the R-1 (~ 43dBZ), followed by the R-2 (~ 38dBZ), the R-3 (~ 34dBZ) and the R-4 (~ 29dBZ). Over ocean, during the premonsoon, maximum radar reflectivity at mixed-phase region are observed over the R-5 (~ 44dBZ), followed by the R-7 (~ 39dBZ), and the R-6 (~ 33dBZ) and during monsoon, maximum radar reflectivity at mixed-phase region are observed over the R-5 (~ 40dBZ), followed by the R-7 (~ 32dBZ), and the R-6 (~ 32dBZ)

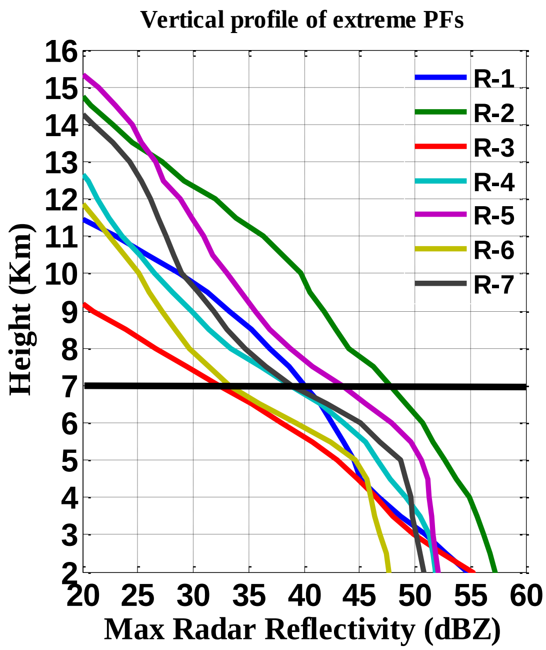
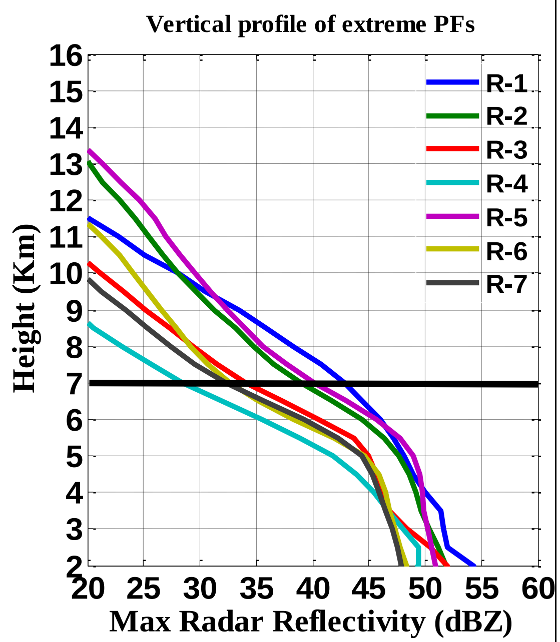
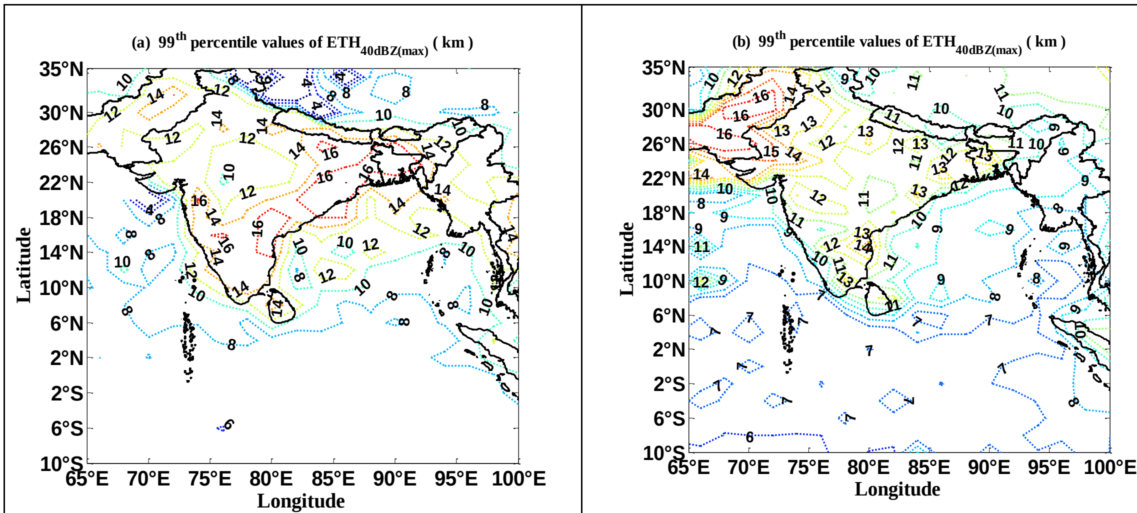
(a) Premonsoon	(b) Monsoon
	

Figure 1.9: shows the vertical profiles of maximum radar-reflectivity factor for the extreme rain intensity during the (a) Premonsoon and (b) Monsoon.

Further, the spatial variation of the most extreme value of $ETH_{40dBZ\ (max)}$ (at 99 percentile; top 1%) during the premonsoon and monsoon seasons are provided in Figure 1.10 (a, b) respectively. During the premonsoon, over the land, its value varies in the range of 4-16 km with the maximum value over the Chota-Nagpur-plateau, Bangladesh-plain, central and northern part of the East-coast of India and minimum over the Tibetan-plateau. Over the ocean its value varies in the range of 8-14 km with maximum value over the northern Bay-of-Bengal near the coastal area and minimum over the Indian-ocean. During the monsoon season, over the land its value varies in the range of 8-16 km with its maximum value shifted to the Western-Himalaya-Indentation and minimum value over the southern Myanmar and adjoining region. During this season, the region of Chota-Nagpur-Plateau, Bangladesh-plain and northern East-coast are no longer the region of maximum value. Over the ocean, its value varies in the range of 7-11 km, with a maximum value over the Bay-of-Bengal very near to the eastern coast and the minimum value over the Indian-ocean. It is observed that over the Bay-of-Bengal, its value decreases considerably compared to the premonsoon season. Overall significant land, ocean contrast is observed in their values,



(a) (b)

Figure 1.10: Spatial variation of 99th percentile value of $ETH_{40dBZ(max)}$ during the (a) pre monsoon and (b) monsoon.

1.3.5 Spatial & seasonal variation of ice microphysical properties.

To have a better insight of the regional and seasonal variability of the, ice microphysical properties, the vertical profiles of the ice water content (IWC) are considered for further analysis. During the premonsoon and monsoon seasons, the contour plots of median value of the IWC for height vs longitude cross section over the R_1 (22° N–35° N, 65° E–100° E), R_2 (6° N–22° N, 65° E–100° E) and R_3 (10° S – 6° N, 65° E–

100^o E) are shown in Figure 1.11 (a, b) and 1.11 (c, d) and 1.11 (e, f) respectively. To study the microphysical process in the mixed phase region, which is conducive for development of severe weather (lightning and hail features in the convective systems), a reference height of 10 km is selected. Over the R_1, during the premonsoon, significant value of the IWC is observed at around 10 km (the mixed-phase region) in between 85^o-95^o E, which coincide with the longitude range of the Meghalaya-plateau, Chota-Nagpur-Plateau and Bangladesh-plain. This is the region where the higher occurrence of lightning and hail features are significantly prevalent during the premonsoon (Roy *et al.* 2017). During the monsoon significant value of the IWC is observed at around 10 km in between the 65^o-70^o E, which coincide with the longitude range of the Western-Himalaya-Indentation and adjoining area, the region where ICSs are most prevalent along with a higher occurrence of lightning and hail features (Roy *et al.* 2017) . During premonsoon to monsoon, shifting of the higher amount of the IWC in the mixed-phase region from the Meghalaya-plateau, Chota-Nagpur-plateau and Bangladesh-plain to the Western-Himalaya-Indentation is in agreement with the seasonal shifting of the preferred location of lightning and hail features (Roy *et al.* 2017).Over the R_2, during the premonsoon, significant value of the IWC is observed at around 10 km (in the mixed-phase region) in between the 75^o-90^o E, which coincide with the longitude range of the southern part of West-coast of India, Sri Lanka and the northern part of East-coast of India. It is the region where occurrence of ICSs is maximum during the premonsoon, particularly towards the northern part of East-coast. During the monsoon, lower value of the IWC in the mixed-phase region over the same longitude range is consistent with the reduced occurrence of ICSs with lightning and hail features over this region (Roy *et al.* 2017) . Over the R_3, during the premonsoon and monsoon, there is relatively low value of the IWC at 10 km (in the mixed phase region) compared to the other two regions. The lower value of the IWC at the mixed-phase heights may be attributed to the weak updrafts over the oceanic region (Zipser and Lutz, 1994). Overall, the results are in agreement with the spatio-temporal variation of IDCSs with lightning and hail features (Roy *et al.* 2017). The preferred locations of ICSs are associated with a relatively higher value of the IWC in the upper part of the mixed-phase region. Over the ocean, with insignificant occurrence of

ICSs, the parameter has relatively low values in the mixed-phase region.

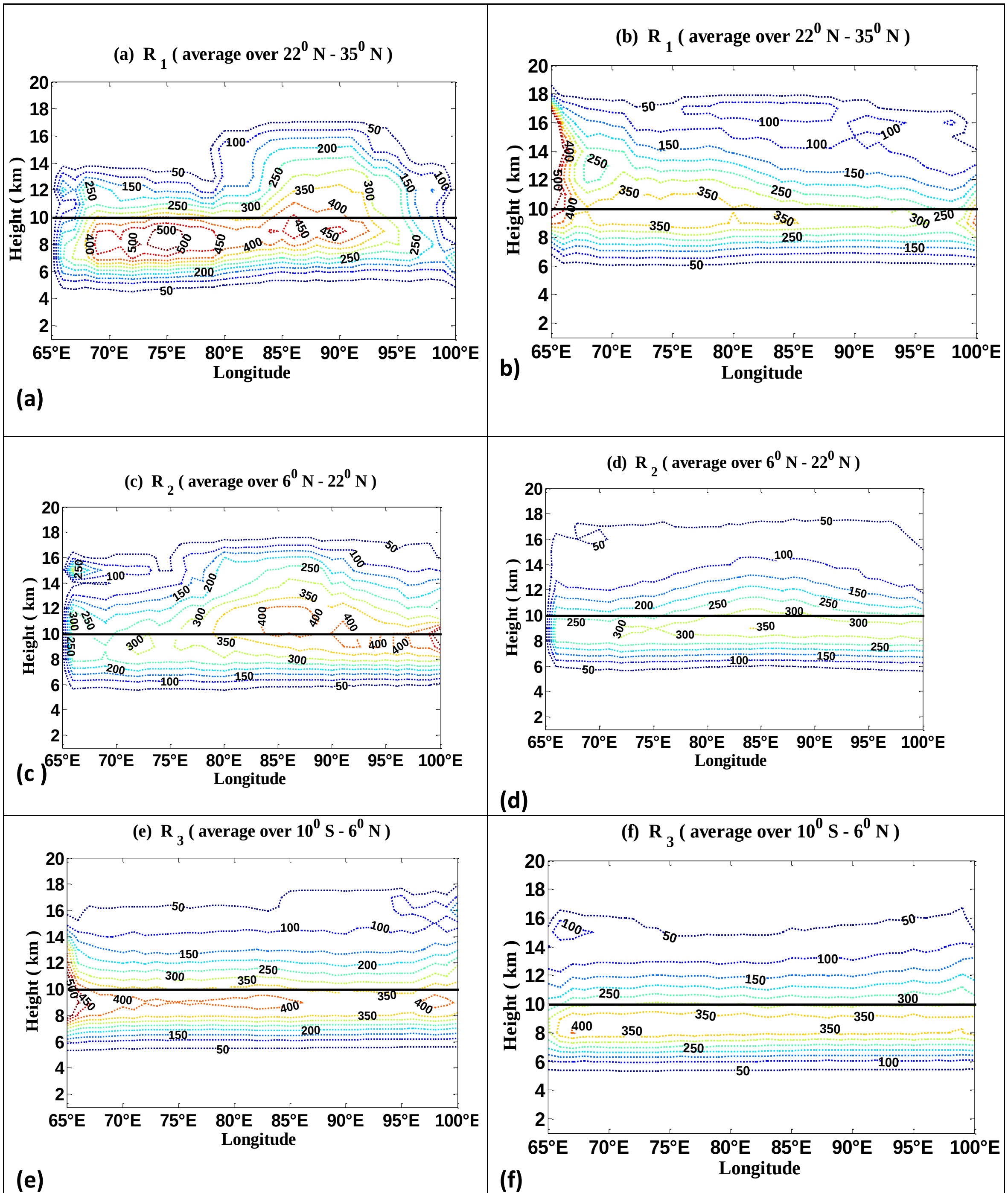


Figure 6: The height longitudinal cross section of IWC (mg m^{-3}) (a) over the R_1 during the premonsoon (b) over the R_1 during the monsoon (c) over the R_2 during the premonsoon (d) over the R_2 during the monsoon (e) over the R_3 during the premonsoon and (f) over the R_3 during the monsoon.

1.4 Summary and conclusion

- Convective systems are classified into three categories namely, Large Convective Systems (LCSs), Deep Convective Systems (DCSs) and intense Convective Systems (ICSs). Rain characteristics from these three systems are studied in terms of rainfall contribution and rain intensity. The analysis is carried out during the premonsoon and monsoon seasons as well as during the active and break periods of the monsoonseason.
- (i). Rainfall contribution by LCSs, in both the seasons, is predominantly over the oceanic region, with maximum over the northern Bay of Bengal and central Arabian Sea. Over the land during the premonsoon its maximum contribution is along the Himalayan foothills and during the monsoon its maximum contribution is over the central India region along with the Himalayan foothills. (ii). Rainfall contribution by DCSs, during the premonsoon, is predominantly over the oceanic region with maximum contribution over the central Bay of Bengal and central Arabian sea, whereas during the monsoon, it is predominantly over the land with maximum contribution over the Sindh region of Pakistan. (iii). Rainfall contribution by ICSs, in both the seasons, is predominantly a land phenomena. During the premonsoon the maximum contribution is over the eastern India and during the monsoon the maximum contribution is over the western Himalaya Indentation region.
- (i). Rainfall contribution by LCSs over the land during the active monsoon days is predominantly over the core monsoon region, whereas during the break days rainfall contribution is shifted towards the Bangladesh plain, north east India and central & eastern Himalaya foothills region. Rainfall contribution by LCSs over ocean region is maximum over Bay of Bengal during the active days, and during the break days , it shifts to equatorial Indian oceanic region (ii). The nature of spatial variation of rainfall contribution by DCSs during active and break days are similar to LCSs. (iii). As far as contribution of rainfall from ICSs during active

and break days is concerned, there is no appreciable shift in the region of the maximum rainfall during these days (which is over the northern part of the East Coast of India and Western Himalaya Indentation). The pattern remain same in both the periods albeit with varying rainfall contribution.

- The extreme rain intensity (irrespective of type of convective systems namely LCSs, DCSs and ICSs) is generally higher over the land compared to the ocean. During both the seasons, over the land, the most extreme rain intensity are found over the Himalaya-foothills (particularly eastern Himalaya foothills), northern part of east-coast of India, Gangetic West Bengal, Chota-Nagpur-plateau, Bangladesh-plain and Meghalaya-plateau albeit with relatively higher values during the premonsoon seasons. Over the ocean the most extreme rain intensity is observed over the Bay of Bengal and Arabian sea.
- The characteristics of ICSs have strong regional variability. The ICSs are stronger during the premonsoon compared to the monsoon seasons and also ICSs over the land are stronger compared to the ocean. Over land, during the premonsoon and monsoon seasons, the maximum radar reflectivity at mixed-phase region (at 7 Km height) are observed over the northern part of East Coast of India (~48dBZ) and Western-Himalaya Indentation (~43dBZ) respectively , Over the ocean, during the premonsson as well as the monsoon season, the maximum radar reflectivity at mixed-phase region are observed over the Bay of Bengal (~ 44 dBZ and ~40dBZ).
- The preferred locations of ICSs are associated with a relatively higher value of the IWC in the upper part of the mixed-phase region. Over the ocean, with insignificant occurrence of ICSs, the parameter has relatively low values in the mixed-phase region.

Chapter 2

Diurnal variation of the occurrence of convective systems over north eastern part of India and adjoining region

Diurnal variation of the occurrence of convective systems over north eastern part of India and adjoining region

2.1 Introduction

The mechanism of the rainfall peak associated with overland afternoon instability are well understood and observed, however the diurnal cycle of rainfall associated with MCSs remain poorly understood and modelled (Nesbitt and Zipser 2003). Most of the previous work comparing the tropical rainfall diurnal cycle over land and ocean surface agree that the amplitude of the diurnal cycle over continent is larger than that over the open ocean. (Gray and Jacobson 1977). However studies conducted over different region of the tropics, have found significant differences in the characteristics of the diurnal cycle. Over land many studies using surface rain accumulation ((Oki and Musiake 1994; Dai et al. 1999) and surface weather report of precipitation frequency (Dai 2000) link the timing of the diurnal precipitation frequency maximum to afternoon boundary layer destabilization caused by day time insolation. However many studies noted that there are land area with midnight to early morning maxima of the precipitation , which may be linked to local effects such as complex terrain and see breeze circulations (Oki and Musiake 1994; Yang and Slingo 2000) or the long nocturnal life cycle of MCSs (Dai et al. 1999). There is no comprehensive study of the diurnal variation of the convective activity over the study region. In the present section an attempt is being made to study the diurnal variation of the occurrence of MCSs and DCSs over the study region.

2.2 Result

2.2.1 Spatiotemporal variation of occurrence of MCSs during the premonsoon and monsoon season (Diurnal variation)

The spatio-temporal variation of the occurrence of MCSs during during 0-6, 6-12, 12- 18 and 18-00 mean standard time (MST) in the pre-monsoon seasons are shown in Figure 2.1 (a-d) respectively. It is observed that during the premonsoon season the occurrence MCSs is predominantly over the eastern Himalaya foothills and Meghalaya Plateau, with the exception of 18-00 MST, when the MCSs occurrence is also observed over the plain region Bangladesh and Gangetic west Bengal.

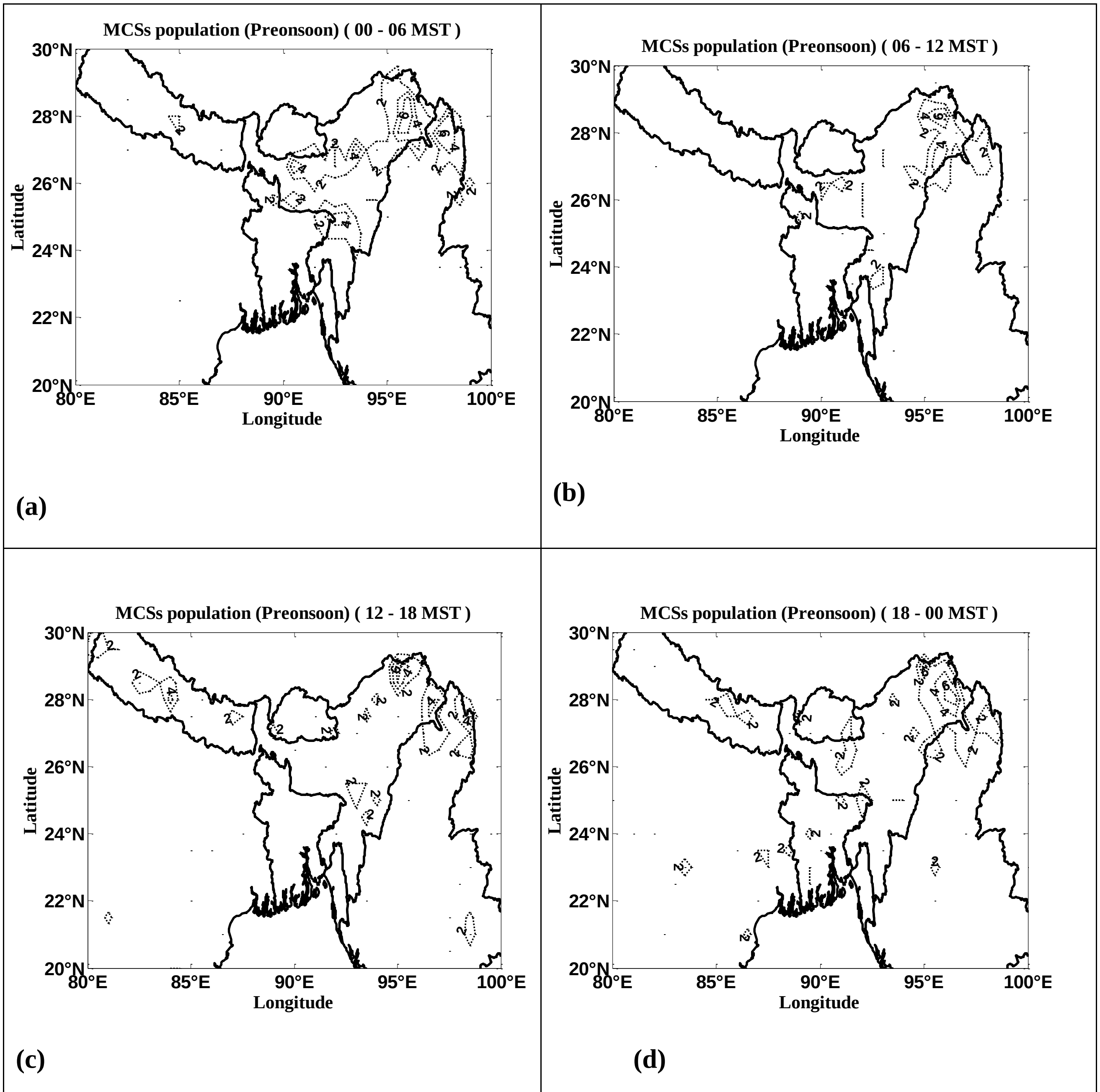
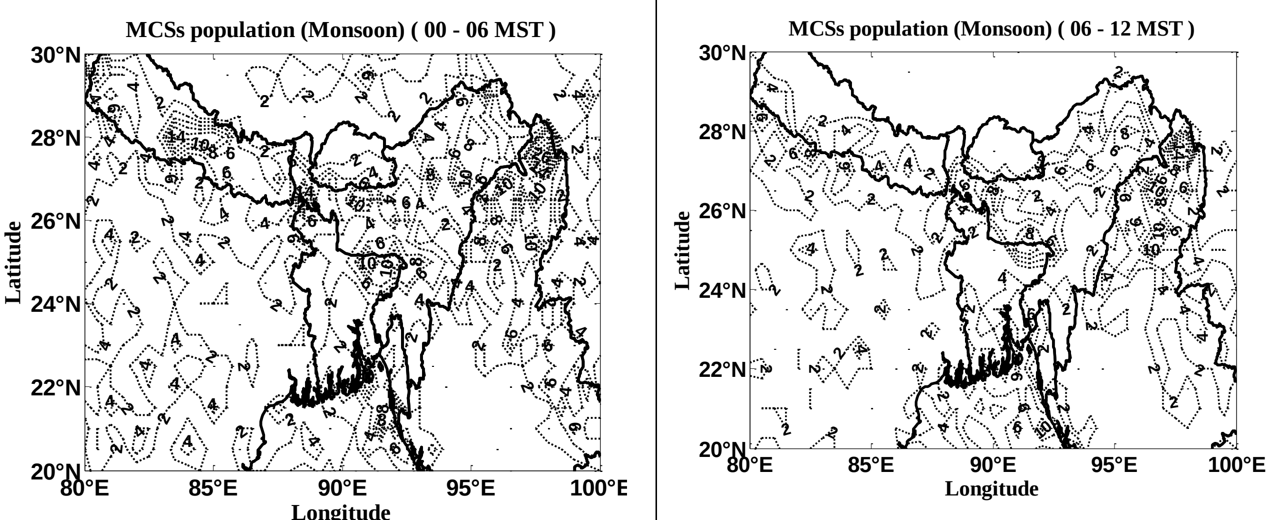


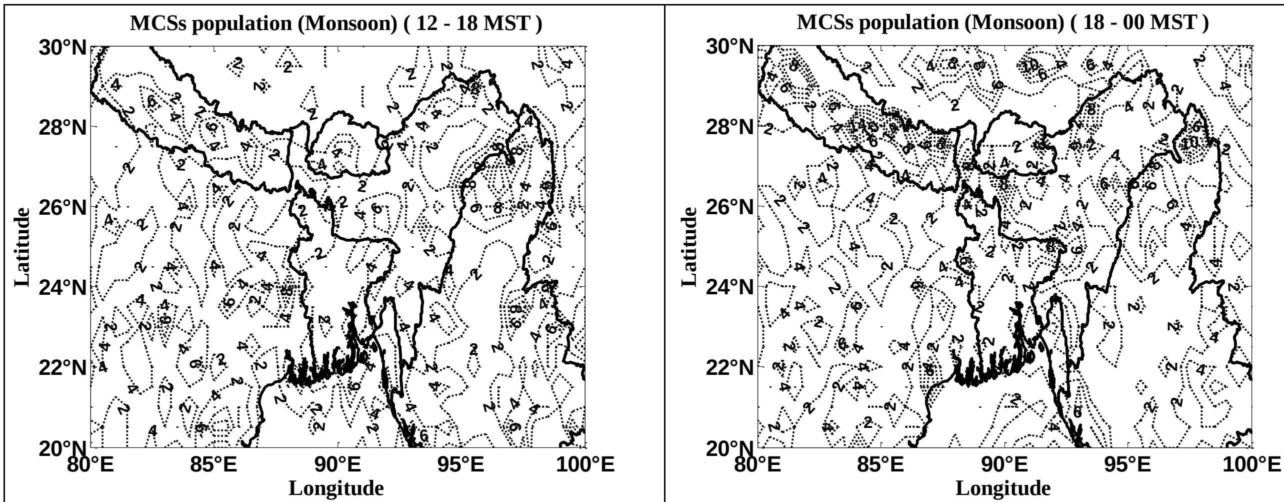
Figure 2.1: Spatio temporal variation of the MCSs population over the study region during the pre-monsoon season at (a) from 00-06 MST (b) from 06-12 MST (c) from 12-18 MST and (d) from 18-00 MST.

Further, the spatio-temporal variation of the occurrence of MCSs during 0-6, 6-12, 12- 18 and 18-00 mean standard time (MST) in the monsoon seasons are shown in figure 2.2 (a-d) respectively. Overall it is observed that over the Himalayan foot hill region , Patkai Bum and Meghalaya plateau there is significant diurnal variation whereas over the plain region of Bangladesh and Gangetic west Bengal diurnal variation in the occurrence of MCSs is insignificant. During 00-06 MST, the significant occurrence of MCSs is over the Central Himalaya Foothill region (around 14 number of MCSs) , Patkai Bum region (around 20 number of MCSs) and Meghalaya Plateau region (around 10 number of MCSs). Over the plain region of Bangladesh and Gangetic west Bengal the occurrence is significantly less varying in the range of 2-4 MCSs. During 06-12 MST, overall there is relative decrease in the occurrence of MCSs but still significant occurrence over the Patkai Bum region (around 14 number of MCSs). During 12-18 there is further decrease in the occurrence of MCSs over the Patkai Bum region (around 8 number of MCSs). Thereafter during 18-00 MST there is again increase in the occurrence of MCSs over Himalaya foothills, Meghalaya Plateau and Patkai Bum region.



(a)

(b)



(c) (d)

Figure 2.2 : Spatio temporal variation of the MCSs population over the study region during the monsoon season at (a) from 00-06 MST (b) from 06-12 MST (c) from 12-18 MST and (d) from 18-00 MST.

Overall it is observed that during the premonsoon season the occurrence MCSs is predominantly over the eastern Himalaya foothills and Meghalaya Plateau, with the exception of 18-00 MST, when the MCSs occurrence is also observed over the plain region Bangladesh and Gangetic west Bengal. As far as diurnal variability of the MCSs over the study region during monsoon season is concerned it is observed that over the foothill region there is strong diurnal variability with early morning maxima compared to the plain region. With afternoon maxima.

2.2.2 Diurnal variation of occurrence of MCSs over two different climatic regions, A and B during the premonsoon and monsoon seasons

Over the study region two distinct climatic zones are considered in terms of intensity and population characteristics of MCSs, namely the region *A* (22^0N- 26^0 N; 84^0E-90^0E; the Gangetic West Bengal, plain of Bangladesh, Chota Nagpur plateau) and the region *B* (24^0N- 28^0 N; 94^0E-100^0E; the North of Patkai- upper Brahmaputra basin, Pegu

Yoma- Shan Plateau) as shown in Figure 2.3. The region *A* is characterized as a region with the most intense MCSs with moderate MCS population. The region *B* is characterized as a region with moderately intense MCSs with the maximum MCS population (Choudhury *et al.* 2015)

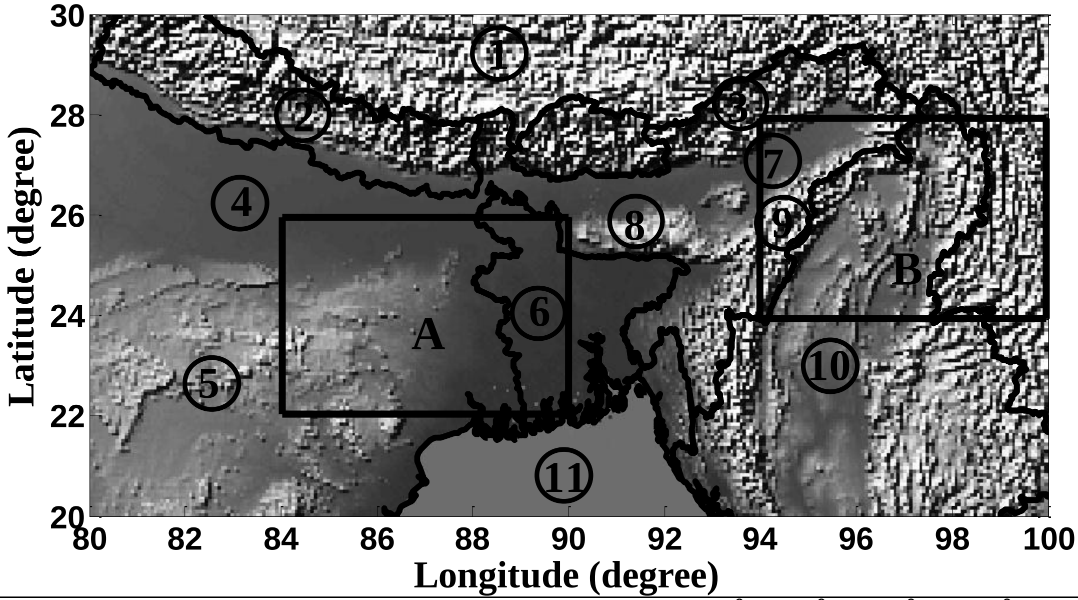


Figure 2.3: Physical map of the study region (20^0 N-30^0 N; 80^0 E-100^0 E)

The temporal or diurnal variation of the frequency occurrence of MCS during the premonsoon and monsoon seasons over region A and B are shown in Figure 2.4 (a, b) respectively. The total number of MCSs in each season is provided in the respective figure panels. There is distinct difference in the diurnal variation over these two regions. Over region A the diurnal variability is stronger compared to region B and also there is different characteristics of the diurnal pattern over these two regions. Over the region A there is maximum occurrence during the late evening to mid night and minimum during morning to mid day. Over the region A there is time lag of maximum occurrence of MCSs between the pre monsoon and monsoon seasons. During the pre monsoon the maximum occurrence is at around 18-23 hours whereas during the monsoon the maximum occurrence is at around 16 hrs. Over the region B the diurnal variability is weak and also the maximum occurrence is during 03-06 hrs in contrast to region A.

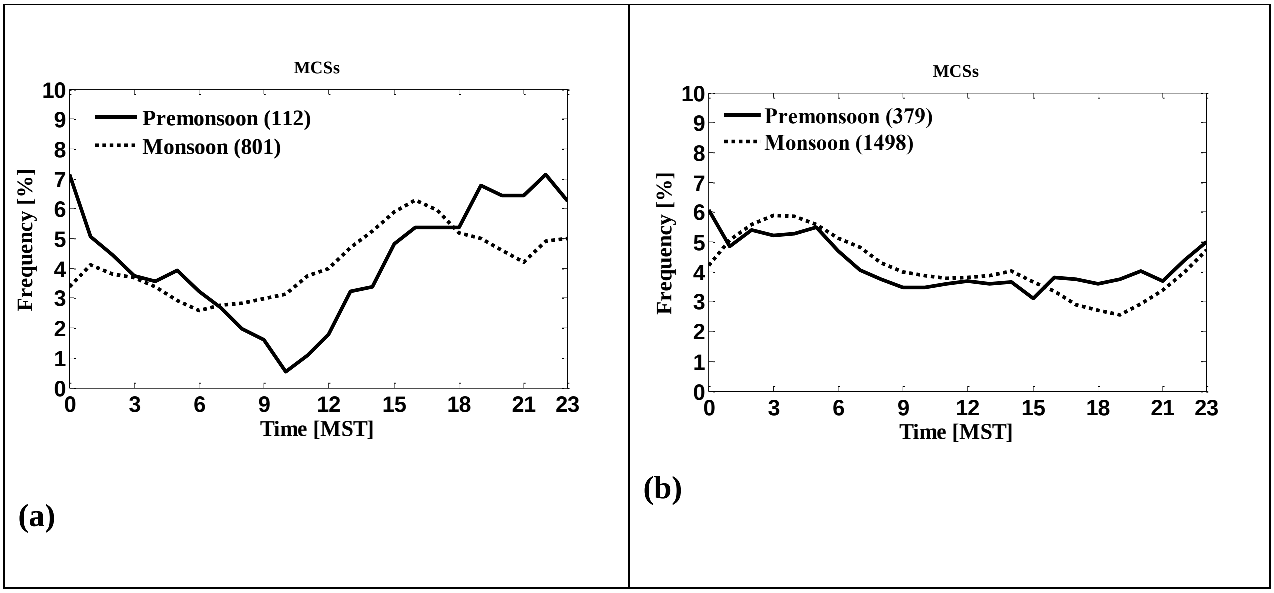
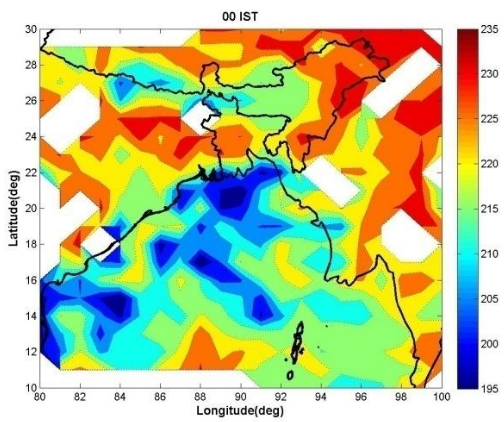


Figure 2.4 : Diurnal variation of the occurrence of MCSs population during the pre-monsoon and monsoon seasons over the (a) region A and (b) region B region.

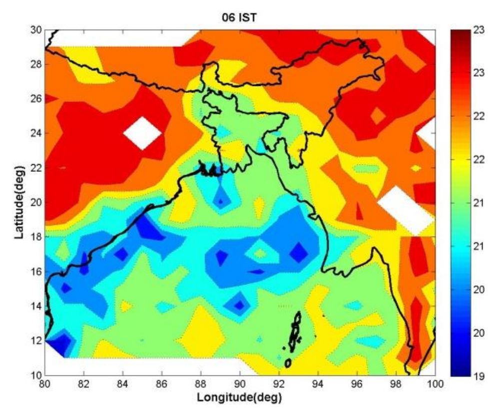
Overall it is observed that the diurnal variation of the occurrence of MCSs have a regional variability over the study region. The continental region A has the continental characteristics where the occurrence of MCSs have afternoon maxima whereas continental region B has oceanic character where the occurrence of MCSs have early morning maxima. This is also supported by the fact that the amplitude of the diurnal variation of the occurrence of MCSs over region A is larger compared to the region B.

2.2.3 Diurnal variation of the convective activity as observed by INSAT 3D infrared thermal channel

Further an analysis of thermal imagery data of geostationary satellite INSAT 3D is also analyzed. For this purpose half an hour images of infrared thermal band (48 images/day) are utilized. At present INSAT-3D data are analyzed during the premonsoon months (March-May) for three years (2014-2016). It is to be mentioned that , lower the value of the parameter more the convection. The median value of the brightness temperature at 12 µm band T_{b12} is estimated at $2^o x 2^o$ grid scale. In the present report spatial variation of the the median value of the T_{b12} at different time of the day is presented. The spatial variation of 6 hourly averaged value of T_{b12} at 00, 06, 12 and 18 hrs (IST) are shown in figure 2.5 (a-d) respectively. Significant spatiotemporal variation of the T_{b12} value is observed. It is observed that during the night (00 hrs) the convective systems are predominantly over the oceanic region (Bay of Bengal) and also over the foothills of central and eastern Himalaya, whereas during the afternoon (18 hrs) convective systems are predominantly over the land region. Overall, deepest convective systems are observed over the Bay of Bengal during the night time. It is interesting to mention that over the land region, the night time maximum occurrence of MCSs over the foothills of Himalaya and after noon maximum occurrence over the Bangadesh plain as observed by the TRMM (Figure 2.1, 2.2 and 2.3) is in agreement with the high temporoal resolution observations from the INSAT 3D (Figure 2.5).



(a)



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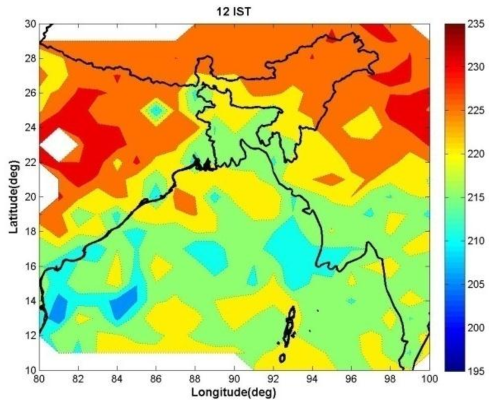

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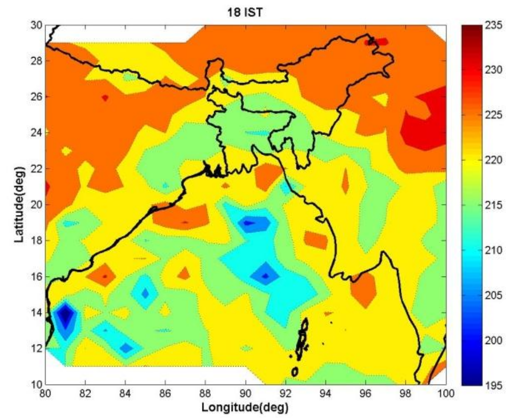


(d)

Figure 2.5: Spatio temporal variation of the median value of T_{b12} during the premonsoon season at (a) from 00-06 MST (b) from 06-12 MST (c) from 12-18 MST and (d) from 18-00 MST.

2.3 Summary and Conclusions

A climatological study of diurnal variability of the properties of MCSs is carried out during 1998 to 2012 over the eastern and north eastern region of India along with the adjoining area (20^0-30^0N; 80^0-100^0E), a region of complex topography. The MCSs properties are studied with the help of TRMM sensors. Significant spatiotemporal variability of the properties of MCSs is observed. The salient features of the present study are as follows –

- The observation from TRMM as well as INSAT 3D suggests that there is a significant regional variability in the diurnal characteristics of the convective systems over the study region. The foothills region of Himalya including the Assam valley have maximum occurrence during night to morning hours, whereas the plain region of Bangladesh, Gangetic west Bengal, northern part of east coast have maximum occurrence during afternoon to night hours.

Chapter 3

Detection of Hail Features (HFs) by satellite onboard microwave sensors over the north eastern part of India

Detection of Hail Features (HFs) by satellite onboard microwave sensors over the north eastern part of India

3.1. Introduction

Thunderstorm with hail is a meteorological hazard, which causes significant property damage. Hail is labelled severe, when it is greater than 20 mm in diameter. Diameter greater than 8 mm is used to differentiate hail from graupel. Hail storms are manifestation of severe and deep layer moist convection in the atmosphere. The essential ingredients for the occurrence of severe storms are the presence of an environment of deep layer instability in a warm and humid air mass with high value of Convective Available Potential Energy (CAPE). The general atmospheric conditions under which hail storms occurs are as follows –

(a) High instability with Cb clouds growing to very high levels.

(b) Presence of large vertical currents inside the clouds. Large vertical current is associated with large thermal instability. The hail size is proportional to the updraft velocity in the thunder clouds.

(c) High moisture content in the atmosphere. The greater the moisture content, larger is the size of the hail stones.

(d) Lower freezing level is conducive to hail storms. One of the factors favourable for hail storms in north and central India in winter and early spring is the lower freezing level. Large hails are generally reported with wet bulb zero heights in the range of 2-3 km.

(e) Earlier analysis of upper tropospheric conditions on the day of hail storms show that the occurrence of hails over central and southern peninsula was generally associated with deep upper tropospheric westerly trough and the associated Southern Tropical Jet (STJ) core coming down to lower latitude.

Many researchers have studied the hail phenomena and associated thunderstorms over different parts of India and Bangladesh (Eliot, 1899; Misra and Prasad, 1980; Chaudhaury and Mazumdar, 1983; Ramanamurthy, 1983; Chowdhury and Banerjee, 1983;

Pandharinath and Bhavanarayana, 1990; Kumar, 1992; Nizamuddin, 1993; Chakravorty and Bhowmik, 1993). Eliot (1899) studied the 597 hail events over India and reported that 153 hail events were with hail stone ≥ 3cm diameter. Chowdhury and Banerjee, (1983) studied the eight year's hail data over the north-eastern state and reported 30 hail storms/year Misra and Prasad (1980) pointed out that over the west coast and central inland India (15^0-20^0N), the frequency of hail event is relatively low. Chaudhaury and Mazumdar, (1983) pointed out that expectancy % of hail (number of days with hail/no. of days with thunderstorms) decreases from 5 to less than 2 % from March to May in north eastern states and Bangladesh. Pandharinath and Bhavanarayana (1990) carried out a case study of hail storms from 11-13 March 1981 in Andhra Pradesh (16 0N) which inflicted heavy damage to life and property in the state. Nizamuddin (1993) reported around 228 hail days over India during 1982-1989, primarily concentrated over the central high land and Himalayan region. Ramanamurthy (1983) studied the hail frequency for 100 years period and they reported one hail event/year in north-eastern India and 5 to 10 hail events /year in northern India and in the Himalayan region.

Conventionally the above mentioned hail storms studies are based on the ground reporting of the events by the staffers and volunteers. The midlatitude regions boast the existence of dense network of hail pad, whereas tropical region lacks the good network of hail paid or other hail detecting device. Therefore satellite based detection of hail features is an alternative option with promising potential. Satellite-borne passive microwave radiometers record brightness temperature depressions due to the scattering of upwelling radiation by large ice hydrometeors (graupel, hail). Spencer et al. (1983, 1987) and Spencer and Santek (1985) examined satellite measurements of 37-GHz brightness temperature as an indicator of intense convection and severe thunderstorms

In particular, Spencer et al. (1987) matched storm brightness temperatures to U.S. severe weather reports and Spencer and Santek (1985) mapped low–brightness temperature storm events globally. Cecil et al. (2005) and Zipser et al. (2006) have used Tropical Rainfall Measuring Mission (TRMM) measurements of several parameters as proxies to examine intense thunderstorms. These parameters include minimum 85- and 37-GHz brightness temperatures, maximum radar reflectivity at certain altitudes and maximum heights attained by certain reflectivity, lightning flash rates, and other measures. More recently Ceil (2009, 2011; Cecil and Blankenship 2012) has utilized the passive microwave brightness temperature as a proxies for the detection of hail storms.

Conventionally the hail storms studies are based on the ground reporting of the events by the staffers and volunteers. The tropical region lacks the good network of hail paid or other hail detecting device. Therefore, satellite based detection of hail features is an alternative option with promising potential. Satellite-borne passive microwave radiometers record brightness temperature depressions due to the scattering of upwelling radiation by large ice hydrometeors (graupel, hail). Spencer et al. (1987) examined satellite measurements of 37-GHz brightness temperature as an indicator of intense convection and severe thunderstorms. Recently Ceil (2009) has utilized the minimum 37-GHz brightness temperatures, as proxies for the detection of hail storms. Motivated by the encouraging results of Cecil (2009), a study is carried out over north-east India to study the hail features in CSs.

The main focus of the present chapter is to study the spatial and monthly variability of the thunderstorms with hail features over the north east part of India by using the 37 (V, H) GHz channels of TRMM Microwave Imager (TMI) and TRMM-PR along with the ground reporting in association with the atmospheric convective parameters. the U.S. severe storm database has been used to quantitatively link TRMM Microwave Imager (TMI) measurements to the occurrence of large hail. Motivated by the encouraging results of Cecil (2009; 2011), a study is carried out over a north-east India to study the hail features in CSs.

3.2 Study Area

The present study is carried out over the north-east part of India within a domain of 23 – 29 ^{0}N and 89-100 ^{0}E as shown in Figure 3.1. The selected region has a complex topography, where height of the terrain is changing from mean Sea Level (MSL) to mountains of average height of 5000 meters. The ground hail reporting data are considered over the eleven IMD stations over the region. The details of the stations, namely their name, geo-location and MSL height of each station is provided in Table 6.1.

Topographically region consists of Eastern Himalya range, Patkai hill range and there is a valley region, Assam valley along west - east direction.

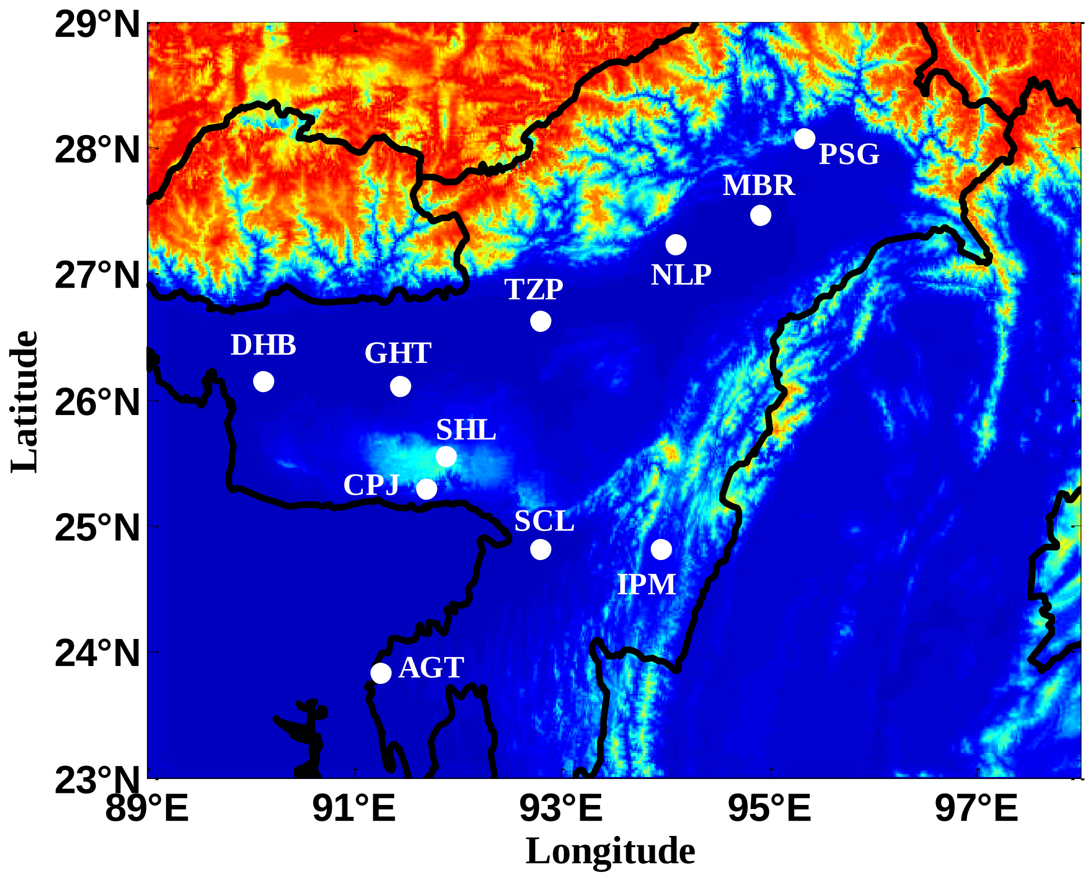


Figure 3.1: Physiographic map of the study region

Table- 3.1: Geospatial information about the reporting station and reported thunderstorms

Station Name	Lat (deg)	Long (deg)	Height from MSL (meter)	Total TS
Agartala (AGT)	23.30	91.26	16	189
Cherapanji (CPJ)	25.30	91.70	1313	277
Dhubri (DHB)	26.15	90.13	35	417
Guwahati (GHT)	26.11	91.44	54	1047
Imphal (IMP)	24.82	93.95	781	901
Mohonbari (MBR)	27.47	94.91	111	706

North Lakhimpur (NLP)	27.24	94.10	102	490
Pasighat (PSG)	28.07	95.33	157	253
Shillong (SHL)	25.56	91.88	1598	411
Silchar (SCL)	24.82	92.80	20	1040
Tezpur (TZP)	26.63	92.80	90	1298

3.3 Data products

In this present study, we collected hail reports from journal records available at the Regional Meteorological Center at Guwahati from 1998 to 2014. These reports are based on 11 stations (Figure 6.1) over North-East India. Surface-based hail reports depend on storm spotter reports. These reports generally have some uncertainty associated with the precise times and locations. Therefore, we identified multiple reports within an hour at a station and it considers a single report, because the hails are coming from same storm.

The University of Utah TRMM level-2 cloud and precipitation feature datasets is utilized (Liu *et al.*, 2008) in this study. This dataset was developed through the collocation of TRMM-Precipitation Radar (TRMM-PR), TRMM microwave Imager (TMI), visible and infrared scanner (VIRS), and lightning imaging sensor (LIS). For the present study, radar detected Precipitation Feature (RPFs) database is utilized. The PFs are defined by contiguous TRMM-PR 2A25 v6 (Iguchi *et al.*, 2000) near-surface raining pixels. The PFs with at least four contiguous pixels are only taken into account to eliminate noise. Six parameters are used to study the characteristics of storms, namely, maximum echo top heights of 20 and 40 dBZ ($ETH_{20dBZ(max)}$; $ETH_{40dBZ(max)}$), flash counts (FC), minimum polarization corrected brightness temperatures at 85 and 37 GHz ($PCT_{85(min)}$; $PCT_{37(min)}$) (Spencer et al., 1989) and area of the system. In addition to this parameters, vertical profiles of maximum reflectivity area of the system is defined as number of PR raining pixels multiplied by resolution of TRMM-PR pixel. $ETH_{20dBZ\ (max)}$ is an indicator of precipitation height, which represent how high the updraft can lift the precipitation size particles, whereas, $ETH_{40dBZ(max)}$ is an indicator of the convective intensity or the updraft speed of the convective cells (Xu and Zipser 2012). PCT_{85} and PCT_{37} are scattering signatures of precipitation size ice particles (Cecil, 2009; Nesbitt *et al.*, 2000). Moreover, the vertical profile of maximum radar reflectivity is a direct indicator of the vertical structure of the convective core (Xu and Zipser, 2012).

National Centers for Enviromental Prediction (NCEP) reanalysis on a 2.5^0 x 2.5^0 grid resolution (Kalnay et al. 1996) are used for this study. We use 4-times daily data to create composite large-scale patterns.

3.4 Methodology

Cecil (2009) provided an approach to quantify the fraction of precipitation features (PFs) with minimum PCT threshold that has corresponding large hail (about 2 cm) in the comparison with the United States storms reports. PFs with minimum PCT_{37GHz} had most effective for identifying hail storms. About 24%, 44%, and 70% of PFs with minimum PCT_{37GHz} below 255, 220 and 180K have the large hail reports. Minimum 37-GHz PCT depends on vertical profile of hydrometeor contents, types and sizes in the PFs. There are many combinations of them which can be resulted the same brightness temperature over different meteorological regimes (Cecil 2011). So, probability of hail reports of PFs with minimum PCT_{37GHz} over the United States are not directly use to other regimes. Cecil (2011) scaled the minimum 37-GHz PCT values to the equivalent subtropical land (United States) values using a linear best fits coefficients between minimum 37-GHz PCT and mixed phase region ice water content. Here, we scaled the tropical India minimum 37-GHz PCT toward an equivalent subtropical land value using the scale coefficients from Cecil (2011). Using the fit coefficients 257, 210, and 156 K of minimum 37-GHz PCT from the tropical India would be equivalent to 255, 220, and 180 K values from subtropical land.

For the present study, three types of Hail Features (HFs) are defined using its scaled minimum PCT_{37}. They are type one (T-1), type two (T-2), and type three (T-3). Criteria of minimum PCT_{37GHz} are given in Table 3.2. Three types of HFs are observed at 11 stations within 100 Km from stations. Here, we mainly focus on the characteristics of these storms during the premonsoon season (March-April-May) from 1998 to 2014.

Table- 3.2: Criteria for three different types of HFs

Criteria	Probability of hail reporting for large hail (>2cm)	Type of HFs	Total No. of Detected HFs	No. of Detected HFs with MCSs
210-K ≤ $PCT_{37GHz(min)}$< 257 K	24 %	T-1	1131	194
156-K ≤ $PCT_{37GHz(min)}$< 210 K	45 %	T-2	166	31
$PCT_{37GHz\ (min)}$ < 156 K	70 %	T-3	31	13

In the present study the HFs are further associated with TRMM-PR observations in terms of Echo Top Height (ETH), The detail data base is described by Liu *et al.* (2009). For the present study data are downloaded from the University of Utah website.

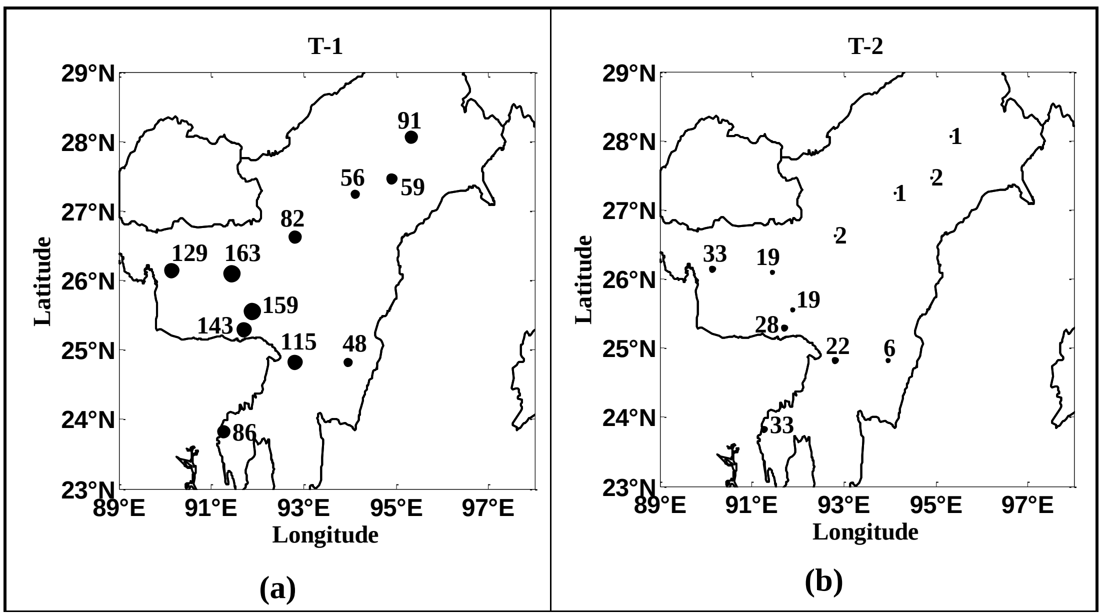
3.5 Results

3.5.1 Spatial variation of hail events

The Table 3.1 also shows the number of reported thunderstorms over each selected station. The significant spatial variability is observed over the study region. The maximum thunderstorms are reported over the Tezpur station (1298) and followed by Guwahati (1047) and Silchar (1040) in Assam. The minimum reported thunderstorms are over Agartala (189) Tripura in and closely followed by Pasighat (253) in Arunachal Pradesh

At the outset, with the help of TMI observation, the occurrence of HFs are identified over each station at different thresholds criteria of PCT_{37} namely as provided in Table 3.2. The number of detected HPFs for different thresholds over each station are shown in Figure 3.2 (a-c) respectively. The HPFs are considered within the 100 km diameter, with the location of the station at the centre. It is observed that there is change in the characteristics of the spatial variation of the occurrence of HFs for different threshold criteria. The most significant occurrence of type T-1 HFs is found over Guwahati Station (163), followed by Shillong (159) and Cherapungi (143) stations. Apart from them, over Dhubri (129) and Silchar (115) also occurrence is significant. It is also observed that towards the upper part of the Assam valley stations (Tezpur, North Lakhimpur, Mohanbari and Pasighat), the occurrence of type T-1 HFs is relatively less, varying in the range of 56-

91, compared to other stations. For the type -2 HFs, overall occurrence is reduced and the characteristic of spatial variation is changed. Now the maximum occurrence is over the Agartala (33) and Dhubri (33). Over the upper part of the Assam valley, the pattern is similar to type -1 HFs, albeit with significantly reduced occurrence. Further for type -3 HFs, overall occurrence is further reduced and yet the characteristic is same i.e. maximum occurrence is over the Agartala (11) followed by Dhubri (6). Over the upper part of Assam valley, the type-3 HFs are absent. Further the spatial variation of the ground reporting of the hail events at different stations are shown in the **figure 3.2 (d).** Except over Tezpur station, the pattern of the spatial variation of the ground reporting of hail is similar to the type-3 HF (**Figure 3.2 c).** In both the cases the maximum occurrence is over Agartala (Type-3 HFs11; Ground reporting: 22).



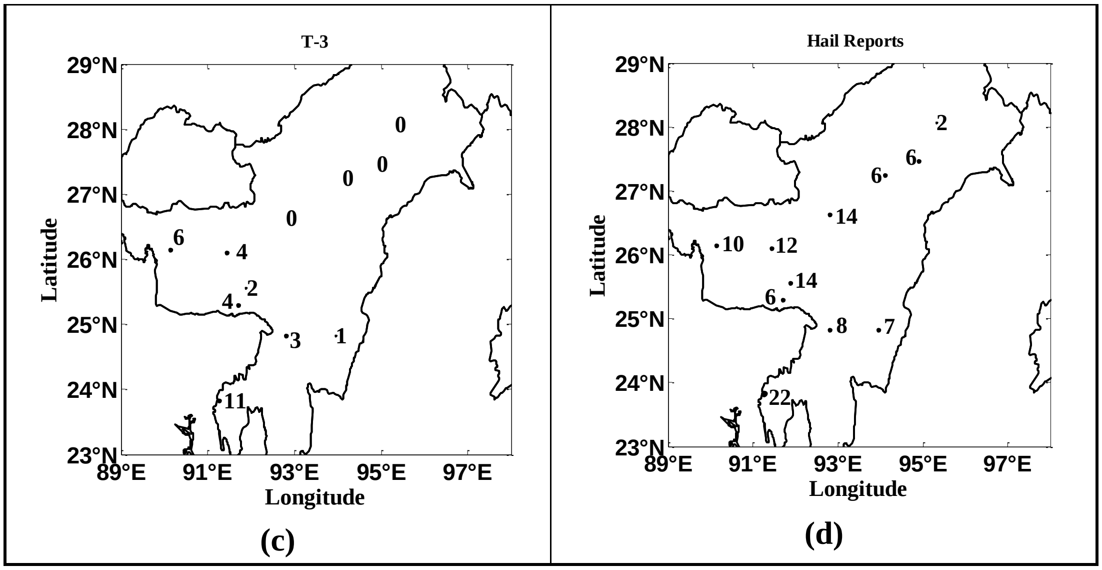


Figure 3.2: Spatial variation of occurrence of thunder storm with (a) T-1 HFs (b) T-2 HFs (c) T- 3 HFs. and (d) ground reporting.

Overall it is observed that HFs with low probability of ground reporting (T-1, probability-24%) occur most frequently in Guwahati with 186 features. In addition, HFs also show more frequent occurrence in Shillong with 180 features, Cherrapunji with 175 features, Dhubri with 168 features and Agartala with 130 features. HFs with high probability of ground reporting (T-3, probability-70%) occur mostly in Agartala with 11 features. Moreover, the occurance is more frequent in Dhubri with 6 features, Guwahati with 4 features, Cherrapunji with 4 features and Shillong with 2 features. These HFs are relatively less at Pasighat, Tezpur, Mohanbari, North Lakhimpur, Imphal. These stations are mainly dominated by HFs with less probability of ground reporting (T-1, probability – 24%). It is important to mention that, the TMI detected HFs are for larger hail size (> 2 cm). there is possibility that the ground reporting of the hail event with smaller hail size may not be detected by the TMI. Further due to poor temporal resolution, there is large probability to miss the detection of hail event. Imphal has not detected the most severe HFs as well as associated MCSs. This result is in reasonably good agreement with the ground reporting of the hail.

3.5.2 Verical profiles of radar reflectivity during hail events

The height profiles of the median value of radar reflectivity factor (dBZ) for T-1, T-2 and T-3 HPFs are shown in **Figure 3.3.** Convective vertical profiles show that T-3 HFs have strongest vertical profiles and T-1 HFs have weakest vertical profiles throughout all the heights. T-1, T-2, and T-3 HFs have about 35, 45, and 49 dBZ radar reflectivity at 9 Km height (within the mixed-phase region). These differences in vertical structures correlates with hail reporting probability at ground for T-1, T-2, and T-3 HFs, as T-3 HFs have a highest hail detection probability (around 70%) and T-1 HFs have lowest probability of detection, (around 24%). The strongest vertical structure of T-3 HFs indicates strong updraft and large ice particles presence in the mixed - phase region. It also represents that strong mixed-phase microphysical processes (i.e., freezing of raindrops and riming) involved for production of hail/graupel. Overall, for T-1 the gradient is sharper than the T-2 and T-3. The higher value of dBZ at mixed phase region support the defined category of the hail storms, which suggests that T-2 and T-3 are more conducive for hail stone. Overall, the correlation coefficient for PCT_{37} vs ETH_{40dBZ} are found to be - 0.69.

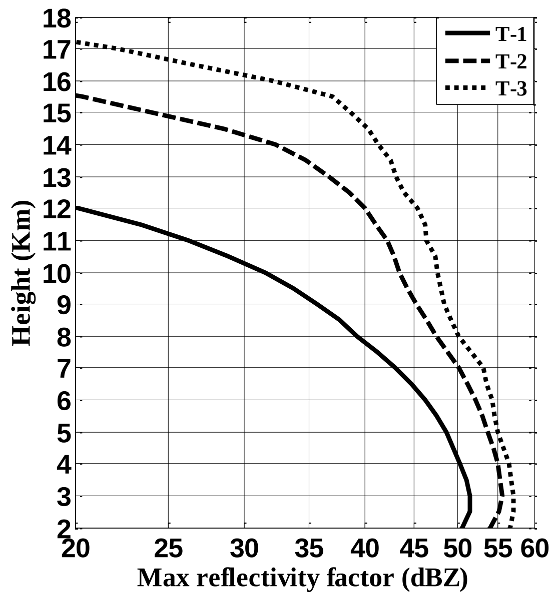


Figure 3.3 : Vertical profiles of radar reflectivity factor for T-1, T-2 and T- 3 HFs

The top 50 % (50th percentile) and 1% (99th percentile) values of Echo top height of 40dBZ each type of PCT_{37} are provided in the **Table 3.3**. It is observed that the maximum value of the parameters in both the cases is for T-3 HFs. This is in agreement with the top 50 % (50th percentile) and 1% (99th percentile) values of PCT $_{37}$ **(Table 3.3)** , which have the minimum value for T-3 HFs.

Table 3.3: 50th and 90th percentile values of various parameters for three different types of HPFs

Parameters	HPFs					
	50th percentile			90th percentiles		
	T-1	T-2	T-3	T-1	T-2	T-3
Max-ETH-40 dBZ (Km)	7.75	11.50	14.75	10.50	14.50	16.50
Min-PCT_{37GHz} (K)	245.73	192.90	149.67	222.87	171.21	126.55
Area (Km^2)	295.84	314.33	1164.87	4178.70	5473.00	28104.80

The mean vertical profiles of the radar reflectivity factor over 8 stations are shown in Figure 3.4. A strong spatial variation in the characteristics of vertical profile is observed over these stations. It is observed that over Agartala and and Dhubri the 40 dBZ echoes are observed upto 9.50 and 9.25 km respectively, suggesting a strong mixed phase process (rimming) over these two stations. The strong mixed phase process is an indicator of greater probability of hail storms over these stations, which is in good agreement with the PCT_{37} observations. On the other hand over Mohanbari and Pasighat stations the 40 dBZ echoes are observed upto 7.50 and 5.00 km respectively, suggesting a weak mixed phase process over these two stations, which is not a favourable situation for the large hail storms over these two stations. The result over these two stations is also in agreement with the PCT37 observations.

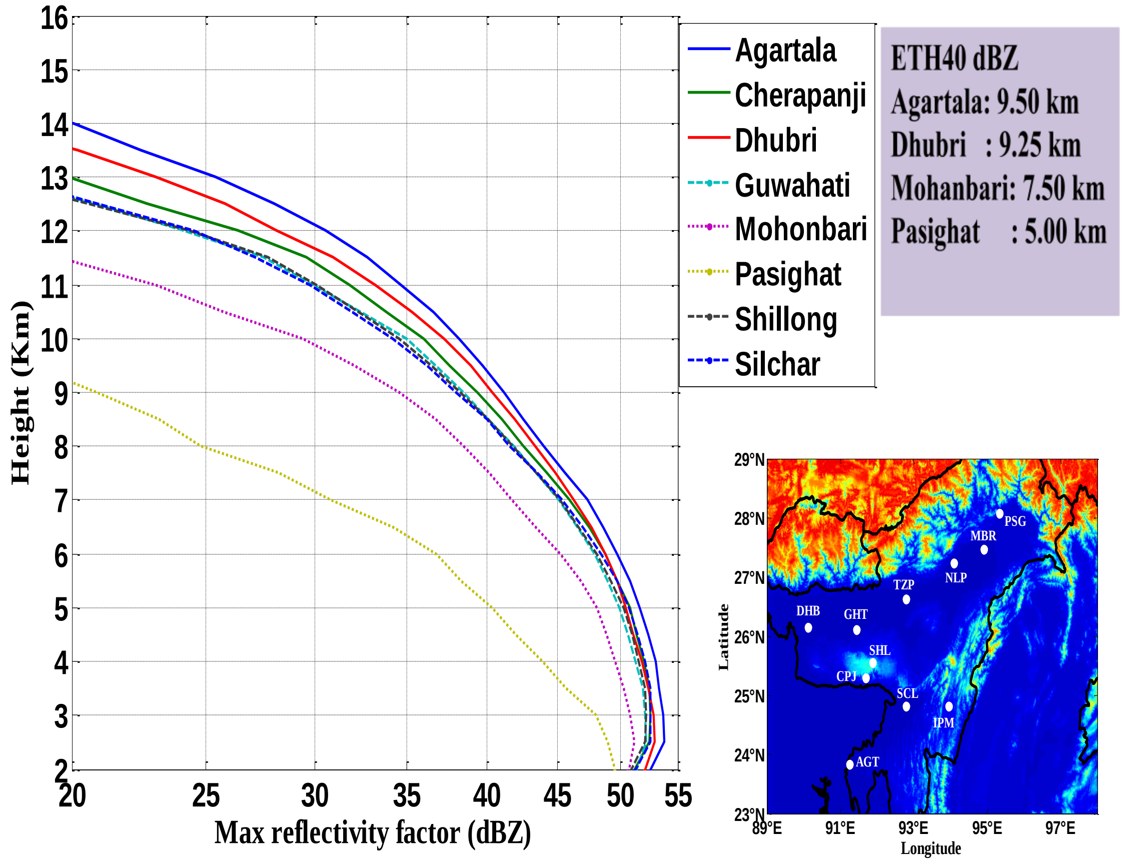


Figure 3.4: Mean vertical reflectivity profile over eight stations

3.5.3 Monthly and diurnal variation of hail events

During the pre-monsonn, the monthly variation of the occurrence of satellite detected T-1, T -2 and T-3 type of HFs along with the reported hail events are shown in **Figure 3.5 (a, b)** respectively. It is observed that for all types of storms the maximum occurrence is during the month of April albeit with different occurrence for each case. The similar pattern is observed for reported hail events also. These results are consistent with the previously reported work on hail storm occurrence. Chaudhary and Mazumdar (1983) shows that the expectancy percentage of the hail derease from 5% to less than 2% from

March to May for north eastern India and Bangladesh. Chowdhuiry and Banerjee (1983) examined eighth year years data for north eastern India. They found that 30 hail storms occurs per annum. The seasonal variation shows the influence of westerly trough in the pre-monsoon seasons with maximum in April. They further find a jet stream maximum, upper lecvel divergence accompanying the trough. They also showed the late evening hail storms maximum. They further pointed out that shear in the 850-300 mbar level is four time greater than average for the pre-monsoon months. Ramamurthy (1983) studied the frequency of hail for a 100 years period. They showed there is one event per year in north - east India.

Further during the pre-monsoon season the diurnal variation (at the increment of 03 hrs) of the occurrence of T-1, T-2 and T-3 type of HFs along with the reported hail storms are shown in **Figure 3.6 (a, b)** respectively. It is observed that the T-2 and T-3 HFs occurs predominantly during 2100-2400 hrs with minimum occurrence during 0600-0900 hrs. The reported hail storms are during 1800 to 2100 with minimum occurrence at 2400 to 0300 hrs.

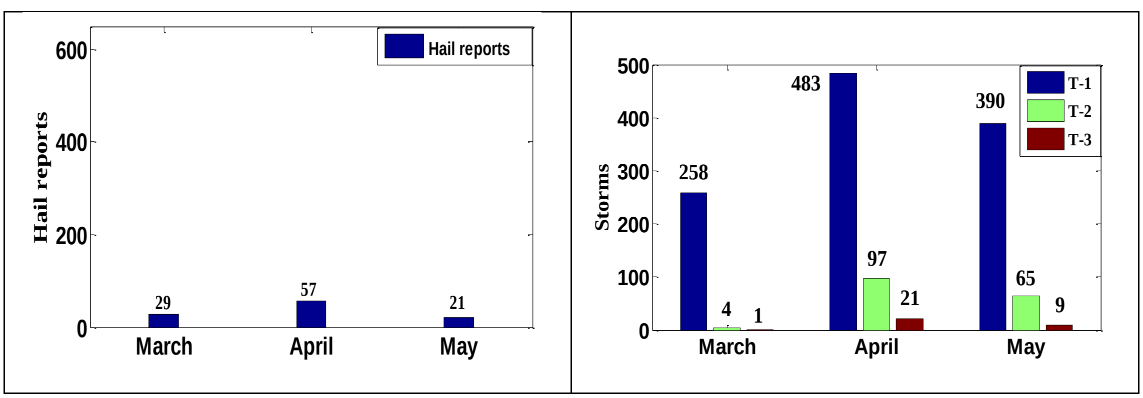


Figure 3.5: Monthly variation of (a) reported hail storm events (b) Satellite detected thunderstorm for Type1, Type 2 and Type 3 HPFs

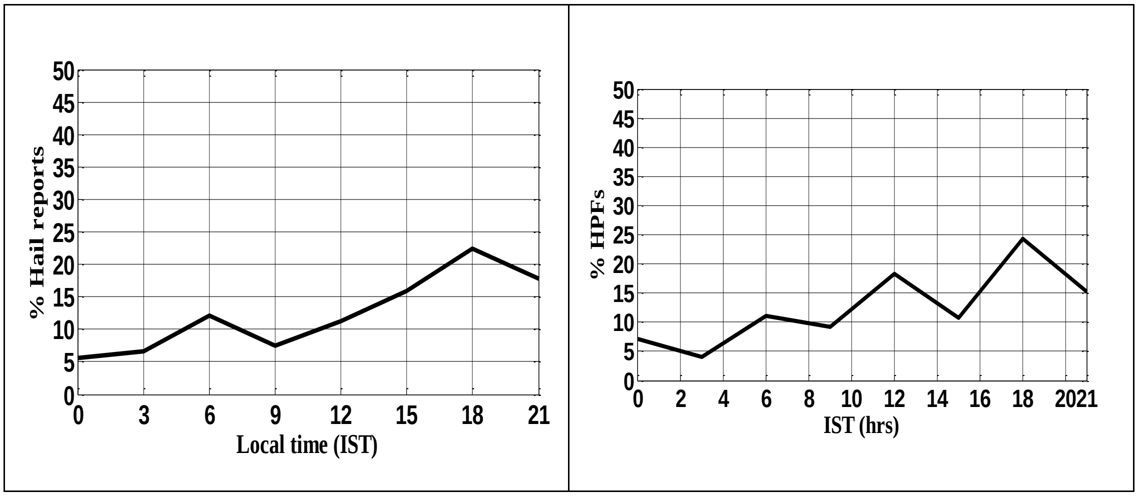
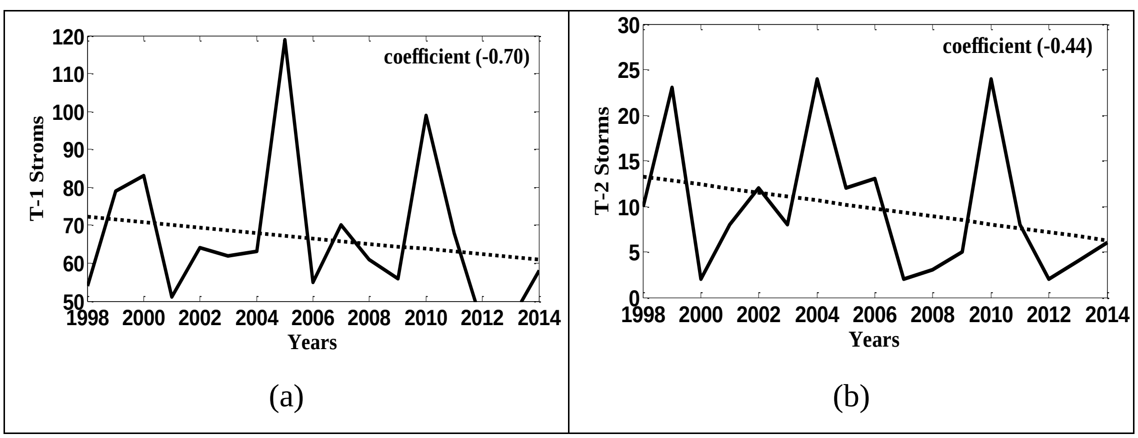


Figure 3.6: Diurnal variation of (a) reported hail storm events (b) Satellite detected thunderstorm for Type1, Type 2 and Type 3 HPFs

3.5.4 Interannual variation of occurrence of detected and reported hail events

The inter-annual variation of the occurrence of T-1, T-2, T-3 HFs and reported hail storms are shown in **Figure 3.7 (a-d)** respectively. The peaks (1999, 2004, 2010, and low (2007,2011, 2013) of the satellite detected and ground reporting are matching



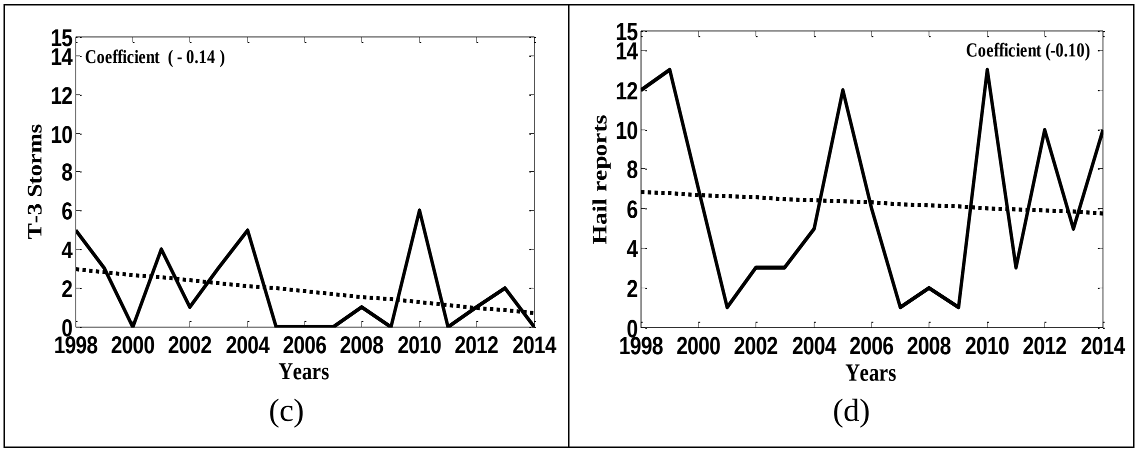
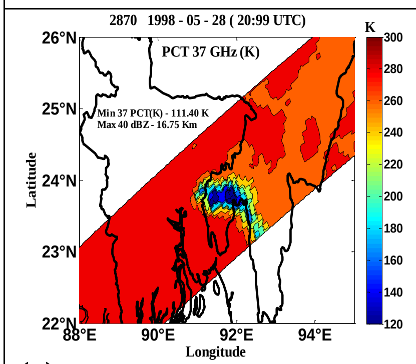
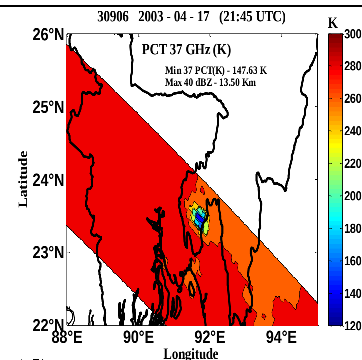
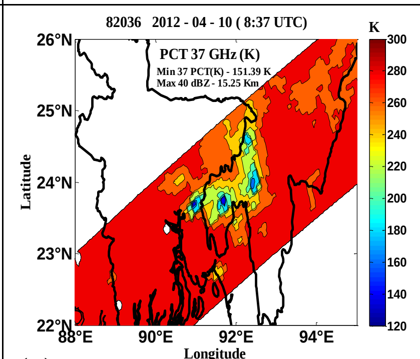
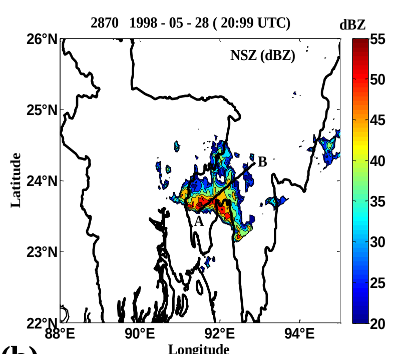
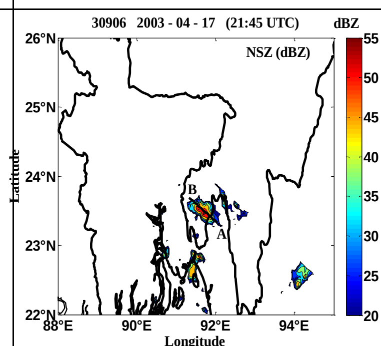
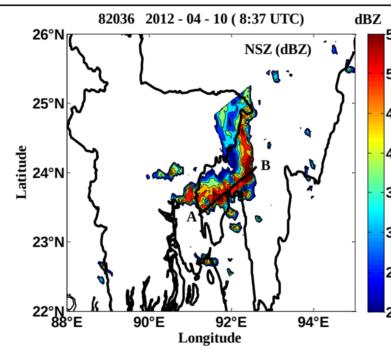
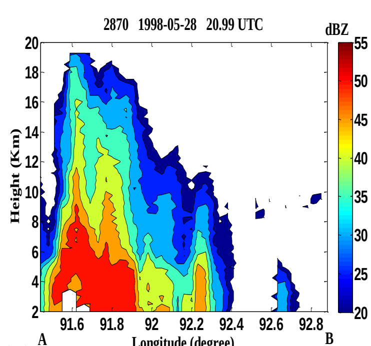
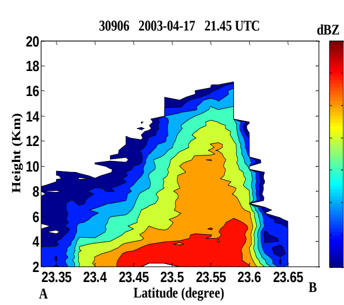
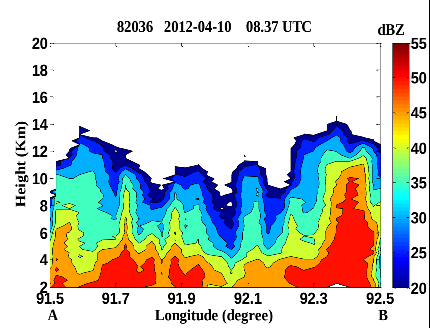


Figure 3.7 : Trend of annual variation of Satellite detected thunderstorm for (a) T-1, (b) T-2 (c) T-3 HPFs and (d) reported hail storm events.

3.5.5 Case study of the hail events

Three case studies of the reported hail events over the Agartala stations on May 28th 1998 , April 7th , 2003 and April 10th , 2010 are presented. On these three days near simultaneous collocated observation by TRMM sensors are available. The simultaneous observations of PCT_{37}, near surface radar reflectivity and longitude/latitude vs height cross section of reflectivity during 1998, 2003 and 2010 are provided in figure 3.8 (a-c), 3.10 (d-f), 3.10 (g-i) respectively. The hail storms in 1998 and 2010 were multi cellular bow echoes events and a hail storms in 2003 was a single cell event. It is observed that during all these three events, the value of PCT_{37} and surface reflectivity are in the range of 120 -140 K and 50-55 dBZ respectively. It is also observed that in 1998, 2003 and 2010 the 40 dBZ echoes were observed upto 16 km, 13 km and 10 km respectively, indicating the presence of strong mixed phase process during the hail events.

Agartala: May 28th , 1998 Figure 3.8 (a-c)	Agartala: April 7th, 2003 Figure 3.8 (d-f)	Agartala: April 10th, 2010 Figure 3.8 (g-i)
 (a)	 (d)	 (g)
 (b)	 (e)	 (h)
 (c)	 (f)	 (i)

3.6 Summary and Conclusion

The present work is carried out to study the spatial and temporal variability of the occurrence of HFs over the north east India. The analysis is carried out over the 11 stations. The results are as follows

- On the basis of threshold value of the Polarization corrected temperature of 37 GHz channels (PCT_{37}), hail features (HFs) are classified into three categories namely, T-1 (with hail detection probability of 24%) , T-2 (with hail detection probability of 45%) and T-3 (with hail detection probability of 70%).
- T-1, T-2, and T-3 HFs have about 35, 45, and 49 dBZ radar reflectivity at 9 Km height (within the mixed-phase region). The nature of vertical structures of reflectivity for T-1, T-2, and T-3 HFs. correlates well with hail reporting at ground. The strongest vertical structure of T-3 HFs indicates the strong updraft and large ice particles presence in the mixed - phase region. It also represents that the strong mixed-phase microphysical processes (i.e., freezing of raindrops and riming) are involved for production of hail/graupel.
- The two stations in the plain region, namely Agartala and Dhubri, detected the maximum occurrence of most severe HFs (type T-3). The stations in the valley regions namely Tezpur, Mohanbari, North Lakhimpur, Pasighat, and Imphal have not detected the most severe HFs. The spatial variability in the HFs is amply supported by the vertical profiles of reflectivity and its value at mixed phase region.
- During the premonsoon, the maximum occurrence of HFs is found in April. The occurrence of HFs is minimum in March.
- HFs show strong diurnal variation. with maximum occurrence during the afternoon hours
- Occurrence of HFs show noticeable year to year variation. There is a decreasing trend during the period 1998 - 2013. The trend values are -0.70, -0.44, -0.14 and -0.10 for T-1, T-2 and T-3 HFs and ground reporting respectively.

Climatologically, there is a spatial and temporal variability in the occurrence of HPFs over the study region. With preferential occurrence over the plain regions. The patterns of seasonal and diurnal occurrence of MCS with hail features as detected by satellite derived parameters are consistent with the ground report over the stations. Compared to other parameters, the ETH_{40dBZ} is better correlated with PCT_{37} with a CC values of -0.69 respectively. It is suggested that these values can also be considered as a proxies for the detection of hail features. The present work is still in a developing stage. Regional or regime dependent variability of hail detection can lead to similar brightness temperatures coming from different hydrometeor profiles. This methodology provides an approach for objective climatologies that do not rely on surface reports or spotter networks, which vary greatly from region to region".

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Future Plan

(i) Installation of Instruments at different locations

Kohima Science College:	Micro Rain Radar
	Parsivel Disdrometer
	Lightning Detector (LD -100)
	Electric Field Mill (EFM-350)
	Automatic Rain gauge.
Indian Statistical Institute, Giridih:	Parsivel Disdrometer
(Jharkhand)	Lightning Detector (LD -100)
	Electric Field Mill (EFM-350)
	Automatic Rain gauge
Fazal Ali College, Mokokchung (Nagaland):	Automatic Rain gauge
Phek College, Phek (Nagaland)	Automatic Rain gauge
Sao Chang College, Tuensang (Nagaland)	Automatic Rain gauge
Patkai Christian College, Dimapur (Nagaland)	Automatic Rain gauge
Zunheboto College, Zunheboto (Nagaland)	Automatic Rain gauge
Mounttiyi College, Wokha (Nagaland)	Automatic Rain gauge
Mon College, Mon, (Nagaland)	Automatic Rain gauge
Zisaji College, Kiphre (Nagaland)	Automatic Rain gauge
(ii). Analysis of Socio-Psycho data	Data over west Bengal and Nagaland and Assam
(iii) Downloading and Analysis of satellite data	INSAT 3D, GPM and CloudSat

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1.	. Prof. Srimanta Pal	Associate Member	Electronics and Communication Science Unit (ECSU), Indian Statistical Institute, Kolkata
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6	Utpal Misra	Associate Member	Head, Department of physics, Patkai Christian College, Dimapur
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6.	Dr. Sanjay Sharma Member Secretary	Member Secretary	Assistant Prof. (PI –RUSA R & I Project) Department of Physics, Kohima Science College , Jotsoma, Kohima Nagaland-797002
7.	State Project Director RUSA, Nagaland	Special Invitee	Department of Higher Education Kohima, Nagaland-797004
8.	Nominee Nagaland State Disaster Management Authority (NSDMA)	Special Invitee	Department of Home, Nagaland. Kohima, Nagaland-797004

Annexure III A: Publication				
Sl. No	**Authors**	**Title**	**Reference**	**Impact factor (Thomson Reuter)**
1.	Roy P, Biswasharma R, Deshamukhya A, Sharma S, Gairola R M	A study of the spatio-temporal variability of the properties of intense precipitation features over South Asian region: An integrated multi sensor approach.	International Journal of Climatology, doi: 10.1002/joc. 5027. (2017) In Press	3.61 A Journal of Royal Meteorological Society, UK (Published by Wiley International)

Annexure III B: Paper presented in the conferences			
Sl. No	**Author**	**Title**	**Place and date**
1	Sharma S	Study of Hail Features over the North East India by using 37 GHz TRMM Microwave Imager Channels and TRMM Precipitation Radar	India Conference on Radar Meteorology, IIT Kharagpur, January 8 - 11, 2017
2	Roy P	Seasonal and Intraseasonal variability of rainfall characteristics of convective systems over the South Asian region using TRMM-PR	India Conference on Radar Meteorology, IIT Kharagpur, January 8 - 11, 2017

3.	Biswasharma R	Properties of Deep convective clouds over the northeastern part of India and adjoining region as observed by CloudSat onboard Cloud Profiling Radar	India Conference on Radar Meteorology, IIT Kharagpur, January 8 - 11, 2017
4.	Roy P	A study of the spatio-temporal variability of the properties of intense precipitation features over the South Asian region: An integrated multi sensor approach,	North East Space Application Centre (NESAC) -Academia and Students Interaction meet, Umiam, Shillong,, June 24th , 2016.
5.	Biswasharma R	A study of convective systems over over north eastern India by using INSAT – 3D observations	North East Space Application Centre (NESAC) -Academia and Students Interaction meet, Umiam, Shillong, June 24th , 2016.

Annexure III C: Participation to short term courses/training programs

Sl. No	**Name**	**Name of the Training program**	**Resource Persons**	**Place and date**
1.	Sharma S	Forecasting severe convection I	Dr. C A Doswell USA	ESSL Science and Training Wiener Neustadt, Austria June 20th -24th , 2016.

2.	(i). Roy P (ii) Bishawasharma R (iii) Imolemba (iv) Sharma S	Short term course on Radar Meteorology	(i). Prof. V Chandrasekar Colarado State University, USA (ii), Dr, N. Bharadwaj North Western University, USA (iii) Prof. U Ushio, Osaka University, Japan, (iv)	IIT, Khragpur, January 8th, 2017
3.	**Project Assistant** (i) Nyuthe V **Associate Members** (ii). Meniele K.Nuh (iii).Selie Puro (iv) Kekhriele Nakhro (v) R. Bendangtemjen (vi) Forchiba Kichu	Short term course on "Landslide and debris flow systems: Prediction, control and reclamation" [Under Global Initiatives of Academic Network (GIAN) initiative, MHRD]	(i). Prof. Martin Haigh, Oxford Brook University, UK. (ii) Prof. G. T. Thong Nagaland University, (iii) Prof M S Rawat Nagaland University	Nagaland University, March 7th - 11th, 2017

Annexure IV: Severe Weather Survey North Eastern India 2016 © A.G.Keul & S.Sharma final version 29-9-16

The following questions deal with your daily weather information and with severe weather. Thank you very much for your interest to take part in this anonymous survey !

1. Are you weather-exposed in your daily life?

☐ yes, always ☐ yes, often ☐ sometimes ☐ no, not at all

2. Do you follow the daily weather report(s) in the media?

☐ yes, always ☐ yes, often ☐ sometimes ☐ no, not at all

3. Where do you get your daily weather information? [*please mark the most important sources]* ☐ newspaper ☐ internet ☐ cellphone ☐ radio ☐ television ☐ family

☐ other:……… ☐ other:……… ☐ other:………

4. Is the quality of the weather report in radio/TV OK for you?

☐ yes ☐ not always ☐ no

5. Do you easily get your local weather from media weather reports?

☐ yes ☐ not always ☐ no

6. Should media weather reports give precautions?

☐ yes ☐ only in severe danger ☐ no

7. How dangerous do you think are any of the following severe weather phenomena for you? [*Give each of them a number between 10=very dangerous* and *0=not dangerous at all]*

….. cyclones ….. heat/drought ….. landslides ….. hail …..tornadoes

….. floods ….. lightning ….. heavy rainfalls …..wildfires …..thunderstorms

8. Are you personally afraid about severe weather?

☐ yes, very ☐ at times ☐ no, never

9. Do you feel well-informed about severe weather?

☐ yes, very ☐ at times ☐ no, never

10. Did you learn about severe weather protection in your school education?

☐ yes ☐ no

11. Areas called „high"/"low" on a weather map:

☐ are hotter/colder ☐ are more windy/calm ☐ have different air pressure ☐ I don't know

12. Do you know different cloud types?

☐ yes ☐ no

Give an example: ………………………………………

13. Can you find out by your own observation whether severe weather (excessive rain, hail, lightning, storm) is upcoming? ☐ yes, certainly ☐ not always ☐ no ☐ I don't know

I4. When three seconds pass between a lightning flash and its clap of thunder, this lightning flash had a distance of ………. kilometer(s) / ……….. miles from my own position. ☐ I don't know

I5. Who is hit by lightning, is killed instantly ☐ yes ☐ no ☐ don't know

I6. You are safer from lightning inside a building. ☐ yes ☐ no ☐ I don't know

I7. Out in the open, lie flat on the ground in a thunderstorm. ☐ yes ☐ no ☐ I don't know

I8. Re-animation/resuscitation can help people hit by lightning. ☐ yes ☐ no ☐ I don't know

19. In which seasons storms are most likely in Northeastern India? *Mark the correct season(s)*: ☐ December-February ☐ March-May ☐ June-August ☐ September-November ☐ I don't know

20 In which season lightning is most likely in Northeastern India? *Mark the correct months*: ☐ January ☐ February ☐ March ☐ April ☐ May ☐ June ☐ July ☐ August ☐ September ☐ I don't know

21 In which season usually monsoon rainfalls occur in Northeastern India? *Mark the correct months*: ☐ April ☐ May ☐ June ☐ July ☐ August ☐ September ☐ October ☐ November ☐ December ☐ I don't know

22 In which season(s) hail is most likely in Northeastern India? *Mark the correct season(s)*: ☐ December-February ☐ March-May ☐ June-August ☐ September-November ☐ I don't know

23 In Northeastern India, falling hailstones: [Mark correct answers]

☐ do no damage at all ☐ can damage crops ☐ can damage cars/houses

☐ can injure people/animals ☐ can kill people/animals ☐ I don't know

24 In Northeastern India, hailstones can reach a size of ….. cm [/……inches?].

25 In India, landslides are mostly caused by: ☐ lightning ☐ heavy rainfall ☐ earthquakes

26 When a big landslide occurs in India, usually:

☐ you have enough time to escape ☐ you have no time to escape ☐ I don't know

27. Inside a house, you are safe from a landslide: ☐ yes ☐ no ☐ I don't know

28. Do you see a change in the occurrence of severe weather in the last 15-20 years?

☐ yes, increasing ☐ yes, decreasing ☐ no change ☐ I don't know

29. Was your house/property ever hit by lightning?

☐ yes, severe damage ☐ yes, moderate damage ☐ no

30. Was your house/property/crops ever hit by a flood?

☐ yes, severe damage ☐ yes, moderate damage ☐ no

31. Was your house/property/crops ever hit by a storm?

☐ yes, severe damage ☐ yes, moderate damage ☐ no

32. Was your house/property/crops ever hit by hail?

☐ yes, severe damage ☐ yes, moderate damage ☐ no

33. Was your house/property/crops ever hit by heavy rain?

☐ yes, severe damage ☐ yes, moderate damage ☐ no

34. Was your house/property/crops ever hit by a landslide?

☐ yes, severe damage ☐ yes, moderate damage ☐ no

35. Do you feel personally prepared for possible risks of severe weather? ☐ yes ☐ partly ☐ no

36. Do you hold an insurance for risks of severe weather? ☐ yes, for most ☐ for some ☐ no

37. Did you receive government support after a severe weather calamity?

☐ yes, full ☐ yes, partly ☐ none

38. Should severe weather protection be a part of the school education curriculum?

☐ yes ☐ no ☐ I don't know

39. Do you know the homepage of the National Disaster Management Authority of India?

[http://www.ndma.gov.in] ☐ yes ☐ no

40. Did you read safety tips on disaster protection by the National Disaster Management Authority of India? ☐ yes ☐ no

41. Should there be a voluntary rescue training available for all people? ☐ yes ☐ no

I am: ☐ female / ☐ male My age: …... years My profession: ………………..………

In my household, I live together with ……… adults and ………. children/youngsters.

My home town/city: ……………………...…….. My federal province: …………………………..……

I live in a: ☐ single house/hut ☐ double or row house ☐ multistorey house ☐ high-rise

My highest education level: [*only mark the highest]*

☐ elementary/primary school ☐ apprenticeship ☐ middle/secondary school

☐ higher secondary/board exam ☐ college/university/vocational (Bachelor, Master, PhD)

In my home town/city: ☐ I do professional rescue work ☐ I do voluntary rescue work ☐ I was emergency-trained by a helping organization

Many thanks for your valuable help! Please return the filled-in questionnaire directly to the person who gave it to you. If you are interested in our results, you can leave us your e-mail address.

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