# DIAGNOSTIC STUDY OF AEROSOL, CLOUD PROPERTIES AND SUMMER MONSOON RAINFALL OVER INDIA AT INTERANNUAL AND INTRASEASONAL SCALE

Thesis submitted to the Andhra University, Visakhapatnam in partial fulfilment of the requirement for the award of *Master of Technology in Remote Sensing and GIS*


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# ABSTRACT

Interannual and Intraseasonal variability of Indian Summer Monsoon Rainfall is known to be linked with aerosol cloud interactions. In the present work, attempts have been made to elucidate the impact of remotely sensed aerosol loading and associated parameters (Cloud Fraction, Cloud Optical Depth, Cloud Effective Radii, Cloud Top Pressure, UV Aerosol Index and Single Scattering Albedo) on rainfall during the Indian Summer Monsoon season at interaanual and intraseasonal scale. Satellite derived rainfall, aerosol and cloud products have been utilized in this study. The interannual variation in summer monsoon rainfall shows significant correlation with cloud parameters and aerosol characteristics during the last decade over the Central Indian, Arabian Sea and Bay of Bengal regions. Present study reveals that the rainfall and the Aerosol Optical Depth are significantly (significant at 1% significance level) negatively correlated over the Central India, Arabian Sea and Bay of Bengal. Further to this the analysis also suggests that the cloud parameters might be considered as an indicator for understanding the aerosol-precipitation interlinks over the three study regions. The high amount of aerosol concentration in the peak monsoon months (implies inadequate wet deposition) over Indian land region might be due to the role of long range transport of aerosols and the type (composition) of the aerosols available in the rainy season. Active and break spells has been identified using the satellite derived data sets over the Central Indian region which shows a good match with previous studies. Present analysis suggests that the Central Indian region is loaded with higher aerosol concentration and also indicates significant correlation of 0.56 (significant at 95% confidence level) between Cloud Effective Radii & rainfall. Contrary to the composite based previous studies, it has been observed that the behaviour of the active and break events are distinct while considering individual cases. For break events, composite representation shows that aerosols are stacked along the Himalayan region while all individual break events do not portray such an aerosol dispensation and it has been illustrated that the associated parameters also influencing these events. Therefore it appears from the present analysis that the aerosols are supposed to be a regional contributor in affecting the intraseasonal variability of summer monsoon rainfall and in addition to this, other significant mechanisms may be involved during these contrasting rainfall conditions.

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## List of Abbreviations

| | |
|---|---|
| AI | Aerosol Index |
| AOD | Aerosol Optical Depth |
| AS | Arabian Sea |
| BFA | Break Followed by the Active spell |
| BoB | Bay of Bengal |
| CER | Cloud Effective Radii |
| CF | Cloud Fraction |
| CI | Central India |
| COD | Cloud Optical Depth |
| CTP | Cloud Top Pressure |
| HYSPLIT | HYbrid Single-Particle Lagrangian Integrated Trajectory |
| IMD | India Meteorological Department |
| ISMR | Indian Summer Monsoon Rainfall |
| MODIS | MODerate resolution Imaging Spectrometer |
| NOAA | National Oceanic and Atmospheric Administration |
| SSA | Single Scattering Albedo |
| SST | Sea Surface Temperature |
| TP | Tibetan Plateau |
| TRMM | Tropical Rainfall Measuring Mission |

# CHAPTER 1

# INTRODUCTION

Indian Summer Monsoon Rainfall (hereafter referred as ISMR) is the most important climatic process as it influences the economic, agricultural and social sectors of the Indian subcontinent. ISMR is affected by different internal and external factors and aerosols are one of the influential components among them. Aerosols have direct radiative effects by scattering and absorbing solar radiation and indirect effects by changing the cloud and precipitation formation processes. Even though many studies have focused on the aerosol-precipitation relationship, it still remains as an uncertainty in climate research because of the complex mechanisms involved and the nature of the aerosols and its regional scale variations.

Atmospheric aerosols are solid or liquid particles suspended in air having wide range of differences between their composition, size, shapes, optical properties and their impact on global radiation budget is crucial in climate change perspective. Both natural and anthropogenic activities can influence the aerosol concentrations in atmosphere and there are complex aerosol **-** cloud **-** precipitation interlinks exist which is remains as a largest uncertainty in climate research. The influence of aerosols on cloud **-** rainfall relationship is studied from the long term precipitation **-** aerosol statistical data sets and from the regional case studies using ground based instruments and remote sensing measurements by sensors abroad on satellites (Tanre et al., 2009). Aerosols affect the cloud properties, radiation balance of the planet, water cycle and the influence of aerosols on precipitation is far from the understood, which depends upon the location, season and spatio temporal scale of the analysis (Koran et al., 2012). Atmospheric aerosols encompasses a wide range of particle types having different compositions, sizes, shapes, and optical properties and the aerosol loading (amount in the atmosphere) is usually quantified by mass concentration or by an optical measure, AOD (refer Synthesis and assessment product 2.3; 2009 January; U.S. Climate Change Science programme).

The effect of aerosols on rainfall can be categorized as follows (Lau et al., 2008):

1. Aerosol direct effect – Aerosols scatter and/or absorb solar radiation, thus cooling the earth's surface which is known as direct effect. The reduction of solar radiation at the surface is referred to as the solar dimming effect.
2. Aerosol semi-direct effect - Because of the presence of aerosols, earth's surface cools more than the atmosphere above it, the surface cooling may stabilize the lower troposphere, thus limiting convection, known as the semi-direct effect.

3. First indirect effect – Aerosol can affect the water cycle through the interaction with the cloud microphysical processes, whereby aerosol increases the number of cloud condensation nuclei, forming smaller water droplets that increases scattering cross sections, brightens clouds, and reflects more solar radiation. This is known as first indirect effect or Twomey effect.
4. Second indirect effect – The small droplets forming as a result of the first indirect effect can limit collision and coalescence, prolonging the lifetime of clouds and inhibiting the growth of cloud drops to rain drops. This is known as second indirect effect.

The flow chart (fig 1.1) demonstrates the different processes involved in the aerosol and rainfall interactions. Aerosol affects the climate system mainly through direct radiative effects and by changing the cloud and precipitation formation processes through indirect effect. The surface cooling by aerosols increases atmospheric stability and reduces convection potential and at the same time heat the atmosphere depends on their chemical composition. Aerosols increase the concentration of cloud condensation nuclei, increase cloud amount and decrease coalescence and collision rates, leading to reduced rainfall. Depending on the atmospheric conditions and feedback processes, aerosols can have an increasing, decreasing or a mixed effect on rainfall. Mainly the aerosol induced rainfall is due to the strong thermodynamic effect resulting from solar absorption of aerosols.

In addition to the regional scale impact of aerosols originated from local sources on monsoon rainfall effects, it can alter the rainfall pattern over other regions through transport by large scale wind systems that prevail. Aerosol-induced monsoon rainfall is most prominent in areas with high aerosol loading such as from industries/urbanization or areas prone to large scale wind circulation systems which can transport aerosols. It is found that Saharan desert, African- East Asian regions and Indo - Gangetic plain etc. are always having high aerosol loading and at the same time connected to areas with high Indian summer monsoon activity. Dust transported by the large-scale circulation from the deserts adjacent to northern India may affect rainfall over the Bay of Bengal (hereafter referred as BoB) and aerosols over the northern Arabian Sea (hereafter referred as AS) during July-August (Lau et al., 2010).

In the present work we attempted to study the association of aerosols and cloud properties with ISMR at interannual and intraseasonal scale. The satellite derived products for example TRMM 3B42 rainfall data, MODIS derived Aerosol Optical Depth (hereafter referred as AOD) and cloud properties have been used to study the variation in ISMR with respect to these products over Indian land and adjacent oceanic regions. Attempts have been made to discuss rainfall – aerosol - cloud interaction to highlight the fact that aerosols can have a significant influence on interannual and intraseasonal variation of ISMR. The study has been carried out for 2003 to 2012 over the Central India (hereafter referred as CI), AS and BoB. The present study is different from the previous studies in the following two ways. One of them is that the study is based on both Indian land and surrounded oceanic regions.

And the second one is that we discussed the variations in ISMR both at interannual and intraseasonal scales.

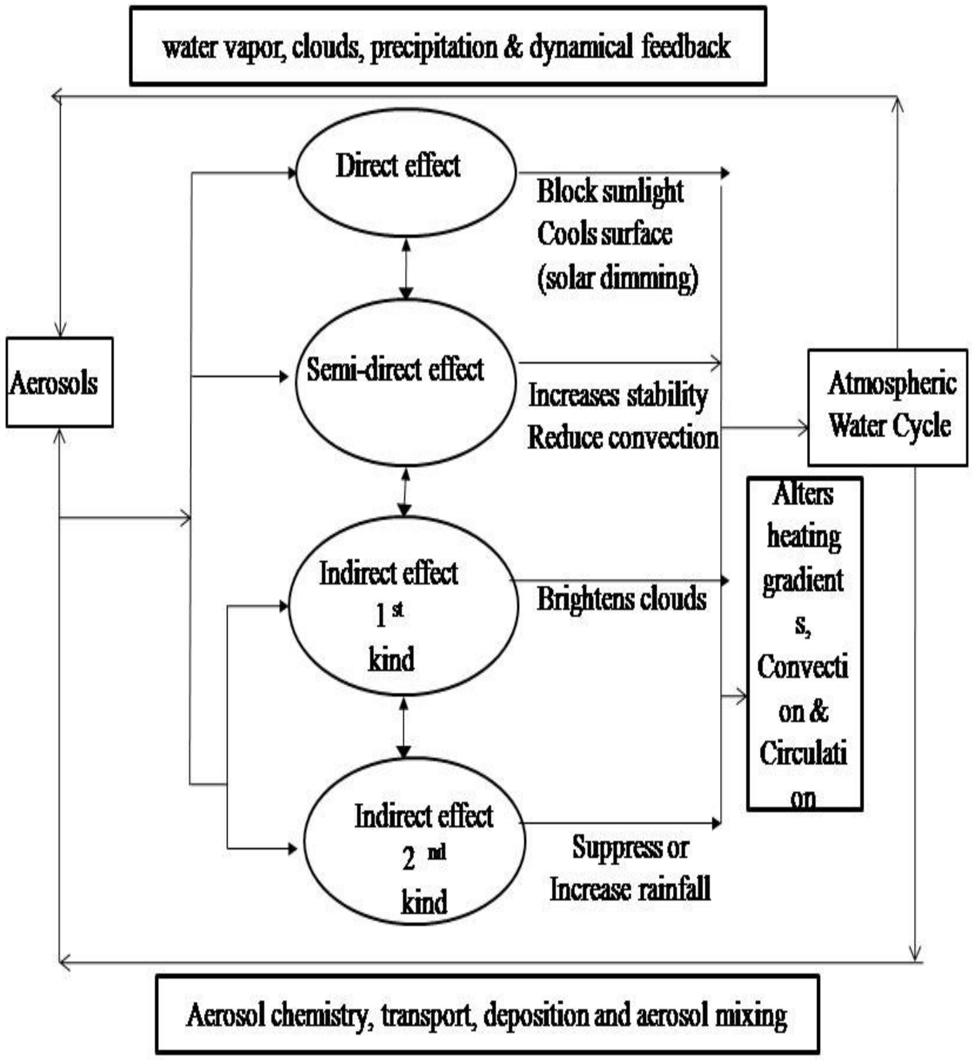


**Figure 1.1. Schematic interaction pathways for aerosols.** Aerosol local forcing, response, and feedback by the atmospheric water cycle through clouds, precipitation and large scale circulation, aerosol transport, chemistry, deposition and aerosol-aerosol interaction are provided in this diagram. (refer Lau et al., 2008; The joint aerosol - monsoon experiment, a new challenge for monsoon climate research; doi: 10.1175/bams-89-3-369).

The impact of aerosols on rainfall has given in the following schematic. This schematic depicts the different types of aerosol rainfall interactions such as cloud albedo and life time effect, semi-direct effect and glaciation effect.

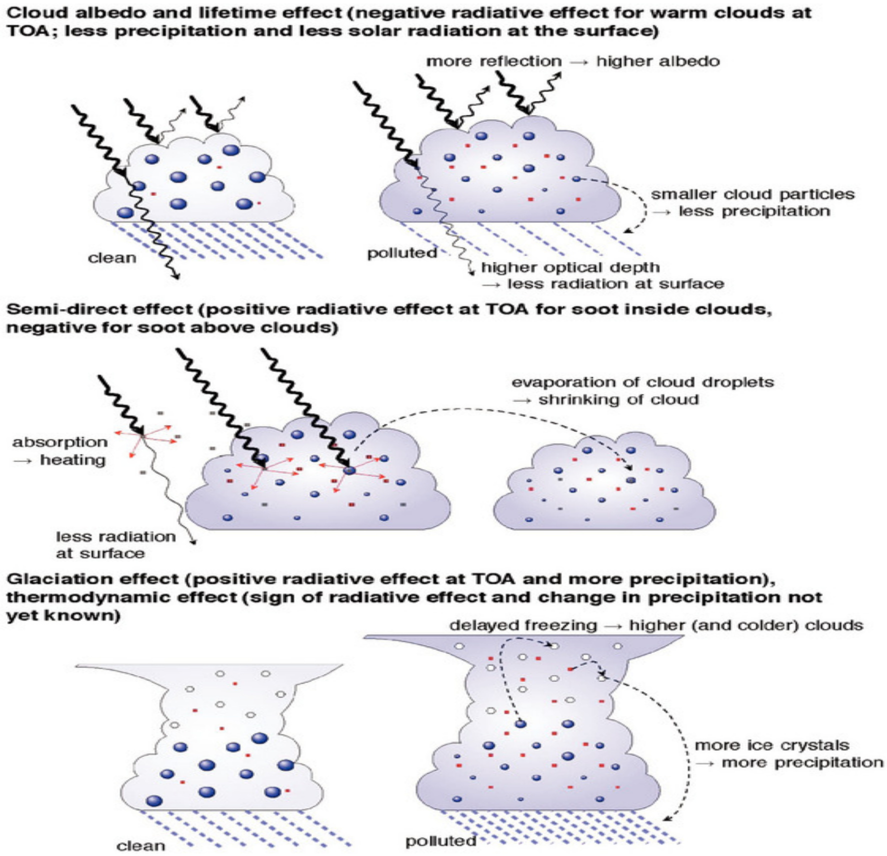


**Figure 1.2. Impact of aerosols on rainfall.**

(Refer http://www.ipcc.ch/publications_and_data)

The outline of the thesis is as follows:

Previous studies based on the spatio-temporal distribution of aerosols, and their association with rainfall along with the impact of cloud properties on ISMR are discussed in chapter 2. The details of the study region are provided in chapter 3. Data used for the present study and the methodology adopted are discussed in chapter 4. Results, discussions, conclusion and recommendation are given in the chapter 5, chapter 6 and chapter 7 respectively.

# CHAPTER 2

# LITERATURE REVIEW

Changes in solar radiation, cloud cover, cloud type, atmospheric trace gases, and aerosols in the atmosphere can affect the radiative forcing and alter the regional climate (Niyogi et al., 2007). From a global perspective, the combined effects of aerosols from local sources and from transport processes occurring in different parts of the globe and in different seasons are likely to alter the large-scale heating and pressure gradients and induce changes in the atmospheric general circulation, affecting the processes of generating clouds and rainfall (Lau et al., 2008). Seasonal variation of the temperature, pressure and rainfall associated with the monsoon is evident not only on the large scale but also for sub-regions of the country and even individual stations. This interannual variation of the summer monsoon rainfall over the country as a whole, has always had a significant impact on the agricultural production and hence the economy of the region (Gadgil, 2006***).*** Summer monsoon over India is largely controlled by the internal and external forcing such as sea surface temperature (SST), Tibetan Plateau (TP) heating, soil moisture, Eurasian snow cover, greenhouse gas concentration, and aerosols (Sajani et al., 2012).

Aerosols can affect the cloud-radiation feedback and the precipitation over the Indian monsoon region (Niyogi et al., 2007).The local dust, thermal stability of the air, precipitation and their inter-dependence has given the indications that the dust enters into the precipitation picture by virtue of its role in radiation balance during the relatively dry period (January to June) and through the cloud microstructure during the July to September (Ramachandra murty and Ramana murty, 1973). Based on the extensive measurements of aerosols in surface air and in the lower troposphere over the inland and coastal stations of different regions in India, Kapoor et al., (1978) observed that aerosols are a crucial link in the physical processes, involved in the formation and growth of precipitating clouds. They further observed that the hygroscopic fraction of the total aerosol content is found to be a useful characteristic for distinguishing between the monsoon and summer airflow, as well as an indicator for a good or a badly developed monsoon.

Using a limited area atmospheric model, Pathirana et al., (2007) studied the impacts of aerosol radiative forcing on the rainfall process. They concluded that the negative impact of increase in anthropogenic aerosols on rainfall would be more severe on regions and seasons with lower rainfall yields. As per the observations by, Niyogi et al., (2007) large magnitude of aerosol loading and its impact on land–atmosphere interactions can significantly influence the mesoscale monsoonal characteristics in the Indo-Ganges basin. They further observed that the fluxes of carbon dioxide, water vapour, and energy are closely coupled over vegetated areas, and the effect on carbon fluxes exemplifies the role of aerosols in land–atmosphere interactions. They further noticed that an aerosol feedback on carbon fluxes indicates a more vigorous land–atmosphere interaction due to aerosol loading. Using the CAM3 model Sajani et al., (2012) noticed that when total aerosol loading is prescribed, dust and black carbon aerosols are found to cause significant atmospheric heating over the monsoon region. Another observation from their studies is that the aerosol-induced weakening of meridional lower tropospheric temperature gradient (leading to weaker summer monsoon rainfall) offsets the increase in summer-time rainfall resulting from the atmospheric heating effect of absorbing aerosols, leading to a net decrease of summer monsoon rainfall.

However, since aerosol forcing is much more pronounced on regional scales than on the global scale because of the highly variable aerosol distributions, it would be insufficient or even misleading to place too much emphasis on the global average. Also, aerosol radiative forcing at the surface is stronger than that at top of the atmosphere, exerting large impacts within the atmosphere to alter the atmospheric circulation patterns and water cycle. Therefore, impacts of aerosols on climate should be assessed beyond the limited aspect of globally averaged radiative forcing at top of the atmosphere (refer Synthesis and assessment product 2.3; 2009 January; U.S. Climate Change Science programme). Based on the climate simulations with globally constant AOD values and constant AOD values over the extended Indian region replaced by realistic AOD values, Sajani et al., (2012) observed that the regional aerosol radiative forcing perturbations over the Indian region having impact over the region of aerosol loading and remote tropical regions. Hence they are suggesting the need to prescribe realistic aerosol properties in regions such as India in order to accurately assess the aerosol impact on rainfall. The consequences of the increased aerosol problem on the industries that depend on rainfall and on the general livelihood of societies in low-rain areas can be serious (Pathirana et al., 2007).

Based on the numerical study using the NASA finite-volume GCM, Lau et al., (2006) elucidate a hypothesis (elevated heat pump effect) for aerosol impact on the Asian summer monsoon involving interaction with physical processes over the TP. As per this hypothesis in the pre monsoon dusts from the deserts of western China, Afghanistan, Pakistan, and the Middle East are stacked up against the northern and southern slopes of the TP and the absorption of solar radiation by dust heats up the elevated surface air over the slopes and the atmospheric heating is reinforced by black carbon from local emission. They suggest that increased dust loading coupled with black carbon emission from local sources in northern India during late spring may lead to an advance of the rainy periods and subsequently an intensification of the ISMR and suppressing rainfall over East Asia and the adjacent oceanic regions. As per the observations of Dey and Singh, (2002) using remotely sensed data, the BoB shows more dynamic nature of aerosols compared to the AS and aerosol size-distribution is bimodal in nature during summer season. They further observed that the spatial gradient of AOD is found to be higher over the BoB compared to the AS and the BoB is dominated by finer particles compared to the AS.

Using MODIS data from 2000 to 2007, Ravi Kiran et al., 2009 studied about the variations of cloud and aerosol properties over the Indian region in associated with the intraseasonal variations of ISMR. They further observed that during the break spells, aerosol loading from the north AS is transported to CI and the increase in aerosol content decreases the CER (indirect effect of aerosols on cloud properties). As per the studies by Manoj et al., (2011) the circulation during break spells followed by the active (BFA) cases helps in the accumulation of absorbing aerosols over CI, results in the increase of AI and the meridional gradient of temperature at low level between aerosol - rich CI and pristine equatorial Indian Ocean is large which can sustains for long time during BFA leading to significant moisture convergence to CI. Using the pentad-resolution observational datasets, analysed the interannual variations of absorbing aerosols and related hydrometeorology over South Asia in the pre-monsoon period is investigated by Bollasina et al., (2009) and they noticed the complex interplay among aerosols, dynamics and precipitation also shows the challenge of extracting the aerosol impact from an observational analysis. Kumar, 2013 studied the spatial and temporal variations in aerosol particles over north east India during 2001 to 2010 and noticed that AOD increased >15% during the last decade.

Aerosol and precipitation in the monsoon area and adjacent deserts are closely linked to the large-scale circulation and intertwined with the complex monsoon diabatic heating and dynamical processes during pre monsoon and monsoon periods. Coupled atmosphere ocean-land dynamical processes are the primary driver of the Asian monsoon, extreme care must be exercised in identifying aerosol rainfall relationships that are truly due to aerosol physics and do not arise because both aerosol and rainfall are driven by the same large-scale dynamics (Lau et al., 2010). During summer monsoon season over AS, aerosol visible optical depths are as high as 0.4 to 0.7 with aerosol single scattering albedo of - 0.97 indicating the presence of large non-absorbing aerosols (Vinoj and Satheesh, 2003). Aerosol visible optical depths over BoB were as high as 0.6 with aerosol single-scattering albedo of 0.88 indicating the presence of a significant amount of submicron absorbing aerosols (Vinoj et al., 2004).

Cloud characteristics can be extensively used to understand the interlinks between aerosol-precipitation mechanisms. As per the studies by Li et al., (2011) cloud density and the radiative balance of the atmosphere can be altered by means of aerosols, which leads to changes in cloud microphysics and atmospheric stability and it ultimately suppress or foster the development of clouds and precipitation. They have further shown that the precipitation frequency and rain rate are altered by aerosols and precipitation increases with aerosol concentration in deep clouds that have high liquid-water content, but declines in clouds that have low liquid-water content. Based on the numerical simulations Rosenfeld et al., (2012) shown that the suppression of rain is well described in terms of cloud drop effective radius. Another study by Sekiguchi et al., (2003) tried to investigate the correlations between aerosol and cloud parameters derived from satellite remote sensing for evaluating the radiative forcing of the aerosol indirect effect. They further mentioned about the aerosol indirect effect by correlating the effective particle radius and the optical thickness of low clouds with the column number concentration of the aerosol particles. Cloud fraction can be considered as another cloud parameter which can provide much information behind the cloud aerosol interactions. Grandey et al., 2013 mentioned about the significant positive relationships between cloud fraction and AOD using the data from MODIS. They further noticed that an increase in cloud fraction with changes in AOD over both land and ocean and the negative correlations between cloud fraction-AOD can be arise due to rain scavenging of aerosol. Quaas et al., (2008) derived a statistical relationship between planetary albedo - cloud properties and between the cloud properties-column aerosol concentration and based on this they further estimated an anthropogenic radiative forcing of -0.9 ±0.4 W/m$^2$ for the aerosol direct effect and of -0.2 ± 0.1 W/m$^2$ for the cloud albedo effect. Lebsock et al., (2008) demonstrated that high aerosol concentrations are associated with reduced liquid water path in non-precipitating clouds which in turn reduces the albedo enhancement expected from decreasing effective radius and the onset of precipitation requires high amount of cloud condensate in an increased aerosol environment.

Ramachandran and Kedia, 2013 studied about the interannual variations in ISMR during the month of July over the Indian land region in association with the cloud and aerosol parameters. The impact of aerosols on the intraseasonal variability of ISMR has been analysed by several previous studies (Ravi Kiran et al., 2009; Manoj et al., 2011). Understanding the complex reaction mechanisms between the rainfall and aerosols is a crucial topic and hence, in the present work attempts has been made to elucidate the aerosol-cloud-precipitation interaction over the Indian land mass and adjacent oceanic regions. The variability of the ISMR has been studied at interannual and intraseasonal scale with respect to the aerosol and cloud properties.

# CHAPTER 3

# STUDY AREA AND DATA USED

## 3.1 Study Area

Variability of ISMR has been analysed at interannual and intraseasonal scale in association with aerosol – cloud parameters during 2003 to 2012 over CI, AS and BoB. Selection of these study areas are concerned with the importance of aerosol loading over land and oceanic regions in altering the rainfall pattern. The study regions and spatial locations are provided in the table 3.1 and figure 3.1.

**Table 3.1 Study areas selected for the present study**

| **Study Region** | **Latitude** | **Longitude** |
|---|---|---|
| Arabian Sea (AS) | $14^0$-$19^0$N | $63^0$ -$69^0$ E |
| Bay of Bengal (BoB) | $14^0$-$19^0$ N | $86^0$-$92^0$ E |
| Central India (CI) | $17^0$-$27^0$ N | $74^0$-$82^0$ E |

Interannual variabity of ISMR has been analysed during 2003 to 2012 (10 year time scale) considering the variations in aerosol characteristics [AOD , UV Aerosol Index (hereafter referred as AI)] and cloud parameters [Cloud Effective Radii, Cloud Fraction, Cloud Optical Depth, Cloud Top Pressure (hereafter referred as CER, CF, COD, CTP respectively)]. ISMR interannual variability has been analysed along with the variations in aerosol-cloud parameters during 10 year time scale over the CI, AS and BoB region. Intraseasonal variability of ISMR (active and break spells) has been studied during 1998 to 2011 over the CI. CI region has been supposed to be loaded with substantial aerosol concentration due to increased air pollution and it receives moderate rainfall during the ISMR season as compared to other regions of the Indian subcontinent. Therefore, this region has been selected to analyse the intraseasonal variations in rain and aerosols. Extensive studies has been carried out over CI for examining the monsoon variability (Goswami and Ajaya Mohan 2001; Krishnamurthy and Shukla 2007; Rajeevan et al., 2010; Singh 2013; Sinha et al., 2011). In the present study the variability of AOD, SSA, COD, CF and CER are analysed during the active and break days over the CI region. HYSPLIT backward trajectory model has been used to check the movement of air mass towards the CI region during the individual active (break) days.

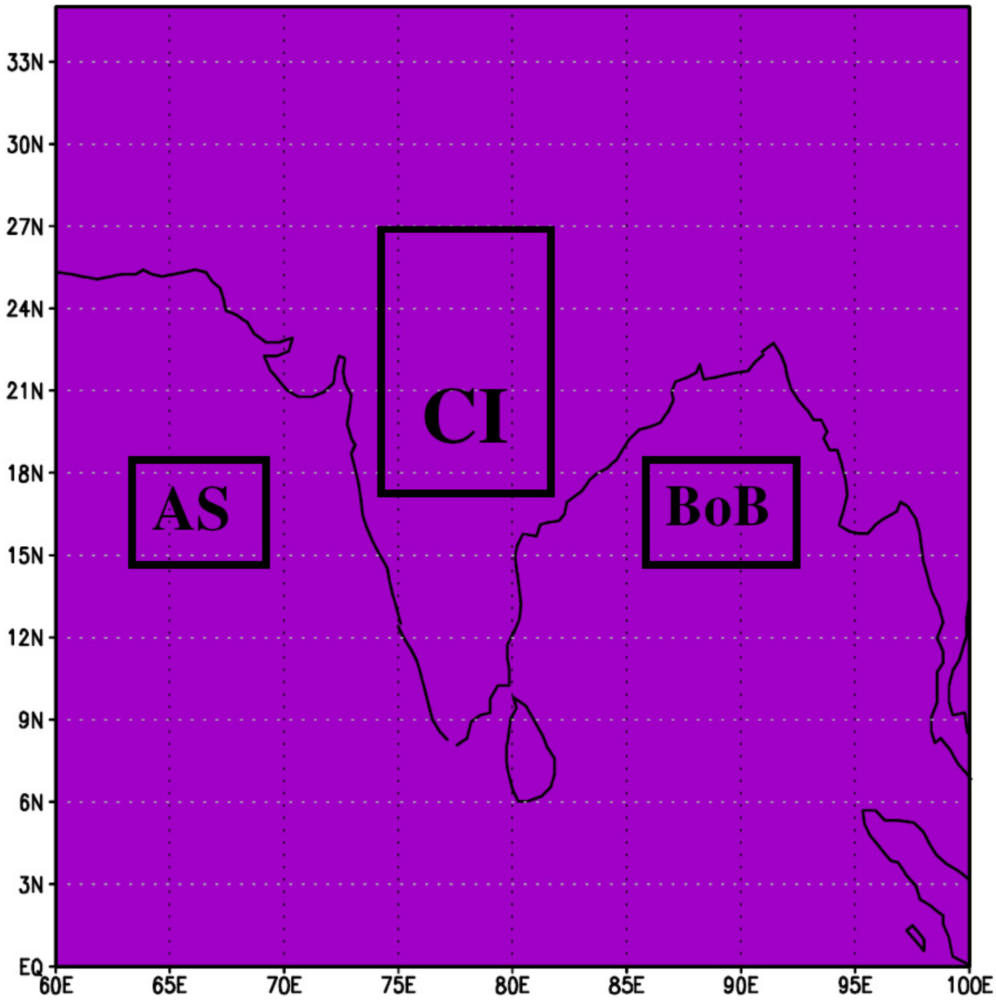


**Figure 3.1 The study areas selected for the present study.** (CI) Central India. (AS) Arabian Sea. (BoB) Bay of Bengal.

## 3.2 Data used

### 1. TRMM 3B42 (V7) rainfall data

In the present study, Tropical Rainfall Measuring Mission (TRMM) 3B42 (V7) data with 0.25 × 0.25 spatial resolution has been used to examine the variability of ISMR at interannnual and intraseasonal scale. TRMM is designed to increase the extent and accuracy of tropical rainfall measurement and monitors rainfall over a large area of the globe (50N-50S). Interannual variations of ISMR during 2003 to 2012 has been analysed in association with aerosol and cloud characteristics over CI, AS and BoB. Selection of these study areas are concerned with the importance of aerosol loading over land and oceanic region in altering the rainfall pattern. Intraseasonal variability in ISMR has been examined during

2003 to 2011 over CI region along with the variability in aerosol-cloud properties. For identifying the active and break spells which represent the intraseasonal variability of ISMR, the 14 years (1998-2011) of TRMM 3B42 data has been used. Data has been acquired from http://gdata1.sci.gsfc.nasa.gov/daacbin/G3/gui.cgi?instance_id=TRMM_3B42_Daily.

**2. IMD rainfall data**

High resolution (1° × 1°) gridded rainfall data set from the National Climate Centre (NCC), India Meteorological Department (IMD), Pune has been used in the comparative analysis of satellite derived rainfall data set. IMD rainfall data set is based on a weighted average of rain gauge measurements over the Indian subcontinent. A large network of 6300 rain gauge stations are available across the country, out of which 1800 stations have been considered for the preparation of the gridded rainfall data (Rajeevan et al., 2010). It is observed from the comparative analysis that TRMM 3B 42 V 7 data is suitable for capturing the spatial and temporal pattern (figures are not shown) of summer monsoon rainfall over Indian region. The correlation analysis (refer figure 3.2) of daily ISMR for the year of 2003 and 2004 between IMD gridded data and TRMM 3B42 V7 data indicates significant correlation (at 1% significance level) between the two data sets over the CI region.

**2. AOD at 550 nm**

MODerate resolution Imaging Spectrometer (MODIS) level-3 atmosphere daily global $1^{0} \times 1^{0}$ AOD at 550nm, from Aqua and Terra satellites has been used for analysing the impact of aerosol loading on the spatio-temporal variability of ISMR. MODIS data are acquired from thewebsite,http://gdata1.sci.gsfc.nasa.gov/daacbin/G3/gui.cgi?instance_id=MODIS_DAILY_L3. The MODIS aerosol data products from both the Terra platform (aerosol data product file name MOD08_D3.051) and the Aqua platform (aerosol data product file name MYD08_D3.051) have been used for the present AOD Analysis. MODIS retrievals of AOD at $1^{0} \times 1^{0}$ resolution correspond well to the single-column ship-based sun photometer measurements, and the sparse temporal sampling of MODIS agrees well with the daytime averages of the ship-based observations over the AS and BoB regions (Cherian et al., 2012)

**3. AI**

UV AI level 3 data having spatial resolution $1^{0} \times 1.25^{0}$, from Earth Probe Total Ozone Mapping Spectrometer (TOMS) has been used in the present study during 2003 - 2004 in relation to the interannual variations of ISMR over CI, AS and BoB. Ozone Monitoring Instrument (OMI) onboard AURA satellite, AI data with spatial resolution $1^{0} \times 1^{0}$ from 2005 - 2012 has also been examined. Positive values of AI represents absorbing nature of the aerosols while high negative values for small non absorbing aerosols and near zero values correspond to the presence of clouds or larger non absorbing particles (Torres et al., 2007).

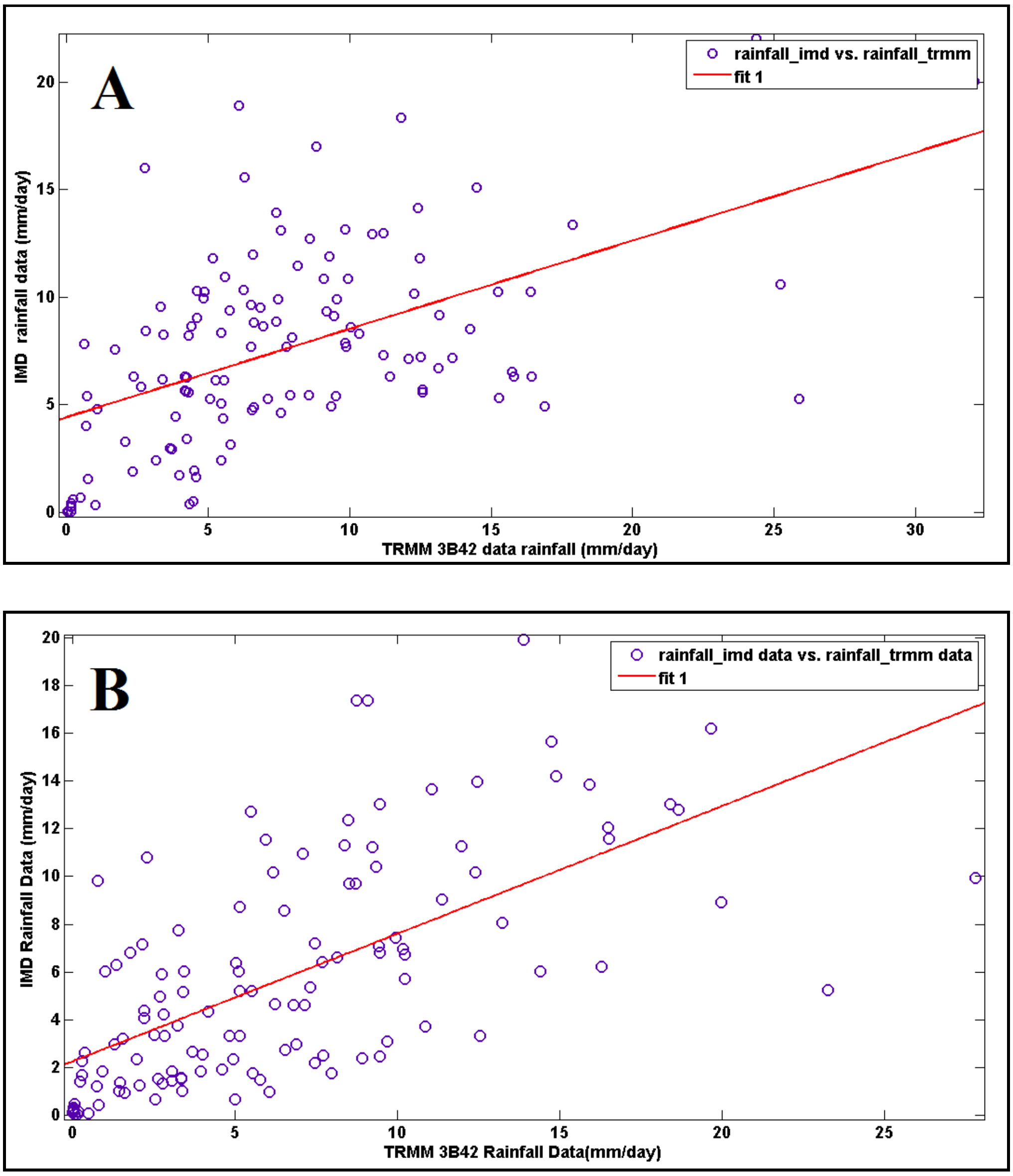


**Figure 3.2. Scatter plot of TRMM 3B42 daily rainfall data and IMD daily rainfall data for CI.** (A) Scatter plot for 2003 (B) Same as (A) but for 2004. Correlation is significant at 1% significance level.

## 4. SSA

SSA at 500 nm, from AURA-OMI has been used for analysing the impact of aerosol loading on the intraseasonal variability of ISMR. SSA data has been taken from the website http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=omi.

## 5. Cloud Parameters

Cloud parameters such as CER, CF, COD and CTP are examined in relation with the variation in rainfall and AOD over the study areas. Data has been acquired from the weblink-http://gdata1.sci.gsfc.nasa.gov/daacbin/G3/gui.cgi?instance_id=MODIS_DAILY_L3.

(a) CER

MODIS level-3 atmosphere daily global $1^{0} \times 1^{0}$ CER has been used to analyse the relation between aerosol-CER-rainfall. CER is an area weighted mean radius of the cloud droplets. CER in microns is defined as below:

$$r_e = \frac{\int_0^\infty r^3\, n(r)dr}{\int_0^\infty r^2\, n(r)dr} \tag{3.1}$$

r = particle radius; n(r) = particle size distribution (number of particles per $cm^2$ with radius in the range r and r + dr µm). CER data are extensively used in the radiative transfer models, earth radiation budget, studies related to climate change and air quality of fog (refer http://disc.sci.gsfc.nasa.gov/giovanni/additional/data-holdings/PIP/cloud_effective_radius.shtml).

(b) CF

MODIS level-3 atmosphere daily global $1^{0} \times 1^{0}$ CF data has been used along with other cloud parameters. It is the fraction of the sky that is covered by the cloud and also referred as cloud amount or cloud cover. CF is defined as the number of cloudy pixels divided by the total number of pixel. It also refers to the amount of sky estimated to be covered by a specific cloud type, cloud particle phase (water, ice, liquid, mixed), cloud height (low, mid, high) or by all cloud types.

(c) COD

MODIS level-3 atmosphere daily global $1^{0} \times 1^{0}$ COD was used in the present analysis. It is a measure of attenuation of the light passing through the atmosphere due to the scattering and absorption by cloud droplets. The COD or optical thickness (τ) is defined as the integrated extinction coefficient over a vertical column of unit cross section. Extinction coefficient is the fractional depletion of radiance per unit path length [refer http://disc.sci.gsfc.nasa.gov/giovanni/additional/dataholdings/PIP/cloud_optical_thickness_or_depth.shtml].

(d) CTP

MODIS level-3 atmosphere daily global $1^{0} \times 1^{0}$ CTP has been used. CTP is atmospheric pressure at the level of the cloud top. Accurate information on CTP and height are needed in order to retrieve properly many atmospheric and surface properties. It also plays an important role in the net earth radiation budget studies (refer http://disc.sci.gsfc.nasa.gov/data-holdings/PIP/cloud_top_pressure.shtml).

### 6. HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model

HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model is used to analyse the backward trajectories during individual active (break) events. The model available from National Oceanic and Atmospheric Administration (NOAA) - Air Resources Laboratory (ARL) through the weblink: http://www.ready.noaa.gov/ready/open/traj.html.

# CHAPTER 4

# METHOD OF ANALYSIS

The methodology for analysing the ISMR variability in association with aerosols and cloud properties over the AS, BoB and CI are described in the following flow chart (figure 4.1).

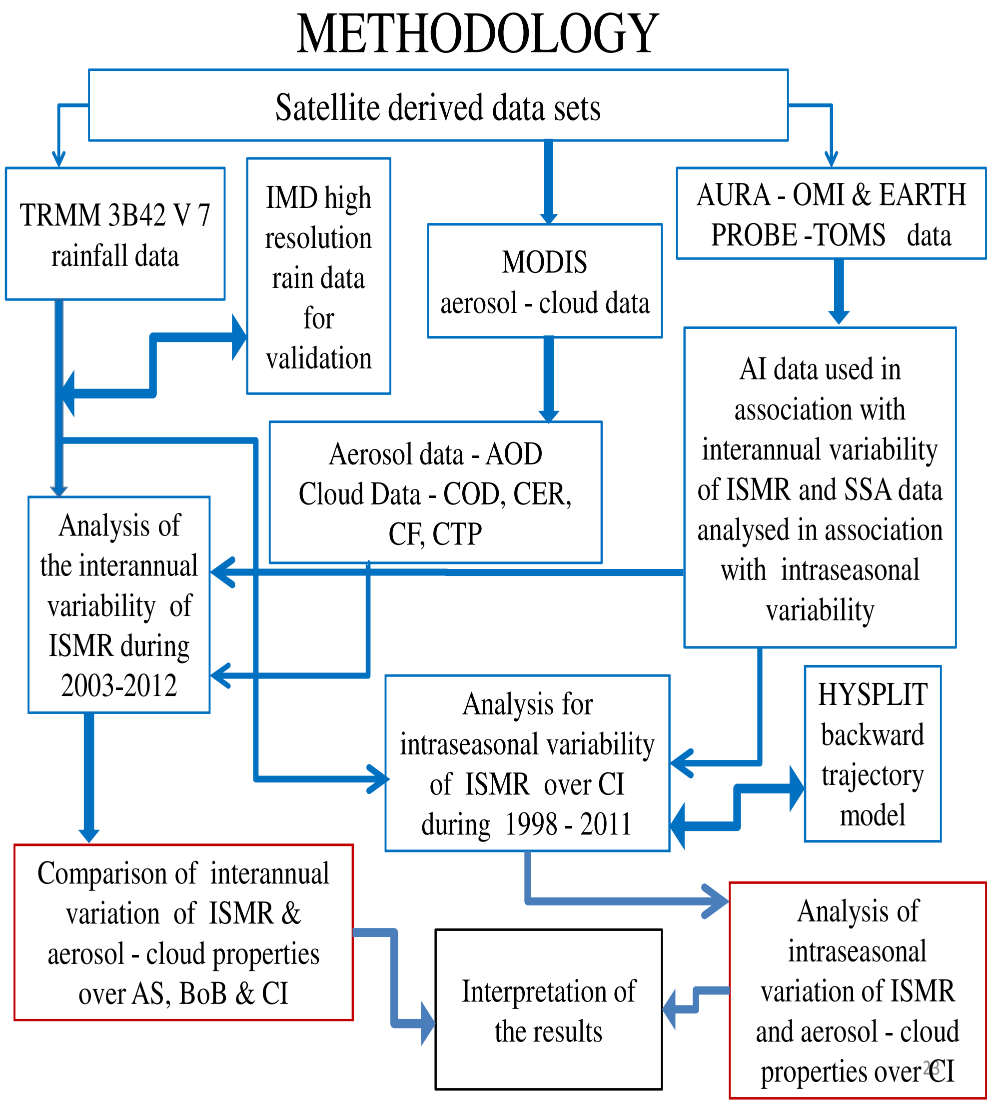


**Figure 4.1. Flowchart for the methodology**

## 4.1. Interannual variability of ISMR for 2003 -2012

The spatio-temporal and statistical analysis of the ISMR season (June to September; 122 days) has been carried out during 2003 to 2012 over the CI, AS and BoB regions. Further the aerosol characteristics such as AOD, AI along with the cloud parameters - CER, CF, COD and CTP have been analysed in order to understand the interlinks with the ISMR.

Following the traditional definition (for example Parthasarathy et al., 1994), we have identified the flood and drought years from TRMM 3B42 V7 rainfall data sets over CI region for the period 1998 – 2011. As per the definition the drought (flood) years have been identified as those years when the normalized index is less (more) than or equal to -1 (+1). The normalized index may be expressed as follows:

$$\text{Normalized index} = (X_i - X) / (\sigma_{Xi}) \qquad (4.1)$$

$X_i$ = Area averaged mean monsoon rainfall for year i (i =1998 - 2012);
X = Area averaged climatological mean monsoon rainfall;
$\sigma_{Xi}$ = Standard deviation of $X_i$ ;

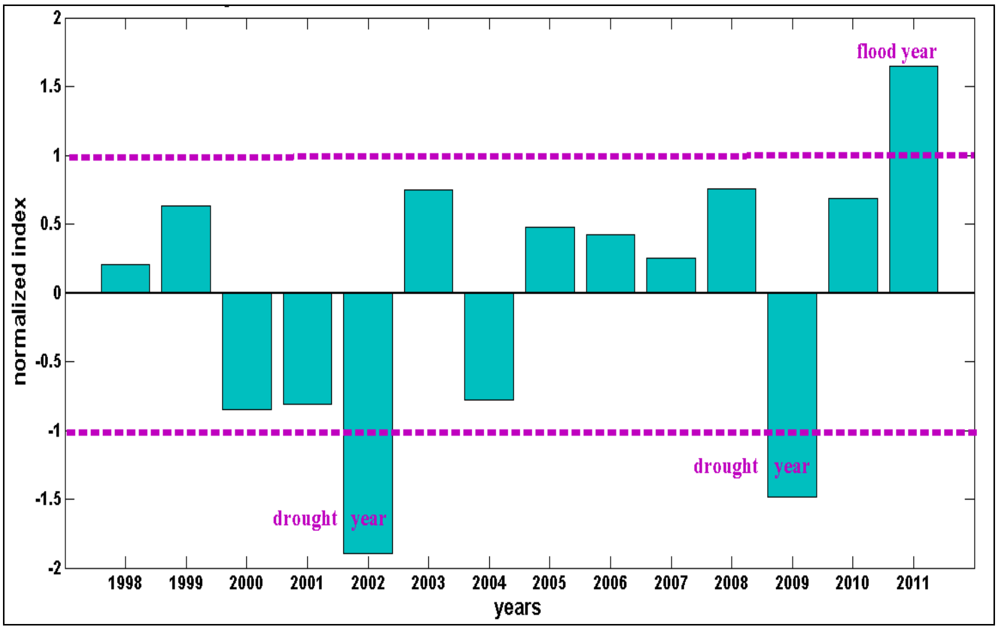


**Figure 4.2: Bar diagram showing the drought, flood and normal monsoon years during 1998 – 2011 based on the ISMR rainfall data over the CI region** (18-28 $^{0}$ N & 74-84 $^{0}$ E). Drought years are having normalized index value ≤ -1 and flood years having normalized index value ≥ +1. All other monsoon years having normalized index values in between -1 and 1 are considered as normal monsoon year.

The results obtained from the satellite derived rainfall data (TRMM 3B42 V7) are well comparable to those drought, flood and normal monsoon years calculated using rain gauge measurements. The ISMR seasons of 2002, 2004 and 2009 are considered as drought years (refer http://www.tropmet.res.in/~kolli/MOL/Monsoon/frameindex.html).

### 4.1.1 Statistical Analysis

Mean and standard deviation have been considered for all the parameters over the three study regions to investigate the interlinks between the rain and all the parameters. The correlation analysis for interannual variation of ISMR with respect to the aerosol properties (AOD,AI) and cloud parameters (CER, COD, CF, CTP ) has been carried out over the three study regions (CI, AS and BoB). The mathematical expression for the correlation coefficient is as follows:

$$C = \frac{v_{12}}{\sigma_1 \, \sigma_2} \tag{4.2}$$

C = Coefficient of correlation;

$v_{12}$ = Covariance of the parameter 1 and the parameter 2;

$\sigma_1\sigma_2$ = Product of the standard deviation of the parameter 1 and the parameter 2;

The significance of the correlation coefficients has been tested up to a significance level of 5 %

## 4.2 Intraseasonal variability of ISMR: active and break spells

Active and break events has been identified using the 14 years (1998-2011) TRMM 3B42 (V7) data over the CI. Active and break spells are calculated on the basis of the criteria defined by Rajeevan et al., (2010), but using satellite derived data sets. Following the traditional research on monsoon variability and considering the substantial amount of aerosol loading, the CI has been selected to investigate the active (break) spells. After imparting a sensitivity analysis on TRMM 3B42 V 7 data set, it has been observed that for the computation of active and break spells from satellite data the threshold has to be kept at 0.5. Based on the new definition, the active (break) event has been identified as the period during which the normalized index is more (less) than or equal to 0.5 (-0.5), at least for three consecutive days.

$$\text{Normalized index} = (R_i - R)/\,\sigma_{Ri} \tag{4.3}$$

$R_i$ = Area averaged daily rainfall for the specific year i (i = 1998 – 2011);
R = Long term area averaged daily rainfall;
$\sigma_{Ri}$ = Daily standard deviation of area averaged daily rainfall;

The active and break spells identified during the peak ISMR months of July and August using satellite data sets are well comparable to those active (break) events identified by Rajeevan et al., (2010), using the updated version of the IMD high resolution gridded daily rainfall data set (refer table.4.1). We have observed distinct variability in the spatial pattern of AOD over the CI region during each active (break) event. The analysis was started with the composites of AOD for nine years duration and further to this, we considered the aerosol distribution during the spells of individual years. The individual active and break events are analysed along with the variations in aerosol characteristics such as AOD, SSA and cloud properties (CER, COD and CF).

**Table.4.1. Active and break spells identified for1998 -2011**

| Year | Present Study<br>Study Area: 17- 27 $^0$N & 74 - 82 $^0$E | | Rajeevan et al., 2010<br>Study Area: 18-28 $^0$N & 65 - 88.0 $^0$E | |
|---|---|---|---|---|
| | Active spells | Break spells | Active spells | Break spells |
| 1998 | 3-5 J, 27-29 J | 20-22 J | 3-6J | 20-26J, 16-21A |
| 1999 | Nil | 1-4 J | Nil | 1-5J, 12-16A, 22-25A |
| 2000 | 6-8 J, 11-13 J,17-20 J | 21-27 J, 31 J- 6 A | 12-15J, 17-20J | 1-9A |
| 2001 | 8-10 J | 24-30 A | 9-12J | 31J-2A, 26-30A |
| 2002 | Nil | 1-11 J, 24-29 J | Nil | 4-17J, 21-31J |
| 2003 | 21-23 A | 28-31 J | 26-28J | Nil |
| 2004 | Nil | 8-10 J, 18-20 J,24-31A | 30J -1A | 10-13J, 19-21J, 26-31A |
| 2005 | 9-11J, 24-27 J,30J-1 A | 7-13 A, 23-28 A | 1-4J, 27J-1A | 7-14A, 24-31A |
| 2006 | 2-4 J, 4-6 A | 9-11 J | 3-6J, 28J-2A, 5-7A, 13-22A | Nil |
| 2007 | 6-8 J, 26-28 A | 2-5 J | 1-4J,6-9J, 6-9A | 18-22J, 15-17A |
| 2008 | 27-29 J, 9-11 A | 13-15 J, 21-23 A | | |
| 2009 | 20-22 J | 24 J - 9 A | | |
| 2010 | 11-13 A | 7-10 A | | |
| 2011 | 13-16 J,24-27 A | 1-3 J | | |

# CHAPTER 5

# RESULTS

## 5.1 Interannual variability of ISMR over CI, AS and BoB and its association with cloud-aerosol characteristics

### 5.1.1 Interannual variability of ISMR over CI, AS and BoB

ISMR exhibits substantial interannual and intraseasonal variations and in the present study analyses the variability in association with aerosol - cloud parameters over the CI, AS and BoB regions. Spatial representations of climatological mean rainfall derived from TRMM observations over the Indian region ($50^{0}$ to $120^{0}$ E & $-10^{0}$ to $40^{0}$ N) for 1998 - 2012 (June-July-August-September) and its standard deviation is provided in figure 5.1.

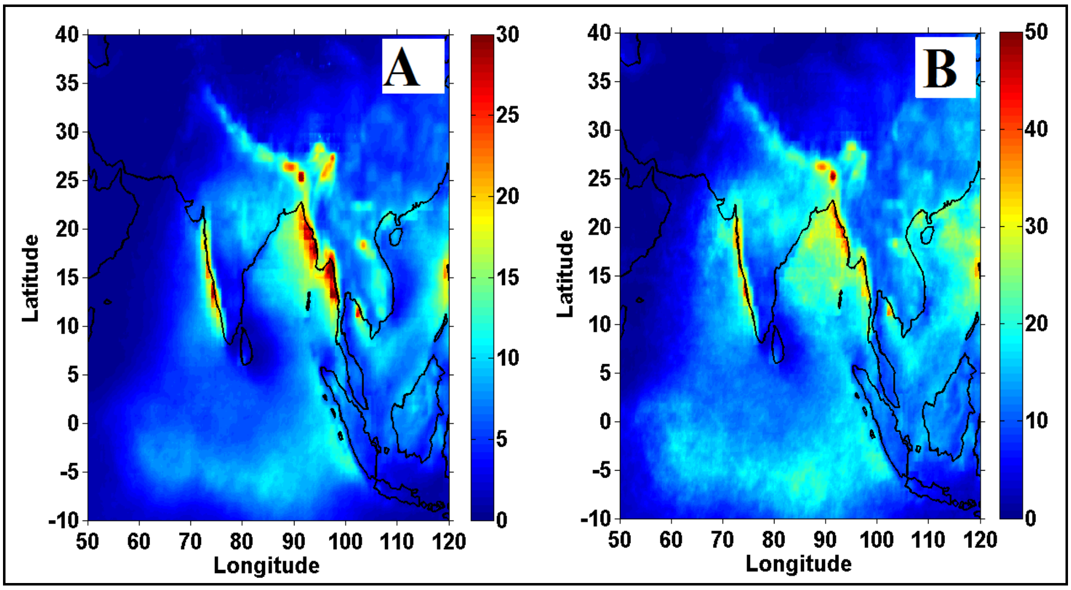


**Figure 5.1: (A) Spatial distributions of climatological mean rainfall during 1998 to 2012** (over Indian land and adjacent oceanic regions). (B) Same as (A) but the standard deviation. The color bar represents rainfall in mm/day.

It was observed from the figure 5.1 that, high rainfall is received along the Western Ghats region and north - eastern regions of Indian subcontinent. Other regions of the Indian subcontinent show substantial reduction in rainfall as compared to the regions having high rain and it depends upon many factors. The anomalies (deviation from long term mean) in ISMR for 1998 - 2012 are illustrated in the following figure (figure 5.2) and it is noticed that during 2002, 2004 and 2009, the negative anomalies are very prominent over the Indian land region especially over CI.

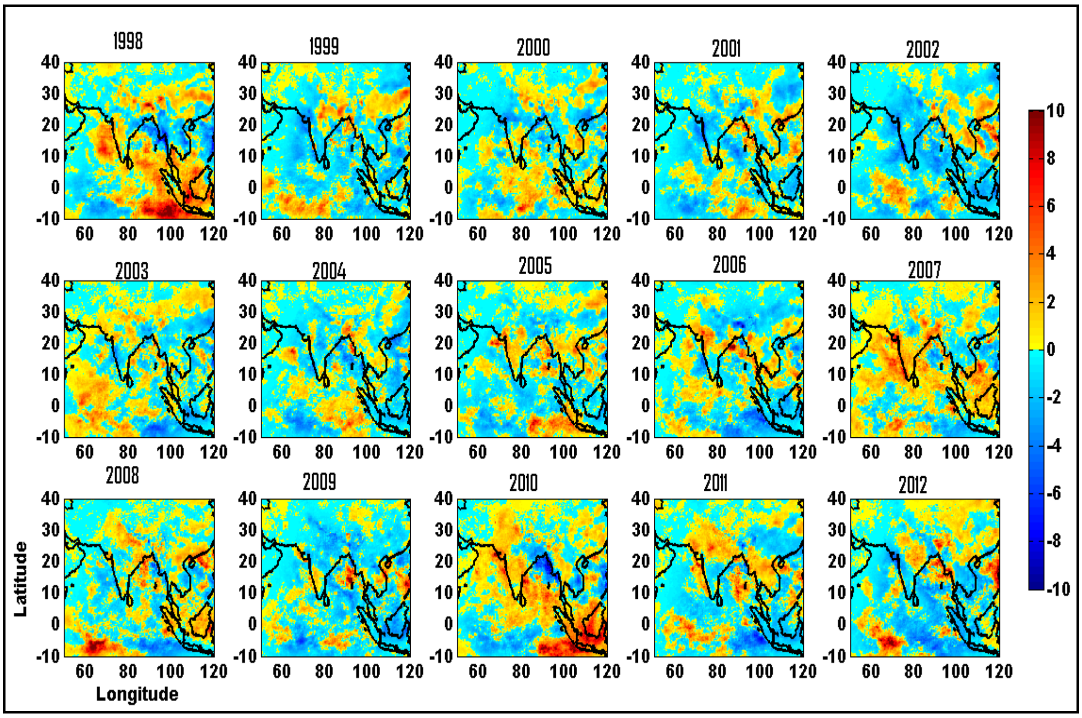


**Figure 5.2: Spatial distributions of ISMR anomalies for 1998 – 2012 over the Indian subcontinent.** Top panel represents the anomaly of the ISMR from 1998 – 2002. Middle panel represents the anomaly of ISMR from 2003 – 2007. Bottom panel represents the anomaly of the ISMR from 2008 – 2012. Colour bar represents the rainfall anomaly in mm/day.

The statistical analysis over the three study regions are given in the table 5.1. It is observed that during the drought years of 2004 and 2009 the mean rainfall over the CI region was lesser (6.53 and 6.02 mm/day respectively) as compared to the flood year 2011(8.12 mm/day). It was noticed that BoB receives high rainfall as compared to AS (refer table 5.1 ) and having higher value of mean rainfall for the drought year 2009 as compared to the flood year 2011. The mean value of rain for 2004 (drought year) was lesser in comparison with 2011 over the BoB region. AS region having substantially reduced amount of rainfall as compared to CI and BoB during the study period. Over AS region during the drought year 2004 mean value of rain was higher as compared to flood year, but during 2009 the mean rainfall of about 2.10 mm/day. Therefore it is clearly identifiable that the ISMR exhibiting notworthy interannual and spatial variations which may depend on the regional peculiarities and other monsoon system parameters.

**Table 5.1: Statistical analysis of ISMR during 2003-2012**

| CI - Central India AS - Arabian Sea BoB - Bay of Bengal<br>m - mean s - standard deviation<br>**2004, 2009 - drought year 2011- flood year** | | | | | | |
|---|---|---|---|---|---|---|
| Year | CI | | AS | | BoB | |
| | m | s | m | s | m | s |
| 2003 | 7.63 | 5.65 | 3.37 | 9.11 | 13.23 | 15.06 |
| **2004** | **6.53** | **5.49** | **4.32** | **10.84** | **11.39** | **11.23** |
| 2005 | 8.06 | 7.09 | 2.33 | 5.56 | 14.34 | 14.59 |
| 2006 | 7.88 | 7.37 | 3.74 | 8.70 | 15.13 | 17.63 |
| 2007 | 7.37 | 6.07 | 5.02 | 10.09 | 11.89 | 14.3 |
| 2008 | 7.53 | 5.15 | 1.98 | 5.91 | 14.16 | 14.32 |
| **2009** | **6.02** | **6.31** | **2.10** | **4.64** | **15.28** | **16.26** |
| 2010 | 8.12 | 6.24 | 3.51 | 6.05 | 11.36 | 13.65 |
| **2011** | **8.40** | **5.72** | **2.95** | **8.13** | **14.08** | **13.07** |
| 2012 | 7.83 | 6.29 | 1.69 | 3.01 | 14.03 | 14.10 |

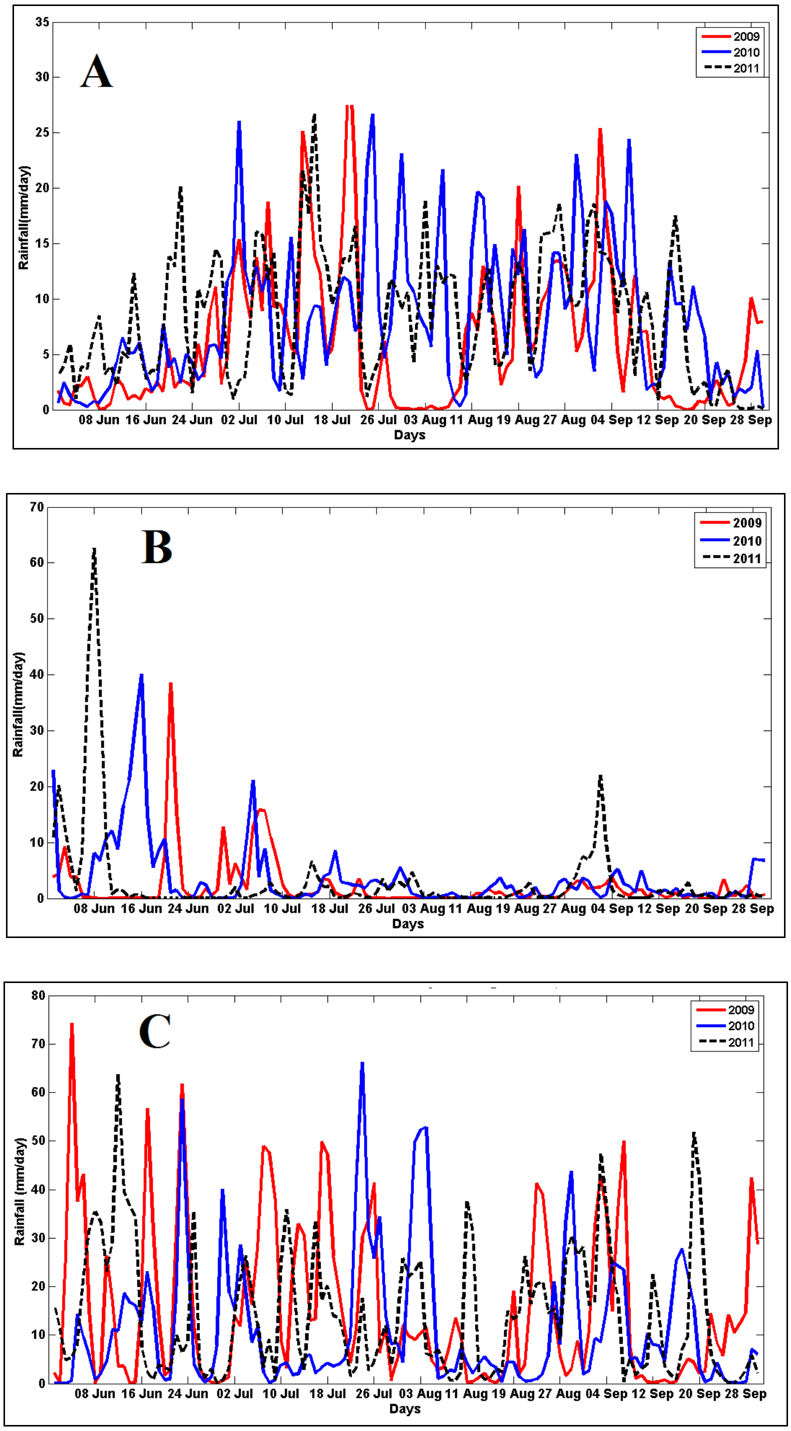


**Figure 5.3: Time series plots for the area averaged ISMR (01 June to 30 September) during 2009, 2010 and 2011.** (A) Represents CI. (B) Same as (A) but for AS. (C) Same as (A) but for BoB. The red colour line indicates the drought year 2009, blue colour line indicates normal monsoon year 2010 and black dotted line indicates the flood year 2011. Rainfall in mm/day.

Time series analysis has been done on the selected monsoon years of 2009 (drought year), 2010 (normal monsoon year) and 2011 (flood year) over the CI, AS and BoB. It is inferred from the figure 5.3 that AS region receives high amount of rainfall associated with the onset of ISMR and also the flood year 2011 attained more rain on the initial days itself and subsequently with the monsoon progression towards the CI region it was getting decreased over AS. Over CI region in comparison to the rainfall during 2009 and 2010, the flood year 2011 received more rain during the onset days and 2009 shows less monsoon rain during the peak monsoon months of July and August. In 2010, (normal monsoon year) less rain was observed during the initial days and it tends to pick up the intensity during the peak monsoon months of July and August and afterwards in September it is started retreating from the region.

### 5.1.2 Interannual variability in AOD over CI, AS and BoB during the ISMR season

Interannual variations in aerosol concentration have been examined in terms of spatio - temporal and statistical analysis over the CI, AS and BoB regions from 2003 to 2012. The mean climatological analysis of AOD (refer figure 5.4) during the ISMR season shows that aerosols are confined over the north western regions of India, north eastern AS and along the foothills of Himalayas. It is observed that even during the ISMR season, wet deposition was not able to remove the higher aerosol dispensation over the north western regions due to the continuous supply of aerosols attributed to anthropogenic influence and long range transport of aerosols from other regions (Ganguly et.al 2012).

Monthly mean aerosol distribution over the Indian landmass and adjoining oceanic regions (refer figure 5.5) shows that during the peak ISMR month of July, AOD was observed to be higher as compared to other months of ISMR season. During August, higher aerosol concentration was observed over north eastern AS region as compared to June and September. During the peak monsoon months, due to the wet removal aerosol concentrations are supposed to be very less, but the spatial analysis shows that aerosol dispensation was high especially over the north western regions and north eastern AS which extended up to the eastern end of Himalayan foothills. There might be the possibilities of higher local pollution and wind driven transport of air mass from other regions. The presence of coarse mode aerosols or the growth of fine mode water soluble aerosols might be the cause of the higher AOD values (Ramachandran and Cherian, 2008) observed even during the peak monsoon months.

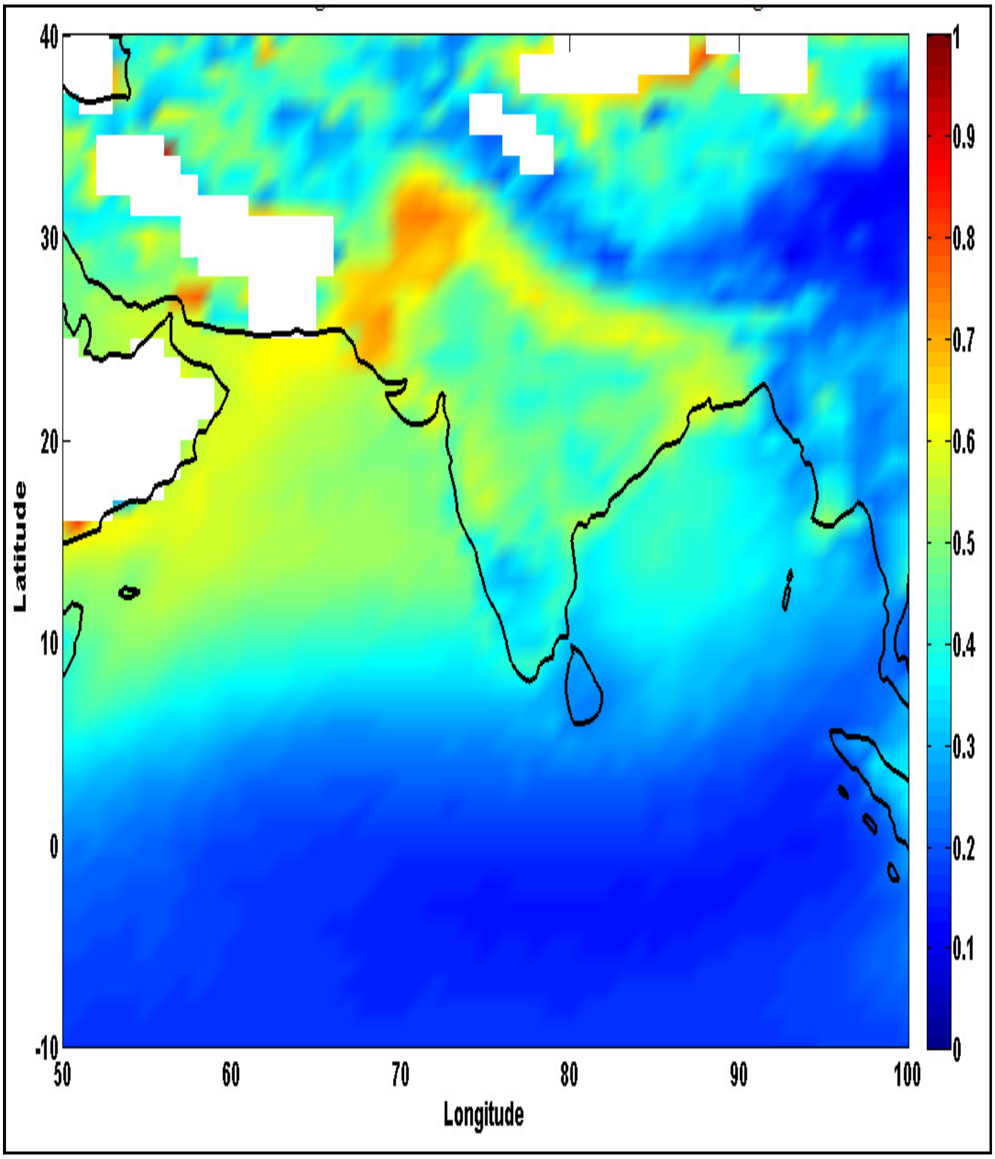


**Figure 5.4: Spatial distribution of climatological mean AOD for 2003 to 2012 over the Indian land and adjacent oceanic regions.** The colour bar indicates the mean AOD which is a unit less quantity. The value ranges from 0 to 1.

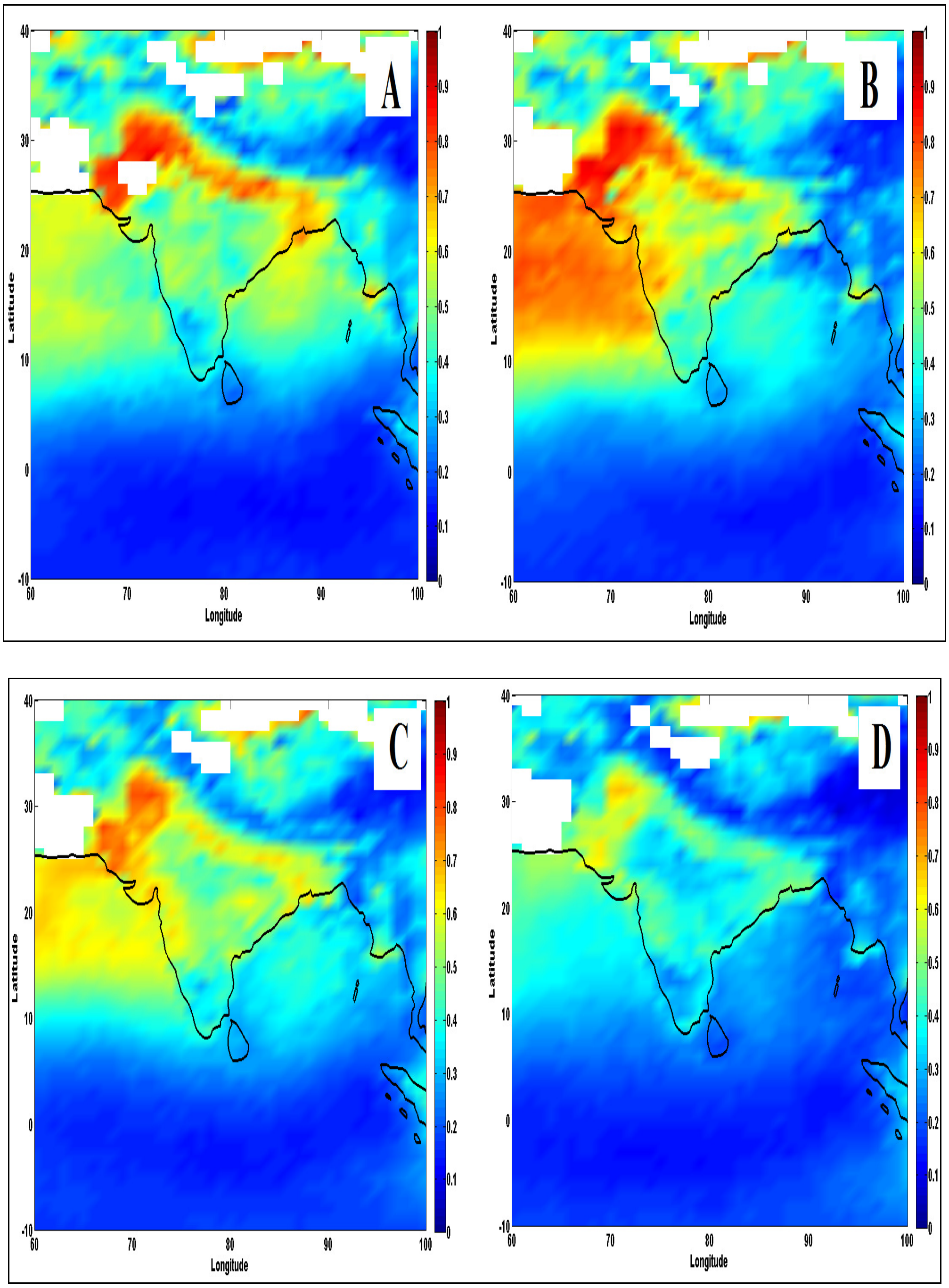


**Figure 5.5: Spatial distributions of climatological monthly mean AOD for the ISMR seasons of 2003 to 2011 over the Indian subcontinent and adjacent oceanic regions.** (A) Represents the AOD during June for 2003 to 2011. (B) Same as (A) but for July. (C) Same as (A) but for August. (D) Same as (A) but for September. The colour bar indicates the mean AOD which is a unit less quantity and the value ranges from 0 to 1.

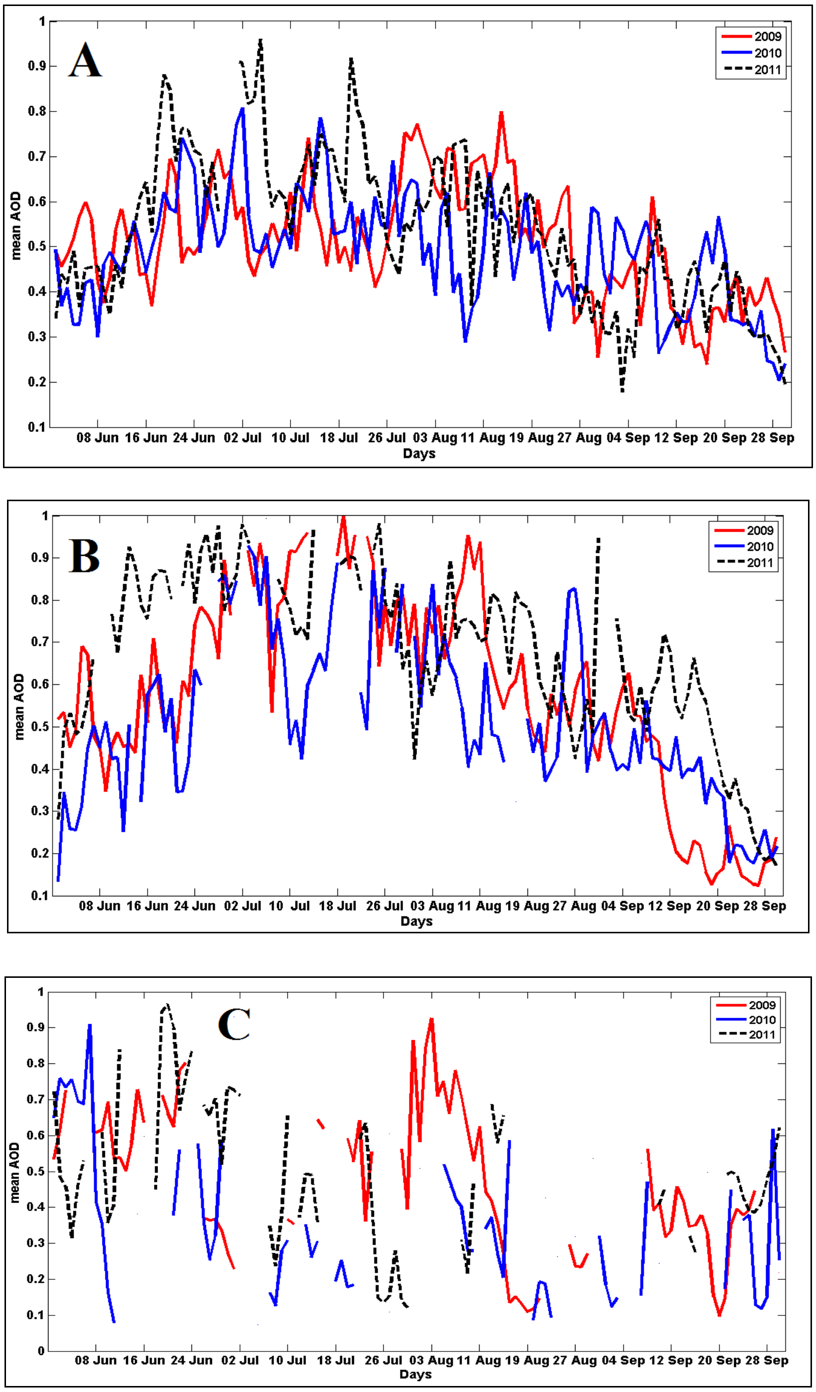


**Figure 5.6: Time series plots for the area averaged AOD during the ISMR seasons of 2009, 2010 and 2011** (A) Represents AOD over the CI. (B) Same as (A) but for AS region. (C) Same as (A) but for BoB region. The data gaps were observed over the BoB region due to the cloudiness. The red colour line indicates the drought year 2009, blue colour line indicates normal monsoon year 2010 and black dotted line indicates the flood year 2011. AOD is a unit less quantity and the value ranges between 0 - 1.

It is observed from the time series plots (refer figure 5.6) that, during most of the summer monsoon days AOD values are higher than 0.6 over the CI. It was noticed that at the end phase of the monsoon season the AOD values are less than 0.6 over CI. Higher AOD values (> 0.6) are observed over CI region during the 2009 which was associated with the long break spells (Manoj et al., 2012). It has been noticed that the AS region is loaded with higher AOD values (0.4 to 0.9) during the ISMR seasons of 2009, 2010 and 2011 as compared to CI and BoB. BoB region found to be loaded with higher AOD concentration during 2009 (ISMR drought year). At most of the instances, the AOD data was missing due to high cloud cover over the BoB region.

Based on the AOD measurements in situ and derived from the MODIS sensor over the BoB and AS, Kedia and S Ramachandran (2008) observed that, the surface level and the columnar aerosol properties are exhibit large spatial variations and the MODIS track well the sun photometer measurements. They further observed that these two measurements are found to agree well within $\pm 1\sigma$ variation over these two oceanic regions both as a function of latitude and longitude.

Time series analysis of June-July-August-September area averaged AOD distribution during the ISMR season between 2003 - 2012 is given in the figure 5.7. The peak summer monsoon rainfall month (July) exhibits higher AOD concentration over the CI and AS. During July aerosols which are accumulating over the CI region are supposed to be removed by wet deposition by rainfall. But higher AOD values as compared to other monsoon months imply the role of either coarse mode aerosols or fine mode aerosols with hydrophilic properties (Ramachandran and Cherian, 2008).

Long range transport of aerosols might be the second reason behind the high AOD values observed over the Indian land region. Higher aerosol concentration was observed in 2009 during the month of August as compared to July and also it is worth to note that there was a long break from July 24 to August 9 in 2009. It could be because of the high aerosol mass invigorating the cloud-precipitation interactions and helps in sustain the break spells over the CI region. All the three study regions demonstrate the notworthy monthly variation at interannual scale in aerosol concentration. Therefore aerosols over the CI, AS and BoB regions showing spatio - temporal variabilities during the ten year time scale and the variations are closely related to the summer monsoon rainfall.

The area averaged mean AOD values with standard deviation, over CI, AS and BoB for 2003 to 2012 has given in the table 5.2. During ISMR season, AOD values are observed to be more than 0.4 and in the drought years 2004 and 2009, the AOD values are 0.52 and 0.51 respectively over the CI region. The higher AOD value of the order of 0.54 observed over the CI region during the flood year 2011.

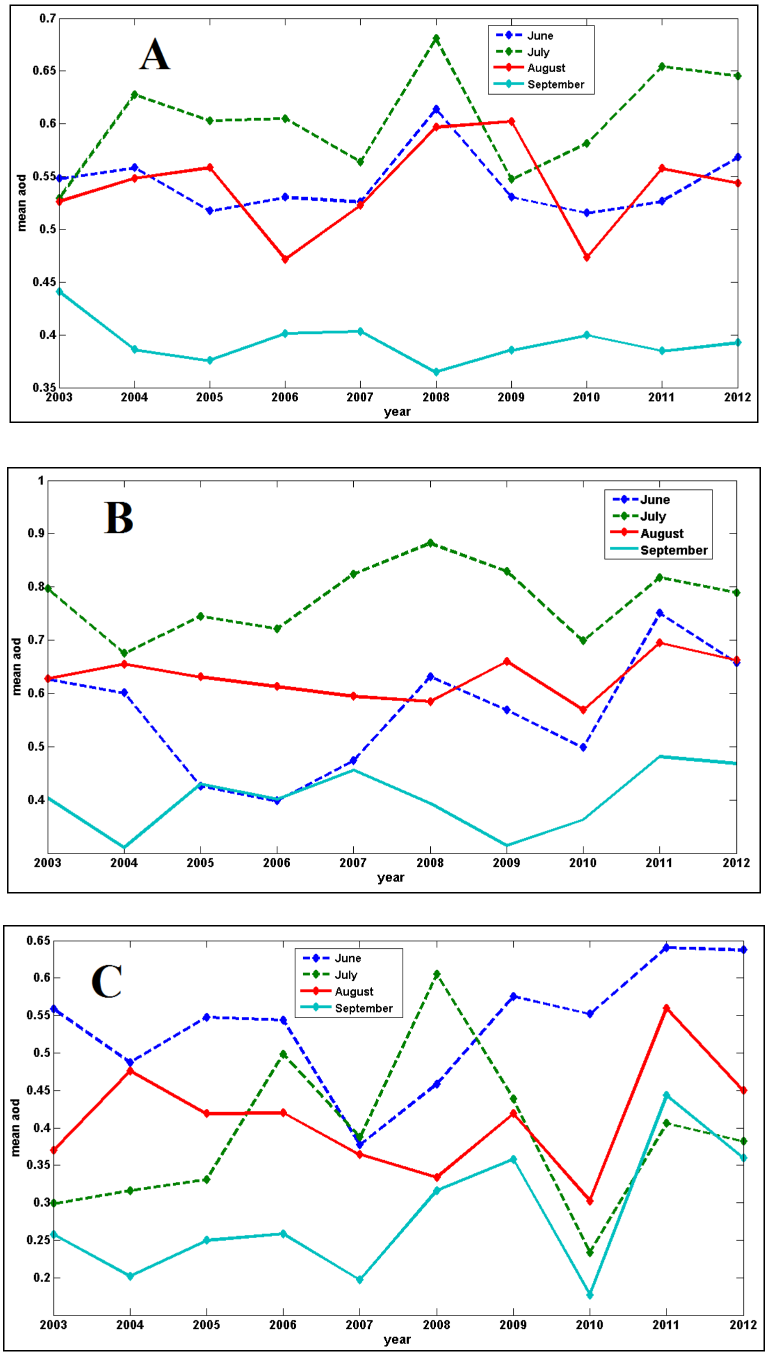


**Figure 5.7: Time series plots for the area averaged AOD during the ISMR seasons of 2003 - 2012.** (A) Represents the CI region. (B) Same as (A) but for AS. (C) Same as (A) but for BoB region. Blue dotted line indicates the month June. Green dotted line indicates the month July. Red and Cyan colour lines indicate August and September respectively. AOD is a unit less quantity and the value ranges between 0 - 1.

**Table 5.2: Statistical analysis of AOD for the ISMR season of 2003 – 2012**

| CI - Central India AS - Arabian Sea BoB - Bay of Bengal<br>m - mean s - standard deviation<br>**2004, 2009 - drought year 2011 - flood year** | | | | | | |
|---|---|---|---|---|---|---|
| Year | CI | | AS | | BoB | |
| | m | s | m | s | m | s |
| 2003 | 0.51 | 0.12 | 0.60 | 0.22 | 0.37 | 0.20 |
| **2004** | **0.52** | **0.14** | **0.55** | **0.21** | **0.38** | **0.20** |
| 2005 | 0.52 | 0.15 | 0.58 | 0.21 | 0.40 | 0.21 |
| 2006 | 0.48 | 0.14 | 0.53 | 0.22 | 0.41 | 0.20 |
| 2007 | 0.49 | 0.12 | 0.58 | 0.21 | 0.33 | 0.19 |
| 2008 | 0.57 | 0.18 | 0.63 | 0.25 | 0.41 | 0.21 |
| **2009** | **0.51** | **0.13** | **0.58** | **0.24** | **0.47** | **0.20** |
| 2010 | 0.49 | 0.12 | 0.52 | 0.20 | 0.35 | 0.21 |
| **2011** | **0.54** | **0.17** | **0.67** | **0.20** | **0.50** | **0.20** |
| 2012 | 0.54 | 0.15 | 0.63 | 0.19 | 0.45 | 0.19 |

### 5.1.3 Correlation study for ISMR and AOD over AS, BoB and CI

The correlation analysis between ISMR and AOD over the three study regions has been carried out for 2003 to 2012 (refer table 5.3.). It is observed from the table that, AOD and rainfall over the three study regions are significantly negatively correlated (significant at 1 % significance level; on an average p - value is 0.0019) for 2003 to 2012.

**Table 5.3 ISMR and AOD correlation analysis during 2003 - 2012**

| CI - Central India AS - Arabian Sea BoB - Bay of Bengal<br>C - Coefficient of correlation<br>**2004, 2009 - drought year 2011 - flood year** | | | |
|---|---|---|---|
| Year | CI | AS | BoB |
| | C | C | C |
| 2003 | -0.2906 | -0.4067 | -0.5130 |
| **2004** | **-0.5392** | **-0.4994** | **-0.5878** |
| 2005 | -0.5370 | -0.3393 | -0.6401 |
| 2006 | -0.3708 | -0.4533 | -0.5609 |
| 2007 | -0.2778 | -0.4687 | -0.4611 |
| 2008 | -0.3674 | -0.3556 | -0.5174 |
| **2009** | **-0.5136** | **-0.3567** | **-0.5616** |
| 2010 | -0.5955 | -0.3534 | -0.3603 |
| **2011** | **-0.5500** | **-0.4044** | **-0.4607** |
| 2012 | -0.5809 | -0.2796 | -0.3946 |

### 5.1.4 Analysis of cloud parameters during the ISMR season over CI, AS and BoB

Aerosols can influence the precipitation by acting as a surface on which water molecules can combine and such aerosols are known as cloud condensation nuclei. Therefore aerosols may be a major influencing factor and the variations in aerosol concentrations can alter the precipitation on regions where there is an availability of natural and anthropogenic aerosols.

Hence it may be possible that variations in cloud properties such as CTP, COD, CF and CER during the monsoon season can act as an indicator for the changes in aerosol characteristics. There are numerous possible reasons exist for the observed relationships between aerosols and cloud properties (Grandey et. al 2013). Therefore to study the interlinks between the rainfall, aerosol and the cloud parameters a correlation analysis has been carried out over the different study regions for ten years time scale.

### (a) CER

The CER data over the CI, AS and BoB regions have been examined for 10 year time scale (2003 to 2012) in order to find out the aerosol-CER-precipitation relationship. The increase in aerosol concentration might be causing a decrease in the CER and it is explained as the indirect effect of aerosols on cloud properties which in turn impacts the rainfall (as discussed in introduction section; refer http://www.ipcc.ch/publications_and_data).The number of particles from a given aerosol population that can act as cloud condensation nuclei can be the function of the water supersaturation (Seinfeld and Pandis 2006) and there might be the possibility that the aerosols present in the atmosphere can decrease the coalescence and collision rates which lead to the suppression of rainfall.

The present analysis (refer table 5.4.A and 5.4.B) reveals that CER and rainfall are significantly positively correlated (significant at 1 % level for the entire study period) whereas AOD and CER are negatively correlated (significant at 1 % significance level except in 2006 and 2007) over CI region. In general no clear inference could be drawn based on the CER - rain - AOD relationship over both of the oceanic regions, however AOD and CER are negatively significantly correlated for 2004 over BoB and 2009 over AS.

**Table 5.4.A: Correlation Analysis of CER, AOD and rainfall for 2003 – 2007**

| CI - Central India AS - Arabian Sea BoB - Bay of Bengal<br>C - Coefficient of correlation<br>**2004 - drought year** | | | | | | |
|---|---|---|---|---|---|---|
| CER | Study Region | 2003 | **2004** | 2005 | 2006 | 2007 |
| | | C | **C** | C | C | C |
| Rain | CI | 0.2830 | **0.2580** | 0.3359 | 0.1412 | 0.1143 |
| | AS | 0.0637 | **-0.0390** | 0.0433 | -0.0930 | 0.0654 |
| | BoB | 0.0354 | **0.1476** | -0.0198 | 0.0751 | 0.0712 |
| AOD | CI | -0.4669 | **-0.3363** | -0.4330 | -0.1203 | -0.0639 |
| | AS | -0.0215 | **0.0242** | -0.1591 | 0.0478 | 0.0037 |
| | BoB | -0.0725 | **-0.2801** | -0.0223 | -0.0326 | -0.0966 |

**Table 5.4.B: Correlation analysis of CER, AOD and rainfall for 2008 - 2012**

CI - Central India AS - Arabian Sea BoB - Bay of Bengal
C - Coefficient of correlation
**2009 – drought year** **2011 – flood year**

| CER | Study Region | 2008 | **2009** | 2010 | **2011** | 2012 |
|---|---|---|---|---|---|---|
| | | C | **C** | C | **C** | C |
| Rain | CI | 0.2636 | **0.3642** | 0.2473 | **0.3395** | 0.2835 |
| | AS | 0.0328 | **0.1519** | 0.1066 | **0.0102** | 0.0403 |
| | BoB | 0.0872 | **-0.0209** | 0.1885 | **0.1535** | 0.0437 |
| AOD | CI | -0.4270 | **-0.5164** | -0.5058 | **-0.4359** | -0.4337 |
| | AS | 0.0412 | **-0.2565** | -0.0836 | **0.0490** | -0.0317 |
| | BoB | -0.0853 | **-0.0156** | -0.1490 | **-0.1133** | -0.1221 |

The temporal variation in CER over the three different regions for ISMR seasons of 2009 (drought year), 2010 (normal monsoon year) and 2011 (flood year) is shown in figure 5.8. It is observed that CER values are more than 14µm (14 µm is referred to as the threshold value for initiating the precipitation; Rosenfeld et.al 2012) over the CI region during the 2009, 2010 and 2011 ISMR seasons except the monsoon onset days and the break spells of 2009 (24 Jul. - 9 Aug.). It has been observed that CER consistently increases during the initial phase and then fluctuates approximately between 16 to 22 µm in July and August and then gradually decreases in the month of September over CI. No noticeable seasonal trend in CER has been observed over the AS and BoB, however on an average CER values are higher over the oceanic regions as compared to the land region throughout the ISMR season. The statistical information of CER for 2003 to 2012 summer monsoon season is mentioned in table 5.5.

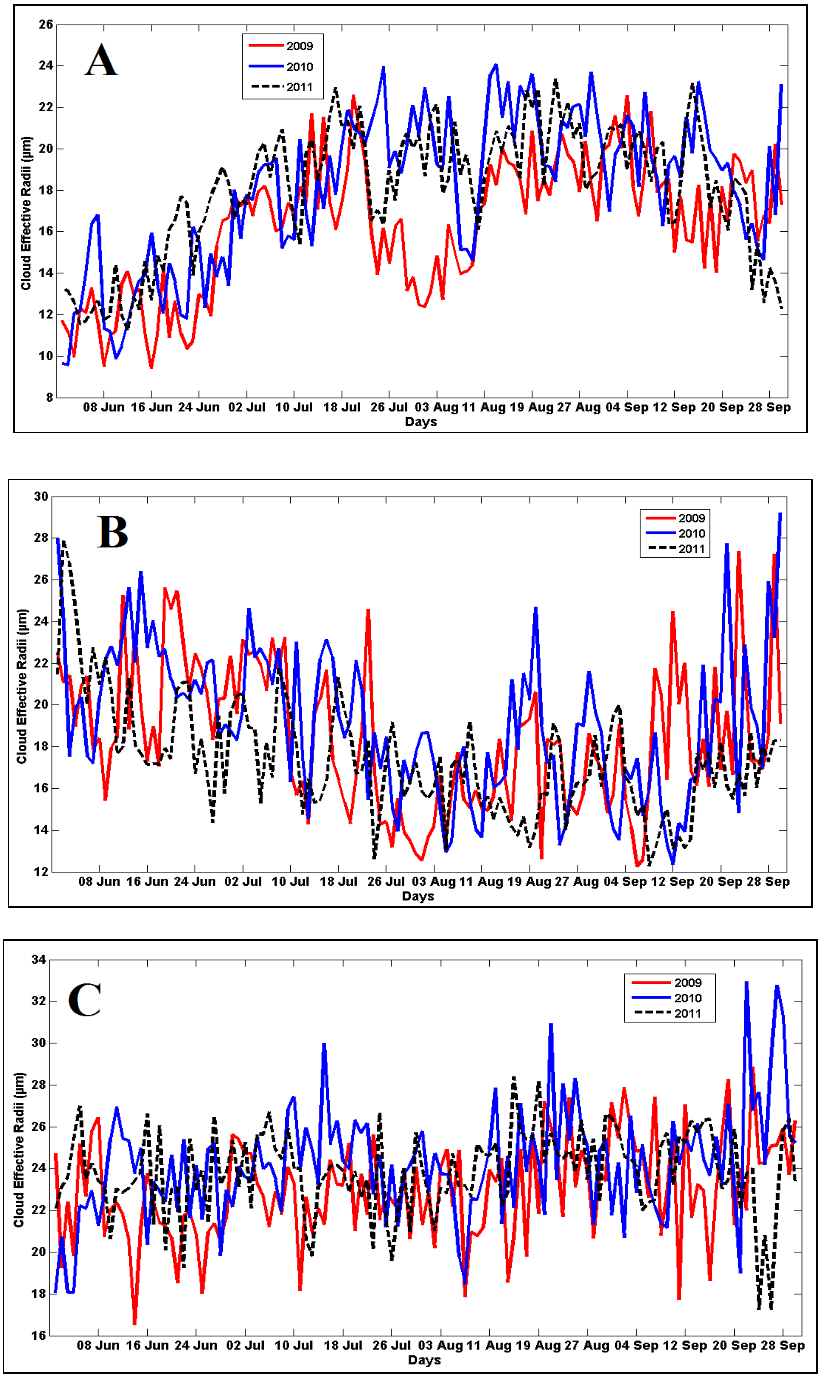


**Figure 5.8: Time series plots for CER during the ISMR seasons of 2009, 2010 and 2011.** (A) Represents the CER over the CI during the ISMR seasons (01 June to 30 August). (B) Same as (A) but for AS region. (C) Same as (A) but for BoB region. The red colour line indicates the drought year 2009, blue colour line indicates normal monsoon year 2010 and black dotted line indicates the flood year 2011. The unit of CER is μm.

**Table 5.5: Statistical analysis of CER for 2003 - 2012**

| CI - Central India AS - Arabian Sea BoB - Bay of Bengal<br>m - mean s - standard deviation<br>**2004, 2009 - drought year 2011 - flood year** | | | | | | |
|---|---|---|---|---|---|---|
| Year | CI | | AS | | BoB | |
| | m | s | m | s | m | s |
| 2003 | 17.98 | 3.61 | 17.40 | 4.01 | 23.17 | 2.99 |
| **2004** | **16.98** | **2.99** | **17.18** | **4.19** | **23.61** | **3.21** |
| 2005 | 17.01 | 3.84 | 17.00 | 3.60 | 22.85 | 3.10 |
| 2006 | 17.10 | 2.99 | 17.67 | 3.46 | 23.23 | 3.68 |
| 2007 | 18.15 | 3.08 | 18.41 | 4.15 | 23.84 | 3.62 |
| 2008 | 18.27 | 2.74 | 17.23 | 3.51 | 23.13 | 3.27 |
| **2009** | **16.14** | **3.48** | **18.20** | **3.81** | **22.78** | **3.19** |
| 2010 | 17.91 | 3.97 | 18.97 | 3.91 | 23.98 | 3.45 |
| **2011** | **17.87** | **3.51** | **17.21** | **3.15** | **23.64** | **2.93** |
| 2012 | 17.14 | 3.28 | 17.17 | 3.37 | 22.17 | 2.96 |

The area averaged mean rainfall (refer the table 5.1) and CER are higher and mean AOD was lesser (refer the table 5.2) over the BoB region as compared to CI and AS regions during the ISMR seasons. This implies the significant correlation between AOD, CER and Rainfall over the three study regions. It means that for all these selected study regions aerosols may be the important factor in deciding the variability in rainfall during ISMR season which effectively involving in the formation of CCN. Area averaged mean CER value over the CI region for 2004 and 2009 are observed to be lesser (refer Table 5.5) as compared to other ISMR seasons and these values are 16.98 µm and 16.14 µm respectively. These CER values are observed during the drought ISMR season to be more than the threshold value of CER (14 µm) for the initiation of precipitation (Rosenfeld et. al 2012).

(b) **CF**

Correlation analysis (refer table 5.6.A and 5.6.B) between CF, AOD and rainfall during the ISMR season of 2003 to 2012 have been carried out over the CI, AS and BoB region. Rainfall - CF correlation over CI is highly significant (at 1% significance level) during 2003, 2008, 2010 and 2012 ISMR seasons with positive correlation coefficients.

Wind speed (10m) is capable of explaining the observed AOD – CF relationships over the oceanic regions (Engstr¨om and Ekman, 2010) and higher CF values are likely found for meteorological conditions associated with higher wind speeds (Grandey et al., 2013). The correlation analysis between CF and rainfall over CI region reveals that there existed a positive relationship (significant at 1 % for the 2003, 2008, 2009, 2010, and 2012) between these parameters. The negative correlation between AOD and CF is significant at 5 % significance level (except 2007 and 2011). Rain and CF are found to be significantly correlated only in 2004 and 2009 (drought) over AS. It was observed that AOD - CF relationship is not significant over AS region during the study period. It has been observed that CF-AOD and CF-rain are not significantly correlated over BoB.

The time series analysis of CF during the 2009, 2010 and 2011 ISMR seasons have been given in the figure 5.9 and it has been observed that CF values are higher ( $\leq 0.9$) over the CI region during the normal monsoon year as compared to the drought year. But during the monsoon onset lesser CF values are observed over the CI region. AS (CF $\leq 0.9$) and BoB (CF $\leq 0.95$) regions also having the higher CF values during the normal monsoon year 2010 as compared to the drought year 2009. CF values gradually increases over the CI region during the initial phase of the monsoon and thereafter attains highest value during a season in the month of July and August and further decreases sharply.

The statistical information of CF over AS, CI and BoB are provided in table 5.7. It has been observed that the area averaged mean CF over AS and CI regions indicates lesser values (0.79 and 0.82 respectively) during the drought year 2009 as compared to the other ISMR years. The area averaged mean CF values are in the range of 0.94 to 0.97 over BoB region throughout the study period.

**Table 5.6.A: Correlation analysis of CF with AOD and rainfall for 2003 - 2007**

| CI - Central India AS - Arabian Sea BoB - Bay of Bengal<br>C - Coefficient of correlation<br>**2004 - drought year** | | | | | | |
|---|---|---|---|---|---|---|
| CF | Study Region | 2003 | **2004** | 2005 | 2006 | 2007 |
| | | C | **C** | C | C | C |
| Rain | CI | 0.3853 | **0.1107** | 0.1057 | 0.1425 | 0.0489 |
| | AS | 0.0322 | **-0.0983** | -0.0147 | -0.0275 | 0.0228 |
| | BoB | -0.0489 | **-0.0376** | -0.0527 | 0.0093 | -0.0560 |
| AOD | CI | -0.7940 | **-0.1797** | -0.1641 | -0.2465 | 0.0182 |
| | AS | 0.1088 | **0.0006** | 0.0863 | 0.0625 | 0.1014 |
| | BoB | 0.0458 | **0.0577** | -0.0087 | 0.0899 | -0.0573 |

**Table 5.6.B: Correlation analysis of CF with AOD and rainfall for 2008 - 2012**

| CI - Central India AS - Arabian Sea BoB - Bay of Bengal<br>C - Coefficient of correlation<br>**2009 - drought year 2011 - flood year** | | | | | | |
|---|---|---|---|---|---|---|
| CF | Study Region | 2008 | **2009** | 2010 | **2011** | 2012 |
| | | C | **C** | C | **C** | C |
| Rain | CI | 0.2288 | **0.1585** | 0.5172 | **0.0312** | 0.5161 |
| | AS | -0.0542 | **0.0670** | 0.0470 | **0.0160** | -0.0106 |
| | BoB | 0.0049 | **-0.0200** | 0.0685 | **0.2494** | 0.0102 |
| AOD | CI | -0.3332 | **-0.1867** | -0.8305 | **-0.0026** | -0.8066 |
| | AS | 0.1128 | **-0.0559** | 0.0602 | **0.1194** | 0.1241 |
| | BB | -0.0188 | **-0.0451** | 0.0169 | **-0.1346** | -0.0320 |

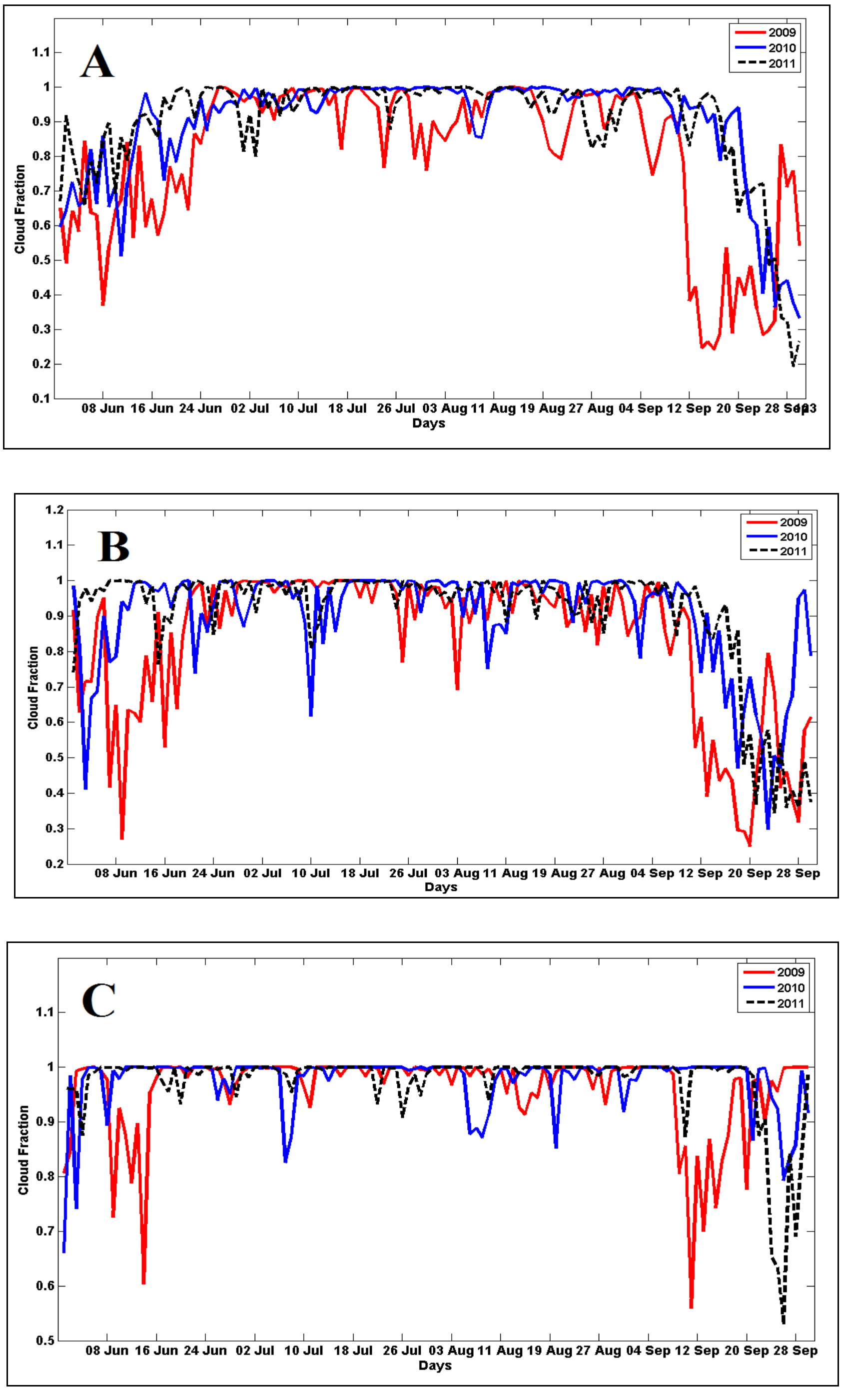


**Figure 5.9: Time series plots for CF during the ISMR seasons of 2009, 2010 and 2011.** (A) Represents the CF over the CI during the ISMR seasons (01 June to 30 August). (B) Same as (A) but for AS region. (C) Same as (A) but for BB region. The red colour line indicates the drought year 2009, blue colour line indicates normal monsoon year 2010 and black dotted line indicates the flood year 2011 .CF is a unit less quantity.

**Table 5.7: Statistical analysis of CF for 2003 - 2012**

| CI - Central India AS - Arabian Sea BoB - Bay of Bengal<br>m - mean s - standard deviation<br>**2004, 2009 - drought years 2011 - flood year** | | | | | | |
|---|---|---|---|---|---|---|
| Year | CI | | AS | | BoB | |
| | m | s | m | s | m | s |
| 2003 | 0.91 | 0.16 | 0.87 | 0.18 | 0.95 | 0.12 |
| **2004** | **0.86** | **0.15** | **0.88** | **0.15** | **0.94** | **0.14** |
| 2005 | 0.87 | 0.18 | 0.86 | 0.20 | 0.96 | 0.10 |
| 2006 | 0.87 | 0.17 | 0.84 | 0.20 | 0.94 | 0.13 |
| 2007 | 0.91 | 0.14 | 0.92 | 0.15 | 0.96 | 0.11 |
| 2008 | 0.89 | 0.19 | 0.89 | 0.18 | 0.96 | 0.13 |
| **2009** | **0.79** | **0.23** | **0.82** | **0.22** | **0.95** | **0.12** |
| 2010 | 0.89 | 0.18 | 0.89 | 0.17 | 0.97 | 0.10 |
| **2011** | **0.89** | **0.18** | **0.90** | **0.18** | **0.97** | **0.11** |
| 2012 | 0.90 | 0.17 | 0.87 | 0.20 | 0.97 | 0.10 |

(c) **COD**

COD-aerosol-rain interlinks have been examined for 2003 to 2012 ISMR season over the CI, AS and BoB regions. The effect of change in CER and cloud life time (first and second indirect effects) supposed to change the COD (Sekiguchi et al., 2003). Costantino and Br´eon, 2013 demonstrated through the statistical analysis that COD value of the order of 10 may be considered as the threshold beyond which precipitation is most likely formed, in both clean and polluted environments, and also the larger COD values are associated with the polluted clouds which could suppress the rainfall.

The correlation analysis carried out for the present study (refer table 5.8.A & 5.8 B) reveals that COD and rain are positively correlated, whereas the correlation between the COD and AOD is negative over CI (significant except for 2006 and 2007). COD and AOD are negatively correlated over the BoB, but found to be significantly correlated only for 2004. No clear inferences could be drawn based on the relationship between AOD and COD over AS, however both of the parameters are found to be significantly negatively correlated in

2009. Over both of the oceanic regions the COD and rain are not strongly correlated (significant positive correlation between COD and rain over BoB for 2010 only).

**Table 5.8.A: Correlation analysis of COD with AOD and rainfall for 2003 - 2007**

| CI - Central India AS - Arabian Sea BoB - Bay of Bengal<br>C - Coefficient of correlation<br>**2004 - drought year** | | | | | | |
|---|---|---|---|---|---|---|
| COD | Study Region | 2003 | **2004** | 2005 | 2006 | 2007 |
| | | C | **C** | C | C | C |
| Rain | CI | 0.2830 | **0.2615** | 0.3384 | 0.1428 | 0.1162 |
| | AS | 0.0649 | **-0.0364** | 0.0443 | -0.0908 | 0.0686 |
| | BoB | 0.0421 | **0.1533** | -0.0109 | 0.0821 | 0.0772 |
| AOD | CI | -0.4670 | **-0.3387** | -0.4357 | -0.1214 | -0.0658 |
| | AS | -0.0226 | **0.0220** | -0.1612 | 0.0455 | 0.0021 |
| | BoB | -0.0759 | **-0.2835** | -0.0291 | -0.0372 | -0.0993 |

**Table 5.8.B: Correlation analysis of COD with AOD and rainfall for 2008 - 2012**

| CI - Central India AS - Arabian Sea BoB - Bay of Bengal<br>C - Coefficient of correlation<br>**2009 - drought year 2011 - flood year** | | | | | | |
|---|---|---|---|---|---|---|
| COD | Study Region | 2008 | **2009** | 2010 | **2011** | 2012 |
| | | C | **C** | C | **C** | C |
| Rain | CI | 0.2650 | **0.3649** | 0.2474 | **0.3400** | 0.2851 |
| | AS | 0.0352 | **0.1528** | 0.1087 | **0.0125** | 0.0407 |
| | BoB | 0.0947 | **-0.0118** | 0.1961 | **0.1596** | 0.0517 |
| AOD | CI | -0.4272 | **-0.5171** | -0.5056 | **-0.4361** | -0.4350 |
| | AS | 0.0394 | **-0.2579** | -0.0851 | **0.0468** | -0.0336 |
| | BoB | -0.0896 | **-0.0213** | -0.1519 | **-0.1160** | -0.1254 |

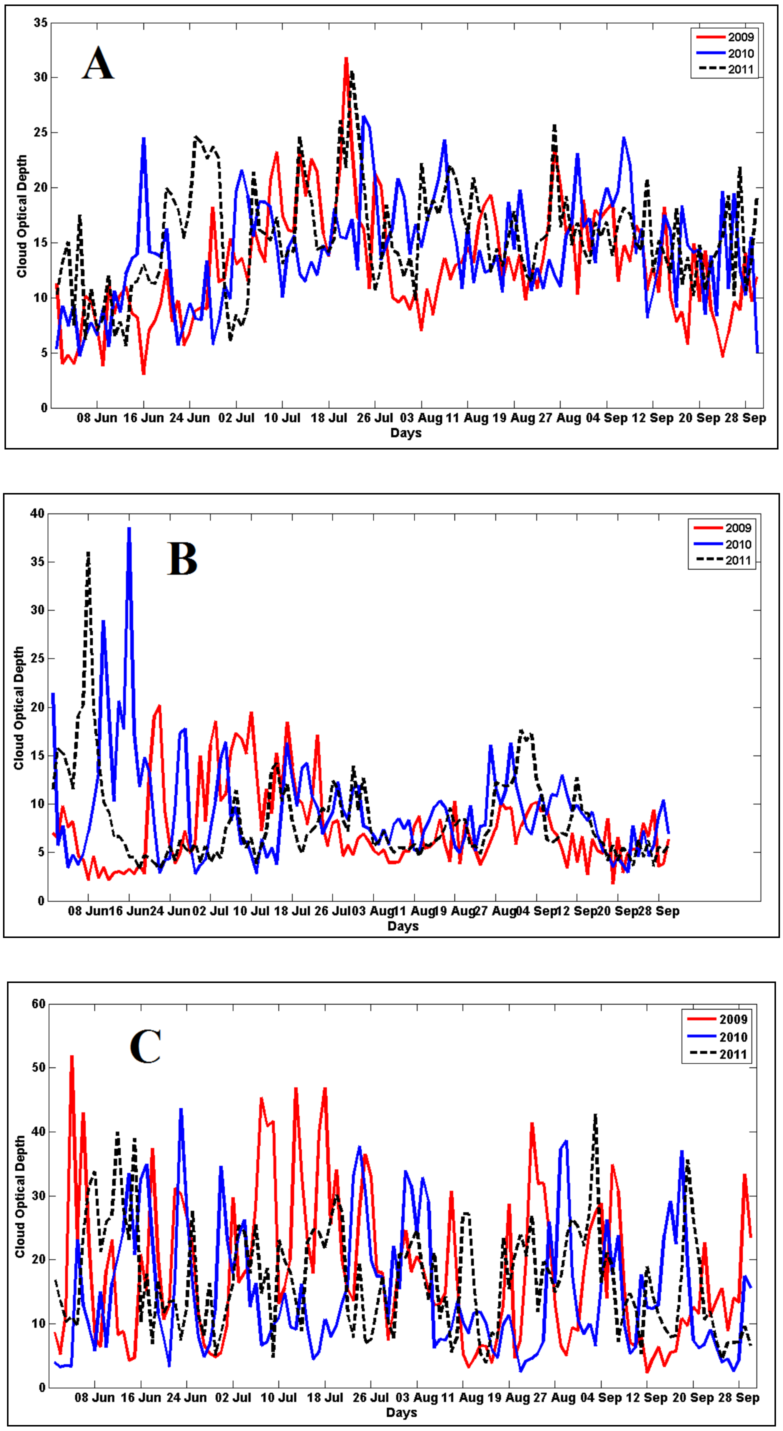


**Figure 5.10: Time series plots for COD during the ISMR seasons of 2009, 2010 and 2011.** (A) Represents the COD over the CI during the ISMR seasons (01 June to 30 August). (B) Same as (A) but for AS region. (C) Same as (A) but for BoB region. The red colour line indicates the drought year 2009. Blue colour line indicates normal monsoon year 2010. Black dotted line indicates the flood year 2011. COD is a unit less quantity.

The temporal variation in COD during the 2009, 2010 and 2011 ISMR seasons have been shown in the figure 5.10. It is observed from the figure that over the CI region, the COD values are gradually increases during the initial phase of the monsoon season and thereby reaches approximately between 10 and 25 during the peak monsoon months and gradually decreases by the end phase of the monsoon. But the COD values are observed to be less (≤ 15) over the AS region, however the onset days of the monsoon rainfall shows higher COD values. No perceptible seasonal trend in COD values has been observed over the BoB region for the summer monsoon seasons of 2009, 2010 and 2011.

The statistical analysis of the COD over the three study regions have been given in the table 5.9. It is observed that, from the mean COD values over the CI region for the drought monsoon years 2004 and 2009 are lesser (13.80 & 12.84 respectively), as compared to the other years considered for the present analysis. However, the COD values over the AS region are comparatively less (< 10) with respect to the CI and BoB regions during the ten year time scale.

**Table 5.9: Statistical analysis of COD for 2003 - 2012**

| CI - Central India AS - Arabian Sea BoB - Bay of Bengal<br>m - mean s - standard deviation<br>**2004, 2009 - drought year 2011 - flood year** | | | | | | |
|---|---|---|---|---|---|---|
| year | CI | | AS | | BoB | |
| | m | s | m | s | m | s |
| 2003 | 15.06 | 4.76 | 7.73 | 4.31 | 15.47 | 9.44 |
| **2004** | **13.80** | **5.97** | **9.24** | **6.20** | **15.39** | **9.09** |
| 2005 | 14.62 | 6.37 | 8.68 | 4.72 | 18.60 | 11.84 |
| 2006 | 15.46 | 5.17 | 9.29 | 5.64 | 18.01 | 12.95 |
| 2007 | 14.14 | 4.99 | 9.84 | 6.34 | 15.09 | 10.41 |
| 2008 | 14.88 | 4.61 | 7.49 | 5.16 | 17.11 | 9.94 |
| **2009** | **12.84** | **5.19** | **7.55** | **4.25** | **17.93** | **11.69** |
| 2010 | 14.02 | 4.91 | 9.18 | 5.20 | 14.86 | 9.90 |
| **2011** | **15.32** | **4.96** | **8.19** | **4.62** | **16.80** | **8.43** |
| 2012 | 15.33 | 5.94 | 7.50 | 3.64 | 17.16 | 10.35 |

### (d) CTP

As per the observations by Massie et al., (2007), aerosol indirect effects are present throughout the troposphere and cloud microphysical processes that determine CER inside a cloud, are influenced by the microphysics. Besides, this microphysical process is initiated at the cloud base, and its influence proceeds throughout the cloud as air parcels rise upward, which in turn changes the phase from liquid to ice. They further mentioned about the possibility to bin cloud reflectivity as a function of CTP, which helps to test the hypothesis of aerosol indirect effect in the troposphere.

The correlation analysis between CTP and rain over the CI, AS and BoB regions are given in table 5.10.A and 5.10.B. It is noticed that, the CTP and rainfall are significantly (significant at 1 % significance level) negatively correlated. However the correlation is not significant in 2009 (over the CI) and 2011 (over the CI and AS). AOD and CTP are significantly positively (negatively correlated in 2009 at 1% significance level) correlated at 1 % significance level over the CI region, except for the flood year of 2011 during the entire study period. The correlation between AOD and CTP are positively correlated over the AS and BoB regions at 1 % significance level in ten year time scale.

**Table 5.10.A: Correlation analysis of CTP with AOD and rainfall for 2003-2007**

| CI - Central India AS - Arabian Sea BoB - Bay of Bengal<br>C - Coefficient of correlation<br>**2004 - drought year** | | | | | | |
|---|---|---|---|---|---|---|
| CTP | Study Region | 2003 | **2004** | 2005 | 2006 | 2007 |
| | | C | **C** | C | **C** | C |
| Rain | CI | -0.3356 | **-0.5889** | -0.5099 | -0.3719 | -0.3599 |
| | AS | -0.3327 | **-0.4348** | -0.3166 | -0.3899 | -0.3173 |
| | BoB | -0.3744 | **-0.3896** | -0.4512 | -0.2965 | -0.3283 |
| AOD | CI | 0.4958 | **0.5912** | 0.5200 | 0.5276 | 0.3868 |
| | AS | 0.5738 | **0.5603** | 0.6471 | 0.6638 | 0.6145 |
| | BoB | 0.4827 | **0.5494** | 0.4738 | 0.4580 | 0.3630 |

The variation of CTP over the three study regions, during the ISMR seasons (June to September) in 2009, 2010 and 2011 are given in the figure 5.11. It is observed that the CTP values are higher (>600 hPa) during the initial phase of the monsoon rain and subsequently decreasing in the July and August associated with the peak rainy days over the CI region and again tend to increase by the end phase of ISMR. However over the oceanic regions, the temporal variations in CTP are not clearly identifiable.

**Table 5.10.B: Correlation analysis of CTP with AOD and rainfall for 2008 - 2012**

| CI - Central India AS - Arabian Sea BoB - Bay of Bengal<br>C - Coefficient of correlation<br>**2009 - drought year 2011 - flood year** | | | | | | |
|---|---|---|---|---|---|---|
| CTP | Study Region | 2008 | **2009** | 2010 | **2011** | 2012 |
| | | C | **C** | C | **C** | C |
| Rain | CI | -0.2205 | **0.0331** | -0.6517 | **-0.0850** | -0.7078 |
| | AS | -0.3272 | **-0.3035** | -0.2444 | **-0.2739** | -0.2016 |
| | BoB | -0.3183 | **-0.3799** | -0.2707 | **-0.0134** | -0.2763 |
| AOD | CI | 0.4285 | **-0.2039** | 0.5270 | **0.0658** | 0.7374 |
| | AS | 0.6182 | **0.5632** | 0.6023 | **0.5718** | 0.5848 |
| | BoB | 0.4625 | **0.4030** | 0.3447 | **0.2806** | 0.2019 |

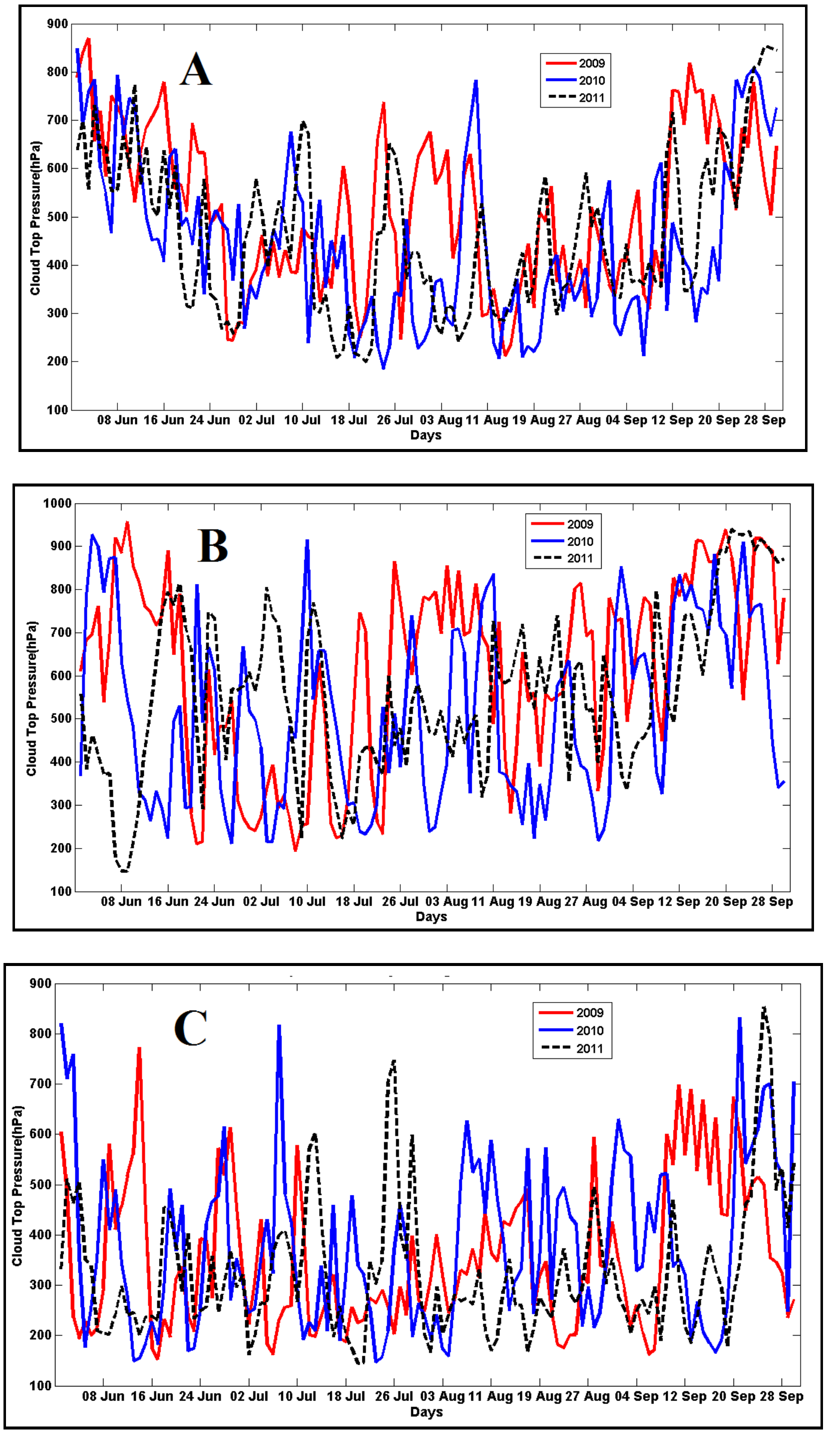


**Figure 5.11: Time series plots for CTP during the ISMR seasons of 2009, 2010 and 2011.** (A) Represents the CI. (B) Same as (A) but for AS region. (C) Same as (A) but for BoB region. The red colour line indicates the drought year 2009. Blue colour line indicates normal monsoon year 2010. Black dotted line indicates the flood year 2011.CTP is expressed in hPa.

**Table 5.11: Statistical analysis of CTP for 2003 - 2012**

| CI - Central India AS - Arabian Sea BoB - Bay of Bengal<br>m - mean s - standard deviation<br>**2004, 2009 - drought year 2011 - flood year** | | | | | | |
|---|---|---|---|---|---|---|
| year | CI | | AS | | BoB | |
| | m | s | m | s | m | s |
| 2003 | 423.72 | 138.02 | 608.68 | 207.07 | 379.31 | 178.09 |
| **2004** | **471.10** | **162.94** | **599.49** | **212.14** | **351.85** | **176.13** |
| 2005 | 460.57 | 168.20 | 571.30 | 203.49 | 336.19 | 178.43 |
| 2006 | 468.44 | 156.39 | 572.85 | 217.41 | 359.70 | 174.83 |
| 2007 | 425.75 | 136.87 | 479.54 | 190.54 | 349.54 | 141.53 |
| 2008 | 420.92 | 164.85 | 566.97 | 192.85 | 340.72 | 153.60 |
| **2009** | **510.20** | **166.35** | **607.14** | **222.29** | **351.74** | **147.46** |
| 2010 | 442.25 | 174.30 | 512.79 | 212.63 | 373.72 | 168.63 |
| **2011** | **460.15** | **166.94** | **556.75** | **194.81** | **323.47** | **137.60** |
| 2012 | 444.53 | 158.07 | 583.59 | 189.15 | 346.62 | 155.22 |

The statistical analysis of the CTP over the CI, AS and BoB regions is provided in the table 5.11. It is shown in the table that over the CI region, the mean CTP values are higher (> 470 hPa) during the two drought monsoon years (2004 & 2009) as compared to other monsoon years. However, the mean CTP values are observed to be less (< 400 h Pa) over the BoB in comparison to the AS region. Ravi Kiran et al., (2009) noticed the presence of deep convective clouds with CTP < 300 hPa over North BoB associated with the enhanced rainfall days of the ISMR season. Hence it might be possible that the increase in rainfall over the BoB region as compared with the CI and AS region is considerable in association with the decreased CTP observed over BoB region.

### 5.1.5 Correlation analysis of AI, AOD and rainfall

The analysis between the AOD and AI over the CI, AS and BoB are given in the table 5.12.A & 5.12.B. It is observed that the rain and AI are significantly (at 1 % significance level) negatively correlated over the CI region, AS and BoB (except in the 2003 and 2004) during the ten year time scale.

**Table 5.12.A: Correlation analysis of AI with AOD and rainfall for 2003 - 2007**

| CI - Central India AS - Arabian Sea BoB - Bay of Bengal<br>C - Coefficient of correlation **2004 - drought year** | | | | | | |
|---|---|---|---|---|---|---|
| AI | Study Region | 2003 | **2004** | 2005 | 2006 | 2007 |
| | | C | **C** | C | **C** | C |
| Rain | CI | -0.0511 | **-0.0967** | -0.5088 | -0.4396 | -0.3267 |
| | AS | -0.0598 | **-0.1594** | -0.2149 | -0.2623 | -0.3148 |
| | BoB | -0.0073 | **-0.1199** | -0.2171 | -0.2925 | -0.1925 |
| AOD | CI | 0.2023 | **0.0549** | 0.5225 | 0.3202 | 0.3295 |
| | AS | 0.2285 | **-0.0927** | 0.0206 | -0.0497 | 0.0168 |
| | BoB | -0.0642 | **0.0695** | 0.1089 | 0.1893 | 0.1649 |

**Table 5.12.B: Correlation analysis of AI with AOD and rainfall for 2008 - 2012**

| CI - Central India AS - Arabian Sea BoB - Bay of Bengal<br>C - Coefficient of correlation **2009 - drought year** **2011 - flood year** | | | | | | |
|---|---|---|---|---|---|---|
| AI | Study Region | 2008 | **2009** | 2010 | **2011** | 2012 |
| | | C | **C** | C | **C** | C |
| Rain | CI | -0.3044 | **-0.4436** | -0.3682 | **-0.3623** | -0.3786 |
| | AS | -0.2409 | **-0.1792** | -0.2483 | **-0.2271** | -0.1465 |
| | BoB | -0.2175 | **-0.2557** | -0.2276 | **-0.2330** | -0.3321 |
| AOD | CI | -0.0765 | **0.4784** | 0.4104 | **0.3587** | 0.4270 |
| | AS | -0.0750 | **-0.0731** | 0.0653 | **0.0051** | 0.0722 |
| | BoB | 0.0163 | **0.3154** | 0.2895 | **0.1214** | 0.3880 |

The correlation analysis between AOD and AI indicates a significant (significant at 1% significance level) positive correlation over the CI. However, over the CI the correlation is not significant in 2004 and 2008 ISMR seasons. The analysis between these parameters shows significant positive correlation over the AS region during the monsoon season of 2003 (correlation coefficients for other years are not significant). It is observed that there is a significant positive correlation between AOD and AI over the BoB region in 2009, 2010 and 2012 (at 1 % significance level), but the correlation coefficients for other monsoon years are not significant.

## 5.2 Intraseasonal variability of ISMR (active and break spells) and its association to aerosol - cloud properties

### 5.2.1 Spatial pattern of active and break events

Active and break events of the ISMR have been identified, based on the area averaged rainfall over the CI box between $17.0^0$ to $27.0^0$ N and $74.0^0$ to $82.0^0$ E. The differences in the spatial pattern of the composite active (break) events during 2003 to 2011 are given in the figure 5.12

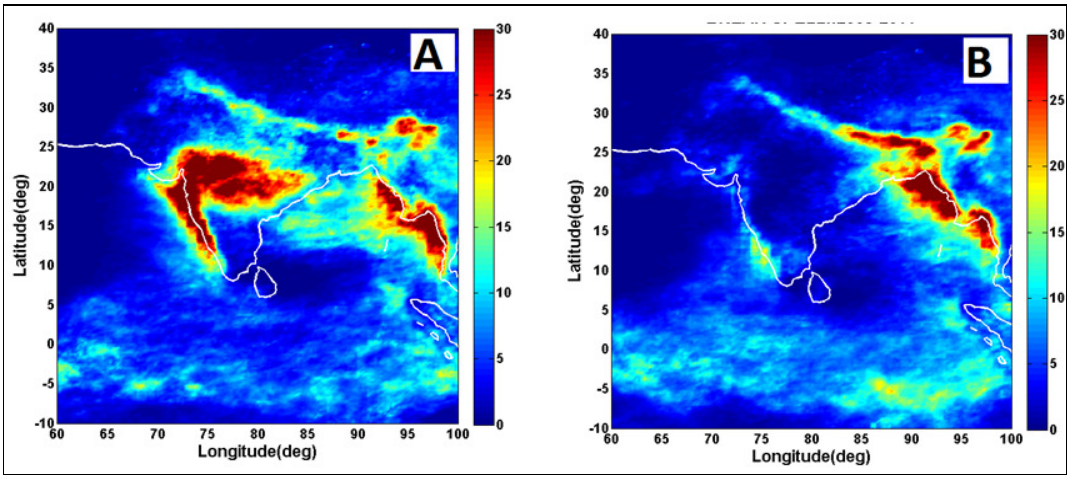


**Figure 5.12: Spatial plots of composite representation** of (A) Active spells during the peak ISMR months of July and August for 2003 to 2011 over the Indian Subcontinent. (B) Same as (A) but for break spells. The colour bar indicates rainfall in mm/day.

As mentioned in the table 4.1, the changes in active and break days and their duration may be due to the slight difference in the study region selected for the present study and that by Rajeevan et al., (2010). It has been noticed that, active and break spells occurs every year and the summer monsoon season of 2004 is the exception with not a single active spell occurred (refer table 4.1). Present results also support the finding that break spells tend to have a longer life-span than active spells (Rajeevan et al., 2010). It has shown that weak monsoon years are associated with higher probability for the occurrence of break conditions (Goswami and Ajaya Mohan, 2001). The life span of active spell is about three to four days as per the current analysis. Using TRMM data, total fourteen active spells and thirteen break spells are identified for the summer monsoon season of 2003 to 2011. During the active spells CI, Western Ghats and eastern India receive increased rainfall, while during the break spells there is suppressed rainfall over CI. The position of the monsoon trough changes day to day and there are differences between the dynamic and thermal characteristics of eastern end and western end of the trough (Potty et al., 2001). It has been noticed (figure 5.12) that on break days less rainfall is observed over Western Ghats region but Himalayan region and north east India receives substantial amount of rainfall. Increased (decreased) rainfall over Western Ghats and CI has been observed during active (break) days. In addition to this, south east India receives very less (no) rainfall in both cases. There is increased rainfall over north east India during active and break days while Himalayan region receives considerable amount of rainfall during break days. This is in agreement with the studies by Ravi Kiran et al., 2009, but they considered cloud properties as well.

## 5.2.2 Spatial pattern of aerosols associated with active and break events

### 5.2.2.1 Analysis of aerosol distribution using composites of nine years

It is noticed from the spatial distribution (refer figure 5.13) of the composites of AOD that, during the active events, aerosols are confined over the north western regions of Indian landmass and over the north Eastern AS. Deep layer of moist air present over this region makes strong monsoon during the active days, while the non availability of moist air weakens the heat low and results in breaks (Ramage, 1966). So there might be the possibility that the aerosols observed over this region interacting with the mechanisms associated to develop active spell during the monsoon months. Even though the enhanced rainfall during active spells remove most of the aerosol content, considerable AOD values are observed during these spells (figure 5.13.A). There may be a possibility that large portion of aerosols are coming towards the CI region through long range transport from African continent and Arabian countries (Manoj et al., 2011).

During the break spells aerosols exhibiting an increment over the entire Indian region especially over Himalayan foothills and towards the southern parts of CI in addition to the north western regions where it confined largely. Break spells showing a substantially decreased AOD over the north eastern AS, as compared to those during active days. As in the case explained above for active days, long range transport might be a reason for the increased AOD values observed during break days all over the Indian subcontinent except southern end of India (AOD values in the range 0.3 - 0.4) and some parts of northern India (AOD in the range 0.4 - 0.5). Aerosols are observed to be confined over Himalayan range starting from western parts and extended up to the northern side. During active and break spells, it has been observed that the AOD values over BoB and southern AS region are in the range between 0.3 - 0.4.

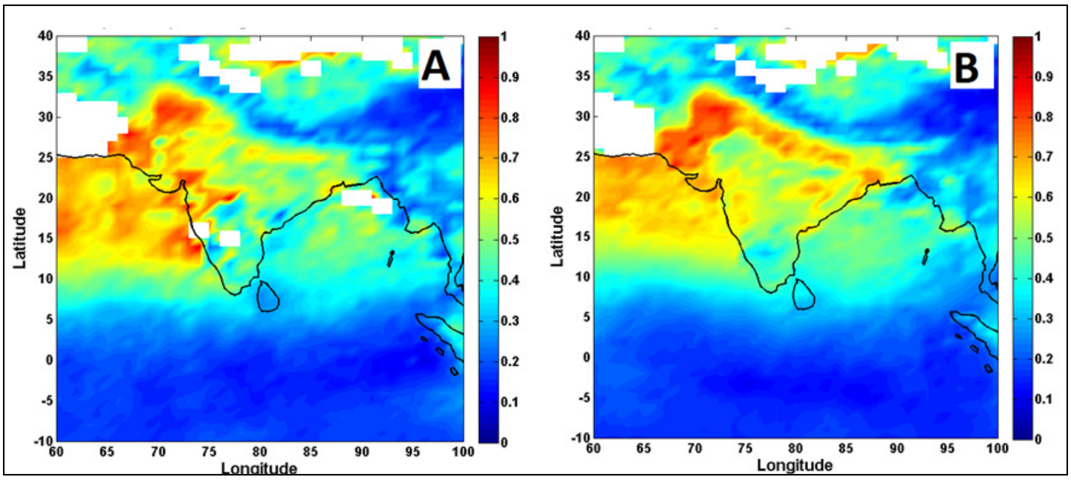


**Figure 5.13: Spatial plots of composite representation of AOD from 2003 to 2011** (A) During the active spells which are the enhanced rainfall days within the peak ISMR months of July and August over the Indian Subcontinent. (B) Same as (A) but for break spells having suppressed rainfall. The colourbar indicates AOD and its value ranges between 0 - 1.

#### 5.2.2.2 Analysis of aerosol properties based on composites of individual years

Since, some inferences are obtained from the composites of nine years aerosol properties associated with active and break events, the analysis has been further extended to the active and break spells by considering the composites of aerosol properties for individual years. Spatial pattern of aerosol loading observed from the composites of active (break) spells for individual years shows different implications from those observed by considering the composite of nine years data set. The spatial patterns of AOD during the active spells of 2005, 2007, 2011 (a1, a2 & a3 respectively) and break spells 2004, 2005, 2008 (b1, b2 & b3 respectively) have given in figure 5.14.

There were a total of three active spells in 2005 and two active spells in 2007 & 2011. In 2004 three break spells and in 2005 & 2008 two break spells are observed over the CI region. It was observed from the figure 5.14.a1 that in 2005 active spell, aerosols are confined over north eastern AS and western parts of India and substantial reduction over CI. But in 2007 aerosol dispensation pattern is different and more aerosol loading is towards the southern parts of AS and many isolated small regions with higher AOD values are observed over eastern side of CI. In 2011 active spell (figure 5.14.a3), it has been noticed that, the aerosols are confined over north eastern AS and substantial reduction towards CI with isolated higher AOD regions all over CI. Therefore, it appears that the aerosol distribution was different during all these active spells identified for individual years and their impacts on rain pattern might be different.

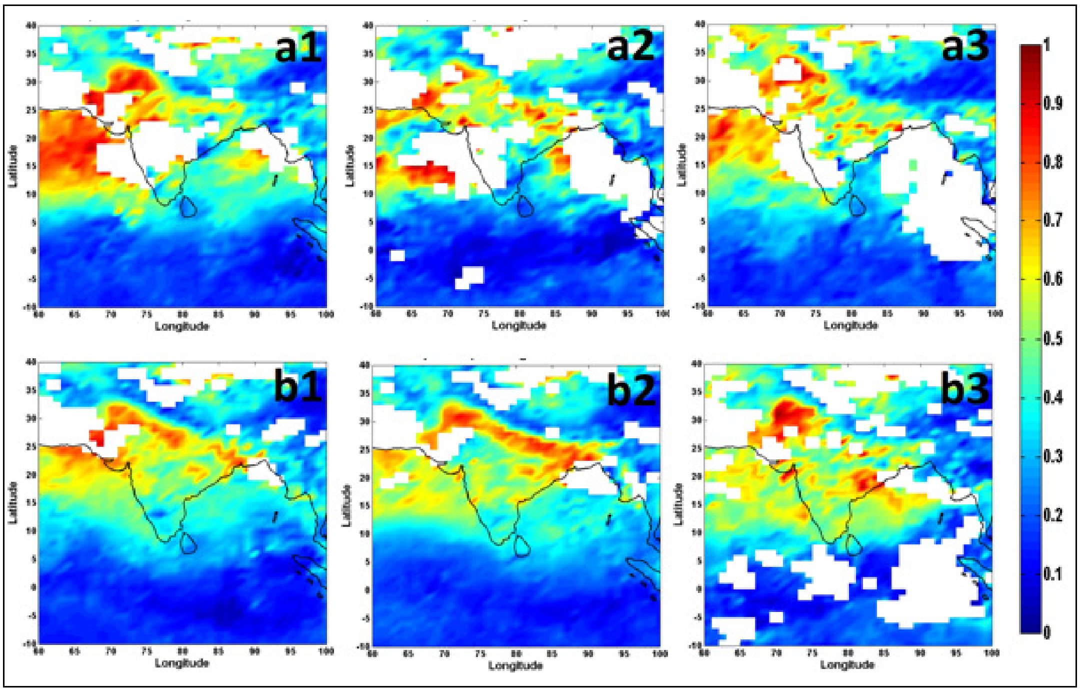


**Figure 5.14: Spatial plots of composite representation of AOD for the individual ISMR years.** Top panel represents the AOD during active spells and Bottom panel represents the AOD during break spells. (a1) 2005 (a2) 2007 (a3) 2011 (b1) 2004 (b2) 2005 (b3) 2008.

During the break spells of 2004, 2005 and 2008 (figure 5.14.b1, b2 and b3) aerosols are confined over the north eastern AS, as it was observed during the active spells of 2005 and 2011, but lesser AOD values as compared to active spells. During the break spells of 2004, aerosol concentration is substantially increased from the western parts of the subcontinent towards the CI and confined over the Himalayan range, extended up to the north eastern parts of the subcontinent**.** The composite spatial pattern of the 2005 break spells reveal that, the aerosols are confined over Himalayan range and it get reduced towards the southern region. It is observed that the BoB region having less aerosol loading during the break spells of 2004 and 2005.

The spatial pattern of the 2008 break spell (figure 5.14.b3) shows that the aerosol mass is not confined over Himalayan range even though lesser AOD values are observable over north eastern AS. The aerosol dispensation in 2008 break spell over the BoB region shows that there is a substantial increase in AOD as compared to 2004 and 2005 break spells. In 2008, aerosol concentration substantially increased towards southern India and higher AOD values are observed over the south eastern part of CI. From the present analysis it was understood that aerosol distributions are distinct during the break spells of individual years. It may be possible that other meteorological parameters having an equal and significant contribution along with aerosols in controlling the life span of break spells.

### 5.2.2.3 Analysis of aerosol and cloud properties during individual active events

Since it has been noticed that the spatial properties of aerosols are distinct even during the composite active (break) events of individual years, the present study has been extended to find out the cloud characteristics such as CF, COD, CER and SSA during individual active (break) events.

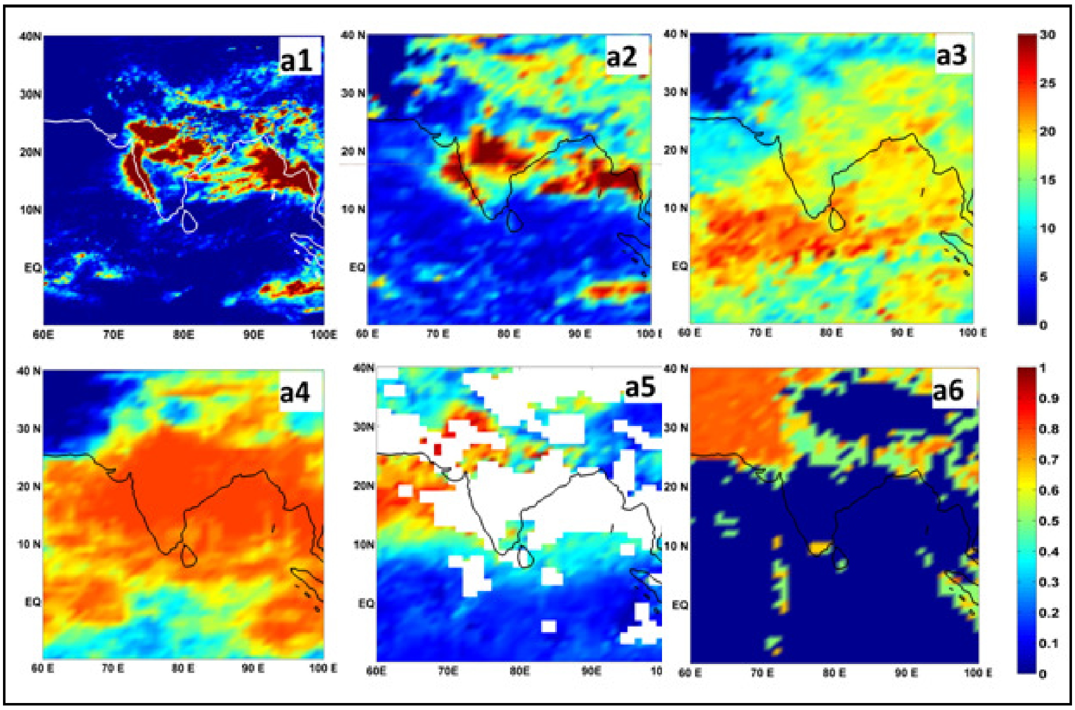


**Figure 5.15: Spatial plots of aerosol - cloud characteristics during individual active events** (a1) Spatial pattern of rainfall during the active spell (Jul. 24 – 27) of 2005. (a2) COD (a3) CER (a4) CF (a5) AOD (a6) SSA. Colour bar in the top panel represents the rainfall in mm/day, COD (unit less) and CER in µm. Colour bar in the bottom panel indicates the CF, AOD and SSA (unit less).

Two individual active spells (2005 & 2007) are considered for examining the associated aerosol distributions. The rainfall spatial pattern of the active spell which was identified during 2005 July 24 to 27 and its associated AOD, SSA, CF, COD, and CER are given in fig.5.15. It is noticed from the fig.5.15.a5 that, the aerosols are confined over north eastern AS and showing a substantial increase over the western regions of Indian landmass. This region is the western end of the monsoon trough and diffused because of the weak wind field associated with the heat low (Potty et al., 2001). Due to the non availability of cloud free MODIS data there was a difficulty in examining the exact spatial distribution of aerosols over some parts of CI region and southern India. The spatial pattern of the active spells reveal that the CI, Western Ghats, some parts of north eastern region and the eastern BoB receive high rainfall and the CF values are more than 0.8 over the entire Indian subcontinent including north eastern AS and BoB (fig.5.15.a4). The COD values are higher than 20 over the CI and Western Ghats regions during these days. The CER values are observed to be lesser (<20 μm) over northern eastern AS and almost the entire Indian subcontinent even during the active event. The aerosols which are confined over the north eastern AS and the western regions of Indian landmass indicate the role of long range transport of aerosols (Bollasina and Nigam, 2009; Lau et al., 2006; Manoj et al., 2011) during these active spells. The spatial analysis of aerosol SSA reveals that, some portions of CI having lesser values (< 0.7) which might be due to the absorbing nature of aerosols accumulated during these days. HYSPLIT backward trajectories have been analysed in order to trace the sources behind the higher AOD values observed during these active spells (figures are given in appendix).

The backward trajectories at three altitudes above ground level (500, 1500 & 3000 meters) ending on the mid day of the active spell was constructed, which were ended up at three locations selected over CI and air mass appears to be coming from Middle East, countries on the eastern side of Indian subcontinent and AS. Therefore it might be inferred from the back trajectory analysis that both continental and marine contributions towards the increased aerosol loading over land region.

The active spell of 2007 having a life span of three days (Aug. 26-28) was also examined along with the aerosol dispensation on these days. The higher AOD values are observed over the north western sides of India including some parts of Pakistan and parts of north India. As in the case observed during the active spell of 2005 considered earlier, aerosols are not confined over north eastern AS (figure 5.16.b5). The aerosol SSA values are observed to be less than 0.8 over the CI region (figure 5.16.b6). The CF values are in the range between 0.8 - 0.7 over the entire CI region, AS and BoB. The lesser COD values are observed over CI region (< 20) as compared to the higher COD values during the active days of 2005 which was discussed earlier.

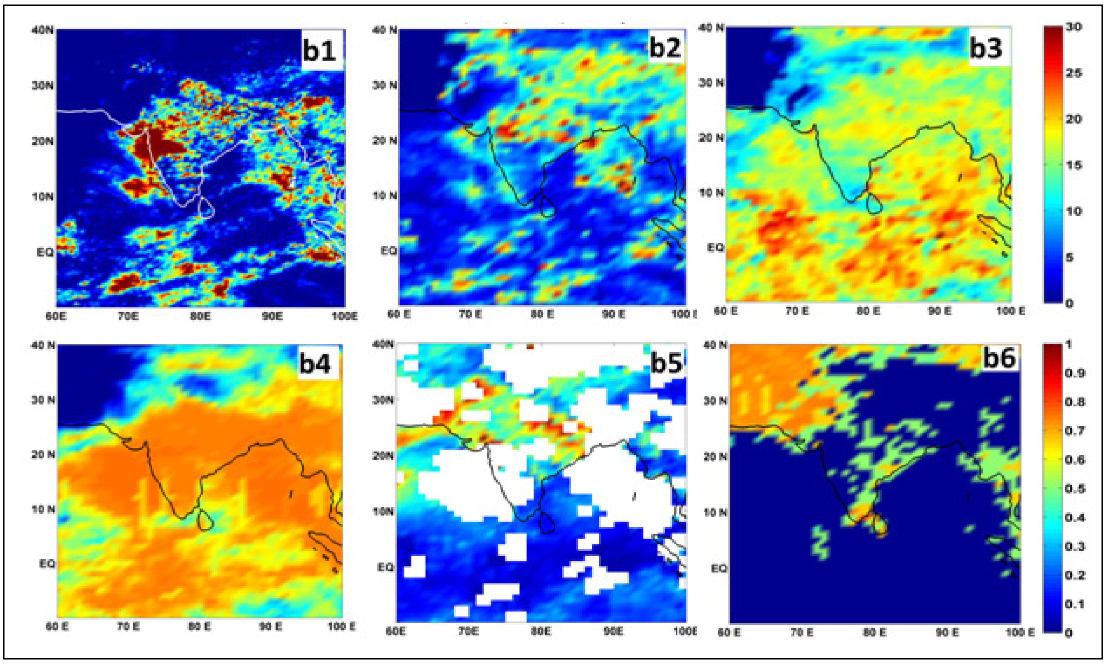


**Figure 5.16: Spatial plots of aerosol-cloud characteristics during individual active events.** (b1) Spatial pattern of rainfall during the active spell (Aug. 26-28) of 2007. (b2) COD (b3) CER (b4) CF (b5) AOD (b6) SSA. Colour bar in the top panel represents the rainfall in mm/day, COD (unit less) and CER in µm. Colour bar in the bottom panel indicates the CF, AOD and SSA (unit less).

### 5.2.2.4 Analysis of aerosol and cloud distribution during individual break events

It has been noticed from the spatial pattern (fig.5.17.c5) of the break spell of 2005 (Aug. 23-28) that the aerosols are confined over Himalayan range, started from the north western side and extended up to north eastern side of India. Sustantially reduced AOD values (0.3 - 0.4) have been observed all over the CI and southern India. The aerosols are not confined over north eastern AS as it was observed during some of the individual active events and the AS and BoB having very less AOD values. Break spells having a distinct heat trough type circulation (Gadgil and Joseph, 2003) and aerosol characteristics might have changes with the circulation patterns. Aerosols which were confined over Himalayan ranges trapped in lower boundary layer and might be the major contributor for sustaining break days. The CF values are observed to be higher (>0.8) over the north eastern AS, some portions of CI and southern India but lesser over remaining CI (fig.5.17.c4). It is observed that COD values are very less over most of the CI with substantial increase over north eastern region. The CER values are lesser (<20 µm) over the CI, but higher values are observed over BoB (fig.5.17.c3). The area averaged correlation was 0.56 with 95% confidence bounds for CER and ISMR during 2003 and for the entire CI, maximum rainfall was obtained between the CER values 5 - 30 µm (Scatter plot is not given). The CER values are lesser over the western parts of India, Western Ghats and some portions of north east India and the aerosol stack observed over the Himalayan range may be invigorating with the cloud properties and suppressing rain. The HYSPLIT backward trajectory analysis shows that, the air mass is mainly coming through north western region of the subcontinent (figures are given in appendix) and continental aerosol contribution is more as compared to marine aerosols. The aerosols are more likely to confine over north western side and Himalayan range which was already noticed from the spatial representation of aerosols.

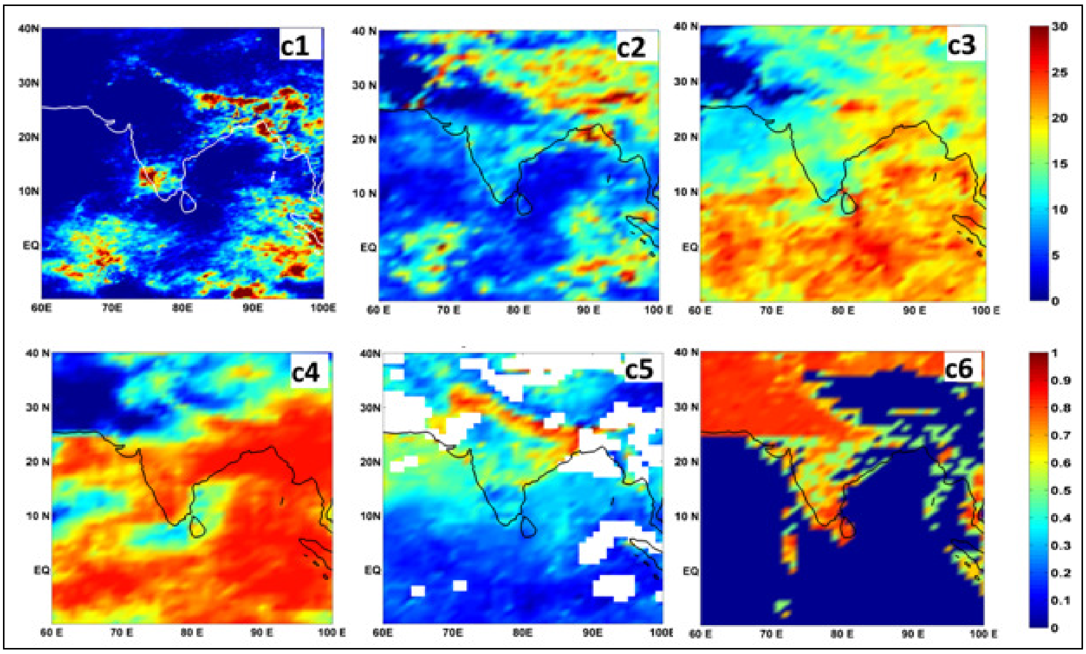


**Figure 5.17: Spatial plots of aerosol-cloud characteristics during individual break events**. (c1) Spatial pattern of rainfall during the break spell (Aug 23-28) of 2005. (c2) COD (c3) CER (c4) CF (c5) AOD) (c6) SSA. Colour bar in the top panel represents the rainfall in mm/day, COD (unit less) and CER in µm. Colour bar in the bottom panel indicates the CF, AOD and SSA (unit less).

The long intense break was identified during 2009 Jul. 24 **-** Aug. 9 and the aerosol-cloud spatial distributions are given in fig.5.18. The entire Indian region is covered with high aerosol loading and AOD values more than 0.8 over northern India and north eastern AS, which extends over BoB (fig.5.18.d5). There might be the influence of long range transport and local emission on the higher aerosol loading over entire Indian region. The CER is less (< 15 µm) over the CI may be because of the higher AOD loading observed during this long intense break event (fig.5.18.d3). The SSA values are < 0.8 over the CI and it may be an implication of the absorbing nature of aerosols. Ravi Kiran et al., (2009) reported that CER is lower over central and north western parts of India, on break events as compared to the active days. They further explained this on the basis of the indirect effect of aerosols on clouds and precipitation. As per IMD, 2009 is a drought year and high aerosol loading might have played an important role for altering the cloud properties and thereby suppressing rainfall on those days. The simultaneous variations in aerosol - cloud dispersion over the CI region, has been analysed from the normalized rainfall index along with daily aerosol and cloud distribution for the drought ISMR of 2009 and it has given in fig. 5.19.

In the fig. 5.19. ,long break spell of 2009 is shown inside the rectangular box and it was noticed that the CF and AOD values are relatively higher during the break days. As per the studies by Sikka and Gadgil (1980), the northwest shift of monsoon depression towards Himalayan foothills are followed by break spells of monsoon season. The aerosols are vertically advected to elevated altitudes against the foothills of the Himalayas as shown in the fig.5.18.d5 due to the enhanced convection (Gautam et al., 2009). Manoj et al., 2012 studied the role of aerosol cloud interaction during the two break spells of 2009 and identified the positive aerosol indirect effect which inhibiting efficient precipitation over CI region. Even though this was a long high break, the CF values are observed more than 0.8 over the entire Indian land mass and, north eastern AS and BoB (fig.5.18.d4) and COD values are less (<15) over the CI region and AS.

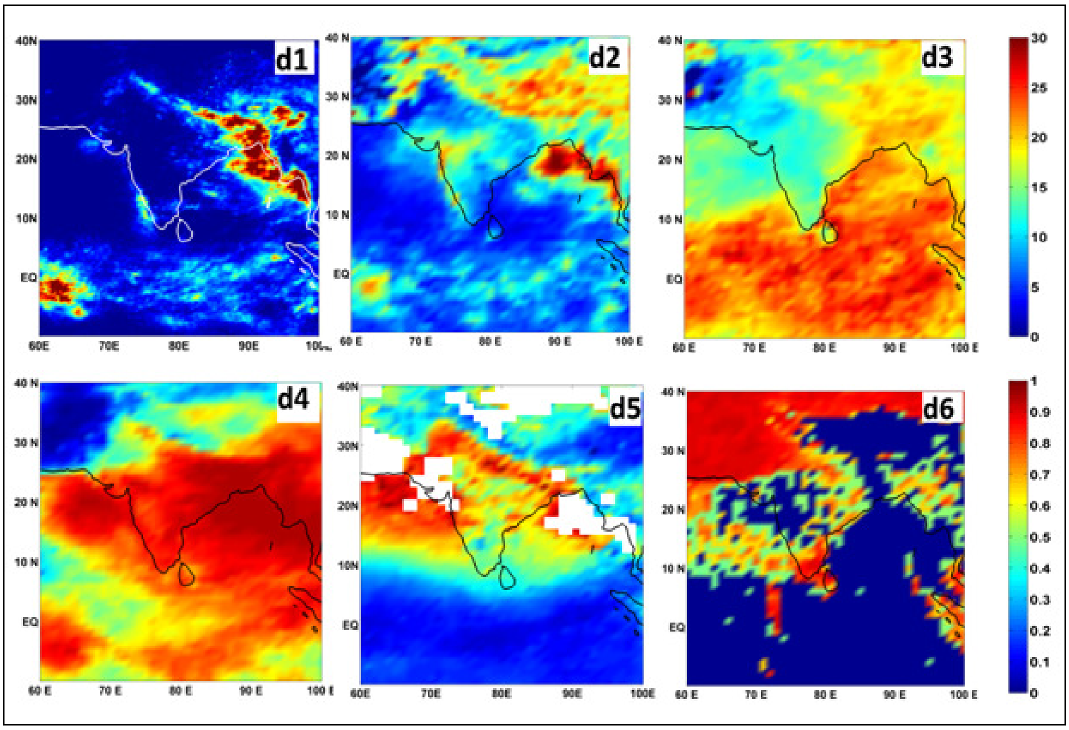


**Figure 5.18: Spatial plots of aerosol - cloud characteristics during individual break events.** (d1) Spatial pattern of rainfall during the break spell (Jul. 24 - Aug 9) of 2009. (d2) COD (d3) CER (d4) CF (d5) AOD (d6) SSA. Colour bar in the top panel represents the rainfall in mm/day, COD (unit less) and CER in μm. Colour bar in the bottom panel indicates the CF, AOD and SSA (unit less).

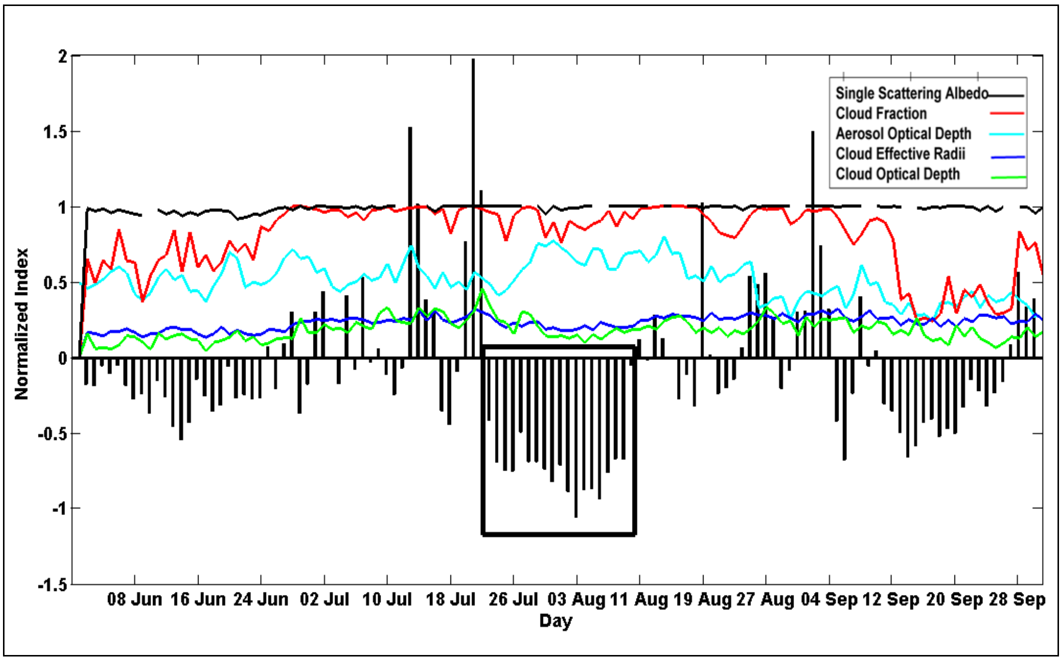


**Figure 5.19: Time Series plot for the 2009 ISMR and associated aerosol-cloud characteristics.** Normalized index of rainfall (vertical bars) and daily variability in COD, CER, CF, AOD and SSA over CI for 2009 summer monsoon rainfall. The rectangular box represents the long break event in 2009.

It was observed that the aerosol dispensation was distinct during the two break spells of 2005 (Aug. 23-28) and 2009 (Jul.24 - Aug. 9). During 2005 break spell, Himalayan range was fully confined with aerosols and in 2009 break spell entire Indian subcontinent having higher AOD values except over the southern end. It might be possible that circulation during the active and break events may have an equal and important contribution in deciding the existence of these events along with the aerosols.

# CHAPTER 6

# DISCUSSION

## 6.1 Interannual variability of ISMR over CI, AS and BoB

Interannual variability of the ISMR and aerosol - cloud interactions have been investigated for the last ten years (2003 – 2012) over CI, AS and BoB regions. The internal dynamics could also be significantly affected by the cloud – aerosol interlinks by positive or negative feedback to the monsoon system. As per the studies by Suhas et al., (2012) significant fraction of interannual variability of the ISMR has been governed by 'internal' dynamics arising from interactions between high frequency fluctuations and the annual cycle.

In the present analysis, attempts have been made to compare the aerosol - cloud properties during the drought, flood and normal monsoon years over the CI (18 – $28^0$ N & 74 – $84^0$ E) , which were identified based on the normalized index of the rainfall and the analysis has been extended to AS and BoB. Based on the normalized index values, 2004 and 2009 are identified as drought years and it was observed from the statistical analysis that the mean monsoon rainfall was 6.53 mm/day and 6.02 mm/day over the CI for these two years respectively. The seasonal mean monsoon rainfall over CI for the flood year 2011 (8.12 mm/day) is found to be the maximum during the study period (2003-2012). The BoB region receives higher amount of seasonal mean rainfall as compared to AS. In the drought year 2009, BoB having higher value of mean rainfall as compared to the flood year 2011, which implies that the variation in the ISMR over the CI doesn't vary in the same phase with BoB region (drought condition was calculated based on the rainfall data available over the 18-$28^0$ N & 74- $84^0$ E). The spatial representation of rainfall illustrates that the drought conditions during 2009 were limited over AS and the Indian land region. The statistical analysis demonstrates that the AS region receives less amount of mean rainfall as compared to CI and BoB. During the drought year 2004 (as per IMD) mean value of rain was higher as compared to flood year 2011 over the AS region. Noticeable interannual fluctuations in mean monsoon rainfall over oceanic region have been observed. AS receives the spells of high rainfall during the initial days of the monsoon season and then the amount of rainfall decreases as the monsoon progressed over the land region. Over the CI region the flood year 2011 received more rain during the onset days and the summer monsoon season of 2009 shows reduced rainfall during the peak rainy months of July and August.

## 6.2 Interannual variability in AOD over CI, AS and BoB during the ISMR season

Aerosols can interact with clouds and precipitation through 'first indirect effect' acting as CCN and increase cloud's lifetime - 'second aerosol indirect effect', while absorbing aerosols heat the atmosphere, reduces relative humidity, results in decreased cover of low clouds known as the 'aerosol semi-direct effect' (refer http://www.ipcc.ch/publications_and_data). Impact of atmospheric aerosols on precipitation depends on a number of factors such as location, season and the spatiotemporal scale of analysis (Koren et al., 2012).

Spatio - temporal and statistical analysis have been done to investigate the interannual variations in aerosol concentration for the period 2003 to 2012 in association with the variability of ISMR over the CI, AS and BoB. The spatial distribution of the mean climatology of AOD during the ISMR season (10 year time scale) shows that the aerosols are confined over the north western regions of India, north eastern AS and along the foothills of Himalayas (refer figure 5.13). In rainy season, aerosols are supposed to be removed from the atmosphere by wet deposition (Wang et al., 2009). But the monthly mean spatial distribution for 10 years time scale shows that aerosol concentration was more during the peak monsoon months of July and August over the north western and most of the CI region. Time series analysis of mean AOD distribution during the ISMR season between 2003 to 2012 (June-July-August-September) over the AS, CI and BoB regions have been carried out and it was noticed that the CI and the AS are loaded with higher aerosol concentration during the month of July. As per the studies by Ramachandran and Cherian (2008) AOD values are higher during the month of July on an annual scale and they further noticed that coarse mode aerosols and growth of fine mode water soluble aerosols during monsoon season lead to higher aerosol concentrations. It was illustrated that the 2009 ISMR season (drought year) having high AOD values over the CI region, during the month of August as compared to July and it is worth to mention that high AOD values were found during the long intense break spells (24 Jul to 9 August).The high aerosol mass over the CI, may be invigorating the cloud-precipitation interactions and sustain the break spells. The similar finding has been reported recently by Manoj et al., (2012).

There might be two possible reasons for the observed aerosol loading over the Indian land mass during the rainy season. First reason may be the contributions from the regional anthropogenic air pollution and second is the contributions from far away sources through long range transport of aerosols. Ganguly et al., (2012) suggested that precipitation responses are driven by local aerosol forcing and transported aerosols from other regions. Dust transported by the large-scale circulation from the deserts adjacent to northern India affect the rain over the BoB and aerosols over the northern AS during July-August (Lau et al., 2010). Present analysis reveals that, during most of the summer monsoon days AOD values are higher than 0.6 over the CI region even during the flood year of 2011. Dust storms originated from the Middle East and the Thar Desert act as the dust source for the India because of the prevailing westerlies which helps in the piling up of aerosol-cloud against the Himalayan foothills extend towards Pakistan (Bollasina and Nigam 2009). In addition to the increased transport of desert dust from the Middle East by low-level westerly flow from the AS, in the northern branch, Taklimakan desert contributes dust aerosols towards Indian subcontinent (Lau et al., 2006). Aforementioned studies provide an indication that the long range transport might be a major contributor towards the increase in aerosol concentration observed over the Indian land region during the monsoon months. It is inferred from the analysis using the HYSPLIT backward trajectory model that there are contributions from both near and far sources on the high aerosol loading during the monsoon rainfall season over the India. During September, lesser AOD values are observed over AS, CI and BoB for ten year time scale. It has also been noticed that during the end phase of the monsoon season AOD values are less than 0.6 over CI region, which might be due to the wet removal by rain. The limitation in the availability of the aerosol data due to the cloud cover over the BoB region during many days of the ISMR season makes it difficult to extract the clear picture of the aerosol-precipitation interaction during the summer monsoon months.

It is inferred from the present analysis that the ISMR and the AOD are significantly negatively correlated over the three study regions during the study period. It suggests that with increase in rainfall, aerosol concentration decreases due to the wet removal by precipitation and the situations with high aerosol concentrations can lead to suppressed rainfall. It is observed by Wang et al., (2009) that during the summer monsoon season the value of aerosol absorbing optical depth over the subcontinent is greatly reduced due to the enhanced precipitation scavenging. The aerosol characteristics such as AOD and AI are analysed during the ISMR seasons of the study period over the AS, CI and BoB. The correlation analysis between rain and AI suggests significant negative correlation over the CI during the 2005 to 2012 monsoon seasons and AOD - AI shows significant positive correlation. For the AS region correlation between AOD and AI are not significant and for BoB region the correlation was significant during the ISMR seasons of 2006, 2007, 2009, 2010 and 2012.

## 6.3 Analysis of cloud parameters in association with the interannual variability of the ISMR

### 6.3.1 CER

Significant positive correlation has been observed between rain and CER over the CI and CER and AOD are found to be negatively correlated. As per the studies by Konwar et al., (2012) high CCN concentrations gave rise to clouds with smaller drops with greater number concentrations and the CER increased with distance above cloud base. Therefore the variations in CER can be connected with the initiation conditions for precipitation.

Based on numerical simulations, Rosenfeld et al., (2012) observed that rain is initiated when CER near cloud top is around 12–14 µm and the CER reaches a critical effective radius (rep) above which coalescence is creating drizzle and raindrops. The value of rep was shown to be between 12 and 14 µm using different satellite derived measurements such as the MODIS retrieved CER (Suzuki et al., 2010) and the TRMM measurements comparing the retrieved CER with the TRMM precipitation radar (Rosenfeld, 1999; Rosenfeld et al., 2001). Rosenfeld et al., (2012) shown that when initiation of rain near cloud top is inhibited by aerosols, no rain occurs at cloud base either. All these earlier studies well establish the relationship existing between CER, precipitation and the aerosols. Based on the simulations Rosenfeld et al., (2012) observed that aerosol can incur the situations when the accretional growth of rain embryos that form near cloud top is responsible for the rain intensity near cloud base and large aerosol concentrations prevents precipitation. Initial phase of the monsoon season and the break spell of 2009 (24 Jul - 9 Aug) are associated with lesser CER values over the CI and the same condition existed during the drought year over the BoB. Statistical analysis reveals that the mean rainfall and the mean CER values are high over BoB, whereas the mean AOD values are less. Therefore the above mentioned results indicate the inter relatioship between AOD, CER and rainfall over the BoB.

### 6.3.2 CF

Rainfall **-** CF correlation over CI was significantly positively correlated during 2003, 2008, 2010 and 2012 ISMR seasons. In addition to this present study reveals that there were a significant negative correlation between AOD and CF over the CI. This can be explained as semi-direct effect of aerosols where high aerosol concentrations decrease the CF.

Grandey et al., (2013) reported positive AOD **-** CF relationship across most of the globe using the data retrieved from MODIS. They further observed that a global mean CF increase of ~0.2 between low and high AOD condition was found for both land and oceanic regions. Another observation made by Grandey et al., (2013) that over the tropical region, negative simulated AOD **-** CF relationships existed which might be due to the scavenging of aerosol by convective precipitation and CF generally increases with relative humidity (aerosols swell hygroscopically in high relative humidity conditions) which in turn increases AOD. The positive correlation between aerosol number concentration and CF can be considered as the cloud lifetime effect or secondary effect of aerosols, except for the area of extremely high aerosol loading with a tendency of weak or negative correlation (Sekiguchi et al., 2003).Over the AS, the relation between rain and CF was significant during the drought ISMR seasons (2004 and 2009) and the AOD **-** CF relationship was not significant for the study period. Even though the BoB region having positive correlation between CF **-** rain and negative correlation between CF **-** AOD during the flood year 2011, other ISMR seasons exhibit insignificant correlations.

### 6.3.3. COD

The effect of changing the CER and cloud life time (first and second indirect effects) supposed to change the COD (Sekiguchi et al., 2003). Costantino and Br´eon, (2013) demonstrated through the statistical analysis that COD value of 10 was the threshold beyond which precipitation is mostly formed, in both clean and polluted environments and also larger COD values and polluted clouds shows suppressed rainfall.

It has been observed that COD and rain are positively and AOD and COD are negatively correlated over the CI region. BoB region shows significant negative correlation between COD and AOD during 2004 ISMR season. COD values over the CI region are observed to be more than 20 during some days of the peak monsoon months of July and August for 2009, 2010 and 2011 ISMR seasons. The lesser COD values ($\leq 15$) are observed over the AS region as compared to the BoB with higher COD values ($\geq 20$).

### 6.3.4. CTP

As per the observations by Massie et al., (2007) aerosol indirect effects are present throughout the troposphere and cloud microphysical processes that determine CER inside a cloud are influenced by the microphysics that is initiated at cloud base, and this influence proceeds throughout the cloud as air parcels rise upward, finally change phase from liquid to ice. It is possible to bin cloud reflectivity as a function of CTP, and hence aerosol indirect effects are present throughout the troposphere (Massie et al., 2007).

The CI shows a negative correlation between CTP and rainfall which means that with increase in CTP values rainfall getting reduced and vice versa. During the drought year and the flood monsoon year the relationship between CTP and rain was not significant over the CI. It was noticed on the basis of correlation analysis that, AOD and CTP was significantly positively correlated over the three study regions. It was observed that during the peak rainfall days of the ISMR, CTP values are lesser as compared to the onset and retreating days over the CI region. The area averaged mean CTP over CI region was higher (> 470 hPa) during the two drought monsoon years as compared to other monsoon years. BoB region shows lesser CTP values (< 400 h Pa) as compared to other two study regions. Ravi Kiran et al., 2009 noticed the presence of deep convective clouds with CTP < 300 hPa over North BoB associated with the enhanced rainfall days of the ISMR season. Therefore the increase in rainfall over BoB region as compared with the CI and AS can be considered in association with the decreased CTP observed over BoB.

## 6.4 Analysis of aerosol - cloud parameters during the intraseasonal variability of the ISMR

The intraseasonal variability of the ISMR can be represented as active days having enhanced rainfall and break days having suppressed rainfall over the CI. Active and break events, are identified based on the remotely sensed rainfall over the CI region between $17.0^0$ to $27.0^0$ N and $74.0^0$ to $82.0^0$ E.

Active and break days are calculated using TRMM 3B 42 V7 data during the ISMR seasons of 1998 – 2011 and it was observed that these active (break) spells are comparable to those identified by Rajeevan et al., (2010) using IMD data sets. Based on the objective criteria used for the identification of active (break) spells, there might be changes in the duration and the frequency of the spells (Goswami and Ajaya Mohan, 2001;Krishnamurthy and

Shukla, 2007;Rajeevan et al., 2010; Singh, 2013; Sinha et al., 2011; Yoon and Chen,2005). The active and break spells identified using the satellite data sets also support the finding that break spells tend to have a longer life-span than active spells (Rajeevan et al., 2010). The life span of active spell is about three to four days as per the current analysis. During the active days CI, Western Ghats and Eastern India receives increased rainfall, while during break days there is suppressed rainfall over CI. It has been noticed (refer figure 5.12 B) that on break days less rainfall is observed over Western Ghats region but Himalayan region and North East India receives substantial amount of rainfall. In addition to this, South East India receives very less (no) rainfall in both of the cases. This is in agreement with the studies by Ravi Kiran et al., (2009) but they considered cloud properties.

Based on the spatial distribution of the composites of AOD for the period 2003-2011 (during the ISMR season) it is noticed that, aerosols are confined over the north western regions of Indian landmass and over the north eastern AS during the active spells. Deep layer of moist air present over this region makes high monsoon during the active days, while the non availability of moist air weakens the heat low and results in breaks (Ramage, 1966). Hence the fluctuations in AOD values might be in close association with active spells of the ISMR.

The spatial properties of aerosols are distinct even during the composite active (break) events of individual years, the present analysis has been extended to find out the cloud characteristics such as CF, COD, CER and SSA during individual active (break) events. In order to discuss the rain-aerosol interactions at intraseasonal scale, two individual active (break) spells are considered in the present analysis. It is understood that the aerosol cloud properties are distinct during the individual active and break days over the CI region. Hence it would be more appropriate to investigate individual active and break event to discuss about the cloud-aerosol-precipitation interlinks.

# CHAPTER 7

# CONCLUSION AND RECOMMENDATION

Interannual and intraseasonal variability of ISMR for JJAS has been examined in association with aerosol and cloud properties using remotely sensed TRMM 3B42 V7, MODIS (aerosol and cloud), AURA-OMI and EARTH PROBE-TOMS data sets. Interannual variability of ISMR has been studied over CI, AS and BoB for 2003-2012. Intraseasonal variations in ISMR have been investigated over the CI region along with the aerosol and cloud properties for the period starting from 2003 to 2011. Drought, flood and normal monsoon years have been identified over the CI region following the normalized index approach and the analysis has been further extended for AS and BoB. Present study makes use of the satellite derived rainfall data and shows a good match with the drought, flood and normal monsoon years identified using the rain gauge data in previous studies (refer http://www.tropmet.res.in/~kolli/MOL/Monsoon/frameindex.html; Joseph et al., 2009). It is worth mentioning here that the AOD and rainfall over the three study regions are significantly negatively correlated. Therefore it suggests that, for the three study regions aerosol could be one of the influential factor in deciding the interannual variations in ISMR.

Cloud properties such as CER, CF, COD and CTP are analysed in association with the interannual variability of aerosols and rainfall for the last decade. It has been observed from the correlation analysis that, over the CI region rain and CER are significantly positively correlated, whereas AOD and CER are negatively correlated. The result from the statistical analysis suggests that the mean rainfall and CER over the BoB region was higher and AOD was lesser as compared to CI and AS. It has been noticed that there is a significant negative correlation between AOD and CF over the CI region which implies the higher aerosol concentration. Therefore it suggests the semi - direct effect of aerosols over the CI. Rainfall and CF correlation over CI was highly significant during most of the monsoon seasons considered for the present analysis and therefore CF might be considered as an indicator for the precipitating clouds.

The present analysis suggests significant positive correlation between COD and rain and significant negative correlation between AOD and COD over the CI region. The negative correlation between CTP and rainfall implies that, with increase in CTP values over the CI region rainfall getting reduced and vice versa. It was observed that over the three study regions the AOD and CTP were significantly positively correlated. Therefore all the cloud parameters considered for the analysis in association to rainfall variability at interannual scale provided noticeable interlinks between cloud-aerosol-precipitation relations.

Using the satellite derived 3B42 V7 rainfall data set, active and break spells of the ISMR has been investigated during the peak monsoon months of July and August (1998 -2011). These active and break spells are comparable to those active and break spells of ISMR identified from the previous studies on the basis of rain gauge estimates over the CI (refer table 4.1). The objective was to examine the aerosol loading and associated parameters during the active and break spells.

The spatial pattern of the composite of AOD during the active spells reveals that the aerosols are reduced over the CI, however the aerosols are confined mostly over north eastern AS (wet deposition may not remove the confined aerosol concentration or it could be because of the continuous supply of aerosols due to long range transport). The composite spatial representation of AOD during the break spells portrays that the aerosols are confined over the Himalayan foothills. It has been observed that there were no spatial similarity in aerosol distribution and cloud properties during the individual active and break spell. This implies that the composite representations may not be appropriate to reveal the impact of aerosol distributions and associated cloud properties during the active (break) spell. It is quite complicated to make an assumption about the impact of aerosols on active (break) spell by examining the composite representations of aerosol characteristics. It is suggested to consider the aerosol characteristics during the individual active (break) events, as different mechanisms might be involved in deciding enhanced (suppressed) monsoon rainfall.

Analysis of aerosol impacts on ISMR itself a challenging research theme as many more factors can change the nature and distribution of aerosols during summer monsoon season. Apart from the cloud parameters considered for analysing the interannual variations in aerosols and rainfall, other meteorological factors might be equally important which are outside the scope of the present study. The associated explanation for the inter - connection observed between rain and aerosol and cloud parameters has been provided based on the recent research on this theme. Nonetheless, the detailed underlying mechanism of aerosol-cloud - rain interlinks could not be explained in the present study and it still remain as an open question for further research. Needless to say that field measurements, atmospheric models and satellite measurements coupled together would be more appropriated to get the important information about the aerosol - cloud interaction and subsequently their impact on precipitation.

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http://www.ipcc.ch/publications_and_data
http://disc.sci.gsfc.nasa.gov/giovanni/additional/data-holdings/PIP/cloud_effective_radius.shtml
http://disc.sci.gsfc.nasa.gov/giovanni/additional/dataholdings/PIP/cloud_optical_thickness_or_depth.shtml
http://disc.sci.gsfc.nasa.gov/data-holdings/PIP/cloud_top_pressure.shtml
http://www.tropmet.res.in/~kolli/MOL/Monsoon/frameindex.html

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# APPENDIX 1

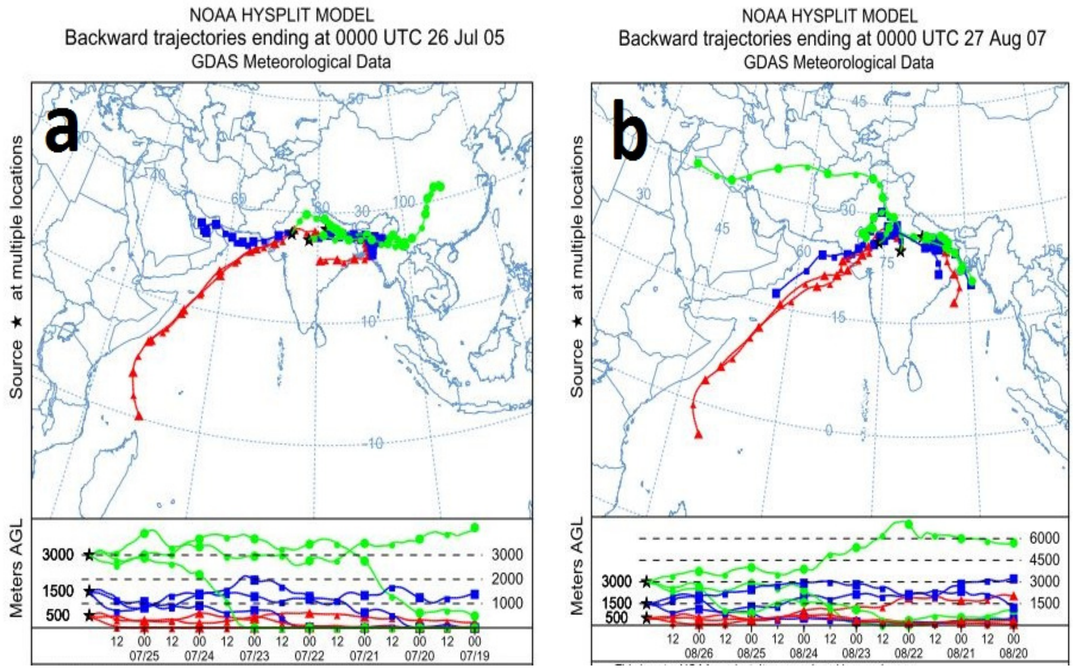


**Figure: A1.1. (a) HYSPLIT backward trajectory for the air mass movement during the active spell in 2005 (24 to 27 Jul).** The green, blue and red coloured lines indicate the trajectories at 3000 m, 1500 m & 500 m respectively above ground level. (b) HYSPLIT backward trajectory for the air mass movement during the active spell in 2007 (26 to 28 Aug). The green, blue and red coloured lines indicate the trajectories at 3000 m, 1500 m & 500 m respectively above ground level.

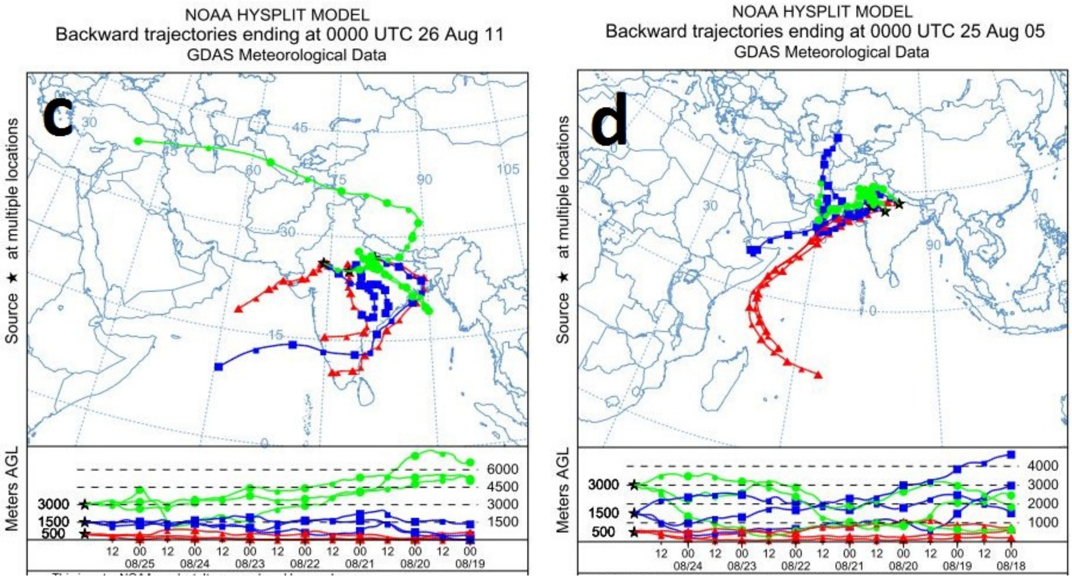


**Figure: A1.2. (c) HYSPLIT backward trajectory for the air mass movement during the active spell in 2011(24 to 27 Aug).**The green, blue and red coloured lines indicate the trajectories at 3000 m, 1500 m & 500 m respectively above ground level. (d) HYSPLIT backward trajectory for the air mass movement during the break spell 2005 (23 to 28 Aug).The green, blue and red coloured lines indicate the trajectories at 3000 m, 1500 m & 500 m respectively above ground level.

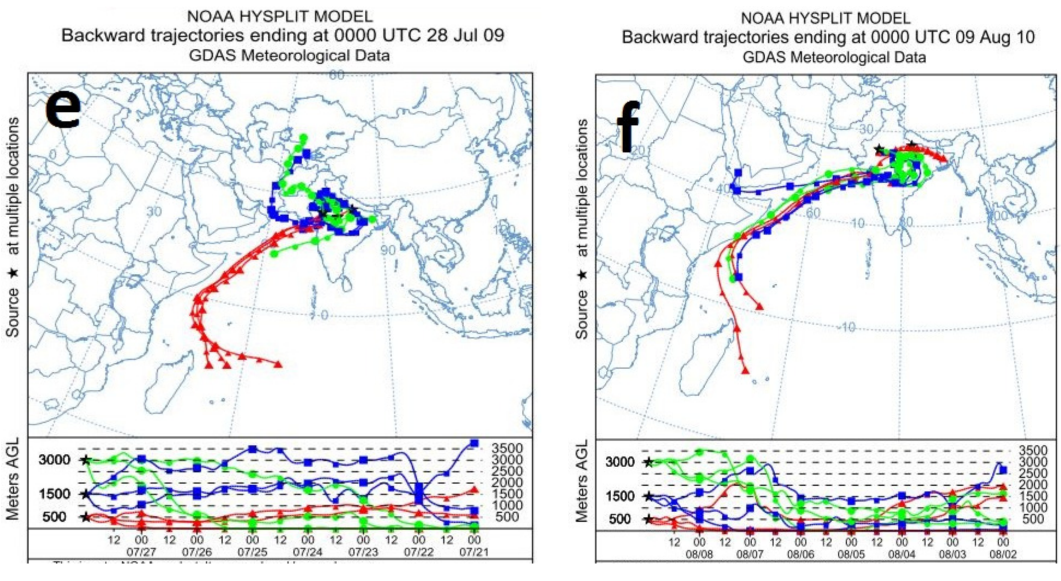


**Figure: A1.3. (e) HYSPLIT backward trajectory for the air mass movement during the break spell 2009 (24 Jul to 9 Aug).** The green, blue and red coloured lines indicate the trajectories at 3000 m, 1500 m & 500 m respectively above ground level. (f) HYSPLIT backward trajectory for the air mass movement during the break spell 2010 (Aug 7 to 10). The green, blue and red coloured lines indicate the trajectories at 3000 m, 1500 m & 500 m respectively above ground level.

# APPENDIX 2

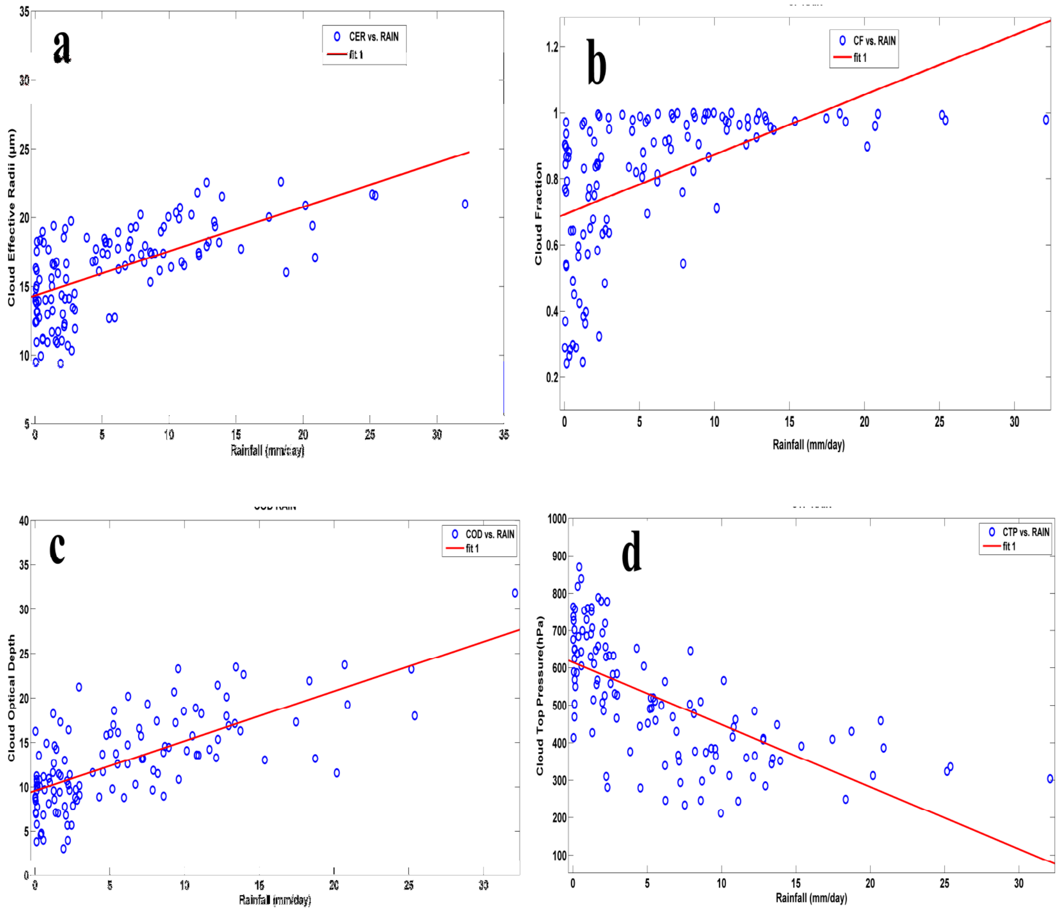


**Figure A2.1 Scatter plots of the 2009 summer monsoon rainfall over the CI region** (a) Rainfall and CER (b) Rainfall and CF. (c) Rainfall and COD. (d) Rainfall and CTP. Rainfall in mm/day, CER in µm and CTP in hPa. CF and COD are unit less parameters.

# APPENDIX 3

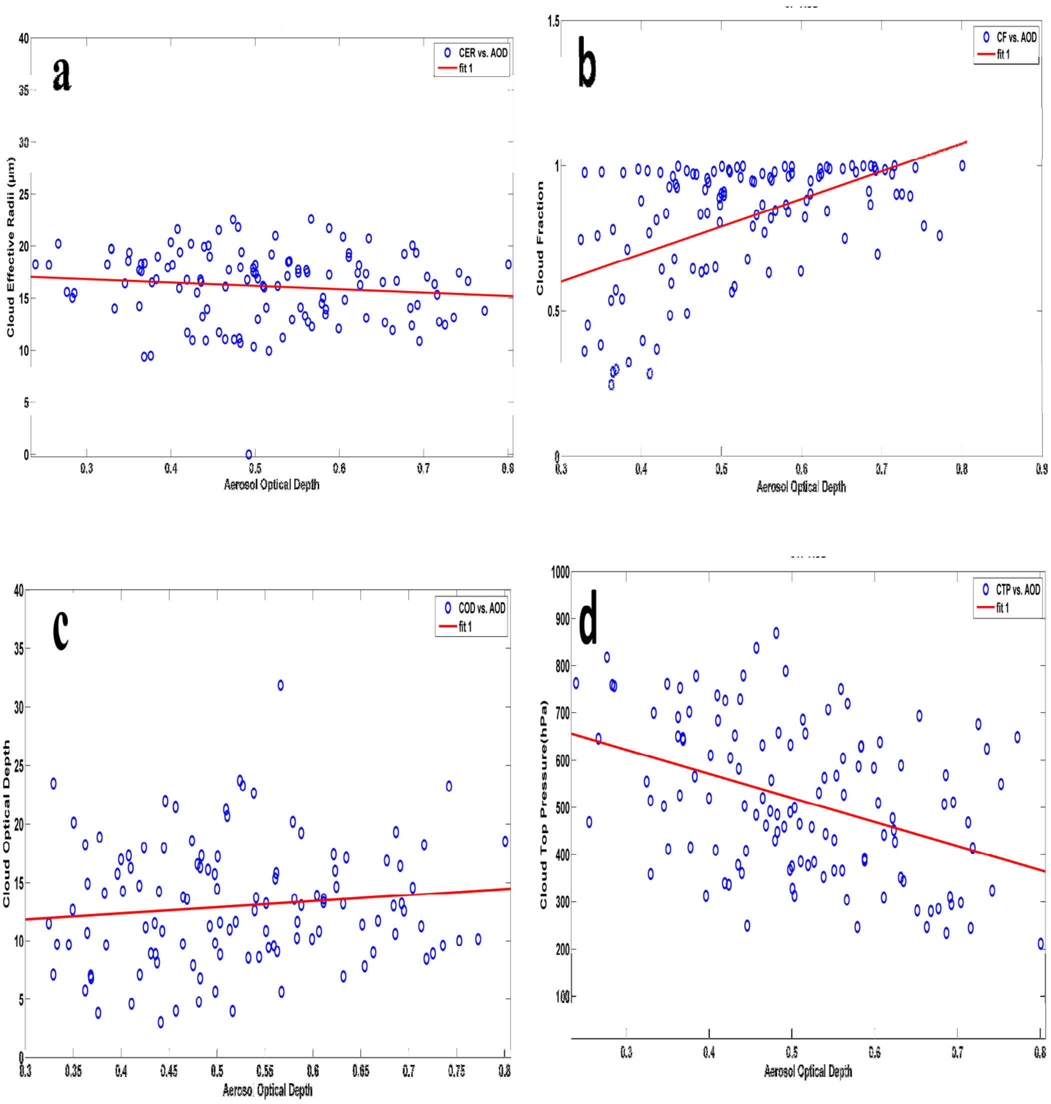


**Figure A3.1.Scatter plots of the AOD during the 2009 summer monsoon season over the CI region** (a) AOD and CER (b) AOD and CF. (c) AOD and COD. (d) AOD and CTP. CER in µm and CTP in hPa. AOD, CF and COD are unit less parameters