# AN INVESTIGATION ON AEROSOL TREND OVER INDIA AND THE ADJOINING OCEANIC REGIONS

*Project report submitted to the*

***University of Kerala***

*In partial fulfillment of the requirements for the award of the degree of*

***MASTER OF SCIENCE IN PHYSICS***


**2020-2022**

# ABSTRACT

Atmospheric aerosol particles impact Earth's radiation balance and therefore, its climate. They alter Earth's albedo by scattering and absorbing solar radiations and by influencing cloud formation and properties. The interaction of solar and terrestrial radiation on aerosols in affects the modification of cloud properties, and the influence on ocean biogeochemistry all affects the earth's climate. When we analyze satellite data, a number of patterns emerge from Earth's aerosols. Some are driven by nature and others by man. Surges of aerosol can make their way into the atmosphere almost anywhere on Earth depending on the season and weather conditions. The spatial distribution of aerosol over the Bay of Bengal, Arabian Sea and Indian Sub-continent is examined using satellite observations for the period from 2011 to 2020. Various weather patterns are observed in the vertical structure of aerosol over the region. This study of aerosols provides information on climatology at the specified region using a long spectroradiometer like MODIS. AOD (Aerosol Optical Depth) data from MODIS and aerosol extinction profiles are analyzed for a time period of 2011 to 2021 and a 3D distribution of aerosol over BoB, AS and Indian regions is studied. By combining long-term satellite observations from MODIS, it shows rapid changes in aerosol spatial distribution over the region. A statistically significant trend in boundary layer aerosol concentration is noticed over the regions. The AOD data of aerosol was taken from the Giovani site provided by NASA. The data is analyzed and aerosol trends in the Bay of Bengal, the Arabian Sea and the Indian region are studied for 10 years. This study of aerosols provides information on climatology and varying trend over the region using data from the spectroradiometer MODIS and their proper analysis. AOD (Aerosol Optical Depth) data from MODIS is analyzed for a time period of 2011 to 2020 and the distribution of aerosol over the region is studied.

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# INTRODUCTION

## 1.1 Introduction

Over a few decades the advancement in industrialization and rapid increase in population brought atmospheric pollution caused an effect on air quality and climatic change directly or indirectly in Asian regions. Atmospheric aerosol was found to be a major factor for modification in the climatic systems. These air borne particles having wide range of size, shape and composition are propagated over by long range transportation. (IPCC, 2007). Due to varying reasons the distribution of aerosol particles over atmosphere is different. The trend of this distribution and its effect on climate over Bay of Bengal, Arabian Sea and Indian region is investigated by satellite data using certain tools like MODIS on observing the Aerosol Optical Depth (AOD).

## 1.2 Atmospheric aerosols

Atmospheric aerosols also known as particulate matter (PM) consist of small particles of solids, like dust, and liquids like water suspended in the atmosphere. A variety of liquids and solids are included in the atmosphere that exists as dispersed phases of the air. They are collectively called aerosols. Atmospheric aerosols can be directly emitted into the atmosphere as particles like ash or form from when are emitted when gases undergo complex chemical reactions and condense as particles. Aerosol particle sizes are in the range of 2nm to 10micrometer in ambient atmosphere. These particles originated either from natural processes or from human activities. Although we generally associate the word particle with solid material, atmospheric aerosols may be liquid or solid or have exotic morphologies such as gels surrounding solid cores, two-phase liquid particles, or organic glasses. These aerosol particles formed in the atmosphere may stay airborne for several days after being emitted since they are small size particles and the individual aerosol particles have little inertia. Due to this particles may be carried a long distances during their atmospheric lifetime, especially in chemical reactions and they affect human health, climate and even environmental quality.

About 90 percent of bulk of aerosols by mass have natural origin. Volcanoes eject huge columns of ashes into the air, also sulfur dioxide and other gases, yielding sulfates. Partially burned organic carbon is formed from forest fires. Smoke is produced when gases produced by plants react with other gases. This is especially seen at Great Smoky Mountains of United States. In ocean, some types of microalgae produce dimethyl sulfide which is converted to sulfates in atmosphere. Here the two most abundant aerosols are Sea salt and dust. The remaining 10 percent of aerosol are considered anthropogenic and they come from a variety of sources. Even anthropogenic sources are less abundant they can dominate air downwind of urban and industrial areas. Sulfur aerosols are created from fossil fuels which reacts with water vapors and other gases. Smoke comprising of organic carbon and black carbon is formed by biomass burning. Sulfates, nitrates, black carbon and other particles are produced by smelters power plants, automobiles .Altering of land surface increases aerosols, which includes deforestation, overgrazing, drought and extensive irrigation. Even indoors, cigarettes, cooking stoves, fireplaces, and candles are sources of aerosols.

One of the primary air pollutants within troposphere are atmospheric aerosols which has adverse effect on hydrological cycle, crops, plants, human health and visibility. Even the role of aerosol is highly uncertain and difficult to understand, they are capable of influencing weather and climate over a particular region. Satellites make a unique contribution to atmospheric aerosol studies by providing global coverage at reasonably good spatial and temporal resolution. Aerosol properties can be derived from space based observations with well-defined uncertainties and is used successfully in a wide array of applications.

Atmospheric aerosol particles has a vital role to play in climate system. These particles effects the climatic system both directly and indirectly. Direct effect is by absorbing or scattering incoming radiations from sun to earth's surface that modulates factors like PBLH(planetary Boundary Layer Height), wind speed, air temperature[1]. Indirect effect include cloud formation due to some aerosol particles which acts as seed for droplets and ice crystals formation in the cloud. Aerosol particles are generated in natural way like seas spray wind blow, pollen emission from trees, forest fires, volcanic ash and by result of anthropogenic activities like vehicular exhausts, industrial chimney exhausts, agricultural activities[2].

## 1.3 Classification of aerosol particles

Atmospheric aerosols are classified based on origin and sources. Considering origin aerosol particles(like dust) that are released into atmosphere are called primary aerosols and those formed in atmosphere through oxidation, condensation, gas to particles conversion are called secondary aerosol particles. These particles can exit in liquid state, solid state or mixed of both liquid and solid. Chemically these particles can be organic, inorganic or mixed of both organic and inorganic. Sources of aerosols can be natural, anthropogenic and biogenic[3][4].

### 1.3.1Natural Sources

Marine Aerosols:

70% of earth's surface cover ocean which produces most potential source of natural aerosols. Sea salt aerosol and sulfate aerosol produced by dimethyl sulfide emissions from oceanic phytoplankton include marine aerosol [5]. Wind on ocean surface produce sea salt aerosol through mechanical disintegration. Here wind naturally induces aerosol production. Breaking waves produced over oceans by these winds produces bubbles at sea surface. Breaking of these bubbles produces droplets that blows into air. On evaporation these droplets produce the sea salt aerosols. Size of these particles range from 0.03μm to 100μm. While travelling through inland regions sea salt concentration decreases rapidly as large particles are not transported very far[6].

Mineral dust:

Mineral dust arises due to the action of wind on soil particles. Their main sources are arid and semi-arid regions. Both mineral and organic materials are included in mineral dust. 20-50% of total mineral dust are contributed by anthropogenic activities too [7]. Particle size ranges from 0.1μm to ~100μm, but size of 10 μm is commonly found. Due to this dust is quickly removed from the atmosphere than others. The average life time of dust aerosols in atmosphere is about 2 weeks, but by this time it travels thousands of kilometers and interact with the cloud system over large distances.

Volcanic Aerosols:

The contribution of volcanic aerosols to atmosphere is limited to space and time since volcanoes are the point sources of natural aerosols. Large amount of aerosols are emitted by volcanic eruptions and it is responsible for direct injection of aerosol into stratosphere .Here the aerosol life time is very higher. Pulverized rocks and minerals, called volcanic ashes are emitted by volcanoes during explosive eruptions. Sulfur dioxide gas forms the dominant layer of aerosol layer which is converted to droplets of sulfuric acid in stratosphere over a week to several months after eruption. These particles stays in atmosphere for about 2 years, once it is formed. Sunlight is reflected by them which reduces the amount of energy approaching the lower atmosphere which leads to cooling of earth's surface. Both direct particle emissions and production of particles from succeeding reaction of emitted gases consist of volcanic effluvia[8].

Desert Dust:

In sub-tropical and tropical region soil dust gives a major contribution to aerosol loading and optical thickness. Dust is composed of minerals, so the particles absorb sunlight and scatter it. Due to absorption of sunlight dust particles warm the residing area of atmosphere. Thus this warm air may hinder the formation of storm clouds. Suppression of storm clouds and consequent rain enhance further dust expansion. Erosion of dust soil is the main contributor to mineral dust aerosols, lifted to high altitudes by convection and is transported over long distance from source region and is mixed with continental aerosols like sulfate, nitrate [9]. Size and shape of dust particle determine its atmospheric residence time. By acting as CCN, mineral aerosol plays a critical role in atmospheric phenomena that effect local and global atmospheric dynamics and photochemical processes, suppressing the precipitation, modifying earth's radiation budget[10].

## 1.3.2 Anthropogenic Sources

Human activities contribute to about 10% of global atmospheric aerosol mass. Major anthropogenic sources of aerosol emission are industrial effluents, exhaust from vehicles, fossil fuel and bio-fuel combustion, biomass burning, etc. Over past two decades burning of agricultural and crop waste has tremendously increased and it is contributing to about 95% of total biomass emission. These aerosols are emitted from densely polluted and industrialized region over the

globe due to various activities and effect greatly on climate and these aerosols are short lived and mostly of fine particle size. The main components of these are sulfate, nitrate and carbonaceous aerosols.

Sulfate

Aqueous phase reaction within cloud droplets by oxidation of sulfur dioxide by gas phase reaction with OH condensation growth of pro-existing particles mainly produces sulfate particles. Fossil fuel burning along with biomass burning contribute to sulfate particles. Condensation, nucleation and coagulation process in atmosphere determines the size distribution of aerosols. Sulfate production leads to CCN since they are hydrophilic in nature and effect the cloud properties[11].

Nitrate

Nitrates are secondary aerosol particles. Their sources are vehicular dust, fertilizers, emission during chemical reaction involving gases, etc. The predecessor are the oxides of nitrogen like NO2, NO, N2O, NO3, N2O4 and volatile nitrogen bearing acids. Ammonium nitrate is most commonly found in atmosphere[5].

Carbonaceous aerosols

It is a complex mixture of elemental carbon and organic carbon and has a great effect on environment due to its impact on visibility and toxicity. Fossil fuel is the main source of carbonaceous aerosols. Incomplete combustion of carbonaceous materials produces black carbon and organic carbon. Black carbon cause a direct effect due to light absorbing characteristics and has a significant irradiative implication in absorption properties. Cloud formation can be inhibited or reduced when solar radiation is absorbed within the cloud [12].This effect is called semi direct effect. Depending upon hydrophobic and hydrophilic nature life time of carbonaceous aerosol in atmosphere are controlled by wet and dry decomposition.

### 1.3.3 Biogenic Sources

Spores, fragments of plants and animals, micro-organisms contribute to biogenic sources. Particulates of biological origin are derived from living organisms which include wide range of biogenic particles, like small viruses, algae, pollen grains, plant debris, etc. Bio aerosols react with air current and move quickly or slowly depending on the environment. Once produced in

atmosphere they can move large distances. Oceans are prominent sources of viable microbes which are ejected into the air from the sea as well as when bubble burst. It is an important sources of natural aerosols [13].

## 1.4 Properties of aerosols

Suspension of fine particles in a gas most approximately air, and is generally taken to include both solid and liquid particles with dimensions ranging from a few nanometers up to around 100 micrometers in diameter are called aerosols. Aerosol science is a study of physics and chemistry of aerosol behavior and this includes techniques of generating particles of nanometer and micrometer dimensions, size classification, measurement, transport, deposition properties chemical properties of aerosols in the atmosphere and industry, etc. Aerosols have important commercial implications like pressure packaged aerosol products, agricultural sprays, atmospheric visibility and high technology materials and knowledge of aerosol properties.

### 1.4.1 Physical properties

#### 1.4.1.1 Aerosol size distribution

Size is one of the key factor for characterizing the behavior of atmospheric aerosols and it is a significant one for different atmospheric process. Size of particle varies from 1nm to few hundred micrometers in diameter. Formation mechanism controls the shape of the particle and it controls their optical properties and hence radiative forcing. Shape of a the particle is spherical when formed by condensation of vapor molecules and the shape is non spherical when formed by breaking larger particles [14]. Particles are classified into fine mode and coarse mode. Fine mode is further classified into nucleation mode, Aitken mode and accumulation mode having particle size of $10^{-3}$-$10^{-2}$, $10^{-2}$-$10^{-1}$and $10^{-1}$-1 μs and are produced by gas to particle conversion, coagulation and heterogeneous condensation. Coarse mode is of particle size 1μs and is produced by bulk to particle conversion respectively. Production, growth and transformation is different for each mode which is depicted in figure below,

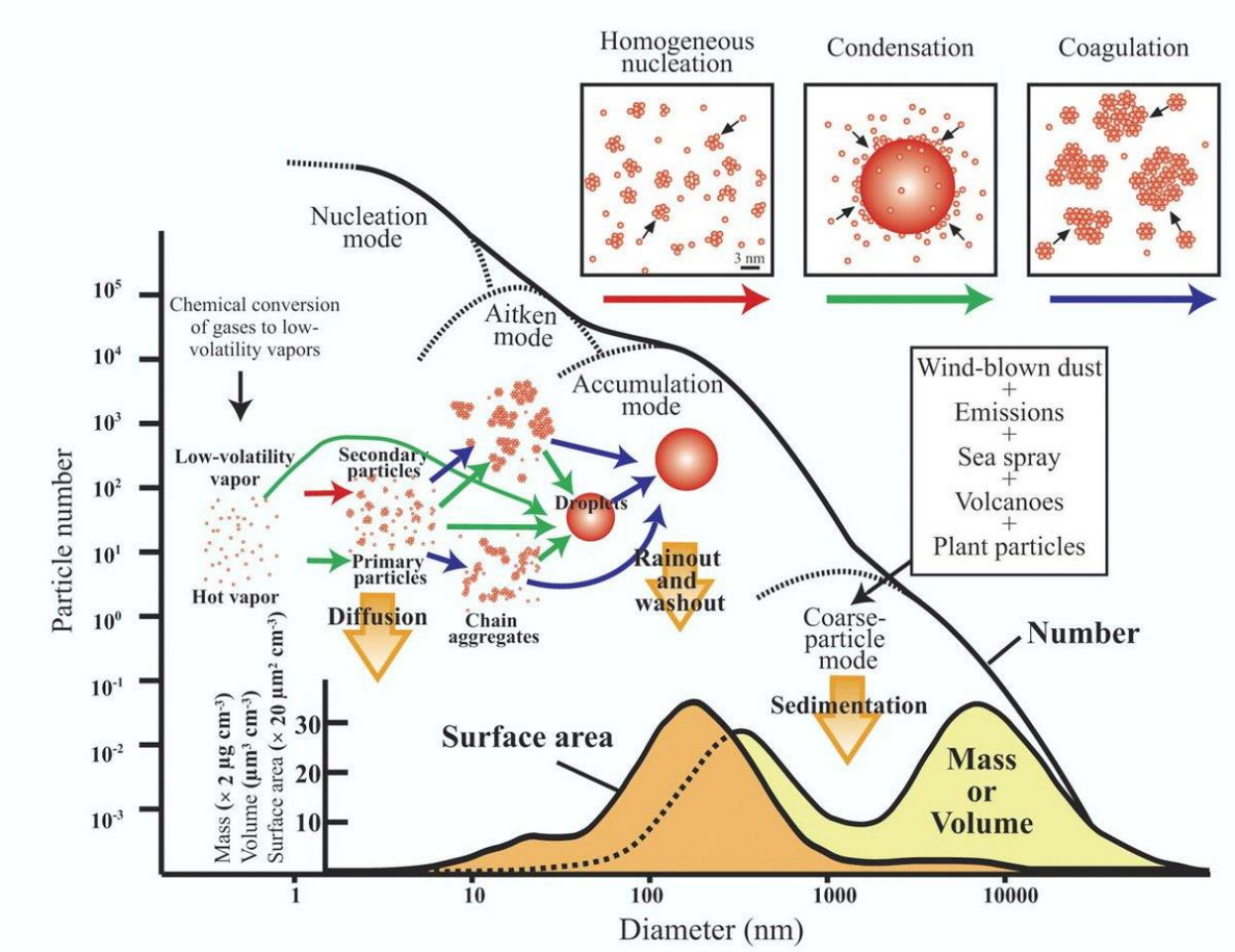


**Figure 1: Aerosol particle size distribution schematic diagram for various parameters in an idealized environmental sample and their formation mechanism**

Contribution of Aitken mode is to number, accumulation mode to surface area and coarse mode to volume size distribution [15].

Mathematical frame work for describing the number size distribution (NSD) of aerosol is that number of concentration of particle (dN) per unit volume of air over an infinitesimal radius range dr centered at r

$$n(r) = \frac{dN}{dr} = \frac{dN}{rd\ln r} \qquad (1.1)$$

n(r) –number density of the particles at a given radius r.

Aerosol NSDs is mathematically expressed using different analytical/empirical relations like power law, modified gamma distribution and log-normal distributions. An empirical inverse power law relationship for r > 0.1 μm is the simplest and most widely used [16],

$$n(r) = C_0 r^{-v} \qquad (1.2)$$

Where,

$C_0$ is a constant

-v is the slope for plot of power law distribution on log scale and particle size r.

This distribution function come across a monotonic decrease in particle number concentration with size. So multi-modal log- normal distribution has evolved to represent size distribution represented by log normal distribution, [17] [18]

$$n(r) = \sum_{i=1}^{n} \frac{Ni}{\sqrt{2\,\pi\sigma i\, ri}}\, e^{\frac{[\ln(r)-\ln(ri)]^2}{2\sigma i^{\,2}}} \qquad (1.3)$$

Along with NSDs surface area is important in nucleation event, volume size distribution is important in interaction of aerosol with radiation and mass distribution important in visibility and health impact investigations.

### 1.4.1.2 Refractive index

The most significant parameter that determines the scattering, absorption, and size distribution is the refractive index. It depends on wavelength and shows a large spatial and temporal variation. Real part of refractive index represents scattering properties and the imaginary part represents absorbing properties. The imaginary part of refractive index is larger for particles originating from combustion since they have high absorption properties.

Refractive index for some aerosol particles at 550 nm like water soluble is having 1.53 at imaginary part and 6.0 x $10^{-3}$ at imaginary part, for dust 1.53 at imaginary part and 8.0 x $10^{-3}$ at imaginary part, for soot 1.75 at real part and 0.44 x $10^{1}$ at imaginary part and for sea salt 1.5 at real part and 1.0 x $10^{-8}$ at imaginary part. [19]

### 1.4.2 Chemical properties

Aerosols get its chemical composition depending on different sources, mixing of different aerosol species, transformation processes like condensation, coagulation and heterogeneous reactions during long distance transport of aerosol particles. It is one of the factor determining the radiative properties of aerosol controlled by chemical, physical characteristics of constituent individual particles. Aerosol mixing can be internal or external. . In external mixing there is no chemical or physical interaction between individual particles. In Internal mixing change in chemical composition of individual particles through chemical reaction or coating is induced. The complex internal structure complicates the estimation of refractive index of internally mixed multi component aerosol particles. It is observed that absorptive properties of aerosols like mineral dust is enhanced on mixing with other aerosols [20]. It is important to characterize the mixing states of aerosols since it cause large uncertainty in accurate evaluation of radiative effects of aerosols in climate forcing [21].

### 1.4.3 Optical properties

As electromagnetic radiation penetrates through aerosol in the atmosphere, it undergoes various changes due to gaseous and particulate matter in the atmosphere. Solar radiation is attenuated by aerosols through scattering and absorption and produces cooling or warming of Earth's surface.

#### 1.4.3.1 Absorption

Process in which radiation loses its energy when passing through a matter is called absorption. Depending on refractive index of matter placed in path of radiation absorbs the energy of incoming radiation, which results in increased internal energy. Energy can be re emitted at another wave length. Black carbon is the main absorbing aerosol particle of light passing through absorber.

#### 1.4.3.2 Scattering

Physical process in which incident electromagnetic radiation is distributed in different directions due to localized refractive index in medium through which it passes. During scattering the scatterer abstracts energy from radiation and re radiate it into the total solid angle ($4\pi$) centered at the particle. No net internal energy change is produced by scattering. Parameters that depends on

scattering are the particle size, particle refractive index, and wave length of incident radiation. Refractive index is maximum for soot particles (Black carbon) and minimum for sea salt particles. [22]. It varies from 1. 3 to 1.6 and $5x10^{-9}$ to $5x10^{-1}$ for real and imaginary parts respectively [23].Scattering is classified into elastic and inelastic scattering based on incident and emitted wave length. Further scattering can be classified into two depending on size of particle in relation with wave length of incident radiation. They are Rayleigh and Mie scattering which are elastic scattering.

#### 1.4.3.2.1 Rayleigh Scattering

When particle size is smaller when compared to wavelength of incident radiation the scattering is elastic and is called Rayleigh scattering. Molecules of atmospheric gases constitute the scattering substrate. The dominant scattering mechanism in upper atmosphere is Rayleigh scattering. Scattering intensity directly varies as the second power of particle volume and as inverse fourth power of wavelength of incident radiation.

#### 1.4.3.2.2 Mie scattering

When size of particle become comparable to wave length of incident radiation scattering become asymmetric and more energy is scattered in forward direction. This type of scattering is explained using Mie scattering. Mie scattering is the chief scattering mechanism for atmospheric aerosols interacting with the visible and near infrared wavelengths. Interaction of electromagnetic radiation with aerosols generates array of dipoles in which the oscillating dipole give rise to secondary waves that combines to produce resulting scattering patterns. The phase of incident wave is not uniform over particle due to large size of aerosol and it gives rise to spatial and temporal difference between secondary waves. Forward scattering increases with increase in the Size of the particle [23].

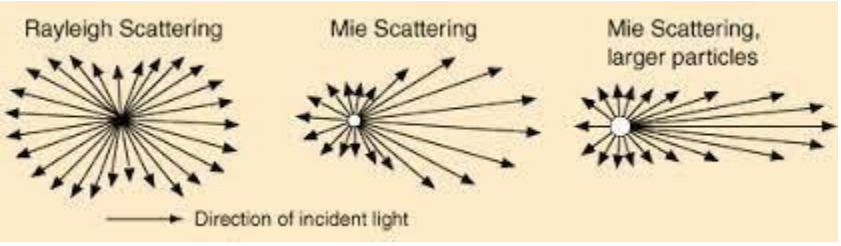


**Figure 2: Sample diagram on Rayleigh scattering and Mie scattering**

## 1.5 Atmospheric Aerosol production Mechanism

Production of aerosols are by two mechanisms :

1.Bulk to particle conversion (BPC , mechanical disintegration process)

2.Gas to particle conversion process (GPC)

In BCP process aerosols are produced by direct mechanisms and are larger in size compared to that formed indirectly in GPC process [24].

### 1.5.1 Bulk to particle conversion (BPC) process

The wind action makes fine solid and sand particles airborne. BPC contribute to considerable component of global aerosol system , that include process like weathering , raising dust, sea spray, etc. Dispersal of surface materials (production of sea salt, sea spray, soil and mineral dust) by action of wind is an important example of BPC. Bursting of air bubbles at water surface produces sea salt aerosols. Bubble bursting is considered as the primary mechanism of producing spray, since a large volume of air can be entrained by breaking waves [25]. This produces a jet of water that rises rapidly from bottom of collapsing bubble cavity to become unstable and breaks up into number of drops. Film drops and jet drops are created by bursting. The film drops are created very early in the bubble break up process from the shattering of liquid film which constitutes the bubble cap but the jet drops are produced much later from the disintegration by the instability of the liquid jet that arises from the bottom of the collapsing bubble cavity [26] .From observations it is found that particles produced are less than 0.1μm in size but the largest particle has size greater than 100 μm. Droplets serves as carriers for the transfer of various chemical substances into the atmosphere [27]. Over forest area several organic particles like pollen, spores, seeds and leaf fragments ore released by plants. BPC produces large particles usually of size greater than 0.1μm.

### 1.5.2 Gas to particle conversion (GPC) process

GPC is an indirect process by which aerosols are formed within the atmosphere through conversion of low volatile gases by nucleation and condensation.

Main nucleation processes are:

(i)Homogeneous homomolecular nucleation

(ii)Homogeneous hetromolecular nucleation

(iii)Heterogeneous heteromolecular nucleation

Homogeneous homomolecular nucleation involves formation of new ultrafine particles from a gas phase consisting of a single gas species. Homogeneous heteromolecular nucleation involves formation of new particles from gas phase consisting of two or more gases. Water vapor is the most common species here. In heterogeneous heteromolecular nucleation condensation of gaseous species on pre-existing nuclei takes place. First two process (nucleation) requires more energy than third one (condensation). Chemical reactions between various gaseous species result in products, which are highly volatile in nature and then undergo nucleation or condensation. These are catalyzed by UV radiation from the Sun and presence of water vapor or OH radical. Since the particles produced by GPC are generally hygroscopic in nature, they can act as cloud condensation nuclei (CCN). The most important process for sulfate and nitrate aerosols is GPC process.

## 1.6 Aerosol removal mechanism

Aerosols are removed from atmosphere by dry and wet deposition processes. They also get removed by collision with rain drops and snowflake and by undertake of aerosols by droplets in cloud. Aerosol can get scavenged by precipitation and the process is called as wet scavenging. Wet scavenging is a major sink for aerosol globally, that removes nearly 80-90% of aerosol mass from the atmosphere. The process where aerosol particles acts as CCN and gets scavenged is called as nucleation scavenging. Properties that depends on aerosol particle life time are chemical composition, size and height at which these particles are present in the atmosphere [28]. In the free troposphere, the lifetime of aerosol is usually of the order of 3 to10 days and they can be transported to long distances in that time. Near the earth surface in the boundary layer, the lifetime of aerosol is less than a week. 1 year is the aerosol lifetime in stratosphere. The small aerosol particles are removed efficiently due to coagulation with the other particles and they have lifetime from minutes to day. The larger particles sediments very fast and have very short lifetime. The accumulation mode particles where coagulation and sedimentation are not efficient have an average lifetime from 3 to 10 days and they can be removed from the atmosphere by the rain.

## 1.7 Aerosol radiative forcing

### 1.7.1 Direct effect

Scattering of solar radiation and absorption of solar and terrestrial radiation causes the direct effect of aerosols on radiative balance.The process depends on composition and phase. Optical depth and the single scattering albedo are the fundamental parameters in computing aerosol influence [29]. The optical depth is the extinction resulting from absorption and scattering of radiation by the aerosols in a column, and albedo is the ratio of the scattering efficiency to the total extinction. The optical depth depends on aerosol amount, size and composition. To investigate radiative effect of aerosol, to retrieve aerosol parameters from satellite remote sensing, and to correct for aerosol effects in remote observations the spectral characteristics of optical depth is enforced. Of greatest interest for small optical depth the climate response to optical depth is nearly linear.

### 1.7.2 Indirect effect

The first indirect effect, the cloud albedo effect or Twomey effect is the microphysically induced effect on cloud droplet number concentration and hence cloud droplet size, with the cloud water content held fixed [30]. Second indirect effect or Albrecht effect is the micro physically induced effect on liquid water content, cloud height, and life time of clouds. A complete feedback cycle exists in nature in which the changes in the solar radiation caused by the aerosols alter cloud formation, precipitation atmospheric water cycle as well as aerosol chemistry and transport properties.

### 1.7.3 Semi direct effect

Process in which absorption of radiation by the aerosol results in greater atmospheric temperatures causing evaporation and prevention of cloud formation is the semi direct effect.

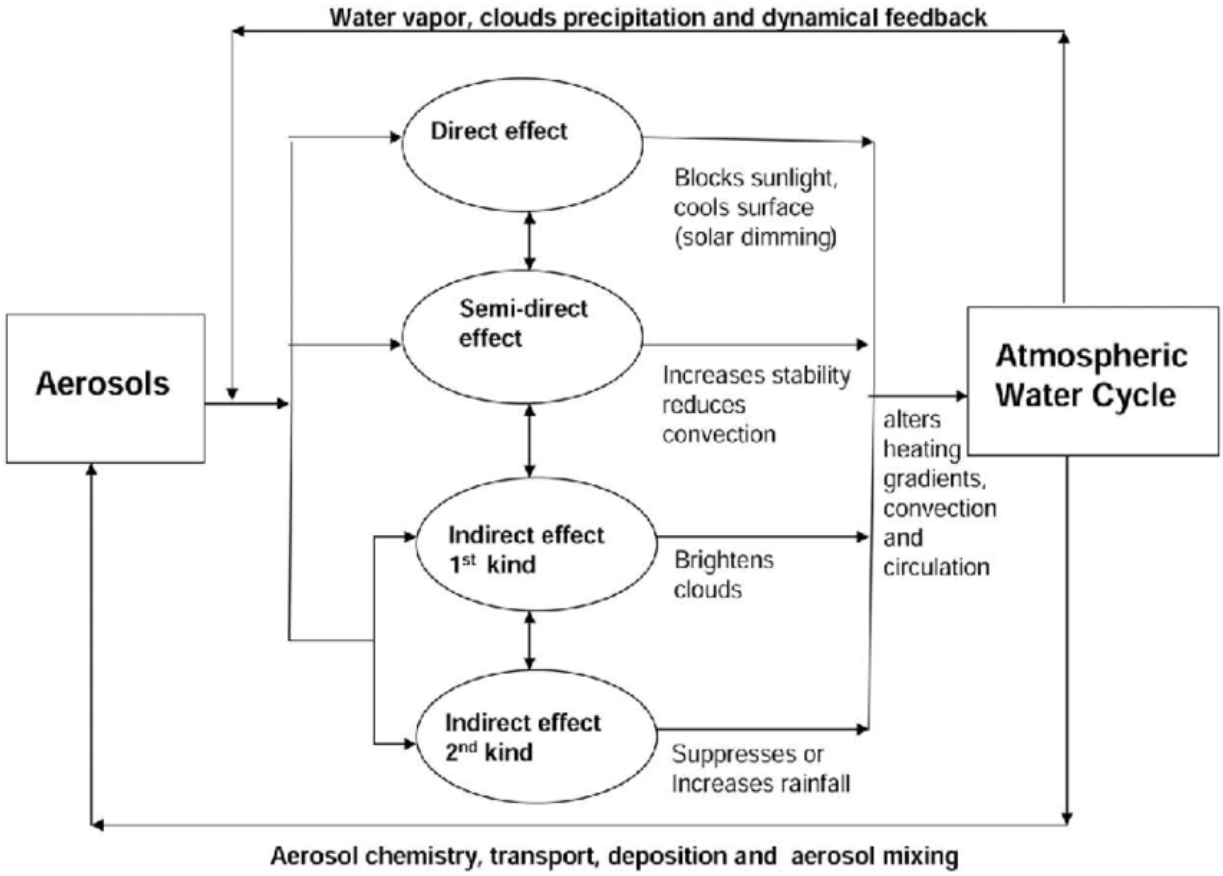


**Figure 3: Schematic of interaction pathways for aerosol forcing (direct, semi-direct and indirect effects) and their response to the Earth atmospheric system**

## 1.8 Impacts of aerosol on climate

By changes in the meteorological parameters and its distribution over the region the direct, indirect and semi direct effects of aerosols leads to significant climatic responses. Climate feedback of aerosol effect is shown by numerous studies which are due to (i) precipitation pattern change due to the direct effect of BC aerosols over tropical oceans , (ii) reduction in evaporation and slow down of hydrological cycle, (iii)change in circulation pattern and reduction in wind speed, precipitation pattern , (v) effect on land surface and sea surface temperature(SST) [Chung et al., 2002], (vi) effect on monsoon [30] [31]. In south Asian regions the influence of aerosol-cloud-radiation interaction on water cycle is highly complicated and is important since in this region living habit of people is directly related to the seasonality of rainfall. The main two doctrines of

aerosol induced climate change assume importance over South Asia are due to reduction in evaporations and slow down of hydrological cycle and change in the circulation pattern and monsoon.

## 1.9 Residence time of atmospheric aerosols

The ratio of number concentration to the production or loss rate is called residence rate. The number density of aerosol particles reaches an equilibrium when the rates of production and loss of aerosol are balanced. Residence time of aerosols depends on size, chemistry and altitude in atmosphere. Aerosols between 0.1 - 1.0μm are important in aerosol studies because they (the accumulation mode) remain in the atmosphere longer. The coarser particles ($r > 1\mu m$ radius) have less residence time due to their higher sedimentation rates. The residence time varies from a few days in the lower troposphere to few years in the stratosphere, due to lack of effective removal mechanisms. The residence time is a function of size, altitude and atmospheric conditions[24].

## 1.10 Aerosol transport mechanism

Aerosols get transported from their source region to distant places by current winds. Synoptic scale air mass types influence the aerosol properties through transport[80] .Change in optical characteristics at far off locations is caused by transfer of aerosols from distinct source regions by air trajectories as pathways [32]. Large scale transport of dust occurs from Africa to south Indian Ocean, from West Asia to Arabian Sea, from China across the Pacific, from Australia over to Indian Ocean.

## 1.11 Aerosol optical depth

The quantitative measure of the extinction of solar radiation by aerosols between the point of observation and the top of the atmosphere is called Aerosol Optical Depth (AOD). It is an important parameter in estimation of direct radiative forcing and is a dimensionless quantity. Basically AOD is indicative of amount of aerosols present in a vertical column of AOD of unit

cross section of the atmosphere. AOD is received from observations of atmospheric spectral transmission since it is not directly observable.

Extinction coefficient is defined as the fraction of radiant flux lost through scattering and absorption from a collimated beam per unit thickness when it passes unit distance in the atmosphere and is given in units of reciprocal length. For a parallel monochromatic flux, Lo (extraterrestrial) to L at a distance 'x' is described by the well-known BEER-LAMBERT LAW. This means that radiation gets attenuated exponentially as it traverses the medium.

$$L = Lo \exp(-\beta x) \qquad (1.4)$$

Aerosol extinction coefficient integrated along a vertical column of atmosphere with unit cross section area is aerosol optical depth (AOD). Integrating the above equation over a distance 'S', the radiance left in the original beam can be obtained as;

$$L = Lo \exp\left( - \int_0^S \beta(z) dz \right) \qquad (1.5)$$

Where, Lo is the radiance at distance s=0.

In the atmosphere, the extinction suffered by the incident radiation as it passes through the entire vertical column of aerosols can thus be expressed as

$$L = Lo \exp(-\tau) \qquad (1.6)$$

Where, $\tau = \left( - \int_0^S \beta(z) dz \right)$ is called Aerosol Optical Depth (AOD).

AOD describes the extent to which aerosols impede the direct transmission of sunlight of certain wavelength through the atmosphere. The greater the optical depth, the lesser is the light passing through the material.

## 1.12 Satellite measurements

Satellite based observations of aerosols remains the most promising tool for attaining regional and global distribution of aerosols. The spectral radiance measured by aerosol sensing satellite at the top of the atmosphere can be used to derive the aerosol optical depth information. The radiance measured in the visible and near infrared channels can be used for this purpose. Generally this

technique is used for obtaining the information of aerosols over dark objects such as ocean where surface reflectance is very small, spatially nearly uniform and can be modeled mathematically. But over the land where surface reflectance is not negligible and has large pixel to pixel variability, the problem becomes complicated. However recent satellite sensors employ several advanced techniques to estimate aerosol properties over land. They include Advanced Very High Resolution Radiometer (AVHRR), Global Imager (GLI), Medium Resolution Imaging Spectrometer (MERIS), Moderate Resolution Imaging Spectrometer (MODIS) etc. Validations of satellite measurements are highly demanding because of the uncertainties in the retrieval algorithms [33]. Inter comparison and validation of satellite measurements with accurate in-situ measurements were carried out extensively during the last decade and uncertainty in AOD measurements at 550 nm using MODIS were reduced significantly over the ocean [Remer et al., 2009]. Generally, satellite measurements of AOD over the ocean during the clear sky arc reliable, while its spectral dependences are deviating from the in-situ observations, which demands further scientific attention.

## 1.13 Aerosol characterization over Indian region

Presence and long range transport of light absorbing aerosols into free atmosphere was disclosed by Lidar measurements conducted over the Indian Ocean and few surrounding locations during Indian Ocean Experiment. atmosphere [34]. Using lidar research aircraft and high altitude balloons considerable campaigns were conducted over Indian region to develop understanding of vertical distribution of aerosols and their spatiotemporal variations. These campaigns provide deeper insight into location specific aerosol properties. Seasonally varying presence of high altitude aerosol layers leading to a meridional gradient in vertical distribution of aerosols was observed in Indian mainland using apace borne lidar observations. The major source of distinct aerosol types ore observed in Indian region consisting of highly polluted Indo Gangetic Plain over northern side and Thar Desert over western side. The aerosols from these contrasting source regions are advected across the IGP and the north-eastern region to the Bay of Bengal (BoB) and are often observed as elevated layers [35]. In northern part of India irrespective of season west to east transport is consistent even there is a reversal in synoptic wind direction during post monsoon and winter in

southern part. Comparing to north-east part north-western part of India has altitudes at which elevated layers are higher [36].

## 1.14 Aerosol characterization over Arabian Sea and Bay of Bengal

By modulating monsoon circulation and precipitation AS and BoB plays a critical role in Indian climate. Monsoon circulations are driven by large heating gradient from land to ocean. Variation of convection over BoB links the distribution of summer monsoon rainfall over Indian region. Change in climate over the region due to natural or anthropogenic sources will have large impact on people living in the country.

Oceanic regions surrounding the Indian peninsula experience different air masses in association with the change in synoptic monsoon circulations (Northeast and Southwest). Modulation of aerosol characteristics and consequent radiative forcing by outflow of pollutants like aerosols to adjoining ocean regions due to wind directed from continental regions during northeast monsoon period. By previous studies over region surrounding Indian peninsula aerosol properties are highly heterogeneous in spatial and temporal domains as other oceanic regions imparted by polluted continents. BoB is a small oceanic region confined between 80 to $100^0$E in longitude and 5 to 22°N in latitude, surrounding three sides by densely populated continental landmass having diverse geographical features and industrial activities. The Asian monsoon and precipitation pattern over India is controlled by BoB. Indo Gangetic plains are highly polluted by pollutants, aided by prevailing winds natural channels created by orography of high Himalaya in north and south consist of Vindhya satpura ranges that result in accumulation of anthropogenic and natural aerosols. East Asian regions also contribute aerosols and gases into BoB by advection.

Due to particular geographical location of AS ranging 4°N to 20°N and 50°E to 78°E has unique weather pattern attribution to Indian monsoon and associated winds that reverse direction seasonally, followed by contrasting precipitate. Due to close proximity and seasonally changing synoptic air mass associated with monsoon it is influenced by anthropogenic activities along densely populated west coast of India. Aerosol properties of AS is modified by transport of aerosols from west Asia, Africa and south East Asia. Climate simulations over the oceanic regions around India revealed several regional impacts due to anthropogenic aerosols on precipitation

pattern. Chung and Zhang, [2004] have reported that the absorbing aerosols over the AS and NIO would change the precipitation pattern in association with vertical distribution of aerosols. Recently, Lau et al., [2006] have reported a probable enhancement in the precipitation over the northern India and head BoB due to the elevated aerosol heating over the Tibetan Plateau (EHP hypothesis). Wang, [2007] also has reported that the direct radiative forcing due to BC aerosols would significantly alter the precipitation pattern.

## 1.15 Objectives of present study

Characterisation and aerosol studies has a grater importance over Indian region, AS and BoB owing to their effect on energy budget of the earth atmosphere system, thermal structure of atmosphere, regional circulation and hydrological cycle. Aerosols over India strongly exhibit seasonal and inter annual variability mainly driven by the regional monsoon system, seasonally changing air mass patterns and spatio-temporal distribution of air masses. The most populated as well as polluted region is the Indo-Gangetic Basin of northern India. Addional to this deserts over middle east and Arabia get dust aerosols load over the region. Arabian sea surronds the Penisular Indiain the west, east by Bay of Bengal and south by Indian ocean. The seas surrounding the peninsular Indian region have significant impact in the control of atmospheric characteristics and aerosol composition.The present study make a detailed investigation into the aerosol distribution over the Indian subcontinent, Arabian sea and Bay of Bengal using 10 years of aerosol data.

## 1.16 LITERATURE REVIEW

**I Ocean et.al** ., derived AOD from satellite data and other methods to study regional distribution and long range transport of aerosol over oceanic region and around Indian subcontinent during Asian summer and monsoon seasons. Aerosol properties over oceanic areas are different during summer, winter and monsoon due to contrasting air mass types. Oceanic area around Indian subcontinent in northern hemisphere is Arabian Sea and Bay of Bengal. The transport of aerosol takes place from continental area in northern hemisphere to ocean region during various seasons on India. Over the year spatial gradient in AOD is larger over Arabian Sea particularly in meridian direction. Forest fires in Indian subcontinent, long aerosol plume, contribution of natural and anthropogenic aerosol loading over each season, long term changes in aerosol loading, interaction between aerosol and clouds are all investigated to study spatial distribution of aerosol over the region. Over Arabian Sea and Bay of Bengal, particularly near the southeast Arabian Sea, coastal Arabia, and northwest Bay of Bengal, the aerosol loading and its latitude variation during February-April period is larger than those during the November-January period. The AOD values as well as its latitude gradient over the Arabian Sea are maximum during the southwest summer monsoon season. This is largely governed by the transport of mineral dust from the Asian desert regions. The contribution of the sea salt generated by high surface wind speed is also significant in this season. The AOD over the southern hemisphere Indian Ocean is less than ~0.15 during most of the periods and inter annual variability is negligible. Inter annual variability in AOD is large during February-April period over the Arabian Sea and Bay of Bengal. Changes in the lower tropospheric circulation play a major role in governing this inter annual variability. [37]

**Q. Jin et.al,** observed that during summer a high aerosol loading was seen over Arabian Sea. This was detected using satellite observations. This has a great impact on Indian monsoon due to absorption of dust aerosols. The Arabian Sea and Arabian-peninsula have a summer peak and among that dust aerosols dominates. Aerosol over Arabian Sea are largely transported from south and East Peninsula by anti-cyclonic winds in the middle troposphere and from Iran-Afghanistan-Pakistan by anti-cyclonic winds in middle troposphere. This extremely high aerosol loading over Arabian sea exist during 2000-2011 but disappeared during 2000-2016 indicating strong inter-decadal variability of dust activities. This study revealed high summer time AOD over Arabian

Sea due to pathways linking dust emissions in Middle East and identified the atmospheric conditions favorable for dust emissions and transport. Analysis based on satellite retrieved AOD and meteorological reanalysis data identified the meteorological conditions favorable for high aerosol loading over Arabian Sea. Low pressure and cyclonic circulations centered over Arabian Sea and Middle East benefits the transport of dust aerosols from Middle East and Africa to Arabian Sea resulting in positively coupled aerosol loading over Arabian Sea. Study also showed an extreme high and low aerosol loading over Arabian sea during 2008 June and 2009 June, which is associated with low pressure and pressure system both over Arabian sea and Middle east consistent with climatological composite analysis.[38]

**S.Shalin et.al** ., observed that in account of Indian monsoon and associated winds that reverse direction seasonally Arabian Sea has a unique weather pattern. The aerosol data collected by satellite measurements including MODIS data is used evolve comprehensive characterization of spatial, chemical and radiative properties of aerosol over AS. There is an increase in AOD found at latitude between equator. The AOD over summer season was greater than winter season. The latitudinal gradient in AOD in Southern AS is larger during summer compared to Winter season.[39]

**P.Banerjee.S.K et.al** ., found that dust aerosol loading over Arabian Sea on a short time affects the intensity of Indian summer monsoon rainfall over central India. Satellite measurements are used to modulate both rainfall over India and aerosol loading over Arabian Sea. Long term satellite based aerosol and gridded rainfall data sets are used to get correlation on AS aerosol and central India rainfall. The high aerosol loading are associated with increased winds over AS that shift it eastward towards the Indian mainland and enhancing rainfall over central India and other regions of India. Increased precipitation over central India is due to cyclonic circulation over Bay of Bengal. The northwesterly wind transporting the dust aerosols to Arabian Sea are part of regional circulation. Circulation changes induced by regional features enhance over all dust loading over AS, causing changes to rainfall in central India. So even at drought condition, rainfall increases over central India during high aerosol loading conditions. Hence AS dust effect is important. [40]

**S.K. Satheesh et.al** ., investigated the significant impact of aerosol over climate over decades. The AOD measurements over Bay of Bengal is done using satellite measurements like MODIS and it is compared with those made over Indian ocean and Arabian sea. There is a decrease in AOD with distance from coast with an experimental scale distance of approximately 1000 km for visible wavelengths and approximately 1600km for near infrared wavelengths. Over Arabian Sea and Bay of Bengal a significant dominance of small particle concentration near coast is observed. Mean AOD is greater for BoB compared to AS at shorter wave lengths. Over equatorial Indian Ocean region, aerosol optical depths are much lower comparing to AS and BoB and it shows lower wavelength dependence. Dominance of smaller aerosol particle is higher over BoB compared to AS. AOD on AS was mostly influenced by air masses from countries lying north west of India, BoB by air masses from east and west coast of India and island station in Arabian sea. The atmosphere over BoB was found to be more turbid than that over Arabian Sea. Comparison of near coastal value of AOD with coastal values shows a large difference in near UV and visible wave lengths compared to IR wavelengths, which shows a relative dominance of small particles near coast. Trajectory analysis showed BoB is influenced by eastern coast of India and Arabian Sea by countries lying north-west of India. [41]

**T.S Sarin et.al .,** studied the impact of Covid19 circumstances on aerosol distribution. WHO in March 2020 declared the Covid19 pandemic which spreads over the countries globally which changed the socio-economic situation. Restriction and Covid19 lockdown were implemented by various countries that affected the people in every aspects of life. This totally changed the economic and atmospheric balances. Studies have documented multiple impacts of lockdowns and associated decrease in anthropogenic emissions in improving air quality. Atmospheric aerosols directly affects surface radiation budget by absorbing and scattering incoming solar radiation and modify cloud micro physical properties. The Indian Ocean rim countries significant economic growth in recent times with increased emission and atmospheric aerosol loading. Continental outflow, especially from high aerosol loaded Indo-Gangetic plain dominate aerosol loading over BoB region during pre-monsoon and winter season. So BoB is highly effected by fine anthropogenic particulates. This high aerosol loading period is coupled with lock down period of pandemic effecting BoB. Covid19 lockdown declined activities across large sections of society by

confining population to their homes resulting in significant decline in atmospheric anthropogenic aerosol loading. Studies using MODIS indicated a 30 % decrease in AOD over BoB. Region closer to coast and North central part of BoB were mostly affected by changes in aerosol loading [42].

**P Kishchae et.al.,** done studies on AOD over Bay of Bengal for 10 years over 2000 to 2009 using MODIS showed a strong increasing AOD over north west Bay of Bengal in the absence of AOD trends over east of Indian region. This was not expected since anthropogenic sources for pollution were located over Indian sub-continent and the prevailing wind carries these aerosols from Indian sub-continent to north west BoB. Winds over Indian subcontinent were stronger than winds over North West BoB on October, which resulted in increased trend in accumulation and convergence of AOD over the area. But in November there is no increasing trend of AOD over northwest BoB or Indian region. This is due to lack of wind convergence in the region. At December the domestic heating by growing population resulted in increasing trend of AOD over land and sea. [43]

**M.Mehta et. al.,** studied on a pre-monsoonal AOD over Indian region for a long term of 17 years from 2005 to 2021 using satellite data from MODIS and OMI. Based on dominance of natural, anthropogenic and mixed of both types of aerosols, three zones are selected. Investigation on AOD gave seasonal average of AOD for entire Indian land mass. An increasing trend in AOD distribution was found for this region for past 8 years back from 2021. Trend from MODIS for Indian region was 0.011 $year^{-1}$ and 0.041 $year^{-1}$ for period 2005-2012 and 2013-2021. Indo-Gangetic Plains and south India had an increasing trend during 2005-2021. For desert zone, AOD trend become negative for 2005-2012 and become positive in 2013-2021. IGP has increased atmospheric pollution due to rapid urbanization and has a significant amount of anthropogenic factors along with combined natural aerosol sources. Mineral dust from Thar Desert frequently transported and loaded at pre monsoon over the region. In desert dust loaded region natural aerosols are dominant. Transport of mineral dust from Thar Desert and Middle East to northern and north-western India by south-westerly summer winds during pre-monsoon. Over southern India pollution is smaller compared to other region of India, but rapid urbanization caused anthropogenic sources over the region. Before the year 2019, AOD had a regular increase followed by a dip in 2019 and an increase in 2021. The increasing trend in anthropogenic load along with

increasing population demand set a worry over Indian land mass. But during lockdown period aerosol burden set to a light on decreased emission which provided a solution for in coming years to control increased level of aerosols. [44]

**C.Sarangi et.al.,** noticed that during winter season Indian sun continent is greatly vulnerable to air pollution, especially during winter. Data of 15 years were taken from 2003 to 2017 using satellite over India and adjoining seas to estimate trend in these days during dry winter season. The number of hazy days are increasing at a rate of 2.6 days per year over central India which is higher than that at Indo- Gangetic plain. An increasing trend in absorbing aerosols are visible in recent year up to 2017. So estimated atmospheric warming trend over central India are two- fold higher than that over Indo-Gangetic plain. This anomalous increment in hazy days over central India is associated with relatively high increment in biomass burning over region. During dry winter season trend in aerosol loading over Arabian Sea, located downwind to central India is higher than that over Bay of Bengal. The results provide attention to rapid deteriorating air quality over Central India and gives the significance of increasing biomass burning under recent climate change. It was found that aerosol exerted seven times more atmospheric warming over AS in recent years than BoB at winter which contradicts the previous studies. This is due to mean changes in wind speeds and lower tropospheric stability over Central India and Arabian Sea. [45]

**J. Zhang et.al .,** analyzed regional and global aerosol trends over ocean is studied for 10 years from 2000 to 2009 using Terra and Aqua MODIS. Indian region, Bay of Bengal and Arabian Sea showed an increasing trend of 0.07, 0.06 and 0.06 per decade for MODIS over the period. The trend reflected increase in optical intensity of aerosol events in the region due to anthropogenic aerosol over east coast China and Bay of Bengal and stronger influence from dust events over Arabian Sea. MODIS showed a large increase over Indian region, AS and BoB for corresponding 10 years creating worse scenario to already existing heavily polluted air and has a strong impact on local regional climate. Analysis reveals that increasing trends are caused mostly by increased intensity of anthropogenic aerosol events for Bay of Bengal region, but Arabian Sea regions experience stronger influence from dust events [46].

**P Sivaprasad et.al .,** observed that on comparing to North India South India has entirely different Climate. So aerosol loading also show comparable difference. Climatic features of region is investigated by studying transport of aerosol over the region. Satellite measurements available in two stations in west coast and equatorial Indian region is used for analysis. Aerosol concentration is less in South India compared to that in North India with 0.5 in north India and 0.4 in South India. Studies also revealed the seasonal variability in aerosol loading with high aerosol loading in summer and less during winter. Sea surrounding South India have significant have significant impact on aerosol loading as they are sources of sea-salt, sulfates, etc. The coastal region of south India experiences high aerosol loading during June to August period. A mixed aerosol content including aerosols of marine and continental origin is leading to different climatic pattern of the region. In North India anthropogenic and natural aerosols are dominant in atmosphere. [47]

# CHAPTER 2

# METHODOLOGY

## 2.1 Introduction

Detailed information on aerosol over large geographical region on routine basis is required to study time evolution of distribution of aerosols. Satellite measurements of atmospheric gases and aerosols are used due to its significance in understanding climate change. Uncertainty in understanding radiative effects of aerosols results due to lack of accurate and repetitive measurements at global scales .Magnitude of uncertainty in earths radiative forcing can also be measured by studying about atmospheric aerosols. Atmospheric aerosol concentration is dynamically and spatially varying and so it is important to monitor it regionally and globally. Aerosols are distributed between continents. Aerosol particles are derived from relatively local sources and their distribution and compositions are highly variable worldwide. So the advantage of satellite over its ability to measure global distributions of atmospheric constituents are used. Application of satellite remote sensing was started about 30 years ago for determination of aerosol properties. A unique sensor with capabilities to attain nearly a full global coverage every day both over land and ocean is the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Earth observing satellite (EOS) Terra and Aqua. No other orbiting sensors at present can beat the specification of MODIS for aerosol measurement.

Present study uses Aqua MODIS data for period January 2011 to December 2020 to analyze AOD at 0.55 micron for land and ocean. Matlab software is used to produce spatial maps of AOD. Relative changes per year for AOD on seasonal and annual basis are calculated.

## 2.2 MODIS (Moderate Resolution Imaging spectroradiometer)

MODIS sensor was launched by NASA on basis of Terra satellite in1999 and Aqua satellite in 2002. It is first kind which characterize the spatial variation of aerosol properties over ocean and

land on daily basis. At an inclination of 98.2° and field of view 155°from an altitude of 705 km, sensor's swath is about 2330 km. Hence it is possible to cover entire globe once in a day. Once in every 16 days revisit over a particular region occurs. To perform radiometric, spatial and spectral calibrations onboard calibrations are used. Operation of MODIS are at 36 spectral channels ranging from 0.42 to 14.24μm, of which seven are used for aerosol retrieval. 250-500m is the primary resolutions of these seven bands. For MODIS sensor the spectral stability is better than 0.002 μm

Central wavelengths of 0.66, 0.86, 0.47, 0.55, 1.2, 1.6 and 2.1 μm are identified in agreement with common references of aerosol literature. Spectral AOD at six bands corresponding to 0.55, 0.66, 0.86, 1.2, 1.6, 2.1 μm over ocean and at two bands corresponding to 0.47 and 0.66 μm over land are the principal aerosol parameter retrieved by MODIS.

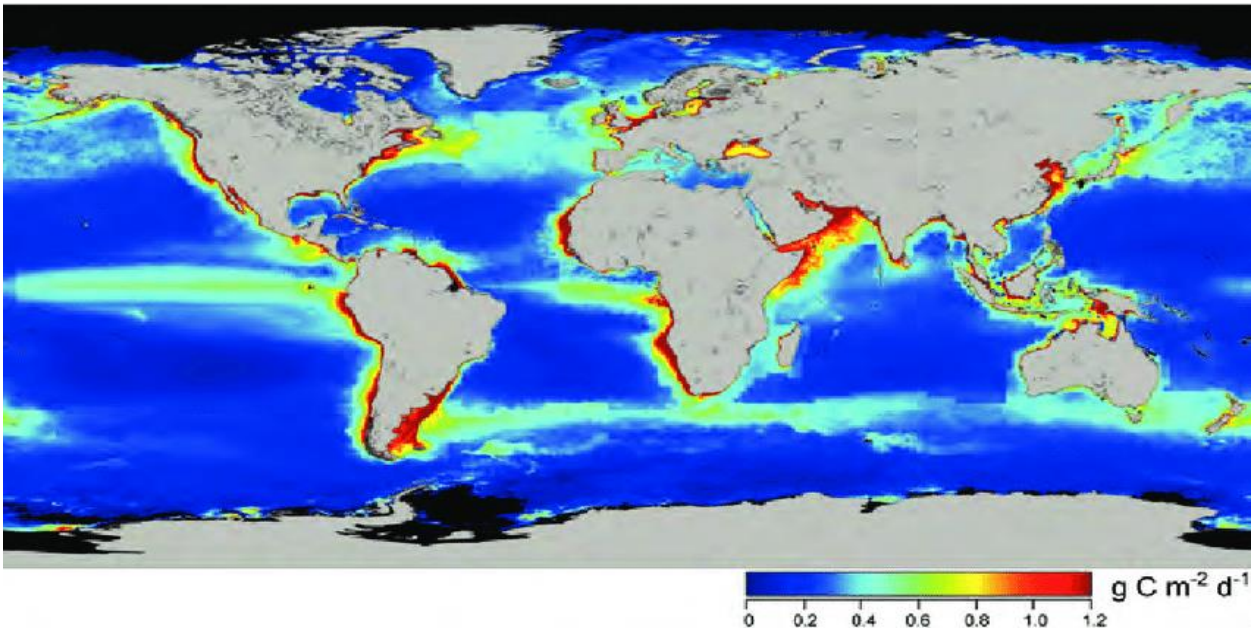


**Figure 4: Global primary production computed using MODIS-Aqua data from July 2002 to June 2005 from NASA**

Figure 4 shows primary production computed using MODIS-Aqua data from July 2002 to June 2005 with a wavelength, depth-resolved, primary production model down to the 0.1% light-level.

### 2.2.1 Cloud screening in MODIS

By making use of a combination of 14 wavelength bands involving 40 different tests Ackerman in 1998 and Gao in 2002 developed an excellent cloud masking scheme for MODIS. Elimination of all types of clouds including thick high clouds, thin clouds, upper tropospheric thin clouds and cirrus were confirmed by these several tests. But thick aerosol features could be misidentified as clouds since these tests are clear sky conservative. Martins in 2002 implemented additionally spatial variability tests that further produced adequate difference between aerosols and clouds. Due to the high spectral resolution and specialized cloud masking scheme, MODIS retrieves aerosol properties near the clouds better than many other sensors.

### 2.2.2 MODIS aerosol algorithms

The MODIS aerosol algorithm is actually two entirely independent algorithms. It derives aerosol over land and aerosol over ocean. Both these land and ocean aerosol algorithm rely on calibrated, geolocated reflectance provided by the MODIS characterization Support Team (MCST), identified as products MOD02 and MOD03 for Terra MODIS products and MYD02 and MYD03 for aqua MODIS products. The uncertainties in measured reflectance in the visible and mid IR bands are less than 2%. These reflectance along with MODIS cloud mask product identified as MOD/MYD35 and meteorological data from the National Centers for Environmental Prediction provide the input for the algorithms. The MOD/MYD35 cloud mask product also supplies the earth's surface information that identifies whether a pixel is a land pixel or water pixel.

MODIS data are organized by "collections". A collection consists of data products that were generated similar, but not necessarily by the same, versions of the algorithm. An individual MODIS image scene, called a granule, consist of 5m swath of data. The MODIS level 1b granule consists of calibrated radiances and reflectance. This reflectance is corrected for water vapour, ozone and carbon dioxide before the algorithm proceeds. The first step in deriving Aerosol products over land is to organize the measured reflectance of the three MODIS channels used in the procedure .All three channels are organized in to normal 10km boxes corresponding to 20 by 20 or 400pixels for each box. This organization requires the 250m resolution 0.66μm channel to be degraded to 500m in order to match the resolution of the other two channels. The land algorithm

will retrieve aerosol for coastal boxes that contain one or more pixels identified as ocean, but will decrease the quality of the land retrieval.

Ocean retrieval requires all 400 pixels in the box to be identified as water. The standard MODIS could mask (MOD/MYD35) provide all masking information. As in land algorithm, after the water vapour ,ozone and carbon dioxide, are applied; the first step in the ocean algorithm organize the reflectance from the six wavelengths which can be used in procedure in to normal 10km boxes of 20 by 20 pixels at 500m resolution. This requires degrading the resolution of the 250m channels and this helps to minimize problems introduced by shallow water near the costal. If any land is encountered, the entire box is left for coastal land retrievals. The estimated surface reflectance are compared with the Look-up table (LUT) to retrieve the values for the aerosol optical thickness at 0.47 and 0.66µm. In the land algorithm, the two the wavelengths are derived independently. LUT further adopts a bimodal lognormal distribution function for aerosol distributions with 9 basic models. The Reflectance is computed for different aerosols models and for different viewing geometries. The expected error for MODIS- derived AOD over the ocean is ± (0.03+0.05 AOD) and that over the land is ± (0.05+.0.15AOD).

### 2.2.2 Calibration of MODIS

For performing radiometric, spectral and spatial calibration of instrument onboard MODIS sensor has an efficient in-built system. System includes

1. Black Body (BB): Primary source for thermal bands calibration located between 3.5 µm and 14.4µm.

2. Solar Diffuser (SD): source for calibration of short wave IR, near IR and visible bands.

3. Solar Diffuser Stability Monitor (SDSM): Changes in the reflectance of SD in reference to sun is tracked by this device, and the changes in calibration source will not be incorrectly attributed to the instrument error.

4. Spectro-Radiomertic Calibration Assembly (SRCA): Provides in flight spectral, radiometric and spatial calibration.[48]

### 2.2.3 Levels of MODIS products

The aerosol products retrieved by processing Level IB data at 10 km x l0 km resolution (at nadir) are called the Level-2 products. Global composites of Level 2 granule products for a day, geometrically corrected and gridded to 1° x 1° resolution for an earth based coordinate system are termed Level-3 daily products. During the re-gridding, the data quality is ascertained by appropriately weighting the Level 2 data based on its quality flags. It should be noted that each grid square in a Level 3 product can contain multiple orbits and hence are not synchronous in time, but is a better representation of daily average. From Level 2, weekly and monthly Level 3 global products are also generated.[49]

### 2.2.4 MODIS data used for present study

Day-to-day variations in the spatial distribution of AOD over large domain comprising Indian subcontinent and adjoining oceans Bay of Bengal and Arabian Sea is involved in the study. Monthly data for 10 years are collected. Monthly average for these years are plotted. Level 3 daily data at $1^o$ x $1^o$ grid resolution for Aqua satellites are used optimally.

## 2.3 Meteorological parameters influencing the aerosol properties

Highly heterogeneous in spatial distribution are the atmospheric aerosols and they show significant temporal variation. Factors responsible for spatio-temporal variability are wide range of aerosol generation mechanism, their varying strengths and long range transport through atmospheric circulation. Variation in spatial distribution of AOD through atmospheric circulation are due to features of wind like wind speed or direction, wind convergence, vorticity and up/down drafts. Prevailing atmospheric relative humidity also play important role in determining AOD at a particular location at a given time.

## 2.4 MATLAB

It is a programming platform designed to analyze and design systems and products that transform the world. It contains desktop environment tuned for iterative analysis and design processes with a programming language that expresses matrix and array mathematics directly. The data used to study aerosol trends are obtained from Aqua MODIS data from Giovanni site of NASA.

# CHAPTER 3

# RESULT AND DISCUSSION

## STUDY ON SPATIAL DISTRIBUTION TRENDS OF AEROSOLS OVER THE BAY OF BENGAL, ARABIAN SEA AND INDIAN REGION

Atmospheric aerosols significantly modulate the radiation budget, cloud properties, atmospheric thermodynamics and overall climate of Earth-atmosphere system. The rapid economic growth and budding energy demands, drastically increase the aerosol emission and their possible local/regional and global climate impacts, especially over the South Asia, which make essential to characterize the aerosols over both land and ocean.

## 3.1 Spatial distribution of aerosol over Arabian Sea and Bay of Bengal

Intrusion of aerosols from the adjacent landmass through atmospheric circulation strongly influence ocean environment around Indian peninsula. Large scale change in the synoptic circulation from winter (dry) to summer (monsoon) associated with the changes in meteorology characteristic to this region show corresponding variations in the physical properties and chemical composition of aerosols.

Collection of MODIS data on spectral AOD from Aqua at a particular location are combined to represent monthly mean aerosol properties at Arabian Sea and Bay of Bengal region.

Data analysis is done by observing the plot of aerosol distribution of monthly mean data over 10 years from 2011 to 2020. AOD data at 1°×1° resolution from Aqua satellites were used to generate monthly AOD plots.

### 3.1.1 ARABIAN SEA

#### 3.1.1.2 Seasonal variation of AOD over Arabian Sea

The plot given below shows variation of aerosol distribution over each month averaged over 10 years**.**

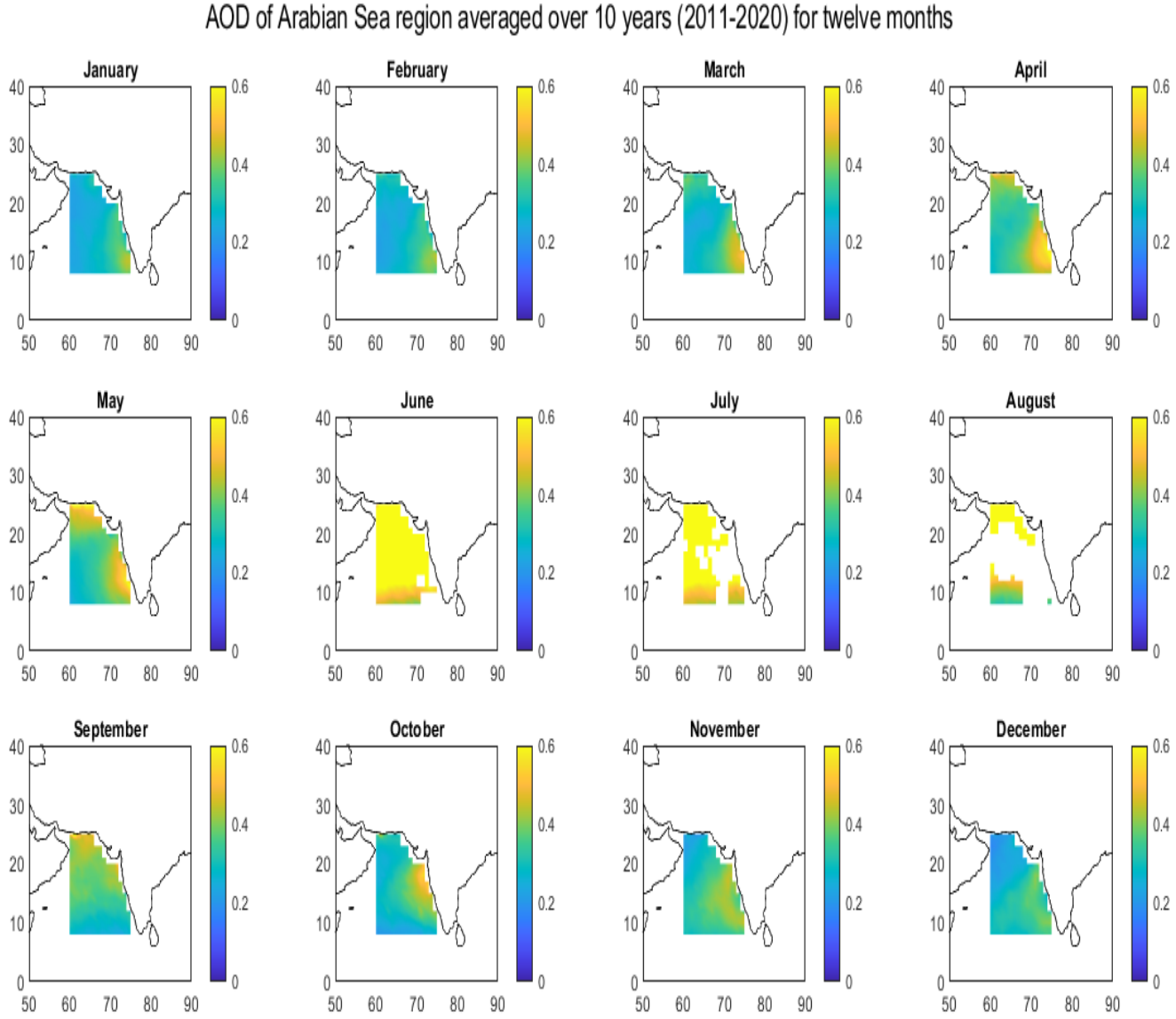


**FIGURE 5**

From the above plots it was observed that:

1. AOD has highest value in months of June, July and August. This implies that AOD has its larger values on late summer and early monsoon season.
2. AOD has moderate distribution at months of January, February, March, April and May.
3. AOD has a fall in month of September, October, November and December. This corresponds

to late monsoon and winter season.

Observations concluded that AOD has seasonal variation over Arabian Sea region. Mineral dust and sea salt aerosols are the most abundant aerosols by mass. These dust aerosols can be transported long distances from land to Arabian Sea. The seasonal variation of these aerosols is due to certain reasons. Several studies have shown that aerosol over Arabian Sea are correlated with Indian summer monsoon, rainfall, etc. During summer monsoon season in India, strong surface winds with velocities around 15m/s are experienced over most part of AS. These winds are capable of increasing sea spray activity, thereby enhancing production of Marine aerosols. About 60 % of the total aerosol content is by components of marine aerosols over the region increased by strong winds. The remaining part of aerosol comes from western and northern land mass around sea. Absorbing dust aerosols over Arabian Sea in lower and middle troposphere strengthens the south west monsoon flow by heating the troposphere.[50]Major part of aerosol loading is contributed by coarse-mode particles. But concentration of coarse mode aerosol is least during winter.

So can be concluded that increase in aerosol content over the AS during June, July and August is due to increase in marine aerosols and dust particles transported from nearby deserts. Hence increased AOD in monsoon is due to wind, rain fall and moisture transport and least AOD in winter season.

### 3.1.1.3 Regional variation of AOD over Arabian Sea

It is found that mean AOD over west Arabian Sea is least during January-February and increases in March-May period and increases drastically in July but decreases by September. The mean AOD over east Arabian Sea close to Indian peninsula is least during January –February. This increases in March to April period, also at south east Arabian sea, while it remains lesser in northern parts. At east Arabian sea AOD values decrease up to June. July to August shows high value of AOD over entire Arabian Sea. Throughout the year Northern part has higher AOD values compared to Southern parts of Arabian Sea.[46]

### 3.1.1.4 Monthly analysis of AOD for 10 years over Arabian Sea

From figure 6 it is observed that AOD distribution over each months are different. This variation is carefully analyzed. At each year the variation are similar but AOD has different rates.

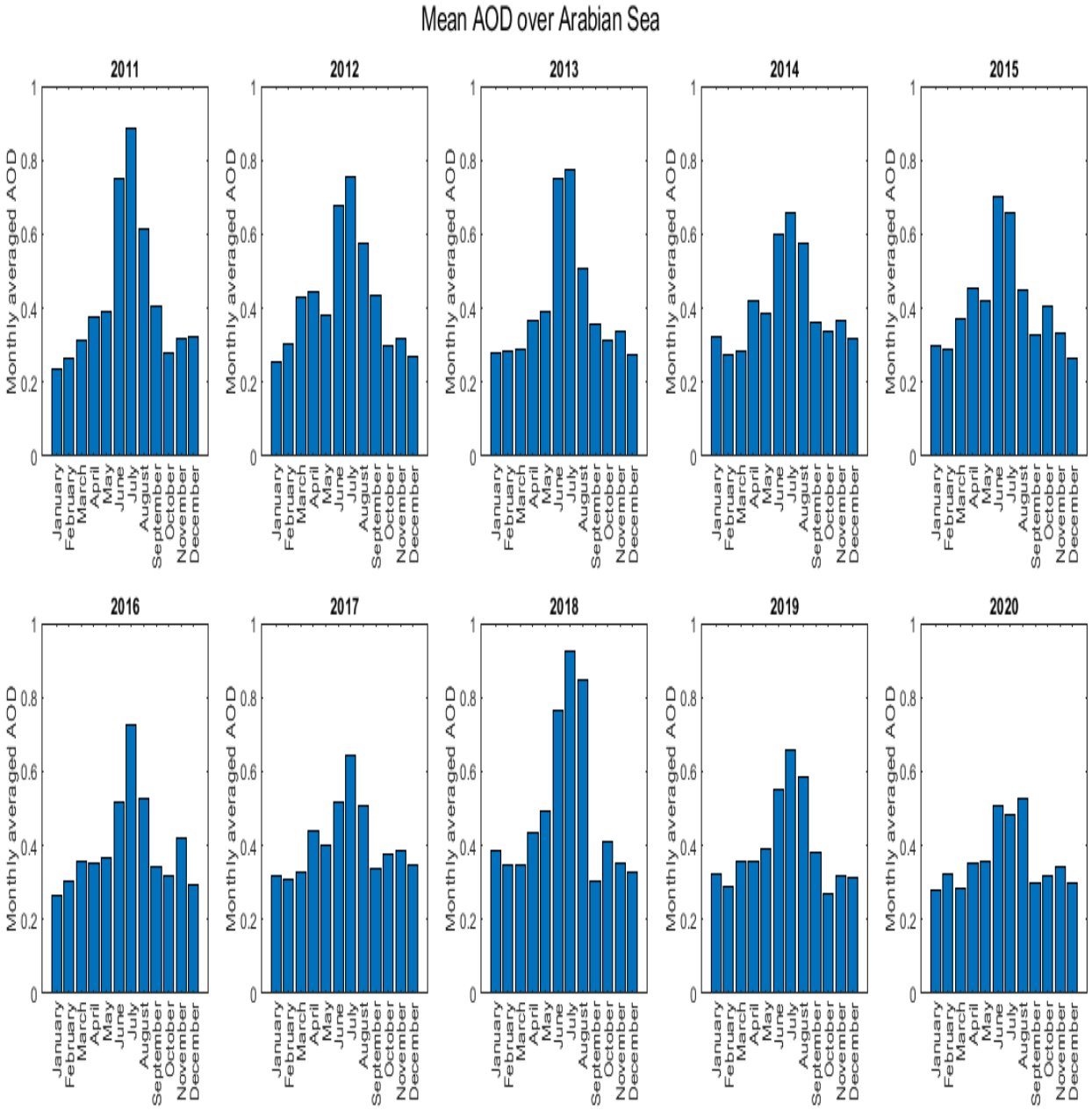


**FIGURE 6**

During 2011, 2012, 2013 and 2018 the AOD distribution over AS at monsoon increased rapidly and it is decreased by 2019 and 2020. The least values of AOD is over 2020 especially during monsoon compared to others. High amount of aerosol from India is brought to AS during monsoon

causing higher loading of AOD at monsoon season during 2011, 2012 and 2013. Years 2014, 2015, 2016 and 2017 corresponds to drought years in India leading to lower AOD over India and hence AS [51]. 2014 and 2017 had much drought effects that corresponds to most decreased trend in AOD over monsoon. Again in 2018 the AOD trend increases at monsoon due to heavy rain fall in India causing precipitation that increases aerosol content. Lowest AOD distribution is observed by 2020 especially at monsoon causing decreased anthropogenic aerosol in India due to outbreak of Covid19. So at 2020 the main contribution of Aerosol in AS is natural aerosol especially the dust particulates.[52]

### 3.1.1.5 AOD trend on Arabian Sea for 10 years

Combined monthly AOD of Arabian Sea and Bay of Bengal during the years 2011 to 2020 is given in figure 9. From the plot variation of AOD for different years can be compared in a monthly basis. The AOD values increase and decrease over different years randomly.

The yellow line that is continuously varying represents AOD variation over years. From graph it is approximated that peak value is almost at middle of the year, mostly over July corresponding to monsoon season as inferred from above observations. The amount of variation of AOD is changing by some units for different years. So it is important to study the overall trend of this AOD during this 10 years for Arabian Sea .This is possible by linear square fitting of average monthly AOD for 10 years. This linear fitting showed a decreasing trend of AOD over 10 years with a slope of –0.00022116. This decreasing trend is due to decline in aerosol over some years due to specific factors that influence AOD production and transportation over various regions. The decline is more on 2020 creating a great distribution to the decreasing trend over Arabian Sea.

## 3.1.2 BAY OF BENGAL

### 3.1.2.1Seasonal variation of AOD over Bay of Bengal

The figure 7 given below shows variation of aerosol distribution over each month averaged over 10 years

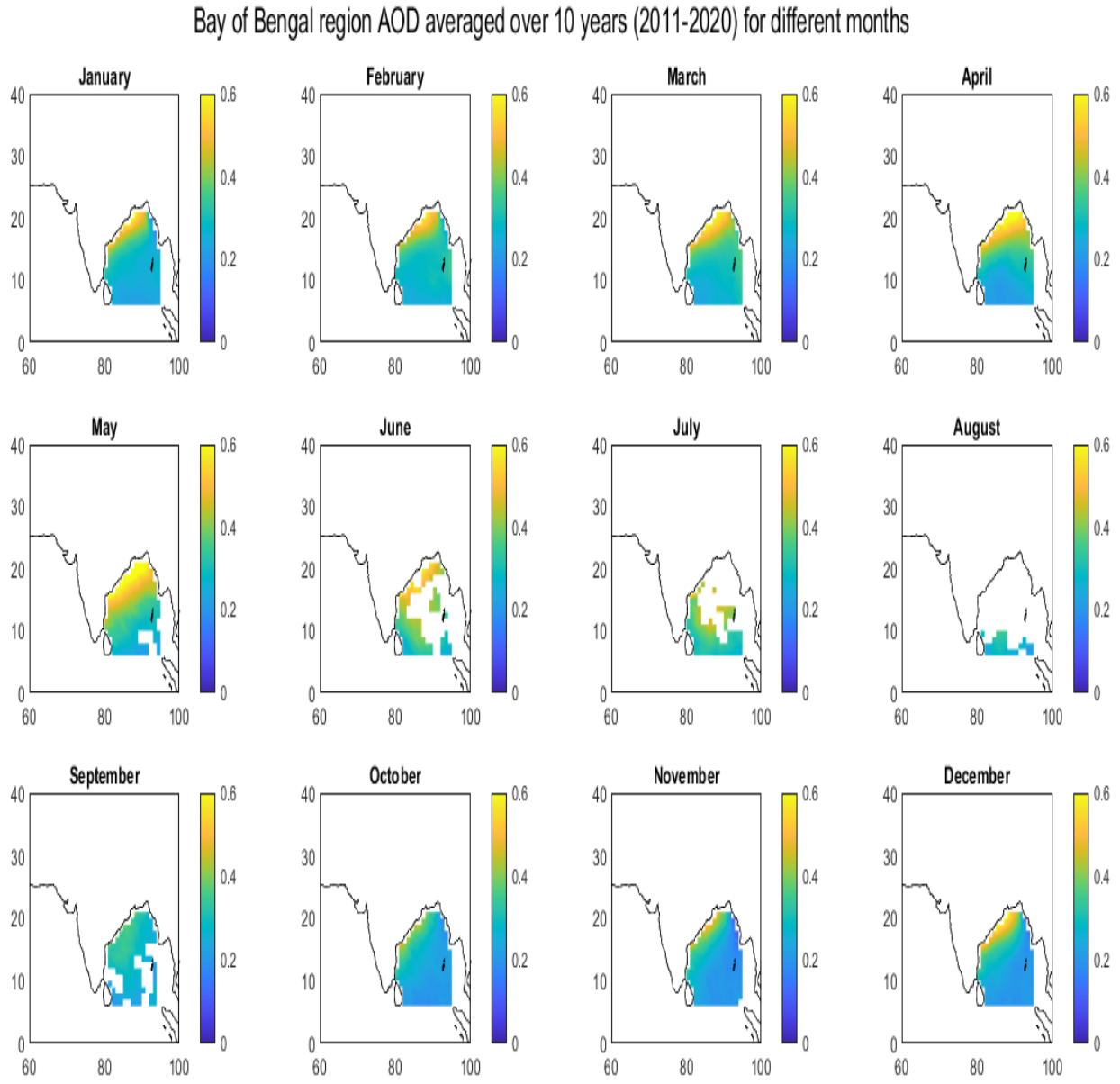


**FIGURE 7**

From the plot it is observed that:

1. The maximum value of AOD is in months of April, May, June and the June. This reflects that AOD has highest values almost in pre monsoon.

2. AOD is moderately distributed at months of December, January, February and March. This corresponds to late winter and early summer.
3. AOD has least values at months of August, September, October and November. This is corresponding to minimum value of AOD at winter

In general it is found that summer monsoon system is accompanied by heavy rain causing precipitation as well as the clouds formed are significant sources of wet removal of aerosol particle from atmosphere.

Elevation from Indo Gangetic Basin region are present at the region during pre-monsoon. Due to this, transport of aerosols at higher altitudes enhances extinction at altitudes of 1 to 3 Km over BoB, associated with advection from west Asia and western India. This Indian continental out flow into BoB during pre-monsoon and early monsoon season shows enhanced aerosols[49] . Relatively stable meteorological conditions during winter season inhibit long range transportation of polluted air-masses from land to oceanic regions. Aerosols transported to the BoB appear to originate from west Asia, north western central India and coastal areas of central eastern India. The mechanisms responsible for the aerosol production in these regions are dust storms, industrial emissions and biomass burning (as part of regional agricultural activities during the pre-monsoon period)[53]. Thus, the aerosols over the B0B will be a mixture of fine and coarse particles. However, the abundance of coarser particles will be relatively low as they get lost during the long-range transport before reaching the B0B.

### 3.1.2.2 Regional variation of aerosol over BoB

From early studies MODIS data a steady sharp increase on western BOB in AOD values are indicated when compared with southern BoB. During winter (November, December, January, February) wind blow dominantly from northeast, northwest during spring (March and April) southwest during summer and fall monsoon season (May to October) over BoB. So aerosols are received by western BoB from Indian subcontinent and eastern BoB receives from the Southeast Asia during winter. Also BoB receives pollutants from southeast of India during summer and fall monsoons. Nair et al. (2008) reported that emissions coming out of BoB is from emissions coming out of biomass burning transported from Myanmar. Where in Southern BoB fossil fuel emission

from east coast of India. AOD over northwest BoB has higher levels during spring and least during fall monsoon period. Higher total AOD central BoB is during May to July and least during September to November, which is due to transportation of aerosol by monsoonal winds [54] .

### 3.1.2.3 Monthly analysis of AOD for 10 years over Bay of Bengal

Figure 8 gives the detailed distribution of monthly averaged AOD over BoB for each month for 10 years.

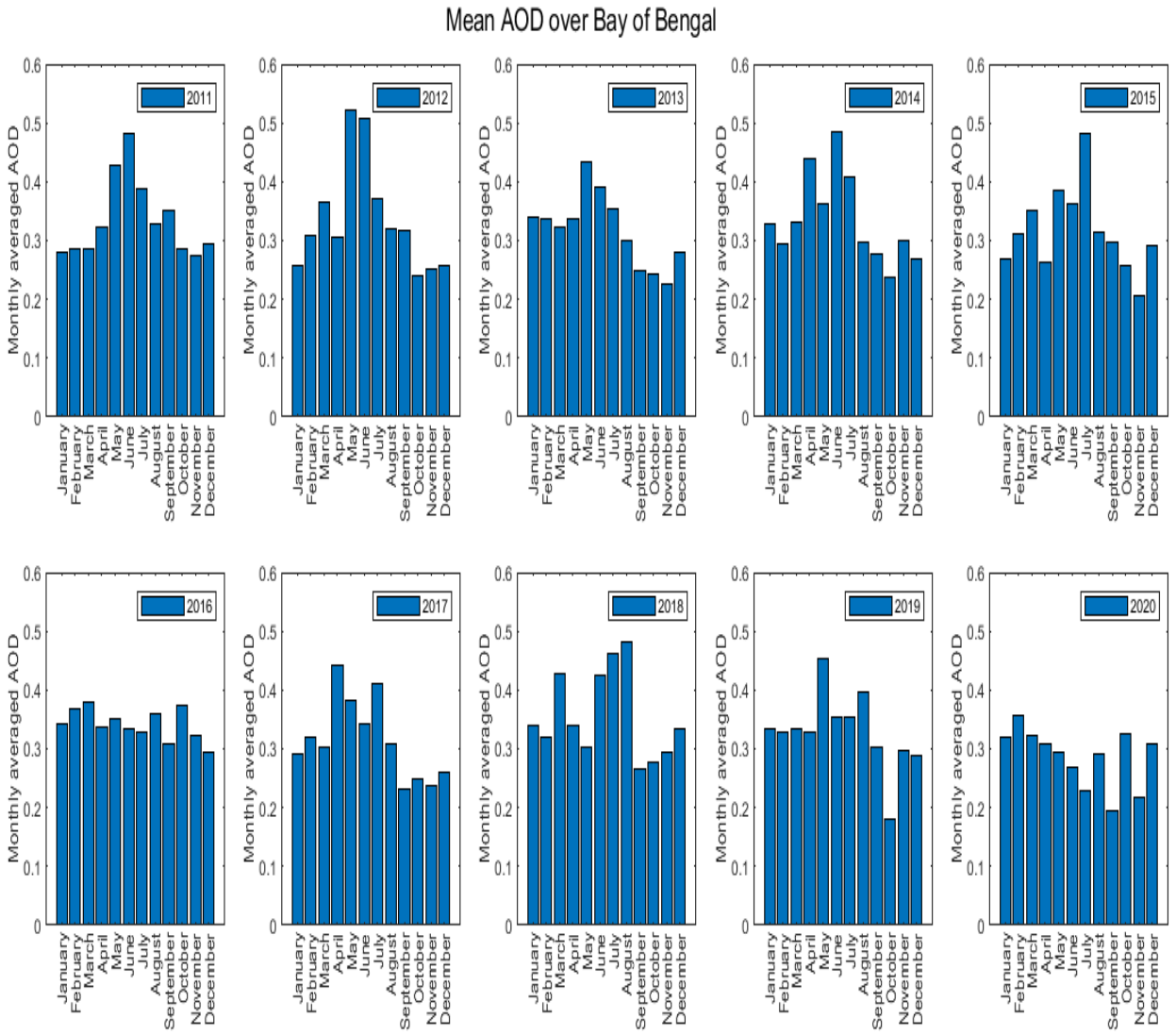


**FIGURE 8**

From the graph it is observed that the variation over different months are varying for different years. So it should be analyzed in detailed.

During 2011, 2012, 2013 higher AOD is over May, June and July. In 2014 AOD is higher over June followed by April and July. In 2015 the peak value of AOD is over July followed by May and March. AOD is least over October, November and March. Higher AOD distributions in these years corresponds to monsoon, which is caused due to high humidity in these month. Also transport of aerosol by summer monsoonal winds or long range dust transportation and growth of aerosol particles due to condensation process causes larger AOD. This higher distribution of AOD during monsoon is not observed in 2014 and 2015 due to drought condition of the year. All the 10 years have lower peak at winter. Relative smaller AOD in winter is due to calm meteorological condition that inhibit long range transport of aerosol from settlement area in winter. [53]

Year 2016 shows an anomalous behavior on AOD distribution over different months compared to previous years. Highest peak of AOD is shown at October followed by March and February. In 2017 higher peak of AOD is at April, July and May. In 2018 the highest AOD peak is over August, July, June and March. This trend in 2016 and 2017 were marked by strong El Niño and weak La Niña events which are trade winds which caused there variation. [55]

By 2019 the highest AOD peak is over May followed by August, June and July. AOD distribution is it at its lowest value over these 10 years at the month of October of the year. 2020 as year 2016 showed some anomalous behavior of AOD distribution over months with overall decrease in AOD for all months. The highest peak of AOD is over February followed by October and December. AOD is least over September, November and July. This is due to least anthropogenic contribution to aerosol due to outbreak of Covid19.

### 3.1.2.4 AOD trend on Bay of Bengal for 10 years

The trend of AOD over BoB is given by Figure 9 which shows a varying level along each month for continuous 10 years. It is represented by blue lines in the plot. Monsoon months shows peak in every year. It is observed that by 2020 the AOD reached a lower value. The overall trend is analyzed using least square fitting of the curve and it denoted by green line in the plot and it showed

a decreasing trend over 10 years and trend is observed mainly due to drop of AOD level in 2020 by COVID outbreak. The decreasing slope is given by -0.00022116.

### 3.1.3 Comparative analysis of AOD over Arabian Sea and Bay of Bengal

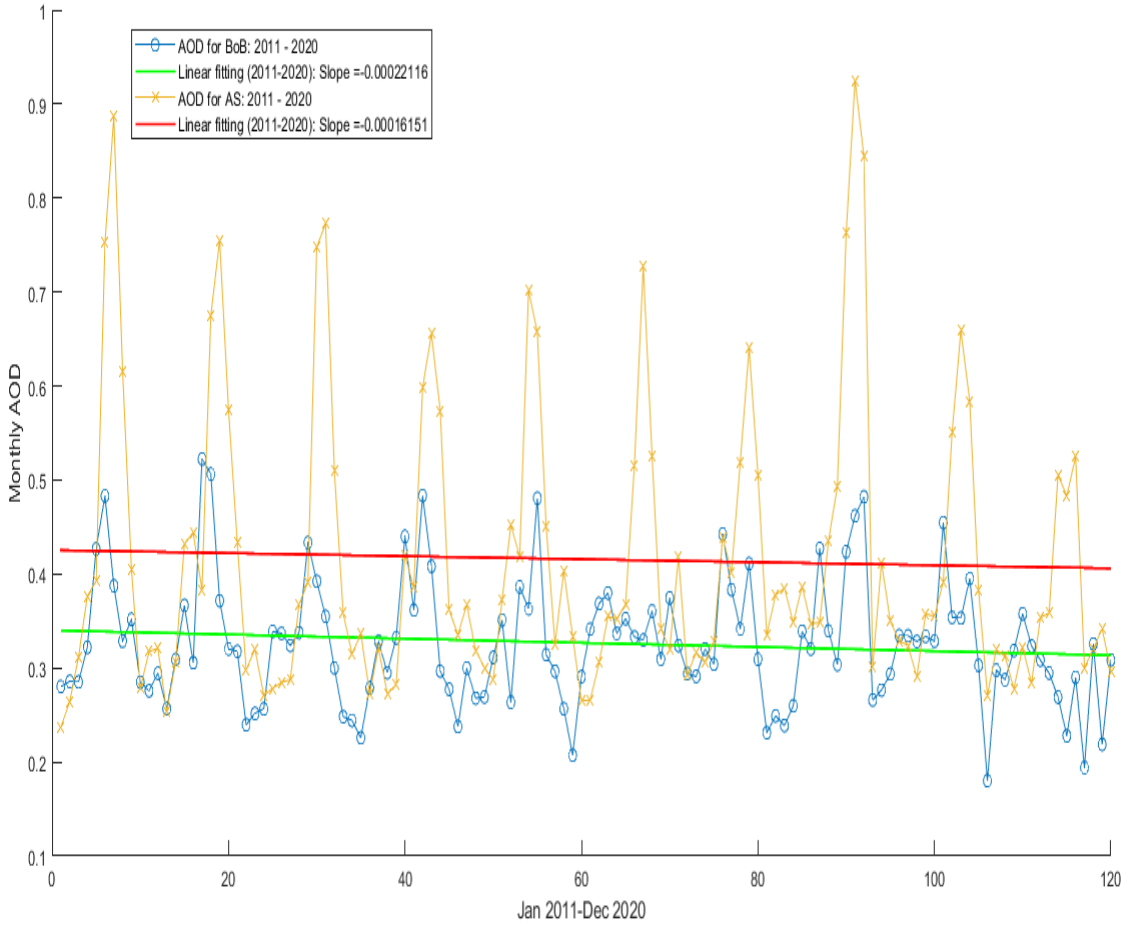


**FIGURE 9: Combined AOD trend over Bay of Bengal and Arabian Sea for 10 years from 2011-2020.**

Comparing to AOD trend of AS, BoB has a lesser contribution. The continental outflow of fine anthropogenic particulates especially from heavy aerosol containing Indo-Gangetic Plains dominate aerosol loading over BoB region during pre-monsoon and winter. AOD over BoB

declined during the period of Covid19 in 2020 compared to other years due to lesser aerosol loading in Indo-Gangetic Plains. BoB experience maximum AOD in pre-monsoon followed by monsoon season .Relative lower aerosol loading is observed over both the regions during post monsoon and winter season. Maximum AOD is found in July followed by June month over AS. There is a one month lag between AS and BoB for maximum aerosol loading in all years of observation, which is due to synoptic wind pattern and air mass back trajectories analysis. Elevated aerosol layers are found during May-August over both regions with more prominent over AS than BoB that could be rationalized by higher fraction of long range transported aerosol at higher altitude over AS .Elevated aerosol layer are also observed during October-November is more prominent over BoB than AS due to dominant long range transportation of agricultural biomass burning aerosol from IGP region. [42]

## 3.2 INDIAN REGION

In India aerosol distribution shows large variability in daily seasonal and inter-annual scales leading to short life time, heterogeneity in sources and dependency of aerosols on meteorological conditions. Aerosol distribution is also effected by large variability in vegetation cover and topology over India. Variation of AOD is studied in India for 10 years from 2011 to 2020 with respect to 3 zones, North, South and Central India. These regions are divided in the basis of considering North India consisting of Indo-Gangetic Plains, Central India consisting of Desert region and South India in a normal condition.[56]

### 3.2.1 Variation of AOD over North India

North India lies in one of the hotspots of increasing atmospheric pollution due to rapid urbanization and growing energy demand. Over this region there is a significant variability of aerosol loading due to complex combination of anthropogenic factors like biogenic burning, industrial activities, etc mixed with contribution from natural sources. This is particularly in pre-monsoon season where mineral dust are frequently transported from Thar Desert. Towering Himalayas in North, lowering plain topography, and wind direction favor accumulation of aerosol over the region.

### 3.2.1.1 Seasonal variation of AOD over North India

Using MODIS data spatial variation of averaged AOD over Indian region is found out. Analysis showed an over all higher AOD distribution over Northern region of India due to meteorogical factors.

1. Highest AOD is over months of May, July and July. Which corresponds to late summer and early monsoon season.
2. Least AOD is at March and April corresponding to spring season.
3. AOD has moderate distribution at September, October, November, December, Jnauary, February and March corresponding to late monsoon and winter season.

The summer season shows high AOD over whole basin south of Himalayan mountain range. North-east region shows high aerosol loading which may be due to forest fires during pre monsoon months along with cloud condamination due to cloud cover that prevail over region during pre monsoon. In monsoon season Eastern part show comparitively lower AOD as monsoon rain washes away most of aerosol from toposphere. But it is seen that large anthropogenic aerosols over the region prevails over the region during early monsoon that creates highest AOD over entire year.During monsoon season wide area of high aerosol is along Indo Gangetic Plains extending from North AS through north west India and Himalayan foothills. During winter season western zone show lower values and it gradually increases to eastern zone. In spring season AOD has its lowest value in North zone of India with high value on north west part of India. So over all AOD is highly present  Norther India or Indo-Gangatic Plain throughout each year.[57]

### 3.2.1.2 Average monthly variation of AOD over 10 years in Northern India

Figure 10 shows the monthly averaged AOD distribution for each year from 2011 to 2020. So distribution of AOD over various months and years can be analized in detail.

2011 and 2012 shown a similar pattern of AOD distribution with maximum AOD over June and July. The monsoon wind causing dust transport from Arabian desert and aerosol over IGP contribute natural aerosol over this month. The anthropogenic sources bring a greater contribution over this period where the aerosol wash out at early monsoon is lesser. 2013 represented an over all decrease in AOD especially over larger Aerosol contributed months of June and July. This

decreased trend on 2013 is found to be due to large amount of rain fall along with cyclone over Northern India causing decreased anthropogenic activities that effected decrease amount in aerosol on these years.

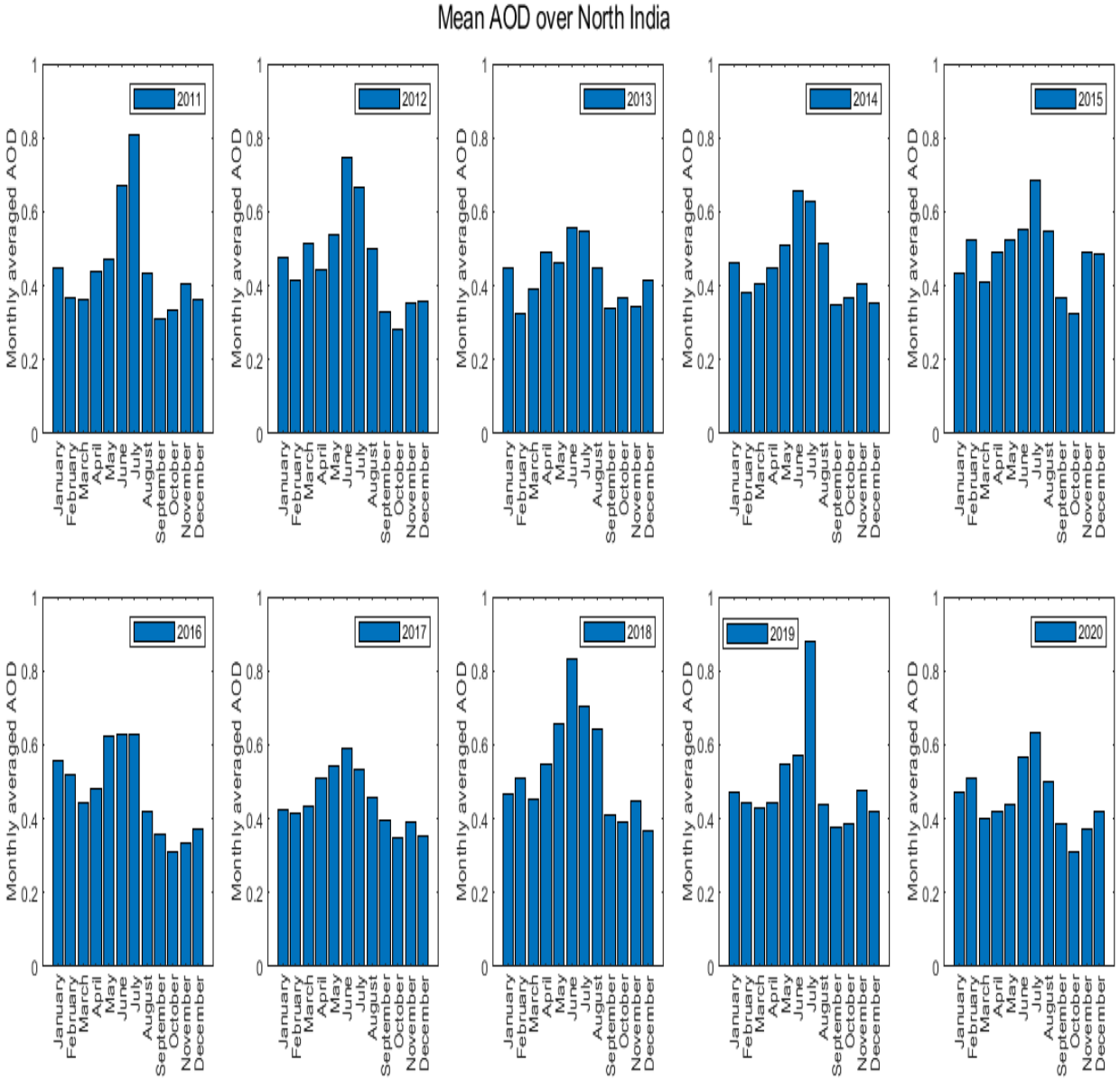


**FIGURE 10**

Years 2014, 2015, 2016, 2017 showed an incresed AOD in monsoon comparing to 2013 but an over all decrease in monsoon comparing to previous years.2014,2015, 2017, 2018 showed drought

at monsoon causing lesser rainfall. So the scarcity of humidity caused decreased AOD in June, July and Audust over these period comparing to other years. Black carbon concentration is more in Winter followed by post monsoon, pre monsoon and monsoon.[58]

At 2018 and 2019 there is a rapid increase in AOD at June and July which may be due to anthropogenic aerosols caused by large urbanistion. Again in 2020 there is a large decrease in highly AOD producing month. The major cause is the COVID 19 out break that decreased the level of anthropogenic aerosol production that mainly contributed to AOD .

The reason for higher AOD over monsoon is found to be due to increase in rainfall causing high humidity leading to hydroscopic growth of water soluble aerosols. A contrasting phenomena of rainfall causing wet romoval of aerosols decrease the AOD over the region. But the increased AOD due to hydroscopic growth dominate wet romoval of aerosol. So an over all great increase in AOD at monsoon arise due to insufficient removal of aerosol by wet deposition, replenishment of aerosol due to natural sources and growth of existing hydroscopic aerosol due to high ambient relative humidity during summer season. [59]

## 3.2.2 Variation of AOD over Central India

The second zone considered is central part of India lying in desert region. Here there is a dominence of natural aerosols as it lies in desert dust dominated region in Indian sub-continent. Large fraction of aerosol over this region is due to transported dust from arabian sea.

### 3.2.2.1 Seasonal variation of Aerosol over central India

By analyzing the plot of averaged AOD for 12 months over 10 years

1. Highest AOD is in the month of June, July and August corresponding to monsoon season.
2. AOD is moderately distributed at March, April and May corresponding to summer season.
3. AOD is least at Winter season.

Change in wind speed over AS also influence loading of aerosol over the region along with anthropogenic sources. Over this region a dry and humid climate is experienced except at monsoon season. Mean wind speed is high during monsoon and post monsoon and it is maximum over June

and July which is observed from figure 9. So aerosol concentration also increses corresponding to this. So AOD increases and reaches a high value and decreases by winter and starts increasing in late winter and pre monsoon. [56]

### 3.2.2.2 Average monthly variation of AOD over 10 years in central India

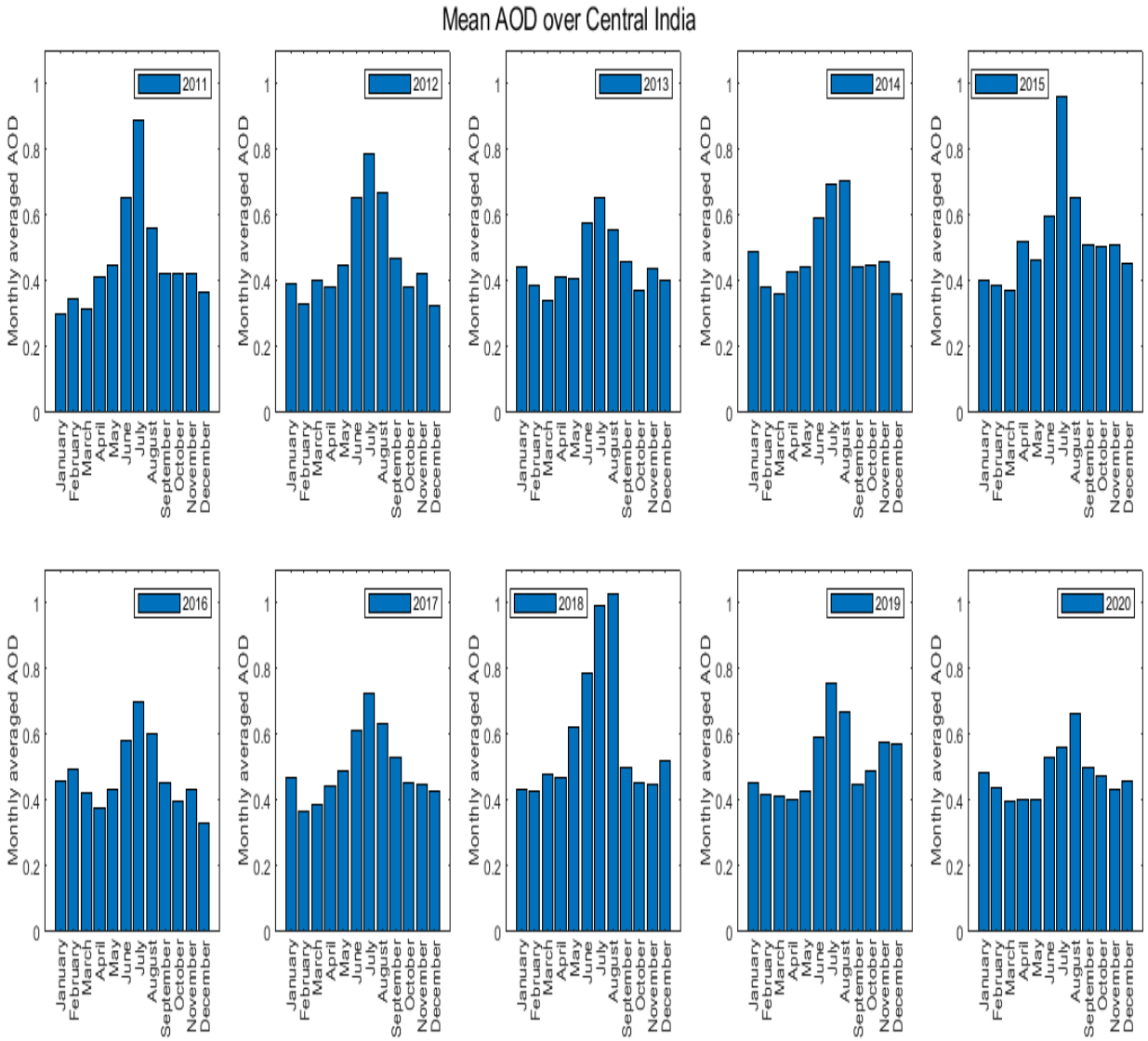


**FIGURE 11**

The detailed distribution of AOD over central india is given for each month in 10 years. This can be analysed in detail to get a better idea.

AOD distribution of June, July and August of 2011 and 2012 has higher values. It decreases in 2013 and slightly increase in 2014 and reaches a very high value for June in 2015. This trend slowly decreases and reaches a reasonable range on 2016 and 2017. At 2018 AOD reaches a very high value over this 10 years on June and July. In 2019 trend start to decrease and by 2020 AOD range decreases slightly compared to other years. This variation of AOD over years is due to specific reasons or changes taken place. AS is located down wind to CI so aerosol over here effect AS. In central india most of aerosols are anthropogenic due to increased biomass burning activities over tne region. Biocarbon mass concentration is highest in winter and lowest in monsoon. It remain moderate in pre monsoon and post monsoon. [59]

In Central India during lockdown increased tropospheric RH and decreased wind speed along with residual emission and favourable wind direction maintained high AOD comparing to other regions of India. Factors like biomass burning in adjacent region and long range transport of desert dust also may have contributed to this.

### 3.2.3 AOD variation over South India

South India is bounded by AS to west and western ghats to east. It is entirely covered by ocean to the south. Over this region cleaner air is generally expected compared with North Indian region since marine air prevails over much on the region, but rapid industrialization and urbanisation leads to large amount of anthropogenic aerosol in this region. Additional temperature during summer season also plays an important role in heating and lifting loose soil with association of wind speed. AOD of South India is entirely different from that of North India. Region shows lesser AOD compared to North [56] .

#### 3.2.3.1 Seasonal variation of AOD over South India

By analyzing the plot of averaged AOD for 12 months over 10 years

1.AOD is highest over May to August. Corresponding to post summer and monsoon season

2.AOD distribution is moderate at February- April, September – October corrsponding to spring.

3.Least AOD distribution is at November to February corresponding to Winter.

Wind and temperature has a significant influence on aerosol content over the region. In BoB aerosols are transported from India during winter. In summer, spring and monsoon marine aerosols are loaded to India. South east and south west India are seperated by western ghats that act as barrier for transport of aerosols between these region.

During January air masses move towards north east region including BoB and south tip of India. But presence of Western ghats in India act as hindrance to transport of aerosol from eastern part. So during January there is no aerosol over east. During october transport occurs from south from Indian ocean and trajectory is confined in nearby regions in AS. Trade winds that had northeasterly direction reverse during summer months due to increasd heating of land region in comparisin to Indian ocean. So transport of marine aerosol from ocean to land takes place in summer. In April, transport occurs mainly from the Arabian Sea. The trajectory does not elongate much towards the Arabian Sea at 1500 m as observed at the surface and is confined to the west coast region of the sea. This is the altitude where the core of the Low Level Jet stream is located in association with the summer monsoon [59]. These indicate the presence of marine aerosols besides locally originated particles. During July, transport occurs from far interior parts of the Arabian Sea. This is associated with the south westerly monsoon wind, which brings moisture and aerosols from the Arabian Sea and the Indian Ocean. During this season, presence of marine aerosols is expected over the station since the high-speed wind makes sea surface rough and causes increase in production of marine aerosols [50].

### 3.2.3.2 Average monthly variation of AOD over 10 years in South India

Figure 12 gives a clear picture of aerosol distribution over different months on South India for 10 years.

Greater distribution of  aerosol is over May,june, July and August at 2011,2012 and 2013. This is due to conditions over monsoon causing high humidity leading to higher water soluble aerosol consentation, hence higher AOD in late summer and monsoon months. This hydroscopic growth dominates wet removal of aerosol by rainfall.

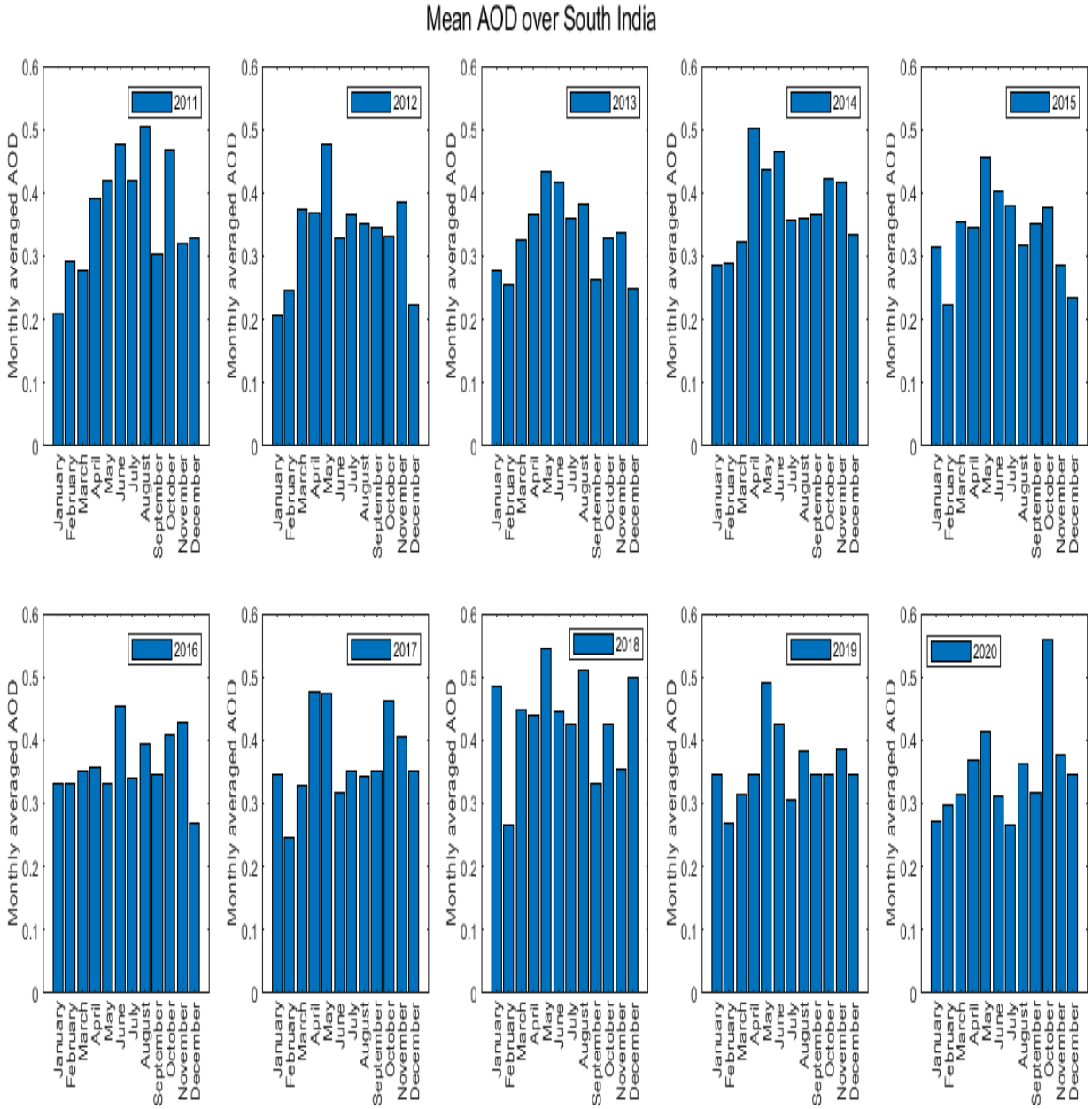


**FIGURE 12**

At 2014, 2015, 2016 AOD peaks are over April, May, June July. This is due to conditions over monsoon causing high humidity leading to higher water soluble aerosol consentation. The hydroscopic growth dominates wet removal of aerosol by rainfall. Hence higher AOD in late summer and monsoon months. The unexpected peak on April for these years is due to increased anthropogenic activities during these periods. During 2017 there is an unexpected trend of

maximum AOD at April and May. The decresed AOD over monsoon period of June July and August is due to insufficient raifall caused due to drought in 2017 [60]. Coming to 2018 there is a random variation of AOD over different months. It has peaks at May, August, December and January. At 2019 peak of AOD are at May, June August. At 2020 a contrasting AOD peak is seen in October but the over all distribution is not much lesser as comparing to other years in south India. 2020 is an year of outbreak of covid 19. Due to this Sothern India resulted in reduced anthropogenic emission of primary aerosols and precursor gases but there is no much change due to ongoing anthropogenic activities during lockdoown.

From the above plot the over all AOD is decreased other than in 2020 over 2014, 2015, 2016 and 2017. This is more in 2014 and 2017 which are due to drough period in India.

The over all AOD is decreased in 2020, 2014, 2015, 2016 and 2017. This is more in 2014 and 2017 which are due to drough period in India.

## 3.4 Over all trend of AOD over Indian region

The over all AOD over 3 regions of India over 10 years corresponding to different months are plotted and the trend is analysed.

The figure contains a blue line showing a variation of AOD over North Indian in 10 years through 12 months creating an over all 120 month data distribution. Yellow line shows variation of AOD over 10 years through different months in Central India and black line shows a variation of AOD over 10 years through different months in South India. The data is carefully analysed.

We can see a higher AOD over North India followed by Central India and least in South India. This is because Noth India consist of Indo Gangetic plain which are highly poppulated and urbanistion causes increased anthropogenic aersols. The varying trend over different years continues and by 2020 there is a decreased peak of AOD over North India due to decreased anthropogenic aerosol due to Covid19 outbreak. Followed by this Central India is the next higher

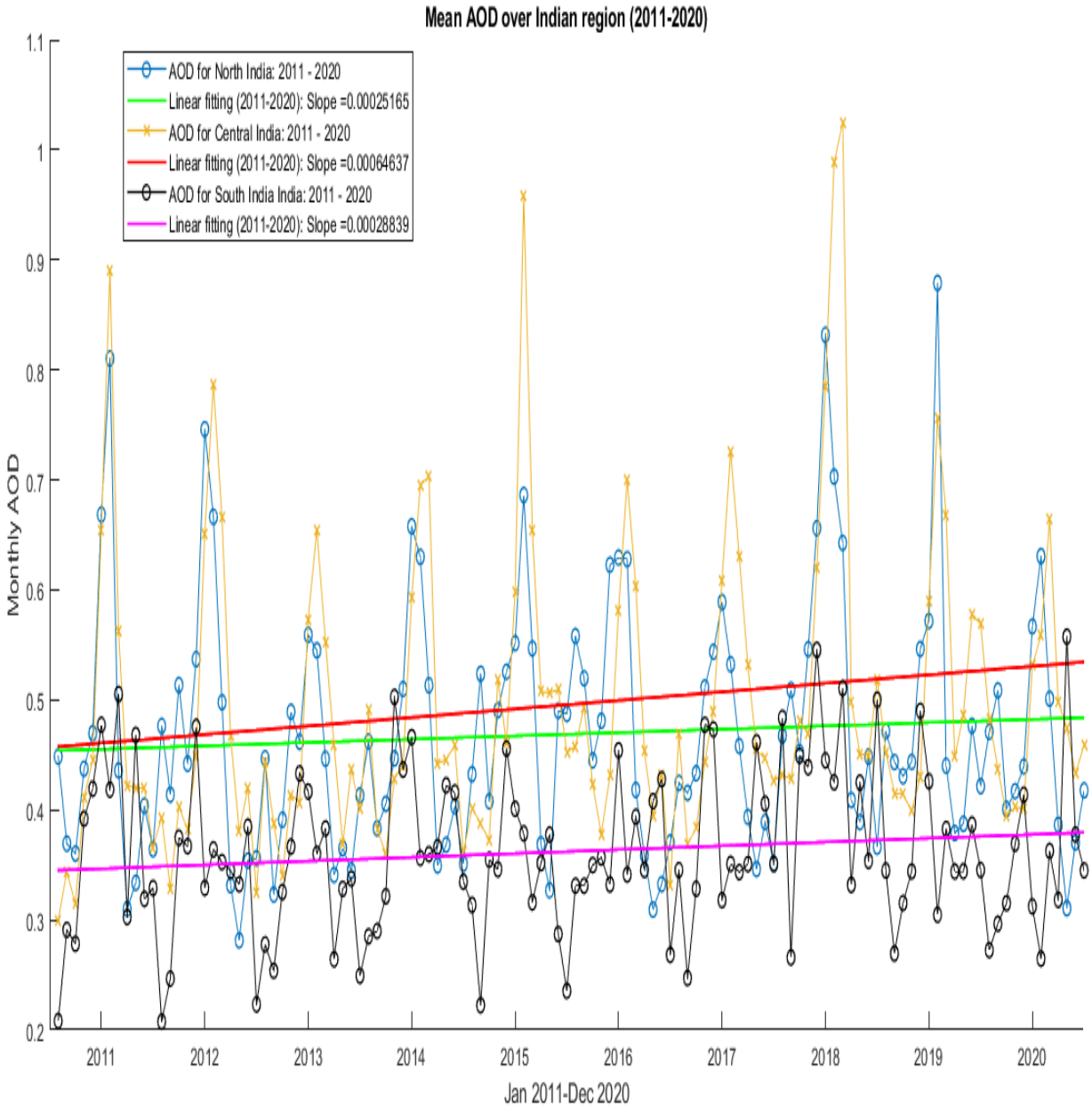


**FIGURE 13: Combined AOD trend over Indian region for 10 years from 2011-2020.**

AOD distributed region. Central India surrounded by Indian desert , IGP in North and Costal India in east and west has a dry and humid semi-climate prevailing through out the year causing lesser

AOD compared to North. It shows a moderate AOD values. Thar desert from north east region and transport of dust from middle east contribute AOD in summer. Thar desert and dry season provide higher AOD in pre monsoon and highest AOD of year is provided by humidity of the season. So this variation over season continues for different year and by 2020 there is no much decrease in AOD as in the case of North India. Elavated dust aerosol layers transported from Middle East and Africa via long range transport and decrease in wind speed cause aerosol to stagnate over Central India. Increase in relative humidity amplified the aerosol further. So besides emission natural aerosols played the crucial role of increased AOD over the region in 2020. The least peaks at the plot is for South India. In general marine air prevails over much of Southern India surrounded by ocean and so cleaner air is expected. This leads to lower AOD over the region. As in above case there is a comparitive raise in AOD at monsoon due to humid air trapping water soluble pollutants. Even the Covid19 break out at 2020 doesnot effected the aerosol content over South India.

The overall trend of AOD over 10 years are studied for the 3 region by linear fitting of the 3 curves seperately. North India, Central India and South India showed an increasing trend with a small slope of 0.00025165, 0.00064637 and 0.00028839 respectively. So an over all increasing trend is observed in India for a period of 2011 to 2020. By comparing the slopes highest slope is found to be for central India followed by South and North India. The decreased anthropogenic aerosol sources in North India may be the reason for least slope in North.

# CHAPTER 4
# GENERAL CONCLUSION AND FUTURE SCOPE

The aerosol loading and distribution is studied for Indian region and the ocean region enclosing India which are Bay of Bengal and Arabian sea. AOD data from MODIS for the years 2011 – 2020 has been used to make a detailed investigation into the spatial and yearly trends in AOD over the Indian subcontinent and oceanic regions. There is an increasing trend over North, South and Central India. This also shows the larger contribution of AOD on North India over all these years followed by Central India and least AOD distribution over South India. Comparing to Bay of Bengal, Arabian sea has larger AOD. Air back trajectory analyses suggests that aerosols from different source regions contribute differently to the optical characteristics over the Bay of Bengal and Arabian Sea. Trajectory analysis showed that the Bay of Bengal was mainly influenced by the eastern coast of India, the Indian Ocean mainly by the Indian subcontinent and the Arabian Sea by the northwest of India and countries lying northwest of India.

Over the Indian region the AOD trend is increasing at a period of 2011 to 2020. The main contribution of AOD variation is due to anthropogenic sources along with natural pollutants. Seaonal variation also contribute to AOD distribution over india which also effects AOD in oceanic region around India. The yearly average regional analysis shows that AOD increases as we move from South towards North of India. AOD values are very high over the Indo-Gangetic Plain with the highest values noticed in Delhi compared to many of the states along the IGP. Seasonal Climatology and monthly climatology shows the heavy aerosol loading over the IGP over the Indian subcontinent. Considering the oceaninc regions both Bay of Bengal and Arabian Sea has a decreasing trend which is due to aerosol loading variation from Indian region. The highest loading in aerosol over India is found during the summer monsoon season with the highest values occurring in July. The lowest values in AOD are seen during the pre-monsoon season. The moderately high value of AOD seen over the South-Eastern Arabian Sea during the pre-monsoon months is a typical feature. The spatial variability of AOD depends upon source strength of emissions and weather conditions, which are subject to change with season. The overall increasing and decreasing tendency of AOD related to fluctuation of aerosol load is sensitive to total volume

of emission and production of aerosol through natural process and its removal through dry and wet deposition.

Covid19 break out in India has a great influence in increasing decreasing trends in Indian region and ocean region surrounding them which is effected by low anthropogenic source emission due to declined industrialisation and urbanisation especially in North India. So it gave an idea of decresing aerosol attainement for better future.

This seasonal heterogeneity could be understood as the effect of long range/short range transportation from various emission sources on aerosol properties over the oceanic region. The present study also indicates the possible role of Indian summer monsoon in modulating the aerosol behaviour over AS and BoB, which needs further deep inspection with higher temporal/spatial resolution data. Further this study can be extended to predict the change in climate over various regions due to the present aerosol content. The aerosol content over atmosphere effect further rain fall and temperature of specific regions. Increase in AOD during different season cause adverse effect to agricultural crops and human health. Increasd aerosol loading affect the rainfall which is responsible for observed drought condition over India. Detailed analysis of AOD is required to understand impact of aerosol loading over India. It is important to control the amount of aersol over the atmosphere to prevent its ill effects on both health, environment and earth balance.

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