LIGHTNING DISTRIBUTION DURING ACTIVE AND BREAK MONSOON PERIODS OVER SOUTH ASIA

A thesis submitted towards partial fulfillment of
BS-MS Dual Degree Programme

by

ARSHAD ARJUNAN NAIR
Reg. No. 20091025

under the guidance of

DR. A. K. KAMRA
(INSA Honorary Scientist)
Indian Institute of Tropical Meteorology, Pune

Date of Thesis Submission: 25.03.2015

Indian Institute of Science Education and Research, Pune

Certificate

This is to certify that this thesis entitled **Lightning Distribution during Active and Break Monsoon Periods over South Asia** submitted towards the partial fulfillment of the BS-MS dual degree programme at the Indian Institute of Science Education and Research (IISER), Pune represents original research carried out by **Mr. Arshad Arjunan Nair** at the **Indian Institute of Tropical Meteorology (IITM), Pune**, under my supervision during the academic year 2014–2015.

A. K. Kamra

Dr. A. K. Kamra
(INSA Honorary Scientist)

Pune
25.03.2015

Declaration

I hereby declare that the matter embodied in the report entitled **Lightning Distribution during Active and Break Monsoon Periods over South Asia** are the results of the investigations carried out by me at the **Indian Institute of Tropical Meteorology, Pune**, under the supervision of **Dr. A. K. Kamra** and the same has not been submitted elsewhere for any other degree.

Arshad

Arshad Arjunan Nair
Reg. No. 20091025

Pune
25.03.2015

Acknowledgments

I thank Dr. A. K. Kamra (INSA Honorary Scientist) for choosing to guide me as an IASc-INSA-NASI Summer Research Fellow in 2011. Since then, under his guidance, I have had exposure to various themes in atmospheric sciences, enjoyable and fruitful discussions on the various problems we've worked on, and learned how to present my research to the scientific community. I am extremely grateful to him.

I thank the Director, IISER Pune and the Dean (Graduate Studies), IISER Pune for all the facilities at the institute and for the stipend that enabled me to devote time to my academics and research.

I thank the Director, IITM Pune for access to computing facilities, the library, and a workspace, which helped me complete my thesis.

I thank Dr. Prasad Subramanian, Associate Professor, IISER Pune for his graciousness in agreeing to supervise my project as Thesis Advisor Committee member.

I thank Ms. Sagarika Basak for her constant support and much needed distraction and for the encouragement to complete my work on time.

I thank my dear mother and brother for encouraging me to pursue science and for being there for me for the last twenty-three years. I am indebted to them.

Finally, I thank all my teachers at IISER Pune.

Publications

August 2014 to March 2015

A. K. Kamra and A. A. Nair (2015) The impact of the Western Ghats on lightning activity on the western coast of India, Atmospheric Research, Volume 160, Pages 82–90, ISSN 0169–8095. doi: 10.1016/j.atmosres.2015.03.006

A. A. Nair and A. K. Kamra (2015) Monsoon trough position and lightning distribution in the Indian sub-continent (*Manuscript under preparation*)

Abstract

LIGHTNING DISTRIBUTION DURING ACTIVE AND BREAK MONSOON PERIODS OVER SOUTH ASIA

ARSHAD ARJUNAN NAIR

The Indian summer monsoon rainfall and its annual variability is generally determined by the performance of monsoon in the monsoon zone of India. Variability of monsoon rainfall, especially in the monsoon zone of India strongly depends on the intensity and duration of the active and break monsoon periods. Several factors such as rainfall, convection, convective available potential energy (CAPE), surface temperature, relative humidity, topography, etc. considerably differ during the active and break monsoon periods. These factors also affect the lightning activity in a particular region. Since the performance of monsoon crucially depends on the intensity and the duration of the active and break periods, it is important that the link between the lightning activity and these environmental factors is examined over the monsoon zone of India. This thesis tries to examine these related links over South Asia with the help of satellite data for lightning activity. We first identify active and break spells during 1995–2012 based on the precipitation in the monsoon core zone. Then, we examine lightning distribution in this region during active and break spells during the monsoon for this eighteen year period. The relation between the position of the monsoon trough and the zone of maximum lightning flash rate is then examined. Correlation is observed between lightning distribution and the monsoon trough position during these active and break spells. Further work is to be carried out to understand this observed correlation, by studying the link of the above mentioned environmental factors with lightning within the regimes of active and break spells.

Contents

Page

List of Figures

List of Tables

Chapter 1

Introduction

This thesis examines the lightning distribution over South Asia during active and break periods of the Indian Summer Monsoon. This exercise is expected to shed light on the differences in cloud electrification in these two regimes and the factors that may have a contribution to causing these differences. This thesis identifies active and break spells of the Indian Summer Monsoon. Subsequently, lightning activity in these spells is analyzed with respect to the monsoon trough position.

The questions we hope to answer are: Does the monsoon trough have any role in modulating lightning activity? If yes, how? What are the factors that cause periods of the monsoon to be active/break that also affect lightning activity? By looking at these questions, and trying to find answers within the contrasting regimes of active and break spells, we hope to increase our understanding of how lightning is modulated.

Chapter 1 introduces the scope and motivation of this thesis. In Chapter 2, the context of the thesis is established with a literature survey of topics relevant for a background. Chapter 3 delves into the methods used to answer our questions and also includes a primer on the data used in this study. Chapter 4 summarizes the observations and results of this investigation. These are discussed in further detail in Chapter 5. Chapter 6 concludes the thesis and briefly indicates the work that can be explored in the future as an extension of the work presented in this thesis.

Chapter 2

Background

In this chapter, some ideas about monsoon, its origin, and its variability are introduced. The idea of active and break spells is discussed with a literature survey of the various criteria for identifying the same. A primer into lightning is given. The effect of climatic factors on lightning is discussed. Some idea about the climatology of lightning over South Asia, our area of interest, is also developed. This chapter aims at establishing a suitable background of the study.

Contents

2.1 The Monsoon

Monsoon comes from the Arabic word — *mausim* — for season. It was first used to describe the winds over the Arabian Sea, which blow from the northeast for one half of the year and from the southwest for the other half. This seasonal reversal in the direction of wind is accompanied by a dramatic change in precipitation [4] due to variations in the heating of Earth's surface [5]. One associates this heavy rainfall with monsoon, although the monsoon is *both* wet as well as arid conditions of the seasonal cycle.

Monsoons are caused chiefly due to larger variation in temperatures over land than over sea. This difference is due to the higher heat capacity of seas (3.93 $Jg^{-1}K^{-1}$) [6] establishing stable sea surface temperatures (SSTs) and the lower heat capacity of land (0.19 (dry) to 0.35 (wet) $Jg^{-1}K^{-1}$) [7] resulting in larger temperature variation over land. The difference in temperatures translates to pressure gradients that cause these large monsoon winds to blow between land and sea.

Ramage's conditions [4] require that monsoon winds have direction between January and July shift 120°, >40% show preferential direction, and their mean speed exceeds 3 ms^{-1}, and also that pressure patterns satisfy a steadiness criterion.

These conditions determine the three main monsoon systems of the world: (1) Southwest Indian monsoon, (2) Sub-Saharan/West African monsoon, and (3) North Australian monsoon. The North American *monsoon* and South American *monsoon* fail to satisfy Ramage's criterion of complete wind reversal, and hence are currently not considered as monsoons.

2.1.1 A gigantic land-sea breeze?

Monsoons are classically described as large land-sea breezes that happen due to varying variation in temperature over land and sea. That is, land has a tendency to attain and lose heat faster than sea. This, as mentioned earlier, is primarily due to the higher heat capacity of sea as compared to land. The resulting temperature

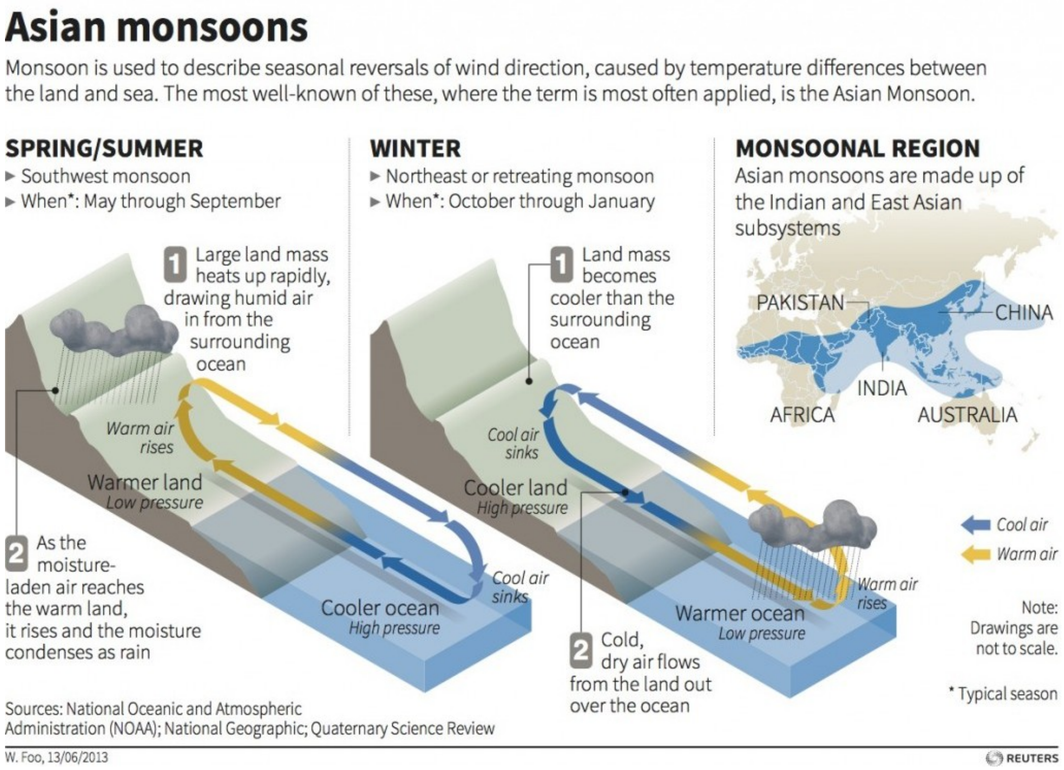


Figure 2.1: **Land-sea breeze** of the Asian Monsoon. (REUTERS/W. Foo)

gradients translate to pressure gradients, such that air from above the cooler surface is pulled towards the hotter surface. This air ascends above the hotter surface. When this air is sufficiently loaded with moisture, and when condensation occurs due to the ascent, we receive rainfall (see Fig. 2.1).

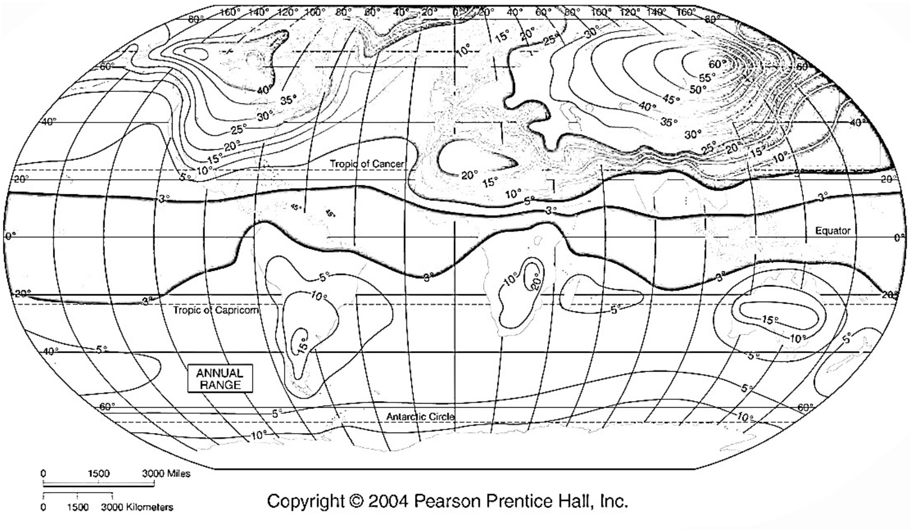
However, there are other factors to be considered as well. One other factor that also results in stable sea surface temperatures (SSTs) is the ability of seas to convect heat. Thus there is a larger depth involved, where temperatures are relatively stable. In the summer months, we then have a sea-land breeze (summer monsoon) and in the winter months, we have a land-sea breeze (winter monsoon).

Still, the classical idea of monsoons being a gigantic land-sea breeze is not satisfactory when you think about the following question: Why does the monsoon progress even though rainfall drastically cools the land it is traversing above?

Let us try and understand this. Consider a slab that is being heated by a source. The factors that determine the rate of heating are the (1) heat capacity of the slab, (2) flux of energy at the surface of the slab, and (3) thickness of the slab. Moist soil has a heat capacity up to 184% that of dry soil [7]. Moist soil has a higher albedo (40%) than dry soil (20%) [8], which has a higher albedo than even sea water(10%). Moist soil will also involve a deeper amount of land in the process due to the effect of convection. The rainclouds reduce the amount of insolation through occlusion. Thus, the combined effect would be the reduction of heating of land and therefore one would expect a reduction in the intensity of the monsoon. What is observed, however, is strengthening of the monsoon, with wind speeds increasing beyond 10 ms^{-1} (at the surface) after the onset of monsoon on land.

This can be explained once we realize that latent heat of vaporization is released into the atmosphere above land during the process of rainfall. This overcompensates the effect of the cooling land. Thus, the initiator of monsoon is the land-sea temperature contrast, while the driver of monsoon is the tropospheric heating due to latent heat release over land. In addition, due to the evaporation of water from the sea, the sea becomes even cooler and the winds even stronger, and thus result in mixing of water to a greater depth, and cooling the sea even further. These processes play major role in the acceleration of monsoon.

There are several other factors that control monsoon dynamics, such as the rotation of the Earth resulting in Coriolis forces having maximum gradient at the equator, the meridional pressure gradient force subject to the Coriolis effect and the consequential frictional dissipation, secondary ageostrophic circulations, meridional ocean heat transport, coupling of above factors, and effects of orography. Discussion regarding these factors are beyond the scope of this thesis. It is hoped that a basic idea of monsoon and its dynamics is developed. For further reading, one may be directed to [1,4,9–15]. We now discuss about the monsoon in South Asia.



Copyright © 2004 Pearson Prentice Hall, Inc.

Figure 2.2: **Temperature variation within a seasonal cycle** The Tibetan Plateau shows a variation over a range of 60° C as compared to 3–5° C over the Indian Ocean.

2.1.2 Monsoon in South Asia

The dramatic change in precipitation associated with the monsoon makes it the most anticipated weather event for any Indian. The Indian monsoon involves the south-west monsoon, where generally rain bearing winds blow into the subcontinent from the Indian Ocean during the months of June-September. The south-west or summer monsoon brings in 75% of the annual rainfall in most parts of India [16]. Later, in October, these winds reverse direction and cause the north-east monsoon and bring rains to the rice bowl of India.

The highly dramatic nature of the Indian monsoon can be attributed to topography. The Tibetan plateau acts as an initiator and driver of the summer monsoon. During the pre-monsoon months, the Tibetan plateau acts as an elevated heat source (Fig. 2.2). This overcomes its effect as a barrier and the monsoon is carried further inland, bringing rains deeper into the subtropics. Without the Tibetan plateau, India's subtropical regions would be as arid as in the subtropical regions of the rest of the world [17–19]. The East African Highlands act as barrier to low-level easterly winds and result in the transport of moisture rich air as the So-

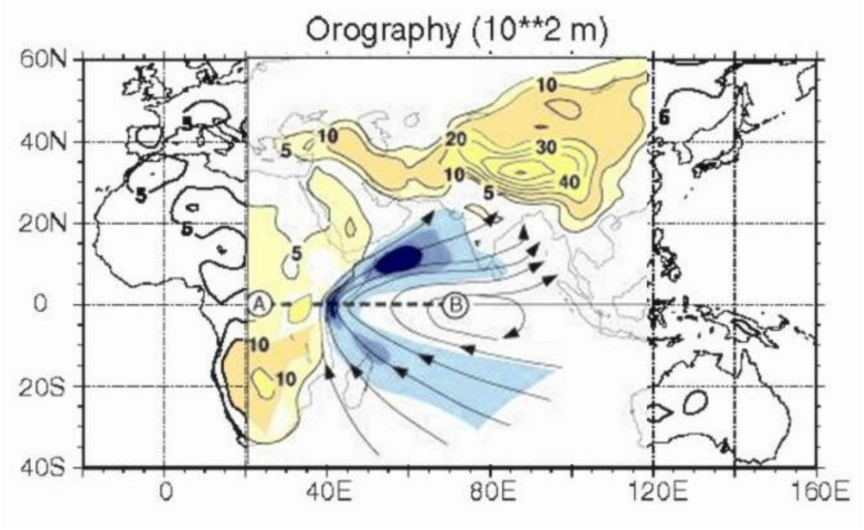


Figure 2.3: **Orography and the monsoon** Eastern African Highlands to the west and the Himalayas to the north ensure that moisture laden winds are confined to South Asia. Image modified from [1].

malia jet to the Indian subcontinent, while simultaneously lowering Arabian Sea temperatures [20,21]. The Himalayas orographically lift the moisture laden clouds and lead to precipitation [18,19] (Fig. 2.3).

2.1.3 The Monsoon Trough

The monsoon trough is a region of low pressure formed during the monsoon season. It typically develops from northwest India to the Bay of Bengal as a region of heat low. The monsoon trough runs roughly parallel to the Himalayas typically about 300 km southwards. When it is close to the foothills of the Himalayas, there is usually intense rainfall in the area and deficit rainfall over the monsoon core zone that lies over most of Central India. This characterizes a break event as discussed in Sec. 2.2. When the axis of the monsoon trough moves southwards, it brings rainfall to the monsoon core zone resulting in an active spell. Although the heat low in the monsoon trough are not enough to intensify into depressions, the shallow systems embedded in the trough bring copious amounts of rainfall.

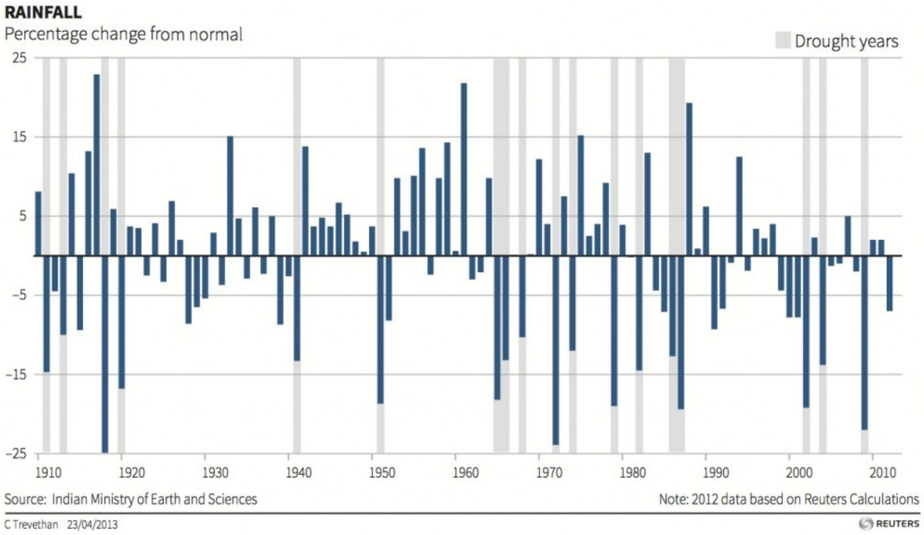


Figure 2.4: **The last 100 years of rainfall in India.** The relative stability of the monsoon and the interdecadal variability are quite evident from the infographic. (REUTERS/C. Trevethan)

2.1.4 Variability of the South Asian monsoon

The South Asian monsoon or the Indian Summer Monsoon is relatively stable (85.31±8.29 cm) [22]. It is characterized by high rainfall with relatively less deviation from the mean. Prolonged conditions of drought or flood are rare events.

Intra-seasonal variability

Intra-seasonal variability is observed in the Indian Summer Monsoon. There are quasi-periodic oscillations of 3–5 days, 10–20 days, and 30–60 days. These oscillations are believed to be caused primarily by the atmosphere dynamics. However, the land surface temperature and seas surface temperature also have a role in these oscillations. These affect the onset of the monsoon and periods of break. They may also intensify or alleviate the effect of El Niño Southern Oscillation (ENSO) on monsoon. [23]

Inter-annual variability

The strength of monsoon in one year determines the strength of monsoon in the next. Assume that in this year, the summer monsoon is stronger than usual due to some forcing factors (could be higher temperatures over land, lower SSTs, etc.) Then there would be deeper extent of ocean mixing and increased storage of heat, which would mean that the seas surface temperatures (SSTs) reduce further. Now, once it is time for the winter monsoon, the sea is at a lower than normal temperature and thus the winter monsoon is weaker than usual. This further feeds back into the summer monsoon that comes the next year. Thus, inter-annual variability is reduced and the effect of forcing factors such as anomalous SSTs is taken care of. This could be one of the reasons for why the Indian Summer Monsoon has seen prolonged drought/flood conditions very rarely.

Biennial variability

It has been observed that monsoon shows biennial oscillation [23]. Its strength alternates between high and low values on alternate years. The reason for the biennial oscillation is attributed to the above mentioned feedback mechanism of nullifying the effect of anomalous conditions. There is also the idea that the quasi-biennial oscillation in the stratosphere may carry its effects into the troposphere [24–29]. The biennial oscillation in monsoon could also be an effect (or cause) of ENSO, which is generally biennial with El Niño (warm) phase and La Niña (cold) phase.

Inter-decadal variability

It has been observed that on a decadal scale, monsoon-ENSO interaction is not stationary [23]. Indian rainfall has been shown to be correlated with the Southern Oscillation Index highly during some decades and weakly in others. These changes occur on a 20-year periodicity.

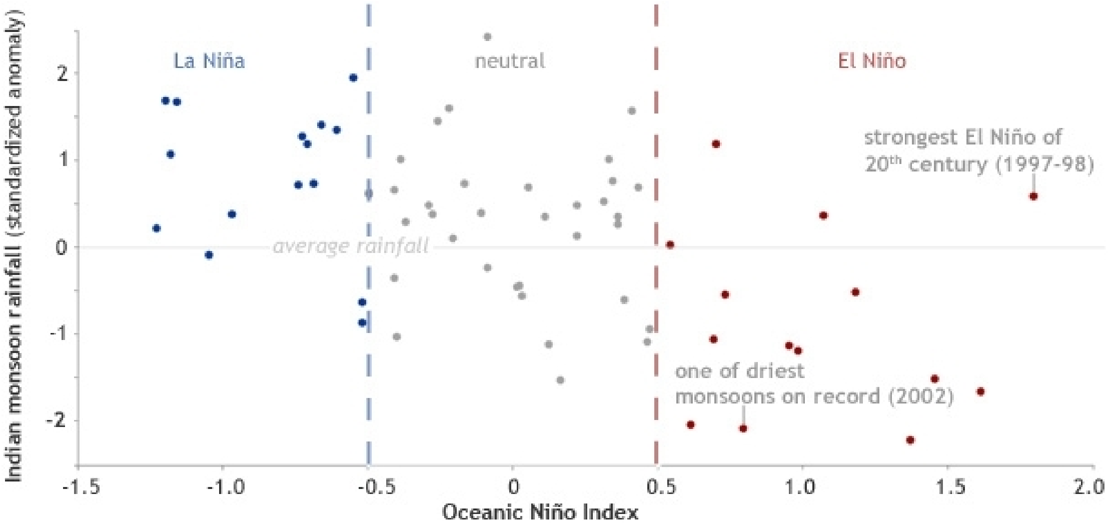


Figure 2.5: **Monsoon rainfall and ENSO** from 1950–2012. Image adapted from [2].

2.1.5 ENSO and Monsoon

El Niño Southern Oscillation (ENSO) has been observed to impact the Indian monsoon rainfall. In the 1920s, Walker [30] discovered that rainfall anomalies over India could be foreseen from the Southern Oscillation of surface temperatures of the tropical eastern Pacific Ocean. However, he was unable to establish a forecasting method based on this observation. Later, Bjerknes [31] realize that the Southern Oscillation and El Niño are closely related. Forecasting based on ENSO were developed. However, there still was a large amount of unpredictability due to regional factors. Most of these factors were discussed in the previous section. Some other factors are snow cover in the Tibetan plateau, which reduces its efficacy as an elevated heat source, thereby weakening the monsoon and the cooling effect of rainfall and rainclouds weakening the monsoon.

2.2 Active and Break Spells

An important theme of the Indian summer monsoon is the occurrence of active and break spells. Fluctuations on the intra-seasonal scale between active spells (good

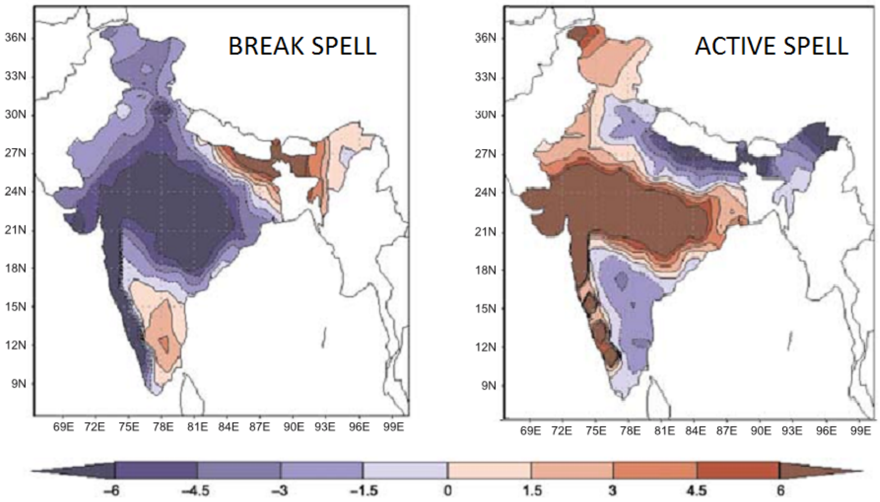


Figure 2.6: **Rainfall anomaly composite** for active and break spells from 1951–2004. The scale denotes deviation from normal rainfall in mm. The difference in active and break spells is well illustrated. Image adapted from [3].

rainfall) and break spells (deficient rainfall) has a large impact on seasonal monsoonal rainfall over India. For example, prolonged breaks in July 2002 (04.07.2002 to 17.07.2002 and 21.07.2002 to 31.07.2002) led to drought in our country. Therefore, identification of active/break spells is necessary.

There have been many attempts at trying to identify active and break spells of the Indian Summer Monsoon. Blanford [32] first identified the 'height of rains' and 'intervals of drought'. In intervals of drought, the monsoon trough was observed to be pushed close to the foothills of the Himalayas. Ramamurthy [33] defined a break spell as a period in the peak monsoon months of July to August when rainfall over the Indian monsoon zone was interrupted for days, based on Blanford's criterion. The Indian Meteorological Department (IMD) identifies a break by considering the low level pressure and wind patterns associated with the corresponding rainfall anomaly [34]. De et. al [35] defined a break situation as one where the monsoon trough is located close to the Himalayan foothills, easterly winds disappear from the sea level and 850 hPa charts, provided the condition was satisfied for more than a day. Krishnan et. al [36] identified break days as those with positive OLR anomalies for over 4 days over northwest and central India (only over the western part of the monsoon trough zone), provided the average OLR anomaly over 73–82° E, 18–28° N exceeded 10 Wm^{-2} during this period. Krishnamurthy and Shukla [37–39] identified spells based on a threshold of half standard deviation of the All-India Daily Rainfall Index. Goswami and Ajayamohan [40] defined a break spell on the basis of the 850 hPa wind at 15° N, 90° E. Gadgil and Joseph [41] defined a break (active) day as that on which the rainfall over the monsoon trough zone is below (above) the specified threshold for western and eastern parts of the monsoon zone. Periods were identified as active (break) when the standardized rainfall anomaly over the Indian core region was more than (less than) 0.7 (-0.7) for three consecutive days in the view of Mandke et. al. [42]. Rajeevan et. al. [3] identifies spells based on the normalized anomaly of the rainfall over a critical area, approximately over 68–88° E, 18–28° N, called the monsoon core zone. When it exceeds 1 (less than -1) for at least three consecutive days, it is an active (break) spell. For the purpose of our study, we use Rajeevan's [3] criterion. This is because rainfall is the best proxy for identifying fluctuations in monsoon and because the spells identified in their study correspond well with that of previous studies as well as with ground based observations.

2.3 Lightning

Lightning is the process of charge neutralization in a thunderstorm. It occurs through a sudden electrical discharge between the regions where charge separation has occurred in a thundercloud — intra-cloud (IC), or between the charged section of the cloud and the ground — cloud to ground (CG), or even from one cloud to another — cloud to cloud (CC). The least common type of lightning is cloud to ground (CG) lightning. However, it is the most understood as it is more relevant to study, is easier to detect, and has greater intensity.

The main mechanism for charge generation in clouds is believed to be charge separation due to formation of ice particles [43–46] and their interaction with water droplets [47], but there are other inductive [48] and non-inductive [49, 50] charging mechanisms.

Once there is sufficient charge separation (of the order of 1 MV), a stepped leader process occurs. Air is broken down in steps of 3–200 m in the form of an ionized plasma leader. Once the leader reaches an oppositely charged region, an electrical discharge as a return stroke travels up this channel. It is then possible that more such return strokes occur. All of this occurs in a time $<$10 ms, and is observed as a single lightning flash. [51]

2.3.1 Environmental factors that affect lightning

Lightning is dependent on several factors such as ground elevation, latitude, wind currents, humidity, proximity to water bodies, thunderstorm updraft growth [52], rainfall rate [43, 53], cloud-top height [54–56], mesocyclone occurrence [57, 58], position of the South Pacific Convergence Zone (SPCZ) [59], surface temperature, water vapor, ozone, updraft speed [60–62], and aerosol concentration.

One important factor modulating lightning is the updraft speed. Updraft speed is reflective of atmospheric convection and the ability to cause rain and lightning. Rainfall occurs with modest lifting, however deeper lifting is needed for lightning to occur. Baker [60, 61] and Boccippio [62] have shown the relation between lightning and updraft speed.

Lightning is closely linked with temperature. A positive relationship between the two is observed with 10–100% increase in lightning with an increase of 1° in surface temperature [63]. Several other studies indicate the same on varying temporal scales [58, 64–76].

Specific humidity in the upper troposphere has been shown to be correlated with lightning activity. In the tropics, it has been observed that high cloud coverage corresponds to higher lightning activity. Studies by Petersen [77] and Sherwood [78] have shown the strong correlation of ice content and size with lightning. Water is the main natural greenhouse gas and thus in its various forms in the troposphere, has an effect on the radiation balance. In increased amounts, it would result in increased warming and accordingly affect lightning.

Lightning is a major producer of ozone and can thus modulate its own occurrence and intensity through greenhouse effect. Experiments have shown the influence of enhancement in lightning activity in enhancing ozone concentrations and the possible positive feedback [79–82].

Aerosols modulate lightning through its effects on cloud microphysics, precipitation, and electrification [83,84], and convection [85]. Increase in the concentration of aerosol reduces mean droplet size, suppresses warm rain coalescence, and enhances cloud water transport to the mixed-phase region [86]. However, enhancement in lightning activity need not always occur. This study by Williams [86] on aerosol and electrical parameters in the Amazon Basin in Brazil during aerosol-rich and aerosol poor conditions could not show the expected contrast in lightning activity. It has been suggested by Kamra and Nair [24] that aerosols can have an enhancing effect on lightning due to the availability of more charge generating particles, but beyond a threshold it may cause insufficient particle sizes and cause reduction in electrification.

Cloud-top height is a measurement of thunderstorm depth made using radars. It is closely related to lightning activity [54–56, 62, 87, 88] as it indicates the gravitational potential energy of ice particles in the upper reaches of a thundercloud. This accumulation of ice shows positive correlation to CAPE and updraft speed. However, radar cloud top height and lightning flash rate are not uniquely related in different meteorological regimes [86, 89–93]. It is therefore useful to study their relationships in contrasting regimes such as during active and break spells.

For an in-depth reading into the relationships between lightning and some of the above mentioned factors, one is directed to the comprehensive review of the same by Williams [94] as well as a discussion by Price [63].

2.3.2 Climatology of lightning over South Asia

Manohar et al. [70] studied the thunderstorm activity over India with focus on the Indian Summer Monsoon. They observed latitudinal variation in lightning activity in the pre-monsoon and monsoon months, using data from a large number of Indian stations (ground-based). During the premonsoon months (M–A–M) it was observed that the lightning activity increases and shows a decreasing latitudinal trend. In the monsoon months (J–J–A–S) they observed a contrasting latitudinal trend of lightning activity. Thunderstorm activity occurred with maxima in the monsoon onset in June and the monsoon withdrawal in September, with low values in the peak monsoon months. This result was also observed by Kamra and Nair [24] in their recent study around the west coast of India. Manohar [70] also observed a semi-annual oscillation in lightning maxima corresponding to the seasonal migration of the Inter Tropical Convergence Zone (ITCZ) as well as the solar heating of the surface. Manohar and Kesarkar [95] indicated an east-west contrast in lightning activity, with the demarcation occurring at about 80°E. Their later study [96] along with Kandalgaonkar's study [97] establish this latitudinal variation of lightning across the Indian subcontinent. This distribution is observed to differ from other regions in the tropics.

South Asia has a unique landmass distribution. The peninsular Indian subcontinent increases in land area at a rate of about 10^6 $km^2/^\circ$ latitude northwards. Also its orography is defined by the Himalayas to the north, which runs in the west-east direction, the Western Ghats running north-south close to the west coast of India, the Indo-Gangetic plains southward of the Himalayas and over most of central India. The Arabian Sea lies to the west of the Indian subcontinent, while the Bay of Bengal to its east. These features have a significant role in controlling lightning in the region.

The monsoon season is characterized by the surface low pressure trough called the monsoon trough. It generally runs from northwest India to the Bay of Bengal. The monsoon trough is a region of high atmospheric instability and deeper convection.

Thus most lightning occurs above the monsoon trough. The monsoon trough is blocked by the Himalayas in the north, lying parallel to it about 300 km south, and therefore the region sees most thunderstorm activity, with increased lightning in the northwest due to the atmospheric instability due to the convergence of hot air from northern Pakistan and the heat low over northwest India as well as increased lightning in the northeast due to the moisture supply from the Bay of Bengal. During break periods, it is observed that the monsoon trough moves closer to the Himalayan foothills and during active periods southward to the monsoon core zone. It is therefore expected that lightning would follow a similar shift.

On a temporal scale, it is observed that most of the annual lightning (monthly-averaged) occurs in the pre-monsoon months (April and May). In the monsoon season, lightning is strikingly high in the onset (June) and withdrawal (September) of the monsoon and has local minima during the peak monsoon months of July and August.

It is expected that a unimodal monthly variation of lightning activity would be observed due to the convergence of the Julian Madden oscillation of the monsoon coinciding with the monsoon trough position [97]. However observations indicate a bimodal distribution [24, 70, 95–97]. It has been speculated that the retreating ITCZ during the withdrawal of the monsoon dominates over the effect of increased land mass, orography, and the weakening of the monsoon trough.

Chapter 3

Data and Methods

Contents

3.1 Area of Investigation

The area of investigation considered in this study is a rectangle from 17.5–32.5° N and 70–95° E. This area encompasses the monsoon core zone (described in [3]) as well as the Himalayan foothills. The reason for choosing this area is to look at lightning distribution in Central India and in the Indo-Gangetic plains and also as the monsoon trough position is found within this area. The area of investigation is divided into 2.5° x 2.5° grid-boxes. Grid-boxes to the north of the Himalayan foothills are eliminated as the monsoon trough always lies to the south of the Himalayan foothills. Grid-boxes over sea are eliminated due to the order of magnitude land-sea contrast in lightning.

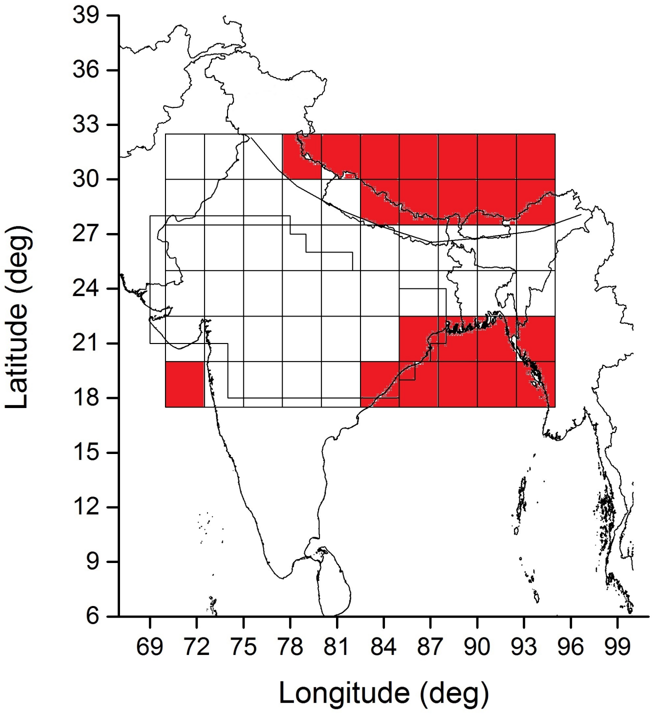


Figure 3.1: **Area of investigation** from 17.5–32.5° N and 70–95° E. The grid-boxes shaded red are omitted as either they are over sea or beyond the Himalayan foothills. Jagged polygon roughly across 18–28° N and 69–88° E is the monsoon core zone [3]

3.2 Indian Daily Weather Reports

The Indian Meteorological Department (IMD) releases its weather reports on a daily basis. The collated hard copies of these reports are available at the Library at IITM, Pune. The daily weather reports from 1995–2012 were analyzed to obtain the monsoon trough position. These weather reports contain the approximate position of the monsoon trough over the nearest IMD weather station. This data was converted into latitude and longitude coordinates.

3.3 Precipitation Data

Precipitation data was obtained from IMD for the period from 1995–2012. Active and break spells were identified based on Rajeevan's criterion [3]. The observed values for precipitation were normalized with respect to the long term normal. Then, active and break spells were identified as described in Section 2.2.

Active and break events are defined as periods during the peak monsoon months of July and August, in which the normalized anomaly of the rainfall over a critical area, called the monsoon core zone exceeds 1.0 or is less than -1.0 respectively, provided the criterion is satisfied for at least three consecutive days [3].

The normalized anomaly of rainfall is calculated as

$$\mathbf{N} = \frac{X_i - X}{\sigma_X} \tag{3.1}$$

where

- X_i is the monsoon core zone averaged daily rainfall for a particular date (i = 1995-2012)
- X is the monsoon core zone long term (1951-2007) averaged daily rainfall for that particular date
- σ_X is the monsoon core zone long term (1951-2007) standard deviation in daily rainfall for that particular date

$\mathbf{N} > 1.0$ for >2 consecutive days implies active spell and $\mathbf{N} < -1.0$ for >2 consecutive days implies break spell. Thus, we determine the active/break spells for 1995–2012 based on this criterion.

3.4 LIS/OTD Gridded Data

Lightning data was sourced from the Lightning Imaging Sensor (LIS) aboard the Tropical Rainfall Measuring Mission (TRMM) satellite and the now defunct Optical Transient Detector (OTD) aboard the MICROLAB-1. The LIS/OTD 2.5° Low Resolution Time Series (LRTS) gives lightning time-series data as a flash rate density (fl km^{-2} day^{-1}) with a spatial resolution of 2.5° and temporal resolution of 24 hours over a period from 04.05.1995 to 31.12.2012 [98]. The data is quality controlled by applying a low-pass temporal filtering in a 110 day window around a chosen date and a spatial moving average filtering (7.5°) around a chosen grid-box. Also, detection efficiency corrections and instrument cross-normalizations on the basis of observations is made.

We observe flash rates for each day of each break spell and for each day of each active spell in the area of investigation. Average flash rates were computed across all active spells and all break spells. Maximum lightning zone was obtained by selecting the latitude for which maximum lightning flash rate occurred on a particular longitude.

In addition, average flash rates for each date in the normal spells (non-active and non-break) were calculated. This was established as the expected flash rate. The percentage deviation of lightning intensity from the expected flash rate was calculated for each day of each active/break spell. Maximum zone of lightning deviation was obtained by selecting the latitude for which maximum (positive) lightning deviation occurred on a particular longitude.

Chapter 4

Results

Contents

4.1 Active and Break Spells

Using Rajeevan's [3] criterion for determining active and break spells as described in Sec. 3.3, we obtain the active and break spells during the period from 1995–2012 in Table 4.1 and Table 4.2.

We observe that break spells are typically 6 days long, with a standard deviation of about 3 days. Active spells are on an average 4 days long, with a standard deviation of approximately 2 days.

During this eighteen year period of study from 1995–2012, there were almost the same total number of active (27) and break (28) spells.

Start Date	End Date	Days	Start Date	End Date	Days
18.07.1995	25.07.1995	8	24.07.1996	28.07.1996	5
19.08.1996	22.08.1996	4	30.07.1997	01.08.1997	3
20.08.1997	26.08.1997	7	03.07.1998	06.07.1998	4
12.07.2000	15.07.2000	4	17.07.2000	20.07.2000	4
09.07.2001	12.07.2001	4	26.07.2003	28.07.2003	3
30.07.2004	01.08.2004	3	01.07.2005	04.07.2005	4
27.07.2005	01.08.2005	6	03.07.2006	06.07.2006	4
28.07.2006	02.08.2006	6	05.08.2006	07.08.2006	3
13.08.2006	22.08.2006	10	01.07.2007	04.07.2007	4
06.07.2007	09.07.2007	4	06.08.2007	09.08.2007	4
27.07.2008	29.07.2008	3	10.08.2008	12.08.2008	3
13.07.2009	16.07.2009	4	20.07.2009	23.07.2009	4
01.08.2010	03.08.2010	3	08.08.2011	11.08.2011	4
25.08.2011	27.08.2011	3			

Table 4.1: Active spells from 1995–2012

Start Date	End Date	Days	Start Date	End Date	Days
03.07.1995	07.07.1995	5	11.08.1995	16.08.1995	6
10.08.1996	12.08.1996	3	11.07.1997	15.07.1997	5
09.08.1997	14.08.1997	6	20.07.1998	26.07.1998	7
16.08.1998	21.08.1998	6	01.07.1999	05.07.1999	5
12.08.1999	16.08.1999	5	22.08.1999	25.08.1999	4
01.08.2000	09.08.2000	9	31.07.2001	02.08.2001	3
26.08.2001	30.08.2001	5	04.07.2002	17.07.2002	14
21.07.2002	31.07.2002	11	10.07.2004	13.07.2004	4
19.07.2004	21.07.2004	3	26.08.2004	31.08.2004	6
07.08.2005	14.08.2005	8	24.08.2005	31.08.2005	8
18.07.2007	22.07.2007	5	15.08.2007	17.08.2007	3
17.07.2008	19.07.2008	3	21.08.2008	24.08.2008	4
28.08.2008	30.08.2008	3	29.07.2009	10.08.2009	13
17.08.2009	19.08.2009	3	01.07.2011	03.07.2011	3

Table 4.2: Break spells from 1995–2012

4.2 Monsoon Trough Position

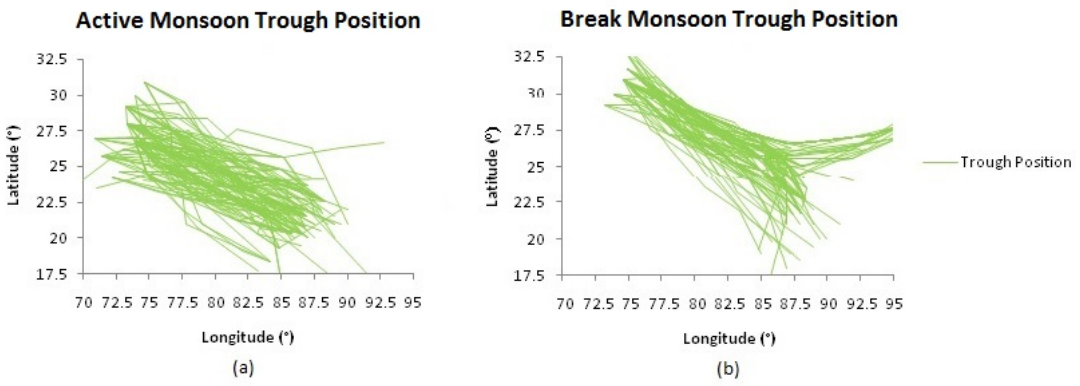


Figure 4.1: **Monsoon Trough Position** (a) During Active Spells from 1995–2012 (b) During Break Spells from 1995–2012. The shifting of the monsoon trough to the Himalayan foothills is evident from the figure.

The monsoon trough position as determined from the Indian Daily Weather Reports (IDWRs) as described in Sec. 3.2 are plotted in Fig. 4.1. We observe that the monsoon trough shifts northwards and close to the Himalayan foothills during break periods. During active periods, the trough is on the monsoon core zone of India.

4.3 Lightning Distribution

The zone of maximum flash rate in the area of investigation is plotted separately for active and break spells in Fig. 4.2. It is observed that the maximum lightning flash zone is shifted northward for a break spell as compared to an active spell. In Sec. 4.4, the maximum lightning flash zone for individual spells (active/break) show to a greater degree of clarity the shift of the maximum lightning flash zone with the monsoon trough.

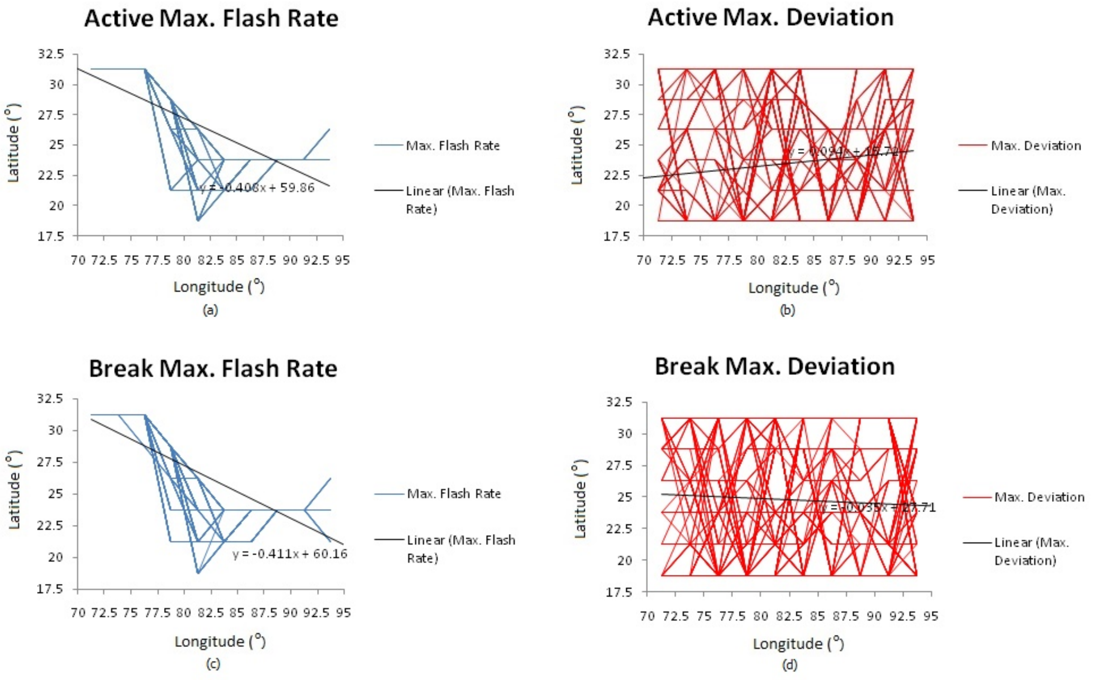
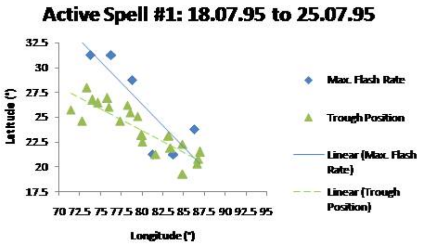
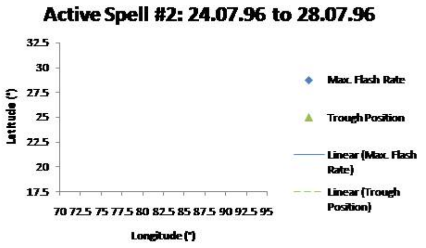


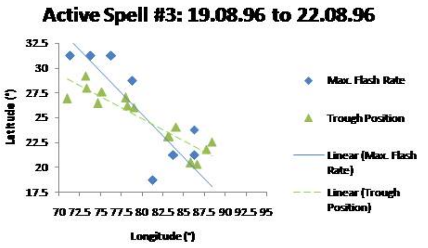
Figure 4.2: **Lightning Distribution** (a) Maximum flash rate zone during Active Spells from 1995–2012 (b) Zone of maximum positive deviation of flash rate during Active Spells from 1995–2012 (c) Maximum flash rate zone during Break Spells from 1995–2012 (d) Zone of maximum positive deviation of flash rate during Break Spells from 1995–2012.

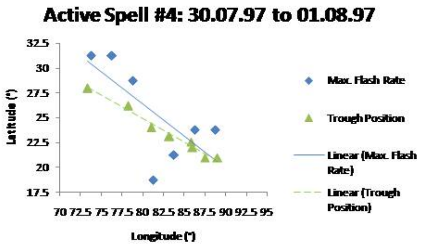
4.4 Trough Position and Maximum Lightning Zone

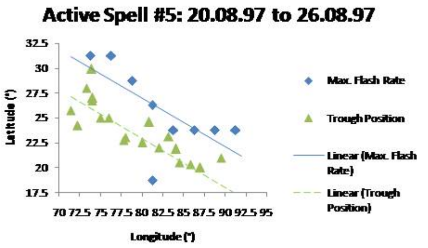
For individual active/break spells of the monsoon, the zone of maximum lightning flash is plotted with respect to the monsoon trough position. The results for active spells are in Fig. 4.3 and for break spells in Fig. 4.4. The statistical tests for our hypothesis that the maximum lightning flash zone and the monsoon trough should be correlated, give us very strong correlation in the case of break spells and moderate correlation in the case of active spells. It is also observed that the maximum lightning zone occurs north of the monsoon trough during active periods and shows a good correlation with the monsoon trough to the east of 80° E. In the case of break periods, this zone occurs south of the monsoon trough and shows a good correlation west of 80° E.

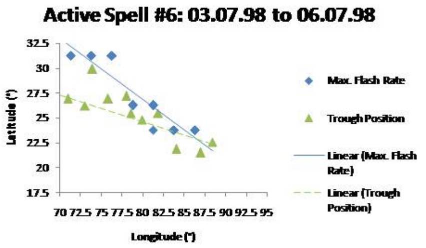

Active Spell #1: 18.07.95 to 25.07.95

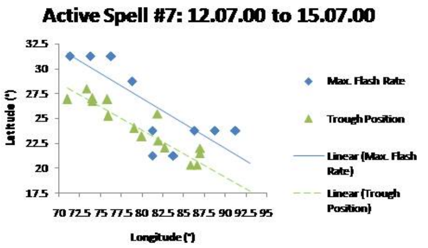

Active Spell #2: 24.07.96 to 28.07.96

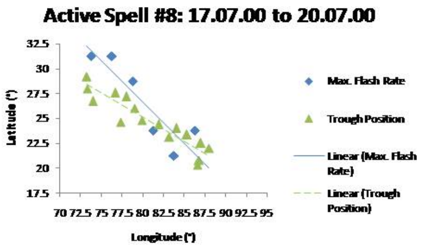

Active Spell #3: 19.08.96 to 22.08.96

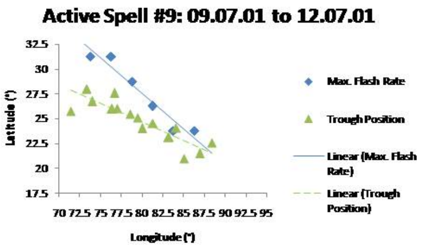

Active Spell #4: 30.07.97 to 01.08.97

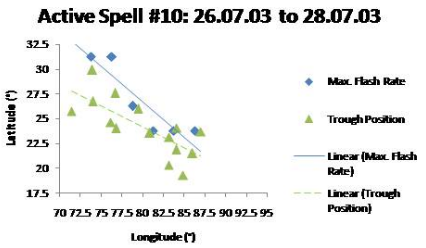

Active Spell #5: 20.08.97 to 26.08.97

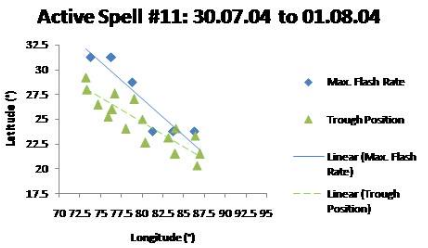

Active Spell #6: 03.07.98 to 06.07.98

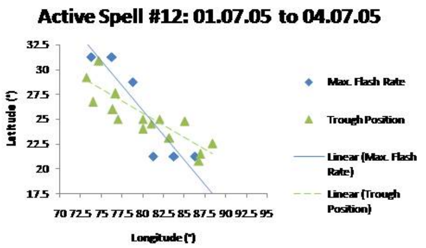

Active Spell #7: 12.07.00 to 15.07.00

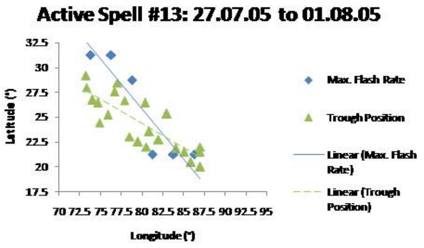

Active Spell #8: 17.07.00 to 20.07.00

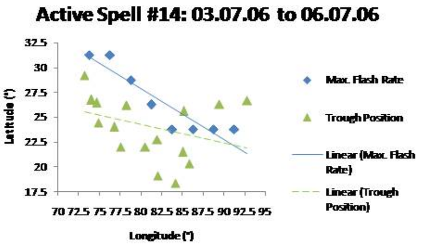

Active Spell #9: 09.07.01 to 12.07.01

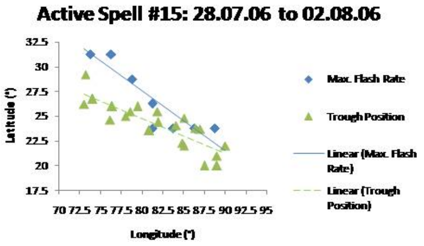

Active Spell #10: 26.07.03 to 28.07.03

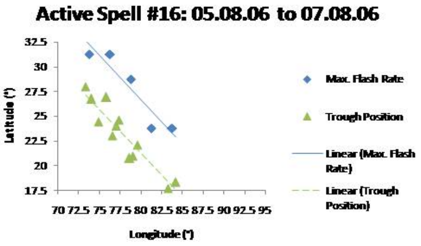

Active Spell #11: 30.07.04 to 01.08.04

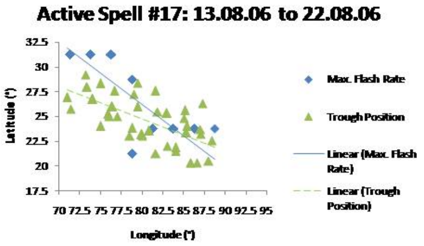

Active Spell #12: 01.07.05 to 04.07.05

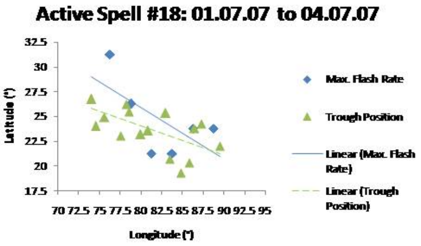

Active Spell #13: 27.07.05 to 01.08.05

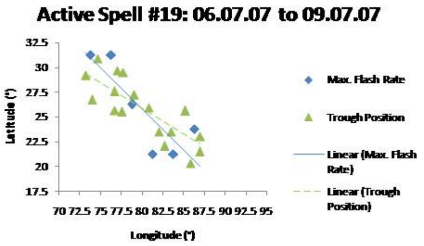

Active Spell #14: 03.07.06 to 06.07.06

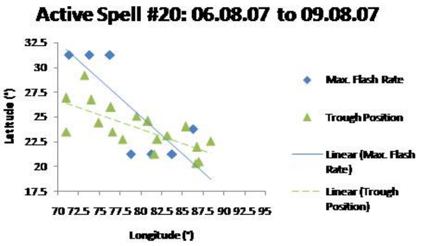

Active Spell #15: 28.07.06 to 02.08.06

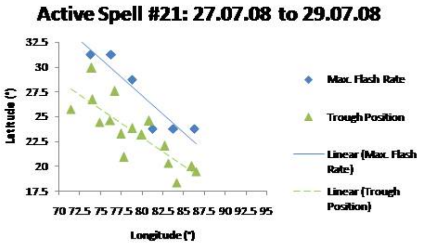

Active Spell #16: 05.08.06 to 07.08.06

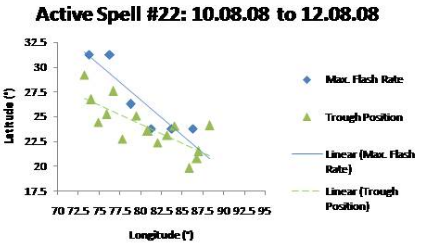

Active Spell #17: 13.08.06 to 22.08.06

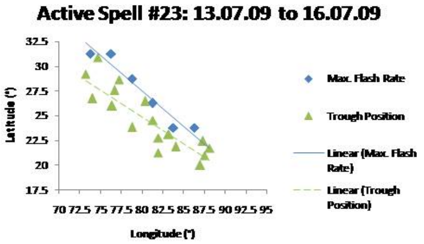

Active Spell #18: 01.07.07 to 04.07.07

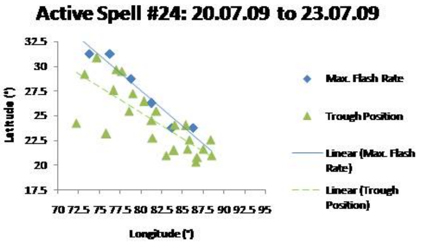

Active Spell #19: 06.07.07 to 09.07.07

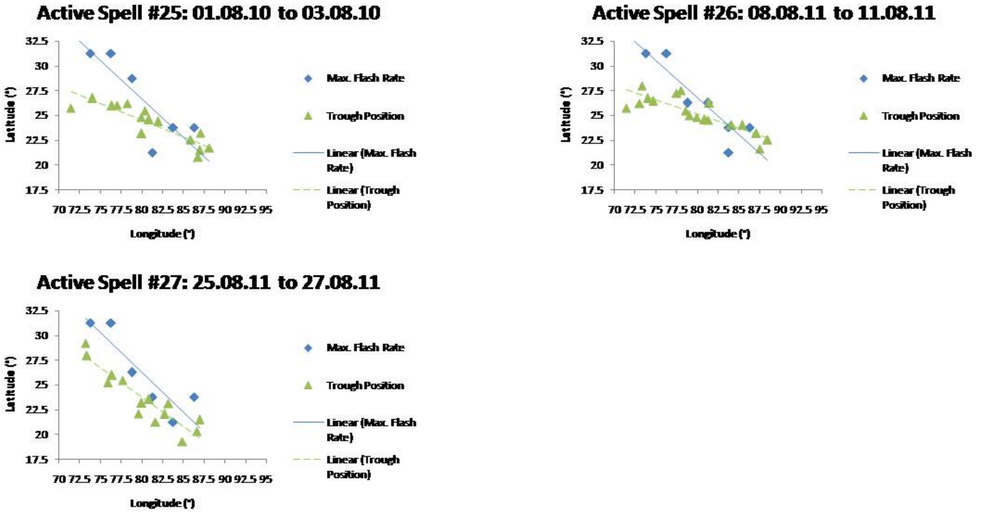

Active Spell #20: 06.08.07 to 09.08.07


Active Spell #21: 27.07.08 to 29.07.08


Active Spell #22: 10.08.08 to 12.08.08


Active Spell #23: 13.07.09 to 16.07.09


Active Spell #24: 20.07.09 to 23.07.09

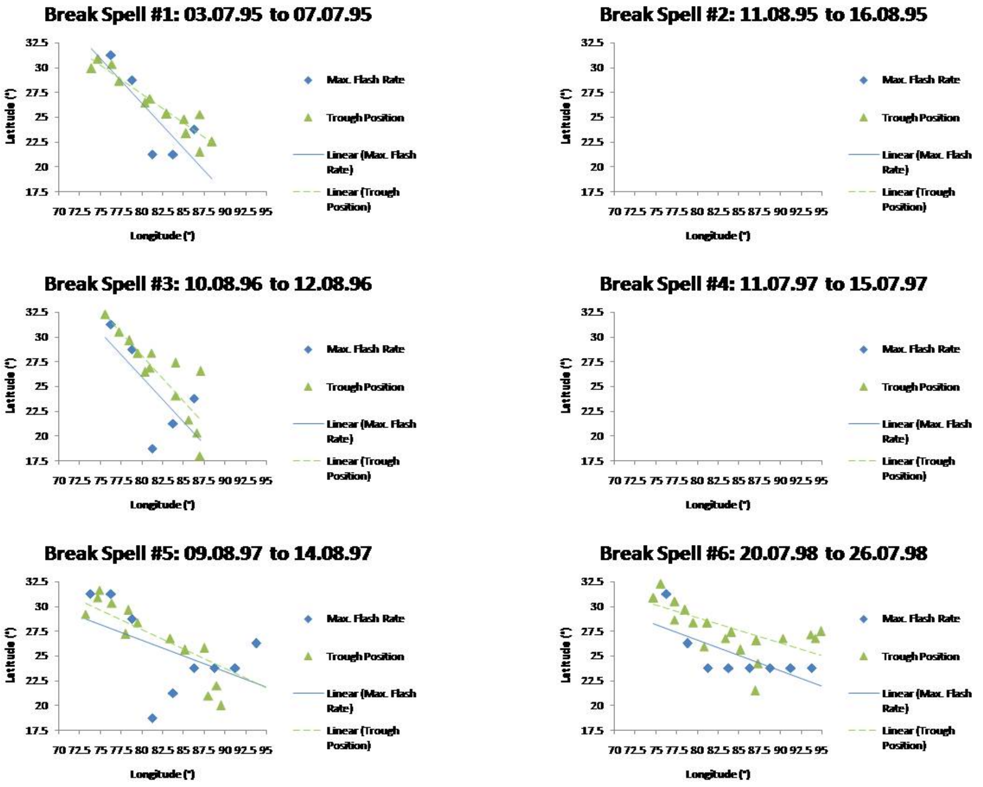


Active Spell #25: 01.08.10 to 03.08.10

Active Spell #26: 08.08.11 to 11.08.11

Active Spell #27: 25.08.11 to 27.08.11

Figure 4.3: Correlation of Maximum Lightning Flash Zone with the Monsoon Trough Position for each active spell in the 1995–2012 period. Empty graphs denote missing trough position information.



Break Spell #1: 03.07.95 to 07.07.95

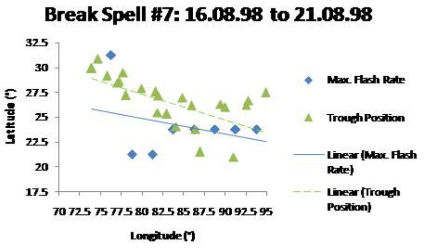
Break Spell #2: 11.08.95 to 16.08.95

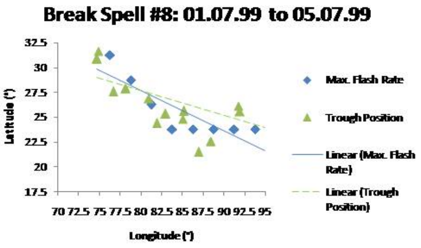
Break Spell #3: 10.08.96 to 12.08.96

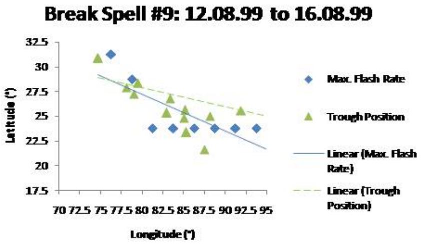
Break Spell #4: 11.07.97 to 15.07.97

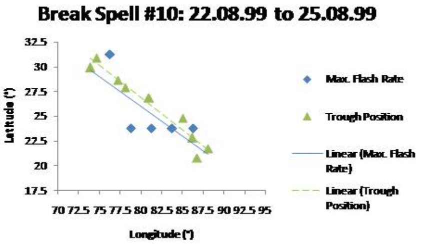
Break Spell #5: 09.08.97 to 14.08.97

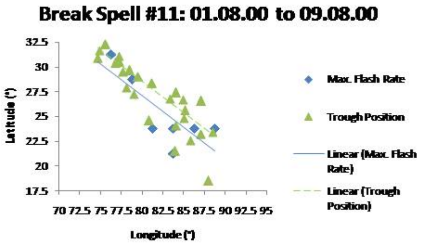
Break Spell #6: 20.07.98 to 26.07.98

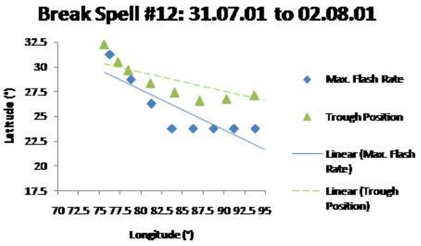

Break Spell #7: 16.08.98 to 21.08.98

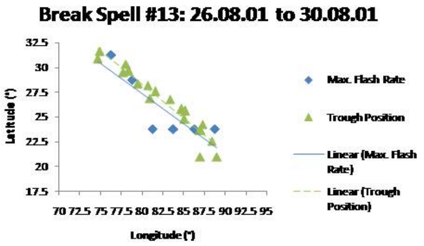

Break Spell #8: 01.07.99 to 05.07.99

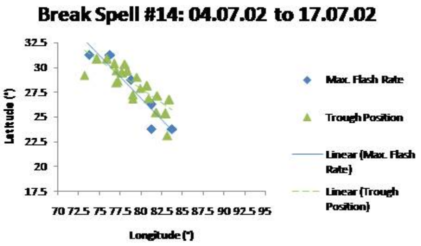

Break Spell #9: 12.08.99 to 16.08.99

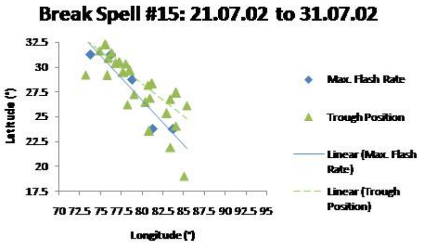

Break Spell #10: 22.08.99 to 25.08.99

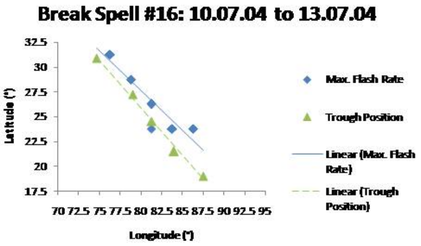

Break Spell #11: 01.08.00 to 09.08.00

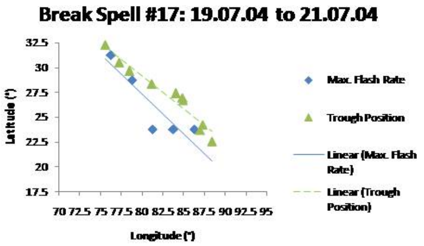

Break Spell #12: 31.07.01 to 02.08.01

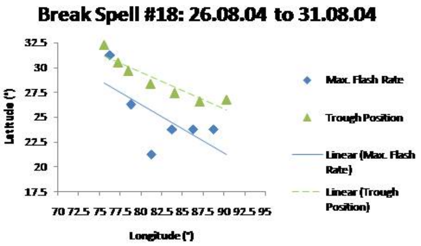

Break Spell #13: 26.08.01 to 30.08.01


Break Spell #14: 04.07.02 to 17.07.02


Break Spell #15: 21.07.02 to 31.07.02


Break Spell #16: 10.07.04 to 13.07.04


Break Spell #17: 19.07.04 to 21.07.04


Break Spell #18: 26.08.04 to 31.08.04

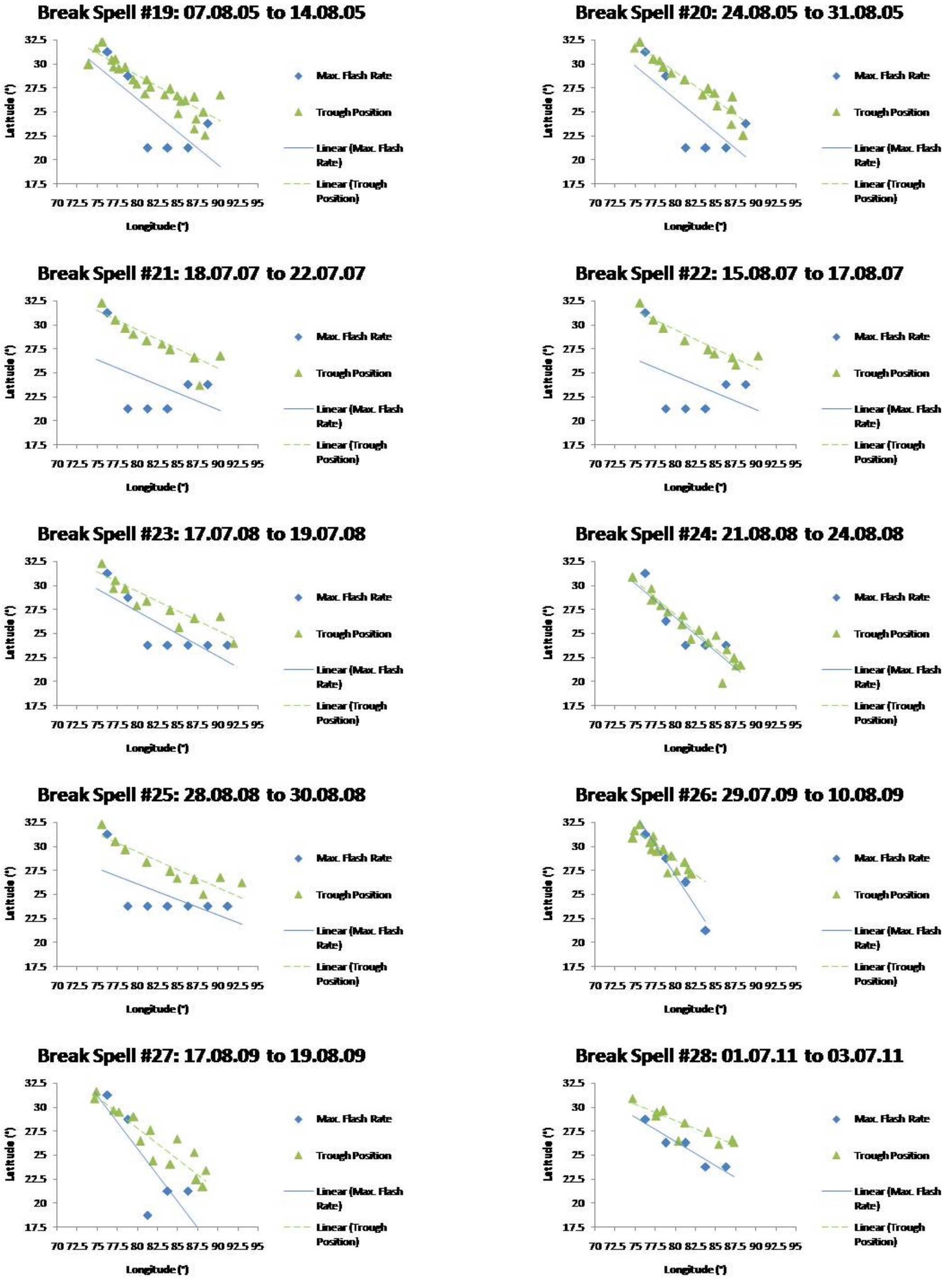


Figure 4.4: Correlation of Maximum Lightning Flash Zone with the Monsoon Trough Position for each break spell in the 1995–2012 period. Empty graphs denote missing trough position information.

Chapter 5

Discussion

The temporal range of investigation was chosen to be an eighteen year period from 1995–2012, as this it had common overlap with the data-sets for lightning, precipitation, and monsoon trough positions. The spatial range of investigation was from 17.5–32.5° N and 70–95° E to understand how lightning activity in South Asia was modulated. Areas north of the Himalayas, where the monsoon trough could never be located due to orographic blocking, were neglected. Due to the differences in convective activity over land and sea, there exists an order of magnitude difference in lightning flash rates over land (higher) and sea. Therefore, areas over sea within this rectangle were neglected.

Rajeevan's [3] criterion was adopted to determine active and break spells during our period of investigation. He had earlier determined the same for the period from 1951–2007, based on the long term normal of precipitation in the monsoon core zone from 1951–2004. We extended this analysis to 2012 for the purpose of our study. We observed that break spells were typically 6 days long, with a standard deviation of about 3 days and active spells were on an average 4 days long, with a standard deviation of approximately 2 days. The number of break spells and active spells during the period of investigation from 1995–2012 were almost same. There were 27 active spells and 28 break spells during this eighteen year period. It is important that the identified spells are reflective of synoptic conditions. To ensure this, we examined the drought years and flood years during this period. From 4.2, we see the longest break spells were in 2002, which was a drought year in India. Similarly, the longest active spells were in 2006, which was a year of abundant rainfall in India. Also, we observe the second longest break spell in 2009, which was also a drought year. This confirms the validity of our identification of active and break spells.

Monsoon trough position was obtained from the Indian Daily Weather Reports issued by the Indian Meteorological Department (IMD). The conversion of trough positions described qualitatively into latitude and longitude coordinates was carried out. It was observed that, as expected, in break spells, the monsoon trough shifted towards the base of the Himalayas, while in the active spell, the trough maintained its position over the monsoon core zone.

Lightning data was sourced from the LIS detector aboard the TRMM satellite and OTD detector that was aboard the MICROLAB-1 satellite. Lightning distribution in the area of investigation was analyzed and the maximum lightning flash rate zone was obtained. We had hypothesized that this zone would follow the monsoon trough position. On the average picture, considering the cases of active and break spells separately, we do not observe our hypothesized result in a striking manner. A look at Fig. 4.2 shows almost similar maximum lightning flash zones when aggregated for the active spells and break spells. However, the linear trend-line does indicate a northward shift of the maximum flash rate zone during break spells as compared to during active spells. This is in tune with our expectation that the zone would follow the monsoon trough position, although it is not to the expected extent.

We then examined our derived dataset of percentage deviation of flash rate from the expected value as described in Sec. 3.4. This was to eliminate the effects due to the latitudinal variations in landmass area and due to varying orography and other factors other than the monsoon trough in the region of investigation. It was expected that the correlation of this zone with the monsoon trough position would improve. However, we observed that there was significant variation in this zone of maximum deviation of lightning flash rate across the area of investigation. The degree of variation in lightning from expected values doesn't show a latitudinal pattern. However, the composite of all such zones does indicate differences between lightning activity during active and break spells. The expected northward shift of this zone is evident during the break spells as compared to active spells. An interesting feature is that this shift becomes less stark as we move towards the east. This could be an effect of the east-west contrast in lightning activity. Further investigation into the causes would be worthwhile.

We resolve at the individual level, by considering each spell. In this analysis, we observe a significant correlation between the monsoon trough position and this zone of maximum lightning flash rate. The discrepancy between the results may most likely be due to the high variability of the factors that affect lightning. By choosing to investigate separately in active and break spells, and looking at the particular monsoon trough position in each case, we were able to show that even in contrasting regimes, lightning is affected by the trough position. However, our results indicate that this correlation is stronger during break spells than active spells. We use Student's t-test as one way of examining the validity of our hypothesis that the zone of maximum lightning flash rate should correlate with the monsoon trough position. In the 27 active spells, we observe significant correlation for 16 (out of 26) spells. In the 28 break spells, we observe significant correlation for 23 (out of 26) spells. This statistical testing indicates that the zone of maximum lightning is strongly correlated with the monsoon trough position during break spells and moderately so during active spells.

During active spells we observe that the (1) maximum lightning zone is north of the monsoon trough position, and (2) there is good correlation between the two east of 80°E. During break spells we observe that the (1) maximum lightning zone is south of the monsoon trough position, and (2) there is good correlation between the two west of 80° E. There has been observations of an east-west contrast in lightning over the Indian sub-continent - our observation could be related to this. The reasons for this deem investigation. One possibility could be the lag in the lightning's response to the shifting southward of the monsoon trough during an active spell and the shifting northward of the monsoon trough during a break spell.

There are some aspects to be considered regarding the limitations of our analysis. Although we tried to increase statistical significance by considering a long temporal range of eighteen years from 1995–2012, the number of active and break spells in the same period as determined by us were only 55 in number. Also, the lightning data for each spell was taken from a daily data-set. The *dailyness* of the data may not be accurate. The temporal smoothing over the 110 day period (as described in Sec. 3.4) could bring in errors due to loss of importance of the synoptic conditions observed during the selected spell. The spatial smoothing may also blur the differences that help in determining the maximum lightning zone. There are also errors associated with the detector's varying efficiency during daytime and nighttime. Although the gridded dataset has corrections based on this, they need not be accurate for (a) our area of investigation, and (b) the time the satellite passes over this area. However, it is hoped that the validity of the data is enhanced due to the long temporal range under consideration in this study. This we confirm from the agreement of results with our hypothesis and also from the differences in raw lightning data between active and break spells.

Currently, we are investigating the cloud top height in each of the spells. Cloud top height would reveal deep convection, which we expect in the monsoon trough. This could contribute to increased lightning. Investigation into the effect of other factors that affect atmospheric dynamics on lightning activity is planned.

Chapter 6

Conclusions and Future Work

At the conclusion of this thesis, we have tried to understand how synoptic conditions affect lightning. It was hypothesized that maximum lightning would occur in the vicinity of the monsoon trough. To test this hypothesis, we examined the daily lightning data from the LIS/OTD sensors and compared it with observed trough positions. We chose to do this exercise within the ambit of contrasting regimes of active and break spells during the monsoon. This required us to re-analyze precipitation data, to determine the active and break spells in our eighteen year period of investigation from 1995–2012. Due to the already well studied differences in the monsoon trough position during these contrasting spells, we investigated the changes in lightning distribution in the same. On an average picture, we were unable to completely verify our hypothesis. However, resolving deeper by considering each spell, we observed correlation between the zone of maximum lightning activity and the monsoon trough. Statistical testing further indicated that this correlation is very strong during break spells and moderately significant during active spells.

Future Work

Currently, we are investigating the cloud-top height during these individual spells. This proxy of the atmospheric instability and conditions could give us an idea of deep-convective processes that may occur in the monsoon trough having an effect on lightning. In addition, it is proposed to continue the work in this thesis by studying the possible effects of convective available potential energy (CAPE), surface temperature, relative humidity, and topography on lightning activity.

References

[1] P. J. Webster, V. O. Magana, T. Palmer, J. Shukla, R. Tomas, M. u. Yanai, T. Yasunari, Monsoons: Processes, predictability, and the prospects for prediction, Journal of Geophysical Research: Oceans (1978–2012) 103 (C7) (1998) 14451–14510. `doi:10.1029/97jc02719`.

[2] K. K. Kumar, B. Rajagopalan, M. Hoerling, G. Bates, M. Cane, Unraveling the mystery of indian monsoon failure during el nino, Science 314 (5796) (2006) 115–119. `doi:10.1126/science.1131152`.

[3] M. Rajeevan, S. Gadgil, J. Bhate, Active and break spells of the Indian Summer Monsoon, Journal of Earth System Science 119 (2010) 229–247. `doi:10.1007/s12040-010-0019-4`.

[4] C. S. Ramage (Ed.), Monsoon Meteorology, Vol. 15 of International Geophysics, Academic Press, 1971. `doi:10.1016/S0074-6142(08)60596-3`.

[5] E. Halley, An historical account of the trade winds, and monsoons, observable in the seas between and near the tropicks, with an attempt to assign the phisical cause of the said winds, by e. halley, Philosophical Transactions 16 (179-191) (1686) 153–168. `doi:10.1098/rstl.1686.0026`.

[6] E. Toolbox, Liquids and Fluids - Specific Heats.
URL `http://www.engineeringtoolbox.com/specific-heat-fluids-d_151.html`

[7] E. Toolbox, Solids - Specific Heats.
URL `http://www.engineeringtoolbox.com/specific-heat-solids-d_154.html`

[8] H. F. M. t. Berge, Heat and water transfer at the bare soil surface: aspects affecting thermal imagery, Ph.D. thesis, Landbouwhogeschool te Wageningen (1986).

[9] J. S. Fein, P. L. Stephens, Monsoons, Wiley New York, 1987. `doi:10.1002/qj.49711448114`.

[10] C.-P. Chang, T. N. Krishnamurti, Monsoon meteorology, Oxford University Press, 1987.

[11] S. Hastenrath, et al., Climate dynamics of the tropics, Kluwer Academic Publishers, 1991. `doi:10.1007/978-94-011-3156-8`.

[12] P. J. Webster, The role of hydrological processes in ocean-atmosphere interactions, Rev. Geophys. 32 (4) (1994) 427. `doi:10.1029/94rg01873`.

[13] G. B. Pant, K. R. Kumar, Climates of South Asia, John Wiley & Sons, 1997. `doi:10.1002/(SICI)1097-0088(199804)18:5<581::AID-JOC267>3.0.CO;2-#`.

[14] P. J. Webster, C. Clark, G. Cherikova, J. Fasullo, W. Han, J. Loschnigg, K. Sahami, The monsoon as a self-regulating coupled ocean—atmosphere system, in: International Geophysics, Elsevier BV, 2002, pp. 198–219. `doi:10.1016/s0074-6142(02)80168-1`.

[15] M. Tomczak, J. S. Godfrey, Regional Oceanography, Elsevier BV, 1994. `doi:10.1016/b978-0-08-041021-0.50005-9`.

[16] B. Parthasarathy, N. A. Sontakke, A. A. Monot, D. R. Kothawale, Droughts/floods in the summer monsoon season over different meteorological subdivisions of india for the period 1871-1984, Journal of Climatology 7 (1) (1987) 57–70. `doi:10.1002/joc.3370070106`.

[17] P. Molnar, P. England, J. Martinod, Mantle dynamics, uplift of the tibetan plateau, and the indian monsoon, Rev. Geophys. 31 (4) (1993) 357. `doi:10.1029/93rg02030`.

[18] C. Li, M. Yanai, The onset and interannual variability of the asian summer monsoon in relation to land-sea thermal contrast, Journal of Climate 9 (2) (1996) 358–375. `doi:10.1175/1520-0442(1996)009<0358:TOAIVO>2.0.CO;2`.

[19] J. Fasullo, P. Webster, A hydrological definition of indian monsoon onset and withdrawal, Journal of Climate 16 (19) (2003) 3200–3211. `doi:10.1175/1520-0442(2003)016<3200a:AHDOIM>2.0.CO;2`.

[20] M. J. Rodwell, B. J. Hoskins, A model of the asian summer monsoon. part ii: Cross-equatorial flow and pv behavior, Journal of the atmospheric sciences 52 (9) (1995) 1341–1356. `doi:10.1175/1520-0469(1995)052<1341:AMOTAS>2.0.CO;2`.

[21] J. Slingo, H. Spencer, B. Hoskins, P. Berrisford, E. Black, The meteorology of the western indian ocean, and the influence of the east african highlands, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 363 (1826) (2005) 25–42. `doi:10.1098/rsta.2004.1473`.

[22] D. A. Mooley, B. Parthasarathy, Fluctuations in all-india summer monsoon rainfall during 1871-1978, Climatic Change 6 (3) (1984) 287–301. `doi:10.1007/bf00142477`.

[23] G. R. North, J. A. Pyle, F. Zhang, Encyclopedia of Atmospheric Sciences, Vol. 1, Elsevier, 2014. `doi:10.1016/b978-0-12-382225-3.00470-9`.

[24] A. K. Kamra, A. A. Nair, The impact of the western ghats on lightning activity on the western coast of india, Atmospheric Research 160 (2015) 82 – 90. `doi:10.1016/j.atmosres.2015.03.006`.

[25] C. A. Hernandez, The QBO's influence on lightning production and deep convection in the tropics, Master's thesis, Texas A&M University 1.
URL `http://hdl.handle.net/1969`

[26] C. A. Hernandez, C. Schumacher, The QBO's influence on lightning production in the tropics, in: 28th Conf. On Hurricanes and Trop. Meteor., Amer. Meteor. Soc., Orlando, FL, 2008.

[27] B. Abish, K. Mohanakumar, Biennial variability in aerosol optical depth associated with QBO modulated tropical tropopause, Atmospheric Science Letters 13 (1) (2012) 61–66. doi:10.1002/asl.364.

[28] S. N. Beegum, K. K. Moorthy, S. S. Babu, R. R. Reddy, K. R. Gopal, Y. N. Ahmed, Quasi-biennial oscillations in spectral aerosol optical depth, Atmospheric Science Letters 10 (4) (2009) 279–284. doi:10.1002/asl.243.

[29] S. Ramachandran, S. Ghosh, A. Verma, P. K. Panigrahi, Multiscale periodicities in aerosol optical depth over india, Environ. Res. Lett. 8 (1) (2013) 014034. doi:10.1088/1748-9326/8/1/014034.

[30] G. T. Walker, Correlation in seasonal variations of weather viii, Mem. India Meteor. Dept 24 (1923) 75–131.

[31] J. Bjerknes, Atmospheric teleconnections from the equatorial pacific 1, Monthly Weather Review 97 (3) (1969) 163–172. doi:10.1175/1520-0493(1969)097<0163:ATFTEP>2.3.CO;2.

[32] H. F. Blanford, Rainfall of India, Memoirs of India Meteorological Department 2 (1886) 658.

[33] K. Ramamurthy, Monsoon of India: Some aspects of break in the Indian South west monsoon during July and August, Forecasting manual 1 (57) (1969) 1–57.

[34] Y. Rao, Southwest monsoon, Vol. 1, India Meteorological Department, 1976.

[35] U. De, R. Lele, J. Natu, Breaks in southwest monsoon, India Meteorological Department, Report No 3.

[36] R. Krishnan, C. Zhang, M. Sugi, Dynamics of Breaks in the Indian Summer Monsoon (2000). doi:10.1175/1520-0469(2000)057<1354:DOBITI>2.0.CO;2.

[37] V. Krishnamurthy, J. Shukla, Intraseasonal and interannual variability of rainfall over India, Journal of Climate 13 (2000) 4366–4377. doi:10.1175/1520-0442(2000)013<0001:IAIVOR>2.0.CO;2.

[38] V. Krishnamurthy, J. Shukla, Intraseasonal and seasonally persisting patterns of Indian monsoon rainfall, Journal of Climate 20 (2007) 3–20. doi:10.1175/JCLI3981.1.

[39] V. Krishnamurthy, J. Shukla, Seasonal persistence and propagation of intraseasonal patterns over the Indian monsoon region, Climate Dynamics 30 (2008) 353–369. doi:10.1007/s00382-007-0300-7.

[40] B. N. Goswami, R. S. Ajaya Mohan, Intraseasonal oscillations and interannual variability of the Indian summer monsoon, Journal of Climate 14 (2001) 1180–1198. `doi:10.1175/1520-0442(2001)014<1180:IOAIVO>2.0.CO;2`.

[41] S. Gadgil, P. V. Joseph, On breaks of the Indian monsoon, Journal of Earth System Science 112 (4) (2003) 529–558. `doi:10.1007/BF02709778`.

[42] S. K. Mandke, A. K. Sahai, M. A. Shinde, S. Joseph, R. Chattopadhyay, Simulated changes in active/break spells during the Indian summer monsoon due to enhanced CO2 concentrations: Assessment from selected coupled atmosphere - Ocean global climate models, International Journal of Climatology 27 (2007) 837–859. `doi:10.1002/joc.1440`.

[43] W. A. Petersen, S. A. Rutledge, On the relationship between cloud-to-ground lightning and convective rainfall, J. Geophys. Res. 103 (D12) (1998) 14025. `doi:10.1029/97jd02064`.

[44] E. R. Williams, M. E. Weber, R. E. Orville, The relationship between lightning type and convective state of thunderclouds, J. Geophys. Res. 94 (D11) (1989) 13213. `doi:10.1029/jd094id11p13213`.

[45] J. E. Dye, B. A. Ridley, W. Skamarock, M. Barth, M. Venticinque, E. Defer, P. Blanchet, C. Thery, P. Laroche, K. Baumann, G. Hubler, D. D. Parrish, T. Ryerson, M. Trainer, G. Frost, J. S. Holloway, T. Matejka, D. Bartels, F. C. Fehsenfeld, A. Tuck, S. A. Rutledge, T. Lang, J. Stith, R. Zerr, An overview of the stratospheric-tropospheric experiment: Radiation, aerosols, and ozone (STERAO)-deep convection experiment with results for the july 10, 1996 storm, J. Geophys. Res. 105 (D8) (2000) 10023–10045. `doi:10.1029/1999jd901116`.

[46] A. Blyth, H. Christian, K. Driscoll, A. Gadian, J. Latham, Determination of ice precipitation rates and thunderstorm anvil ice contents from satellite observations of lightning, Atmospheric Research 59-60 (2001) 217–229. `doi:10.1016/s0169-8095(01)00117-x`.

[47] H. R. Pruppacher, J. D. Klett, Microphysics of Clouds and Precipitation, Springer Science Business Media, 1978. `doi:10.1007/978-94-009-9905-3`.

[48] I. M. Brooks, C. P. R. Saunders, An experimental investigation of the inductive mechanism of thunderstorm electrification, J. Geophys. Res. 99 (D5) (1994) 10627. `doi:10.1029/93jd01574`.

[49] C. P. R. Saunders, W. D. Keith, R. P. Mitzeva, The effect of liquid water on thunderstorm charging, J. Geophys. Res. 96 (D6) (1991) 11007. `doi:10.1029/91jd00970`.

[50] S. Reynolds, M. Brook, M. F. Gourley, Thunderstorm charge separation, Journal of Meteorology 14 (5) (1957) 426–436. `doi:10.1175/1520-0469(1957)014<0426:TCS>2.0.CO;2`.

[51] V. Rakov, M. Uman, Lightning: Physics and Effects, Cambridge University Press, 2007.
URL http://books.google.co.in/books?id=TuMa5lAa3RAC

[52] S. J. Goodman, D. E. Buechler, P. D. Wright, W. D. Rust, Lightning and precipitation history of a microburst-producing storm, Geophysical Research Letters 15 (11) (1988) 1185–1188. doi:10.1029/gl015i011p01185.

[53] A. Tapia, J. A. Smith, M. Dixon, Estimation of Convective Rainfall from Lightning Observations, Journal of Applied Meteorology 37 (1998) 1497–1509. doi:10.1175/1520-0450(1998)037<1497:EOCRFL>2.0.CO;2.

[54] E. R. Williams, Large-scale charge separation in thunderclouds, J. Geophys. Res. 90 (D4) (1985) 6013. doi:10.1029/jd090id04p06013.

[55] E. V. Cherna, E. J. Stansbury, Sferics rate in relation to thunderstorm dimensions, J. Geophys. Res. 91 (D8) (1986) 8701. doi:10.1029/jd091id08p08701.

[56] C. Price, D. Rind, A simple lightning parameterization for calculating global lightning distributions, J. Geophys. Res. 97 (D9) (1992) 9919–9933. doi:10.1029/92jd00719.

[57] D. R. MacGorman, D. W. Burgess, V. Mazur, W. D. Rust, W. L. Taylor, B. C. Johnson, Lightning Rates Relative to Tornadic Storm Evolution on 22 May 1981, Journal of the Atmospheric Sciences 46 (1989) 221–251. doi:10.1175/1520-0469(1989)046<0221:LRRTTS>2.0.CO;2.

[58] E. Williams, B. Boldi, A. Matlin, M. Weber, S. Hodanish, D. Sharp, S. Goodman, R. Raghavan, D. Buechler, The behavior of total lightning activity in severe florida thunderstorms, Atmospheric Research 51 (3-4) (1999) 245–265. doi:10.1016/s0169-8095(99)00011-3.

[59] P. Ortéga, T. Guignes, Lightning activity analyses with respect to the SPCZ location, Geophysical Research Letters 34 (11). doi:10.1029/2007gl029730.

[60] M. B. Baker, H. J. Christian, J. Latham, A computational study of the relationships linking lightning frequency and other thundercloud parameters, Q.J Royal Met. Soc. 121 (527) (1995) 1525–1548. doi:10.1002/qj.49712152703.

[61] M. Baker, A. Blyth, H. Christian, J. Latham, K. Miller, A. Gadian, Relationships between lightning activity and various thundercloud parameters: satellite and modelling studies, Atmospheric Research 51 (3-4) (1999) 221–236. doi:10.1016/s0169-8095(99)00009-5.

[62] D. J. Boccippio, Lightning Scaling Relations Revisited, Journal of the Atmospheric Sciences 59 (2002) 1086–1104. doi:10.1175/1520-0469(2002)059<1086:LSRR>2.0.CO;2.

[63] C. Price, Thunderstorms, lightning and climate change, in: Lightning: Principles, Instruments and Applications, Springer Science Business Media, 2008, pp. 521–535. doi:10.1007/978-1-4020-9079-0_24.

[64] C. Price, Global surface temperatures and the atmospheric electrical circuit, Geophysical Research Letters 20 (13) (1993) 1363–1366. doi:10.1029/93gl01774.

[65] R. Markson, C. Price, Ionospheric potential as a proxy index for global temperature, Atmospheric Research 51 (3-4) (1999) 309–314. doi:10.1016/s0169-8095(99)00015-0.

[66] E. Anyamba, E. Williams, J. Susskind, A. Fraser-Smith, M. Fullekrug, The Manifestation of the MaddenâĂŞJulian Oscillation in Global Deep Convection and in the Schumann Resonance Intensity, Journal of the Atmospheric Sciences 57 (2000) 1029–1044. doi:10.1175/1520-0469(2000)057<1029:TMOTMJ>2.0.CO;2.

[67] G. Sátori, B. Zieger, Spectral characteristics of schumann resonances observed in central europe, J. Geophys. Res. 101 (D23) (1996) 29663. doi:10.1029/96jd00549.

[68] M. Fullekrug, A. C. Fraser-Smith, Global lightning and climate variability inferred from ELF magnetic field variations, Geophysical Research Letters 24 (19) (1997) 2411–2414. doi:10.1029/97gl02358.

[69] A. Nickolaenko, G. Sátori, B. Zieger, L. Rabinowicz, I. Kudintseva, Parameters of global thunderstorm activity deduced from the long-term schumann resonance records, Journal of Atmospheric and Solar-Terrestrial Physics 60 (3) (1998) 387–399. doi:10.1016/s1364-6826(97)00121-1.

[70] G. K. Manohar, S. S. Kandalgaonkar, M. I. R. Tinmaker, Thunderstorm activity over india and the indian southwest monsoon, Journal of Geophysical Research: Atmospheres 104 (D4) (1999) 4169–4188. doi:10.1029/98JD02592.

[71] A. P. Nickolaenko, M. Hayakawa, Y. Hobara, Long-term periodical variations in global lightning activity deduced from the schumann resonance monitoring, J. Geophys. Res. 104 (D22) (1999) 27585. doi:10.1029/1999jd900791.

[72] H. J. Christian, Global frequency and distribution of lightning as observed from space by the optical transient detector, J. Geophys. Res. 108 (D1). doi:10.1029/2002jd002347.

[73] E. R. Williams, Global circuit response to seasonal variations in global surface air temperature, Monthly Weather Review 122 (1994) 1917–1929. doi:10.1175/1520-0493(1994)122<1917:GCRTSV>2.0.CO;2.

[74] A. Nickolaenko, L. Rabinowicz, Study of the annual changes of global lightning distribution and frequency variations of the first schumann resonance mode, Journal of Atmospheric and Terrestrial Physics 57 (11) (1995) 1345–1348. doi:10.1016/0021-9169(94)00114-4.

[75] S. J. Heckman, E. Williams, B. Boldi, Total global lightning inferred from schumann resonance measurements, J. Geophys. Res. 103 (D24) (1998) 31775. doi:10.1029/98jd02648.

[76] E. Williams, K. Rothkin, D. Stevenson, D. Boccippio, Global Lightning Variations Caused by Changes in Thunderstorm Flash Rate and by Changes in the Number of Thunderstorms, Journal of Applied Meteorology 39 (2000) 2223–2230. doi:10.1175/1520-0450(2001)040<2223:GLVCBC>2.0.CO;2.

[77] W. A. Petersen, H. J. Christian, S. A. Rutledge, TRMM observations of the global relationship between ice water content and lightning, Geophysical Research Letters 32 (14) (2005) n/a–n/a. doi:10.1029/2005gl023236.

[78] S. C. Sherwood, V. T. J. Phillips, J. S. Wettlaufer, Small ice crystals and the climatology of lightning, Geophysical Research Letters 33 (5). doi:10.1029/2005gl025242.

[79] H. Huntrieser, H. Schlager, A. Roiger, M. Lichtenstern, U. Schumann, C. Kurz, D. Brunner, C. Schwierz, A. Richter, A. Stohl, Lightning-produced nox over brazil during TROCCINOX: airborne measurements in tropical and subtropical thunderstorms and the importance of mesoscale convective systems, Atmos. Chem. Phys. 7 (11) (2007) 2987–3013. doi:10.5194/acp-7-2987-2007.

[80] J.-H. Ryu, G. Jenkins, Lightning-tropospheric ozone connections: EOF analysis of TCO and lightning data, Atmospheric Environment 39 (32) (2005) 5799–5805. doi:10.1016/j.atmosenv.2005.05.047.

[81] V. Grewe, Impact of climate variability on tropospheric ozone, Science of The Total Environment 374 (1) (2007) 167–181. doi:10.1016/j.scitotenv.2007.01.032.

[82] R. Toumi, J. D. Haigh, K. S. Law, A tropospheric ozone-lightning climate feedback, Geophysical Research Letters 23 (9) (1996) 1037–1040. doi:10.1029/96gl00944.

[83] D. Rosenfeld, I. M. Lensky, Satellite-Based Insights into Precipitation Formation Processes in Continental and Maritime Convective Clouds, Bulletin of the American Meteorological Society 79 (1998) 2457–2476. doi:10.1175/1520-0477(1998)079<2457:SBIIPF>2.0.CO;2.

[84] D. Rosenfeld, W. Woodley, Closing the 50-year circle: From cloud seeding to space and back to climate change through precipitation physics, Cloud Systems, Hurricanes, and the Tropical Rainfall Measuring Mission (TRMM), Meteor. Monogr (51) (2003) 59–80.

[85] M. O. Andreae, Smoking rain clouds over the amazon, Science 303 (5662) (2004) 1337–1342. doi:10.1126/science.1092779.

[86] E. Williams, Contrasting convective regimes over the amazon: Implications for cloud electrification, J. Geophys. Res. 107 (D20). `doi:10.1029/2001jd000380`.

[87] B. Vonnegut, Some facts and speculations concerning the origin and role of thunderstorm electricity, Meteorol. Monogr 5 (27) (1963) 224–241.

[88] T. Ushio, S. J. Heckman, D. J. Boccippio, H. J. Christian, Z.-I. Kawasaki, A survey of thunderstorm flash rates compared to cloud top height using TRMM satellite data, J. Geophys. Res. 106 (D20) (2001) 24089. `doi:10.1029/2001jd900233`.

[89] S. A. Rutledge, E. R. Williams, T. D. Keenan, The down upper doppler and electricity experiment (dundee): Overview and preliminary results, Bulletin of the American Meteorological Society 73 (1992) 3–16. `doi:10.1175/1520-0477(1992)073<0003:TDUDAE>2.0.CO;2`.

[90] E. R. Williams, The schumann resonance: A global tropical thermometer, Science 256 (5060) (1992) 1184–1187. `doi:10.1126/science.256.5060.1184`.

[91] E. J. Zipser, Deep cumulonimbus cloud systems in the tropics with and without lightning, Monthly weather review 122 (8) (1994) 1837–1851. `doi:10.1175/1520-0493(1994)122<1837:DCCSIT>2.0.CO;2`.

[92] A. I. Watson, R. L. Holle, R. E. Lopez, Lightning from two national detection networks related to vertically integrated liquid and echo-top information from wsr-88d radar, Weather and forecasting 10 (3) (1995) 592–605. `doi:10.1175/1520-0434(1995)010<0592:LFTNDN>2.0.CO;2`.

[93] W. A. Petersen, S. A. Rutledge, R. E. Orville, Cloud-to-ground lightning observations from toga coare: Selected results and lightning location algorithms, Monthly weather review 124 (4) (1996) 602–620. `doi:10.1175/1520-0493(1996)124<0602:CTGLOF>2.0.CO;2`.

[94] E. Williams, Lightning and climate: A review, Atmospheric Research 76 (1-4) (2005) 272–287. `doi:10.1016/j.atmosres.2004.11.014`.

[95] G. Manohar, A. Kesarkar, Climatology of thunderstorm activity over the indian region: A study of east-west contrast, Mausam 54 (4) (2003) 819–828.

[96] G. Manohar, A. Kesarkar, Climatology of thunderstorm activity over the indian region: Iii. latitudinal and seasonal variation, Mausam 56 (3) (2005) 581.

[97] S. Kandalgaonkar, M. Tinmaker, J. Kulkarni, A. Nath, M. Kulkarni, H. Trimbake, Spatio-temporal variability of lightning activity over the indian region, J. Geophys. Res. 110 (D11). `doi:10.1029/2004jd005631`.

[98] D. J. Cecil, D. E. Buechler, R. J. Blakeslee, Gridded lightning climatology from TRMM-LIS and OTD: Dataset description, Atmospheric Research 135-136 (2014) 404–414. `doi:10.1016/j.atmosres.2012.06.028`.